

**Prepared in cooperation with Washington State Department of Ecology and
U.S. Environmental Protection Agency**

Estimation of Total Nitrogen and Total Phosphorus in Streams of the Middle Columbia River Basin (Oregon, Washington, and Idaho) Using SPARROW Models, with Emphasis on the Yakima River Basin, Washington

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**U.S. Department of the Interior
U.S. Geological Survey**

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Contents

Abstract.....	1
Introduction.....	1
Purpose and Scope	2
Methods.....	2
The SPARROW Model.....	2
Model Domain	2
Model Datasets.....	2
Hydrologic Network	2
Nutrient Sources.....	4
Land-to-Water Delivery	4
Calibration Loads	4
Model Calibration.....	6
Evaluation of Calibrated Models	7
Modeling Results for the Yakima River Basin	10
Yields	10
Source Shares.....	10
Longitudinal Changes in Nutrient Sources Comprising the Load in the Yakima River	10
Model Calibration and Uncertainty.....	16
Nutrient Yields and Land Use.....	18
Comparison with Regional SPARROW Model.....	22
Summary.....	22
References Cited.....	23
Appendix A. Prediction Results and Calibration Loads	27

Figures

1. Map showing land cover and major rivers of the Middle Columbia River Basin, Oregon, Washington, and Idaho.....	3
2. Map showing model residuals of stream load for the total nitrogen SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho	8
3. Map showing model residuals of stream load for the total phosphorus SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho	9
4. Map showing incremental yield of total nitrogen for the Yakima River Basin, Washington.....	11
5. Map showing incremental yield of total phosphorus for the Yakima River Basin, Washington.....	12
6. Map showing largest source of total nitrogen in each incremental catchment in the Yakima River Basin, Washington.....	13
7. Map showing largest source of total phosphorus in each incremental catchment in the Yakima River Basin, Washington.....	14
8. Graph showing sources of total nitrogen contributing to the total nitrogen load in the Yakima River, Washington	15
9. Graph showing sources of total phosphorus contributing to the total phosphorus load in the Yakima River, Washington	15
10. Boxplot showing distribution of total nitrogen yield in catchments with a single dominant land use in the Yakima River Basin, Washington	19
11. Boxplot showing distribution of total phosphorus yield in catchments with a single dominant land use in the Yakima River Basin, Washington	19

Tables

1. Nutrient sources and model statistics for the total nitrogen SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho.....	5
2. Nutrient sources and model statistics for the total phosphorus SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho	6
3. Values of total nitrogen and total phosphorus yield from published reports and values of total nitrogen and total phosphorus yield calculated from data in published reports.....	20
4. Comparison of model diagnostic statistics and directly comparable source-term model coefficients for the SPARROW models developed for the United States Pacific Northwest and the Middle Columbia River Basin, Oregon, Washington, and Idaho	21

Conversion Factors, Datum, and Abbreviations and Acronyms

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Flow rate	
cubic meter per second (m ³ /s)	35.3107	cubic foot per second (ft ³ /s)
	Length	
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km ²)	247.1	acre
	Mass	
kilogram per year (kg/yr)	2.205	pound avoirdupois per year (lb/yr)
	Application rate	
kilogram per hectare (kg/ha)	0.8921	pound per acre (lb/acre)
kilogram per hectare per year [(kg/ha)/yr]	0.8921	pound per acre per year [(lb/acre)/yr]
kilogram per square kilometer per year [(kg/km ²)/yr]	0.008921	pound per acre per year [(lb/acre)/yr]

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datum

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Abbreviations and Acronyms

Abbreviation or acronym	Definition
IQR	interquartile range
NAWQA	National Water-Quality Assessment Program
NHD	National Hydrography Dataset
NLLS	nonlinear least squares regression
PNW	Pacific Northwest
RK	river kilometer
RMSE	root mean squared error
SPARROW model	Spatially Referenced Regression on Watershed attributes model
TN	total nitrogen
TP	total phosphorus
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WDOE	Washington State Department of Ecology
WWTP	wastewater treatment plant

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Abstract

The watershed model SPARROW (Spatially Related Regressions on Watershed attributes) was used to predict total nitrogen (TN) and total phosphorus (TP) loads and yields for the Middle Columbia River Basin in Idaho, Oregon, and Washington. The new models build on recently published models for the entire Pacific Northwest, and provide revised load predictions for the arid interior of the region by restricting the modeling domain and recalibrating the models. Results from the new TN and TP models are provided for the entire region, and discussed with special emphasis on the Yakima River Basin, Washington.

In most catchments of the Yakima River Basin, the TN and TP in streams is from natural sources, specifically nitrogen fixation in forests (TN) and weathering and erosion of geologic materials (TP). The natural nutrient sources are overshadowed by anthropogenic sources of TN and TP in highly agricultural and urbanized catchments; downstream of the city of Yakima, most of the load in the Yakima River is derived from anthropogenic sources. Yields of TN and TP from catchments with nearly uniform land use were compared with other yield values and export coefficients published in the scientific literature, and generally were in agreement. The median yield of TN was greatest in catchments dominated by agricultural land and smallest in catchments dominated by grass and scrub land. The median yield of TP was greatest in catchments dominated by forest land, but the largest yields (90th percentile) of TP were from agricultural catchments. As with TN, the smallest TP yields were from catchments dominated by grass and scrub land.

Introduction

Numerous streams and rivers throughout the Middle Columbia River Basin do not meet State water-quality standards directly or indirectly because of nutrient enrichment (Oregon Department of Environmental Quality, 2013; Idaho

Department of Environmental Quality, 2013; Washington Department of Ecology, 2013a). High concentrations of nitrogen and phosphorus nourish communities of algae and photosynthetic cyanobacteria, which can cause large diurnal swings in dissolved oxygen and pH that can be toxic to sensitive fish species, including threatened and endangered salmonids. Decomposition of those communities in the late summer and autumn consumes dissolved oxygen that can stress or kill aquatic organisms (Carter, 2005; Wise and others, 2009). Nutrient enrichment also affects the cost of treatment and the quality of drinking water. Algae cause taste and odor issues in public-water supplies and the organic carbon content of the organisms contributes to the production of harmful disinfection byproducts in treated drinking water. Blooms of toxic photosynthetic cyanobacteria have been documented throughout the Pacific Northwest (PNW) (Oregon Health Authority, 2013; Washington Department of Ecology, 2013b). These blooms increase the expense of treating drinking water and are a public health hazard (Stone and Hitchko, 2009).

Water-quality models can help regulatory and management agencies address nutrient issues by providing insight into sources, transport paths, and transformation mechanisms. Since 2006, the U.S. Geological Survey (USGS) has been developing SPARROW (Spatially Related Regressions on Watershed attributes) models for the PNW as part of the National Water-Quality Assessment (NAWQA) Program. New SPARROW models for total nitrogen (TN) and total phosphorus (TP) for the PNW were recently published by Wise and Johnson (2013). These models updated the original models (Wise and Johnson, 2011) with a refined hydrologic network, updated nutrient source data, and revised calibration load estimates. In 2011, the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (WDOE) requested assistance from the USGS in understanding the sources and transport of nutrients in the Yakima River Basin, Washington. Although the Wise and Johnson (2013) SPARROW models can provide such information, it was expected that the models could be improved by recalibrating them for a region that excluded the wet, western areas of Oregon and Washington.

Purpose and Scope

This report describes the methods used to develop and the results of two SPARROW surface-water nutrient models of the Middle Columbia Basin, Oregon, Washington, and Idaho. The objectives of this study were (1) to recalibrate the Wise and Johnson (2013) PNW SPARROW models for TN and TP for a modeling domain limited to the Middle Columbia River Basin, (2) to predict the nutrient load in monitored and unmonitored streams in the Yakima River Basin, and (3) to evaluate the relative importance of the modeled TN and TP sources to the nutrient load of streams in the Yakima River Basin.

Methods

The SPARROW Model

The SPARROW model is a hybrid statistical and mechanistic model for estimating the movement of mass through the landscape under long-term, steady-state conditions (Schwarz and others, 2006). A calibrated model provides predictions of the annual load and annual yield (load per unit area) for the constituent of interest (TN and TP for this report) for every reach in the modeled surface-water network.

The SPARROW model uses data describing catchment attributes (nutrient sources, landscape characteristics, and stream and water body properties) to explain the spatial variation in estimated, mean annual stream load (expressed as kilograms per year). Estimated, mean annual stream loads are the dependent variable (calibration dataset) for the model, and the catchment attributes are the explanatory variables. The model uses a weighted nonlinear least-squares (NLLS) regression to estimate coefficients for the terms representing catchment attributes. Confidence intervals for the estimated coefficients are obtained by resampling using non-parametric bootstrap analysis as described by Schwarz and others (2006).

Model Domain

The Middle Columbia River Basin model domain is 318,778 km² and is comprised of parts of Idaho, Nevada, Oregon, and Washington (fig. 1). The climate in the region is characterized by hot, dry summers and cold winters. Most precipitation falls between October and March, and snow is common during the winter months. Mountainous regions typically are forested, and low elevations are dominated by desert grasses and shrubs and agriculture. The region is sparsely populated; major population centers include the cities of Spokane, Washington, and Boise, Idaho.

In 2001, shrub and grass land covered 47 percent of the Middle Columbia River Basin, forest covered 35 percent, agriculture covered 14 percent, and developed land covered

2 percent. The remaining 2 percent land cover was barren, ice, water, or wetlands (Homer and others, 2004). Much of the land is managed for agriculture, forestry, or cattle. Federal and private irrigation projects across the basin provide water to farms growing a wide variety of crops, including tree fruit, corn, hay, potatoes, grapes, vegetables, and hops. The basin also is one of the major wheat production regions of the county, although the majority of the wheat is grown without irrigation. Timber is harvested on private and public lands, and much of the high desert shrub and grass land is used as range land for cattle. Dairies and aquaculture are locally important industries.

Model Datasets

Datasets used to develop the Middle Columbia River Basin SPARROW models were identical to those used to develop the recent PNW SPARROW models documented in Wise and Johnson (2013), but were limited to the Middle Columbia River Basin. The datasets are described briefly here to give the reader an overview of the data; refer to Wise and Johnson (2013) for additional details.

Hydrologic Network

The National Hydrography Dataset Plus Version 2 (NHDPlus Version 2) for the PNW (McKay and others, 2013; Horizon Systems, 2013) was used to represent the surface-water drainage network in the models developed for this study. Hereafter, this dataset will be referred to as the “NHD.” The NHD is a comprehensive set of digital spatial data composed of information about surface-water features, such as lakes, ponds, streams, and rivers (Simley and Carswell, 2010). The surface-water features represented in the NHD largely correspond to the features shown on 1:100,000 scale USGS topographic maps.

The NHD within the Middle Columbia River Basin model domain is composed of 105,961 reaches, which vary in size from small, ephemeral streams that experience years without streamflow to the Columbia River at The Dalles, Oregon, which has a mean annual streamflow of 5,373 m³/s. A reach generally is defined as a section of stream between two confluences. The NHD identifies the incremental catchment for each reach. An incremental catchment is defined as the area that drains directly to a reach without passing through another reach. Most reaches in the NHD represent streams or inland water bodies, such as lakes and reservoirs. However, some reaches represent closed basins, which do not have a surface-water connection to other reaches in the NHD. In developing the hydrologic framework for the SPARROW models, reaches representing streams and inland water bodies were retained, but reaches representing closed basins were removed from the network.

