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Prioritization Framework for Ranking Riverine Ecosystem Stressors Using Example Sites from the Tualatin River Basin, Oregon

Scientific Investigations Report 2018–5153

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

Cover: Tualatin River at Tualatin Park, upstream of Boones Ferry Road, Tualatin, Oregon.
Photograph by S. Rounds, U.S. Geological Survey, July 19, 2008.

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By Steven Sobieszczyk, Krista L. Jones, Stewart A. Rounds, Elena B. Nilsen, and Jennifer L. Morace

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Datums

Vertical coordinate information is referenced to the Oregon Lambert (HARN).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

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

Abbreviations

ALR	aquatic life ratio
CWS	Clean Water Services
DO	dissolved oxygen
EPT	Ephemeroptera/Plecoptera/Trichoptera
FNU	formazin nephelometric unit
GIS	geographic information system
$7Q_2$	7-day minimum streamflow, 2-year recurrence interval
ODEQ	Oregon Department of Environmental Quality
PK_{10}	peak 10-year high flow statistic
RB	Richards-Baker Flashiness Index
TMDL	Total Maximum Daily Load
WWTF	wastewater treatment facility
USGS	U.S. Geological Survey

Prioritization Framework for Ranking Riverine Ecosystem Stressors Using Example Sites from the Tualatin River Basin, Oregon

By Steven Sobieszczyk, Krista L. Jones, Stewart A. Rounds, Elena B. Nilsen, and Jennifer L. Morace

Abstract

As human populations increase, so does their influence over the environment. Altered terrain, degraded water quality, and threatened or endangered species are all-too-common consequences of a growing anthropogenic influence on the landscape. To help manage these effects, researchers have developed new ways to characterize current environmental conditions and help resource managers seek solutions to bring affected areas back to their best attainable health. Before an ecosystem can be improved, however, its current level of ecological stress must be determined. Characterizing environmental conditions at many sites across a landscape helps managers understand the range of current conditions and prioritize where they might focus restoration and protection efforts.

This report details the development of a prioritization framework to score riverine ecosystem stressors in a watershed based on example sites from the Tualatin River Basin in northwestern Oregon. The framework incorporated the most influential site-specific stressors throughout the basin built on a long history of data collection. These stressors were characterized with 13 metrics that were organized into 4 groups: hydrologic, water quality, physical habitat, and biological. Each stressor metric used readily accessible data and was translated to a score between 0 and 10. The higher the score, the healthier the site. This initial application of the framework used field observations and measurements to rank site conditions at two Tualatin River sites and four Tualatin River tributary sites. Given the versatility of this framework, it easily could be expanded to include more sites or new metrics, if necessary. Because stressors varied by season, all metrics for the tributary sites were scored separately during the wet season (November through April) and dry season (May through October). Water-quality data were available over a prolonged period; therefore, water-quality metrics were assessed by season and by decade (1990–99 compared to 2000–12) to evaluate long-term stressor trends.

Results for the Tualatin River Basin prioritization framework indicated that the urban tributaries demonstrated the greatest stress throughout the year, especially during the dry summer months. Spatially, the upper Tualatin River was healthier than the lower reaches of the river. Water-quality has improved in the last 10 years, mostly due to improvements in the dry period contaminant scores, but challenges remain with high water temperatures and low dissolved-oxygen conditions.

The biggest challenge with this type of research derived from inconsistencies within the available data. Both spatial and temporal data gaps must be addressed to improve the prioritization. Incorporating both discrete and continuous datasets into the prioritization framework remains a challenge because the datasets have slightly different information and criteria and are not always comparable. Regardless, this report provides guidelines for developing a prioritization framework that ranks the ecological health of sites in a watershed and provides guidance on management actions for improving conditions by targeting factors that greatly affect the health of river ecosystems.

Introduction

Background

Across the world, humans routinely alter their surrounding natural landscape. They channelize streams, regulate streamflow, convert wetlands into agricultural lands, and pave over forests to develop cities. These alterations to the environment greatly affect the hydrology, water quality, physical habitat, ecological processes, and biological communities within a watershed (Walsh and others, 2005; Paul and Meyer, 2008; Wenger and others, 2009). Regulators at the federal, state, and local levels attempt to mitigate some of these human-related effects through the passage of laws, such as the Clean Water Act (Public Law 92–500, 33 U.S.C. §1251 et seq. [1972]) and Endangered Species Act of 1973 (Public Law 93–205, 87 Stat. 884, as amended). Recently, proactive mitigation techniques have become more commonplace, especially the practice of stream, floodplain, and wetland restoration (Rood and others, 2003; Puls and others, 2014).

Restoring aquatic and floodplain habitats can be effective at lessening the effects of human activities on river ecosystems, such as altered flows and introduced species. However, stream restoration is expensive and requires information and foresight to identify sites that would benefit most from immediate action. Similarly, any restoration project needs to be optimized to fit within the existing landscape and stream features. One method for prioritizing restoration and pollution control efforts involves ranking the degree of impairment or ecological stress at sites in an area and then designing suitable solutions for addressing the impairments and stresses. Such a prioritization framework is useful for addressing implementation challenges caused by limited financial resources, while still providing insight into ecosystem stresses throughout a watershed. Prioritization frameworks that rank riverine ecosystem disturbances are developed mostly at a watershed scale using widely available spatial datasets in a geographic information system (GIS), such as land cover, human population density, and wastewater treatment plant locations (Waite and others, 2008; Wang and others, 2008; Esselman and others, 2011). In contrast, few prioritization frameworks incorporate site-specific field measurements and observations to capture real-world environmental conditions and then target appropriate management and restoration actions (Bunn and Arthington, 2002; Bunn and others, 2010; LimnoTech, Inc., 2013; University of Maryland, 2014; University of Maryland, 2015).

Purpose and Scope

In this study, a prioritization framework was proposed for scoring and ranking site-specific ecosystem stressors in a watershed. This report documents a straightforward and scientifically based approach that resource managers could apply to various stream systems to identify effective management and restoration strategies. The prioritization framework used observations and field measurements from monitored locations and, if needed, incorporated additional data from nearby sites to fill missing data. The framework included example scores for four tributary and two main-channel sites in the Tualatin River Basin based on hydrologic, water quality, physical habitat, and biological data from 1990 to 2012.

The general approach used in the framework included four steps:

1. Characterize riverine ecosystem functions and any observed alterations;
2. Identify key stressors, metrics, and scoring translators;
3. Select sites based on identified metrics and available data; and
4. Score sites and derive insights.

This approach was applied to valley bottom streams in the Tualatin River Basin but could be adjusted to other streams based on site-specific modifications to the framework. The stressors identified for this Tualatin River example were intentionally designed for lowland environments. This meant that the selected stressors and metrics may not be directly applicable to upland Tualatin River Basin streams or streams in other basins. Identifying key stressors and developing appropriate metrics should be among the first steps for applying this prioritization framework elsewhere.

Study Basin

The Tualatin River Basin encompasses 712 square miles (mi^2) of northwestern Oregon, including the western part of the Portland metropolitan area (fig. 1). The Tualatin River begins in the Coast Range as a mountainous stream and meanders a total of 80 miles (mi) eastward across a low-gradient fertile valley before reaching the Willamette River at the City of West Linn. Numerous tributaries, such as Scoggins, Gales, Dairy, Rock, Chicken, and Fanno Creeks feed into the Tualatin River and serve as natural resources for anglers, boaters, and farmers. Although the Tualatin River has undergone modifications, such as diversions for irrigation, only one large dam and associated reservoir is present in the basin. Located on Scoggins Creek in the foothills of the Coast Range, Henry Hagg Lake (herein after “Hagg Lake”; impounded by Scoggins Dam) provides water for irrigation, municipal water supply, flow augmentation, and recreation. Across the Coast Range divide to the west and south, a diversion from Barney Reservoir in an adjacent watershed also provides water for municipal water supply and flow augmentation to the Tualatin River. Other key infrastructure affecting streamflow in the basin includes large withdrawals for municipal and irrigation use at the Spring Hill Pump Plant, and effluent from four wastewater treatment facilities (WWTFs): Rock Creek, Durham, Hillsboro, and Forest Grove WWTFs. During summer, treated wastewater effluent can account for as much as 25–40 percent of the total streamflow in the lower reaches of the Tualatin River (Bonn, 2012).

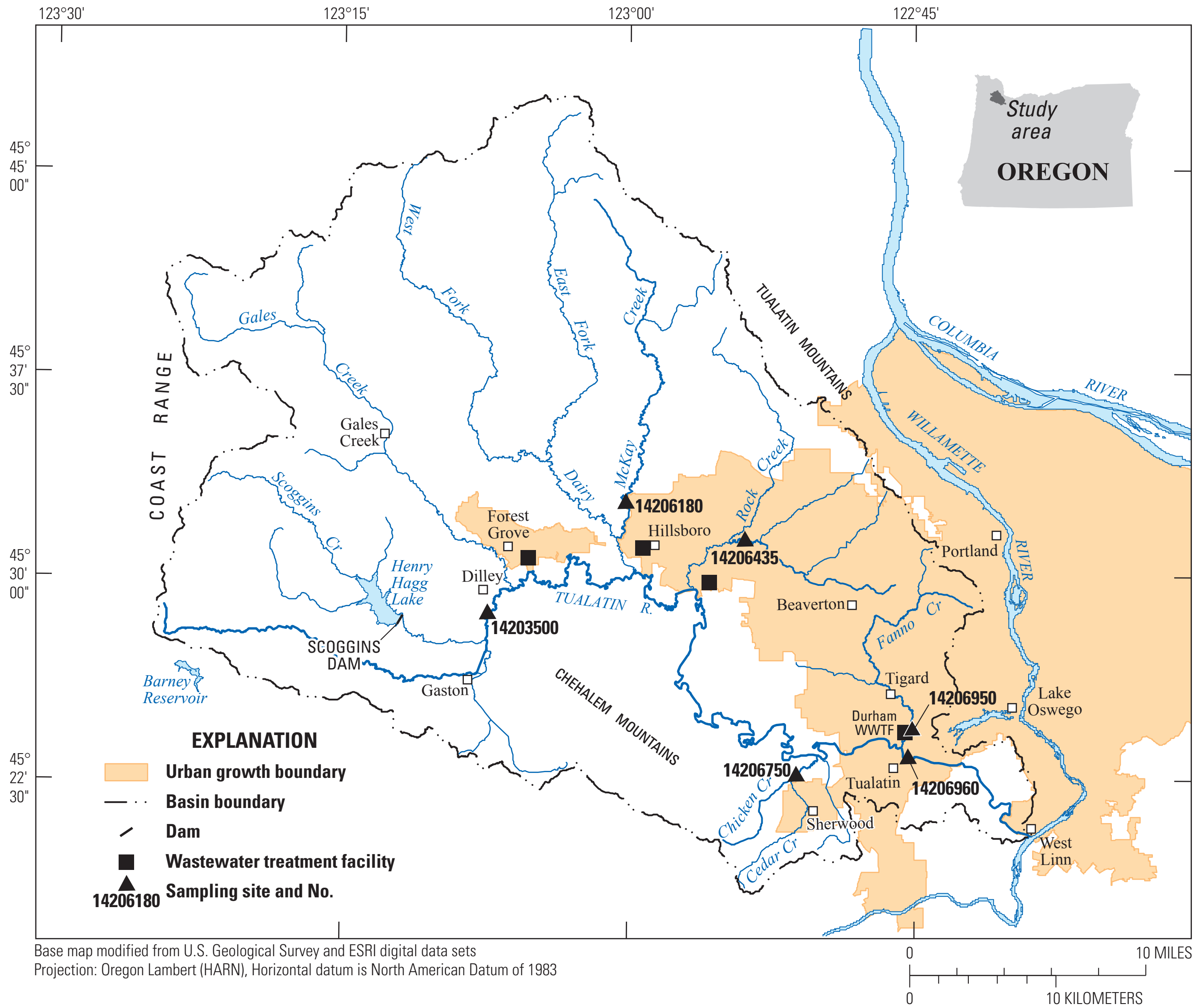

Figure 1. Locations of rivers, reservoirs, and wastewater treatment facilities in the Tualatin River Basin, Oregon.

Controls, Processes, and Stressors That Shape Riverine Ecosystems

The first step to create a prioritization framework is to identify the most important processes, controls, alterations, and stressors acting upon the target ecosystem. Without an understanding of these key factors, it is difficult to properly select metrics that provide useful data for deriving insights for restoration and management. This section provides an overview of the type of examination of processes and controls used to identify the main stressors in a riverine system.

Natural Inherent Controls

Riverine habitats and biological communities are shaped by the interplay between inherent landscape-level controls and human modifications to the landscape (fig. 2). Inherent controls like climate, underlying geology, and the surface hydrology are all responsible for establishing the baseline conditions that exist in a particular environment. These inherent controls dictate what the environment is and how organisms adapt to the landscape over time. The controls dictate what restoration options are possible due to the physical and biological characteristics of the stream. They also set up the normative and seasonal fluxes of material like water, sediment, wood, and nutrients throughout a watershed. However, when human modifications alter the landscape, they can exacerbate material fluxes and create ecological stresses that negatively affect the health of the aquatic environment.

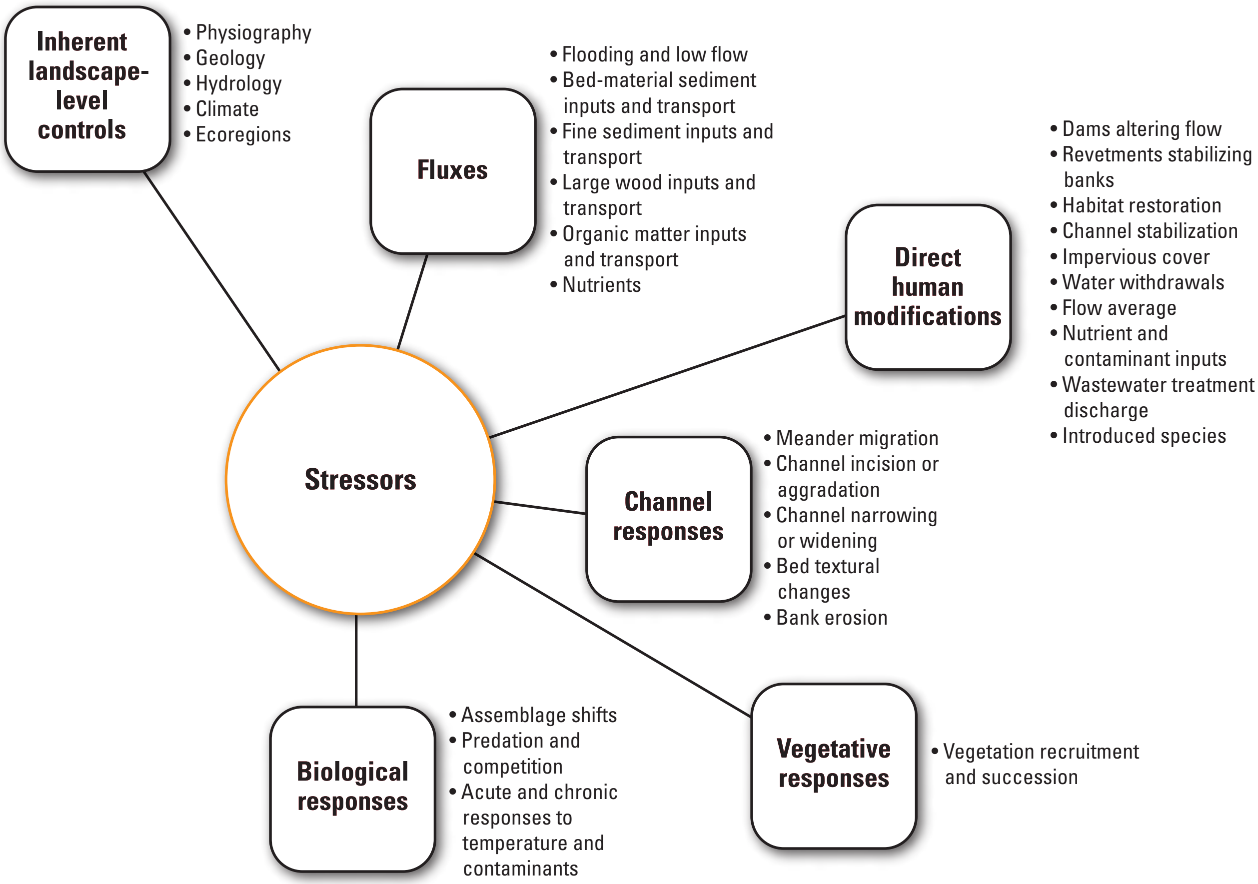

Figure 2. Conceptual diagram of the inherent controls and human modifications to the landscape that influence aquatic ecosystems.

