National Water Quality Program

Using Regional Watershed Data to Assess Water-Quality Impairment in the Pacific Drainages of the United States

Scientific Investigations Report 2021–5087

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

Cover. The lower Snake River, which forms part of the border between Idaho and Oregon, has been identified by both states as an impaired waterway because of excess nutrients. (Photograph by Ken Tiffan, U.S. Geological Survey, public domain image, https://www.usgs.gov/media/images/hells-canyon-snake-river.)

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
	Mass	
ounce, avoirdupois (oz)	28,349	Milligram (mg)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Application rate	
pound per acre per year ([lb/acre]/yr)	1.121	kilogram per hectare per year ([kg/ha]/yr)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Mass	
milligram (mg)	0.00000353	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Application rate	
kilogram per hectare per year ([kg/ha]/yr)	0.8921	pound per acre per year ([lb/acre]/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

EPA	U.S. Environmental Protection Agency
NPDAT	Nitrogen and Phosphorus Pollution Data Access Tool
USGS	U.S. Geological Survey
WATERS	Watershed Assessment, Tracking & Environmental Results System

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Abstract

Two datasets containing the first complete estimates of reach-scale nutrient, water use, dissolved oxygen, and pH conditions for the Pacific drainages of the United States were created to help inform water-quality management decisions in that region. The datasets were developed using easily obtainable watershed data, most of which have not been available until recently, and the techniques that were used provide a framework for integrating watershed data to assess water-quality impairment across other large hydrologic regions in the United States. These datasets were used to summarize regional nutrient and water-use conditions within impaired water bodies and to summarize regional dissolved oxygen concentrations and pH conditions for free-flowing stream reaches. Two examples are also presented that show how the datasets can be applied to specific water-quality management issues: (1) nutrient conditions in water bodies that have recently experienced problems with harmful algal blooms; and (2) dissolved oxygen and pH conditions in stream reaches likely to be populated by steelhead trout (*Oncorhynchus mykiss irideus*) during their summer run. The nutrient and water-use estimates could help inform actions aimed at managing water-quality conditions in impaired water bodies while the dissolved oxygen and pH predictions could be useful as screening tools to identify water bodies experiencing potential impairment.

Introduction

Government agencies responsible for managing watersheds for a variety of uses and benefits rely on many types of information to guide their assessments, management, and decision making. It's important that these agencies have access to readily available water-quality and watershed data that represent the time period in which they are interested, but until recently such data were often incomplete, outdated, or non-existent. With the advent of large-scale spatial datasets describing atmospheric, hydrologic, and terrestrial characteristics, detailed spatial and temporal analyses at the watershed level can now be performed to help inform management decisions. The U.S. Environmental Protection Agency's (EPA) Watershed Assessment, Tracking & Environmental Results System (WATERS; EPA, 2020a) and Nitrogen and Phosphorus Pollution Data Access Tool (NPDAT; EPA, 2020b), which bring together watershed data that were previously available only from several independent and unconnected databases, are examples of how national watershed data can be compiled and made available through on-line databases. While both the WATERS and NPDAT applications can help inform local water-quality assessments, they are limited to nationally available datasets. This report describes how regional watershed data were used to assess water-quality impairment related to nutrient enrichment in the Pacific drainages of the United States, which are the watersheds that ultimately drain to the Pacific Ocean.

Nutrient over-enrichment is a serious threat to inland waters throughout most of the United States (U.S. Geological Survey, 1999) and is also a problem within the Pacific drainages (California Water Resources Control Board, 2017; Idaho Department of Environmental Quality, 2017; Montana Department of Environmental Quality, 2017; Oregon Department of Environmental Quality 2017; Washington Department of Environmental Conservation, 2017; Wyoming Department of Environmental Quality, 2017). Many of the streams, ponds, lakes, and reservoirs within the Pacific drainages included on recent state 303(d) lists of impaired water bodies were placed there because they were not supporting their designated beneficial uses (for example, drinking water, recreation, aquatic life, and irrigation) due to excessive nutrient levels, nuisance algal or rooted plant growth, low dissolved oxygen concentrations, or elevated pH. These types of impairment are often associated with increases in primary productivity related to nutrient enrichment caused by humans (known as "cultural eutrophication," but referred in this report as simply "eutrophication"), but there are other factors such as wastewater discharge, water use, water temperature, and soil chemistry that can influence nutrient impairment when it occurs.

The six states with jurisdiction over the Pacific drainages (California, Idaho, Montana, Nevada, Oregon, Washington, and Wyoming) use a variety of water-quality and watershed data to assess water bodies with regards to eutrophication. Because of the substantial resources required to obtain acceptable data with regards to quantity (both temporally and spatially) and quality; however, it is not possible for these water-quality agencies to do site-specific assessments of all water bodies. A general indication of the overall ecological health of the water bodies within the Pacific drainages is provided by the EPA's National Rivers and Streams Assessment (NRSA). The NRSA, which all six states participate in, is a collaborative probabilistic survey that provides a statistical representation of the condition of rivers and streams across a region and the key stressors that affect them. The states use data collected through the NRSA in their evaluations of individual water bodies as part of their assessment process but do not use those data to perform state-wide assessments of eutrophication. The states also identify the important sources of nutrients causing impairment as part of their Total Maximum Daily Load (TMDL) development process. While the contributions from point sources (for example, wastewater treatment plants and other permitted dischargers) are typically easy to estimate because of the legal requirements for facilities to perform routine monitoring and submit those results to state regulatory agencies, the contributions from diffuse (often called "non-point") sources such as agriculture, urban runoff, and natural sources are often difficult to quantify or are not readily available. One tool that allows water-quality managers to account for both point and non-point nutrient sources is the Spatially Referenced Regression On Watershed Attributes (SPARROW) model, which was developed by the U.S. Geological Survey (USGS) (Schwarz and others, 2006).

Purpose and Scope

This report describes how SPARROW predictions and other available watershed data were used to develop two new datasets that can help state regulatory agencies assess water-quality impairment within the Pacific drainages. These two datasets are available in an accompanying USGS data release (Wise, 2021). The first dataset consists of reach-scale estimates of nutrient conditions (loads, yields, concentrations, and the contribution from different sources) and water use, which water-quality managers can use to identify the contribution from different sources to the nutrient loads delivered to individual water bodies and evaluate their susceptibility to water stress. The second dataset consists of reach-scale predictions for two indicators of water-quality impairment often associated with eutrophication: (1) mean warm-weather minimum daily dissolved oxygen concentration and (2) mean warm-weather maximum daily pH. These predictions were based on multiple linear regression models that related measured values for those indicators to mean annual SPARROW predictions and other watershed data. This approach is substantially different than conventional approaches to modeling dissolved oxygen and pH conditions such as the CE-QUAL-W2 model (Cole and Wells, 2006) and QUAL2K model (Chapra and others, 2012), which use detailed measurements or estimates of climatic and in-stream conditions to simulate diel water-quality conditions. It is not feasible, however, to use those rigorous approaches to evaluate thousands of stream reaches across an entire watershed or across a state the way the predictions described in this report can be used. The dataset representing dissolved oxygen and pH conditions resulted from a novel type of analysis that was only possible because of the recent availability of SPARROW predictions and other watershed data.

Description of the Study Area

The Pacific drainages cover a total area of 1,060,580 square kilometers and include the Columbia River basin, the watersheds draining to Puget Sound, the coastal drainages of Washington, Oregon, and California, the Klamath River basin, the Sacramento River basin, the San Joaquin River basin, and the watersheds surrounding San Francisco Bay (fig. 1). In 2011, scrub and grassland covered 39 percent of the modeling domain, forest covered 34 percent, agricultural areas covered 10 percent, urbanized areas covered 4.3 percent, and the remaining areas consisted of various minor land cover types (Homer and others, 2015). The climate varies widely across the modeling domain, with a humid continental climate in western Washington and Oregon, a semi-arid steppe climate in eastern Oregon and Washington and most of Idaho, a Mediterranean climate along most of the California coast and in the Central Valley, a desert climate in southern California, and an alpine climate in the Sierra Nevada in California, the Cascade Range in northern California, Washington, Oregon, and the Rocky Mountains in Idaho, Montana, and Wyoming. A detailed description of the Pacific drainages, including the extensive manipulation of the natural hydrology that occurs throughout the region, is included in Wise (2019a).

Figure 1. Pacific drainages of the United States.

Methods

The two datasets described in this report were referenced to version 2 of the NHDPlus stream network (referred to as "the NHDPlus2" in this report; Horizon Systems, 2013). The NHDPlus2 is a comprehensive set of digital spatial data that represents streams, ponds, lakes, and reservoirs that largely correspond to the features on 1:100,000 scale USGS topographic maps. Stream reaches in the NHDPlus2 are represented by line segments that start at any point of channel initiation (headwater reaches) or a tributary junction and end at the next downstream tributary junction. The NHDPlus2 also includes the incremental catchment for almost all reaches, which is the area that drains directly to a that reach without passing through another reach. The Pacific drainages contain 324,454 NHDPlus2 incremental catchments.

Analysis

Nutrient and Water-Use Conditions

Nutrient and water-use conditions were estimated for all NHDPlus2 stream reaches. A subset of that larger dataset was selected to represent water bodies in the Pacific drainages that were not supporting their designated beneficial uses because of impairment related to eutrophication (based on the state 303[d] lists for 2012), which was consistent with the time frame represented by the watershed data used in this analysis. Nutrient conditions, as estimated by the USGS SPARROW models developed for the Pacific drainages for 2012 (Wise, 2019a), consisted of the mean annual total nitrogen and total phosphorus loads, yields, and flow-weighted concentrations and the contributions from individual anthropogenic and natural sources to the mean annual loads. Water-use conditions were represented by two indicators. One was a general water use index for each reach that equaled the current streamflow divided by the streamflow that would occur without any hydrologic manipulation, such as upstream water diversions and the return of water to streams through municipal wastewater discharge and runoff from irrigated land. The second indicator was a groundwater-use index for each reach that equaled the total upstream withdrawal of groundwater divided by the current streamflow in the reach. These estimates were used to provide both a regional summary of nutrient and water-use conditions for impaired water bodies and to show the conditions in four individual impaired water bodies that have recently experienced problems with harmful algal blooms, which are a growing concern across the Pacific drainages and the United States.