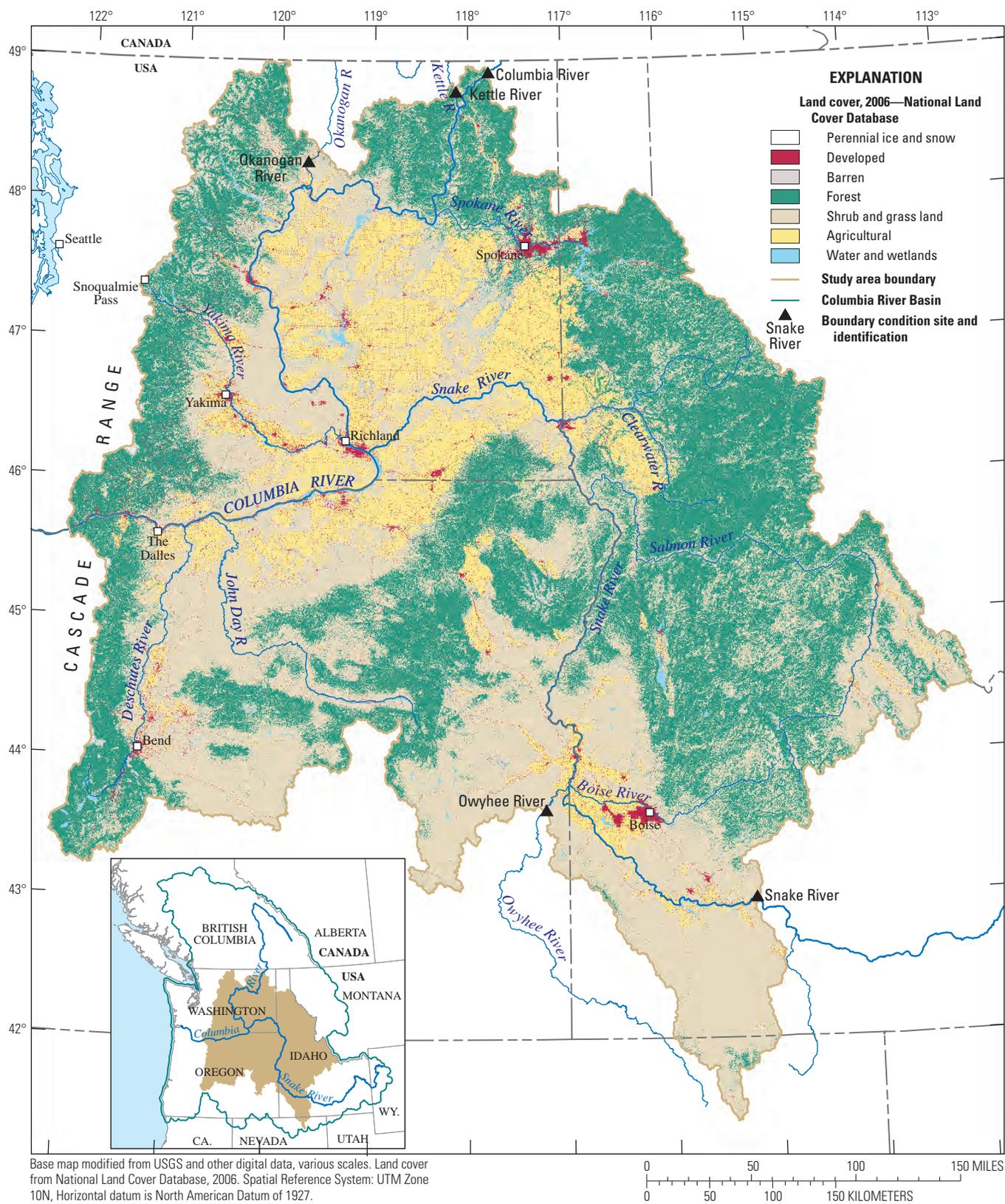


Figure 1. Land cover and major rivers of the Middle Columbia River Basin, Oregon, Washington, and Idaho.

Within SPARROW, the NHD reach network is modified to account for water (and therefore TN or TP load) diverted from streams and reservoirs for irrigation and power generation. Load that is removed for power generation is returned to the model at the appropriate downstream reach. Load that is removed for irrigation is permanently removed from the model. This treatment is justified because (1) the load of nutrients in irrigation water is small relative to the load of nutrients in fertilizer and manure applied to a field, and (2) the high degree of spatial correlation between applied irrigation water and fertilizer would make it difficult or impossible to include both sources in the model.

Nutrient Sources

The nutrient sources used in the TN and TP SPARROW models either were estimates of the annual TN or TP load applied to the land, or were surrogates where direct load estimates were unavailable or unreliable (Wise and Johnson, 2013). Natural nutrient sources represented in the models included fixation of nitrogen from the atmosphere in forested areas and the weathering of geologic phosphorus. Nitrogen fixation in forested areas was represented as area of forest land. Nitrogen fixation in other land-cover types was assumed to be negligible (for example, scrub land) or inseparable from a second, more dominant nitrogen source (for example, agricultural land). Weathering of geologic phosphorus was represented as area of forest land and area of grass and scrub land. As with nitrogen fixation, geologic phosphorus was assumed to be inseparable from agricultural and grazing phosphorus. The representation of natural TN and TP in this manner resulted in some catchments with no sources of TN or TP and, therefore, no modeled load or yield.

Anthropogenic nutrient sources in the models included the discharge of TN and TP from permitted wastewater facilities (treatment plants, fish farms, and fish hatcheries), the application of fertilizer on farmland, and the application or deposition of livestock manure. In the TN model, the fertilizer and livestock manure sources were combined into a single term where both were applied in the same catchment, resulting in a source term for catchments that only receive fertilizer and a second source term for catchments that receive both fertilizer and livestock manure. The nutrient sources used in the TN and TP models are shown in [tables 1](#) and [2](#). The methods used to estimate these nutrient sources are described in Wise and Johnson (2013).

The TN and TP SPARROW models also accounted for nutrient loads from the largest spring complexes (collections of natural springs that discharge into or near a stream and contribute substantially to the flow in that stream) and the nutrient load associated with the return of water from off-stream power generation facilities. Spring complexes and power returns are not sources of nutrients, but are pathways for the return of nutrients to a stream. They are represented in the models as point sources because there is no mechanism

within the NHD hydrologic network or in the SPARROW model to accommodate these unique pathways for nutrient movement from the landscape to the stream. The methods used to estimate these loads are documented in Wise and Johnson (2013).

Land-to-Water Delivery

The delivery of nutrients from land to water was simulated by considering land cover, climate, soil properties, geology, and hydrology. For the Middle Columbia River Basin SPARROW models, the following were used as land-to-water delivery terms: (1) total precipitation, (2) percentage of agricultural land receiving irrigation in a catchment, and (3) percentage of the catchment classified as having very high phosphorus retention potential ([tables 1](#) and [2](#)). Total precipitation was compiled by the NAWQA Program as part of a national effort and was summarized for each incremental NHD catchment (Michael Wiczorek, U.S. Geological Survey, written commun., June 11, 2011). Percentage of agricultural land receiving irrigation was developed for the PNW SPARROW models of Wise and Johnson (2013) and is described therein. Percentage of catchment classified as having very high phosphorus retention potential was developed (but not used) for the PNW SPARROW models of Wise and Johnson (2013). The dataset was derived from a worldwide dataset of phosphorus retention potential in soil developed by the International Soil Reference and Information Center (2013). These data were processed for use in the SPARROW models and are available from U.S. Geological Survey (2013). Hereinafter, this land-to-water delivery term will be referred to as phosphorus retention.

Calibration Loads

The calibration dataset for the models consisted of mean annual TN and TP stream loads that were estimated from water-quality data obtained from Federal and state regulatory agencies and streamflow data collected primarily by the U.S. Geological Survey (USGS). Sites and load estimates are a subset of those used by Wise and Johnson (2013).

Water-quality monitoring stations were selected as TN and (or) TP calibration stations if they were near a streamflow-gaging station (ratio of two catchment areas was between 0.75 and 1.33) and met the minimum criteria for the number of TN and TP samples (20), seasonal coverage (3 samples per season), and period of record (last sample collected no later than 1995 if there were at least 5 years of data or last sample collected no later than 1999 if there were less than 5 years of data). The mean annual TN and TP stream loads were estimated using the USGS Fluxmaster model (Schwarz and others, 2006), which relates the loads measured at water-quality monitoring stations (calibration stations) to measured streamflow, season, and time. TN loads

Table 1. Nutrient sources and model statistics for the total nitrogen SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho.

[Probability level: p -values for the source and aquatic loss variables are based on a one-sided t -test; p -values for the land-to-water delivery variables are based on a two-sided t -test. Abbreviations: (kg/km²)/yr, kilogram per square kilometer per year; kg/yr, kilogram per year; km², square kilometer; mm, millimeter; R², coefficient of determination; –, not applicable]

Source or statistic	Model coefficient units	Non-linear least-squares (NLLS)			Bootstrapped 90-percent confidence interval for model coefficient	
		Estimate of model coefficient	Standard error of model coefficient	Probability level (p -value)	Lower	Upper
Source terms						
Farm fertilizer ¹ (kg/yr)	dimensionless	0.11	0.020	<0.0001	0.068	0.16
Farm fertilizer plus confined cattle manure ² (kg/yr)	dimensionless	0.052	0.026	0.0509	-0.12	0.083
Forest land ³ (km ²)	(kg/km ²)/yr	60	13	<0.0001	40	98
Grazing land ⁴ (km ²)	(kg/km ²)/yr	5.1	2.5	0.0425	-80	6.9
Point sources ⁵ (kg/yr)	dimensionless	1.1	0.52	0.0340	0.44	1.5
Springs and power returns ⁶ (kg/yr)	dimensionless	0.80	0.46	0.0900	-0.37	1.0
Land-to-water delivery terms						
Precipitation ⁷ (mm)	–	1.4	0.30	<0.0001	0.73	1.9
Irrigated agriculture ⁸ (percent)	–	0.018	0.0054	0.0013	0.0083	0.037
Aquatic loss terms						
Free-flowing streams	–	–	–	–	–	–
Impoundments	–	–	–	–	–	–
Model diagnostics						
R ² of yield	–	0.86	–	–	–	–
Root mean square error (RMSE)	–	0.43	–	–	–	–
Number of sites ⁹	–	67	–	–	–	–

¹Commercial fertilizer applied to agricultural land, 2002.

²Sum of commercial fertilizer and manure from cattle in dairies and feedlots applied to agricultural land, 2002.

³Area of forest land, 2001.

⁴Area of grazing land, 2001.

⁵Surface-water discharges from permitted wastewater facilities, 2002.

⁶Surface-water discharge from springs and power returns, 2002.

⁷Natural log of mean annual precipitation, 1971–2000.

⁸Percentage of watershed containing irrigated agriculture.

⁹Does not include the five boundary sites where the load was fixed at the measured value.

were estimated at 72 calibration stations and TP loads were estimated at 88 stations. The mean annual TN and TP stream loads were detrended to 2002 to account for differences in record length, hydrologic conditions, and sample size among the calibration stations (Preston and others, 2009). The estimated loads were evaluated for fit and bias. Loads where the standard error was greater than 55 percent of the estimated load were removed. Bias was calculated as the weighted average of daily measured loads divided by the weighted average of daily loads estimated for monitored days. Bias statistics for the TN load estimates ranged from 0.81 to 1.52

with a median of 1.03 and an interquartile range (IQR) of 0.12. Bias statistics for the TP load estimates ranged from 0.76 to 2.80 with a median of 1.07 and an IQR of 0.25. The TN and TP calibration load estimates, associated standard error, and bias statistic are provided in [appendix A](#).

Five of the calibration stations were used as boundary conditions for the Middle Columbia River Basin SPARROW models ([fig. 1](#)). Boundary condition sites were used to restrict the model domain by fixing the load to a known value at locations on the stream network, and thereby eliminating any effect of the area upstream of the site.

Table 2. Nutrient sources and model statistics for the total phosphorus SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho.

