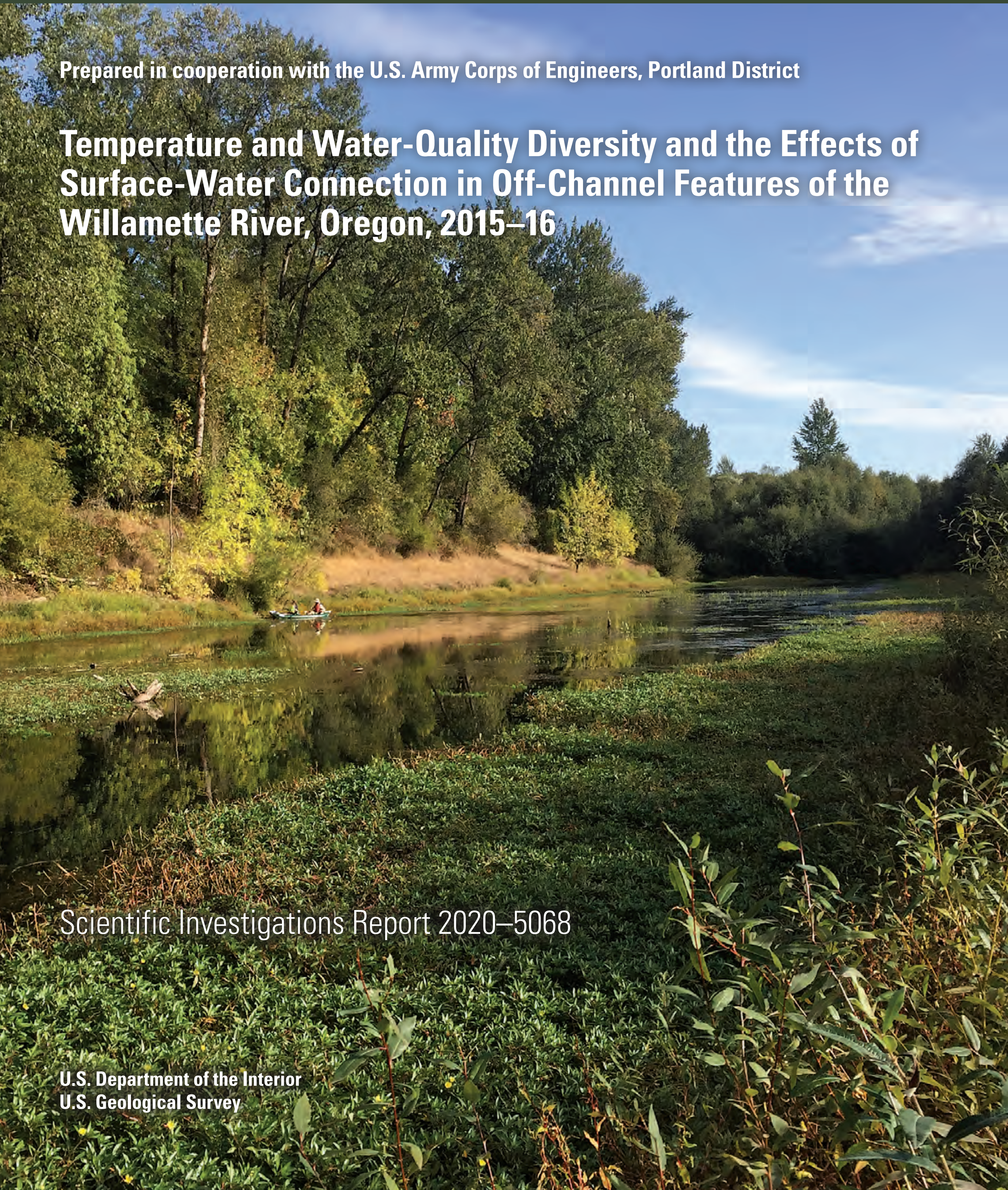
Prepared in cooperation with the U.S. Army Corps of Engineers, Portland District

Temperature and Water-Quality Diversity and the Effects of Surface-Water Connection in Off-Channel Features of the Willamette River, Oregon, 2015–16



Scientific Investigations Report 2020–5068

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

Cover. View looking southeast at off-channel feature on right bank of Willamette River, at river mile 107.5, about 12 miles downstream from Albany, Oregon. Photograph by Joseph Mangano, U.S. Geological Survey, October 6, 2015.

Temperature and Water-Quality Diversity and the Effects of Surface-Water Connection in Off-Channel Features of the Willamette River, Oregon, 2015–16

By Cassandra D. Smith, Joseph F. Mangano, and Stewart A. Rounds

Prepared in cooperation with the U.S. Army Corps of Engineers, Portland District

Scientific Investigations Report 2020–5068

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

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2020

Suggested citation:
Smith, C.D., Mangano, J.F., and Rounds, S.A., 2020, Temperature and water-quality diversity and the effects of surface-water connection in off-channel features of the Willamette River, Oregon, 2015–16: U.S. Geological Survey Scientific Investigations Report 2020–5068, 70 p., https://doi.org/10.3133/sir20205068.

ISSN 2328-0328 (online)

Contents

Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

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

$$°F = (1.8 \times °C) + 32.$$

Datums

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

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

Supplemental Information

Streamflow is measured, reported, and widely used in units of cubic feet per second (ft^3/s) by resource managers and water agencies in the Willamette River Basin; therefore, cubic feet per second is used in this report. Reaches and sites in this report are referenced to river miles (RM) from U.S. Geological Survey topographic maps. All other units in this report and associated data releases are reported in the International System of Units (metric).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

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

Abbreviations

7dADM	seven-day moving average of the daily maximum
CWR	cold-water refuge
>	greater than
≥	greater than or equal to
<	less than
≤	less than or equal to
lidar	light detection and ranging
NWIS	National Water Information System
OAR	Oregon Administrative Rule
PDT	Pacific daylight time
PVC	polyvinyl chloride
RM	river mile
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
YSI	Yellow Springs Instruments

Acknowledgments

The authors thank the U.S. Army Corps of Engineers (USACE) for their support and assistance in this study. Norman Buccola, previously with the U.S. Geological Survey (USGS), was instrumental in the early phases of this project and both field seasons of data collection. Dave Piatt (USGS) was key in all field efforts as well as data processing for many of the continuous water-temperature sensors installed. Field assistance for synoptic data collection was also provided by David Weathers, Heather Bervid, Chauncey Anderson, Brandon Overstreet, Mackenzie Keith, Tess Harden, Alex Costello, Erin Poor, and James White (USGS), and Dan Turner (USACE). Krista Jones and Rose Wallick (USGS) assisted with this study through helpful discussions and feedback.

Temperature and Water-Quality Diversity and the Effects of Surface-Water Connection in Off-Channel Features of the Willamette River, Oregon, 2015–16

By Cassandra D. Smith, Joseph F. Mangano, and Stewart A. Rounds

Executive Summary

Water-quality conditions (including temperature) in the Willamette River and many of its adjacent off-channel features, such as alcoves and side channels, were monitored between river miles 67 (near Salem, Oregon) and 168 (near Eugene, Oregon) during the summers of 2015 and 2016. One or more parameters (water temperature, dissolved oxygen, pH, specific conductance, and [or] water depth) were continuously measured at sites in the main channel (9 sites in 2015; 5 sites in 2016) and select off-channel features (20 features in 2015; 22 features in 2016). Multiple point measurements also were collected in the continuously monitored features and in a variety of other off-channel features to supplement the continuous datasets and provide longitudinal and depth-specific water-quality information.

This study was initiated in reaction to the unusually warm, dry weather and resulting low streamflows that occurred in the Pacific Northwest in 2015 and the need for flow managers to understand the effects of streamflow on water-quality conditions in off-channel features of the Willamette River. Field monitoring for this study was focused on documenting water-quality conditions during low summer streamflows and during fluctuations in streamflow, including when side channels (connected to the main channel at the upstream and downstream ends) became alcoves (connected to the main channel only at the downstream end) and reconnected to become side channels again. These field surveys provided extensive spatial and temporal datasets that were previously lacking for this river system.

Water in the main channel of the Willamette River upstream from river mile 50 near Newberg typically is well mixed during summer (June–August), with warm water temperatures (greater than 18 degrees Celsius) and high dissolved-oxygen concentrations (often greater than 7.7 milligrams per liter). In 2015 and 2016, water temperatures measured in the main channel near Salem, Independence, and Harrisburg (river miles 70.2, 97.7, and 161/164.2, respectively) did not meet the State of Oregon's maximum water-temperature standard of 18 degrees Celsius for the protection of fish rearing and migration. Continuous dissolved-oxygen concentrations measured in the main channel near Independence met the State of Oregon 7-day minimum mean cold-water criterion of 6.5 milligrams per liter throughout the 2016 monitoring period, and instantaneous values during summer ranged from 8.0 to 10.5 milligrams per liter. Point measurements throughout the study reaches in 2016 also showed dissolved-oxygen concentrations in the main channel were consistently greater than 7.0 milligrams per liter. Other water-quality parameters (specific conductance and pH) also were measured in the main channel near Independence in 2016, but results are not extensively discussed in this report.

During low summer flows, a diverse suite of off-channel features such as side channels and alcoves exist adjacent to the main channel of the Willamette River; these features vary substantially in size, morphology, and connection to the main channel. Water quality in off-channel features was found to be heterogenous, and differences were measured vertically, longitudinally, seasonally, and among features. Despite temporal and spatial variability within individual features, comparison of continuous water-temperature data between the main channel and off-channel features revealed that some off-channel features were consistently cooler than the main channel, some were consistently warmer than the main channel, and others fluctuated between warmer or cooler than the main channel. The temperature of some off-channel features responded quickly to changes in the weather and to changes in main-channel temperatures, whereas other features reacted more slowly. Site-specific characteristics including upstream connection, depth, and presence or absence of aquatic or riparian vegetation were factors that seemed to affect the water quality of a feature.

Overlaying continuous water-quality data measured in an off-channel feature with main channel streamflow revealed that the surface-water connections between the main channel and off-channel feature exert important controls on water-quality conditions in off-channel features. Connections to the main channel at the upstream and downstream ends are controlled by the geomorphology of the off-channel feature and the streamflow of the river; during low summer flows, many off-channel features become disconnected at the upstream end from main-channel surface-water flow. Monitored off-channel features that were disconnected at the upstream end for multiple months tended to have large quantities of aquatic vegetation, vertical stratification of water-quality parameters, and cool water temperatures and low (hypoxic or anoxic) dissolved-oxygen concentrations in the deeper parts of the water column. Off-channel features that remained partially connected to upstream surface-water inflow were affected by the warm, oxygenated main-channel inputs; water-quality patterns differed per feature, which was likely related to the amount of main-channel water entering at the upstream connection. Partial or complete disconnection at the upstream end helped reveal other factors (biological processes, subsurface inputs [groundwater/hyporheic]) that affect a feature's water quality, although quantifying the magnitude of these effects was beyond the scope of this study.

Results from this study showed a relation between the geomorphology, hydrology, ecology, and water quality (including temperature) of an off-channel feature. In off-channel features that became disconnected from upstream surface-water inputs from the main channel during summer, water quality was largely affected by local factors and different from the main channel. Downstream of Corvallis (river mile 131), extensive communities of invasive aquatic vegetation have become established in many off-channel features where frequent scouring is absent, and these plant communities affect water quality through physical and biological processes (for example, shading, respiration, and photosynthesis). Data from this study confirmed previous findings that many features that can be classified as cold-water refuges based on water temperature standards established by Oregon Department of Environmental Quality also contained low concentrations (less than 4 milligrams per liter, and in many cases less than 2 milligrams per liter) of dissolved oxygen, which are conditions that may not be suitable for sensitive fish species.