Climate

Climate is an inherent control that drives streamflow patterns, especially in the Tualatin River Basin. The basin has a temperate marine environment, with an average annual air temperature of 52 °F and an average annual precipitation of 43 inches ([in.] Franczyk and Chang, 2009). About 75–80 percent of the annual precipitation falls during the cool months between October and May (Jung and Chang, 2012). Conversely, summers typically have moderate temperatures and little rainfall. Due to this seasonal variability in precipitation, streamflow is always higher in winter and lower in summer. Generally, flooding is limited to low-lying areas during specific storms in exceptionally rainy winters, such as those in 1996, 1997, 2006, and 2007 (National Weather Service, 2014). The effect of droughts has been minimized by increasing water storage through the construction of Scoggins Dam in 1975. Flow augmentation and agricultural irrigation from the reservoir have greatly reduced the frequency of droughts, such as those that occurred in the 1950s (National Weather Service, 2014). Model-simulated future climate scenarios forecast that precipitation disparities between the wet and dry seasons will intensify (Praskievicz and Chang, 2011; Jung and Chang, 2012), leading to a potential increase in the frequency of both floods and droughts that could exceed the mitigating capabilities of Hagg Lake and current flow management of the Tualatin River.

Physiography

The physiography of a watershed influences many aspects or features within. Structurally, the Tualatin River Basin can be viewed as having an upland and lowland region, each with markedly different ecological, physiographical, and geological characteristics (fig. 3). The uplands are steep and heavily forested, with streams that have coarser substrates and more pristine waters. The valley has gentle slopes, is comprised of land that is predominantly agricultural or urban and includes water-quality impaired streams that cut through fine silts and clays. Partly as a response to the different physical stream characteristics, the type and abundance of aquatic species vary greatly between these two regions. Additionally, invasive and other tolerant fish species are more prevalent in the valley streams, where the more sensitive native species have difficulty thriving (Cole and Lemke, 2011).

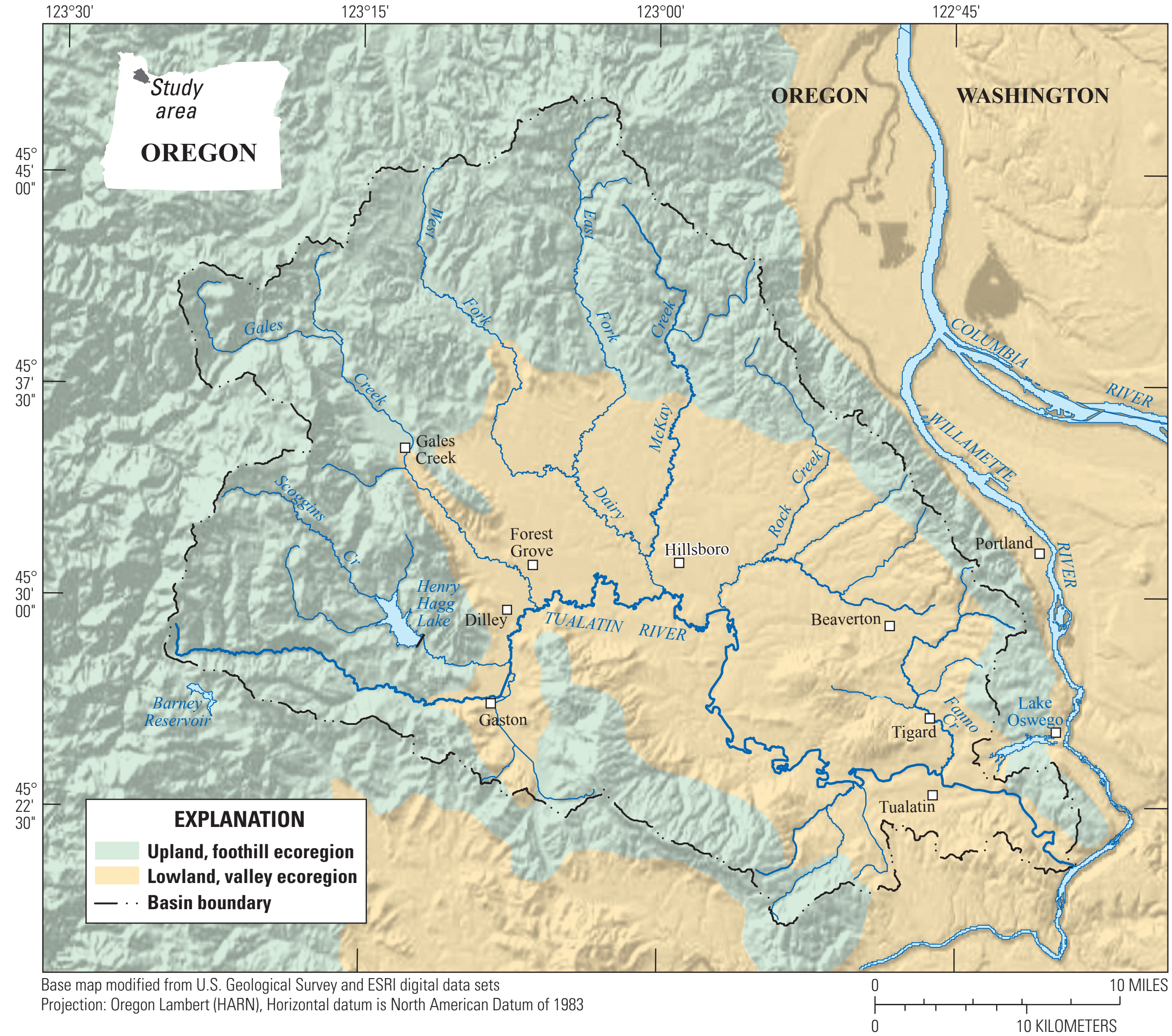

Figure 3. Distribution of uplands and lowlands for the Tualatin River Basin, Oregon, based on generalized level 4 ecoregions (from Omernik, 1987).

Geology

Geology provides the foundation for the structural characteristics of all stream channels in a watershed. The geology of the Tualatin River Basin consists of highly erodible sedimentary and volcanic rocks in the uplands and Missoula flood deposits and other local deposits in the lowlands (fig. 4). The basin is bordered to the west by the Coast Range, to the north and east by the Tualatin Mountains, and to the south by the Chehalem Mountains. Gravel channels are limited mainly to the upland tributaries. Because the upland sedimentary and volcanic rocks tend to disintegrate into sand and silt during river transport (O'Connor and others, 2014), sandy and silty bottom channels dominate the Tualatin River valley downstream of the town of Gaston. The valley bottom streams have migrated across wide floodplains and still have winding channels that, in the absence of bank hardening, continue to migrate. In some locations, the Tualatin River and its tributaries flow over hardpan clay and basalt outcrops that greatly restrict channel adjustments.

Anthropogenic Influences and Controls

Landscape modifications by humans can change water, sediment, and other fluxes, resulting in hydrologic, water quality, physical habitat, and biological conditions that deviate

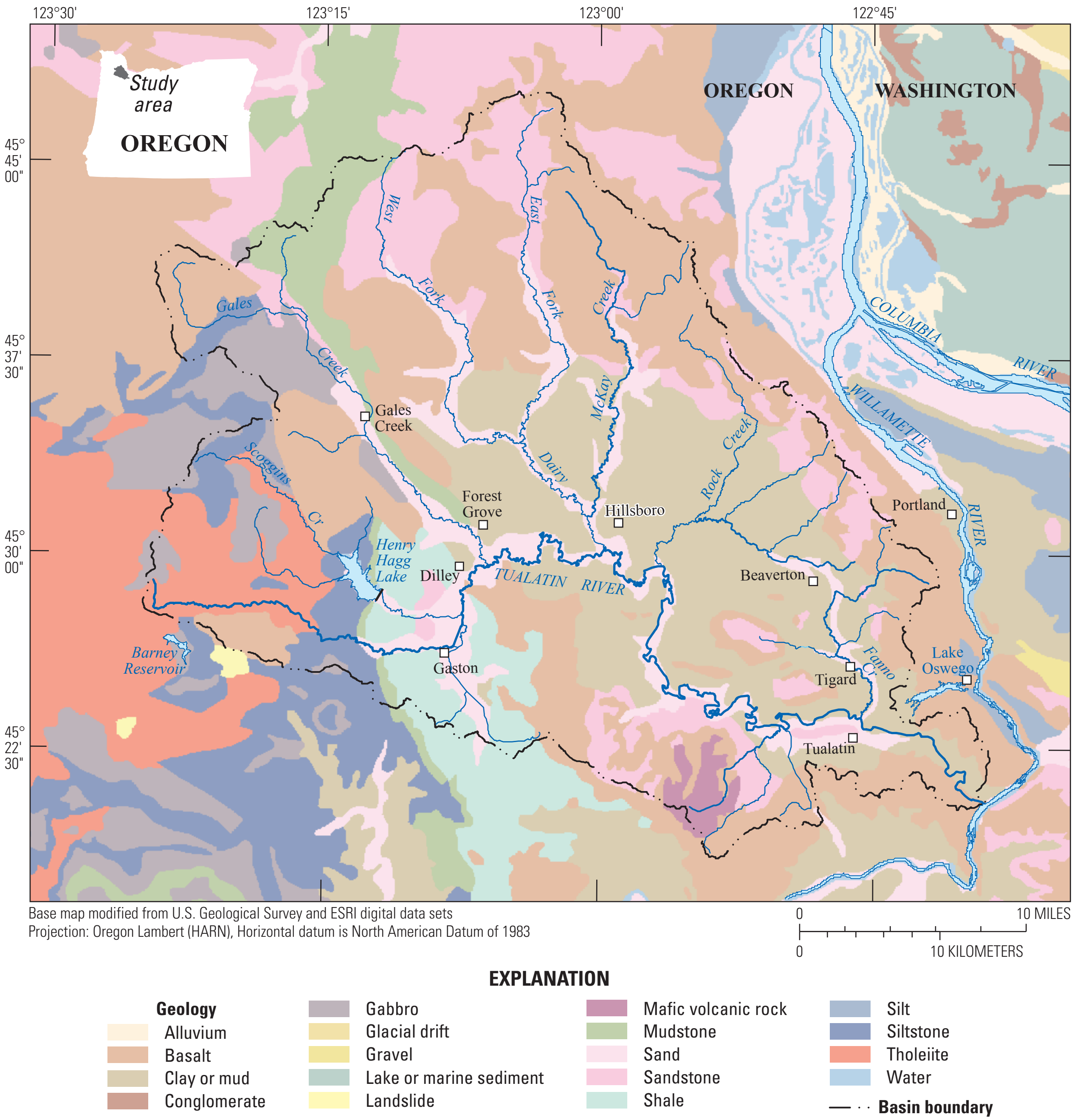

Figure 4. Surface geology of the Tualatin River Basin, Oregon. Geologic units are from Ma and others (2009).

from “healthy” to “disturbed” in urban areas throughout the United States. Examples of direct human modifications specifically in the Tualatin River Basin include:

- **Large-scale land cover changes.** Starting in the 1850s, wetlands in the basin were drained to create robust and productive farmlands (Cass and Miner, 1993). By the late 1800s, forests also began to be logged and converted into farmland (Cass and Miner, 1993). Over the last 150 years, human populations and associated rural, urban, and other developed areas have grown substantially. Current land cover for the Tualatin River Basin consists of about 22 percent urban, 27 percent agriculture, 31 percent forest (Jin and others, 2013), and the remaining 20 percent a mixture of wetland, rangeland, and other lands. The land cover distribution has a distinct pattern, with forests in the west at the higher elevations and agricultural lands in the valley bottom surrounding heavily developed and urbanized areas on the valley floor, especially toward the east (fig. 5). Between 2001 and 2011, the landscape continued to change as trees were harvested and some forested lands were converted to agricultural or urban uses.

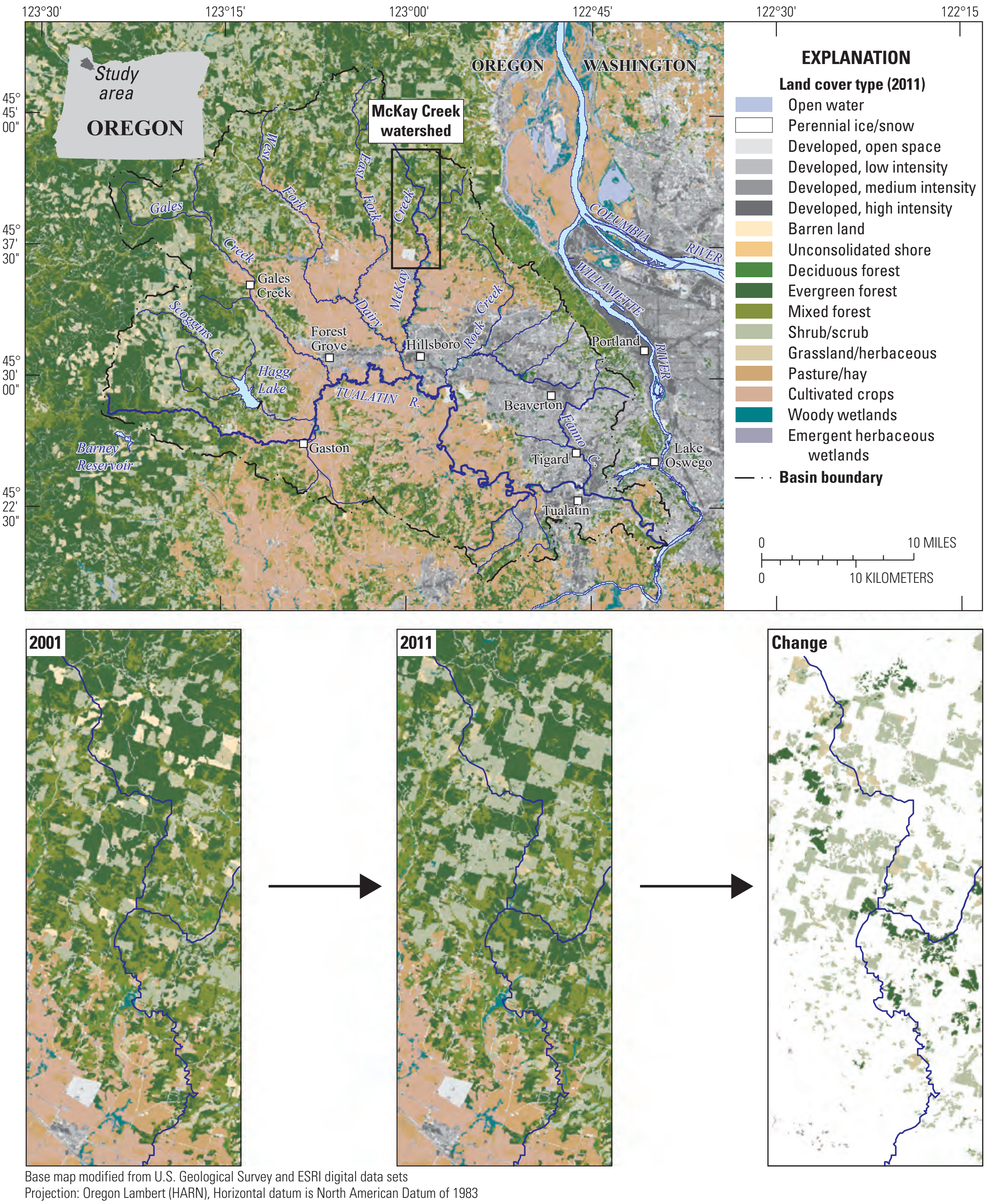

Figure 5. Land cover (2011) derived from the National Land Cover Dataset (Jin and others, 2013) for the Tualatin River Basin, Oregon, including land-cover change between 2001 (Homer and others, 2007) and 2011 (Jin and others, 2013) for an area in the upper part of the McKay Creek watershed.