Linear Regression Models

Linear regression models were developed to relate mean warm-weather minimum daily dissolved oxygen concentrations and mean warm-weather maximum daily pH in 40 and 45 free-flowing stream reaches, respectively, to watershed attributes that were expected to have some influence on those parameters. The explanatory attributes retained in the models represented statistically significant variables (p-value less than 0.05) that provided the best model fit based on the adjusted coefficient of determination (adjusted R^2). Table 1 describes the stream and landscape attributes that were evaluated as explanatory variables in the dissolved oxygen and pH linear regression models. These explanatory variables represented one of the four general types of expected control on primary productivity: water chemistry, light availability, water temperature, and hydrology. The linear regression models were used to predict mean warm-weather minimum daily dissolved oxygen concentrations and mean warm-weather maximum daily pH for free-flowing NHDPlus2 stream reaches in the Pacific drainages. No predictions were made, however, for reaches where the value for at least one of the explanatory variables was either missing or outside the range of values used in the model calibrations. This meant that dissolved oxygen and pH predictions were made for about 83 percent of the 313,032 NHDPlus2 reaches representing free-flowing streams. An example application of those predictions is also presented that shows how they can be used to assess potential impairment in stream reaches likely to be populated by steelhead trout (*Oncorhynchus mykiss irideus*) during their summer run in the Pacific drainages.

Data Sources

The five types of data used to develop the datasets described in this report were:

(1) recent SPARROW model predictions of streamflow, total nitrogen, total phosphorus, and sediment for the Pacific drainages;

(2) minimum daily dissolved oxygen concentrations and maximum daily pH measured at USGS continuous monitoring stations;

(3) results from the U.S. Forest Service NorWest stream temperature modeling project;

(4) values for selected landscape parameters; and

(5) data describing the spatial extent of steelhead trout summer runs.

Table 1. Attributes that were evaluated as explanatory variables in dissolved oxygen and pH regression models developed for the Pacific drainages of the United States.

[**Units**: ft^3/sec, cubic foot per second; $kg/km^2/yr$, kilogram per square kilometer per year; kg/yr, kilogram per year; $kWh/m^2/day$, kilowatt-hour per square meter per day; mg/l, milligram per liter; mohm/cm, milliohms per cm; °C, degrees Celsius. **Source**: EPA, U.S. Environmental Protection Agency; NAWQA, National Water-Quality Assessment; NHDPlus, National Hydrography Dataset; NorWest, The Northwest Stream Temperature database; NREL, National Renewable Energy Laboratory; SPARROW, SPAtially Referenced Regression On Watershed attributes model; USGS, U.S. Geological Survey]

Control	Watershed attribute	Units	Source
Water chemistry	Percentage of mean annual streamflow contributed by WWTPs	Percent	SPARROW
	Mean annual total nitrogen load	kg/yr	SPARROW
	Mean annual total nitrogen yield	kg/sqkm-yr	SPARROW
	Mean annual flow-weighted total nitrogen concentration	mg/l	SPARROW
	Mean annual total phosphorus load	kg/yr	SPARROW
	Mean annual total phosphorus yield	kg/sqkm-yr	SPARROW
	Mean annual flow-weighted total phosphorus concentration	mg/l	SPARROW
	Mean soil salinity for contributing drainage area	mohm/cm	NAWQA
	Active and formerly active mining operations where there was a potential for downstream acid mine drainage pollution	Number	USGS, EPA
Light availability	Stream canopy cover (2001)	Percent	NorWest
	Mean warm period solar radiation (1998–2009)	$kWh/m^2/day$	NREL
	Mean annual suspended-sediment load	kg/yr	SPARROW
	Mean annual suspended-sediment yield	$kg/km^2/yr$	SPARROW
	Mean annual flow-weighted suspended-sediment concentration	mg/l	SPARROW
Water temperature	Mean August water temperature (2000–11)	°C	NorWest
Hydrology	Mean annual streamflow (2012)	ft^3/sec	SPARROW
	Mean annual velocity adjusted for SPARROW streamflow model	ft/sec	NHDPlus/SPARROW
	Base flow index	Percent	NAWQA
	Mean warm period streamflow (2012)	ft^3/sec	SPARROW
	Mean annual streamflow as a percentage of natural streamflow (2012)	Percent	SPARROW
	Upstream groundwater use as percentage of mean annual streamflow	Percent	NAWQA

SPAtially Referenced Regression On Watershed Attributes (SPARROW) Model Predictions

The USGS developed SPARROW models for the Pacific drainages for streamflow and three water-quality constituents– total nitrogen, total phosphorus, and suspended sediment that represented 2012 conditions (Wise, 2019a). The analysis described in this report used either the original predictions from those models or the predictions resulting from minor modifications to the input data for those models. These modifications were made to either correct some of the input data used in original models or to represent conditions that were not within the scope of the original modeling. All predictions represent mean annual conditions for water years 2000–14 that were detrended to water year 2012, which was necessary to account for differences in record length, hydrologic conditions, and sample size among the calibration stations used in the models. This means that the predictions reflect landscape conditions for water year 2012 but mean annual hydrologic conditions for water years 2000 through 2014. Saad and others (2019) and Wise (2019a) contain a detailed description of how SPARROW models were developed for the Pacific drainages, including the limitations, uncertainties, and potential biases associated with the model SPARROW model input data and model predictions.

Two corrections were made to the input data used in the original SPARROW nutrient models to obtain more accurate estimates of reach-scale nutrient conditions. The predictions from the original nutrient models included the contribution from all land classified as “developed” under the 2011 National Land Cover Database (Homer and others, 2015), and this meant that the in-stream nutrient loads predicted by those models included the contribution from paved and unpaved roads. While this contribution was relatively small in urban areas, it was often incorrectly predicted to be the largest nutrient source in many undeveloped areas within the Pacific drainages (Wise, 2019a). To correct this problem, the input data were modified so that the contribution from developed land was limited to those areas located within delineated towns and cities. The predictions from the original total phosphorus model also included the contribution from cattle grazing manure applied to land that was determined to be suitable for grazing, which included areas located within national forests. While grazing manure phosphorus from these forested areas made up only 11 percent of the total contributed by grazing cattle, it was often predicted to be the largest phosphorus source in many areas within the Pacific drainages. Based on discussions with water-quality managers, however, these results do not reflect actual conditions. To correct this problem, the input data for the total phosphorus model were modified so that the contribution form grazing manure was limited to those areas that did not represent forest land.

Because of the way the mean annual flow-weighted nutrient concentrations predicted by the SPARROW models were calculated, there were a very small number of reaches with extremely high values for this parameter. The mean annual flow-weighted concentration for a reach was equal to the SPARROW-estimated mean annual load divided by the SPARROW-estimated mean annual streamflow, and the estimated mean annual streamflow was close to zero in some reaches. This led to unrealistically high estimates of mean annual flow-weighted concentration (sometimes greater than 1,000 mg/l). To overcome this problem, the estimated mean annual flow-weighted concentrations for total nitrogen and total phosphorus were capped at more realistic (but still very high) values. These values were 70 and 12 mg/l, respectively, which represent the highest concentrations of total nitrogen and total phosphorus typically measured in raw sewage (Tchobanoglous and others, 2003).

The predictions from the original streamflow model accounted for consumptive water use for public water supply and agriculture as well as the return of that water to streams through municipal wastewater discharge and runoff from irrigated land, respectively. These diversions include 642 municipal water supply intakes and 248 irrigation withdrawals. The model also accounted for 72 water transfers that occur either within river basins or between river basins. The original streamflow model was used to run a scenario that did not include any of these types of water manipulations to provide an estimate of natural streamflow conditions. These predictions were then used to calculate the general water-use index described earlier that was equal to the current streamflow expressed as a percentage of the natural streamflow.

Because of the spatially explicit nature of the watershed data that were used as input to the 2012 SPARROW models, the contribution to the estimated load in a reach from sources that were not directly accounted for in the models can still be estimated for that reach. The contribution from indirectly modeled sources was estimated for two total phosphorus sources (fertilizer applied to farmland and wastewater discharge) and four total nitrogen sources (fertilizer applied to farmland, wastewater discharge, atmospheric deposition, and runoff from developed land) that were directly accounted for in the models.

(1) The contribution to total nitrogen and total phosphorus load from all fertilizer applied to farmland was disaggregated into the contributions from commercial fertilizer and livestock manure, which were the two forms of fertilizer that made up that source (Wise, 2019b). The contribution from livestock manure used as fertilizer was further disaggregated into its two individual components, which were manure from cattle housed in concentrated animal feeding operations (such as dairies and feedlots) and manure from non-cattle livestock such as poultry, horses, and sheep.

(2) The contribution to total nitrogen and total phosphorus load from wastewater discharge was disaggregated into the contribution from aquaculture facilities such as hatcheries and fish farms and the contribution from other types of discharge, which was primarily from sewage treatment plants (Skinner and Wise, 2019).

(3) The contribution to total nitrogen load associated with atmospheric nitrogen deposition was disaggregated into the separate contributions from oxidized nitrogen (from combustion sources) and reduced nitrogen (from agricultural sources–primarily livestock) (Wieczorek and others, 2019).

(4) The contribution to total nitrogen load associated with runoff from developed land primarily represented two sources–fertilizer use and leaching from onsite wastewater treatment (mostly septic tanks), but this source could not be disaggregated into its separate components in the total nitrogen model because of the way it was parameterized. A general indication of the contribution from onsite wastewater treatment to the in-stream total nitrogen loads was estimated, however, by expressing the upstream population served by onsite wastewater treatment (Wise, 2019c) as a percentage of the total upstream population.

Continuous Monitoring Data

The results from continuous water-quality monitoring provided the data for the dependent variables in the dissolved oxygen and pH regression models. The USGS has a well-established network of water-quality stations in the Pacific drainages where high-quality continuous data have been collected over many years and have undergone a thorough quality-control review of the methods and procedures used to collect and process the data. There is also a limited amount of state and local agency continuous water-quality data available for the Pacific drainages. Based on a review of the non-USGS data and discussions with the state water-quality database managers, however, it was determined that using just USGS data, collected with consistent quality-control and review processes, minimized potential sources of bias in datasets and afford the most consistent quantitative results across all Pacific drainages. Therefore, only the USGS results were used in the development of the dissolved oxygen and pH linear regression models to ensure that those models were based on the highest quality data available.