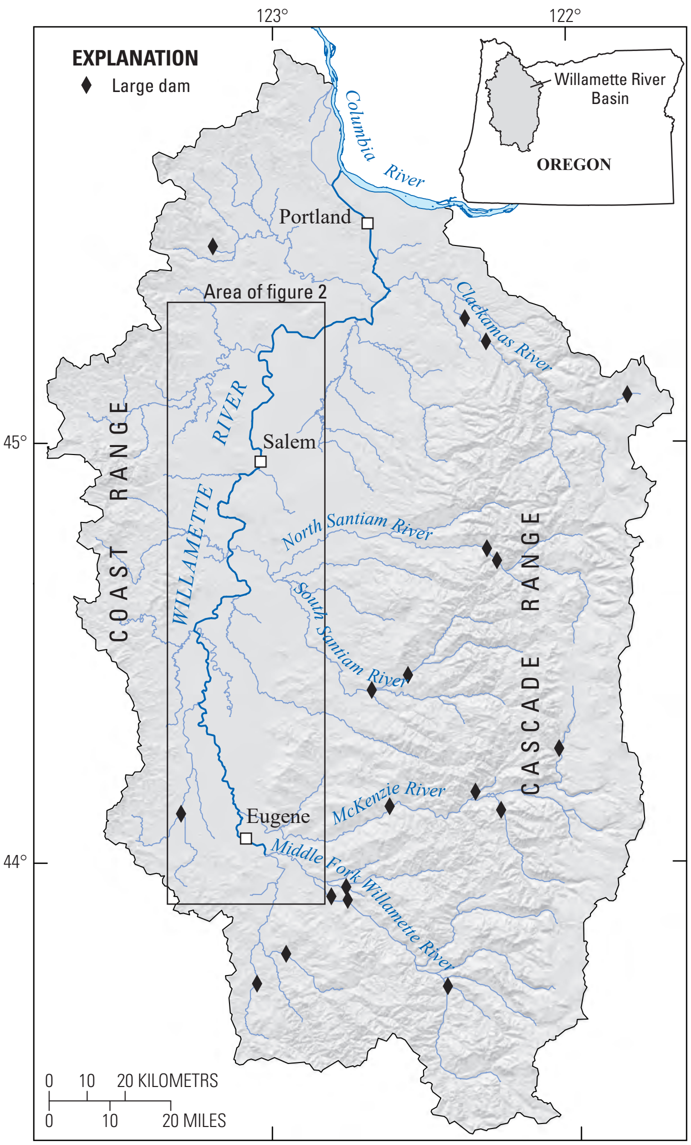
This study documents (1) key differences in water quality within and among off-channel features of the Willamette River during summer, and (2) the important effect of flow variations and main-channel connections on off-channel water quality. Based on data from this study, a simplified site classification scheme is proposed that links water-quality conditions in measured off-channel features with site-specific characteristics and summer streamflows. The Willamette River has a diverse array of off-channel features, however, and only a subset was measured during this study. Therefore, the site classification scheme was extended to create a theoretical process matrix that relates measured water-quality conditions (for example, cool water and low oxygen) to a list of the processes and site-specific characteristics that could create those conditions. This matrix allows researchers and resource managers to think critically about the processes (potentially competing) that may be occurring in off-channel features and to form hypotheses regarding how site-specific characteristics affect water-quality conditions. Future refinements to the proposed site classification scheme and theoretical process matrix could be made by collecting additional information on spatial and temporal water-quality heterogeneities within off-channel features under various flows by quantifying key processes that move water and heat through these systems and by studying the effects of biological processes on water quality.

Introduction

Riverine ecosystems with aquatic thermal diversity allow fish species with differing life histories and thermal requirements to coexist. The Willamette River within the Willamette River Basin in northwestern Oregon (fig. 1) is one such system that is home to native warm-water and cool-water fishes. Native species that tolerate warm water temperatures include the endemic Oregon chub (*Oregonichthys crameri*) and redside shiners (*Richardsonius balteatus*), among others, which are often found in off-channel features (Williams and others, 2014). Native fish species requiring cool water during one or more life stages include spring Chinook salmon (*Oncorhynchus tshawytscha*), cutthroat trout (*O. clarkii*), and winter steelhead (*O. mykiss*; Williams and others, 2014). The anadromous populations of these fishes rear in streams, migrate to the ocean, and then return to their natal stream to reproduce.

Anadromous fish in the Willamette River face a multitude of stressors such as habitat modification (Wallick and others, 2013), migration barriers, disease, and altered water temperatures (National Marine Fisheries Service, 2008; Rounds, 2010). Thermal requirements can be complex and depend on the species (Brett, 1952), population/race (Sauter and others, 2001), and gender of the fish (Jeffries and others, 2012). A wide range of published research has documented many effects of warming water temperatures on salmonids including smaller juveniles (Murray and McPhail, 1988), higher adult mortality during migration (Martins and others, 2011), shifts in migration timing (Quinn and Adams, 1996), and increased susceptibility to infectious diseases (Fryer and others, 1976). Upper Willamette River Chinook salmon and Upper Willamette River steelhead are listed as threatened under the Federal Endangered Species Act of 1973 (Public Law 93–205, 87 Stat. 884, as amended), which has led to water-quality regulations, flow and temperature management actions, and population monitoring to foster their survival (National Marine Fisheries Service, 2008).

The Willamette River has been designated as temperature-impaired and listed under Section 303(d) of the Clean Water Act (Public Law 92–500, 33 U.S.C. §1251 et seq. [1972]). The State of Oregon sets temperature standards for its major waterbodies to aid native fishes and protect aquatic life (Oregon Administrative Rule [OAR] 340–041–0028(4); Oregon Department of Environmental Quality, 2016a). For the Willamette River, the maximum allowed water temperature depends on the time of year and the location, corresponding to how and when sensitive fish species use particular river reaches (Oregon Department of Environmental Quality, 2003, 2005). Reaches upstream from Newberg, Oregon (river



Base from 2012 U.S. Geological Survey 100-meter digital data. Coordinate system: UTM Zone 10 North, North American Datum of 1983

Figure 1. The Willamette River Basin and large dams, northwestern Oregon.

mile [RM] 50; fig. 2), have a summer (May 16–October 14) temperature requirement of 18 degrees Celsius (°C) or less, calculated as the 7-day moving average of the daily maximum (7dADM), to protect fish rearing and migration uses. During the salmon and steelhead spawning period (October 15–May 15), the standard for Willamette River reaches upstream from Newberg requires the 7dADM to be 13 °C or less. The lowermost 50 RM of the Willamette River from Newberg to its confluence with the Columbia River are designated as a migration corridor, and the temperature standard requires a 7dADM of 20 °C or less year-round. The Oregon Department of Environmental Quality wrote a narrative water-quality standard for cold-water refuges (CWRs) that recognizes the need to protect species habitat and to minimize additional anthropogenic warming when the 7dADM criterion is exceeded. This CWR narrative technically only applies to designated migration corridors such as the lower 50 RM of the Willamette River, but it is commonly referenced by researchers as a useful definition for CWRs in the Willamette River system. The definition is written as follows:

> "Cold Water Refugia" means those portions of a water body where or times during the diel temperature cycle when the water temperature is at least 2 degrees Celsius colder than the daily maximum temperature of the adjacent well-mixed flow of the water body (OAR 340–041–0002(10); Oregon Department of Environmental Quality, 2016b).

Water temperatures in the Willamette River commonly exceed the water-temperature standard's rearing and migration criterion during parts of summer. At the Willamette River at Albany, Oregon, streamgage (U.S. Geological Survey [USGS] station 14174000, RM 119; fig. 2), temperatures reached greater than (>) 21 °C (7dADM) in June 2015. The unusually warm water temperatures followed an exceptionally low snowpack in 2015 (Mote and others, 2016) and low summer streamflow. High water temperatures may increase the importance of CWRs for the survival of sensitive cool-water fishes throughout the Willamette River.

Although water temperature is critical to fish health, fish also require other adequate water-quality conditions to survive and thrive. As with water temperature, dissolved-oxygen requirements for fish species are complex and not fully understood. However, salmonids are susceptible to low dissolved-oxygen concentrations (Carter, 2005), and high mortality was observed when salmonids were held in hypoxic (low oxygen) conditions for 24 hours (Doudoroff and Shumway, 1970). Dissolved-oxygen concentrations near or slightly above 2 milligrams per liter (mg/L) have been associated with behavioral changes and diminished swimming speeds (Davis, 1975), and effects of low dissolved oxygen may be exacerbated as the water temperature increases (Davison and others, 1959). The State of Oregon's dissolved-oxygen criteria differ to protect various types of aquatic species. For example, the cold-water dissolved-oxygen criterion applies to waterbodies where salmonids and other cold-water species exist during most of year and specifies a 7-day minimum mean of 6.5 mg/L (Oregon Department of Environmental Quality, 2016c, table 21). The cool-water criterion protects native cool-water fishes (such as sculpin, smelt, and lamprey) with a 7-day minimum mean of 5.0 mg/L (Oregon Department of Environmental Quality, 2016c, table 21). The main channel Willamette River is generally not dissolved-oxygen impaired (Pogue and Anderson, 1995). However, past studies from the Willamette River and other riverine systems in Oregon have shown that areas classified as CWRs can have dissolved-oxygen gradients (vertical and longitudinal) and often have low dissolved-oxygen concentrations (less than [<] 3 mg/L; Ebersole and others, 2003; Gregory and Wildman, 2016).

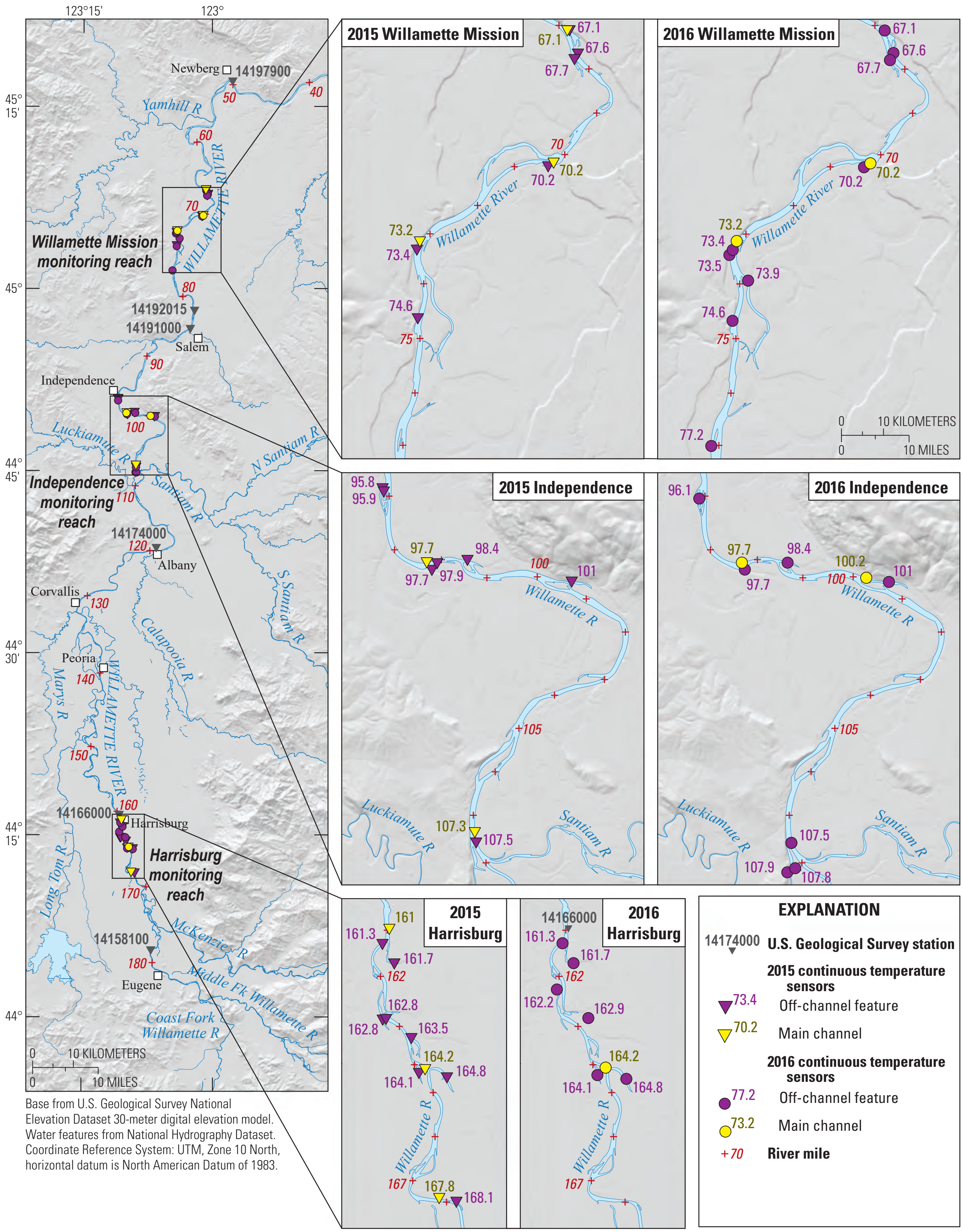


Figure 2. Study reaches and water-temperature monitoring sites along the Willamette River, Oregon, in 2015 (August–October) and 2016 (May–October).

CWRs can exist at a variety of locations within a river system, including alcoves, side channels, tributary junctions, deep pools, and seeps along a riverbank (Torgersen and others, 2012). The Willamette River between Eugene and Newberg, Oregon, is a wide river with some dynamic reaches containing many side channels, alcoves, and gravel bars. However, historical practices of wood removal, bank stabilization, and flow management have disrupted natural processes that create and maintain off-channel features that may function as CWRs (Wallick and others, 2013). Additionally, the large sizes of Willamette River off-channel features affect how they function as CWRs; for example, thermal variability is common within a single feature. Gregory and others (2008) determined that most CWRs in the Willamette River system are in alcoves and tributary junctions; however, it is not clear how CWR temperatures vary during the summer. A network of CWRs along a river system may allow fish to migrate upstream or downstream from cold patch to cold patch during otherwise warm conditions, thereby enhancing their survival (Gregory and others, 2008).