The distribution of these land-cover types is pivotal for understanding the relative importance of the many ecosystem stressors throughout the basin. For example, changes associated with urbanization include decreased infiltration, shorter water residence times, and increased generation of surface runoff resulting in “flashy” streamflows that peak and recede quickly (Walsh and others, 2005; Paul and Meyer, 2008). These types of flashy streams are prevalent in the more highly developed areas of the Tualatin River Basin.

- **Direct hydrologic alterations affecting high and low flows**. Along with changes to the landscape, direct modifications to streams have occurred in the Tualatin River Basin. Examples of altered streamflows include withdrawals for irrigation and municipal water supply, the collection and direct discharge of stormwater to streams from impervious areas, and the retention of water in reservoirs such as Hagg Lake. Since Scoggins Dam was constructed, peak flows in the Tualatin River have decreased by nearly 35 percent between November and March, the period of greatest rainfall (Hawksworth, 2000). Conversely, the reservoir helped increase streamflow in the Tualatin River during the hot and dry summer months when irrigation withdrawals had decreased streamflow to historically low levels (Cass and Miner, 1993). Population growth has further increased water demand, prompting a need for supplemental water to be piped from Barney Reservoir in the adjacent Trask River Basin. This supplemental water combines with discharges from Hagg Lake and four WWTFs to raise summer base flows in the Tualatin River (Hawksworth, 2000; Cole and Lemke, 2008; Bonn, 2010). For instance, flows in the lower Tualatin River are augmented with more than 100 cubic feet per second (ft^3/s) of water from reservoir releases and treated effluent during July through September each year (CH2M Hill, 2006; Carpenter and Rounds, 2013).

- **Water-quality changes**. A variety of management activities and other direct human actions have affected water quality in the Tualatin River Basin. For example, alteration to forest connectivity and changes to tree canopy density greatly influence instream temperatures, especially in the upper basin and along smaller tributaries (Risley, 1997, 2000). In contrast, discharge of treated wastewater from the WWTFs affect instream temperatures in the wider and slower reaches of the lower Tualatin River (Rounds and others, 1999; Risley, 2000). Another common impairment relates to low instream dissolved-oxygen (DO) concentrations, which occur mainly in streams and rivers along the valley bottom. Segments of the Tualatin River and many of its tributaries have a history of low DO and, thus, have been listed as impaired by the Oregon Department of Environmental Quality (ODEQ; Oregon Department of Environmental Quality, 2001). Herbicides, insecticides, fungicides, and other pesticides have been detected in the Tualatin River and its tributaries at concentrations that were elevated relative to other streams in the Willamette River Basin (Rinella and Janet, 1998; Wentz and others, 1998; Bonn, 1999). Lastly, the presence of large algal blooms historically was linked to high pH and high nutrient concentrations in the lower Tualatin River, and was one of the factors behind the implementation of Total Maximum Daily Load programs (TMDLs) in the Tualatin River Basin.

- **Physical habitat modifications**. Removal of large wood, river straightening, and logging of riparian forests are some examples of direct physical alterations to stream channels in the Tualatin River Basin. In the late 1800s, large wood was taken from the Tualatin River and Dairy Creek to aid navigation. Additional removals took place throughout the basin in the 1960s to 1980s (Farnell, 1978; Cass and Miner, 1993; Breuner, 1998; Hawksworth, 2001). Removing large wood resulted in fewer features like secondary channels and pools, less sediment storage, decreased channel migration, and lowering of the channel bed. The historically meandering lowland reaches were channelized and straightened to accommodate agriculture and urban development (Hawksworth, 2001). Increased stream velocities, channel incision, and bank erosion were some typical responses to these modifications. Over time, riparian forests continued to be removed for land development and for construction materials (Hawksworth, 2001). Removing riparian forests commonly decreased bank stability, increased stream temperatures, and decreased inputs of wood and organic matter to streams.

- **Biological assemblage changes.** The flora and fauna in the Tualatin River Basin have changed over the last 100 years due to factors such as riparian deforestation, river and floodplain changes, and the introduction of invasive species. A variety of sport and non-native fish also have been introduced, including sunfish, bass, catfish, and mosquitofish (Leader, 2002). In response, native fish populations in the Tualatin River Basin like Chinook (*Oncorhynchus tshawytscha*) and Coho (*O. kisutch*) salmon, cutthroat (*O. clarkii*) and steelhead (*O. mykiss*) trout, and Pacific lamprey (*Entosphenus tridentatus*) have all declined (Cole and others, 2006;

Cole and Lemke, 2011). Salmon and trout generally are more abundant in the smaller upland streams where temperature and stream substrate conditions are more suitable for their use. Other introduced wildlife include nutria (*Myocastor coypus*), which compete with native beavers (*Castor canadensis*) (U.S. Fish and Wildlife Service, 2011) for habitat and resources. In addition to added competition, beavers historically have been over-hunted in the basin, leading to progressively lower populations (Tualatin River Watershed Council, 1998). Recently, with the aid of restoration and reintroduction, beaver populations in the basin have rebounded in places such as Fanno Creek (Erin Poor, U.S. Geological Survey, written commun., 2017). Previously, an abundant native crayfish (*Pacifastacus leniusculus*) population had supported a commercial fishery in the lower Tualatin River (Ame, 2007); however, this has all but disappeared. Introduced plants, such as English ivy (*Hedera helix* L.), Himalayan blackberry (*Rubus ulmifolius*), and reed canary grass (*Phalaris arundinacea*) now cover considerable areas of the basin (Hawksworth, 2001).

Ecological Stressors

An ecological stressor refers to any action, material, or factor that imposes change on an ecological system, whether derived from human activities or natural events. Whether natural or anthropogenic, all modifications potentially stress systems in a watershed. Such changes may take many forms. In the case of a particular target species, for example, changes might include increased mortality, a decrease in health, changes in population size, changes in mating success, or altered susceptibility to disease. Stressors also may change streamflow, water-quality conditions, and channel habitats. A convenient way to organize stressors is by categorizing them into a prioritization framework using four categories of the stream function pyramid proposed by Harman and others (2012): hydrologic, water quality, physical habitat, and biological. Ecological stressors can appear in any of these four categories. Based on an understanding of the inherent landscape controls and human pressures in the Tualatin River Basin, the main riverine ecosystem stressors identified for this study are shown in table 1. Of these, the study focused on a select few stressors for scoring a subset of lowland streams in the Tualatin River Basin.

Management Constraints

Another influence on the ecological health of a watershed is resource management, primarily in terms of how operational constraints affect land and water usage in a watershed. Water management constraints include anything that puts limitations on physical and biological processes, management strategies, and treatment options. Such constraints could include the size of upstream reservoir storage; the amount of water available for flow augmentation; limits on treatment options imposed by state or Federal regulations; infrastructure requirements of a sizeable human population; or the limits that residence time, turbidity, and nutrients place on system productivity. Several of these constraints are important in the Tualatin River Basin where streams typically have silty bottoms and low gradients, and where flow is an important element of water quality and habitat health.

Table 1. Selected riverine ecosystem stressors organized into four categories based on stream function, Tualatin River Basin, Oregon.

[The subset of stressors that were scored in this study is shown in **bold**]

Stressor			
Hydrologic	**Water quality**	**Physical habitat**	**Biological**
High flow	**Stream temperature**	Habitat quantity	Disease
Low flow	**Low dissolved oxygen**	Habitat quality	Parasites
Flashiness	**Turbidity**	Habitat connectivity	**Species tolerance**
Diversions	Nutrient enrichment	**Bank erosion**	Predators
Withdrawals	Nutrient scarcity	**Riparian vegetation**	Prey abundance
	Contaminants	**Uniform substrate**	**Invasive species**
	High pH	Impervious area	Endocrine disruption
		Absence of large wood	Biological integrity
		Channel incision	**Indicator species**

Selecting Stressors, Metrics, and Scoring Translators

After identifying the inherent processes, controls, and stressors in a system, the next task is to select a subset of ecological stressors and identify useful *metrics* to measure their effects. The stressor metrics selected for the Tualatin River Basin were based on specific criteria including (1) presence of an environmental standard for the stressor; (2) preferential listing of stressor in the scientific literature; (3) professional knowledge of importance of a stressor; (4) data availability for the stressor-related metrics; (5) reduction in redundancies between stressors; and (6) responsiveness of stressor to management activity. Stressor metrics were selected for the prioritization framework to capture the specific needs of the watershed and provide input for selecting appropriate management solutions.

Metrics selected for the Tualatin River Basin captured a broad range of riverine ecosystem stressors across hydrologic, water quality, physical habitat, and biological conditions. Scoring systems were crafted to translate available data for the stressor metrics into scores that were useful in addressing potential protection, restoration, or maintenance actions. The following sections describe the metrics selected to quantify ecosystem stressors for sites in the Tualatin River Basin. Calculation of the metrics and translation of metric values to scores for selected sites are described in section, "Tualatin River Basin Scoring Examples."

Hydrology

The hydrology category includes three stressor metrics that measure the potential stress imposed by altered flow conditions, including one standard metric (for example, stream flashiness) and two metrics developed for this study (for example, high- and low-flow deviation). Other flow statistics could be substituted depending on the availability and reliability of streamflow information, but the following metrics and statistics seem appropriate for the characterization of altered flow conditions.

- **Stream flashiness**. The *stream-flashiness* metric captures how quickly the daily mean streamflow changes at a site, often in response to a storm (Baker and others, 2004). Urban streams tend to have greater "flashiness" (for example, higher Richards-Baker [RB]-Flashiness Index values) because runoff from impervious surfaces does not infiltrate into the ground and tends to be routed rapidly to nearby streams. More-natural watersheds have greater infiltration rates, slower stream response to storms, and lower RB-Flashiness Index values. This metric is indicative of several important influences on the hydrology of streams in urban areas, such as the effect of large areas of impervious surfaces on runoff, erosion, and channel incision.

- **High flow**. The *high-flow* metric captures the degree to which measured high-flow conditions may be different from expected high-flow conditions during the wet season. The peak 10-year (PK_{10}) high-flow statistic was selected as a representative benchmark that measures the maximum instantaneous streamflow that occurs, on average, once every 10 years (Cooper, 2005). Generally, high flows provide energy to move sediment and wood, as well as develop habitat. Flows that exceed the PK_{10} high-flow statistic frequently may be an indicator of excessive stormwater runoff and erosion.

- **Low flow**. The *low-flow* metric captures how lower-than-expected low flows may stress a river ecosystem. Such low flows can alter and decrease habitat, exacerbate water-quality problems, and be indicative of excessive water diversions, all of which may be stressful to the ecosystem. The low-flow metric used in this study is based on the $7Q_2$ low-flow statistic that measures the 7-day minimum streamflow with a 2-year recurrence interval. A 2-year recurrence interval means that a 50 percent chance exists that the 7-day minimum streamflow would be less than the $7Q_2$ in any single year.

Water Quality

Four stressor metrics were selected for the water-quality category, including metrics for stream temperature, dissolved-oxygen concentration, turbidity, and contaminants. Preliminary lists of potential water-quality metrics included measures of pH, phosphorus concentrations, and the trace metals aluminum and manganese. However, these metrics were excluded from the Tualatin River Basin framework for various reasons. For example, phosphorus occurs naturally at high levels in the basin (Kelly and others, 1999), which made it difficult to capture any meaningful ecological effects with a phosphorus metric. Additionally, no regulatory criterion existed for aluminum and the criterion for manganese was withdrawn by the State regulatory agency (Oregon

Department of Environmental Quality, 2012). The criterion for human health also was withdrawn for iron, but the aquatic life criterion for iron is still relevant and was included in the contaminants analysis. Similarly, although arsenic has both natural and anthropogenic sources in the basin, the aquatic life criterion for arsenic was revalidated by the State of Oregon and was considered in the analyses (Oregon Department of Environmental Quality, 2013a). Water-quality metrics were assessed based on discrete water-sample data but could be modified in the future to use continuous time-series data. The water-quality stressor metrics are:

- **Water temperature**. The *water-temperature* metric demonstrates the importance of how high stream temperatures can be confusing, disruptive, or even lethal to cold-water fish species such as salmon and steelhead (Caissie, 2006). This metric is indicative of how maximum daily temperatures can hinder reproduction and viability of fish species. The State of Oregon has criteria for daily maximum stream temperatures suitable for native fish species; this metric is based on the percentage of time in compliance with these criteria.

- **Dissolved oxygen.** The *dissolved-oxygen* metric measures the dissolved-oxygen (DO) concentration of water and is an oft-used indicator of water quality for maintaining healthy aquatic species. Low DO concentrations can be lethal to aquatic organisms; therefore, minimum DO standards have been set for the waters of Oregon (Oregon State Archives, 2013). The dissolved-oxygen metric represents the percentage of samples with measured DO concentrations in compliance with the criteria set by the State.

- **Turbidity.** *Turbidity* is a measurement of water clarity and is a water-quality indicator used to assess the amount and effects of suspended particles, such as sediment or algae, on physical, biological, and ecological processes in a riverine system. Excessive suspended sediment can limit light transmission and hinder algal growth in a river, leading to limited oxygen production and food supply for aquatic organisms (Carpenter and Rounds, 2013). Additionally, suspended particles can transport contaminants, bury spawning habitat, and be indicative of excessive erosion, all of which increase ecosystem stress. The turbidity metric represents the frequency and magnitude where sediment transport and water clarity may be an issue.

- **Contaminants.** *Contaminants* represent a suite of chemicals and other compounds detected in water, fish tissue, or bed-sediment samples that may adversely affect aquatic and predatory terrestrial species (Bonn, 1999; Rounds and others, 2009). Occurrence of trace metals and organic contaminants differs between urban, rural, and headwater streams. Although many compounds are present only at low levels, some occur at high enough concentrations to be of concern. The contaminant metric provides an assessment of the abundance and magnitude of contaminants that have been measured in samples relative to the concentrations that may cause ecological harm.

Physical Habitat

Unlike hydrology and water quality, physical habitat may not change in immediate or predictable ways in response to human-related stressors because of local constraints, such as geology (Nelson and others, 2006; Booth and Henshaw, 2013) and channel slope (Walters and others, 2003; Roy and others, 2006). For example, stream segments with steep slopes or substrates resistant to erosion and scour may change less than other segments with low slopes and highly erodible substrates. Nonetheless, physical-habitat metrics were included in the scoring system to identify sites where physical habitat conditions may cause ecological stress, partly because such metrics may prove useful for managers to prioritize sites for active restoration or protection. Four physical-habitat metrics were included in the proposed scoring system, as follows:

- **Bank stability.** *Bank stability* refers to the strength and cohesion of streambanks. Bank erosion is one way that channels naturally adjust to changes in discharge and sediment inputs over time (Florsheim and others, 2008). The rate of bank erosion, however, can be amplified by decreases in riparian vegetation and increases in the magnitude of streamflow. Therefore, a metric that helps quantify the degree of bank erosion is likely to be helpful in identifying areas affected by excessive stormflow runoff and areas that might be good candidates for restoration.

- **Coarse sediment.** The *coarse-sediment* metric reflects a visual estimate of the areal coverage of the streambed with coarse sediments that are greater than 63 microns in diameter (that is, sand). Habitats and biological assemblages tend to vary between streams with different bed-sediment compositions. Coarse sediment is beneficial for species biodiversity and helpful for improving channel complexity.

- **Large wood.** The *large-wood* metric is an indicator of the amount of instream habitat provided by large wood (Cole and others, 2006). This reflects the amount of large wood at a site that may create pools or offer cover for fish like salmon and trout. Streams that lack wood often have reduced aquatic species diversity, less viable habitat, and are more exposed to predation.