Model Calibration Data

The USGS National Water Information System (U.S. Geological Survey, 2019a, https://dx.doi.org/10.5066/F7P55KJN) was queried to obtain the daily minimum dissolved oxygen concentrations and daily maximum pH values measured at USGS continuous monitoring stations between water years 2000 and 2014. To account for nonstationarity in the data, the original daily values were detrended by centering them on the midpoint of each station record. The mean warm period (July 1–August 31) values for the detrended daily values for each station were calculated, and each station was referenced to an NHDPlus2 reach. Dissolved oxygen and pH data were retained for calibration of the linear models if they represented the warm weather seasons for at least 4 different years. Only the most downstream station was retained when two or more stations were located within the same HUC12 watershed and on the same primary flow path. This approach was used to minimize potential calibration bias from station clustering. Additionally, stations that were not located on free-flowing streams (that is, they were located within a pond, lake, or reservoir), stations with data that were not representative of the stream cross section (for example, studies targeting suspected low dissolved oxygen locations), and stations that were heavily influenced by upstream conditions that could not be accounted for in the regression explanatory data (for example, high dissolved oxygen concentrations downstream of a dam or low dissolved oxygen concentrations downstream of a severely eutrophic water body) were not retained.

The final dataset of mean warm period daily minimum dissolved oxygen concentrations included 40 stations (minimum: 2.10 mg/l, maximum: 11.74 mg/l, mean: 7.18 mg/l, number of values for a single station ranging from 130 to 917) (fig. 2), and the final dataset of mean warm period daily maximum pH included 45 stations (minimum: 6.85, maximum: 9.08, mean: 7.90, number of values for a single station ranging from 150 to 917) (fig. 3). Although the total number of stations used in the linear regression models was small given the large area being modeled, the stations did provide good spatial representation of the region–and the land cover for the areas draining to those stations was generally representative of the land cover for all the Pacific drainages (fig. 4). Most of the stations, however, were located within or close to areas dominated by urban development or agriculture, and only a few stations were in areas consisting mostly of forest, scrub, shrub, or grass land (figs. 2, 3). This pattern was not surprising because water-quality studies tend to focus on impaired water bodies, but it might have introduced some bias into the regressions that were used to develop the dissolved oxygen and pH models.

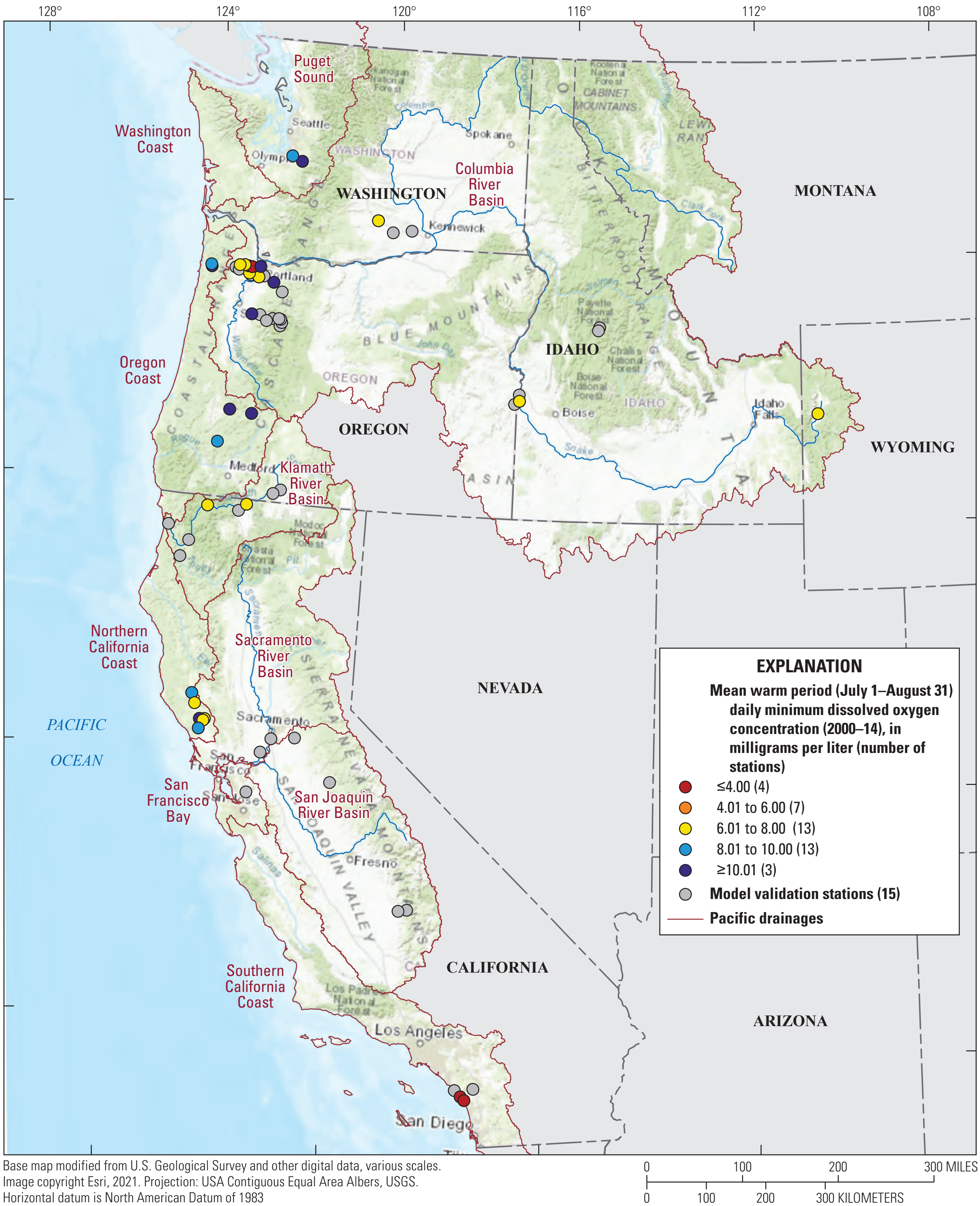

Figure 2. Station locations and calibration data used in the dissolved oxygen linear regression model for Pacific drainages.

Figure 3. Station locations and calibration data used in the pH linear regression model for Pacific drainages.

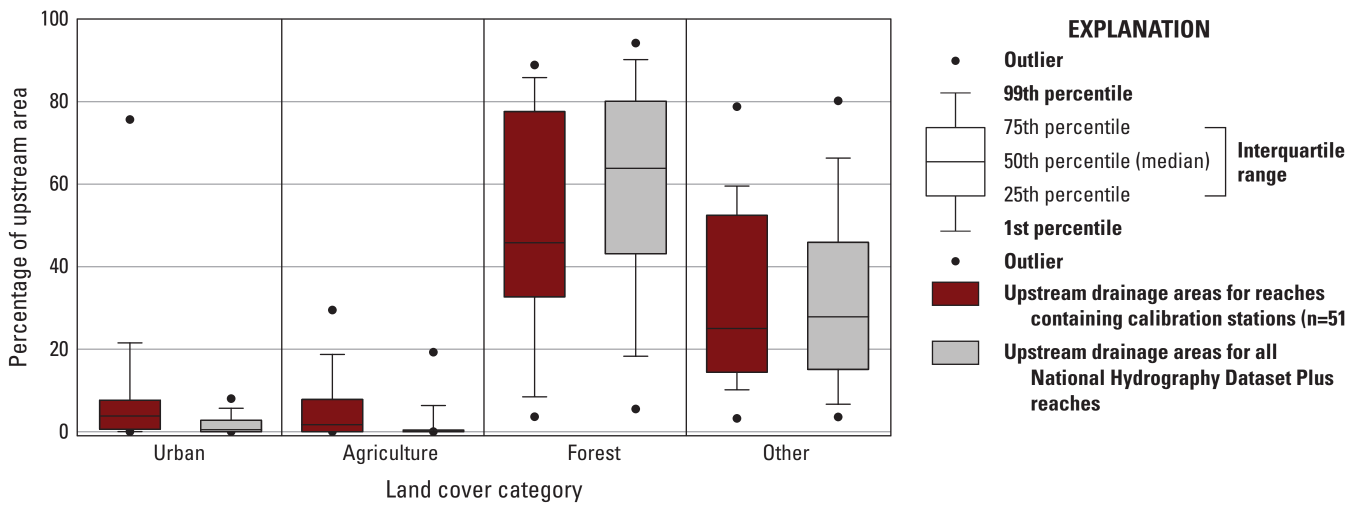

Figure 4. Comparison of upstream land cover for the stations supplying the calibration data used in the dissolved oxygen and pH linear regression models to land cover for all Pacific drainages.

Model Validation Data

The limited amount of data that were used to validate the dissolved oxygen and pH liner models came exclusively from the USGS (U.S. Geological Survey, 2019a, https://dx.doi.org/10.5066/F7P55KJN). Some of the USGS stations had warm weather daily minimum dissolved oxygen concentration and daily maximum pH data that met all criteria for inclusion in the model calibrations except that the data represented fewer than 4 different years. These data provided a way to validate the dissolved oxygen regression model at 15 stations and the pH regression model at 28 stations. The available state data, however, were not adequate to validate the models. While there were stations where states collected continuous water-quality data, data from those stations were sometimes not accessible or were of unknown quality, the period of record was too short or contained substantial gaps, or the data represented impoundments or estuaries where the model predictions do not apply. Figures 2 and 3 show the locations of the USGS stations where model validation was performed.

Stream Temperature Data

The Northwest Stream Temperature (NorWeST) database is a repository for stream temperature data in the western U.S. It hosts more than 220,000,000 temperature recordings from more than 22,700 locations (U.S. Forest Service, 2019). Isaac and others (2017) fit a spatial-stream-network (SSN) model to a subset of the values in the NorWest database to estimate mean August water temperatures (2000–11) for each reach in the NHDPlus2 network located within the NorWest project boundary (which includes all the Pacific drainages). The NorWest database also includes estimates of stream canopy cover for each reach in the NHDPlus2 network. While mean August water temperature estimates existed for each of the reaches containing a model calibration station, there were 181 NHDPlus2 reaches that did not have a value. For those cases a value was estimated using a simple linear regression that related all available mean August water temperature values to the mean maximum annual air temperature (1971–2000) corresponding to their incremental NHDPlus2 catchment (Wieczorek and others, 2019).