[Probability level: p -values for the source and aquatic loss variables are based on a one-sided t -test; p -values for the land-to-water delivery variables are based on a two-sided t -test. Abbreviations: (kg/km²)/yr, kilogram per square kilometer per year; kg/yr, kilogram per year; km², square kilometer; mm, millimeter; R², coefficient of determination; –, not applicable]

Source or statistic	Model coefficient units	Non-linear least-squares (NLLS)			Bootstrapped 90-percent confidence interval for model coefficient	
		Estimate of model coefficient	Standard error of model coefficient	Probability level (p -value)	Lower	Upper
Source terms						
Farm fertilizer ¹ (kg/yr)	dimensionless	0.041	0.013	0.0017	0.00026	0.062
Confined cattle manure ² (kg/yr)	dimensionless	0.0088	0.0044	0.0486	-0.022	0.016
Grazing livestock manure ³ (kg/yr)	dimensionless	0.090	0.035	0.0128	-0.011	0.18
Forest land ⁴ (km ²)	(kg/km ²)/yr	9.0	3.2	0.0060	1.5	15
Scrub and grass land ⁵ (kg/yr)	(kg/km ²)/yr	0.43	0.25	0.0836	-9.6	0.86
Point sources ⁶ (kg/yr)	dimensionless	1.2	0.39	0.0046	0.64	1.6
Spring and power returns ⁷ (kg/yr)	dimensionless	1.5	1.1	0.1720	0.97	3.1
Land-to-water delivery terms						
Precipitation ⁸ (mm)	–	1.4	0.33	<0.0001	0.73	2.1
Phosphorus retention ⁹ (percentage of catchment)	–	-0.0061	0.0027	0.0250	-0.013	-0.0011
Aquatic loss terms						
Free-flowing streams	–	–	–	–	–	–
Impoundments	–	–	–	–	–	–
Model diagnostics						
R ² of yield	–	0.80	–	–	–	–
Root mean square error (RMSE)	–	0.49	–	–	–	–
Number of sites ¹⁰	–	83	–	–	–	–

¹Commercial fertilizer applied to agricultural land, 2002.

²Manure from cattle in dairies and feedlots, 2002.

³Manure from grazing livestock, 2002.

⁴Area of forest land, 2001.

⁵Area of scrub and grass land, 2001.

⁶Surface-water discharges from permitted wastewater facilities, 2002.

⁷Surface-water discharge from springs and power returns, 2002.

⁸Natural log of mean annual precipitation, 1971–2000.

⁹Percentage of incremental catchment consisting of soil with very high phosphorus retention potential.

¹⁰Does not include the five boundary sites where the load was fixed at the measured value

Model Calibration

The fitted coefficients of each term included in the TN and TP models were tested for statistical significance. The significance of the coefficients for each of the nutrient source terms (constrained to positive values) was determined by using a one-sided t -test and a significance level of 0.10. The

significance of the coefficients for each of the land-to-water delivery terms (which were allowed to be positive or negative, representing enhanced or attenuated delivery, respectively) was determined by using a two-sided t -test and a significance level of 0.05. The significance of the coefficients for the terms representing nutrient loss in free-flowing streams and impoundments (constrained to positive values) was

determined by using a one-sided *t*-test and a significance level of 0.10. Final model selection was based on the overall model fit by evaluating the R-squared (R^2) of yield and the root mean squared error (RMSE), and by evaluating the residuals for spatial patterns. The R^2 of yield is the R^2 value for the natural logarithm of yield and is considered a better measure of goodness-of-fit than R^2 because it accounts for the effect of contributing area, which can explain much of the variation in stream load. The spatial patterns in model fit were evaluated by calculating and mapping the residual for each calibration station.

Evaluation of Calibrated Models

The SPARROW model for TN was calibrated using six source terms (farm fertilizer, farm fertilizer plus confined cattle manure, forest land, grazing land, point sources, and springs and power returns) and two land-to-water delivery terms (precipitation and irrigated agriculture) (table 1). Neither aquatic loss functions were significant in the TN model, which is consistent with the latest TN model completed for the PNW (Wise and Johnson, 2013). The TN model explained 86 percent of the variance in the monitored yields.

All estimated coefficients in the TN model were significant (one-sided *p*-value less than 0.1 for source terms, two-sided *p*-value less than 0.05 for land-to-water delivery terms) (table 1). The three terms in the TN model with the largest *p*-values (farm fertilizer plus confined cattle manure, grazing land, and springs and power returns) also had asymmetric confidence intervals determined from bootstrap resampling. This suggests there is greater uncertainty in the SPARROW predictions resulting from these terms than from other terms used in the model. The greater uncertainty in these terms may imply an underlying issue with the terms themselves; for example, combining farm fertilizer and confined cattle manure into a single term was a compromise solution to not including confined cattle manure in the model at all. As a stand-alone term, confined cattle manure was highly insignificant (*p*-value between 0.40 and 0.55), owing to a high degree of spatial correlation with fertilizer, but excluding it from the model was not an option because of its locally large importance. Similarly, the springs and power returns term in the model was locally important, but the source was present only in a few catchments. Excluding the term from the model resulted in poorer fit statistics, so it was retained in the model. The asymmetry in the grazing source term probably is due to the removal or duplication of one or more key calibration sites during the bootstrap resampling procedure. Grazing lands (primarily scrub and grass land) constitute much of the land area in the model domain, but are not well represented by calibration sites.

The SPARROW model for TP was calibrated using seven source terms (farm fertilizer, manure generated at confined cattle operations, manure generated by grazing livestock, area of forest land, area of scrub and grass land, point sources, and springs and power returns) and two land-to-water delivery terms (precipitation and phosphorus retention) (table 2). The aquatic loss functions were not significant in the TP model, consistent with the latest TP model completed in the PNW (Wise and Johnson, 2013). The TP model explained about 80 percent of the variance in the monitored yields.

All estimated coefficients in the TP model were significant (one-sided *p*-value less than 0.1 for source terms, two-sided *p*-value less than 0.05 for land-to-water delivery terms), except the coefficient for springs and power returns (*p*-value = 0.1720) (table 2). The term was retained in the model because it is a locally important source of nutrients. The lack of statistical significance of the springs and power returns term may be due to the small number of catchments influenced by the source. Removal of the springs and power returns term from the model resulted in a poorer model fit and unreasonable values for other model coefficients. After springs and power returns, the two terms in the TP model with the next-largest *p*-values (confined cattle manure; scrub and grass land) had asymmetric confidence intervals determined from bootstrap resampling. These two terms correspond with two of the highly asymmetric terms in the TN model. This is no coincidence, and is indicative of the same underlying issues with the terms in the TP model as were discussed for the TN model.

Model residuals (log-transformed calibration load minus log-transformed predicted load) were plotted on a map and visually inspected for outliers and spatial correlation (figs. 2 and 3). For the TN model, the predicted load was within 2 times the calibration load at 62 of 67 sites (93 percent) and within 1.5 times the calibration load at 49 of 67 sites (73 percent). The smallest TN residual was -1.13, which corresponds to an overprediction where the predicted load is 3.1 times the calibration load; the largest TN residual was 1.11, which corresponds to an underprediction where the calibration load is 3.0 times the predicted load.

For the TP model, the predicted load was within 2 times the calibration load at 73 of 83 sites (88 percent) and within 1.5 times the calibration load at 51 of 83 sites (61 percent). The smallest TP residual was -1.46, which corresponds to an overprediction where the predicted load is 4.3 times the calibration load; the largest TP residual was 1.09, which corresponds to an underprediction where the calibration load is 2.0 times the predicted load.

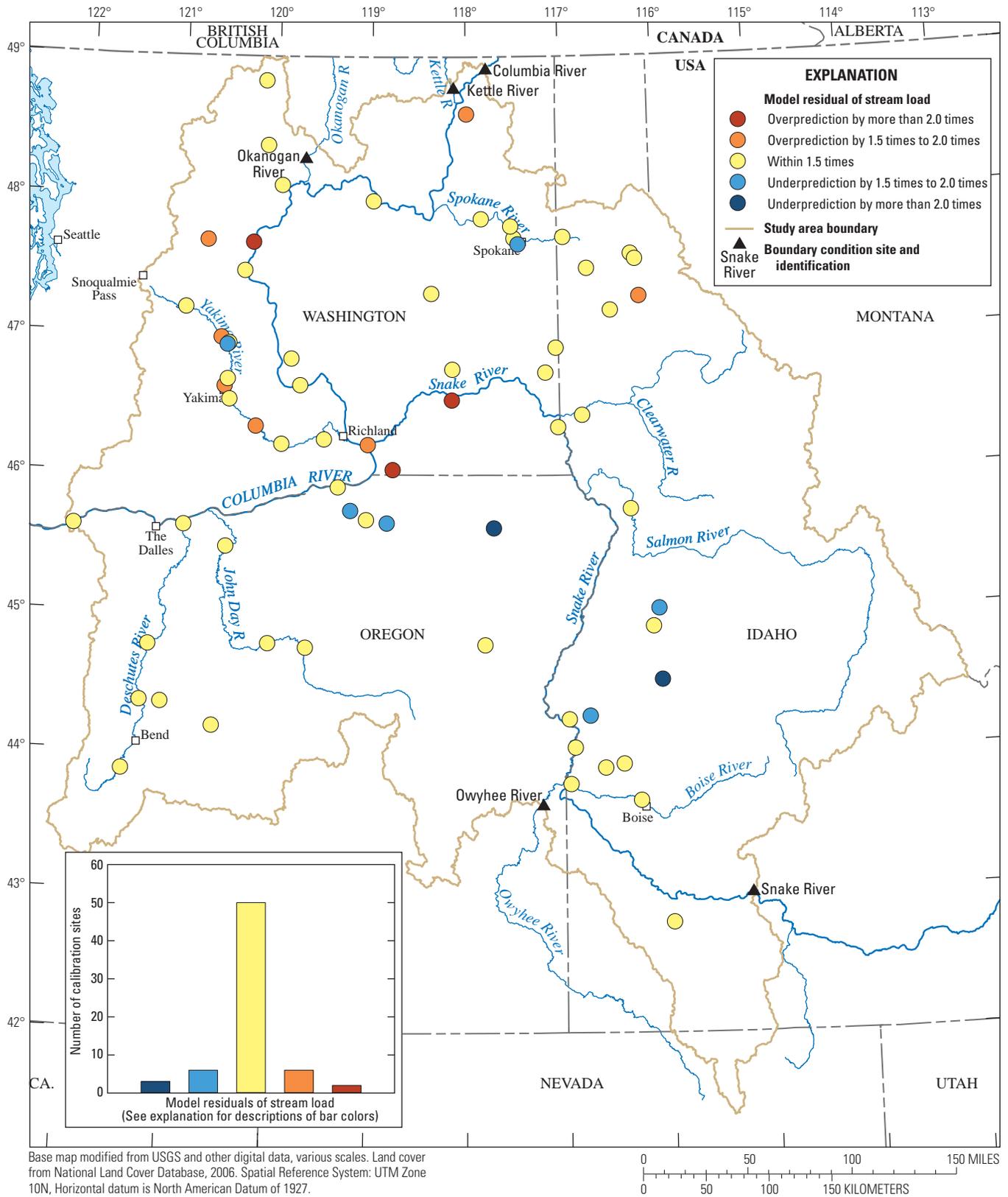


Figure 2. Model residuals of stream load for the total nitrogen SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho.