Changes in main-channel streamflow, largely resulting from flow modifications at upstream dams, affect the main channel and off-channel features (fig. 3). Off-channel features typically remain connected to the river at the downstream end. A variety of subsurface flow paths may connect the main channel to the off-channel features, likely at all flows. During periods of high streamflow (often autumn through spring), off-channel features are connected to the main channel through surface flow at their upstream and downstream extent (fig. 3*D*), causing most off-channel features in the Willamette River to function as side channels during high streamflows. As streamflow increases from low to high, surface water typically will enter the feature at its downstream end before a connection forms with the main channel at its upstream end (fig. 3*C*). During low summer streamflows, off-channel features either disconnect at the upstream end (alcoves) or remain connected at the upstream end with various amounts of flow (side channels); the presence or absence of an upstream connection depends on the height of the landmass at the upstream connection point and stage in the main channel (figs. 3*A*–*C*). Minimum streamflows in the Willamette River from April to October are managed to meet or exceed flow objectives specified in the 2008 Biological Opinion (National Marine Fisheries Service, 2008). Flow objectives for the Willamette River are often exceeded in April and May due to unregulated inputs (snowmelt and runoff) from tributaries, but flow objectives were not met in the spring and early summer of 2015.

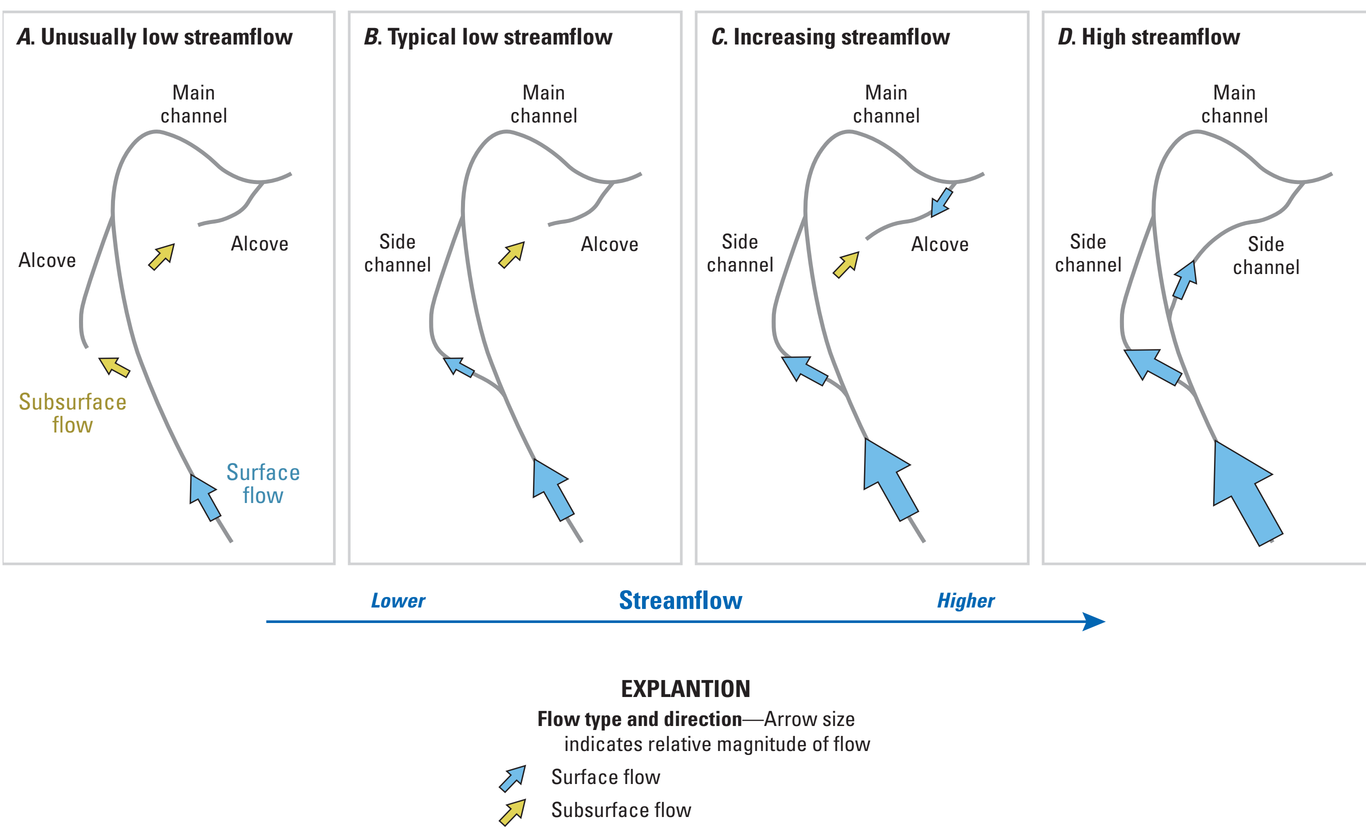


Figure 3. Surface and subsurface flow paths of off-channel features of a river at various streamflows. *A*, unusually low streamflow. *B*, typical low streamflow (typical summer flows in the Willamette River, Oregon). *C*, increasing streamflow. *D*, high streamflow.

Off-channel features receive inputs of water from main-channel surface flow and through subsurface inputs; the quantity and physical properties of water inputs to an off-channel feature affect local temperature and dissolved-oxygen concentrations. Surface-water flow includes inputs from the upstream connection of features, tributary or other discrete inputs, or backwater from downstream connections. The temperature difference between surface-water inputs and an off-channel feature can vary greatly, contributing to either warming or cooling in an off-channel feature. Subsurface inputs occur when water traveling through river-bed gravels or near-river floodplain gravels exits the subsurface and enters the surface water (Fernald and others, 2001). Subsurface water gains and losses can affect stream temperatures and their diel patterns (Burkholder and others, 2008). Flow path length and residence time can affect subsurface water temperature, diel fluctuation magnitude, or daily peak timing (Arrigoni and others, 2008; Burkholder and others, 2008; Poole and others, 2008). Subsurface inputs with a long flow path tend to be cooler than main-channel water in summer and have minimal diel fluctuations (Poole and others, 2008). Similar to temperature, inputs of subsurface or main-channel water into an off-channel feature can also affect dissolved-oxygen concentrations and other water-quality parameters (Runkel and others, 2003). Subsurface dissolved-oxygen concentrations are often low (Ebersole and others, 2003; Hinkle and others, 2014), potentially revealing areas of input. Upstream dam operations that control streamflow levels may affect water quality in off-channel features by affecting the quantity and timing of surface and subsurface inputs.

In addition to flow, localized site characteristics (including aquatic vegetation abundance and type, riparian vegetation cover, and feature morphology) and processes (such as primary production) directly or indirectly affect water temperature and dissolved-oxygen concentrations in off-channel features. Certain processes and inputs may become more evident during periods of low streamflow. Aquatic vegetation and dissolved-organic matter can decrease light penetration, thereby increasing stratification of water temperature and decreasing temperatures at depth (Takamura and others, 2003). Riparian vegetation can also decrease localized water temperature through shading of the water surface (Ebersole and others, 2003). Off-channel features with shallow, stagnant water may warm more than moving water through accumulated absorption of solar insolation.

The types of aquatic vegetation plant communities (such as submerged and emergent) can affect the dissolved-oxygen concentrations in a waterbody. Submerged aquatic vegetation in Willamette River off-channel features (such as coontail [*Ceratophyllum demersum*] and Canadian waterweed [*Elodea canadensis*]) produce oxygen through photosynthesis and release that oxygen into the water column (Caraco and others, 2006). However, invasive emergent macrophytes (*Ludwigia* spp.) also are prevalent in many Willamette River off-channel features and tend to release oxygen to the air more so than to the water (Benton Soil and Water Conservation District, 2014). *Ludwigia* spp. have been associated with low dissolved-oxygen concentrations and high probabilities of water-column hypoxia (Caraco and others, 2006; Bunch and others, 2010). Plant and algal respiration and the decomposition of aquatic vegetation and other organic matter consumes oxygen and tends to decrease dissolved-oxygen concentrations.

The status, location, and susceptibility of CWRs along the Willamette River are not well known. A thorough documentation of water-quality conditions along the Willamette River and in its off-channel features is needed to understand where CWRs exist and how off-channel features might provide usable fish habitat for migration, spawning, and (or) rearing. This study provides spatially and temporally continuous datasets to address key knowledge gaps and to provide a foundation for understanding variations within and among sites. Organizing and discussing the connections between processes and water-quality conditions will provide information about how temperature, dissolved oxygen, and fish habitat might change as a result of varying flow conditions and other factors.

Purpose and Scope

This report documents water-quality conditions in select off-channel features of the Willamette River from Eugene to Newberg in northwestern Oregon (figs. 1, 2) during the summers of 2015 and 2016. Willamette River streamflow was particularly low in 2015 compared to 2000–19 (fig. 4), which was roughly when the current flow targets were adopted by U.S. Army Corps of Engineers (USACE) flow managers (National Marine Fisheries Service, 2008). Low streamflows and warm water temperatures in 2015 led to an increased need to understand the condition and location of potential CWRs and favorable fish habitat. Gregory and Wildman (2016) completed annual surveys of water temperature and dissolved-oxygen conditions in off-channel features during summers 2011–16. This study built on the Gregory and Wildman (2016) surveys by deploying continuously recording temperature and dissolved-oxygen sensors each summer to collect more frequent field measurements over a large area and to include a temporal component. Additionally, researchers collected specific conductance and (or) pH data at select continuous sites and point-measurement locations as part of this study.

In addition to documenting water-quality conditions in the Willamette River's main channel and off-channel features, this report describes how the geomorphology and hydrology of off-channel features affect their ecology and water quality. The report focuses on the processes and site characteristics that combine to create the measured water-quality conditions. This investigation provides insights regarding how main-channel flow connections and local factors (for example, vegetation and feature morphology) may affect water temperature and dissolved-oxygen conditions in off-channel features. To distill the complex conditions and processes affecting the sites that were monitored, a simplified site classification scheme is proposed, linking water-quality monitoring data with measured

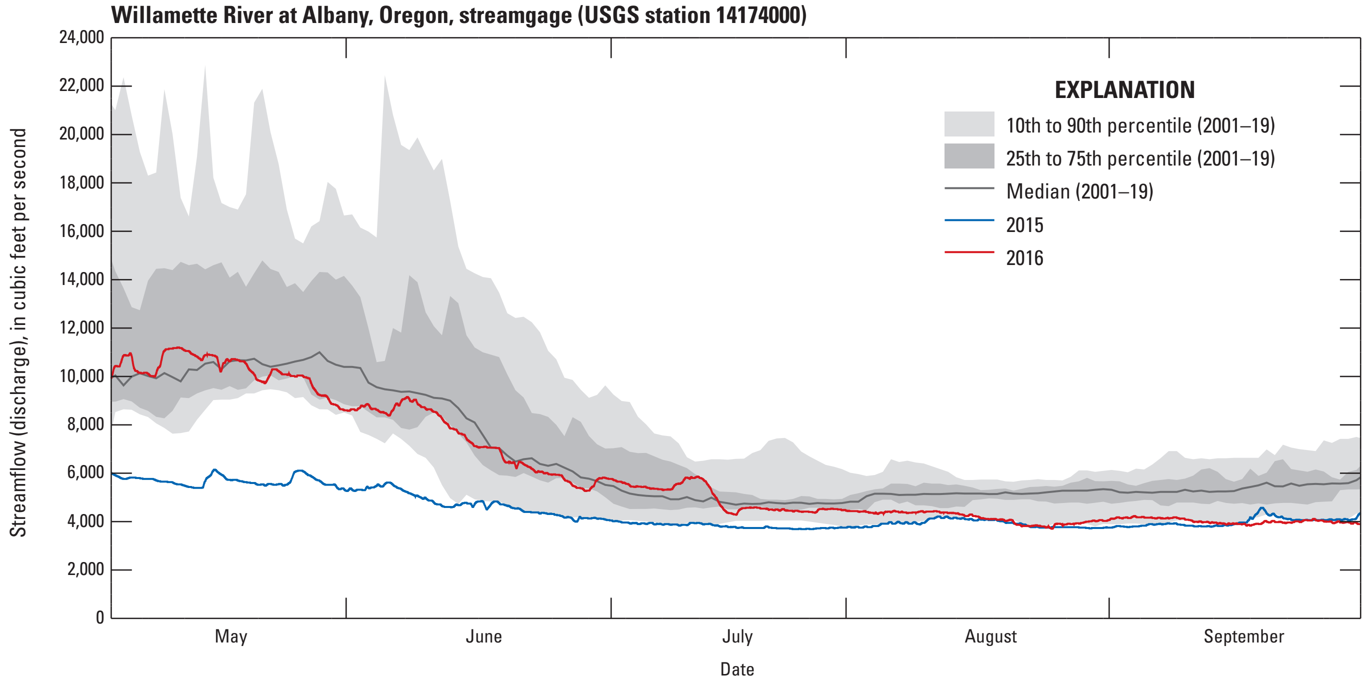


Figure 4. Measured streamflow conditions during the low-flow period of May–September in 2015 and 2016 compared to historical (2001–19) conditions in the Willamette River at Albany, Oregon, streamgage (U.S. Geological Survey station 14174000).

and observed site characteristics. Considering that only a subset of off-channel features along the Willamette River were monitored, an accompanying theoretical process matrix is also proposed to describe the multitude of factors and processes that could interact to create a variety of water-quality conditions in off-channel features. The theoretical process matrix introduces and organizes the interacting processes that occur in aquatic environments and describes the water-quality conditions that may result. The proposed site classification scheme and theoretical process matrix are intended to assist resource managers and researchers in understanding the distribution, duration, and condition of CWRs in the system.