Landscape Data

The landscape data evaluated in this study included two attributes that were averaged for each incremental NHDPlus2 catchment–mean summertime total solar radiation for 1998–2009 (National Renewable Energy Laboratory, 2019) and base-flow index (Wieczorek and others, 2019) and three attributes that were generalized for the total area draining to each NHDPlus2 reach–the mean soil salinity and the total withdrawal of groundwater in 2012 (Wieczorek and others, 2019), and the total number of active mining operations (U.S. Geological Survey, 2019b) and formerly active mining operations (Center for International Earth Science Information Network, 2019) where there was a potential for downstream acid mine drainage pollution (specifically, elevated pH levels). The formerly active operations only included those designated as “Superfund” sites under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. A groundwater use index was also calculated for each reach that equaled the total upstream withdrawal of groundwater (Wieczorek and others, 2019) divided by the 2012 streamflow predicted by the SPARROW model for the reach.

Impaired Water Bodies

A regional geo-spatial dataset of impaired water bodies for 2012 was created from the data available from each of the states with jurisdiction over the Pacific drainages or, in the case of Montana, from the EPA (California Water Resources Control Board, 2017; Idaho Department of Environmental Quality, 2017; 2017; Oregon Department of Environmental Quality, 2017; Washington Department of Environmental Conservation, 2017; Wyoming Department of Environmental Quality, 2017; U.S. Environmental Protection Agency, 2019). These datasets were downloaded and filtered to select water bodies impaired by impacts related to eutrophication and belonging to TMDL Categories 4 (water body is impaired or threatened, but a TMDL has been implemented or is not needed) or 5 (water body is impaired and a TMDL is required). The approaches for defining a water body vary between states and even within states, meaning an impaired water body can be an individual impoundment, an individual stream reach, a small group of stream reaches, or even all stream reaches within a watershed (for example, a HUC8 watershed). Because each water body needed to be referenced to a unique NHDPlus2 reach for this analysis, the most downstream NHDPlus2 reach corresponding to each listed water body was selected to represent that water body. The small number of water bodies that were extensive enough to cover more than one HUC8 watershed were divided into separate water bodies. Listed water bodies that were not represented in the NHDPlus2 (typically smaller streams, isolated ponds, and agricultural returns) were not included in the regional dataset of impaired water bodies. The resulting geospatial dataset included 1,809 water bodies within the Pacific drainages that were referenced to an NHDPlus2 reach.

Fish Run Data

Stream reaches likely to be populated by steelhead trout during their summer run in the Pacific drainages were obtained from the California Department of Fish and Wildlife (2020) and the StreamNet database maintained by the Pacific States Marine Fisheries Commission (2020). The original geo-spatial data obtained from these organizations were referenced to the NHDPlus2, and the combination of the two datasets included 43,403 reaches.

Results

Nutrient Conditions for Impaired Water Bodies

The results from this study were used to describe nutrient and water-use conditions for the 1,809 water bodies within the Pacific drainages identified by their states as nutrient-impaired. Table 2 summarizes the SPARROW nutrient modeling for those impaired water bodies, and figures 5 and 6 show the largest contributors to the total nitrogen and total phosphorus load delivered to those water bodies. The directly modeled sources in table 2 are nutrient sources that were represented in the regression equations used in the SPARROW total nitrogen and total phosphorus models and, therefore, were directly accounted for in those models. But as explained earlier, the contribution to the estimated load in a reach from sources that were not directly accounted for in the models can still be estimated–and these contributions are represented by the indirectly modeled sources in table 2.

The SPARROW predictions showed that, on average, diffuse landscape sources, rather than point-source wastewater discharges, are the largest contributors to the total nitrogen load delivered to impaired water bodies in the Pacific drainages (table 2). While the largest mean contributions to total nitrogen load are from atmospheric deposition (34.0 percent) and fertilizer/manure applied to farmland (30.9 percent), there are areas where other sources dominate (fig. 5). Red alder trees are often the largest source in western Washington and Oregon, developed land is generally the largest source in the urbanized watersheds around Seattle and Portland, and springs are the largest source for many reaches of the Snake River.

The SPARROW predictions showed that diffuse landscape sources are also the largest contributors to the total phosphorus load delivered to impaired water bodies (table 2). The largest mean contributions to total phosphorus load are from natural phosphorus originating along stream channels and from weathering of upslope geology (49.4 percent) and agricultural sources (the combination of fertilizer/manure applied to farmland, and grazing cattle manure; totaling 35.9 percent) (table 2). There are also clear spatial patterns in the delivery of total phosphorus to impaired water bodies (fig. 6). Grazing cattle manure is the largest contributor to most of the water bodies in western Washington and Oregon, while natural phosphorus is the largest contributor to most of the water bodies in eastern Washington and Oregon. Fertilizer/manure applied to farmland is generally the largest source in areas of Washington and Oregon under cultivation, whereas point-source wastewater discharge is the largest source for many reaches of the Snake River. In California, natural phosphorus and grazing cattle manure are generally the largest contributors to impaired water bodies located outside of urban areas and areas under cultivation. The largest source in urban areas within California is generally point-source wastewater discharge and the largest source in cultivated areas is generally fertilizer/livestock manure applied to farmland.

Table 2. Summary of SPARROW nutrient modeling for impaired water bodies in the Pacific drainages of the United States.

[NA, not applicable because this is not a directly modeled source for the constituent or there are no indirectly modeled sources for this constituent]

Directly modeled source	Mean contribution to annual total load (percent)		Indirectly modeled source	Mean contribution to directly modeled source (percent)	
	Total nitrogen	Total phosphorus		Total nitrogen	Total phosphorus
Urban land	7.65	8.81	NA	NA	NA
Point-source wastewater discharge	2.66	5.30	Primarily sewage treatment plants	82.5	80.4
			Hatcheries and fish farms	17.5	19.6
Commercial fertilizer and livestock manure applied to cultivated land and pasture	30.9	18.4	Commercial fertilizer	76.8	74.7
			Livestock manure[1,2]	23.2	25.3
Springs	1.24	0.57	NA	NA	NA
Atmospheric deposition	34.0	NA	Oxidized nitrogen	58.6	NA
			Reduced nitrogen	41.4	NA
Red alder trees	10.6	NA	NA	NA	NA
Scrub and grass land	12.9	NA	NA	NA	NA
Grazing cattle manure	NA	17.6	NA	NA	NA
Stream channels and upslope geology	NA	49.4	NA	NA	NA

[1]37.0 percent of the contribution from livestock manure to total nitrogen load was from CAFO cattle, and 63.0 percent was from non-cattle livestock.

[2]35.0 percent of the contribution from livestock manure to total phosphorus load was from CAFO cattle, and 65.0 percent was from non-cattle livestock.

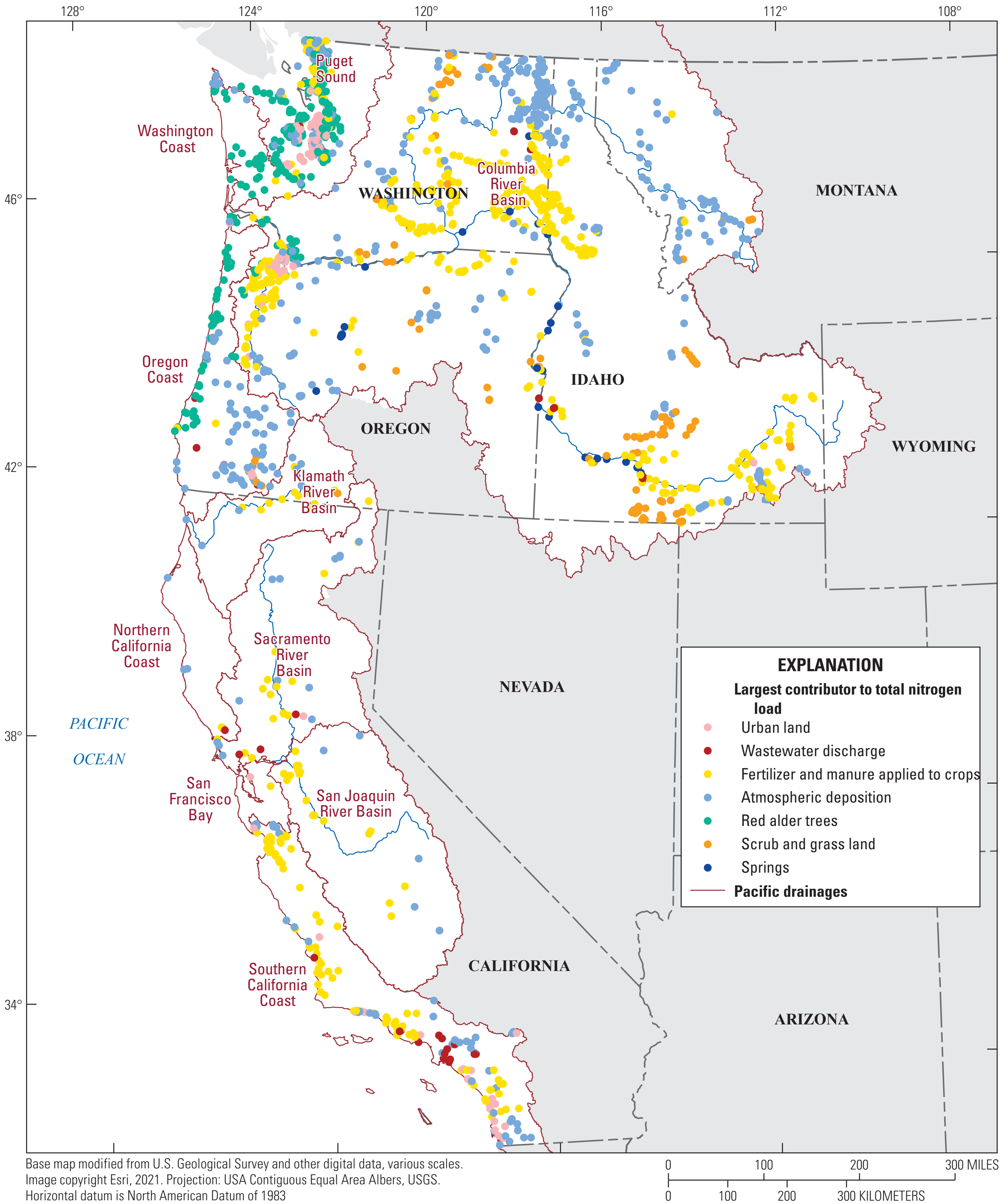

Figure 5. Map showing the largest contributor to total nitrogen load delivered to impaired water bodies in the Pacific drainages of the United States.