- **Canopy cover**. The *canopy-cover* metric corresponds to the percentage of riparian vegetative cover over the channel as measured using a spherical densiometer (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011). This habitat stressor metric relates to the quantity of shading along a channel, and in some cases, correlates to bank stability. This metric does not reflect whether vegetation is native or non-native or a future source of large wood. The amount of canopy covering a stream is important for stream temperature, bank stability, habitat potential, and other ecosystem-quality characteristics.

Biological

The biological category includes one metric indicative of potential biological stressors (for example, percentage of native fish) and two metrics indicative of biological community condition (for example, percentage of sensitive macroinvertebrate and percentage of sensitive native fish). Other metrics may be substituted or added over time as additional datasets become available in the Tualatin River Basin or as methods for scoring biological communities in lowland streams are further developed. The selected biological metrics include:

- **Sensitive macroinvertebrates.** Some form of macroinvertebrate species richness commonly is used as a biological metric to assess ecosystem health (Waite and others, 2008). The most commonly used metric tends to be Ephemeroptera/Plecoptera/Trichoptera richness (EPT richness). Because EPT richness most often is used for streams with coarse stream substrates rather than silty substrates, other macroinvertebrate characteristics were selected. For this framework, the percentage of *sensitive macroinvertebrate* taxa present was selected, which served as a more applicable metric than EPT richness for assessing valley bottom streams that tend to lack course substrates.

- **Native fish.** The *native-fish* metric describes the relative abundance of native fish that may be stressed by introduced fish populations through predation or competition. For instance, smallmouth bass (*Micropterus dolomieu*) is an introduced species that can consume out-migrating juvenile salmon. The presence and abundance of native fish may be a representative factor of other stressors and a good indicator that managers can tie to future restoration plans.

- **Sensitive native fish.** The *sensitive native-fish* metric quantifies the presence of sensitive native fish relative to other fish species that also are present at a site. This metric is useful for identifying sites where some sort of stress or habitat degradation is limiting use by sensitive fish species that often are the target for restoration activities. This metric also helps to identify sites that still support fish that are less tolerant to habitat degradation rather than just an abundance of tolerant native species.

Scoring the Stressor Metrics

For ease of use and comparability, the metrics in this framework were scaled to a numerical score of 0–10 by applying a *scoring translator* to the raw metric values. Under this type of scheme, a 10 represented an ideal condition that was best attainable given the current physiographic and environmental setting. Any score less than a 10 indicated that a site had undergone some form of degradation or stress. Scores then were composited into category scores for hydrology, water quality, physical habitat, and biology so that the most influential type of stressors were identified. Translating scores and classifying raw values was an iterative process and depended on professional judgment, established thresholds, goals for using the scoring system, and observed compared with expected results. The method for classifying raw values and assigning translated scores varied by metric. The values, translators, and equations represented herein apply only to lowland sites of the Tualatin River Basin. Scoring translators for other areas could be developed to highlight any problems or explore restoration goals for those areas.

Presenting Results

How the scores of a prioritization framework are presented depends on the goals of the exercise. One option is to provide a “report card” for the (relative) health of individual sites with a score that helps to visualize the status of each site in a watershed. Depending on the data analyzed, it may be possible to provide a trend analysis of changes in the quality or health of selected sites. Sometimes a final score for a site is not as important as using individual metric scores to guide management actions that could address current concerns. Additionally, using prioritization framework scores in tandem with estimates of how specific restoration actions may affect those scores could guide management decisions for the use of scarce restoration resources. The prioritization framework can be adjusted as additional information becomes available or as management and restoration goals change over time.

Tualatin River Basin Scoring Examples

The prioritization framework is based on identifying key processes and stressors, selecting specific metrics, translating raw metric values to comparable scores, compiling final scores, and deriving insights from those scores. The best way to illustrate the use of this framework is through a set of examples. Representative sites in the Tualatin River Basin were selected and scored as examples.

Data Compilation

Since 1990, some form of hydrologic, water-quality, physical-habitat, or biological data were collected at more than 800 sites in the Tualatin River Basin (fig. 6). Collected data include streamflow measurements and water-quality samples—all data are available in the USGS National Water Information System (U.S. Geological Survey, 2013). Available data also included fish and macroinvertebrate assemblage surveys (Leader, 2002; Cole and others, 2006; Cole and Lemke, 2011), geomorphic site assessments (Clean Water Services, 2000; Simon and others, 2011), and inventories of stream enhancements and restorations (Clean Water Services, written commun., 2012). Although most locations had short-term or discrete data, other sites had long periods of near-continuous data (table 2). Most locations had data for only one metric and about a dozen locations had concurrent data from all four categories of stressor metrics. The available data were sufficient to begin site-specific assessments of ecological stressors (table 3). However, because of spatial and temporal data gaps a more systematic data collection effort will be needed to generate a consistent set of data for future evaluation with this type of prioritization framework.

Site Selection for Scoring

The pool of sites available for scoring in the Tualatin River Basin included locations that had at least some form of hydrologic, water quality, physical habitat, and biological data (fig. 6). This initial group of sites was filtered to include only sites where data were collected from the beginning of 1990 to the end of 2012. This period was selected because the Tualatin River Basin has changed substantially over the last 100 years and “modern” stresses were of greater priority for understanding the “modern” landscape. Applying a data-availability time-filter resulted in 71 preliminary sites that met the period of record of 1990–2012 and had data for at least one-half of the selected stressor metrics, primarily water quality. This group of sites was further refined and classified based on the quantity of data available so sites with the most relevant data for the most possible metrics received priority. That refinement decreased the number of preliminary sites to 29 semi-final locations, all of which had enough data to successfully score. In each case, data for at least three of the four stressor categories were collocated or data were available in immediate proximity. Data at these locations covered the prerequisite 20-year period. If the entire Tualatin River Basin were to be scored, these 29 sites would be the best representative sites. However, for this study, only data from four priority tributary sites and two priority Tualatin River locations were used for scoring ecosystem stressors to demonstrate the application of the prioritization framework. The final sites for this study included long-term monitoring locations on Fanno, Beaverton, McKay, and Chicken Creeks and the Tualatin River upstream near the town of Dilley and downstream at Boones Ferry Road (fig. 7).

All selected sites were located along the valley lowlands and included a range of basin areas (table 4). For the tributary sites, contributing area was largest for McKay Creek and progressively smaller for Fanno, Beaverton, and Chicken Creeks. Urban land covered about 25 percent or less for the drainages upstream of the McKay and Chicken Creek sites, but nearly 90 percent for the drainages upstream of the Beaverton and Fanno Creek sites. Agriculture and forest occupied greater amounts of the McKay and Chicken Creek contributing areas relative to those for the Beaverton and Fanno Creek. Land cover was mostly forest and agricultural upstream of Tualatin River at Dilley and more urban or agricultural downstream at Boones Ferry Road at Tualatin. All sites except for the upstream Tualatin River site at Dilley were within the Portland metropolitan area urban growth boundary.

Gaps in the data were relatively common for the final six sites. Where possible, field observations and data from nearby sites were used to fill these gaps, provided the nearby sites were within a similar physiographic region and were relatively close (for example, within 3 mi proximity) to the site along the same stream. For example, data from McKay Creek upstream of Scotch Church Road was used to provide macroinvertebrate data for the McKay Creek near Hillsboro site because it shared a similar setting and was 2.7 mi upstream from the site where streamflow and water-quality samples were collected. Data for at least one metric were from nearby sites for each of the four tributary sites. Because macroinvertebrate monitoring was done at wadable streams, data were not available for some of the key biological and habitat metrics for the two Tualatin River sites, it was decided to focus only on the water-quality metrics for those sites. No significant gaps were present in the water-quality data, although the types of contaminants monitored did vary substantially over time.

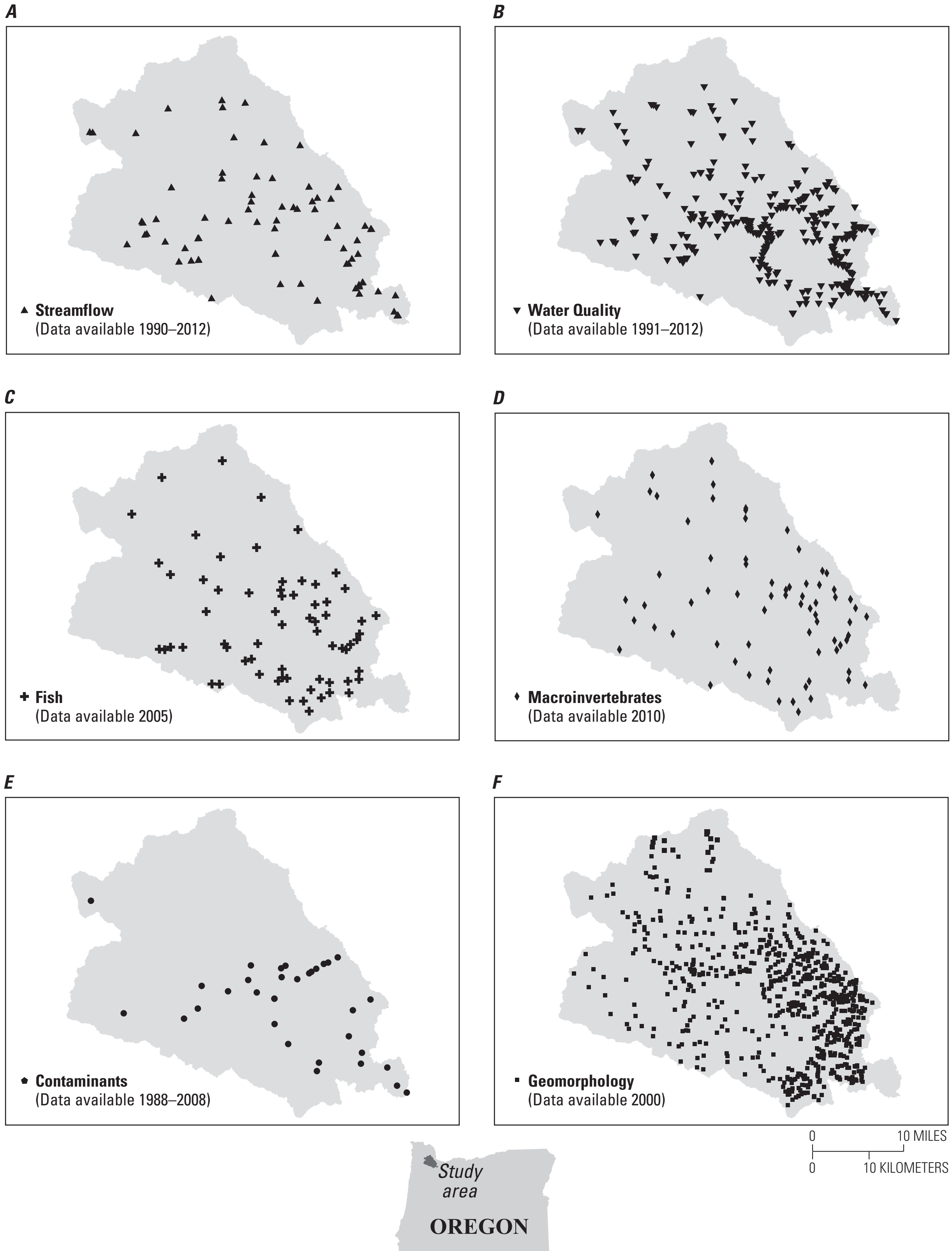

Figure 6. Data collection locations for streamflow (*A*), water quality (*B*), fish (*C*), macroinvertebrates (*D*), contaminants (*E*), and geomorphic characteristics (*F*) in the Tualatin River Basin, Oregon.

Table 2. Datasets used for implementing the ecosystem stressor prioritization framework for sites in the Tualatin River Basin, Oregon.

Category	Metric	Data type	McKay Creek near Hillsboro	Beaverton Creek at SW 216th Ave.	Fanno Creek at Durham
Hydrologic	Streamflow during storms	Continuous, year-round data	October 2002–September 2012	October 2002–September 2013	October 1994–September 1996; October 2000–September 2012
	Deviation of high flow	PK_{10} calculated using continuous data	October 2001–September 2012	October 2001–September 2012	October 2000–September 2012
	Deviation of low flow	$7Q_2$ calculated using continuous data	Climate years (April 1–March 31) for 2002 to 2012	Climate years (April 1–March 31) for 2002 to 2012	Climate years (April 1–March 31) for 1994 to 2012
Water quality	Stream temperature	Discrete sample	July 1992–April 2008	February 1991–May 2011	July 1992–April 2008
	Dissolved oxygen	Discrete sample	July 1992–April 2008	February 1991–May 2011	July 1992–April 2008
	Turbidity	Discrete sample	July 1992–April 2008	February 1991–May 2011	July 1992–April 2008
	Contaminants	Discrete sample	June 1997–April 2008	February 1991–April 2006	February 1991–December 2011
Physical habitat	Stable banks	Field estimate	September/October 2010	September/October 2010	September/October 2010
	Coarse sediment	Field estimate	September/October 2010	September/October 2010	September/October 2010
	Large wood	Field estimate	September/October 2005	September/October 2005	September/October 2005
	Canopy cover	Field estimate	September/October 2010	September/October 2010	September/October 2010
Biological	Sensitive macroinvertebrates	Field survey/inventory	September/October 2010	September/October 2010	September/October 2010
	Native fish species	Field survey/inventory	August–October 2005; April–June 2006	August–October 2005; April–June 2006	August–October 2005; April–June 2006
	Sensitive native fish	Field survey/inventory	August–October 2005; April–June 2006	August–October 2005; April–June 2006	August–October 2005; April–June 2006

Category	Metric	Data type	Chicken Creek near Sherwood	Tualatin River near Dilley	Tualatin River at Boones Ferry Rd. at Tualatin
Hydrology	Streamflow during storms	Continuous, year-round data	October 2002–September 2011	October 1990–September 2012	October 1990–September 2012
	Deviation of high flow	PK_{10} calculated using continuous data	October 2001–September 2012	October 1989–September 2012	October 1989–September 2012
	Deviation of low flow	$7Q_2$ calculated using continuous data	Climate years (April 1–March 31) for 2002 to 2012	Climate years (April 1–March 31) for 1990–2012	Climate years (April 1–March 31) for 1990–2012

Table 2. Datasets used for implementing the ecosystem stressor prioritization framework for sites in the Tualatin River Basin, Oregon. —Continued

Category	Metric	Data type	Chicken Creek near Sherwood	Tualatin River near Dilley	Tualatin River at Boones Ferry Rd. at Tualatin
Water quality	Stream temperature	Discrete sample	May 1991–December 2012	January 1991–February 2012	January 1991–December 2012
	Dissolved oxygen	Discrete sample	May 1991–December 2012	January 1991–February 2012	January 1991–December 2012
	Turbidity	Discrete sample	May 1991–December 2012	January 1991–February 2012	January 1991–December 2012
	Contaminants	Discrete sample	May 1991–December 2011	February 1991–October 2011	February 1991–December 2011
Physical habitat	Stable banks	Field estimate	September/October 2010		
	Coarse sediment	Field estimate	September/October 2010		
	Large wood	Field estimate	September/October 2005		
	Canopy cover	Field estimate	September/October 2010		
Biology	Sensitive macroinvertebrates	Field survey/inventory	September/October 2010		
	Native fish species	Field survey/inventory	August–October 2005; April–June 2006		
	Sensitive native fish	Field survey/inventory	August–October 2005; April–June 2006		

Table 3. Number of water-quality samples collected at sites used in the ecosystem stressor prioritization framework for the Tualatin River Basin, Oregon.