The overall goals of this report are to do the following:

1. Document continuous water-quality datasets (water temperature, dissolved oxygen, and other parameters) and water-quality point measurements in the main channel and off-channel features of the Willamette River during the summers of 2015 and 2016;
2. Describe the measured spatial and temporal variability in water-quality conditions within and among off-channel features and provide context for interpreting the water-quality data and its relevance for fish habitat;
3. Discuss the role of upstream surface-water connectivity on temperature, water quality, and ecology in off-channel features;
4. Develop a means of linking water quality in monitored off-channel features to the possible processes affecting the patterns and values in the data; and
5. Provide a basis for developing hypotheses regarding site-specific characteristics, processes, and the possible water-quality conditions that may exist in other off-channel features along the Willamette River.

Study Area

The Willamette River drains 28,800 square kilometers of forested, agricultural, and urban land between the Cascade Range and Coast Range of Oregon (fig. 1). The Willamette River begins at the confluence of the Middle Fork and Coast Fork Willamette Rivers near Eugene (figs. 1, 2) and flows north nearly 300 kilometers before joining the Columbia River near Portland, Oregon (fig. 1). During its route north, several tributaries add substantial flow to the river, especially the McKenzie, Santiam, and Clackamas Rivers (figs. 1, 2). Before the installation of USACE dams on some of the tributaries in the mid-1900s, much of the Willamette River between Eugene and Newberg (fig. 2) was a wandering gravel-bed river (Church, 1983) with a few short, geologically stable reaches; frequent channel migration created a mixture of single- and multi-threaded reaches containing a variety of wetted off-channel areas, large gravel bars of varying stability, and floodplain surfaces at a range of heights above the channel.

The river meandered within its floodplain except where it flowed adjacent to tall, erosion-resistant Pleistocene floodplain surfaces or Tertiary bedrock of the Salem Hills (O'Connor and others, 2001).

Thirteen USACE dams and six other large dams have been built on tributaries of the Willamette River (fig. 1), affecting modern flow, sediment, and temperature regimes of the river. The primary purpose of many of the USACE dams is to support the USACE's flood-risk management mission (U.S. Army Corps of Engineers, 2019); other benefits include power generation, recreation, and municipal and irrigation water supply. Although no large dams have been built on the main-channel Willamette River, flow management using storage in the tributary reservoirs has greatly altered the flow regime of the river. Peak flows have decreased and summer base flows have increased compared to pre-dam conditions (Rounds, 2010; Wallick and others, 2013). Measured at the Willamette River at Albany, Oregon, streamgage (USGS station 14174000; RM 119; fig. 2), the lowest summer streamflows have increased from an annual range of approximately 1,900–3,300 cubic feet per second (ft^3/s) to approximately 3,700–5,300 ft^3/s after the implementation of summer flow augmentation from reservoir releases beginning in the early 1950s (U.S. Geological Survey, 2018). In combination with channel-stabilizing revetments, the dams also have decreased the supply of bed sediment by about 60 percent in Salem and Portland, Oregon (O'Connor and others, 2014).

Changes in streamflow and sediment supply as a result of the dams, in addition to the removal of instream large wood and other land-use changes, have altered the geomorphic regime of the Willamette River in the last century by reducing gravel-bar area, reducing instream wood supply to the river, and stabilizing the channel and its flanking landforms such as alcoves and side channels (Gregory and others, 2019; Sedell and Froggatt, 1984; Wallick and others, 2013). Willamette River morphology still changes on a nearly annual basis in reaches upstream from Peoria, Oregon (RM 142, about 10 RM upstream from Corvallis, Oregon; fig. 2), but the magnitude of channel change in those reaches is currently less than what occurred before the anthropogenic modifications to the system. Bank erosion, gravel bar growth, and the development of off-channel areas occur, which create and modify an array of off-channel features in the upper reach (Wallick and others, 2013). The modern Willamette River channel downstream from Peoria is less dynamic, with only small, localized areas of geomorphological change. In these more stable reaches, relict off-channel features still exist and are connected to the main channel, but their morphologies rarely change on annual or decadal time scales (Wallick and others, 2013). Throughout the entire river system, side channels and alcoves vary in terms of their area, length, and the relative water-surface elevations at which they connect to the main channel.

Management of water temperature downstream from several USACE dams involves the use of multiple dam outlets to blend warm water from the reservoir surface with cooler, deeper reservoir water to meet a target downstream temperature. River reaches downstream from the large USACE dams quickly exchange heat with their surroundings, however, meaning that releases of cold water from upstream dams typically do not substantially cool the farther-downstream reaches of the Willamette River (Rounds, 2010). Modeling by Buccola and others (2016) and Rounds (2010) showed that the influence of the dams on main-channel temperature is minimal for reaches well downstream (many days or many dozens of river miles) of the large tributary dams. These results indicate the bounds that flow management has regarding cold-water habitats along the main channel and further emphasize the potential importance of CWRs along the Willamette River.

Study Reaches

Data collection for this study focused on the Willamette River's main channel and its off-channel features in three intensively monitored reaches between Eugene and Newberg (fig. 2):

1. Willamette Mission monitoring reach (RMs 67 to 77, near Salem), within the laterally stable reach downstream from Salem.

2. Independence monitoring reach (RMs 96 to 108, near Independence, Oregon), within the laterally stable reach downstream from the confluence with the Santiam River.

3. Harrisburg monitoring reach (RMs 161 to 168, near Harrisburg, Oregon), within the laterally dynamic reach upstream from Harrisburg.

Reaches were chosen for monitoring on the basis of their relative ease of access as well as the need to sample river reaches with different characteristics along the Willamette River upstream from Newberg. These reaches included a variety of types of off-channel features that are representative of features found throughout the different river segments and geomorphic regimes of the Willamette River. Not all off-channel features were monitored within each reach, and the water-quality conditions measured in one off-channel feature do not represent all the off-channel features in that reach. Repeat water-quality point measurements were collected within the monitoring reaches, as well as at sites opportunistically measured outside of the three intensively monitoring reaches between RMs 57 and 175. A similar study to document water-temperature conditions in tributaries and off-channel features of the Willamette River downstream from Newberg occurred in 2016 and 2017 (Mangano and others, 2018c).

Terminology

Certain terms relating to water quality, processes, landforms, streamflows, and data-collection sites are used consistently throughout this report. Some qualitative designations (like "high" and "low") and basic terms are defined below.

Water Quality

In this report, the term "water quality" includes water temperature, dissolved oxygen, specific conductance, and pH. Temperature and dissolved-oxygen values were compared to State of Oregon water-quality standards or relevant biological thresholds.

- *Water temperature*—A physical property and a measure of the kinetic energy of atoms and molecules in aqueous solution, reported in degrees Celsius.
    - *Warm*—Water temperatures >18 °C
    - *Cool*—Water temperatures ≤18 °C
- *Dissolved oxygen*—Molecular oxygen dissolved in water, reported in milligrams per liter.
    - *High*—Dissolved-oxygen concentrations ≥6.5 mg/L
    - *Moderate*—Dissolved-oxygen concentrations ≥4 and <6.5 mg/L
    - *Low*—Dissolved-oxygen concentrations <4 mg/L
    - *Anoxic*—Dissolved-oxygen concentrations approaching zero mg/L
- *Specific conductance*—A measure of the waterbody's capacity to conduct an electrical current; values are compensated to 25 °C and reported in microsiemens per centimeter.
- *pH*—A measure of the acidity or alkalinity of a solution based on a logarithmic scale of the concentration of hydrogen ions; values are reported in standard units.

Water-Quality Processes

- *Photosynthesis*—The process by which plants containing chlorophyll capture and use sunlight as an energy source to convert carbon dioxide and water into organic compounds, releasing oxygen as a byproduct.
- *Primary production*—The synthesis of organic compounds from dissolved or atmospheric carbon dioxide, typically as a result of photosynthesis, and associated with the release of oxygen to the atmosphere or water column.
- *Reaeration*—The process by which gases such as oxygen are transferred across the air/water interface of a waterbody. When the oxygen concentration in surface water is less than its solubility, oxygen can move from the atmosphere into the waterbody; when the concentration exceeds its solubility, excess oxygen is released to the atmosphere.
- *Respiration*—The consumption of dissolved oxygen by living organisms as a result of the routine production of energy from the oxidation of organic substances.
- *Sediment oxygen demand*—The rate at which dissolved oxygen in the water column is consumed as a result of the decomposition of organic matter in surficial sediments.

Flow Type

- *Surface flow*—Water that flows on and above the substrate.
- *Subsurface flow*—Water that flows through the substrate or riverbank material; this includes groundwater and hyporheic flow:
    - *Hyporheic flow*—Water that moves through the subsurface adjacent to a stream and readily exchanges with surface flow and groundwater.
    - *Groundwater*—Water in the saturated zone of a porous geological material, where all pore spaces are filled with fluid. The upper boundary of the saturated zone designates the water table.

Relative Streamflow and Related River Stage

This study does not quantify specific streamflow ranges for the qualitative flow terms defined below because (a) streamflow increases downstream, causing different reaches to have different flow ranges, and (b) this study does not specifically address regulatory streamflow targets or minima. As used throughout this report, relative terms are defined below:

- *High flows*—Small flood or bank-full flows, such that the main channel is at or near capacity and nearly all off-channel features and active channel landforms are submerged. This type of flow was not observed during the monitoring timeframes of this study, but implications about how features function during this type of flow can be inferred from a feature's morphology.
- *Moderate flows*—Streamflows that tend to occur in autumn or spring, when the main channel rises to inundate most active channel areas.

- *Low flows*—Typical low summer streamflows in the post-dam era (after 1950s).
- *Unusually low flows*—Lower than typical low summer streamflows in the post-dam era (after 1950s). These streamflows only occur in years when river streamflow is reduced by uncommon climatic effects (such as low precipitation or low snowpack) or anthropogenic factors (such as decreased reservoir releases or increased diversions for municipal or agricultural uses).

Data-Collection Locales

- *Monitoring reach*—A length of river where continuous monitors were deployed, and repeat point measurements were collected (fig. 2).
- *Site*—A place that was continuously monitored for water temperature or multiple water-quality parameters (see triangles and circles in fig. 2).
- *Location*—A place where water-quality point measurements were collected, often colocated with a site.
- *Feature*—An alcove or side channel (referred to as an off-channel feature). A feature may include a site (that is, a continuously monitored place) and one or more point-measurement locations.

Landforms

- *Active bar*—Channel-flanking gravel bars that are scoured and mobilized annually, resulting in sparse vegetation and potentially annual changes in their shape.
- *Alcove*—Off-channel feature that is connected to the main-channel surface-water flow at its downstream end but not connected by surface flow at its upstream end. An alcove may connect at its upstream end when streamflows increase, turning it into a side channel.
- *Floodplain*—Higher surfaces flanking the active channel built of sediment deposited during periodic flood events and, in some areas, eroded laterally by strong river flows.
- *Main channel*—Primary wetted channel where most river water flows during summer low-flow periods.
- *Pleistocene floodplain/terrace*—Generally the highest land surfaces adjacent to the Willamette River that are no longer inundated by flood waters. Along the Willamette River, these surfaces are underlain by a hard, coarse gravel layer that may limit channel migration.
- *Revetments*—Human-constructed bank stabilization assemblages (often large boulders), typically along the outer bends of the main river channel; historical revetments may be in off-channel features due to channel changes in the past.
- *Side channel*—Off-channel feature where surface water from the main channel is actively flowing through the feature from its upstream end to its downstream end. If main channel stage decreases, it is possible that surface flow may no longer enter the feature at its upstream end, turning it into an alcove.
- *Stable bar*—Channel-flanking and mid-channel bars that were once active gravel bars but are now stabilized by vegetation, with little change annually except by lateral erosion and vertical accretion of fine sediment.

Site and Reach Names

Reaches and sites along the main-channel Willamette River are referenced to river miles identified from local USGS topographic maps (fig. 2; Esri, 2014). Off-channel features in this study were identified based on the river mile of the feature's downstream connection point to the main channel. Sites in the Harrisburg monitoring reach are referred to as "near" river mile values in their official USGS National Water Information System (NWIS; U.S. Geological Survey, 2018) site name because of notable main-channel changes in that reach since topographic maps were published; in text and figures in this report, they are referred to as "at" a river mile. Feature names were only given to the five off-channel features in which multiparameter water-quality monitors were deployed in 2016; these names are based on nearby places or landforms on topographic maps. Location coordinates for all monitoring sites and synoptic point measurement locations are provided on tables within this report or as a field in the published datasets; using coordinates is the most definitive way of identifying a site or synoptic measurement location.