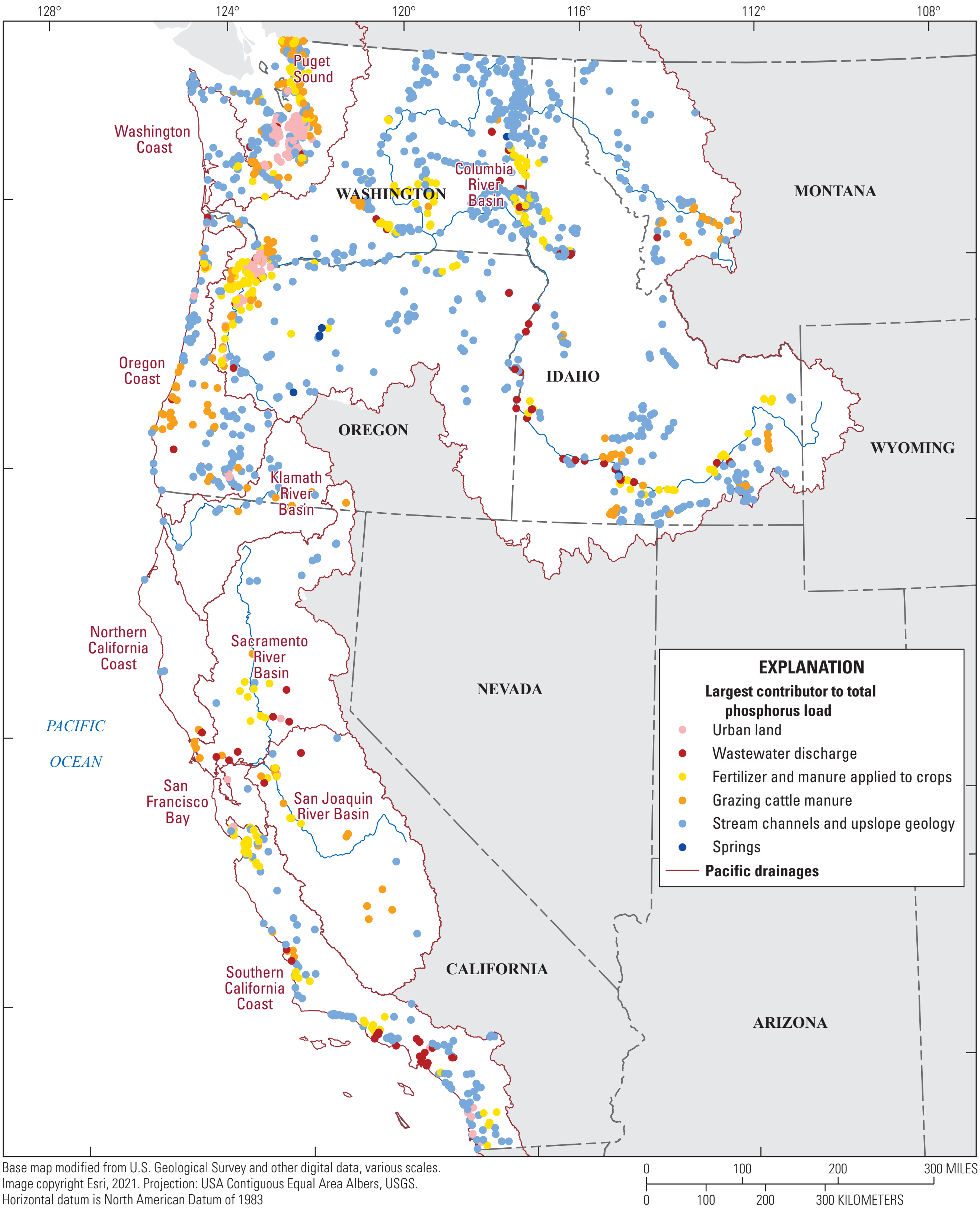

Figure 6. Largest contributor to total phosphorus load delivered to impaired water bodies in the Pacific drainages of the United States.

In addition to the contributions from directly modeled nutrient sources shown in table 2, the contributions from indirectly modeled sources could also be useful to water-quality managers. For example, on average, most of the point-source wastewater discharge comes from sewage treatment plants, commercial fertilizer makes up most of the fertilizer/manure applied to farmland, and of most of the manure applied to farmland comes from non-cattle livestock. And for total nitrogen, table 2 provides information that can be used to estimate the total impact from agricultural activities. Grazing cattle manure was not a significant source in the total nitrogen model for the Pacific drainages, suggesting that most nitrogen from that source is lost to volatilization, denitrification, or mineralization before being delivered to streams. Given that fertilizer/manure applied to farmland contributes on average about 31 percent to total nitrogen load, that a substantial portion of the nitrogen from grazing livestock manure is likely volatilized, and that about 41 percent of the contribution from atmospheric deposition consists of reduced nitrogen (primarily from the volatilization of nitrogen in livestock manure), agricultural activities are likely on average the largest contributor (either directly or indirectly) to the total nitrogen load delivered to many of the impaired water bodies.

Dissolved Oxygen and pH Regression Model Results

Two watershed properties, mean August water temperature and mean annual flow-weighted total nitrogen concentration, were significant predictors of mean warm-season minimum daily dissolved oxygen concentration, and both had a negative coefficient (table 3). These results indicate that the combined effect of lower oxygen solubility and increased plant productivity in response to warmer water with a larger supply of nutrients leads to lower dissolved oxygen concentrations. The SPARROW-estimated total phosphorus concentration was also a significant predictor (with a negative coefficient), but only when total nitrogen concentration was not included, and this reflected the strong correlation between the two parameters. Total nitrogen concentration was retained, however, because its coefficient was more significant and provided a better model fit than the coefficient for total phosphorus.

Four watershed properties were significant predictors of mean warm-season maximum daily pH (table 4). Negative coefficients were estimated for mean annual streamflow as a percentage of natural streamflow, mean annual total nitrogen yield from nitrogen fertilizer/manure used as fertilizer, and mean annual suspended-sediment concentration; and a positive coefficient was estimated for the mean soil salinity of the contributing drainage area. These results indicate that reaches with streamflow close to or greater than the amount expected under natural conditions (the latter situation is possible for reaches located downstream of irrigation returns and wastewater discharge) tend to be less susceptible to ecological imbalance (for example, excessive plant growth) than reaches where natural streamflow is reduced because of upstream diversions. The negative coefficient for the yield from nitrogen fertilizer/manure could be related to the high salt content in agricultural runoff, which tends to buffer pH swings in streams. Suspended sediment concentration was expected to have a negative coefficient because higher concentrations are positively related to turbidity, which attenuates primary productivity (leading to lower maximum pH). In contrast, soil salinity was expected to have a positive coefficient because streams draining areas containing saline soils usually have naturally elevated pH due to the high alkalinity of those soils.

Standard diagnostic techniques were used to evaluate the dissolved oxygen and pH linear regression models (figs. 7, 8). There was a strong relation between the measured values for mean warm-season minimum dissolved oxygen concentration and the predicted values (fig. 7a; adjusted R^2 of 0.690) and between the measured values for mean warm-season maximum pH and the predicted values (fig. 8a; adjusted R^2 of 0. 701). The residuals for both the dissolved oxygen and the pH models were normally distributed (figs. 7b, 7d, 8b, 8d). Figures 7d and 8d include the normal distribution expected for the residuals (blue line) and a kernel plot (red line), which is a smooth curve that represents the actual distribution without assuming normality. There was also no systematic pattern observed in the relation between the residuals and the predicted values for either model (fig. 7c, 8c), which would indicate bias in the model predictions. Also, the errors associated with both model validations were greater than the errors associated with the calibrations. The root mean squared error (RMSE) for the dissolved oxygen model validation was 1.84 mg/l compared to 1.24 mg/l for the calibration, and the RMSE for the pH model validation was 0.43 pH units compared to 0.29 pH units for the calibration.

Table 3. Model statistics for the dissolved oxygen linear regression model developed for the Pacific drainages of the United States.

[**Abbreviations**: mg/l, milligram per liter; <, less than; NA, not applicable; °C, degrees Celsius]

Parameter	Parameter units	Estimated coefficient	Standard error of the model coefficient	t-statistic	Probability level (p-value)	90% confidence interval for the model coefficient	
						Lower	Upper
Intercept	NA	13.396	1.198	11.180	<0.0001	11.374	15.418
Mean August water temperature (2000–11)	°C	-0.327	0.057	-5.770	<0.0001	-0.423	-0.231
Natural log of SPARROW-estimated mean annual flow-weighted total nitrogen concentration[1]	mg/l	-0.821	0.228	-3.600	<0.0001	-1.205	-0.436
Model diagnostics							
Number of observations	40						
R^2	0.714						
Adjusted R^2	0.690						

[1]Mean annual flow-weighted concentration for water years 2000–14, detrended to water year 2012.

Table 4. Model statistics for the pH linear regression model developed for the Pacific drainages of the United States.

[**Abbreviations**: ft^3/s, cubic feet per second; $kg/km^2/yr$, kilogram per square kilometer per year; mg/l, milligram per liter; mohms/cm, milliohms per centimeter; —, not applicable; %, percent]

Parameter	Parameter units	Estimated coefficient	Standard error of the model coefficient	t-statistic	Probability level (p-value)	90% confidence interval for the model coefficient	
						Lower	Upper
Intercept	—	0.801	0.801	13.660	<0.0001	9.600	12.299
Natural log of mean annual streamflow[1] as a percentage of natural streamflow[2]	Percent	-0.500	0.169	-2.960	0.0051	-0.785	-0.216
Natural log of mean annual total nitrogen yield from cultivated crops and fertilized pasture[3]	kg/km^2-yr	-0.039	0.014	-2.760	0.0086	-0.063	-0.015
Natural log of SPARROW-estimated mean annual flow-weighted suspended sediment concentration[4]	mg/l	-0.159	0.050	-3.140	0.0032	-0.243	-0.074
Natural log of mean salinity for contributing drainage area	mohms/cm	0.157	0.169	8.920	<0001	0.127	0.186
Model diagnostics							
Number of observations	45						
R^2	0.728						
Adjusted R^2	0.701						

[1]Mean annual streamflow for water years 2000 through 2014, detrended to water year 2012 (ft^3/s).

[2]Estimated mean annual streamflow for water years 2000 through 2014, detrended to water year 2012, without water diversions for consumptive uses such as public supply and irrigated agriculture or the return of that water to streams through municipal wastewater discharge and runoff from irrigated land, respectively (ft^3/s).

[3]Mean annual total nitrogen yield for water years 2000 through 2014, detrended to water year 2012, from commercial fertilizer and livestock manure used as fertilizer on cultivated crops and pasture.