[The wet and dry seasons are defined as November–April and May–October, respectively]

Site	Season	1990–1999				2000–2012			
		Temperature	Dissolved oxygen	Turbidity	Contaminants	Temperature	Dissolved oxygen	Turbidity	Contaminants
McKay Creek near Hillsboro	Wet	5	4	5	7	40	39	39	201
	Dry	61	61	62	37	201	201	203	226
Beaverton Creek at SW 216th Ave. near Orenco	Wet	85	81	69	337	59	59	33	0
	Dry	158	160	158	209	86	85	61	16
Fanno Creek at Durham	Wet	5	4	5	780	40	43	39	2,200
	Dry	61	61	62	803	201	201	203	2,122
Chicken Creek near Sherwood	Wet	122	121	111	297	152	150	144	645
	Dry	214	211	189	304	297	297	293	766
Tualatin River near Dilley	Wet	133	129	125	321	155	152	143	980
	Dry	291	274	240	331	314	311	314	1,210
Tualatin River at Boones Ferry Rd. at Tualatin	Wet	188	185	135	345	218	218	146	972
	Dry	1,247	1,240	466	401	966	963	326	1,238

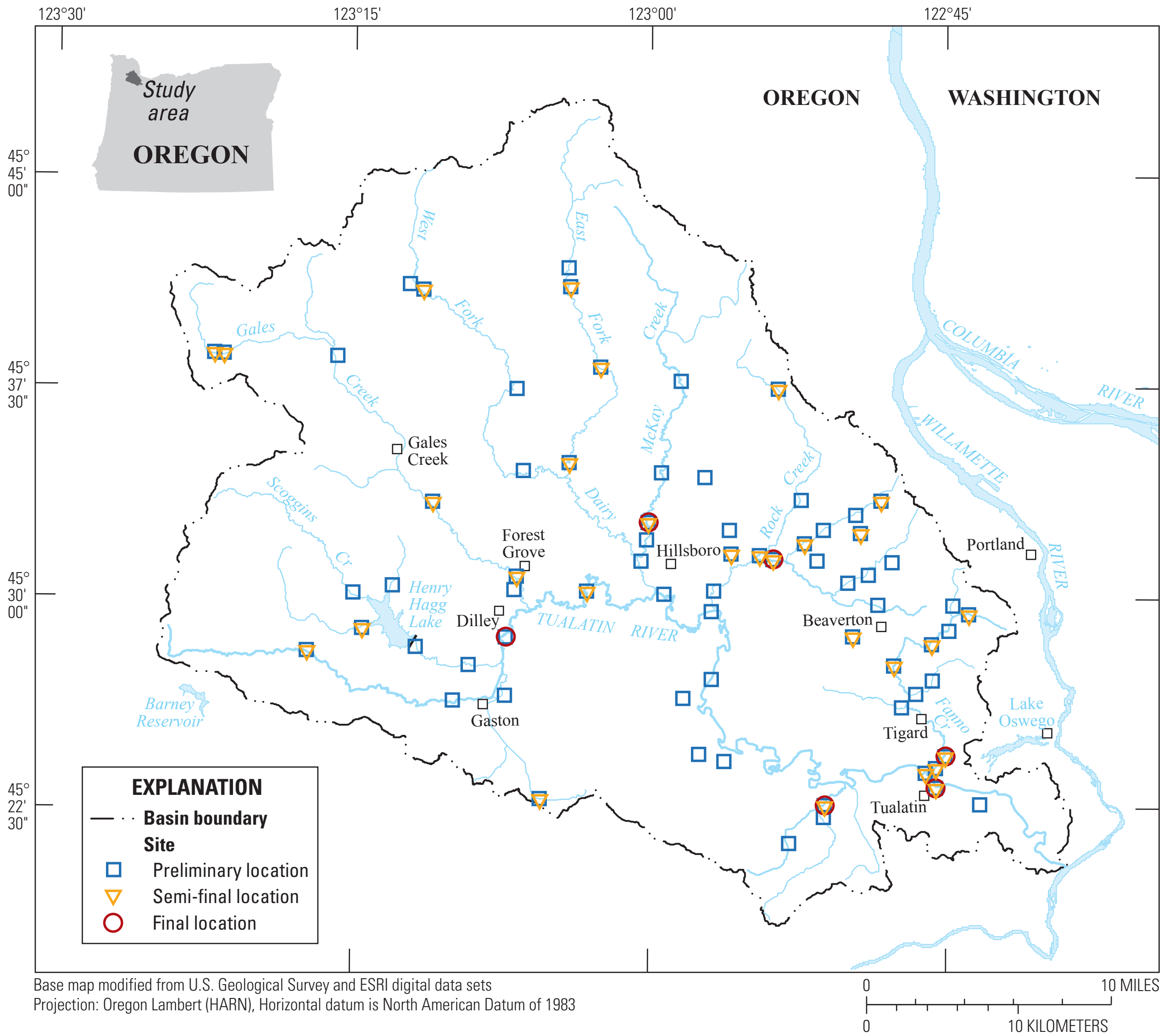

Figure 7. Locations of 71 preliminary, 29 semi-final, and 6 final sites used to test the ecosystem stressor prioritization framework in the Tualatin River Basin, Oregon.

Table 4. Summary characteristics for final sites used to test ecosystem stressor prioritization framework in the Tualatin River Basin, Oregon.

[Locations of sites are shown in figure 1. **Basin area:** From StreamStats (U.S. Geological Survey, 2012). **Landcover class:** Urban, forest, agricultural landcover from National Land Cover Database 2011 (Jin and others, 2013); other, includes water, barren, shrub, scrub, and wetland. **Abbreviation:** CWS, Clean Water Services; mi^2, square mile; USGS, U.S. Geological Survey]

Site name	USGS or CWS site No.	Basin area (mi^2)	Landcover class (percent)			
			Urban	Forest	Agricultural	Other
McKay Creek near Hillsboro	14206180	58.2	10.2	34.3	36.2	19.3
Beaverton Creek at SW 216th Ave. near Orenco	14206435	22.8	87.7	9.1	0.9	2.3
Fanno Creek at Durham	14206950	31.0	89.4	8.2	0.2	2.2
Chicken Creek near Sherwood	14206750	15.3	25.7	28.2	38.8	7.3
Tualatin River near Dilley	14203500	125	4.6	44.5	16.1	34.8
Tualatin River at Boones Ferry Rd. at Tualatin	14206960	692	17.2	30.9	32.3	19.6

Tualatin River Site Scoring

To score Tualatin River sites, each stressor metric was identified, and a scoring translator was developed to change the raw value into a score between 0 and 10.

Stream Flashiness (Annual)

The *stream-flashiness* metric was calculated as the sum of the absolute values of day-to-day changes in daily mean streamflow divided by the sum of daily mean streamflows over the same period. An index near 1.0 meant that the stream tended to have large changes in streamflow from day-to-day relative to the mean streamflow, whereas an index near 0.0 was indicative of streamflow conditions that did not change appreciably from day-to-day. Raw values were translated into final scores based on methods similar to those used by LimnoTech, Inc. (2006). For this study, the raw score was computed as 1.0 minus the RB-Flashiness Index so that low RB-Flashiness Index values represented better scores (table 5). Flashiness was calculated using data collected throughout the entire year; therefore, the scores were applied equally to both wet and dry periods.

High Flow (Wet Season)

The *high-flow* metric was computed as the ratio of the expected PK_{10} value divided by the measured PK_{10} value. The PK_{10} thresholds were based on regional equations (Cooper, 2005) that estimated expected streamflow conditions for individual streams. The distribution of raw percentage scores was examined for usable patterns and translated scores were assigned using natural breaks in the data. Translated scores were calculated using the Tualatin-specific translation equation provided in table 5. Because of rainfall conditions, the high-flow metric was applied only to the wet season within the framework. Use of this type of metric is greatly dependent on the availability of reliable estimates of the expected PK_{10} value. For some of the smaller tributaries, a higher uncertainty was inherent in such estimates; as a result, this metric may be extremely uncertain and have limited utility for some sites and could be excluded from the final scores.

Low Flow (Dry Season)

The *low-flow* metric was scored based on the ratio of the measured to the expected value of the $7Q_2$ streamflow statistic. Expected $7Q_2$ flow statistics were derived from regional regression equations based on unregulated flows at 56 sites in the Willamette River Basin (Risley and others, 2008). The $7Q_2$ values for measured flows were computed using the log-Pearson Type III probability distribution (U.S. Geological Survey, 1982); an overview of the technique used to compute $7Q_2$ values is available in Riggs (1972). A scoring translator was created based on natural breaks in the results. Translated scores and an equation to translate scores are provided in table 5. This metric was applied only to dry season conditions. As for the high-flow metric, this low-flow metric was greatly dependent on reliable estimates of the expected $7Q_2$ value. For some sites, the results were uncertain and called into question the reliability of the resulting ratio used for the metric value. This low-flow metric can be useful and meaningful, but selected results might need to be excluded from final scores if the estimates of this metric are not sufficiently reliable.

Water Temperature (Wet/Dry Seasons)

The *water-temperature* metric was based on the percentage of measured water temperatures in compliance with State of Oregon criteria. The ODEQ has established maximum water temperature standards for Oregon waters such that streams in the Tualatin River Basin must not exceed 13 °C (7-day average of the daily maximum) from either October 15 or January 1 to May 15 to protect fish spawning uses, and 18 °C (7-day average of the daily maximum) during the rest of the year to protect fish rearing and migration uses (Oregon Department of Environmental Quality, 2003, 2005; Oregon State Archives, 2013). The two different start dates (October 15 or January 1) for fish spawning use were due to different fish-use designations assigned to the target Tualatin River Basin stream sites by ODEQ. For the six Tualatin River Basin sites scored in this study, only Fanno Creek was designated as a stream with fish spawning use for January 1–May 15; the rest of the sites had only the rearing and migration fish-use designation. Because water-quality standards were already established for stream temperature related to spawning and rearing, it was straightforward to translate a raw value (that is, percentage of time in compliance with the standard) into a final score. Translation of raw values were based on the stream-temperature metric proposed by LimnoTech, Inc. (2006) and calculated for Tualatin River sites using the equation shown in table 6. Because different seasons had different criteria (for one site), unique values were populated for wet and dry seasons.

Dissolved Oxygen (Wet/Dry Seasons)

The *dissolved-oxygen* metric was based on the percentage of measured water samples where the dissolved-oxygen concentration was in compliance with State of Oregon criteria. The State DO criteria depend on the type of data available (for example, discrete or continuous) and on the fish-use designation for the stream. For discrete water-quality samples in a designated cool-water stream, the standard dictates that the DO concentration should not be less than 6.5 mg/L. However, for continuous monitoring the criteria are more complex. Three periods define the criteria used with continuous data: (1) 30-day mean; (2) 7-day mean of the daily minimum; and (3) instantaneous. For example, to protect native aquatic species in cool-water streams when

Table 5. Hydrology stressor metrics and scoring translators used for lowland tributary sites in the Tualatin River Basin, Oregon.

[**Method for deriving raw scores:** $7Q_2$, 7-day minimum streamflow, 2-year recurrence interval; PK_{10} , peak 10-year high flow statistic. ≥, greater than or equal to]

Metric	Description	Method for deriving raw scores	Source of score translator	Raw score (x)	Translated score (y)	Translation equation
Stream flashiness (annual)	Indicator of frequency and rapidity of short-term changes in streamflow as computed by the Richards-Baker Flashiness Index	Ratio of the sum of the absolute values of day-to-day changes in daily mean flow to the sum of the daily mean flows for each year. Raw score was computed as 1.0 minus the RB-Flashiness Index so that low index values represented better scores.	Modified from LimnoTech (2006)	1.00	10	y = 10x
				0.80	8	
				0.60	6	
				0.40	4	
				0.20	2	
				0.00	0	
High flow (wet season)	Percent deviation from normal streamflow for wet seasons. Indicator of high-flow conditions that are higher than expected	Ratio of the expected PK_{10} high flow statistic to the measured PK_{10}.	Data histograms for lowland sampling sites	≥ 1.00	10	$y = 5.6851x^2 + 4.1196x - 0.8397$
				0.98	8	
				0.85	6	
				0.60	4	
				0.40	2	
				0.20	0	
Low flow (dry season)	Percent deviation from normal streamflow for dry seasons. Indicator of lower-than-expected conditions that may stress river ecosystems	Ratio of the measured $7Q_2$ low-flow statistic to the expected $7Q_2$.	Data histograms for lowland sampling sites	≥ 1.00	10	$y = 5.6851x^2 + 4.1196x - 0.8397$
				0.98	8	
				0.85	6	
				0.60	4	
				0.40	2	
				0.20	0	

salmonids do not form a dominant part of the community structure, the minimum DO criteria are 6.5, 5.0, and 4.0 mg/L for those three conditions, respectively (Oregon Department of Environmental Quality, 2007). The criteria are different for periods in which a stream is designated for spawning use by salmon and trout species. To protect for spawning use in cool-water streams (such as Fanno Creek for the period between January 1 and May 15), the minimum DO concentration must be at least 11 mg/L as a 7-day mean or 9.0 mg/L as a single measurement, or at least 95 percent of the DO saturation concentration (Oregon Department of Environmental Quality, 2007). Translation of raw values (that is, percentage of time DO was in compliance with the standard) into final scores was based on the DO metric proposed by LimnoTech, Inc. (2006) and translation equation for scores is shown in table 6. Because different seasons had different criteria (for one site), unique values were populated for wet and dry seasons.

Turbidity (Wet/Dry Seasons)

The *turbidity* metric was computed as the percentage of time that turbidity measurements at each site were less than the mean of the 90th percentile of turbidity measurements at Tualatin River Basin lowland tributary sites (for example, 11–13 formazin nephelometric units [FNU] in dry seasons and 20–23 FNU in wet seasons, depending on the range of years used). By using the 90th percentile as a reference value, the largest spikes in turbidity data were removed, thus providing a more reasonable threshold for expected turbidities. Therefore, any site with turbidity values greater than the regional lowland threshold would be more likely to stress aquatic species. A regional threshold turbidity was determined for each decade (1990s versus 2000s) and season (wet versus dry) and compared against measurements from each site. The raw percentage scores were translated into final scores based on natural breaks in the data and were calculated with the equations show in table 6. Because different seasons had different criteria, unique values were populated for both wet and dry seasons.

Contaminants (Wet/Dry Seasons)

The *contaminants* metric was based on an aquatic life ratio (ALR), defined as the measured concentration divided by the relevant benchmark concentration for each sample. The analysis was limited to compounds with a benchmark or guidance level. The relevant benchmarks were based on the most stringent water-quality criterion for water (Oregon Department of Environmental Quality, 2013b), determined by selecting the lowest criterion among the aquatic-life criteria (that is, acute and chronic), human-health criteria, and the State of Oregon drinking-water criterion (that is, maximum contaminant level). The contaminant metric was established as using the percentage of samples that were not in compliance with known criteria, where the ALR was used to weight the magnitude of exceedance. Computationally, the metric was set to 1.0 minus the average ALR for the sample results in the analysis, where the ALR was capped at 100 times the exceedance of established criteria. Translation of raw values into final scores was based on the translation equation shown in table 6. Contaminant scores were assessed separately for both wet and dry seasons.

Bank Stability (Annual)

The *bank-stability* metric was based on a visual estimate of the degree to which stream banks were actively eroding and were being undercut at a particular site (Cole and Lemke, 2011). The metric was estimated following methods proposed by LimnoTech, Inc. (2006). However, unlike LimnoTech, Inc. (2006) in which the percentage of bank instability was determined, this framework reversed those values to represent the percentage of banks that were stable. The final scores were calculated based on the translation equations shown in table 7. Due to the timing of data collection and because bank stability represents stream functions that act year-round, the final score was applied annually for both wet and dry seasons.

Coarse Sediment (Annual)

The *coarse-sediment* metric was included in the scoring system to identify lowland sites where fine-sediment substrates, including hardpan clay, may limit the diversity of target aquatic species. The coarse-sediment metric was established as the percentage of coarse sediment samples collected compared to all sediment at a given location. The coarse-sediment metric was calculated as the percentage that was not measured as fine sediment, including sand and hardpan clay substrates in Cole and Lemke (2011). Because coarse sediment provides additional types of habitat, this metric was useful for capturing the overall habitat quality for sites with a greater amount of larger sediment. The measured coarse-sediment metric values were translated into final scores based on the translator equation presented in table 7. Due to the timing of data collection and because coarse sediment represents stream functions that act year-round, the final score was applied annually for both wet and dry seasons.

Table 6. Water-quality stressor metrics selected for final sites in the Tualatin River Basin, Oregon.