Methods

Three reaches between Eugene and Newberg were selected for intensive monitoring (fig. 2) during 2015 and 2016. Continuous temperature sensors, multiparameter water-quality monitors, and pressure transducers were installed in each of the reaches, and synoptic measurements were periodically collected within these reaches to provide broader spatial detail than the continuous monitors could provide.

Within the three reaches, a variety of off-channel features with different characteristics (such as depth, size, presence/absence of aquatic vegetation, and connection to the main channel) were monitored. Water-temperature data were collected at all sites, whereas dissolved oxygen, specific conductance, pH, and (or) river stage data were collected at a subset of the continuous sites and point measurement locations. In a few areas, temperature sensors were deployed in pairs, with a sensor in the main channel near the off-channel feature, to assess temperature differences between the off-channel feature and the main channel. Water-temperature sensors and water-quality monitors were calibrated and operated in accordance with USGS standard protocols (Wagner and others, 2006). The methodology for synoptic measurements and pressure transducer data collection are described in detail in the metadata published with each dataset through USGS ScienceBase (Mangano and others, 2017, 2018a). Differentiating between groundwater and hyporheic inputs to off-channel features was beyond the scope of this study and was not attempted; this report refers to any groundwater or hyporheic flows as subsurface inputs.

Field Data Collection

The methods for the deployment of field sensors are described by year because of slight variations in the deployment methodology and sensors used each year. Most notably, the water-temperature sensors and water-quality monitors were deployed in the middle of the water column in 2016 rather than on the bed of the river, as was done in 2015.

2015

Monitoring equipment was deployed in August 2015 and retrieved in October 2015. A total of 24 Onset Hobo model U22–001 Water Temp Pro v2 (Onset Computer Corporation, Bourne, Mass.) water-temperature sensors (hereafter referred to as “water-temperature sensors”) were deployed in off-channel features or the main-channel Willamette River (table 1; fig. 2). Many of the water-temperature sensors placed in off-channel features were paired with a main-channel water-temperature sensor, resulting in 16 sensors collecting data in off-channel features and 8 in the main channel for the 2-month period. Water-temperature sensors were secured in 30-centimeter segments of polyvinyl chloride (PVC) pipe, attached to short pieces of rebar for weight, cabled to vegetation on the bank, and placed on the bed of the river or off-channel feature. Sensors were programmed to record water temperature hourly.

Yellow Springs Instruments (YSI, Yellow Springs, Ohio) 6-series multiparameter water-quality monitors (hereafter referred to as “water-quality monitors”) were deployed in four off-channel features and at one main-channel site in 2015 (table 2). Water-quality monitors were secured in 1-meter (m) segments of PVC pipe (perforated to allow water to flow across the sensors), attached to a 20-cm cinder block, and secured to vegetation on the bank with a steel cable. The cinder block was positioned on the bed of the off-channel feature with the continuous water-quality monitor on top, but in some instances the top-heavy configuration likely tipped over and recorded data while the monitor was resting on the sediment. All monitors recorded hourly measurements for water temperature and dissolved oxygen, and four of the five monitors also measured pH and specific conductance.

Point measurements (spatially intensive measurements collected over a short period; hereafter referred to as “synoptic measurements or surveys”) were collected on 5 days in August and 5 days in October 2015. These synoptic surveys were conducted in a manner similar to measurements made by Gregory and Wildman (2016) in off-channel Willamette River locations between 2011 and 2016. Synoptic surveys were carried out to document longitudinal and vertical water-quality heterogeneity in the main channel and off-channel features, and for comparison with installed continuous temperature sensors. Synoptic measurements were typically collected between 9:00 a.m. and 6:00 p.m. Pacific daylight time (PDT). Multiple measurements at various depths and locations within individual off-channel features were collected as rapidly as possible (within about 30 minutes) to minimize the effects of diel warming. Equipment used to collect synoptic measurements included a YSI EXO2 water-quality monitor, a YSI 6-series water-quality monitor, and a YSI EcoSense EC300A meter that measured temperature and specific conductance only. Monitors or meters were lowered into the water from a boat for individual synoptic point measurements, typically at multiple depths at the same location. Synoptic measurement locations were often colocated with deployed equipment or within off-channel features of the monitored reaches; additional measurements were collected during a 2-day trip from RM 72 to 122 (Salem to Albany; fig. 2). All measurements included location, date, time, depth below water surface, and water temperature, and most also included specific conductance, dissolved oxygen, and pH.

2016

The same equipment used in 2015, plus additional sensors, was deployed from about May to October 2016 at many of the same sites within the three intensively monitored reaches, but the methods of deployment differed from 2015. Eighteen water-temperature sensors were deployed in off-channel features, and an additional four were installed in the main channel (table 1; fig. 2). Water-temperature sensors were suspended in the water column above the sediment using foam and their own buoyancy, which floated them above cement-block anchors. Water-temperature sensors were positioned at about mid-depth in the water column, with depths ranging from 0.2 to 1.5 m above the bed. The cement blocks were attached to riparian vegetation with steel cables, and the sensors were configured to record measurements hourly.

Table 1. Sites and dates of data collection for continuous water-temperature sensors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Feature monitored in 2015 and 2016: Sensors may have been placed in the same feature but in different locations within the feature in 2015 and 2016, resulting in different coordinates associated with the same NWIS site number. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)
					2015					
67.1	Yes	Willamette River alcove on right bank at RM 67.1	450808123004200	499076	4998007	Alcove	2015-08-18	2015-10-08	Willamette Mission	<0.1
67.1	No	Willamette River on right bank at RM 67.1	450808123004500	499011	4998002	Main channel	2015-08-18	2015-10-08	Willamette Mission	<0.1
67.6	Yes	Willamette River alcove on right bank at RM 67.6	450746123003100	499323	4997315	Alcove	2015-08-18	2015-10-08	Willamette Mission	<0.1
67.7	Yes	Willamette River alcove on right bank at RM 67.7	450740123003600	499222	4997154	Alcove	2015-08-18	2015-10-08	Willamette Mission	<0.1
70.2	Yes	Willamette River on right bank at RM 70.2	450601123010400	498605	4994090	Main channel	2015-08-18	2015-10-08	Willamette Mission	<0.1
73.2	Yes	Willamette River on left bank at RM 73.2	450445123040500	494648	4991760	Main channel	2015-08-27	2015-10-08	Willamette Mission	<0.1
73.4	Yes	Willamette River alcove on left bank at RM 73.4	450438123040900	494559	4991516	Alcove	2015-08-27	2015-10-08	Willamette Mission	<0.1
74.6	Yes	Willamette River alcove on left bank at RM 74.6	450332123040800	494586	4989486	Alcove	2015-08-27	2015-10-08	Willamette Mission	<0.1
95.8	No	Willamette River alcove on left bank at RM 95.8	445056123105600	485598	4966190	Alcove	2015-08-19	2015-10-07	Independence	<0.1
97.7	Yes	Willamette River alcove on left bank at RM 97.7	444938123094900	487060	4963775	Alcove	2015-08-19	2015-10-07	Independence	<0.1
97.7	Yes	Willamette River on right bank at RM 97.7	444945123095600	486906	4964001	Main channel	2015-08-19	2015-10-07	Independence	<0.1
97.9	No	Willamette River alcove on left bank at RM 97.9	444945123094200	487213	4963972	Alcove	2015-08-19	2015-10-07	Independence	<0.1

Table 1. Sites and dates of data collection for continuous water-temperature sensors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.—Continued

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Feature monitored in 2015 and 2016: Sensors may have been placed in the same feature but in different locations within the feature in 2015 and 2016, resulting in different coordinates associated with the same NWIS site number. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)
2015—Continued										
98.4	Yes	Willamette River alcove on right bank at RM 98.4	444948123090100	488110	4964071	Alcove	2015-08-19	2015-10-07	Independence	<0.1
107.3	No	Willamette River on right bank at RM 107.3	444527123085100	488328	4956019	Main channel	2015-08-26	2015-10-06	Independence	<0.1
107.5	Yes	Willamette River alcove on right bank at RM 107.5	444517123084900	488367	4955713	Alcove	2015-08-26	2015-10-06	Independence	<0.1
161	No	Willamette River on right bank at RM 161	441613123102600	486120	4901907	Main channel	2015-08-20	2015-10-14	Harrisburg	<0.1
161.7	Yes	Willamette River alcove on right bank near RM 161.7	441540123101900	486269	4900885	Alcove	2015-08-20	2015-10-14	Harrisburg	<0.1
162.8	No	Willamette River side channel on left bank near RM 162.8	441446123103500	485925	4899223	Side channel	2015-08-20	2015-10-14	Harrisburg	<0.1
162.8	No	Willamette River alcove on left bank near RM 162.8	441447123103000	486021	4899240	Alcove	2015-08-20	2015-10-14	Harrisburg	<0.1
163.5	No	Willamette River alcove on right bank near RM 163.5	441428123095600	486772	4898677	Alcove	2015-08-20	2015-10-14	Harrisburg	<0.1
164.2	No	Willamette River on left bank near RM 164.2	441359123093800	487178	4897756	Main channel	2015-08-20	2015-10-14	Harrisburg	<0.1
164.8	Yes	Willamette River side channel on right bank at near RM 164.8	441351123090900	487826	4897515	Side channel	2015-08-20	2015-10-14	Harrisburg	<0.1
167.8	No	Willamette River on right bank near RM 167.8	441155123091900	487596	4893946	Main channel	2015-08-20	2015-10-14	Harrisburg	<0.1

Table 1. Sites and dates of data collection for continuous water-temperature sensors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.—Continued

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Feature monitored in 2015 and 2016: Sensors may have been placed in the same feature but in different locations within the feature in 2015 and 2016, resulting in different coordinates associated with the same NWIS site number. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)
					2015 —Continued					
168.1	No	Willamette River side channel on right bank near RM 168.1	441152123085600	488105	4893836	Side channel	2015-08-20	2015-10-14	Harrisburg	<0.1
					2016					
67.6	Yes	Willamette River alcove on right bank at RM 67.6	450746123003100	499314	4997353	Alcove	2016-06-02	2016-10-25	Willamette Mission	0.6
67.7	Yes	Willamette River alcove on left bank at RM 67.7	450740123003600	499211	4997141	Alcove	2016-06-02	2016-10-25	Willamette Mission	0.3
70.2	Yes	Willamette River on right bank at RM 70.2	450601123010400	498631	4994089	Main channel	2016-06-02	2016-10-25	Willamette Mission	0.6
70.2	Yes	Willamette River alcove on right bank at RM 70.2	450557123011100	498442	4993974	Alcove	2016-06-02	2016-10-25	Willamette Mission	0.6
73.2	Yes	Willamette River on left bank at RM 73.2	450445123040500	494676	4991791	Main channel	2016-05-26	2016-11-10	Willamette Mission	0.6
73.4	Yes	Willamette River alcove on left bank at RM 73.4	450332123040900	494560	4991528	Alcove	2016-05-26	2016-11-10	Willamette Mission	0.9
73.5	No	Willamette River alcove on left bank at RM 73.5	450433123041300	494460	4991379	Alcove	2016-05-26	2016-11-10	Willamette Mission	0.3
73.9	No	Willamette River alcove on right bank at RM 73.9	450408123034800	495014	4990619	Alcove	2016-05-26	2016-11-10	Willamette Mission	0.9
77.2	No	Willamette River alcove on left bank at RM 77.2	450130123043800	493924	4985729	Alcove	2016-05-26	2016-11-10	Willamette Mission	0.6

Table 1. Sites and dates of data collection for continuous water-temperature sensors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.—Continued

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Feature monitored in 2015 and 2016: Sensors may have been placed in the same feature but in different locations within the feature in 2015 and 2016, resulting in different coordinates associated with the same NWIS site number. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)
				2016—Continued						
96.1	No	Willamette River alcove on left bank at RM 96.1	445047123105500	485624	4965901	Alcove	2016-05-25	2016-10-24	Independence	0.6
98.4	Yes	Willamette River alcove on right bank at RM 98.4	444948123090100	488239	4964005	Alcove	2016-05-25	2016-11-14	Independence	0.6
100.2	No	Willamette River side channel on right bank at RM 100.2	444932123071200	490565	4963558	Main channel	2016-05-25	2016-11-14	Independence	0.6
101	Yes	Willamette River alcove on right bank at RM 101	444927123064100	491236	4963434	Alcove	2016-05-25	2016-11-14	Independence	1.5
107.5	Yes	Willamette River alcove on right bank at RM 107.5	444517123084900	488350	4955717	Alcove	2016-06-01	2016-11-14	Independence	0.2
107.5	Yes	Willamette River alcove on right bank at RM 107.5	444517123084900	488350	4955717	Alcove	2016-06-01	2016-11-14	Independence	0.6
107.8	No	Luckiamute River alcove on right bank at RM 0.1	444452123084700	488410	4954930	Alcove	2016-06-01	2016-11-14	Independence	0.6
107.9	No	Luckiamute River on left bank at RM 0.1	444453123085300	488273	4954968	Tributary	2016-06-01	2016-11-14	Independence	0.6
161.3	Yes	Willamette River side channel on left bank near RM 161.3	441558123103500	485965	4901496	Side channel	2016-05-24	2016-10-20	Harrisburg	0.6
161.7	Yes	Willamette River alcove on right bank near RM 161.7	441540123101900	486290	4900907	Alcove	2016-05-24	2016-10-20	Harrisburg	0.6
162.2	No	Willamette River alcove on right bank near RM 162.2	441515123104000	485797	4900128	Alcove	2016-05-24	2016-10-20	Harrisburg	0.3