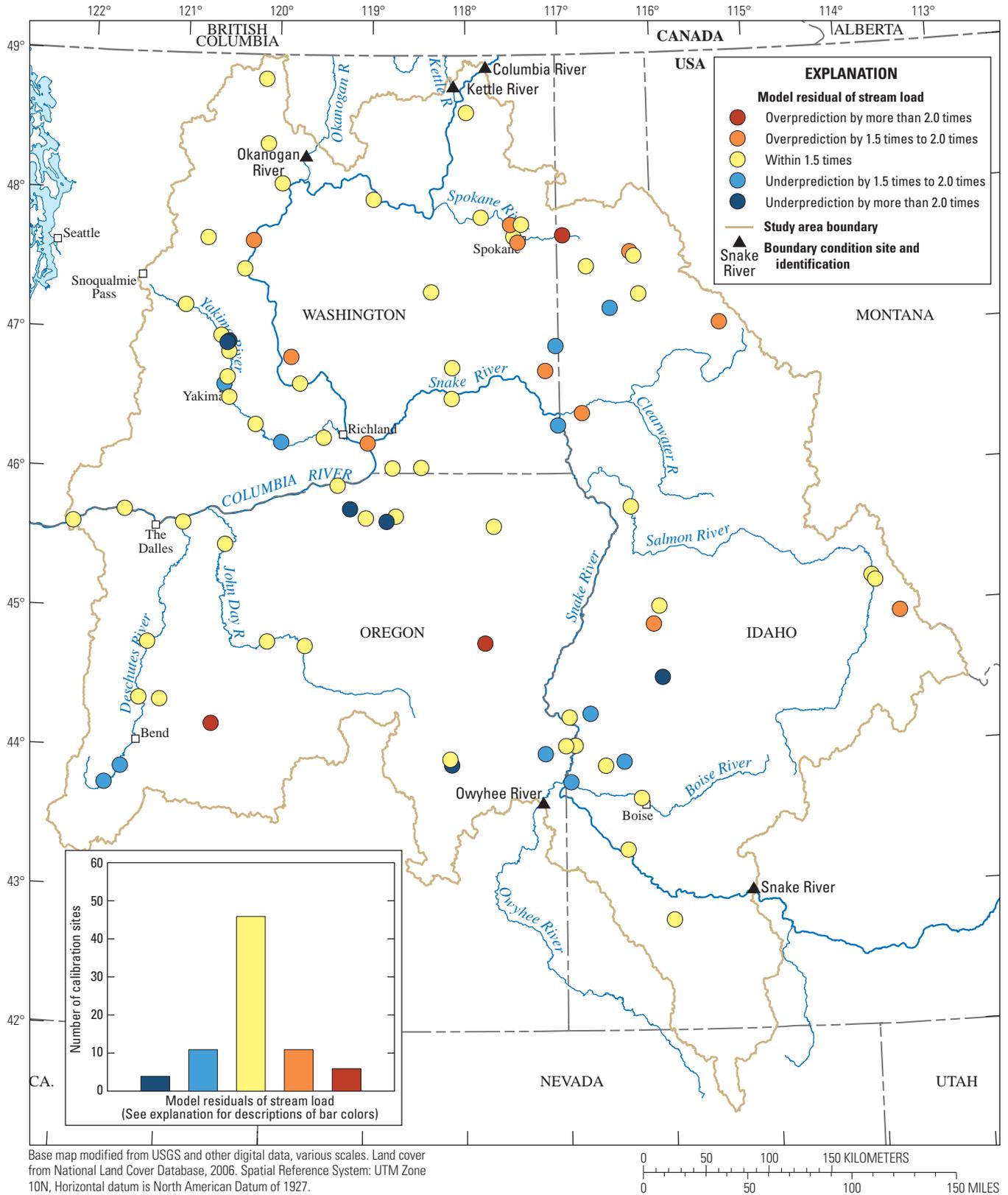


Figure 3. Model residuals of stream load for the total phosphorus SPARROW model of the Middle Columbia River Basin, Oregon, Washington, and Idaho.

Modeling Results for the Yakima River Basin

Modeling results shown in this report are limited to the Yakima River Basin to provide detailed information on the areas of interest to WDOE and EPA. Results for the entire model domain are provided in [appendix A](#).

Yields

The incremental yield of TN and TP was calculated to facilitate comparisons among incremental catchments and to better understand the spatial patterns of nutrient sources. An incremental catchment is defined as the area that drains directly to a reach without passing through another reach. The yield value is expressed as mass per unit area so the relative importance of different areas of the Yakima River Basin as sources of TN and TP can be compared. Catchments with the largest incremental yield of TN and TP are located in the major agricultural regions of the Yakima River Basin ([figs. 4 and 5](#)), with the largest yields in catchments near the cities of Granger and Sunnyside, Washington. Large yields of TN and TP also were predicted in the uppermost-forested catchments of the Cascade Range and in catchments where municipal wastewater-treatment plants discharge their effluent.

Source Shares

The largest source of TN and TP contributing to the load exported from each incremental catchment is shown in [figures 6 and 7](#), respectively. These maps generally reflect the surrounding land use, with natural sources (forest, scrub, and grass land) dominating catchments minimally influenced by agriculture and ranching; agricultural and manure sources are dominant in agricultural and grazed landscapes. The notable exception to this pattern is in catchments where effluent from a municipal wastewater-treatment plant (WWTP) is discharged. Catchments without any modeled nutrient sources are more prevalent on the TN map ([fig. 6](#)) because the only statistically significant natural source of nitrogen in the TN model was forest land. In the TP model, forest, scrub, and grass land were included and were statistically significant sources of natural sources of TP.

Longitudinal Changes in Nutrient Sources Comprising the Load in the Yakima River

The percentage of each modeled source that contributes to the TN and TP load in the main stem of the Yakima River as it flows from its headwaters to its confluence with the Columbia River is shown in [figures 8 and 9](#). These figures

illustrate the effect of anthropogenic nutrient sources on the river as it passes through the agricultural and urban centers along its route.

In the uppermost reaches of the Yakima River, near river kilometer (RK) 350, about 85 percent of the TN load and about 55 percent of the TP load is derived from forest land, about 25 percent of the TP load is derived from grazing livestock manure, and about 15 of the TN and TP load is from the Snoqualmie Pass WWTP. The percentage of TP load from grazing livestock manure is large compared to the TN load from grazing lands (about 2 percent) and suggests the grazing livestock manure source may be serving as a surrogate for natural sources in this portion of the model. The relatively coarse method for estimating grazing manure likely overestimated the actual amounts deposited in the sparsely populated, forested headwaters of the Yakima River Basin. The large percentage of TN and TP attributed to the Snoqualmie Pass WWTP may appear large until the dilute waters into which the treatment plant discharges are considered; the total nutrient load in the Yakima River at its headwaters is about 8 percent of the load at Kiona, Washington (RK 44). Effluent from WWTPs at Cle Elum (RK 292), Ellensburg (RK 246), and Yakima (RK 180) also cause marked increases in the percentage of TN and TP load attributed to point sources, and a concomitant decrease in the percentage attributed to other sources. WWTPs downstream of Yakima do not visibly affect the point-source percentage because the load in the river at those effluent points is much larger than the load in the effluent itself.

Agricultural sources of TN and TP begin to increase near RK 320 and RK 260, respectively, and level off around RK 200. The Naches River joins the Yakima River near RK 190 and provides the last significant influx of naturally sourced TN and TP to the main stem. Downstream of Yakima, TN and TP percentages from forest, grazing, and grass and scrub land continue to decrease with increasing inputs from agricultural lands. Large inputs from agricultural tributaries were predicted near RK 130, where Granger Drain, Marion Drain, and Toppenish Creek join the Yakima River, and again near RK 97, where Sulphur Creek Wasteway enters the river. Manure from confined cattle operations is an important component of the agricultural nutrients downstream of the city of Yakima. Most TN and TP attributed to manure enters the river between RK 150 and RK 100. The proportion of the various nutrient sources is relatively stable downstream of RK 100. Near Kiona (RK 44), the monitoring site farthest downstream on the Yakima River, the TN load in the river is about 74 percent fertilizer and manure from confined cattle operations, 15 percent from forest land, 11 percent from point sources, and less than 1 percent from grazing lands. The TP load in the Yakima River at Kiona is about 39 percent from point sources, 21 percent from forest land, 20 percent from confined cattle manure, 11 percent from farm fertilizer, 9 percent from grazing livestock manure, and less than 1 percent from scrub and grass land.

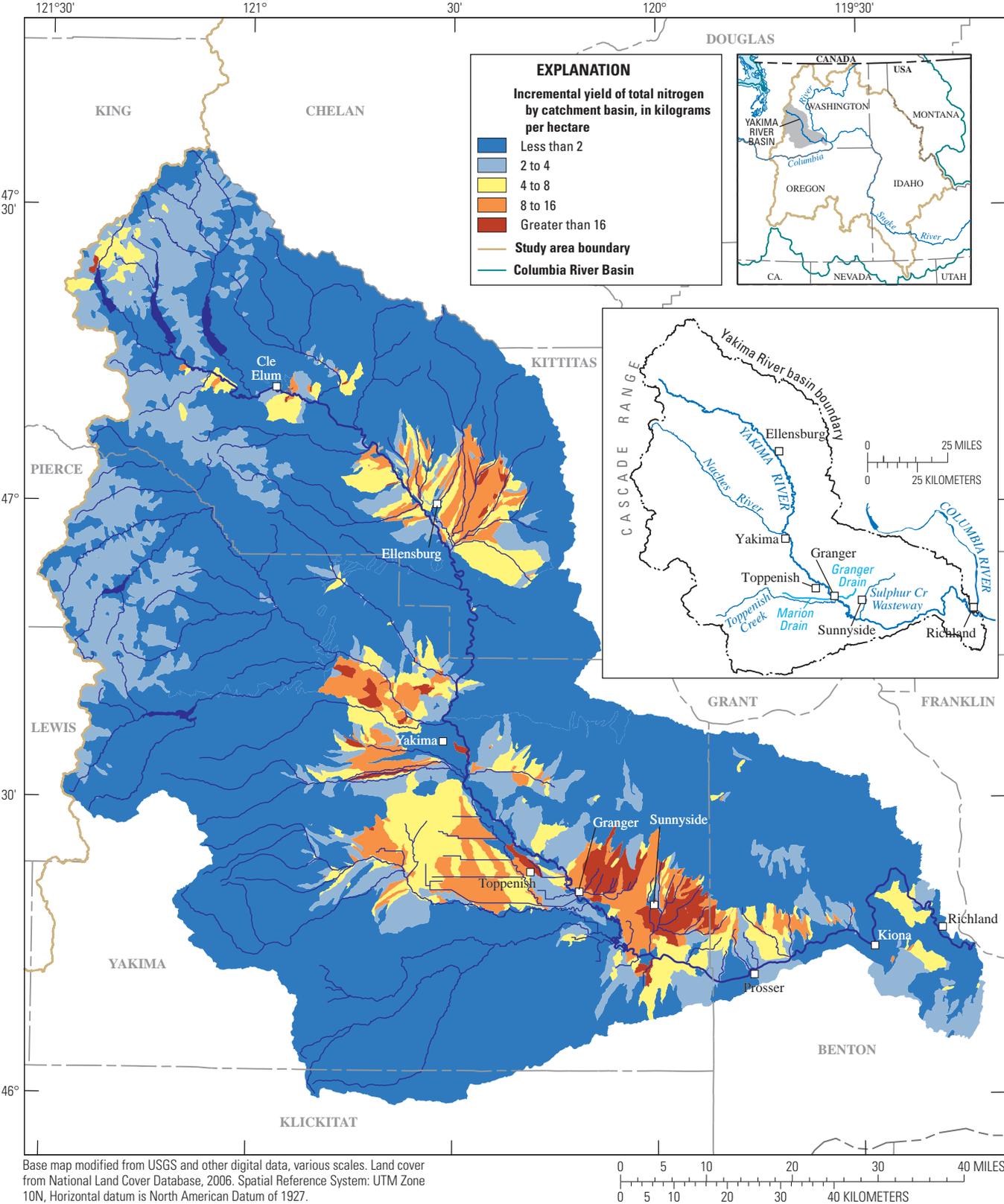


Figure 4. Incremental yield of total nitrogen for the Yakima River Basin, Washington.