[4]Mean annual flow-weighted concentration for water years 2000 through 2014, detrended to water year 2012.

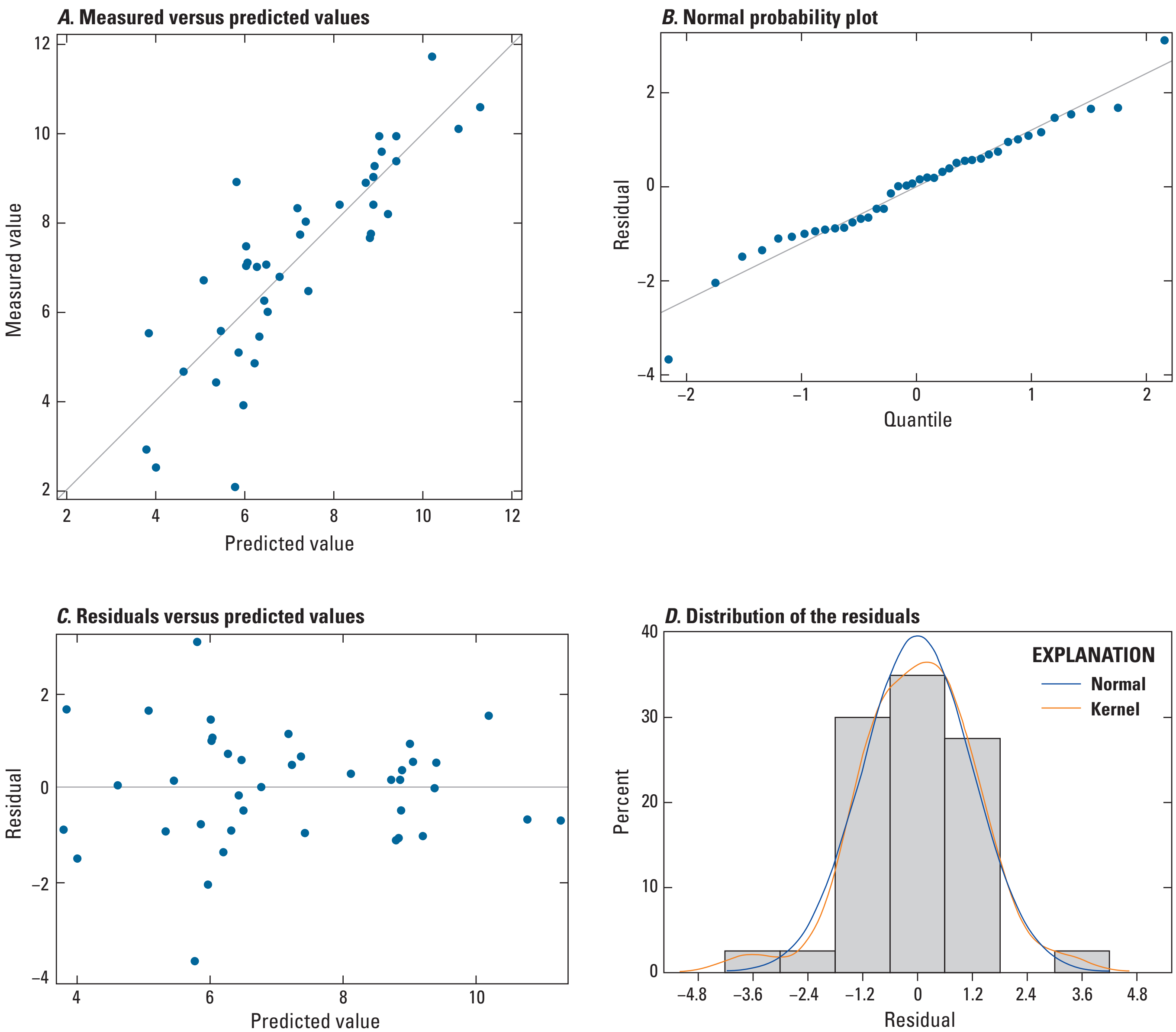

Figure 7. Dissolved oxygen linear regression model developed for the Pacific drainages.

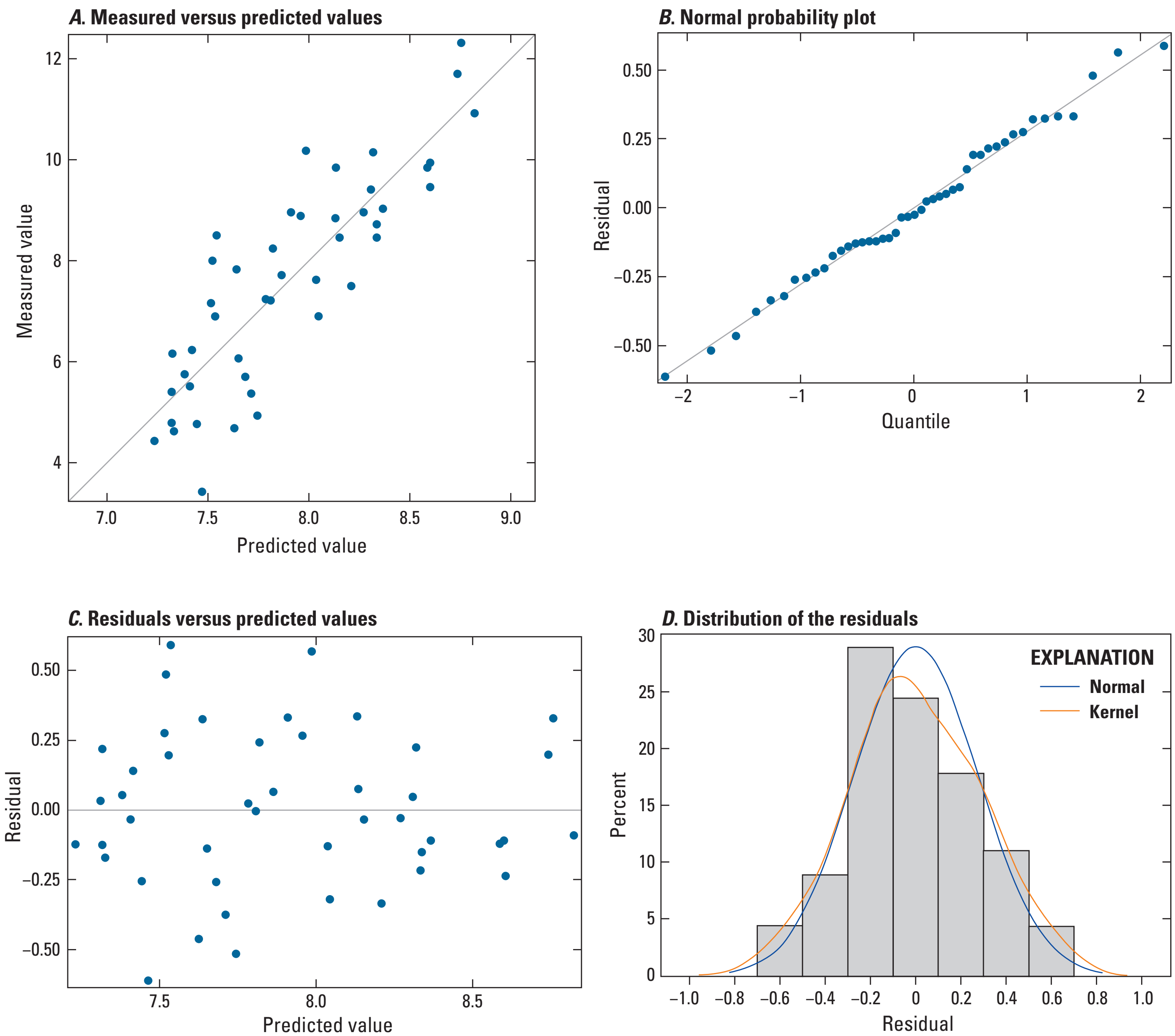

Figure 8. pH linear regression model developed for the Pacific drainages.

Dissolved Oxygen and pH Conditions

The dissolved oxygen and pH linear regression models were used to predict the mean warm-weather minimum daily dissolved oxygen concentration and maximum daily pH for 2000–14 (and the corresponding 90 percent confidence intervals) for all NHDPlus2 reaches other than those representing ponds, lakes, reservoirs, and shorelines. These predictions are shown on figures 9 and 10 and summarized in the legends for those figures. The dissolved oxygen model predicted extremely low (less than 2 mg/l) and even negative values for 6,172 of the 257,813 reaches, and these predicted values were replaced with a value of 2 mg/l (with no corresponding confidence interval), which represented a reasonable lower limit for mean warm-weather minimum daily dissolved oxygen concentration based on the measured values used in the regression. Almost all the 6,172 reaches extremely low or negative predictions were associated with very high stream temperatures (for example, about half of these reaches had a mean August stream temperature that was greater than the 95th percentile of 23.8 °C for all the reaches in the prediction dataset). None of the 40 measured values used in the regression were below 2 mg/l, however, even though many of those values were associated with reaches with mean August stream temperatures that were above 23.8 °C. In contrast, no limits were set on the upper end of the range in the predicted mean warm-weather minimum daily dissolved oxygen concentrations. While the dissolved oxygen model predicted values greater than the greatest calibration value of 11.74 mg/l for 61 reaches (with a maximum of 12.64 mg/l), these were almost always predicted for high-elevation mountain streams with minimum human impact where high dissolved oxygen concentrations are observed even during warm periods. Additionally, no limits were set on the range in the predicted mean warm-weather maximum daily pH (6.89–9.33) because the values were within the expected range for this parameter (99.9 percent of the values were also within the range of the measured values used in the regression).