Table 1. Sites and dates of data collection for continuous water-temperature sensors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.—Continued

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Feature monitored in 2015 and 2016: Sensors may have been placed in the same feature but in different locations within the feature in 2015 and 2016, resulting in different coordinates associated with the same NWIS site number. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)
				2016—Continued						
162.9	No	Willamette River alcove on right bank near RM 162.9	441448123095800	486728	4899284	Alcove	2016-05-24	2016-10-20	Harrisburg	0.6
164.2	No	Willamette River on right bank near RM 164.2	441401123093500	487240	4897818	Main channel	2016-05-24	2016-10-20	Harrisburg	0.6

Table 2. Sites and dates of data collection for multiparameter water-quality monitors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Due to the monitor's proximity to the main channel, it measured main-channel conditions although the site's name says it is in an alcove. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile; Temp, water temperature; DO, dissolved oxygen; SC, specific conductance]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)	Recorded parameters			
											Temp	DO	SC	pH
						2015								
70.2	Yes	Willamette River alcove on right bank at RM 70.2	450557123011100	498443	4993981	Alcove	2015-08-18	2015-10-08	Willamette Mission	<0.3	X		X	X
95.9	No	Willamette River alcove on left bank at RM 95.9	445053123105400	485635	4966094	Main channel	2015-08-19	2015-10-07	Indepen-dence	<0.3	X	X	X	X
101	Yes	Willamette River alcove on right bank at RM 101	444927123064100	491195	4963429	Alcove	2015-08-19	2015-10-07	Indepen-dence	<0.3	X		X	X
161.3	Yes	Willamette River side channel on left bank near RM 161.3	441558123103500	485918	4901460	Side channel	2015-08-20	2015-10-14	Harrisburg	<0.3	X	X		
164.1	Yes	Willamette River alcove on left bank near RM 164.1	441355123094600	486998	4897643	Alcove	2015-08-20	2015-10-14	Harrisburg	<0.3	X	X	X	X

Table 2. Sites and dates of data collection for multiparameter water-quality monitors installed in off-channel features and the main-channel Willamette River, Oregon, in summers 2015 and 2016.—Continued

[Easting and northing coordinates are reference to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. Due to the monitor's proximity to the main channel, it measured main-channel conditions although the site's name says it is in an alcove. **Abbreviations:** NWIS, National Water Information System (U.S. Geological Survey, 2018); RM, river mile; Temp, water temperature; DO, dissolved oxygen; SC, specific conductance]

Willamette River mile	Feature monitored in 2015 and 2016	NWIS site name	NWIS site number	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Height above riverbed (meters)	Recorded parameters			
											Temp	DO	SC	pH
						2016								
67.1	Yes	Willamette River alcove on right bank at RM 67.1	450808123004200	499056	4998019	Alcove	2016-05-23	2016-10-26	Willamette Mission	0.6	X	X	X	
74.6	Yes	Willamette River alcove on left bank at RM 74.6	450332123040800	494553	4989432	Alcove	2016-05-23	2016-10-26	Willamette Mission	0.6	X	X	X	
97.7	Yes	Willamette River alcove on left bank at RM 97.7	444938123094900	486972	4963800	Alcove	2016-05-23	2016-10-25	Indepen-dence	0.6	X	X		
97.7	Yes	Willamette River on right bank at RM 97.7	444945123095600	486885	4964005	Main channel	2016-05-23	2016-10-25	Indepen-dence	0.6	X	X	X	X
164.1	Yes	Willamette River alcove on left bank near RM 164.1	441355123094600	486982	4897693	Alcove	2016-05-23	2016-10-26	Harrisburg	0.6	X	X	X	
164.8	Yes	Willamette River side channel on right bank near RM 164.8	441351123090900	487853	4897486	Side channel	2016-05-23	2016-10-26	Harrisburg	0.6	X	X	X	

As with the water-temperature sensors, the YSI continuous water-quality monitors also were elevated off the substrate during the 2016 field season. Two wire crates were stacked, fastened together, and weighted. YSI 6-series water-quality monitors were housed in perforated PVC pipe segments as in 2015, and the housing was attached to the top of the stacked wire crates. The crates, secured to woody bank vegetation with a steel cable, allowed water to pass freely around and under the monitors while maintaining a constant height (0.6 m) above the substrate. Five continuous water-quality monitors were deployed in this manner in off-channel features. A sixth water-quality monitor was installed at mid-depth in the main-channel Willamette River (RM 97.7, near Independence; fig. 2) in a long, angled PVC pipe, perforated with holes, and secured to the bank. Water-quality monitors in the off-channel features recorded water temperature, dissolved oxygen, and specific conductance. The main-channel monitor recorded pH in addition to water temperature, dissolved oxygen, and specific conductance (table 2).

Synoptic measurements were collected on 18 days between May 24 and November 14, 2016. Most measurements were recorded at the location of deployed equipment on days when that equipment was visited for maintenance, or during synoptic surveys within the three intensively monitored reaches. Additional synoptic measurements were collected when a crew surveying the bathymetry of the Willamette River also collected water-quality measurements in off-channel features between Independence and Eugene (RM 105–175; fig. 2) in late August 2016 (Mangano and others, 2017).

Pressure transducers were installed in seven off-channel features in 2016 (table 3; Mangano and others, 2018a) to record variations in stage within the off-channel features throughout the monitoring period. The transducers were encased in PVC pipes and attached to rebar that was driven into the bed of the off-channel feature, a method that ensured a constant deployment elevation. As the pressure transducers were not placed on the substrate, their readings do not indicate the absolute depth of water in the feature and rely on a local datum for each sensor. The water-surface elevations at five of the pressure transducers were surveyed using real-time kinematic global positioning system equipment, which allowed conversion of the sensor-depth measurements to water-surface elevations in the North American Vertical Datum of 1988. Three barometric pressure sensors—one in each reach—were deployed nearby so the sensor-depth measurements could be corrected for local variations in atmospheric pressure.

Onset Hobo Pendant temperature sensors (model UA–001–08; hereafter referred to as “pendant temperature sensors”) were deployed in May and June 2016 (table 4), when streamflow in the Willamette River was decreasing. Pendant temperature sensors were used in this study to evaluate when the upstream end of an off-channel feature was connected to the main channel. A pendant temperature sensor deployed on the substrate at the upstream end of an off-channel feature recorded its status (wet or dry) through a comparison of the pendant temperature, main-channel water temperature, and nearby air temperature data (method adapted from Arismendi and others, 2017). Four prominent off-channel features were chosen, and pendants were attached to the substrate (with steel cable and a Duckbill anchor) at the lowest point of the channel connecting the upstream end of the off-channel feature to the main-channel Willamette River. Two additional pendants were attached to nearby trees to measure local air temperature. Nearby AgriMet weather stations also were used as an air-temperature reference (Bureau of Reclamation, 2012).

Data Processing

Some continuous 2015 dissolved-oxygen datasets that consistently logged near-anoxic concentrations (close to zero mg/L and based on sensor performance) were deleted because of the high probability that the monitors were somewhat buried in the sediment and not accurately characterizing conditions in the water column. In 2016, multiple water-quality monitors recorded hypoxic and anoxic concentrations for extended periods, but the deployments on top of wire crates ensured that the monitors were measuring conditions in the water column, and those datasets were not deleted.

All water-temperature and dissolved-oxygen data referenced in this report and published online have been scrutinized following USGS protocols (Wagner and others, 2006). Data gaps are visible in some of the figures and were usually the result of equipment battery issues or the sensor having been temporarily removed from the waterbody. This report relies mostly on the continuous 2016 data while referencing the continuous 2015 data, where appropriate. Many synoptic measurements were collected in 2015 and are often used as examples.

Published Datasets of Field Measurements

Multiple datasets were collected and published from this 2-year study. These data are available online in NWIS (U.S. Geological Survey, 2018) or in ScienceBase (Mangano and others, 2017, 2018a, 2018b), as follows:

1. 2015 and 2016 continuous water-temperature data: NWIS, see table 1 for site numbers.
2. 2015 and 2016 continuous multiparameter monitor data (water temperature, dissolved oxygen, pH, and specific conductance): NWIS, see table 2 for site numbers.
3. 2015 and 2016 synoptic measurements: USGS data release in ScienceBase (Mangano and others, 2017).
4. 2016 pressure-transducer data: table 3, USGS data release in ScienceBase (Mangano and others, 2018a).
5. 2016 water-temperature pendant data: table 4, USGS data release in ScienceBase (Mangano and others, 2018b).

Table 3. Sites and dates of data collection for pressure transducers and barometric-pressure sensors installed in off-channel features of the Willamette River, Oregon, from May to November 2016.

[Easting and northing coordinates are referenced to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. **Abbreviation:** RM, river mile]

Willamette River mile	Site name	Easting (meters)	Northing (meters)	Site type	Installation date	Removal date	Monitoring reach (fig. 2)	Water height converted to elevation
			Pressure transducers					
70.2	Pressure transducer at RM 70.2	498440	4993964	Alcove	2016-06-02	2016-11-10	Willamette Mission	No
97.7	Pressure transducer at RM 97.7	486981	4963786	Alcove	2016-05-25	2016-11-14	Independence	Yes
98.4	Pressure transducer at RM 98.4	488019	4964085	Alcove	2016-05-25	2016-11-14	Independence	Yes
107.5	Pressure transducer at RM 107.5	488386	4955712	Alcove	2016-06-01	2016-11-14	Independence	Yes
161.4	Pressure transducer at RM 161.4	485887	4901427	Side channel	2016-05-24	2016-10-20	Harrisburg	Yes
162.8	Pressure transducer at RM 162.8	485910	4899213	Side channel	2016-05-24	2016-10-20	Harrisburg	No
164.8	Pressure transducer at RM 164.8	487870	4897446	Side channel	2016-05-24	2016-10-20	Harrisburg	Yes
			Barometric pressure transducers					
67.1	Barometric pressure transducer at RM 67.1	499051	4998040	Air	2016-05-26	2016-10-25	Willamette Mission	NA
98.4	Barometric pressure transducer at RM 98.4	488019	4964085	Air	2016-05-25	2016-10-24	Independence	NA
164	Barometric pressure transducer at RM 164	486972	4897700	Air	2016-05-24	2016-10-20	Harrisburg	NA

Table 4. Sites and dates of data collection for temperature sensors (pendants) installed in a tree or on gravel bars upstream of off-channel features of the Willamette River, Oregon in summer 2016.

[Easting and northing coordinates are referenced to the North American Datum of 1983, Universal Transverse Mercator Zone 10N. **Abbreviation:** RM, river mile]

Willamette River mile	Site name	Easting (meters)	Northing (meters)	Sensor location	Installation date	Removal date	Monitoring reach (fig. 2)
68.2	Pendant sensor on ground at RM 68.2	499927	4996756	Ground	2016-06-02	2016-10-25	Willamette Mission
68.2	Pendant sensor in air at RM 68.2	499923	4996759	Air	2016-06-02	2016-10-25	Willamette Mission
96.3	Pendant sensor on ground at RM 96.3	485650	4965499	Ground	2016-05-25	2016-11-14	Independence
96.3	Pendant sensor in air at RM 96.3	485647	4965494	Air	2016-05-25	2016-10-24	Independence
98.9	Pendant sensor on ground at RM 98.9	488460	4963664	Ground	2016-05-25	2016-11-14	Independence
161.4	Pendant sensor on ground at RM 161.4	485838	4901421	Ground	2016-05-24	2016-10-20	Harrisburg

Field Observations and Geomorphic Characteristics of Off-Channel Features

During site visits in summer 2016, site characteristics were documented for the five off-channel features that contained water-quality monitors. Descriptions of substrate, aquatic vegetation, and general water color and transparency were based on qualitative observations. Substrate was identified either visually, as seen through clear water, or based on bed hardness when pressed with a metal rod or kayak paddle. Aquatic vegetation was noted as absent or present, with a relative abundance of emergent vegetation on the water surface or submerged vegetation seen through the water column or felt with a kayak paddle; the presence of vegetation attached to monitoring equipment when retrieved at the end of the field season was another indication of the presence of vegetation in or at the bottom of the water column. Water transparency (that is, relative turbidity) and color (for example, absent or dark-tannin colored) were visually categorized by looking through the water column to the deployed equipment on the bottom of the feature.