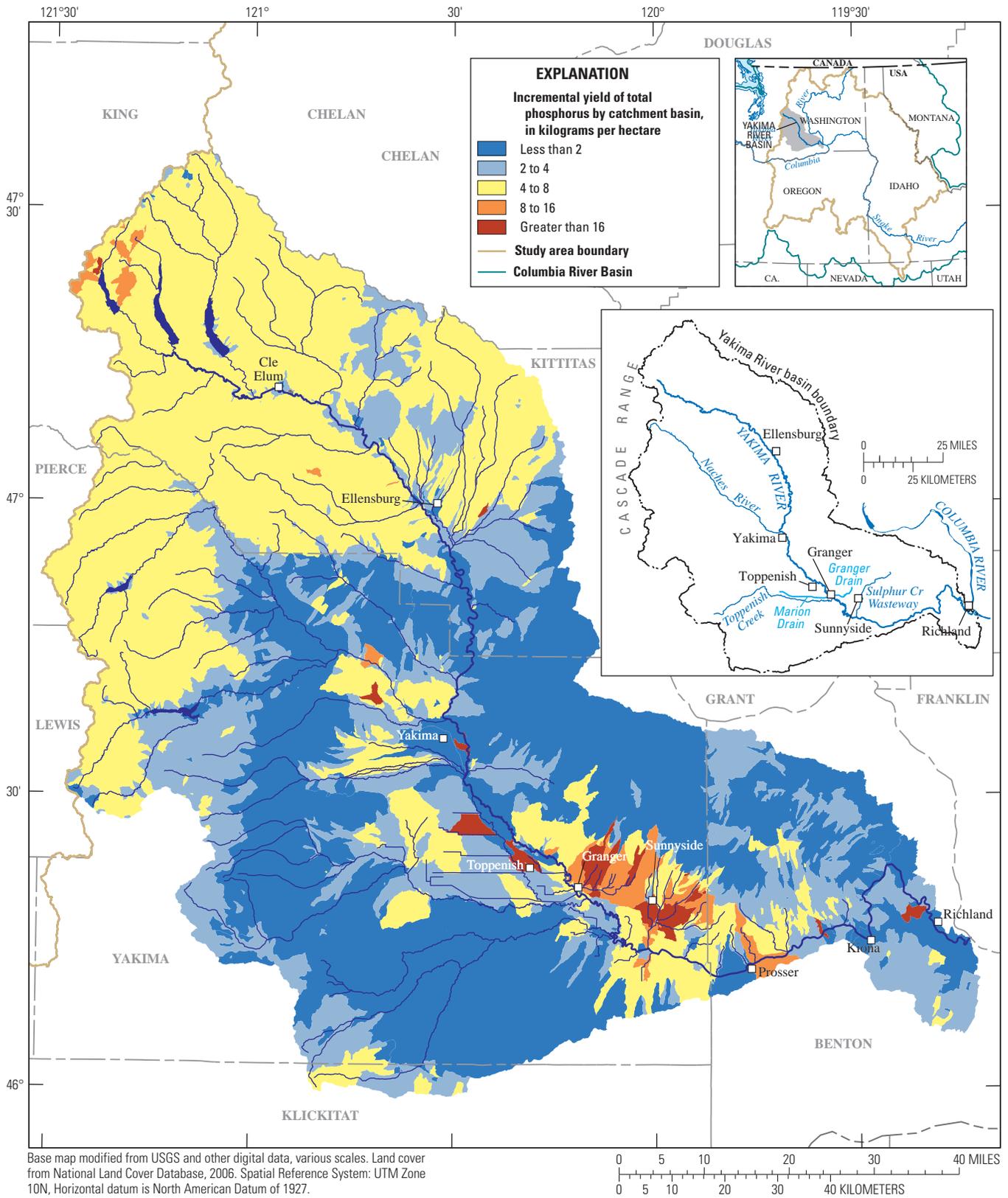


Figure 5. Incremental yield of total phosphorus for the Yakima River Basin, Washington.

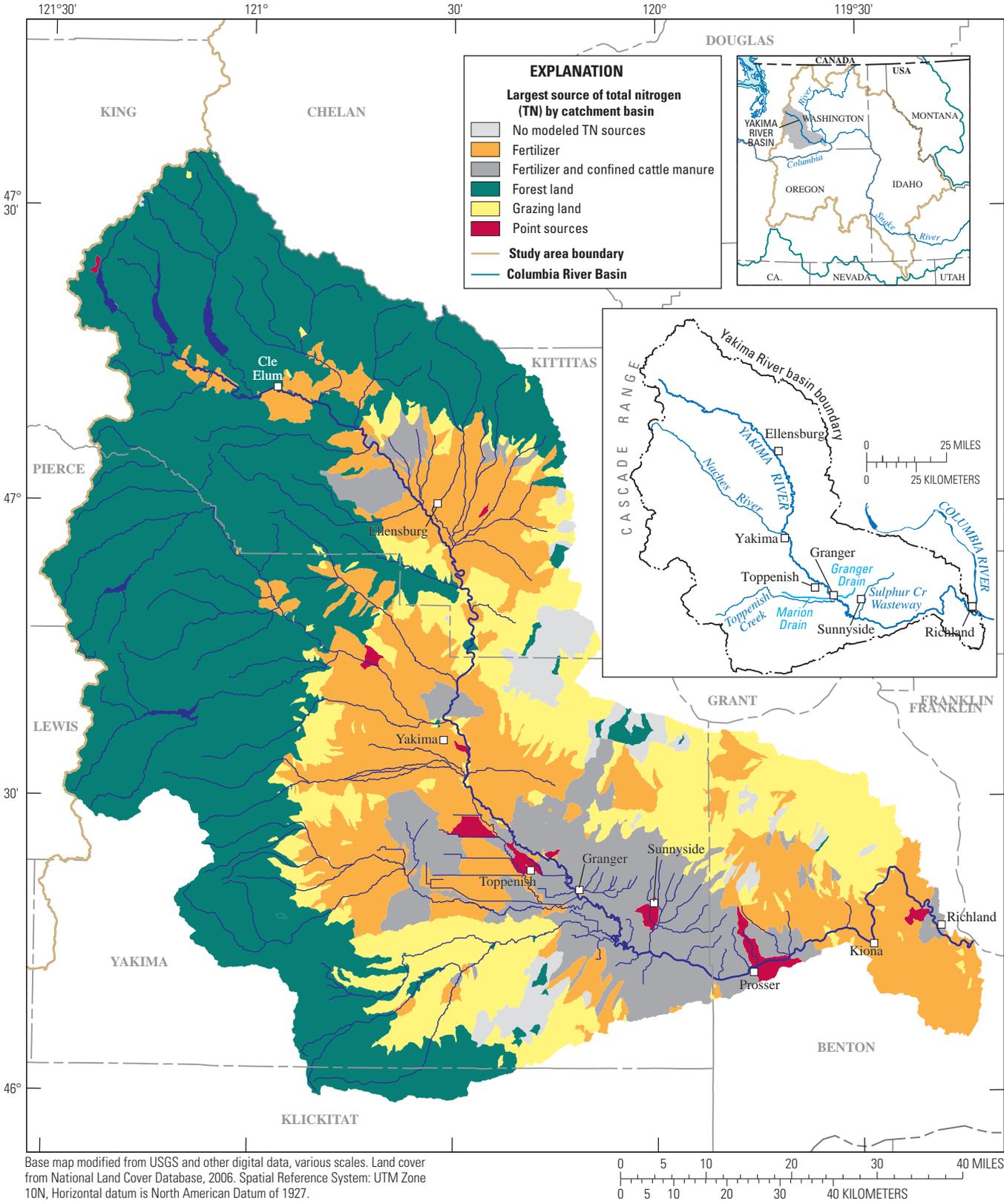


Figure 6. Largest source of total nitrogen in each incremental catchment in the Yakima River Basin, Washington.

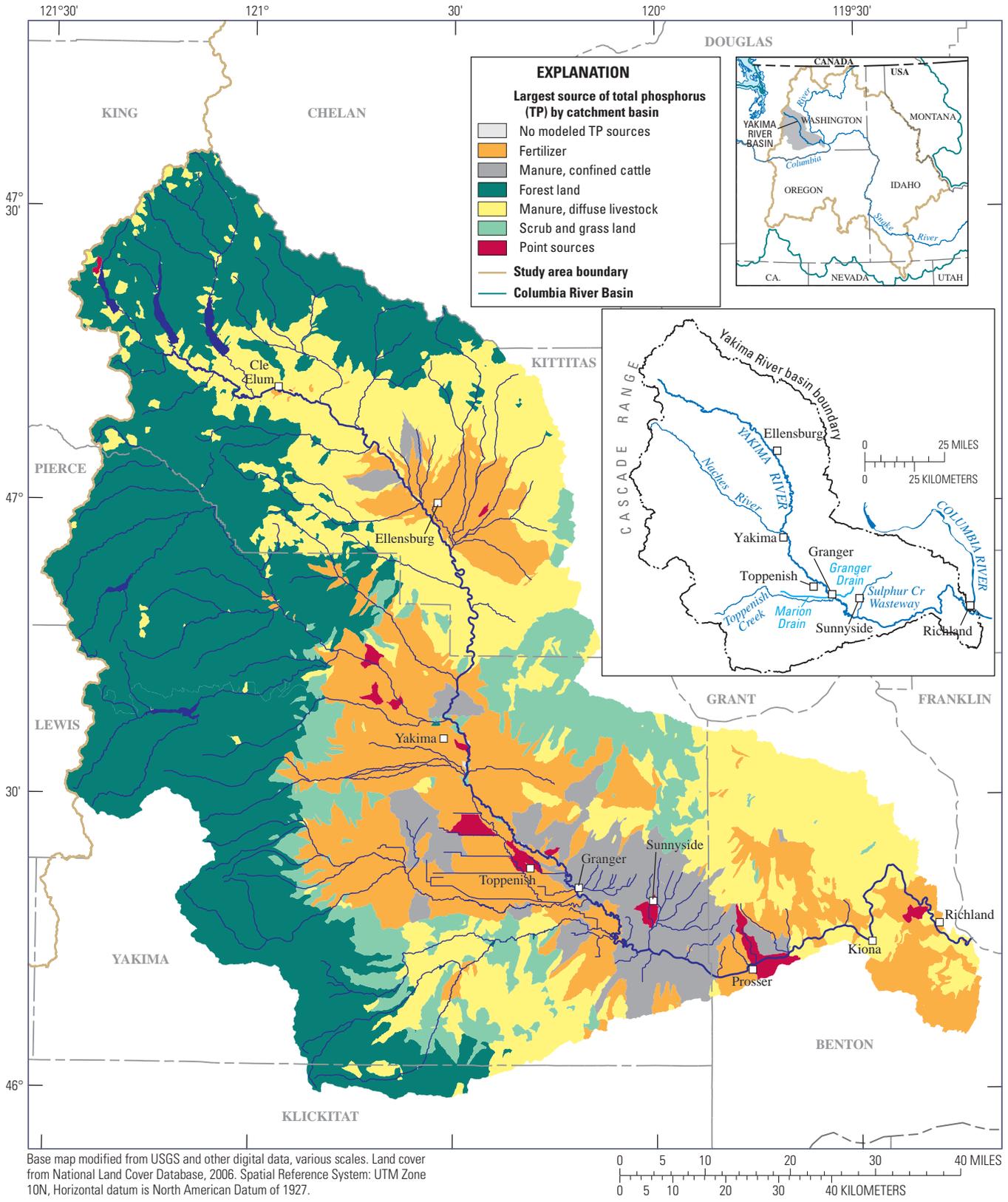


Figure 7. Largest source of total phosphorus in each incremental catchment in the Yakima River Basin, Washington.

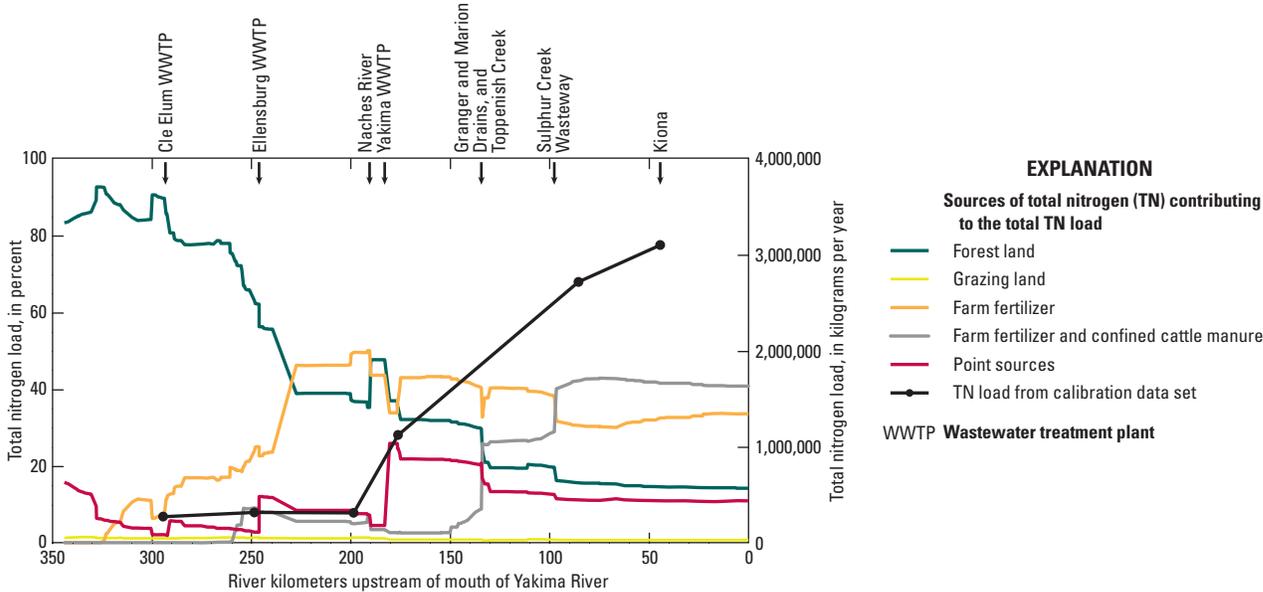


Figure 8. Sources of total nitrogen contributing to the total nitrogen load in the Yakima River, Washington.