[**Abbreviations:** 7dADM, 7-day average of the daily maximum temperature; $7Q_2$, 7-day minimum streamflow, 2-year recurrence interval; ALR, Aquatic Life Ratio; °C, degrees Celsius; FNU, formazin nephelometric unit; mg/L, milligram per liter; PK_{10} , peak 10-year high flow statistic]

Metric	Description	Method for deriving raw scores	Source of score translator	Raw score (x)	Translated score (y)	Translation equation
Stream temperature (wet/dry seasons)	Measured water temperature (7dADM) if based on continuous data. For this study, only discrete field measurements were used.	Percentage of time that measurement or 7dADM was in compliance with standards: 18 °C for rearing and migration fish use; 13 °C for spawning use. Spawning fish use was designated only for Fanno Creek site (January 1 through May 15).	Modified from LimnoTech, Inc. (2006)	1.00 0.95 0.90 0.80 0.60 0.40	10 8 6 4 2 0	$y = 26.011x^2 - 21.064x + 4.5369$
Dissolved oxygen (wet/dry seasons)	Dissolved-oxygen concentration measured by continuous monitors or measured in the field. For this study discrete field measurements were used.	Percentage of time that measurement was in compliance with standards. The cool-water measurement criterion is 6.5 mg/L (9.0 mg/L for periods when fish are spawning). If continuous data were to be used, additional criteria need to be considered.	Modified from LimnoTech, Inc. (2006)	1.00 0.95 0.90 0.80 0.60	10 8 6 4 2	$y = 26.011x^2 - 21.064x + 4.5369$
Turbidity (wet/dry seasons)	Turbidity measured by continuous monitors or measured in the field. For this study discrete field measurements were used.	Percentage of time that turbidity was less than the mean of the 90th percentile for four lowland tributary sites (11–13 or 20–23 FNU depending on decade and wet or dry season designation).	Data histograms for lowland sampling sites	1.00 0.95 0.75 0.50 0.25 0.10	10 8 6 4 2 0	$y = 3.6396x^2 + 5.487x + 0.1602$
Contaminants (wet/dry seasons)	Laboratory measurements of contaminant concentrations in water samples	One minus the average ALR, with each ALR capped at 100 times the exceedance of established criteria. ALR computed as measured concentration divided by lowest aquatic-life, human-health, or drinking-water criterion.	Straight translation of percentage score	1.00 0.80 0.60 0.40 0.20 0.00	10 8 6 4 2 0	$y = 10x$

Table 7. Physical habitat stressor metrics selected for final sites in the Tualatin River Basin, Oregon.

[mm, millimeter]

Metric	Description	Method for deriving raw scores	Source of score translator	Raw score (x)	Translated score (y)	Translation equation
Bank stability (annual)	Visual estimates along both banks from 2011 field surveys (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011).	Percentage stable banks, as measured in field surveys.	Modified from LimnoTech, Inc. (2006)	1.00	10	$y = 2.5436x^2 + 7.2149x - 0.4121$
				0.94	8	
				0.75	6	
				0.50	4	
				0.25	2	
				0.10	0	
Coarse sediment (annual)	Visual estimates of coarse sediment (greater than 0.63 mm) from 2011 field surveys (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011).	Percentange of bed substrate composed of coarse sediment based on field survey.	Straight translation of percentage score	1.00	10	$y = 10x$
				0.80	8	
				0.60	6	
				0.40	4	
				0.20	2	
				0.00	0	
Large wood (annual)	Visual estimate of the abunance of instream cover provided by large wood from 2006 field surveys (Cole and others, 2006).	Ratio of the quality of large wood rating compared to maximum potential from field survey.	Modified from LimnoTech, Inc. (2006)	1.00	10	$y = -2.4362x^2 + 13.325x - 0.9871$
				0.80	8	
				0.60	6	
				0.40	4	
				0.20	2	
				0.10	0	
Canopy cover (annual)	Visual estimates of percentage if riparian cover recorded with densiometer during 2011 field surveys (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011).	Percentage of overhead canopy vegatation from field survey.	Modified from LimnoTech, Inc. (2006)	1.00	10	$y = 3.8509x^2 + 6.0596x + 0.0365$
				0.85	8	
				0.70	6	
				0.50	4	
				0.25	2	
				0.01	0	

Large Wood (Annual)

Streams that lack large wood often have reduced aquatic species diversity. Scoring for the *large-wood* metric was based on observations provided by Cole and Lemke (2011). Field estimates defined the quality of large wood on a scale of 1–5—where visual ratings of 1 indicated no wood and ratings of 5 indicated abundant woody cover. The raw score of the large-wood metric then was expressed as a ratio of maximum potential (that is, classification value divided by 5). The large-wood metric values were translated into final scores based on natural breaks in the data and final scores were interpolated based on the translator equation presented in table 7. Like other physical metrics, the large wood score was applied to both wet and dry seasons.

Canopy Cover (Annual)

The *canopy-cover* metric was established as a way of representing the quality of riparian vegetation at a given location. Measurements were made in Tualatin River Basin streams with a spherical densiometer by Cole and Lemke (2011). Scoring for canopy cover was based on methods proposed by LimnoTech, Inc. (2006) and represented the percentage of riparian canopy over a particular site. Raw percentage values were converted into final scores based on natural breaks in the data and translated with the equation presented in table 7. Although the amount of canopy cover and leaf bulk density may change seasonally for certain trees, their presence generally remains unchanged. Therefore, values from the canopy-cover metric were applied annually.

Sensitive Macroinvertebrates (Annual)

The *sensitive-macroinvertebrates* metric was quantified as the percentage of the target macroinvertebrate taxa (for example, taxa identified as sensitive) observed at a site compared to the total number of taxa observed. The scoring for sensitive macroinvertebrates was based on field surveys by Cole and Lemke (2011). Percentages of sensitive taxa were assessed through natural breaks in the resultant histograms. See table 8 for more information on conversion of raw values into final scores and the final translation equations used. Values were applied to both wet and dry seasons.

Native Fish (Annual)

The first of the two fish biological metrics, the *native-fish* metric, was used to represent the quantity of native species present at a site. Fish surveys by Cole and Lemke (2011) were used for this assessment. The *native-fish* metric was computed as the percentage of abundance of native fish compared to all fish present during fish surveys. Raw percentage values were translated into final scores based on natural breaks in the data and were converted using the equation in table 8. Values were applied to both wet and dry seasons.

Sensitive Native Fish (Annual)

The second fish metric, *sensitive native fish*, expands the previous *native-fish* metric by providing an assessment of the quality of the native species present. Sensitive fish include lamprey, cutthroat, rainbow trout, and coho (*Schistodesmus lampreyanus*, *Oncorhynchus clarkii*, *O. mykiss*, and *O. kisutch*, respectively) and other salmonids (Hughes and others, 1998). Scoring for the sensitive native-fish metric was computed as the abundance of sensitive native fish divided by the total number of native fish observed at a site. Sculpin species were removed from the analysis because they disproportionately skewed the results and were tolerant to almost any stream condition. Raw values were translated into final scores based on natural breaks in the data and were calculated using the equation in table 8. Values were applied to both wet and dry seasons.

Ranking Results

Category scores for Tualatin River Basin sites were calculated as the geometric mean (GM) of the individual stressor metric scores in each category. The GM is the nth root of the product of numbers (n), defined as:

$$GM = \sqrt[n]{\Pi_{i=1}^{n} S_i} = \sqrt[n]{S_1 S_2 S_3 \cdots S_n} \qquad (1)$$

where the S_i values represent individual stressor metric scores. Using the geometric mean allowed scores to be combined in a way that more clearly highlighted and recognized lower scores. This approach muted higher scores within the same category that otherwise might have overshadowed some of the lower scored metrics that are important for identifying problems. By highlighting the problems and helping to identify the most important stressors, this approach is helpful for ensuring that scores can improve if individual metric scores change as a result of targeted management actions. Category scores can be combined into an overall site score by applying a simple arithmetic mean of the category scores.

Table 8. Biological stressor metrics selected for final sites in the Tualatin River Basin, Oregon.

Metric	Description	Method for deriving raw scores	Source of score translator	Raw score (x)	Translated score (y)	Translation equation
Sensitive macroinvertebrates (annual)	Indictor of the presence of sensitive macroinvertebrate taxa at a site.	Percentage of sensitive macroinvertebrates to all observed macroinvertebrates from the autumn 2010 field surveys (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011).	Data histograms for lowland sampling sites	1.00	10	$y = -5.5633x^2 + 17.007x - 1.4867$
				0.75	8	
				0.50	6	
				0.40	4	
				0.20	2	
				0.10	0	
Native fish (annual)	Indicator of native compared to introduced fish detections at a site.	Percentage of native fish collected compared to all fish collected during autumn 2005 field surveys (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011).	Data histograms for lowland sampling sites	1.00	10	$y = 39.145x^2 - 41.333x + 11.087$
				0.98	8	
				0.95	6	
				0.85	4	
				0.70	2	
				0.50	0	
Sensitive native fish (annual)	Indicator of diversity and quality of native fish (sculpins omitted).	Percentage of sensitive fishes collected during autumn 2005 field surveys, not including sculpins (U.S. Environmental Protection Agency, 2000; Cole and Lemke, 2011)	Data histograms for lowland sampling sites	1.00	10	$y = 10x$
				0.80	8	
				0.60	6	
				0.40	4	
				0.20	2	
				0.00	0	

Stressor Scores for Tributary Sites (2000–12)

Seasonal scores for the four example tributary sites in the Tualatin River Basin were computed with the available data, translated into comparable scores on a 0–10 scale, and combined into overall category scores as a geometric mean (table 9). Most physical and biological samples were collected during the dry season but were replicated for the wet season because they are not expected to vary much seasonally. Where data were absent, values were assigned a "not available" (na) score. Although sufficient water-quality data were available to compute water-quality metric scores for 1990–99, the other categories did not have enough data to compute metric scores for that period; therefore, these scores are restricted to the more recent 2000–12 period.

Stressor scores in the water-quality category generally were higher in the wet season than in the dry season. Of the tributaries, the lowest water-quality scores and the greatest contrast to the other three tributary sites in the wet season were from Fanno Creek, whereas the highest overall water-quality scores were from McKay and Chicken Creeks. During the dry season, each of the four tributaries tended to have low DO scores, with McKay Creek having the highest DO scores. Particularly low scores for the temperature metric were determined for Fanno and Beaverton Creeks in the dry season (table 9).

Scores for all of the tributary sites showed some influences from the hydrology and physical habitat categories (fig. 8). All sites showed some deviation from expected streamflow levels. In particular, lower-than-expected flow during the dry season was determined for McKay Creek, and there was strong evidence of wet season flashiness in the streamflow data at Fanno and Beaverton Creeks. None of the tributary sites scored well on some of the physical-habitat metrics, although Chicken Creek did have a reasonable amount of canopy cover. Beaverton and Chicken Creeks scored poorly on the bank-stability metric, indicating high rates of erosion. Lack of coarse sediment may be an important issue for all these valley bottom streams, and lack of large wood may compound the sediment issue in Chicken Creek.

Biological scores were somewhat variable between the sites. All the sites demonstrated a moderate diversity of sensitive macroinvertebrate taxa. A substantial number of native fish was detected at each site during the fish surveys (Cole and Lemke, 2011); however, most fish were native species that can tolerate a wide range of habitat conditions, such as reticulate and prickly sculpin (*Cottus perplexus* and *C. asper*, respectively). These two sculpin species are less sensitive to habitat degradation than the torrent sculpin (*C. rhotheus*) found in the uplands of the Tualatin River Basin. A good presence of sensitive native fish was detected in McKay Creek. The main sensitive fish detected in surveys were lamprey at McKay and Chicken Creeks, and cutthroat at Chicken Creek.The relative abundance of non-native fish was greatest at the Chicken Creek site and included bluegill (*Lepomis macrochirus*), Pumpkinseed (*L. gibbosus*), and largemouth bass (*Micropterus salmoides*). The Beaverton Creek site had Pumpkinseed, whereas the Fanno Creek site had channel catfish (*Ictalurus punctatus*) and mosquitofish (*Gambusia affinis*). These introduced fish tolerate a range of stressors and thrive in warm, slow-moving channels with silty bottoms.

Comparison of Seasonal Water-Quality Scores for Tualatin River Sites between 1990–1999 and 2000–2012

Seasonal water-quality scores were calculated for 1990–99 and 2000–12 for two Tualatin River sites to provide an example of how this scoring system may be useful for assessing site conditions over time on a large river. Water-quality metrics were selected for this comparison because the water-quality data had the most complete coverage over the entire 1990–2012 period of study. Despite the availability of data, there were still some gaps in the datasets and sampling methods differed between the two periods.

Of the two Tualatin River sites, scores indicated that more stress occured at the downstream Boones Ferry site than at the upstream Dilley location (table 10), with the most severe change being dissolved-oxygen metric scores, especially during the dry periods. Water-quality scores for these two sites generally were similar from the 1990s to the 2000s. The biggest improvements occurred for contaminants, but changes in the timing and amount of streamflow led to a decrease in the DO score at the Boones Ferry site, demonstrating that DO is still a concern in the lower river. Stream temperature during summer remained an issue at Boones Ferry, which is not surprising because dry-season flow and weather conditions have resulted in warm water temperatures at that and other downstream sites for decades. Contaminant issues appeared to improve at both Dilley and Boones Ferry, although some of the improvement in contaminant scores might be related to changes in the sampling program and the types of contaminants included in the laboratory analyses.

Table 9. Summary of seasonal scores using data collected at tributary sites in the Tualatin River Basin, Oregon, 2000–12.

[Tributary site locations are shown in figure 8. Wet and dry seasons are November–April and May–October, respectively. na, not available]

	McKay Creek near Hillsboro		Beaverton Creek at SW 216th Ave.		Fanno Creek at Durham		Chicken Creek near Sherwood	
Metric	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**
Stream flashiness	7.9	7.9	5.7	5.7	4.5	4.5	7.7	7.7
High/low flow	10.0	2.0	8.5	10.0	6.8	7.0	10.0	8.7
Hydrologic score	8.9	3.9	6.9	7.5	5.5	5.6	8.7	8.1
Stream temperature	9.5	5.2	9.5	2.5	8.3	2.4	9.5	6.9
Dissolved oxygen	9.5	4.5	9.5	3.6	8.7	2.6	9.5	2.7
Turbidity	8.3	8.5	7.8	8.5	6.4	7.6	8.4	6.2
Contaminants	9.4	9.1	na	10.0	9.5	9.4	9.4	9.0
Water-quality score	9.2	6.5	8.9	5.3	8.1	4.6	9.2	5.7
Bank stability	4.9	4.9	2.2	2.2	3.5	3.5	1.7	1.7
Coarse sediment	1.0	1.0	1.5	1.5	3.3	3.3	2.2	2.2
Large wood	4.2	4.2	6.3	6.3	4.2	4.2	2.2	2.2
Canopy cover	6.1	6.1	5.1	5.1	6.4	6.4	8.4	8.4
Physical-habitat score	3.3	3.3	3.2	3.2	4.2	4.2	2.9	2.9
Sensitive macroinvertebrates	6.8	6.8	4.2	4.2	5.3	5.3	6.4	6.4
Native fish species	8.9	8.9	8.7	8.7	8.1	8.1	8.0	8.0
Sensitive native fish	7.5	7.5	2.2	2.2	3.7	3.7	1.2	1.2
Biological score	7.7	7.7	4.3	4.3	5.4	5.4	4.0	4.0
Overall	7.3	5.4	5.8	5.1	5.8	5.0	6.2	5.2

Comparison of Seasonal Water-Quality Scores for Tributaries between 1990–99 and 2000–12

As with the 2000–12 tributary data, scores for 1990–99 tended to indicate a greater amount of ecological stress during the dry season (table 11). Comparison of the individual stressor metrics for the two periods indicated that wet season scores for stream temperature, DO, and turbidity were comparable based on available data, except for improved turbidity scores at the Beaverton Creek site. Dry season scores had more variability between the two periods, especially for the McKay and Chicken Creek sites. Discerning temporal changes in the contaminant scores was difficult because of differences in the number of samples and analytes tested.