Geomorphic characteristics of the five features that contained water-quality monitors in summer 2016 were determined from field observations and remote-sensing applications. Depth of the off-channel features was measured by lowering a water-quality monitor with a depth sensor to the bed of the features during the various synoptic measurements; however, true bathymetric data were not collected in this study. Recent (2016) aerial photographs were used to measure surface area and to record planform morphology of the off-channel features. Lateral and longitudinal changes that occurred over the last two decades were evaluated by comparing Google Earth aerial photographs from 1994 and 2016 (appendix 2). Width, length, and height above the water surface of the upstream connection points were visually inspected in the field and on aerial photographs and measured from existing 2008 light detection and ranging (lidar) datasets, where appropriate. Additionally, the presence and relative abundance of emergent aquatic vegetation was noted from aerial photographs.

Streamflow and Temperature Data at U.S. Geological Survey Streamgage Sites

USGS streamgages along the Willamette River were used as estimates of local river streamflow and additional water-temperature measurements for each reach. The Willamette River at Harrisburg, Oregon, streamgage (USGS station 14166000; RM 161.0; downstream end of the Harrisburg monitoring reach; fig. 2) measures stage, streamflow, and main-channel temperature. For the Independence and Willamette Mission monitoring reaches, the Willamette River at Salem, Oregon, streamgage (USGS station 14191000; RM 84.2) was used for stage and streamflow information, whereas the nearby Willamette River at Keizer, Oregon, streamgage (USGS station 14192015; RM 82.2) was used as an additional main-channel temperature reference. Although the Willamette River at Albany, Oregon, streamgage (USGS station 14174000; RM 119) is closer to some sites in the Independence monitoring reach, the Santiam and Luckiamute Rivers join the Willamette River between the Albany streamgage and the Independence monitoring reach, making it more appropriate to use the Salem streamgage as a streamflow reference for the two monitoring reaches (Independence and Willamette Mission) downstream from the Santiam River confluence.

Water-Quality Conditions of the Willamette River and Adjacent Off-Channel Features

This section presents the results of the 2015–16 water-quality monitoring of the main channel Willamette River and off-channel features and discusses patterns and implications of the data. The results are divided into three subsections focusing on (1) main-channel conditions, (2) off-channel feature conditions, and (3) comparisons between main-channel and adjacent off-channel conditions.

Main-Channel Water-Quality Conditions

Key result—Water in the main channel of the Willamette River upstream from Newberg (fig. 2) in summers 2015–16 was typically well mixed, had warm water temperatures, and had high dissolved-oxygen concentrations.

Spatial and temporal variations in water quality were characterized in the main channel of the Willamette River using continuous water-quality monitors, water-temperature sensors, and synoptic measurements (tables 1 and 2). Main-channel temperatures in the Willamette River generally warmed in June and July and cooled in August and September (fig. 5). Diel temperature fluctuations in the main channel were often between 0.5 and 2.0 °C, with the largest fluctuations occurring in the more-downstream reaches. Longitudinal water-temperature patterns confirmed previous studies (Rounds, 2010) indicating that Willamette River water typically warms in summer as it flows downstream, although cooler inputs from the Santiam River caused localized decreases in temperatures in the main channel (fig. 5). Continuous water-temperature data from two sensors in the main-channel Willamette River about 24 RM apart (upstream: RM 97.7, near Independence; downstream: RM 73.2, near Salem; fig. 2), with no major inputs between, showed that the difference in daily maximum water temperature was less than 1.0 °C. Main-channel water temperatures within a reach (about 10 RM in length) were considered to be nearly identical for some analyses in this report.

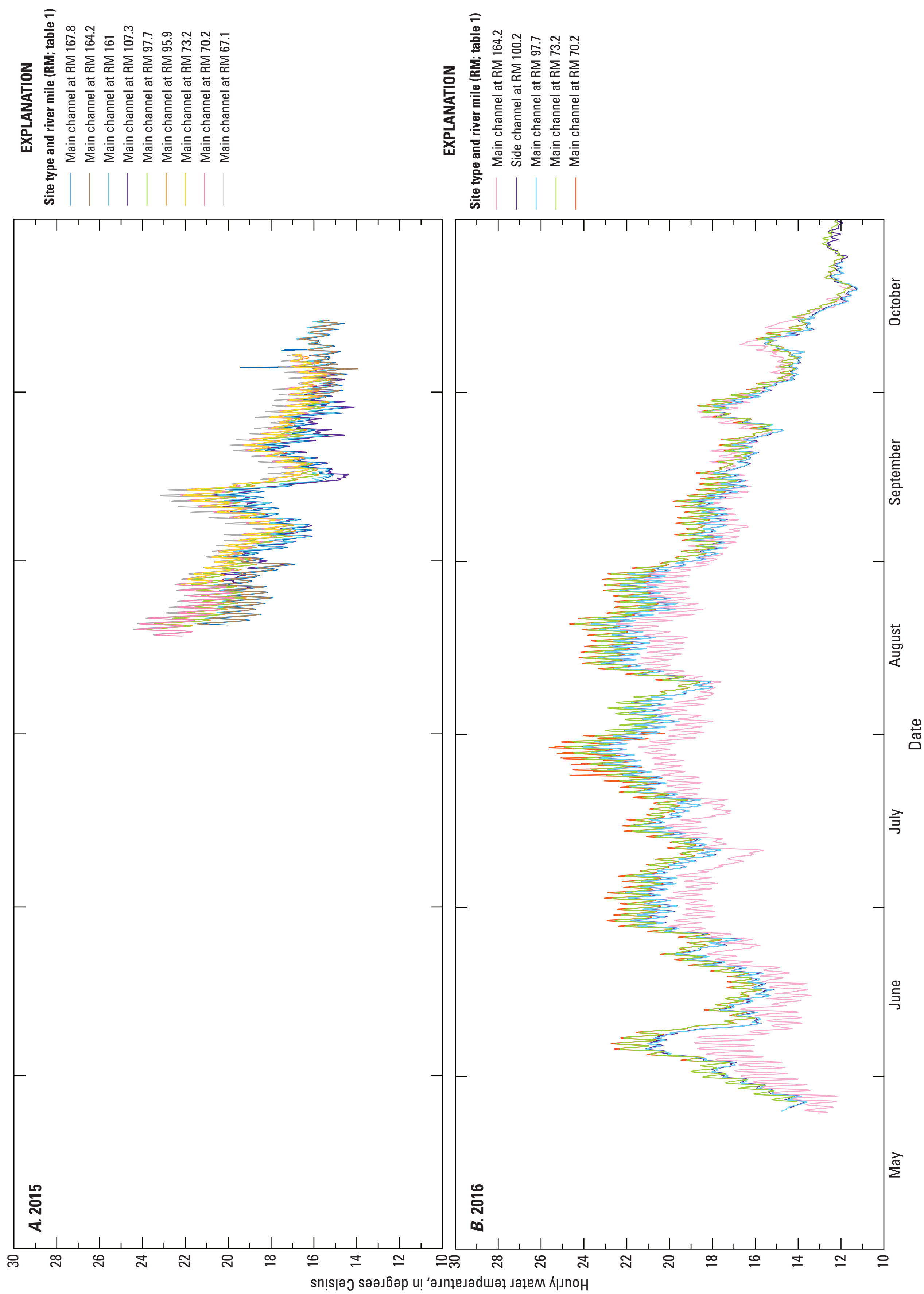


Figure 5. Hourly water-temperature measurements in the main channel Willamette River, Oregon, between river miles 67.1 and 164.2. *A*, late summer 2015. *B*, summer 2016.

Vertical profiles of water-quality measurements showed the main channel to be homogeneous throughout the water column, even at substantial depths. Synoptic measurements at RM 91 (near Independence) on August 27, 2015, were taken at 0.5 and 4.4 m below the water surface, and the difference in water-quality parameters between the depths was minimal (differences: water temperature, <0.1 °C; dissolved oxygen, <0.1 mg/L; specific conductance, zero microsiemens per centimeter at 25 °C; pH, 0.1 standard units). This pattern of main-channel homogeneity was noted throughout all reaches and seasons during synoptic measurements. Relatively well-mixed conditions such as these are consistent with measurements by Gregory and Wildman (2016) and Mangano and others (2018c), which determined that even deep pools (>25 m deep) in the Willamette River tend to be isothermal in summer. The magnitude of main-channel water speed and the scale of turbulence caused by channel shape and morphology probably accounts for this mixing. The “Newberg Pool” and “Portland Harbor” reaches of the Willamette River downstream from RM 50 (not shown) do tend to vertically stratify at times in summer (Mangano and others, 2018c; Rounds, 2010), but this study focuses on reaches upstream from RM 50 where the river tends to be relatively well mixed.

Water temperature in the main channel did not meet the State of Oregon’s summer water-temperature standard for the study area upstream from RM 50 (rearing and migration use: 7dADM ≤18 °C between May 16 and October 14; OAR 340–041–0028(4)(c); Oregon Department of Environmental Quality, 2016a) at times in 2015 and 2016 (fig. 6). For example, continuous water-temperature data from various sites upstream from RM 50 indicated that the river did not meet the rearing and migration criterion from late May (2015; fig. 6*A*) or late June (2016; fig. 6*B*) through mid-September. Water temperature generally increased at more-downstream sites, and 7dADM temperatures reached as high as 24 to 26 °C (fig. 6). Within the study reaches, RMs 70.2, 97.7, and 164.2 reached maximum 7dADM values of 25.0, 23.3, and 21.5 °C, respectively, during 2016 (fig. 6*B*). Upstream reaches tended to warm later and cool earlier than the downstream reaches, except when an upstream site (such as the Willamette River at Owosso Bridge at Eugene, Oregon, USGS station 14158100, RM 178.7; fig. 2) was affected by warmer autumn releases from an upstream reservoir, showing that the upstream reaches of the Willamette River tend to meet the water-temperature standard more often.

Dissolved-oxygen concentrations in the main-channel Willamette River were measured continuously only in the Independence monitoring reach each year. Dissolved oxygen in the Independence monitoring reach typically decreased in late June and July and increased in August and September, largely in response to temperature-related changes in the water solubility of oxygen, which decreases with increasing temperature. Diel fluctuations of 1.5–2.0 mg/L were measured in both years (fig. 7). Continuous dissolved-oxygen concentrations from RM 97.7 (USGS station 444945123095600; fig. 2) met the State of Oregon cold and cool-water minimum dissolved-oxygen criteria (Oregon Department of Environmental Quality, 2016c, table 21) throughout the 2016 monitoring period and were never less than 7.7 mg/L (fig. 7). Longitudinal trends in dissolved oxygen were not determined in this study because only one dissolved-oxygen sensor was deployed in the river each year, and large diel fluctuations in dissolved oxygen make synoptic measurement comparisons (on multiple days and at various times) unreliable. Other studies previously have characterized dissolved-oxygen conditions in the Willamette River. For example, Pogue and Anderson (1995) measured dissolved-oxygen conditions in the Willamette River upstream from Albany in late July and late August of 1994 and determined the river was well oxygenated (dissolved-oxygen concentrations were never less than 80 percent of its water solubility).

Water in the main channel likely remains well-oxygenated for many reasons, such as (1) inputs of well-oxygenated water from upstream, (2) flows that create sufficient turbulence and mixing that enhances reaeration from the atmosphere, (3) primary productivity of periphyton, and (4) only a moderate rate of sediment oxygen demand (Caldwell and Doyle, 1995). The measured diel variations in dissolved oxygen in the Independence monitoring reach are smaller than those that were measured farther upstream by Pogue and Anderson (1995), but many of the upstream reaches they sampled are shallower and known to be more affected by photosynthetic production and respiration by periphyton, which accounts for the difference in diel range. The general seasonal inverse relation between dissolved-oxygen concentration and water temperature measured in the Independence monitoring reach reflects the expected dependence of dissolved-oxygen solubility on water temperature. These dissolved-oxygen results, including the proposed controlling factors, are consistent with the findings of Pogue and Anderson (1995) for areas upstream from Albany.

Continuous data and synoptic measurements from the main-channel Willamette River revealed that the river in summer is well-mixed, warm, and contains high dissolved-oxygen concentrations. Vertical water-quality homogeneity was measured during both seasons and years of the study, and similar main-channel water temperatures persisted for many river miles. Cold-water fishes exposed to these warm water temperatures—warmer than the State of Oregon rearing and migration criterion—for a long period may be negatively affected by that thermal exposure. Additionally, fish confined to the main channel may need to travel substantial distances to find substantially cooler thermal conditions during the warm summer months. The potentially stressful thermal conditions in the main channel emphasize the potential importance of different, and perhaps more favorable, water-quality conditions in off-channel features.