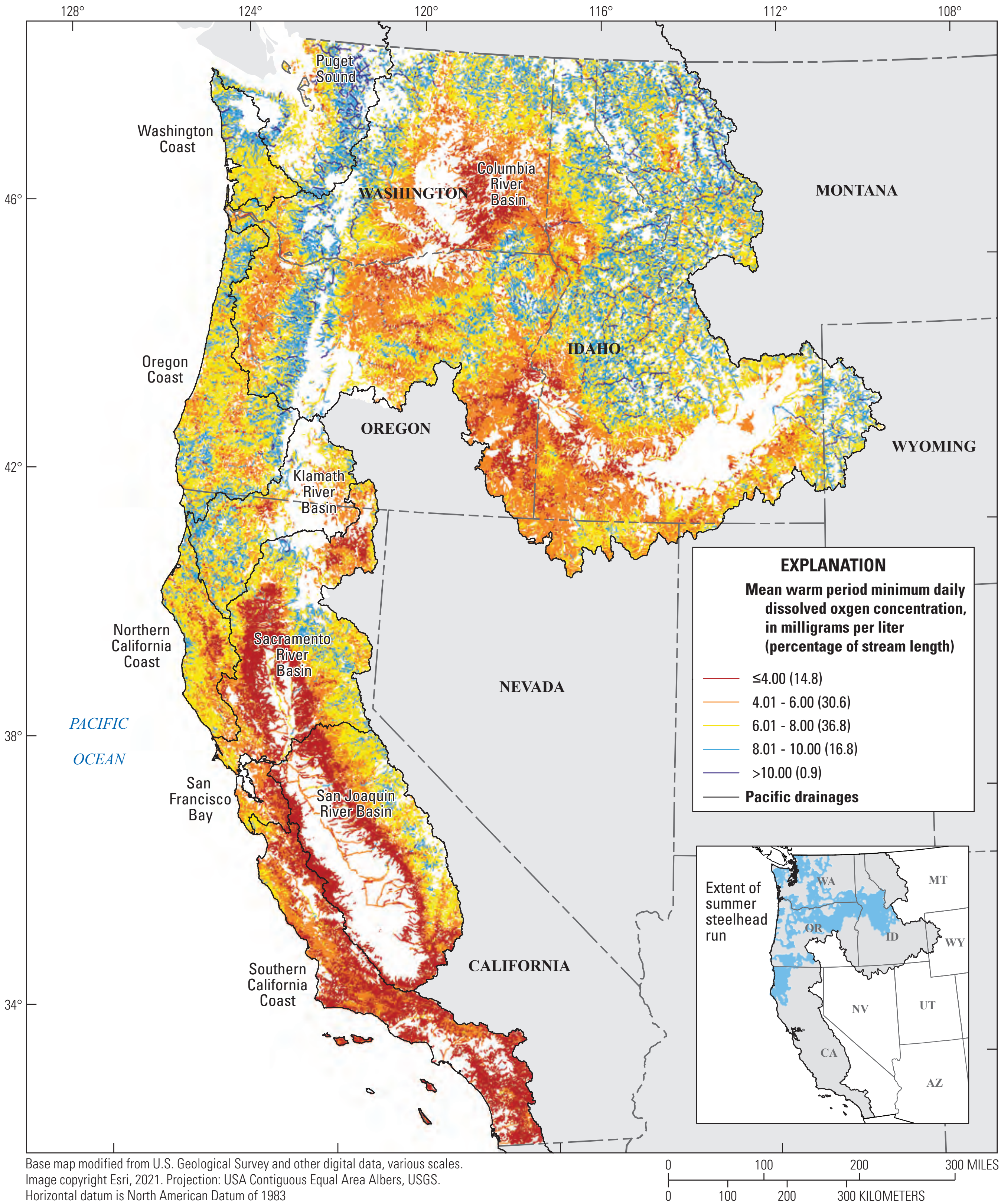

Figure 9. Reach-scale values for mean warm-weather minimum daily dissolved oxygen concentration predicted by the dissolved oxygen linear regression model developed for the Pacific drainages.

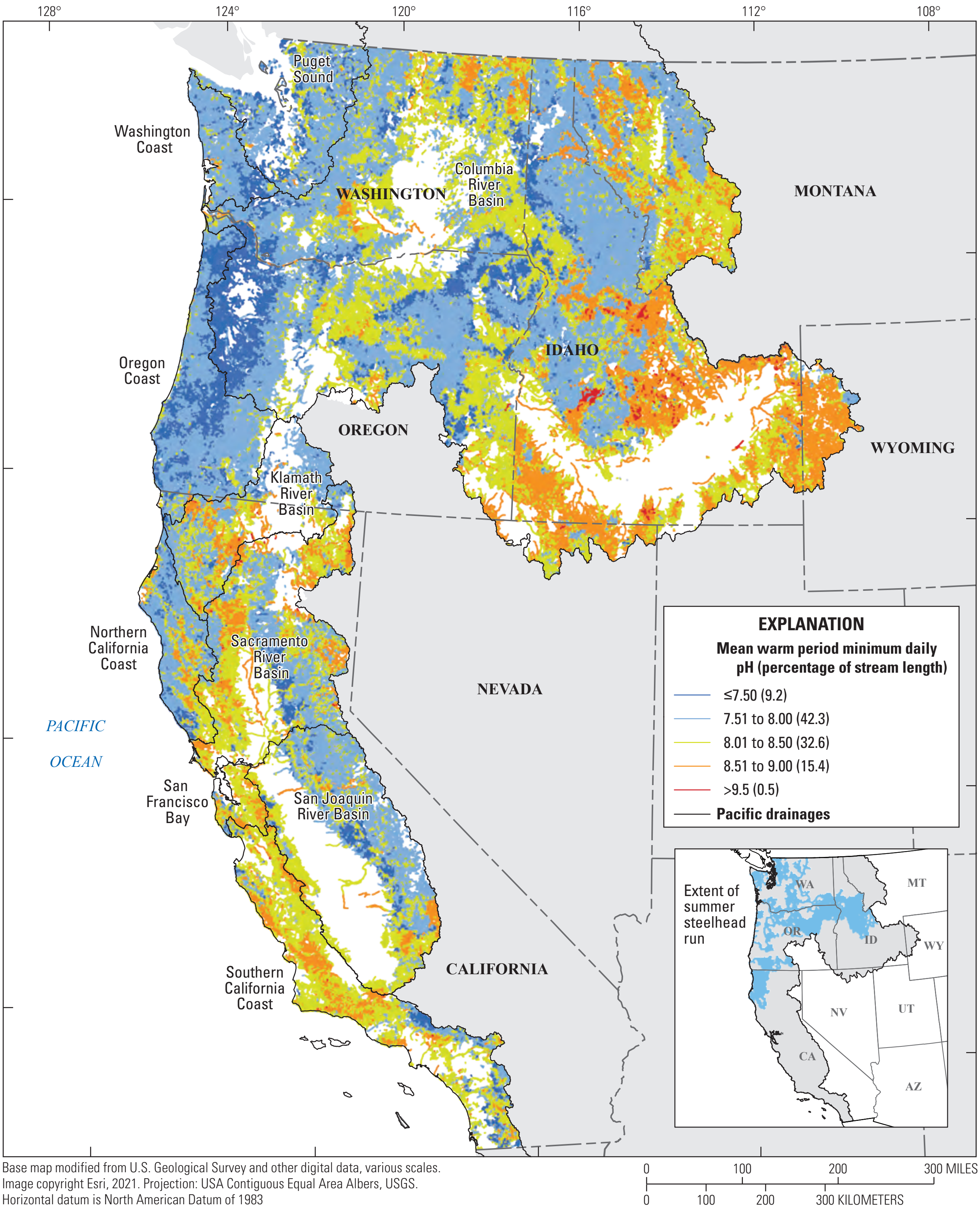

Figure 10. Reach-scale values for mean warm-weather maximum daily pH predicted by the pH linear regression model developed for the Pacific drainages.

Water-Quality Management Applications

The two datasets described in this report were developed to help inform water-quality management decisions in the Pacific drainages of the United States, and this might be accomplished in two ways. First, water-quality managers could use the reach-scale estimates of nutrient and water-use conditions to assess water bodies with suspected or documented impairment. The data release accompanying this study (Wise, 2021) contains those results for all the NHDPlus2 reaches but also includes a field indicating the reaches that represent 1 of the 1,809 impaired water bodies shown in figures 5 and 6 (along with the state-designated identifier for each impaired water body). Second, water-quality managers could use the reach-scale predictions of dissolved oxygen and pH conditions to help identify impaired water bodies that have not yet been assessed.

The nutrient and water-use conditions presented in table 2 are expressed as mean values to provide a regional summary of nutrient and water-use conditions, but a unique profile can be created for any water body that is referenced to an NHDPus2 reach. The four water bodies identified on figure 1 (Clear Lake in California, Fernan Lake in Idaho, Lake Billy Chinook in Oregon, and Vancouver Lake in Washington) have three things in common that make them instructive examples. They were on their state’s 2012 303(d) list due to effects related to eutrophication, they are in watersheds representing different types of landscapes, and they have recently experienced problems with harmful algal blooms, which often form in warm, impounded water bodies with abundant nutrients. Information about nutrient and water-use conditions, therefore, could be helpful to water-quality managers responsible for mitigating the impacts within these four water bodies and other water bodies experiencing similar types of impairment.

As was generally true across the Pacific drainages, diffuse landscape sources rather than point-source wastewater discharges are the largest contributors to the nutrient load delivered to these four water bodies (table 5). The largest contribution to total nitrogen delivered to Clear and Fernan Lakes is from the combination of atmospheric deposition and runoff from scrub and grass land (totaling 74.2 and 86.5 percent for each lake, respectively). The largest contribution to total phosphorus delivered to Clear Lake is from the combination of cattle grazing, manure, and natural sources (stream channels, and upslope geology) (totaling 63.5 percent), and the largest contribution to total phosphorus delivered to Fernan Lake is from natural sources (77.9 percent). Spring discharge is the largest contributor to both total nitrogen and total phosphorus delivered to Lake Billy Chinook (89.3 and 48.3 percent for each contaminant, respectively) and runoff from developed land is the largest contributor to both total nitrogen and total phosphorus delivered to Vancouver Lake (66.7 and 73.8 percent for each contaminant, respectively). What these results suggest is that, if nutrient supply is an important control on the severity of harmful algal blooms in these water bodies, mitigating those impacts through reductions in watershed nutrient inputs might prove difficult.

The predictions of dissolved oxygen and pH conditions described in this report might be useful by themselves or in combination with other data like the results from the NRSA to screen large numbers of water bodies for impairment. Water-quality managers could identify individual stream reaches where the predicted warm-weather values exceed applicable dissolved oxygen or pH criteria or they could evaluate entire watersheds based on the percentage of stream length that is predicted to exceed those criteria. This might be useful information, for example, when assessing the potential impairment of stream reaches where sensitive fish species are likely to be found–such as for steelhead trout during their summer run in the Pacific drainages, which occurs between March and November. Steelhead trout, a salmonid species found in freshwater tributaries flowing to the Pacific Ocean, are the anadromous form of the rainbow trout (meaning that they migrate from the ocean into fresh water to spawn). Coldwater aquatic life water-quality standards apply to reaches where these fish are expected to inhabit, generally meaning a dissolved oxygen standard of not less than 8.0 mg/l and a pH standard of not greater than 8.5. Stream reaches where steelhead trout are expected to be found during their summer run in the Pacific drainages are shown on the inset maps in figures 9 and 10. For those reaches where predictions were made, the linear regression models predicted that 59 percent of the stream length had a mean warm-weather minimum daily dissolved oxygen concentration less than 8.0 mg/l and 11 percent of the stream length had a mean warm-weather maximum daily pH greater than 8.5.