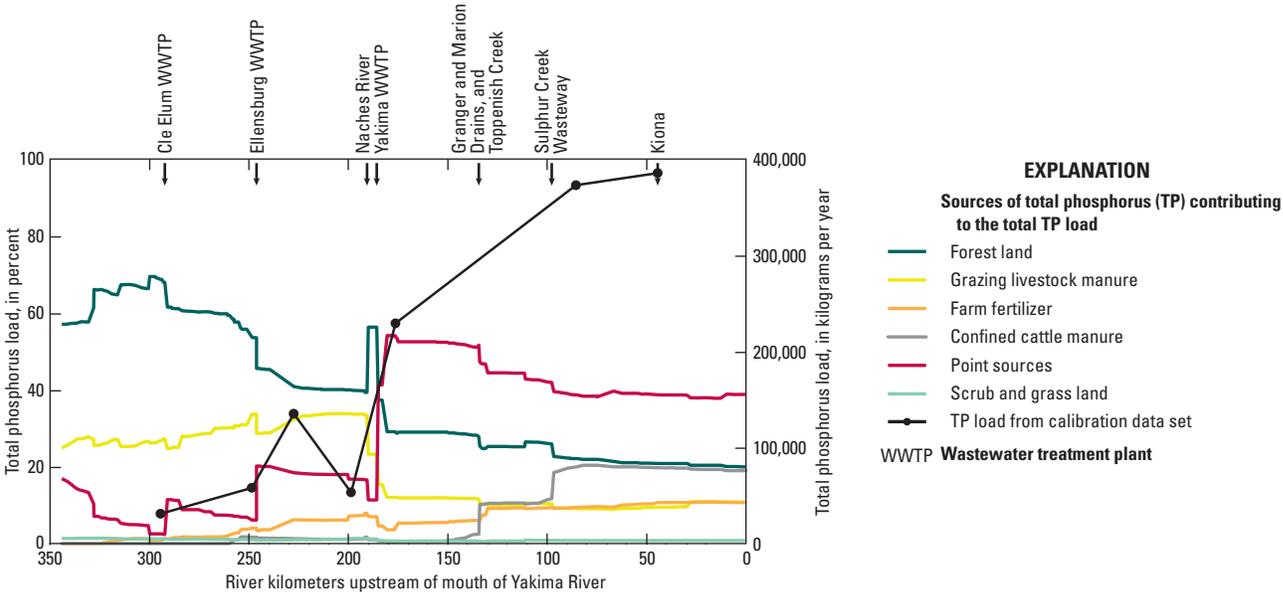


Figure 9. Sources of total phosphorus contributing to the total phosphorus load in the Yakima River, Washington.

The large changes in source percentages upstream of RK 180 generally are not seen farther downstream because (1) few large sources of water enter the river and (2) increasingly large sources of nutrients are required to effect changes in the source percentages as the nutrient load in the river increases. Therefore, the only large changes in the relative proportions of each nutrient source downstream of the city of Yakima are inflows from the largest agricultural drains in the lower Yakima Valley.

Model Calibration and Uncertainty

Successful calibration of a SPARROW model requires appropriate selection and accurate quantification of monitored loads, sources, land-to-water delivery factors, and in-stream attenuation processes. The source and delivery terms that were included in the model were statistically significant or were determined to be mechanistically important to the final calibrated model. Certain nutrient sources and ecosystem processes are not explicitly accounted for in the model because of (1) the inability to quantify the source or process at the appropriate scale of the model, and (2) the statistical nature of the model. The statistical nature of the model can preclude the inclusion of geographically sparse data or the inclusion of a dataset with a high degree of spatial and numerical correlation to another dataset in the model. For example, in the TN model, atmospheric deposition was eliminated as a source term because of a high degree of spatial correlation with forest land. The coefficient of the atmospheric deposition source term was unrealistically large, suggesting it was acting as a surrogate for naturally occurring nitrogen export from forest land. Recognizing this issue, the atmospheric deposition term was dropped in favor of a more readily interpreted source of TN export from forests—area of forest land. A similar issue arose when attempting to include farm fertilizer and manure from confined cattle as two separate sources in the TN model. The high degree of spatial correlation between manure from confined cattle and fertilizer resulted in a coefficient for manure from confined cattle that was not statistically significant. The model compensated by increasing the coefficient on the fertilizer source term to an unrealistic value. As a compromise, the two sources were combined for the TN model. This compromise is not ideal and limits the ability of the user to separate the two sources as one might wish to do, but it was necessary to produce an otherwise realistic model.

The coefficients for the nutrient source terms provide some insight into the model results. The units of the coefficients vary among the sources. Sources expressed in terms of area of land (for example, forest land or grazing land) have a coefficient with units of kilograms per square kilometer per year that is analogous (but not directly comparable) to nutrient export coefficients reported in the literature (for

example, Harmel and others [2006] and references therein). Sources expressed in terms of load per year (for example, farm fertilizer or point sources) have a coefficient that is dimensionless, and can be considered the fraction of the source that is available to be transported to the stream. Although the use of the source coefficients is limited with respect to comparisons with the scientific literature, source coefficients are useful in the model calibration process and should be consistent with our understanding of the nature, transport, and fate of the sources that were modeled. For example, because permitted wastewater discharges release nutrients directly to streams rather than on land, the expected coefficient for the point-source terms in the SPARROW models is 1.0; no land attenuation of the source is expected. The fitted coefficients for the TN and TP models were 1.1 and 1.2, respectively, which suggests that these sources were reasonably captured by the models. Experience has shown that the point-source coefficient typically is not exactly 1.0 (Hoos and McMahon, 2009; Robertson and Saad, 2011; Wise and Johnson, 2013), which is likely due to uncertainties in the estimate of the annual TN and TP discharge from these sources. Source term coefficients with different units should not be compared. For example, it is meaningless to compare the coefficient for farm fertilizer (dimensionless) with the coefficient for grazing land kilograms per square kilometer per year.

Within each model, coefficients with similar units exhibited values consistent with the expected mechanism of nutrient delivery to stream systems. In the TN model, the estimated coefficient for point sources (1.1) and springs and power returns (0.80) were larger than the coefficients for farm fertilizer (0.11) and farm fertilizer plus confined cattle manure (0.052) (table 1). This difference is mechanistically reasonable because the first two sources deliver their load of nitrogen directly to a stream, whereas nitrogen in farm fertilizer and manure is subjected to multiple processing and transport pathways prior to reaching a stream. Comparing the two land-use terms in the TN model, export from forest land is, on average, larger than the export from grazing land, which is reasonable given that ecosystem productivity, precipitation, and land-surface slope generally are greater in the forested parts of the modeling domain.

A similar reasoning explains the greater coefficient values of point sources and springs and power returns in the TP model compared to farm fertilizer, confined cattle manure, and grazing livestock manure (table 2). Although the sources for which they act as surrogates are different, the land-use terms in the TP model also follow the pattern observed in the TN model: the coefficient for forest land is considerably larger than the coefficient for scrub and grass land. Among the quantified TP non-point sources, the coefficient for grazing livestock manure is the largest, followed by farm fertilizer, and then confined cattle manure; less than 10 percent of the TP from these sources is available for transport into nearby

streams. The grazing livestock manure coefficient seems large; however, the NLLS standard error and the bootstrap analysis indicate considerable uncertainty in this coefficient. Despite the relatively large amount of uncertainty and the small fraction of the total TP load that originates from grazing livestock manure (figs. 7 and 9), it is still statistically significant because of its importance in certain catchments in the model.

The relative magnitudes of the coefficients are not directly related to their contribution to the nutrient load issuing from a catchment. The load issuing from a catchment is a function of not only the source coefficient, but also of the size of each source, the delivery terms, and the magnitude of the load entering a catchment from upstream sources.

Because only the sign of the coefficients provides useful insight into the model-calibration process, little information can be acquired by analysis of the coefficients of delivery terms. A positive coefficient indicates the term increases export to streams; a negative coefficient indicates the term decreases export to streams. A positive coefficient was expected for mean precipitation for the TN and TP models, and is due to a positive correlation between precipitation and nutrient runoff in most catchments. A non-significant or negative coefficient for this term would have been highly suspect. In the TN model, the coefficient on the irrigated agriculture delivery term was positive, indicating that TN export is greater from irrigated crops than from non-irrigated crops. This observation may be because of differences in the types of crops grown and their associated applications of nitrogenous fertilizer. Alternately, it may point to differences in nitrogen transport pathways—primarily groundwater or primarily overland runoff—and the associated opportunities for nitrogen uptake and denitrification. In the TP model, the phosphorus retention coefficient was negative, indicating that less TP is transported to streams in catchments with a high percentage of phosphorus-retaining soils. The phosphorus retention land-to-water delivery term is a measure of the capacity of the soil in a catchment to inhibit the movement of soluble forms of phosphorus through one or more sorption or precipitation processes (Cole and others, 1953; Hemwall, 1957; James and others, 1996; Berg and Joern, 2006; Devau and others, 2011). Phosphorus immobilized in this manner is still part of the pool of TP in a catchment, but erosion by wind or water is necessary to move that particle (and its associated TP) into the stream.

In-stream attenuation of nutrients represents a permanent loss or removal of nutrients, and is thought to reflect denitrification (TN) and the settling of particulates (TN and TP). Because SPARROW simulates long-term annual nutrient loads, intra-annual variation of nutrients (such as algal growth and decay) is not reflected in the SPARROW stream attenuation term. In-stream attenuation often is identified as a statistically significant process in SPARROW nutrient models (Smith and others, 1997; Preston and Brakebill, 1999; Moore

and others, 2004; Hoos and McMahon, 2009). This was not the case for either model calibrated for this study, and is consistent with other SPARROW models constructed for the PNW (Wise and Johnson, 2011, 2013). Although a thorough explanation for this finding has not yet been identified, a number of possibilities exist. Recent work in the Yakima River Basin showed little metabolism of nitrate in agricultural streams (Duff and others, 2008), yet this observation can be only a partial explanation because agricultural streams represent a relatively small fraction of all stream reaches in these models. Another possibility is that the lack of a statistically significant in-stream attenuation term for TN could be a modeling artifact resulting from the interaction between the in-stream attenuation term and the representation of natural TN sources using forest land. Stream attenuation of TN is greater in small streams compared to large streams (Alexander and others, 2000; Peterson and others, 2001), and most of the smallest stream reaches in the PNW (first- and second-order streams) are located in catchments that generally included a high percentage of forest land (greater than 50 percent). In-stream attenuation in low-order reaches may be accounted for in the coefficients for the forest land term, thus eliminating the need to account for this process through a separate attenuation term. The lack of a significant in-stream attenuation term for TP suggests dams and reservoirs have little or no effect on TP removal on annual time scales despite the large number of these structures in the PNW. In the Middle Columbia River Basin (and the larger PNW region), most large dams are located in steep, forested areas and provide flood control and water storage for irrigation and drinking water. Most dams are located upstream of the largest sources of TP (agricultural fertilizer and manure) and, therefore, play a small role in the overall removal of TP in the system. The only major dams downstream of the primary agricultural areas in the Middle Columbia River Basin are on the Columbia River, and are “run-of-the-river” dams with little storage capacity. Other aspects of dam construction and operation in the PNW also may contribute to minimal annual TP storage, including seasonal drawdown and bottom-release of stored water.