Given the effect of the contaminant scores on the overall water-quality score, the presence of these compounds was critical in this analysis. The contaminant scores tended to be better during 2000s compared to the 1990s, perhaps reflecting improved water quality with respect to contaminants in surface water. However, comparisons of the contaminant scores over time were inconclusive because of data inconsistency for the contaminants analyzed in water samples during the two periods. Additionally, insufficient data were available to draw meaningful conclusions about contaminants in Beaverton Creek during the wet period in the 2000s. Regardless, the data indicate that these streams still have problems related to temperature and DO in the dry season, and Chicken Creek may still have problems with turbidity.

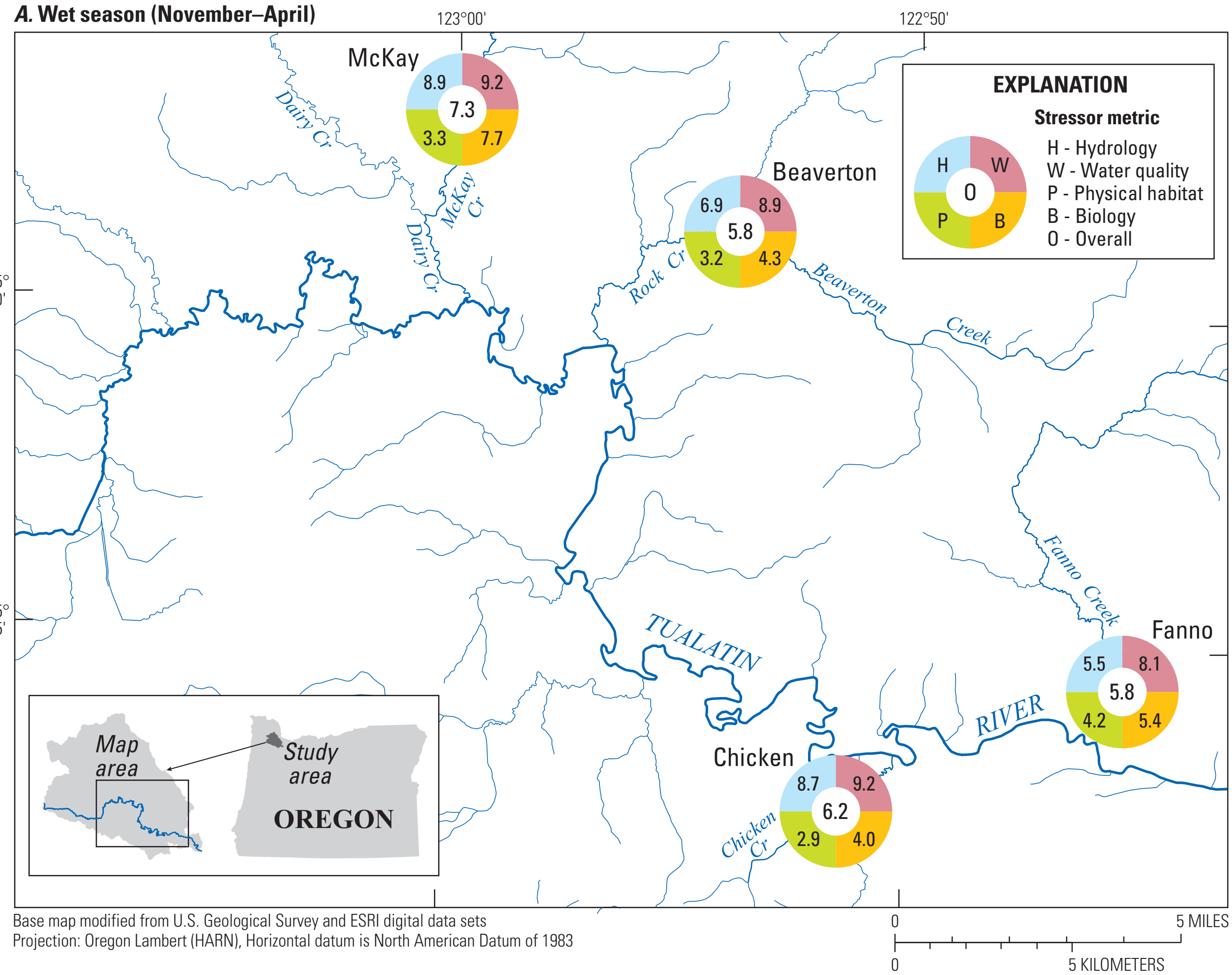

Figure 8. Ecological stressor scores for wet (November–April) (*A*) and dry (May–October) (*B*) seasons using data from four tributary sites in the Tualatin River Basin, northwestern Oregon, 2000–12.

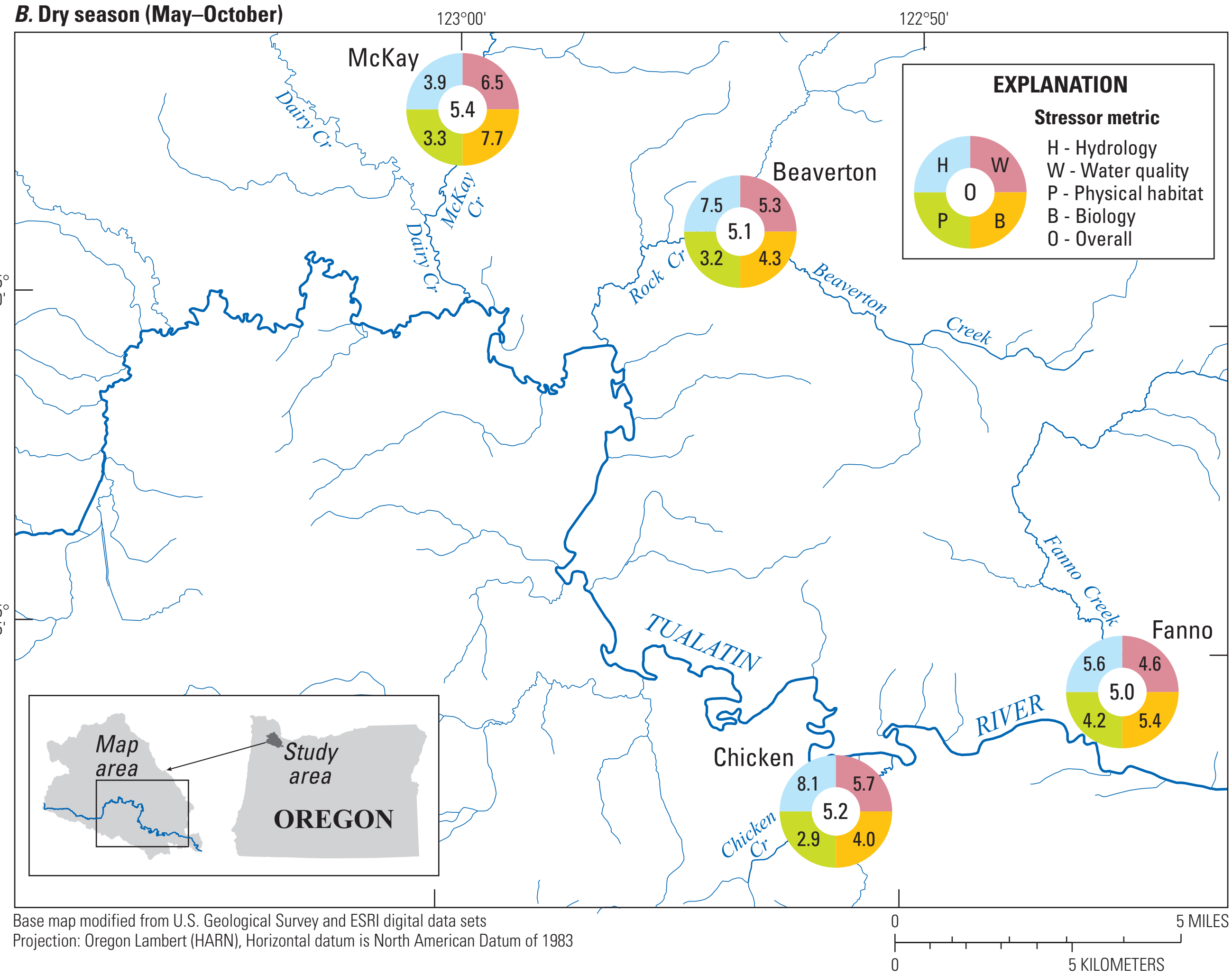

Figure 8.—Continued.

Table 10. Water-quality stressor metric scores comparing data at the two Tualatin River sites, Tualatin River Basin, Oregon, 1990–99 and 2000–12.

[Italic values are score change between decades. Wet and dry seasons are November–April and May–October, respectively. US, upstream river site; DS, downstream river site]

Metric	1990–99				2000–12			
	Tualatin River near Dilley (US)		Tualatin River at Boones Ferry Rd. at Tualatin (DS)		Tualatin River near Dilley (US)		Tualatin River at Boones Ferry Rd. at Tualatin (DS)	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Stream temperature	9.5	9.4	9.5	0.7	9.5	9.4	9.5	0.6
Dissolved oxygen	9.5	9.5	7.7	6.7	9.5	9.5	9.5	4.4
Turbidity	6.9	8.4	6.8	8.3	7.1	8.8	6.4	8.7
Contaminants	5.4	7.2	5.2	6.3	9.6	9.2	9.2	9.5
Water-quality score	7.6	8.6	7.1	4.0	8.8	9.2	8.5	3.9
					(+1.2)	*(+0.6)*	*(+1.4)*	*(-0.1)*

Table 11. Water-quality stressor metric scores comparing data for tributary sites in the Tualatin River Basin, Oregon, 1990–99 and 2000–12.

[Italic values are score change between decades. Wet and dry seasons are November–April and May–October, respectively. na, not available]

Metric	McKay Creek near Hillsboro		Beaverton Creek at SW 216th Ave.		Fanno Creek at Durham		Chicken Creek near Sherwood	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
	1990–99							
Stream temperature	9.5	3.7	9.5	3.3	8.8	2.8	9.5	7.4
Dissolved oxygen	9.5	7.6	9.5	2.3	8.0	3.7	9.5	1.8
Turbidity	9.3	9.1	6.3	8.0	6.0	7.4	8.3	7.5
Contaminants	6.3	3.1	6.6	6.3	5.5	4.1	7.6	3.5
Water-quality score	8.5	5.3	7.8	4.4	6.9	4.2	8.7	4.3
	2000–12							
Stream temperature	9.5	5.2	9.5	2.5	8.3	2.4	9.5	6.9
Dissolved oxygen	9.5	4.5	9.5	3.6	8.7	2.6	9.5	2.7
Turbidity	8.3	8.5	7.8	8.5	6.4	7.6	8.4	6.2
Contaminants	9.4	9.1	na	10.0	9.5	9.4	9.4	9.0
Water-quality score	*9.2*	*6.5*	*8.9*	*5.3*	*8.1*	*4.6*	*9.2*	*5.7*
	(*+0.7*)	(*+1.2*)	(*+1.1*)	(*+0.9*)	(*+1.2*)	(*+0.4*)	(*+0.5*)	(*+1.4*)

Application of Prioritization Framework

The proposed prioritization framework focused on four categories of metrics to separate and identify potential ecosystem stressors related to hydrologic, water quality, physical habitat, and biological indicators. Outlined in this section are (1) ways in which this framework could be applied to help with resource management and restoration prioritization, (2) critical data gaps that will need to be filled to maximize the future use of the framework, and (3) further enhancements that may be implemented to improve the framework and its use in the Tualatin River Basin or other locations.

Linking Site Scores with Habitat Restoration and Conservation Actions

One useful application of the proposed prioritization framework is to categorize sites for protection, restoration, or maintenance based on the level of existing stressors from available data and resulting metric scores and based on knowledge of infrastructural constraints. For instance, sites with scores indicating low stress may merit *protection*, where efforts could focus on preserving already good conditions or making small improvements to conditions at that scale. Sites where scores indicated intermediate stress, particularly where the data or site-specific knowledge showed that scores could be improved, may be targeted for *restoration* and improvement through enhancement efforts. Severely affected sites, where multiple stressors have led to stream degradation and poor ecological health, may be considered for *maintenance* activities to prevent further degradation, support of recreation and education opportunities, and even experimentation with alternative restoration techniques. Sites in the *restoration* category are ideal for management actions, where affordable and feasible mitigation activities likely are to make a measurable difference and reduce ecological stress.

Scores using 2000–12 data indicated that the four tributary sites experienced varying degrees of stress during both wet and dry seasons. Common stresses included sustained flow deviations, flashy streamflow during periods of runoff, contaminant concentrations greater than guidance levels, high stream temperatures and low DO concentrations during summer, and decreased bank stability. Despite these issues, the data revealed that some lowland tributary sites had detections of larval lamprey and cutthroat trout, species that are sensitive to habitat degradation (Hughes and others, 1998). Assessing the site scores and grouping the results into action categories such as protection, restoration, and maintenance may help resource managers and other groups identify and prioritize actions. For instance, the high flashiness associated with the Beaverton and Fanno Creek sites suggest that altered streamflows, which often are associated with bed instability and bank erosion, are an issue that also drives lower scores for physical habitat and other categories. Until a more natural hydrologic response is restored in Beaverton and Fanno Creeks, the effectiveness of various restoration actions addressing habitat, water quality, and biology may be limited. It appears that baseline hydrologic conditions need to be improved to support associated improvements to water quality and biology. In contrast, the intermediate flashiness scores for McKay and Chicken Creeks indicate some stress, but not to the same degree as the Beaverton and Fanno Creek sites. This suggests that the McKay and Chicken Creek sites may benefit from strategies that maintain or decrease existing levels of runoff from impervious surfaces to prevent stresses associated with flashiness. Likewise, several of the sites had contaminant scores that indicated moderate stress. Because contaminants can have lethal effects on fish and wildlife, these sites may benefit from targeted resource management actions that alleviate contaminant levels that exceed aquatic health guidance or regulatory standards. Some actions to improve contaminant scores may include education and outreach, pesticide and drug take-back events, increased or restored riparian buffers, and improved or alternate approaches to stormwater management.

Like some of the tributary sites, it appears that the two Tualatin River sites could benefit from actions that alleviate contaminant levels, as low contaminant scores were important contributors to low overall scores during some time periods. Among other water-quality issues, downstream sites tended to score lower for stream temperature and DO in summer. Wet-season turbidity scores reflect some substantial sediment movement that might be cause for ecological concern. Much of the water quality in the Tualatin River is influenced by flow augmentation. Extra water is released from Hagg Lake in summer months to maintain temperature and DO conditions and alleviate nuisance algal growth.

Potential outcomes of linking site scores and management actions include prioritization of sites where more immediate restoration or other management actions may be cost effective and yield the greatest long-term benefit. Coupling this prioritization framework with other datasets, such as population growth projections and climate change models, would help pinpoint sites that are in relatively good or intermediate health but are in areas with projected population growth and development that may increase ecological stress in the future. Sites meeting these criteria represent important opportunities for near-term management actions. Another outcome might be a system for measuring and tracking site improvements over time and identifying opportunities for adaptive management of restoration programs, where needed. If the ecological system does not respond in expected ways, resource managers and scientists can revisit and update the conceptual framework of ecological stressors in Tualatin River Basin streams, and then reassess the strength of the relations between stressors, management actions, and physical habitat and biological responses.

Prioritization of Data Collection to Fill Data Gaps

After compiling previously collected data for the Tualatin River Basin, it became apparent that important gaps were present in the datasets used for the prioritization framework. For example, there was a disparity between the spatial distribution of the data, as well as the period of record for the data collected between the upland and lowland areas of the basin. In the lowlands, many sites had continuous and long-term streamflow, water quality, fish, and macroinvertebrate data. Conversely, data for upland areas were limited for hydrology, water quality, physical habitat, and biological data. Not only were fewer locations sampled, but the data in the upland areas tended to be discrete rather than continuous. Additionally, given the difference in physiographic setting, upland sites would require different scoring translators than the lowland sites presented in this framework because expectations of the characteristics of the sites and main processes are different from those in the lowlands.

Spatial Data Gaps

Because the physical habitat and biological surveys were available only for the tributary sites, this data gap limited how beneficial the framework could be for the Tualatin River sites. The disparity in data availability made it impossible to compare the composition of fish and macroinvertebrate communities in the Tualatin River with its tributaries and to assess the biological communities. Similarly, physical habitat surveys were more prevalent along the tributaries, but tended not to be frequent enough to capture seasonal or annual changes in the stream morphology.