Table 5. Nutrient and water-use conditions for selected impaired water bodies in the Pacific drainages of the United States.

[**Abbreviations**: kg/yr, kilogram per year; (kg/ha)/yr, kilogram per hectare per year; mg/l, milligram per liter; <, less than]

State	California				Idaho				Oregon				Washington			
Water body name	Clear Lake				Fernan Lake				Lake Billy Chinook				Vancouver Lake			
Water body ID	CAL5135200019980814115549				ID17010303PN033_03				1212676445780_17070305				45122G7H1			
Drainage area (km^2)	1,220				56				17,566				100			
Ratio of current to natural streamflow (percent)	102				100				76				100			
Ratio of total upstream groundwater use to streamflow (percent)	3.9				5.0				7.3				22.4			
Total load (kg/yr)	Total nitrogen		Total phosphorus		Total nitrogen		Total phosphorus		Total nitrogen		Total phosphorus		Total nitrogen		Total phosphorus	
	179,886		17,955		4,099		294		3,868,349		279,624		37,864		3,791	
90 percent confidence interval for total load (kg/yr)	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
	74,686	383,629	6,515	42,224	1,865	8,291	96	807	1,580,152	9,770,052	69,788	832,145	15,333	100,091	1,078	12,174
Total yield (kg/ha-yr)	1.47		0.147		0.73		0.053		2.20		0.159		3.80		0.380	
Flow-weighted concentration (mg/l)	0.459		0.046		0.177		0.013		0.988		0.071		0.690		0.380	

Table 5. Nutrient and water-use conditions for selected impaired water bodies in the Pacific drainages of the United States.

[**Abbreviations**: kg/yr, kilogram per year; (kg/ha)/yr, kilogram per hectare per year; mg/l, milligram per liter; <, less than]

Nutrient	Total nitrogen	Total phosphorus	Total nitrogen	Total phosphorus	Total nitrogen	Total phosphorus	Total nitrogen	Total phosphorus
Urban land	8.2	11.6	9.2	6.5	0.2	<0.1	66.7	73.8
Point-source wastewater discharge	0.0	0.0	0.0	0.0	<0.1	0.4	0.0	0.0
Commercial fertilizer and livestock manure applied to cultivated land and pasture	16.0	11.8	4.2	4.6	3.2	4.7	3.8	7.6
Springs	0.0	0.0	0.0	0.0	89.3	48.2	0.0	0.0
Atmospheric deposition	46.5	NA	75.1	NA	3.7	NA	28.5	NA
Red alder trees	1.5	NA	0.0	NA	<0.1	NA	0.8	NA
Scrub and grass land	27.6	NA	11.4	NA	3.6	NA	0.3	NA
Grazing cattle manure	NA	21.4	NA	11.0	NA	1.6	NA	9.7
Stream channels and upslope geology	NA	55.2	NA	77.9	NA	45.1	NA	8.9

Discussion

The approaches described in the report can also be used to create similar datasets for other regions of the United States. SPARROW streamflow, nutrient, and suspended-sediment models representing 2012 conditions are currently available for the four other major hydrologic regions within the conterminous U.S.: the Southwest (Wise and others, 2019), the Midwest (Robertson and Saad, 2019), the Southeast (Hoos and Roland, 2019), and the Northeast (Ator, 2019). The input data and predictions from those regional SPARROW models provide the same type of detailed, reach-scale nutrient and water-use conditions that were estimated for the Pacific region. The dissolved oxygen and pH regression models developed for the Pacific drainages can likely be reproduced in the other hydrologic regions as well. Between 2000 and 2014 the USGS continuously monitored 873 stream locations across the conterminous U.S. where dissolved oxygen was measured and 745 stream locations where pH was measured. Only 40 values for mean warm-weather minimum daily dissolved oxygen concentration and 45 values for mean warm-weather maximum daily pH were needed to show a strong relation between those parameters and watershed attributes in the Pacific drainages. Therefore, there might be enough water-quality data available to build similar models for the other regions to estimate reach-scale dissolved oxygen and pH conditions and identify the watershed attributes that control those conditions.

The datasets described in this report and similar datasets that might be created for other hydrologic regions should be used with an understanding that, as is true with all models, there is uncertainty associated with their predictions. Therefore, water-quality managers using those predictions to assess water bodies would benefit from recognizing this uncertainty. The SPARROW estimates of reach-scale nutrient and water-use conditions include the 90 percent confidence intervals for the predicted mean annual total nitrogen and total phosphorus loads (as shown in table 5), and this information provides a useful quantitative measure of the model uncertainty. The confidence intervals for the mean annual loads, however, only represent the uncertainty associated with the model calibrations. There is also some uncertainty that was not estimated as part of the development of the Pacific region SPARROW models because this uncertainty is difficult to quantify systematically.

Some of the error in the model predictions could result from applying the regional calibration results to small watersheds, such as the one draining to Fernan Lake (table 5). The results from a mass balance on the nutrients delivered to Fernan Lake between 2014 and 2015, which relied on high intensity streamflow and water-quality monitoring (LaCroix, 2015), suggest that down-scaling the models might lead to inaccurate predictions in some watersheds. The SPARROW-estimated total phosphorus yield for the Fernan Lake watershed was about 23 percent of the measured mean annual yield. The discrepancy between the predicted and measured total phosphorous yields for this watershed might be related to the way that the contribution from diffuse nutrient sources (which dominate the Fernan Lake watershed) are estimated for SPARROW modeling. Diffuse nutrient sources, such as natural phosphorus and agriculture, are estimated by interpolating data representing large areas (for example, surficial geologic units for natural phosphorus) to smaller areas. Therefore, it would not be unexpected if the relative spatial error associated with this approach was often greater for smaller watersheds compared to larger watersheds. But while that pattern would be expected for some watersheds, it would not necessarily be expected for all. Watersheds where the nutrient loads come primarily from point-source wastewater discharge, regardless of size, should have less uncertainty in the model inputs than similarly sized watersheds dominated by diffuse sources. The reason the uncertainty is less is because estimates of wastewater nutrient discharge are facility-specific and, as a result, have relatively low error.

Some of the error in the model predictions could also result from hydrologic and anthropogenic features that are unique to a watershed, such as the one draining to Vancouver Lake (table 5). The results from a mass balance on the nutrients delivered to Vancouver Lake between 2010 and 2012, which also relied on high intensity streamflow and water-quality monitoring (Sheibley and others, 2014), suggest that the presence of unusual hydrologic and anthropogenic features might lead to inaccurate predictions in some watersheds. Vancouver Lake has three inlets, but only one acts as a true surface water tributary to the lake. One of the inlets is an artificial channel that connects the lake to the Columbia River, and this channel only allows water to flow into the lake from the river when the river stage is high enough. The other inlet is a natural connection to the Columbia River that currently has bidirectional flow that changes almost every day. The SPARROW-estimated total phosphorus load delivered to Vancouver Lake from its one true surface water tributary (Burnt Bridge Creek) was about 74 percent of the measured mean annual load for that tributary, but it was only about 55 percent of the total measured net mean annual load delivered to Vancouver Lake (where net load was the total amount delivered to the lake minus the total amount that was discharged from the lake to the Columbia River).

The dataset containing the predictions of mean warm-weather minimum daily dissolved oxygen concentrations and mean warm-weather maximum daily pH values for the Pacific drainages also includes 90 percent confidence intervals for those predictions, and this information should help inform water-quality evaluations that use those predictions. Ideally, the accuracy of the dissolved oxygen and pH linear regression models would have been validated by comparing the predictions against a rich dataset of measured values that were not used in the model calibrations. But this validation was not possible because of the limited amount of continuous dissolved oxygen and pH data available for the Pacific drainages. While the number of stations where model validation was possible (15 for dissolved oxygen and 28 for pH) was likely adequate, the amount of data at any one water-quality station was limited to 3 years of warm period measurements (and often only included 1 or 2 years). It was possible, therefore, that the mean, detrended dissolved oxygen and pH values measured at the validation stations were not as representative of long-term mean conditions as the measured values used in the regression equations. Therefore, although the errors associated with both model validations were greater than the errors associated with the calibrations, these results do not necessarily show that the dissolved oxygen and pH regression models were poor predictors of actual conditions. Rather, the model validations might have been compromised by the availability of the validation data.

Finally, while some general criteria were used to select the prediction networks for the dissolved oxygen and pH models, it was not possible to identify all the reaches where the predictions were not applicable because the reaches were heavily influenced by upstream conditions that could not be accounted for in the regression explanatory data. These included reaches located downstream of dam outlets with elevated dissolved oxygen concentrations caused by air entrainment in spillway releases, reaches located downstream of highly productive water bodies with very low dissolved oxygen concentrations and high pH, and reaches influenced by wastewater discharges and sediments that have high oxygen demands.

Conclusions

The two datasets described in this report contain the first complete estimates of nutrient, water use, dissolved oxygen, and pH conditions for the Pacific drainages of the United States, and the techniques used to develop these datasets provide a framework for integrating watershed data across large regions to assess water-quality impairment. The estimates were possible because of the availability of input data and predictions from recent SPARROW modeling, the results from long-term USGS continuous monitoring, and the predictions from recent stream temperature modeling. The development of the dissolved oxygen and pH linear regression models showed how these three very different types of regional watershed data can be combined to build a set of tools that was not previously available. The predictions from those models will probably be most useful as a screening tool for identifying potential impairment in the Pacific drainages. Water-quality managers, for example, could select reaches in a watershed where the predicted values were outside of the acceptable range for sensitive fish species (in a similar way to what was done regionally in this paper for summer steelhead). They could then use local knowledge about hydrology, water quality, and land use to perform more detailed evaluations. When that type of information is not available, they could use the estimated nutrient and water-use conditions to inform their decisions on how to monitor water-quality and manage upstream nutrient sources. The example applications presented in this paper also showed how estimates of nutrient, water use, dissolved oxygen, and pH conditions could be useful to water-quality managers by filling in data gaps about impaired water bodies and adding to the overall understanding of water-quality impairment.

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