The source and land-to-water delivery terms used in the TN and TP models are statistically significant or were determined to be mechanistically important to the final calibrated model, but do not represent the only or best source or delivery terms that could be used in SPARROW models. A number of additional source and delivery terms were considered, but were eliminated from consideration. In some cases, there was not enough information to parameterize what might be considered an important source or process because of insufficient data. In other cases, it was possible to include and parameterize a source or delivery term in the model, but the term was not statistically significant or it was strongly correlated with another significant term. In some cases, it was necessary to combine correlated source terms into a new source term to examine the role of potentially significant

sources (for example, farm fertilizer and confined cattle manure in the TN model). During calibration, unspecified sources and processes likely were indirectly accounted for in the estimated values of more broadly defined coefficients (for example, point sources, springs, and power returns). Uncertainty in the estimated model coefficients also might have been due to the finite sample sizes of the models and measurement errors associated with model input data. Such uncertainty might be reduced through the collection of additional water-quality data (especially in unmonitored areas) and refinements in the estimates of landscape attributes (especially nutrient source loadings). Refer to Wise and Johnson (2011) for a more thorough discussion of uncertainty in the source and delivery term datasets. Although more abundant and detailed sources and delivery data would improve these models, the percentage of variation explained by the TN (86 percent) and TP (80 percent) is consistent with other SPARROW model results for the PNW (Wise and Johnson, 2011, 2013).

Nutrient Yields and Land Use

The annual yield of TN and TP was determined for incremental catchments with a single dominant land cover (figs. 10 and 11). “Dominant” was defined as more than 90 percent of the catchment area for forest land and grass and scrub land, and as more than 50 percent of the catchment area for agricultural land. Statistical differences in yield among land uses are shown in figures 10 and 11, and were determined using a series of two-sample Wilcoxon rank sum tests followed by a *post hoc* multiple comparison test (Simes, 1986; Hochberg, 1988). The yield of TN and TP from urban land was not evaluated because of (1) the small number of urban catchments (39 catchments with more than 50 percent urban area and only 3 catchments with more than 90 percent urban area); (2) the lack of a diffuse urban source term in the model; and (3) the aridity of the study area, which limits the amount of urban runoff that can occur. The influence of urban areas in the models is primarily through point-source discharges. Catchments where point-source discharges are located show particularly high-yield values of TN and TP; however, the yield calculation is distorted because the area of the discharging catchment is used to calculate yield, although the area contributing load to the point source actually is much larger.

The yield of TN was largest in predominantly agricultural catchments (median = 8.2 [kg/ha]/yr) and smallest in catchments that are largely scrub and grass land (median = 0.012 [kg/ha]/yr). The median yield in forested catchments was 2.1 (kg/ha)/yr. The yield among the three land-use groups

was statistically different ($\alpha=0.05$). The median yields of TN from the Middle Columbia River Basin SPARROW model are typical of values reported in the literature (table 3). The median yield from agricultural land in this study generally is less than central values reported for crop land in the Midwest and Eastern United States, which is consistent with Clesceri and others (1986), and is similar to the yield values derived from nutrient load data presented in Ebbert and others (2003) for two sites in the Yakima River Basin. The forest yields from this study are less than many other forest yields reported for Oregon and Washington in table 3 because of differences in forest species composition and precipitation rates. Of the three land-use groups used for this report, it was most difficult to find comparable yield values in the literature for grass and scrub land. A few yield values for a land-use category named “range” are given in table 3. Range overlaps somewhat with the grass and scrub land group in this report. However, much of the grass and scrub land in the Middle Columbia River Basin is not suitable for range or pasture because of its aridity, steep slopes, rockiness, or distance from water, and this most likely is the reason that the yield values determined for grass and scrub land are so much smaller than those reported in the literature.

In contrast to the yields of TN, the yields of TP generally were greatest in catchments with forest land (median = 0.20 [kg/ha]/yr), although the largest yields from agricultural land exceed the largest yields from forest land by an order of magnitude. The median yield in agricultural catchments was 0.11 [kg/ha]/yr. As with TN, yields from grass and scrub land were the smallest of the three land-use groups (median = 0.0091 [kg/ha]/yr). That the median yield of TP from forested catchments was the largest of the three land-use groups was unexpected because the only significant source of TP in forested catchments was the weathering of geologic material. The yields of TP from forested catchments in the Middle Columbia River Basin SPARROW model are typical of those reported in the literature (table 3). The yields of TP from agricultural catchments in this SPARROW model, however, are small compared to published literature values, including the median value obtained by Wise and Johnson (2011) for agricultural catchments east of the Cascades (table 4). This fact, along with the lack of concurrence with yields from the literature, suggests the TP yields from agricultural catchments might be small as a result of the configuration or structure of the SPARROW model itself. One likely cause is the lack of a sufficient number of calibration sites in catchments dominated by agriculture (there is only one site in the Middle Columbia River Basin SPARROW model). This site may be inadequate for the model to distinguish between forest and agricultural sources in the large, mixed-land-use catchments that dominate the calibration sites in the model.

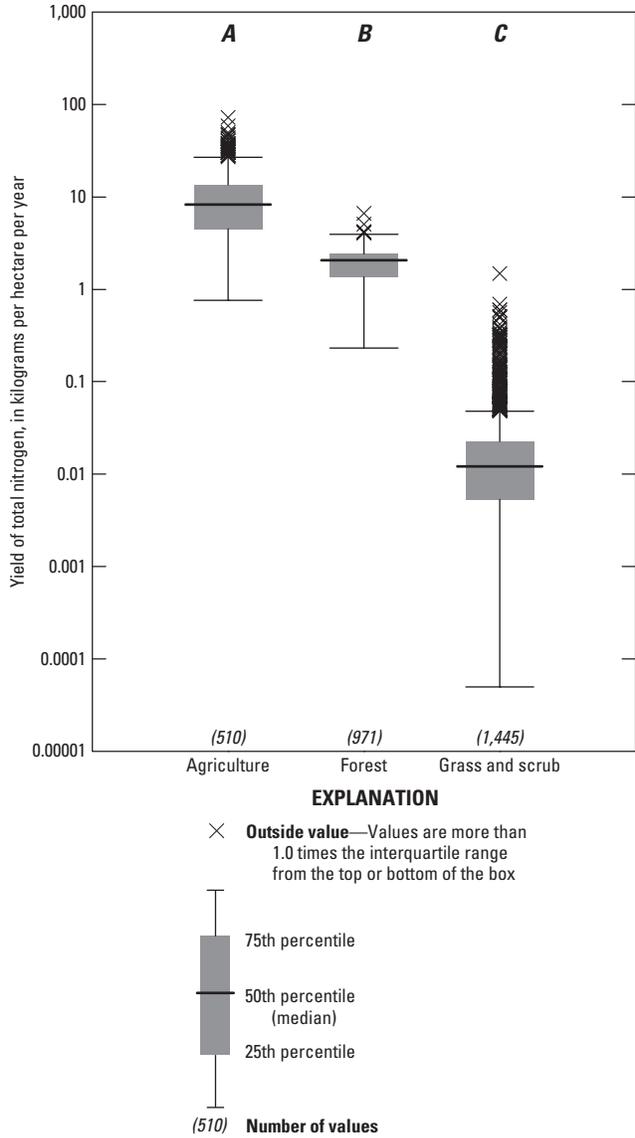


Figure 10. Distribution of total nitrogen yield in catchments with a single dominant land use in the Yakima River Basin, Washington. “Dominant” is defined as 90 percent or more of the catchment area for the forest land and grass and scrub land categories, and as 50 percent or more of the catchment area for the agricultural category.

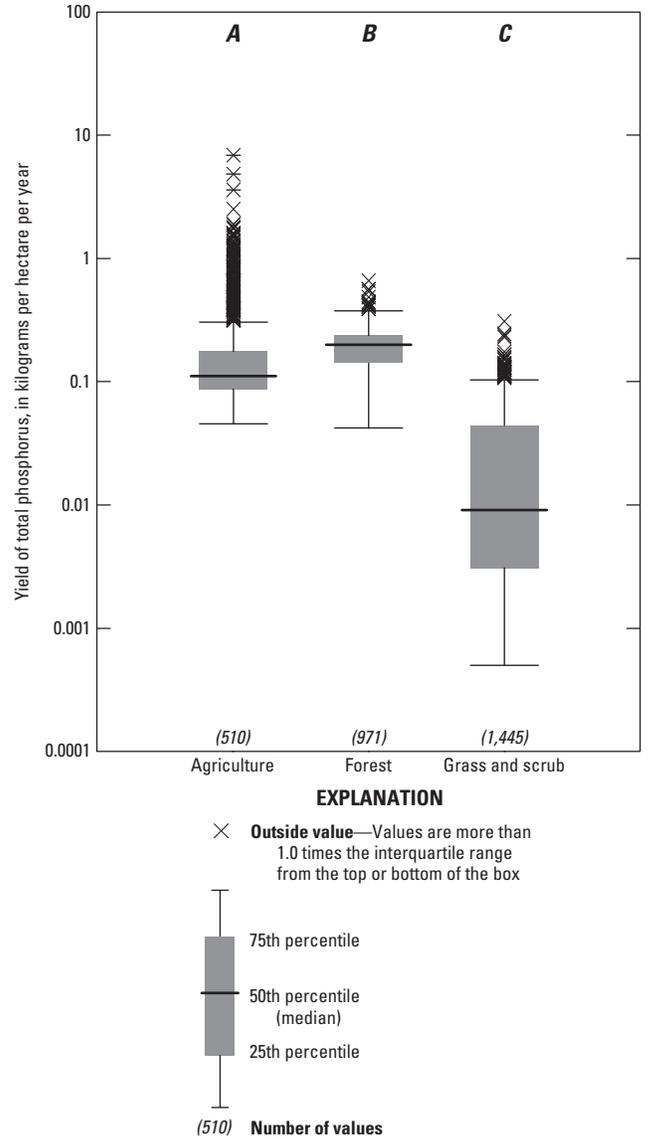


Figure 11. Distribution of total phosphorus yield in catchments with a single dominant land use in the Yakima River Basin, Washington. “Dominant” is defined as 90 percent or more of the catchment area for the forest land and grass and scrub land categories, and as 50 percent or more of the catchment area for the agricultural category.

Table 3. Values of total nitrogen and total phosphorus yield from published reports and values of total nitrogen and total phosphorus yield calculated from data in published reports.