Generally, water-quality sites along the Tualatin River had a longer and more data-rich history than sites in most of the tributaries. Limited contaminant data were collected throughout the basin, with more data available in urban tributaries than elsewhere. Contaminant data were more readily available for water samples at a variety of sites, but sparse for sediments and biological tissues. Tributaries in the urban areas near Portland, such as Fanno, Rock, and Beaverton Creeks, were sampled and monitored disproportionately more than the rural and forested tributaries in the upper basin.

Temporal Data Gaps

Along with gaps in the locations of data, important gaps also existed in the timing and period of record for the available data. Most of the water-quality, physical, and habitat data available in the Tualatin River Basin was discrete and captured only a single period or condition. This type of discrete data often was collected during the dry summer months; therefore, the dataset was biased toward low-flow conditions. Sampling locations along the Tualatin River tended to have longer-term streamflow record than other sites along the tributaries. No data were collected for physical and biological metrics during the wet winter periods.

Continuous data were available only at a few sites, which primarily included streamflow or water quality. For those that had time-dense data, it was primarily for streamflow or water temperature. Only a few sites had several water-quality parameters measured continuously, such as dissolved oxygen, pH, specific conductance, and turbidity. Among the continuous datasets, some sites had 20 years of continuous data, whereas others had data for a few weeks to a few months. In most cases, the sites with continuous streamflow monitoring also had discrete sampling for a range of parameters.

The discrepancy in the data available for the period of record complicated the scoring system for the prioritization framework. For example, the hydrologic metrics required months to years of data to successfully score—the statistics used simply cannot be calculated without a prolonged period of record. This constraint required a decision about whether a model should be used to fill gaps in the period of record for those sites that did not meet the minimum data period requirement. However, because the framework was merely being tested, the time and expense to build, test, and validate a model were deemed unnecessary. Lastly, many datasets, such as the contaminants, fish surveys, and habitat assessments, were collected only sporadically (for example, contaminants and habitat collected once; fish surveyed three to four times), which led to difficulties in attaining consistency for scoring and weighting each parameter equally. The existing and historical sampling programs were set up to achieve certain purposes but were not necessarily meant to inform and guide a basin-wide assessment of all categories of potential ecosystem stressors. For all these reasons, therefore, future work would benefit from a reassessment of the various monitoring programs with an aim toward a more complete and systematic data-collection schedule if this type of prioritization framework is to be fully utilized.

Data Uncertainty

Another important aspect of this framework is consideration of the inherent error or uncertainties in the data. In such a framework, priorities should be set for whether to use a single data source that has identical or consistent methodology, or to use a mixture of best available data. For simplicity, using a single agency’s habitat survey for all sites in a watershed provides a uniform dataset and a straightforward ranking scheme. However, newer or better data may be available. For example, the habitat data (Cole and Lemke, 2011) used in the Tualatin River Basin prioritization suggested that Fanno Creek had abundant coarse sediment. Another study indicated that Fanno Creek had abundant fine sediment and lacked coarse substrate (Waite and others, 2008). Determining which is correct can be difficult. The Waite and others (2008) study also used a different methodology and had information for only 1 or 2 sites rather than the 20–30 sites presented by Cole and Lemke (2011). Essentially, it is important to consider where the data come from, how the data were collected, and the overall quality of the data before incorporating any dataset into the prioritization framework.

Future Monitoring Locations

Future data-collection efforts would benefit from the establishment of sentinel stations where future population growth, in-fill, or land use change is projected, as these areas may be proposed for change, which could cause a potential increase in ecological stress. Such data are needed to monitor stream health and identify opportunities to increase the effectiveness of management actions that are aimed at protecting streams. For example, based on a qualitative examination of the urban growth boundary and recent additions to that boundary, it is possible to look for monitoring opportunities that might have been missed by current data-collection programs. Based on this type of analysis, a few locations that might be useful for monitoring recent changes may include Gales Creek near the urban growth boundary near Forest Grove, McKay Creek upstream of the North Plains urban growth boundary, and Cedar Creek upstream and downstream of the urban growth boundary near Sherwood. Alternatively, it is possible to use the change in land cover between 2001 and 2011 to identify potential monitoring sites near areas of recent infill and land development. Most land-cover change over that period seems to have been along the forested uplands, or near the urban growth boundary.

Next Steps for Implementing the Prioritization Framework

To improve on this version of the prioritization framework, the following steps have been identified that would be helpful for refining future applications.

- **Compare site scores with observed site conditions**. Does a low score using this proposed system truly indicate the presence of significant ecological stress at a particular site, as evidenced in the presence or health of the biological communities? Such comparisons would be helpful for assessing the performance of the framework, identifying key local stressors that may warrant inclusion in the framework, and making refinements to the existing framework. Scoring translators can be adjusted, and different metrics can be selected to optimize estimates that have strong ties to the prioritization or effectiveness of potential management actions.

- **Create and maintain a centralized data repository**. To score sites, more robust and varied data are required from multiple sources and the scoring process would be efficient if all such data were brought together in a way that makes it easy to access and use. Water-quality and streamflow data often come from different agencies, such as the USGS National Water Information System (U.S. Geological Survey, 2013), Oregon Water Resources Department, ODEQ, and other organizations. Contaminant data come from numerous published USGS studies and from ODEQ. Macroinvertebrate, fish, and habitat data are from Cole and Lemke (2011) or other special studies and surveys. Gathering these disparate sources of data together is a labor-intensive exercise. A large quantity of data has been collected in the Tualatin River Basin. Creation of a central data repository would make data queries and future refinements and applications of this prioritization framework more efficient. Increased data accessibility and quality control has many relevant and long-term benefits outside of this effort, including helping partners detect trends in the basin over time and changes associated with restoration and management actions.

- **Coordinate monitoring efforts among agencies.** One important obstacle to applying this framework broadly across the Tualatin River Basin is that the same datasets are not collected at all sites. This is understandable because multiple groups and agencies collect data in the basin, and each organization has different missions, funding constraints, and monitoring objectives. If all groups doing monitoring were to agree that the creation of an optimized dataset for application in this prioritization framework was a useful goal of their monitoring program, then subsequent coordination of monitoring among groups might lead to more uniform and comprehensive datasets and more complete scores to prioritize management and restoration activities (Puls and others, 2014).

- **Include multiple tiers in the framework**. The prioritization framework and scoring system outlined in this study focuses on specific sites in the stream network where field measurements are available. Scaling up the site-level information to reach-scale sections of streams could provide valuable insights and prioritization information for stream restoration and management. Similarly, scaling up even farther to a watershed scale and using GIS data correlated to site data could provide large-scale comparisons of the health of individual tributaries to complement and reinforce the site-level information. Identifying those broad-scale GIS datasets that are strongly connected to site-level stressor information would allow watershed-scale projections of stream health and ecological stress to be made for stream reaches where data have not yet been collected.

- **Refine the framework as new data or standards become available**. This framework conceptualizes the current understanding of riverine ecosystem stressors in the Tualatin River Basin. As data on local stressors, future development patterns, and climate change become available and as water-quality standards are updated or added, refinement to the scoring metrics and stressor indicators may be warranted. For example, wetland spatial datasets, such as those for the Willamette valley (Adamus and others, 2010), may be important to include in a future version of the framework because historical draining of wetlands contributes to less water retention and organic matter processing, as well as greater instream peak flows.

- **Refine scoring translators**. The scoring translators for the various metrics likely will need refinement to ensure that the ranges in scores across the landscape define clear and measurable differences. Such refinements would include the development of a complimentary scoring system for upland sites, as more upland data become available. Insufficient hydrologic, water-quality, physical habitat, or biological data are currently available to develop an upland scoring translator.

- **Balancing continuous and discrete data**. Continuous water-quality monitoring data, such as temperature and DO, have water-quality standards that are different from those used with discrete samples. For example, continuous DO data for a cool-water stream must meet all of three separate criteria as described in “Dissolved Oxygen (Wet/Dry Seasons)” earlier, whereas discrete

DO samples are required to meet only one criterion. Harmonious methods for evaluating continuous and discrete data need to be identified for several of the framework metrics in order to integrate the available continuous data into one uniform framework.

- **Applying the framework**. A primary reason to create this prioritization framework is to provide a tool for resource managers to better assess the ecological health of streams and then prioritize potential actions. To that end, it would be helpful to incorporate a more comprehensive translation of score to action within a feedback loop. Envision an adaptive-management process in which (1) the scores are generated, (2) the scores are assessed to determine whether potential targeted actions are likely to result in significantly improved scores, (3) specific actions are prioritized based on many factors including the potential measurable benefit to the stream ecosystem, (4) the result is measured and compared to the expected change, and (5) the scoring framework is adjusted to incorporate the result. Scores therefore, help to identify stressors, stressors are used to prioritize actions, actions are targeted to cause improvement in scores, and actions are linked to potential benefits. Adaptive management of the process helps to refine goals, data-collection activities, effectiveness monitoring, and adjustments to the prioritization framework.

Summary

A prioritization framework is proposed herein to identify, score, and rank ecosystem stressors using example sites in the Tualatin River Basin. This framework is meant to provide resource managers with a tool to identify problems and aid in management and restoration strategies. This report focuses on scoring four tributary sites and two main-channel sites in the Tualatin River Basin. The framework scored 13 environmental metrics drawn from available hydrologic, water-quality, physical habitat, and biological data for 1990–2012. Metrics were selected as indicators of potential ecological stress and include measures of the deviation of sustained flow from expected conditions, natural stream response to storms, violations of water temperature and dissolved-oxygen standards, exceedances of contaminant criteria, bank stability, quality of large wood habitat, and macroinvertebrate community, among others. The scoring method for each of these metrics was based on the development of new techniques, as well as methods previously documented. To assess variability and potential trends, water-quality data were analyzed for Tualatin River and tributary sites separately for wet (November through April) and dry (May through October) seasons, as well as assessed by decade (1990–99 and 2000–12). The tributary sites were assessed for all stressors for 2000–12 for both wet and dry periods. Raw stressor metric results were translated into scores that ranged from 0 to 10, with the higher scores corresponding to higher quality and healthier environments.

Generally, urban streams such as Fanno and Beaverton Creeks revealed their degree of impairment through poorer scores. Streams with a predominant agricultural land use, such as Chicken and McKay Creeks, fared somewhat better than urban streams. The upper reaches of the Tualatin River scored healthier than the lower reaches. Data were insufficient in the 1990s to evaluate overall trends, so only water-quality metrics were compared between the 1990s and the 2000s. The results indicate that, based on the available data and the selected metrics, water-quality conditions have improved slightly between 1990 and 2012, mostly due to an improvement in contaminant scores, but challenges remain with warm water temperatures and low DO conditions. Many sites suffer from unstable banks, altered hydrology, and shifts in fish communities toward more tolerant and less native populations.

The prioritization framework can be applied as a management tool for stakeholders in the basin. The framework highlights areas where different habitat restoration and conservation actions may be implemented. For example, some sites may benefit from protection, others may require restoration, and some may only merit maintenance due to their level of degradation. The framework can be used to identify these categories of sites, as one mechanism for beginning the process of prioritizing and targeting management actions.

Although this document describes a prioritization framework and uses sites in the Tualatin River Basin as examples, it would still benefit from further development based on additional data. Some important data gaps were found during this study and filling these data gaps would make the framework more robust and useful. Limited data were available in areas in the upland parts of the Tualatin River Basin. Some long-term data tended to be scarce. Some sites had continuous data, whereas others had only discrete samples. Harmonious methods need to be developed to take advantage of some of the continuous water-quality data. Regardless, an important benefit of this framework is that it highlighted some of the spatial and temporal data gaps and can provide guidance to where future monitoring would be beneficial.

The next steps for implementing the prioritization framework likely will include comparing site scores with observed site conditions to verify and refine the meaning of the scores, expanding the framework to include multiple spatial scales, possibly balancing how to best apply continuous and discrete data, greatly expanding upon the number of sites that are scored, and making stronger connections between scores and potential management actions. Currently, the framework provides value by showing when and where ecosystems are likely to be healthy, where they are not, and what factors may be responsible for the disparity. However, the framework was designed with the flexibility to evolve as new information becomes available and as it is implemented and adopted by resource managers.

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Appendix 1. Prioritization Framework Ranking and Raw Scores

The prioritization framework presents final translated scores for the four tributary and two Tualatin River sites that were assessed in this study. The preliminary ranking and raw scores of the data, however, were not included. The actual raw scores for each site based on the best available data used in this study are presented in tables 1-1, 1-2, and 1-3.

Table 1-1. Ecosystem stressor metric raw scores based on 2000–12 data from four tributary sites in the Tualatin River Basin, Oregon.

[na, not applicable]

	McKay Creek near Hillsboro		Beaverton Creek at SW 216th Ave.		Fanno Creek at Durham		Chicken Creek near Sherwood	
Metric	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Stream flashiness	0.79	0.79	0.57	0.57	0.45	0.45	0.77	0.77
High/low flow	>1.00	0.43	0.97	>1.00	0.85	0.87	>1.00	0.98
Stream temperature	1.00	0.84	1.00	0.70	0.96	0.69	1.00	0.91
Dissolved oxygen	1.00	0.81	1.00	0.77	0.98	0.71	1.00	0.71
Turbidity	0.92	0.94	0.88	0.93	0.76	0.87	0.93	0.74
Contaminants	0.94	0.91	na	1.00	0.95	0.94	0.94	0.90
Bank stability	0.61	0.61	0.33	0.33	0.47	0.47	0.27	0.27
Coarse sediment	0.10	0.10	0.15	0.15	0.33	0.33	0.22	0.22
Large wood	0.42	0.42	0.62	0.62	0.42	0.42	0.25	0.25
Canopy cover	0.69	0.69	0.60	0.60	0.72	0.72	0.88	0.88
Sensitive macroinvertebrates	0.61	0.61	0.38	0.38	0.47	0.47	0.57	0.57
Native fish species	1.00	1.00	0.99	0.99	0.98	0.98	0.97	0.97
Sensitive native fish	0.75	0.75	0.22	0.22	0.37	0.37	0.12	0.12

Table 1-2. Water-quality stressor metric raw scores comparing 1990–99 and 2000–12 data for four tributary sites in the Tualatin River Basin, Oregon.

[na, not applicable]

	1990–99							
	McKay Creek near Hillsboro		Beaverton Creek at SW 216th Ave.		Fanno Creek at Durham		Chicken Creek near Sherwood	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Stream temperature	1.00	0.77	1.00	0.75	0.98	0.72	1.00	0.93
Dissolved oxygen	1.00	0.93	1.00	0.69	0.95	0.77	1.00	0.65
Turbidity	1.00	0.98	0.75	0.89	0.72	0.85	0.92	0.85
Contaminants	0.63	0.31	0.66	0.63	0.55	0.41	0.76	0.35
	2000–12							
Stream temperature	1.00	0.84	1.00	0.70	0.96	0.69	1.00	0.91
Dissolved oxygen	1.00	0.81	1.00	0.77	0.98	0.71	1.00	0.71
Turbidity	0.92	0.94	0.88	0.93	0.76	0.87	0.93	0.74
Contaminants	0.94	0.91	na	1.00	0.95	0.94	0.94	0.90

Table 1-3. Water-quality stressor metric raw scores comparing 1990–99 and 2000–12 data for two Tualatin River sites in the Tualatin River Basin, Oregon.

	1990–99				2000–12			
	Tualatin River near Dilley		Tualatin River at Boones Ferry Rd. at Tualatin		Tualatin River near Dilley		Tualatin River at Boones Ferry Rd. at Tualatin	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Stream temperature	1.00	1.00	1.00	0.53	1.00	1.00	1.00	0.52
Dissolved oxygen	1.00	1.00	0.94	0.90	1.00	1.00	1.00	0.80
Turbidity	0.80	0.93	0.79	0.92	0.82	0.97	0.76	0.95
Contaminants	0.54	0.72	0.52	0.63	0.96	0.92	0.92	0.95

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