[Abbreviations: (kg/ha)/yr, kilogram per hectare per year; >, greater than]

Land use	Region	Number of sites	Mean or median yield [(kg/ha)/yr]	Source
Total nitrogen				
Agriculture, >75 percent	Pacific Northwest, east of Cascade Range	180	3.8	Wise and Johnson, 2011, table 6
Agriculture, >50 percent	Washington	2	9.3	Yields calculated from load data provided in Ebbert and others, 2003, table 7
Agriculture, >70 percent	Iowa	10	23.2	Garrett, 2012, table 6
Agriculture, >50 percent	Chesapeake Bay watershed	25	21.1	Langland and others, 1995, table 8
Agriculture, >50 percent	Chesapeake Bay watershed in Virginia	5	11.3	Johnson and Belval, 1998, table 6
Agriculture, >50 percent	South Carolina	2	2.4	Journey and others, 2011, table 9
Agriculture, >50 percent	Arkansas and Oklahoma	2	12.5	Esralew and Tortorelli, 2010, table 9
Agriculture, >75 percent	United States, East of Mississippi River	91	9.8	Clesceri and others, 1986, table 7
Agriculture, >75 percent	United States, West of Mississippi River	91	4.4	Clesceri and others, 1986, table 7
Agriculture, >75 percent	Wisconsin	6	6.7	Clesceri and others, 1986, table 7
Forest	United States	19	2.6	Lewis, 2002, table 2
Forest, >75 percent	Pacific Northwest, east of Cascade Range	1,901	1.3	Wise and Johnson, 2011, table 6
Forest	California	10	1.2	Coats and Goldman, 2001, table 6
Forest, >75 percent	Oregon	40	0.6	Weighted mean of values in Vanderbilt and others, 2003, table 4
Forest, >75 percent	Chesapeake Bay watershed	28	9.6	Langland and others, 1995, table 8
Forest, >75 percent	Chesapeake Bay watershed in Virginia	5	2.9	Johnson and Belval, 1998, table 6
Forest, minimally disturbed	North America	63	0.9	Clark and others, 2000, table 1
Forest, >80 percent	Oregon	9	0.5	Rinella, 1986, table 13
Forest, minimally disturbed	Oregon	2	0.9	Martin and Harr, 1988, table 5
Forest, minimally disturbed	Washington	1	7.1	Edmonds and others, 1995, table 3
Forest, >90 percent	Washington	3	4.6	Yields calculated from data provided in Embrey and Inkpen, 1998, tables 1 and 6
Range, >75 percent	Pacific Northwest, east of Cascade Range	2,181	0.2	Wise and Johnson, 2011, table 6
Range and pasture	North America	unknown	1.0	Harmel and others, 2006, table 5
Range, >50 percent (range + forest >85 percent)	Texas	2	1.2	McFarland and Hauck, 2001
Total phosphorus				
Agriculture, >75 percent	Pacific Northwest, east of Cascade Range	180	0.4	Wise and Johnson, 2011, table 6
Agriculture, >50 percent	Washington	2	1.1	Yields calculated from load data provided in Ebbert and others, 2003, table 7
Agriculture, >70 percent	Iowa	10	1.4	Garrett, 2012, table 6
Agriculture, >50 percent	Chesapeake Bay watershed	25	1.9	Langland and others, 1995, table 8
Agriculture, >50 percent	Virginia	2	1.1	Johnson and Belval, 1998, table 6
Agriculture, >50 percent	South Carolina	2	0.2	Journey and others, 2011, table 9
Agriculture, >50 percent	Arkansas and Oklahoma	2	0.9	Esralew and Tortorelli, 2010, table 10
Agriculture, >50 percent	Arkansas and Oklahoma	5	0.8	Tortorelli and Pickup, 2006, table 5
Agriculture, >50 percent	Washington	1	1.5	Yields calculated from data provided in Embrey and Inkpen, 1998, tables 1 and 6
Agriculture, >75 percent	United States, East of Mississippi River	91	0.3	Clesceri and others, 1986, table 7
Agriculture, >75 percent	United States, West of Mississippi River	91	0.2	Clesceri and others, 1986, table 7
Agriculture, >75 percent	Wisconsin	6	0.3	Clesceri and others, 1986, table 7

Table 3. Values of total nitrogen and total phosphorus yield from published reports and values of total nitrogen and total phosphorus yield calculated from data in published reports.—Continued

[Abbreviations: (kg/ha)/yr, kilogram per hectare per year; >, greater than]

Land use	Region	Number of sites	Mean or median yield [(kg/ha)/yr]	Source
Total phosphorus—Continued				
Forest, >75 percent	Pacific Northwest, east of Cascade Range	1,901	0.1	Wise and Johnson, 2011, table 6
Forest, >75 percent	Chesapeake Bay watershed	28	1.0	Langland and others, 1995, table 8
Forest, >75 percent	Virginia	3	0.4	Johnson and Belval, 1998, table 6
Forest, minimally disturbed	North America	63	0.1	Clark and others, 2000, table 1
Forest, >80 percent	Oregon	9	0.1	Rinella, 1986, table 13
Forest, minimally disturbed	Oregon	2	0.6	Martin and Harr, 1988, table 5
Forest, >90 percent	Washington	3	0.5	Yields calculated from data provided in Embrey and Inkpen, 1998, tables 1 and 6
Range, >75 percent	Pacific Northwest, east of Cascade Range	2,181	0.1	Wise and Johnson, 2011, table 6
Range and Pasture	North America	unknown	0.2	Harmel and others, 2006, table 5
Range, >50 percent (range + forest >80 percent)	Texas	2	0.2	McFarland and Hauck, 2001

Table 4. Comparison of model diagnostic statistics and directly comparable source-term model coefficients for the SPARROW models developed for the United States Pacific Northwest and the Middle Columbia River Basin, Oregon, Washington, and Idaho.[Total nitrogen and phosphorus PNW model: Model diagnostic statistics for the Wise and Johnson (2013) models were recalculated using only sites that were common between those models and the new models for the Middle-Columbia Basin. Abbreviations: (kg/km²)/yr, kilogram per square kilometer per year; PNW, Pacific Northwest; R², coefficient of determination; –, not applicable]

	Model coefficient units	Total nitrogen		Total phosphorus	
		PNW model	Mid-Columbia model	PNW model	Mid-Columbia model
Model diagnostics					
R ² of yield	–	0.86	0.86	0.77	0.80
Root mean square error (RMSE)	–	0.44	0.43	0.54	0.49
Source term coefficient					
Forest land ¹	(kg/km ² /yr)	72	60	6.8	9.0
Farm fertilizer	dimensionless	–	–	0.015	0.041
Confined cattle manure	dimensionless	–	–	0.035	0.009
Grazing livestock manure	dimensionless	–	–	0.12	0.0088
Scrub and grass land	(kg/km ² /yr)	–	–	0.54	0.43
Point sources	dimensionless	1.0	1.1	1.2	1.2
Springs and power returns	dimensionless	0.96	0.80	1.7	1.5

¹PNW coefficient is for “Forest land (east),” representing forest land east of the Cascade Range.

Comparison with Regional SPARROW Model

Wise and Johnson (2013) published TN and TP SPARROW models for the PNW, including the entire area encompassed by the domain of this model. The modeling effort documented in this report was undertaken to provide refined predictions for the arid interior of the PNW, and specifically, for the Yakima River Basin. SPARROW model calibration is driven by gradients in the sources and land-to-water delivery terms, and in the PNW SPARROW models, the precipitation gradient across the Cascade Range strongly influenced the calibration. This influence is due to the precipitation gradient itself, and to indirect influences, such as differences in the type of precipitation (rain-dominated compared with snow-dominated), types of nutrient sources, farming practices, population density, and urban runoff. In recalibrating the SPARROW models for this study, an attempt was made to utilize the same source and delivery terms as were used in the PNW models. Elimination of the red alder and urban sources in the PNW models resulted in the need to restructure the sources in the TN model for this study; as a result, a direct comparison of the PNW and Middle Columbia River Basin TN models was not possible. The PNW and Middle Columbia TP River Basin models are directly comparable.

Only three source terms were directly comparable between the PNW and Middle Columbia River Basin TN models—(1) forest land, (2) point sources, and (3) springs and power returns ([table 4](#)). The forest source in the Middle Columbia River Basin TN model was compared with the “forest land (east)” source in the PNW TN model. The coefficient in the Middle Columbia River Basin model was smaller: 60 (kg/km²)/yr compared with the PNW model coefficient of 72 (kg/km²)/yr, indicating that the Middle Columbia River Basin TN model required less TN from its forested regions to meet the monitored in-stream nutrient load. The reason for this decrease is uncertain, but it could be because of the elimination of the Rocky Mountains from the model domain or perhaps from the use of different source terms in the Middle Columbia River Basin TN model. A decrease also was observed for the source term representing springs and power returns in the TN model, which is most likely due to the elimination of springs and power returns west of the Cascade Range. The coefficients for point sources in both TN models were similar.

All source terms in the TP models for the PNW and the Middle Columbia River Basin are comparable ([table 4](#)). Of the seven terms, only the coefficients for farm fertilizer and confined cattle manure differed by more than a factor of 2. The coefficient for farm fertilizer in the Middle Columbia River Basin model increased compared to the PNW model of Wise and Johnson (2013), and the coefficient on confined cattle manure decreased. That the two terms changed in tandem in opposite directions suggests a potential issue with the

ability of the model to reliably discriminate between the two sources. Because of the spatial correlation between the two data sources, the two terms had to be combined for the Middle Columbia River Basin TN model. This observation also may be related to a lack of calibration sites in areas dominated by agricultural land use (see section, [Nutrient Yields and Land Use](#)).

The fit of the TN and TP PNW SPARROW models was compared to the fit of the Middle Columbia River Basin models by recalculating the RMSE and yield R-squared statistics of the PNW models using only those sites that also were in the Middle Columbia River Basin models ([table 4](#)). The RMSE and R² of yield value of the two TN models were identical or nearly identical, indicating the new model provided no overall improvement in fit compared to the PNW TN model. In one respect, however, the new model improved on the PNW TN model by using fewer terms to characterize the system. The RMSE and R² of yield values for the Middle Columbia River Basin TP model indicate it offers a modest improvement in overall fit compared to the PNW TP SPARROW model.

Summary

SPARROW models for total nitrogen (TN) and total phosphorus (TP) were constructed for the Middle Columbia River Basin of Oregon, Washington, and Idaho, with emphasis on the Yakima River Basin in Washington. The models rely on the same data used by the PNW TN and TP SPARROW models, but the models were recalibrated for a more limited domain in order to refine the nutrient load and source-share estimates for the Yakima River Basin. A direct comparison of the TN models was not possible because of the use of different source terms in the two models; however, a comparison of the two TP models indicated relatively little difference in the magnitude of five of the seven source term coefficients. The coefficients for the farm fertilizer and confined cattle manure changed in opposite directions and the changes were of similar magnitudes in the two TP models.

The Middle Columbia River Basin TN and TP models were used to compute the relative contribution of sources to the TN and TP load in the main stem of the Yakima River. The river is dominated by natural sources of TN issuing from forest land in its upper reaches. Agricultural and point-source discharges constitute a large percentage of the TN load as the river flows through areas of intense cultivation and past cities, and receives effluent from municipal wastewater-treatment plants (WWTPs). The TN load increases slowly for the first 200 river kilometers (RKs), but increases rapidly with inputs from the city of Yakima WWTP and agricultural drains in the lower Yakima Valley. WWTP effluent from cities downstream of Yakima increases the TN load in the Yakima River, but does not appreciably affect the percentage of the TN in the river main stem from point sources due to the magnitude of the

TN output from the large drains in the lower Yakima Valley such as Granger Drain, Marion Drain, Toppenish Creek, and Sulphur Creek Wasteway.

As with TN, the Yakima River is dominated by natural sources of TP issuing from forest land in its upper reaches. TP originating from forest land is presumed to be largely from natural weathering of geologic materials. Contributions of TP from grazing land and point sources (municipal WWTPs) constitute most of the TP in the river downstream to about RK 210, where the city of Yakima WWTP outfall enters the river. Downstream of this point, the dominant sources of TP load in the river shift from predominantly natural to predominantly anthropogenic. TP from farm fertilizer and confined cattle manure become a major part of the TP load in the river downstream of the large lower valley agricultural drains, many of which enter the river between RK 150 and RK 100.

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Appendix A. Prediction Results and Calibration Loads

The mean annual total nitrogen and phosphorus loads and yields predicted by the Middle Columbia River Basin SPARROW models are available online in a tab-delimited ASCII file at <http://pubs.usgs.gov/sir/2013/5199/>. The file includes predictions for individual stream reaches in the National Hydrography Dataset Plus Version 2 (Pacific Northwest) geospatial dataset (Horizon Systems, 2013). Columns in the ASCII file are described in the header (denoted by lines starting with “#”), and include COMID (common identifier of an NHD reach), AreaSqKM (area of the incremental NHD catchment, in square kilometers), TotDASqKM (total area draining to a reach, in square kilometers), predictions of the total mean annual load for each reach that is attributable to all upstream nutrient sources (in kilograms per year), and predictions of the total mean annual load for each reach that is attributable to individual upstream nutrient sources (in kilograms per year). The file also contains the estimated loads used to calibrate the SPARROW models.

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