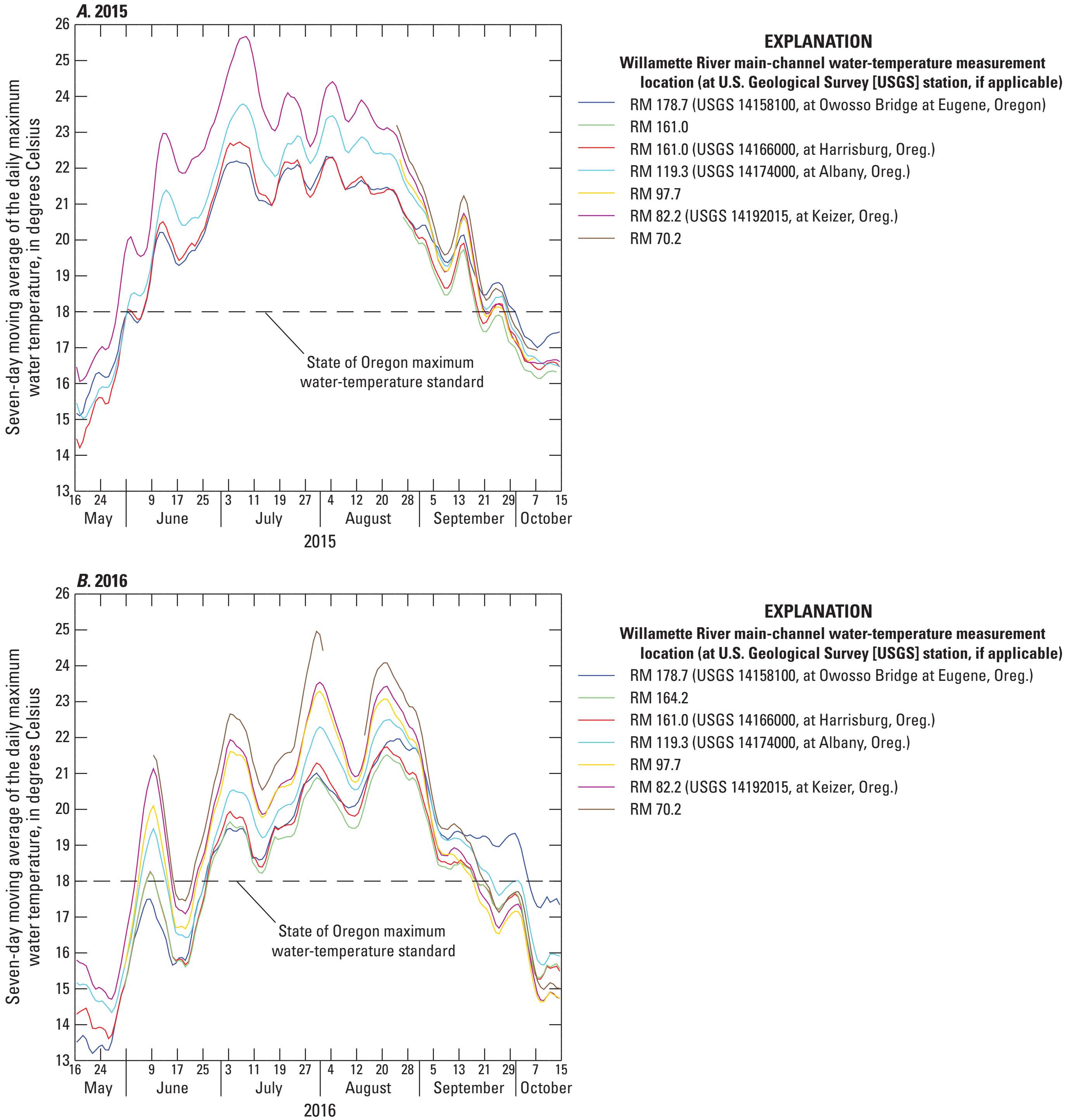


Figure 6. The 7-day moving average of the daily maximum water temperature measured at various sites in the Willamette River, Oregon. *A*, summer 2015. *B*, summer 2016.

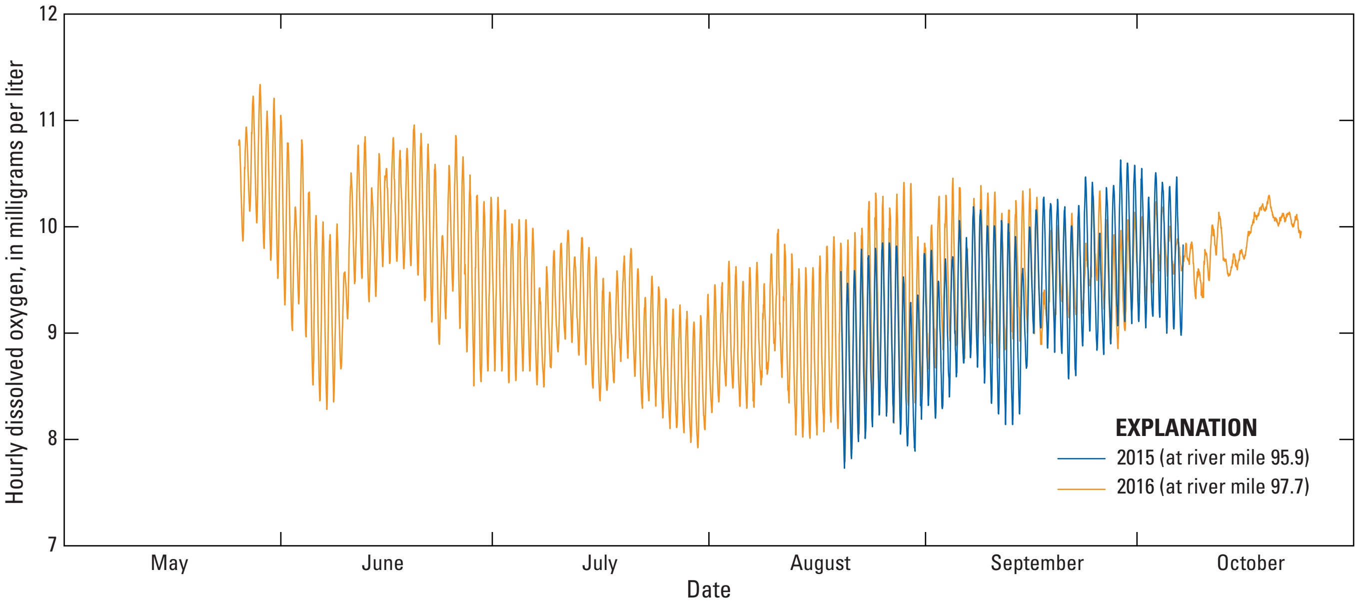


Figure 7. Hourly dissolved-oxygen measurements of the main channel Willamette River, Oregon, in the Independence monitoring reach in late summer 2015 and summer 2016.

Off-Channel Feature Water-Quality Conditions

Key result—Water quality in off-channel features adjacent to the Willamette River typically is heterogenous, varying vertically, longitudinally, and seasonally within a single feature and among features.

Heterogeneity Among Off-Channel Features

Continuous water-temperature sensors deployed in 20 off-channel features in 2015 and 22 features in 2016 showed highly variable temperature patterns and ranges among features (figs. 8 and 9). Instantaneous water temperatures ranged from about 12 to 30 °C, with the highest daily maxima occurring in off-channel features in the Willamette Mission monitoring reach (fig. 2)—the most downstream of the sampled reaches (figs. 8 and 9). In both 2015 and 2016, diel water temperature fluctuations in off-channel features ranged from <1.0 °C to >8.0 °C. Sites that had minimal diel temperature changes tended to be either deep (and vertically stratified in the summer), shaded, or with a sensor position near the bottom of the water column on the substrate (2015 only). Sites with large diel fluctuations tended to be shallow, not shaded, and affected by solar radiation.

Many of the off-channel features followed broadly similar multiday patterns in water temperature, but some off-channel features were consistently cool with patterns that bore no resemblance to main-channel temperatures or weather-related influences. The temperature ranges of off-channel features were highly variable within a study reach, such that no single site's temperature pattern is necessarily representative of a reach (figs. 8 and 9). Reaches contained warm features with large diel fluctuations and cool features with small diel fluctuations. Water-temperature diversity among features was substantial; for example, a comparison of measurements from the Independence monitoring reach (RM 96–101) on July 20, 2016, at 6:30 p.m. Pacific standard time shows that the main-channel water temperature was 20.6 °C, whereas off-channel features within the reach at that time ranged from 13.8 to 26.0 °C (fig. 10). Other reaches displayed similar patterns during the 2015 and 2016 monitoring periods.

Heterogeneity Within Alcoves

Synoptic surveys conducted within alcoves revealed substantial water-quality heterogeneity, often vertically and longitudinally. Water temperatures measured at the top of alcoves were warmer than water temperatures at the bottom of the alcove (fig. 11); temperatures at the top and bottom of the water column varied as much as 7 °C within some features. Dissolved-oxygen concentrations also showed variations between the top and bottom of the water column in alcoves; values varied as much as 11.4 mg/L within one feature (fig. 12). In most alcoves, dissolved-oxygen concentrations at the surface were higher than those at the bottom of the water column. Alcoves with higher dissolved oxygen at the bottom of the water column likely had submerged aquatic vegetation that was producing oxygen through photosynthesis at the time of the measurement. For water temperature and dissolved oxygen, the values and the magnitude of the difference between the top and bottom measurements were dependent on the alcove's morphology, the stage of the river, and the presence or absence of vegetation.

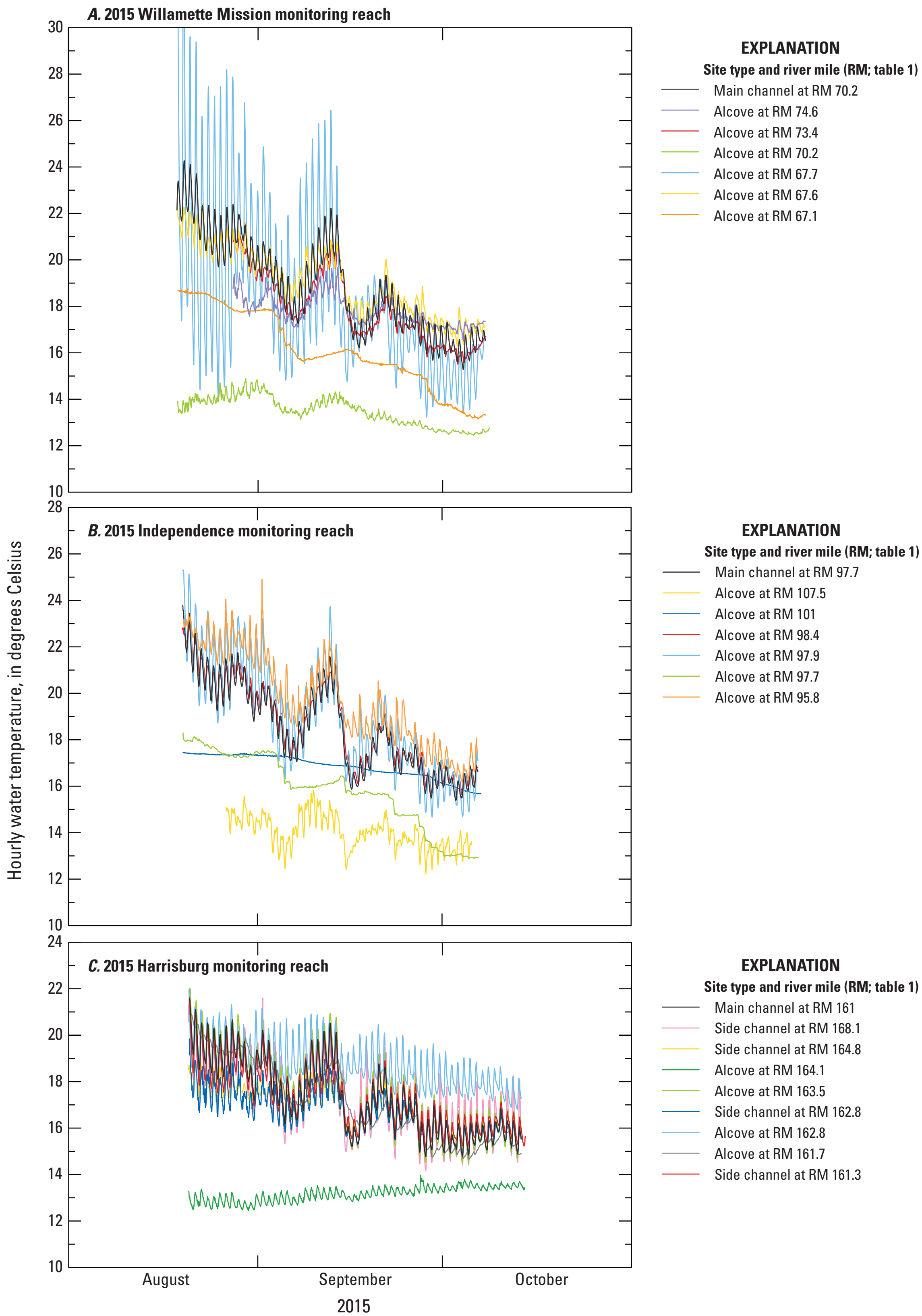


Figure 8. Hourly water-temperature measurements in monitored off-channel features of the Willamette River, Oregon, in late summer 2015. *A*, Willamette Mission monitoring reach. *B*, Independence monitoring reach. *C*, Harrisburg monitoring reach. Note that some temperature records were deleted if data were suspect.

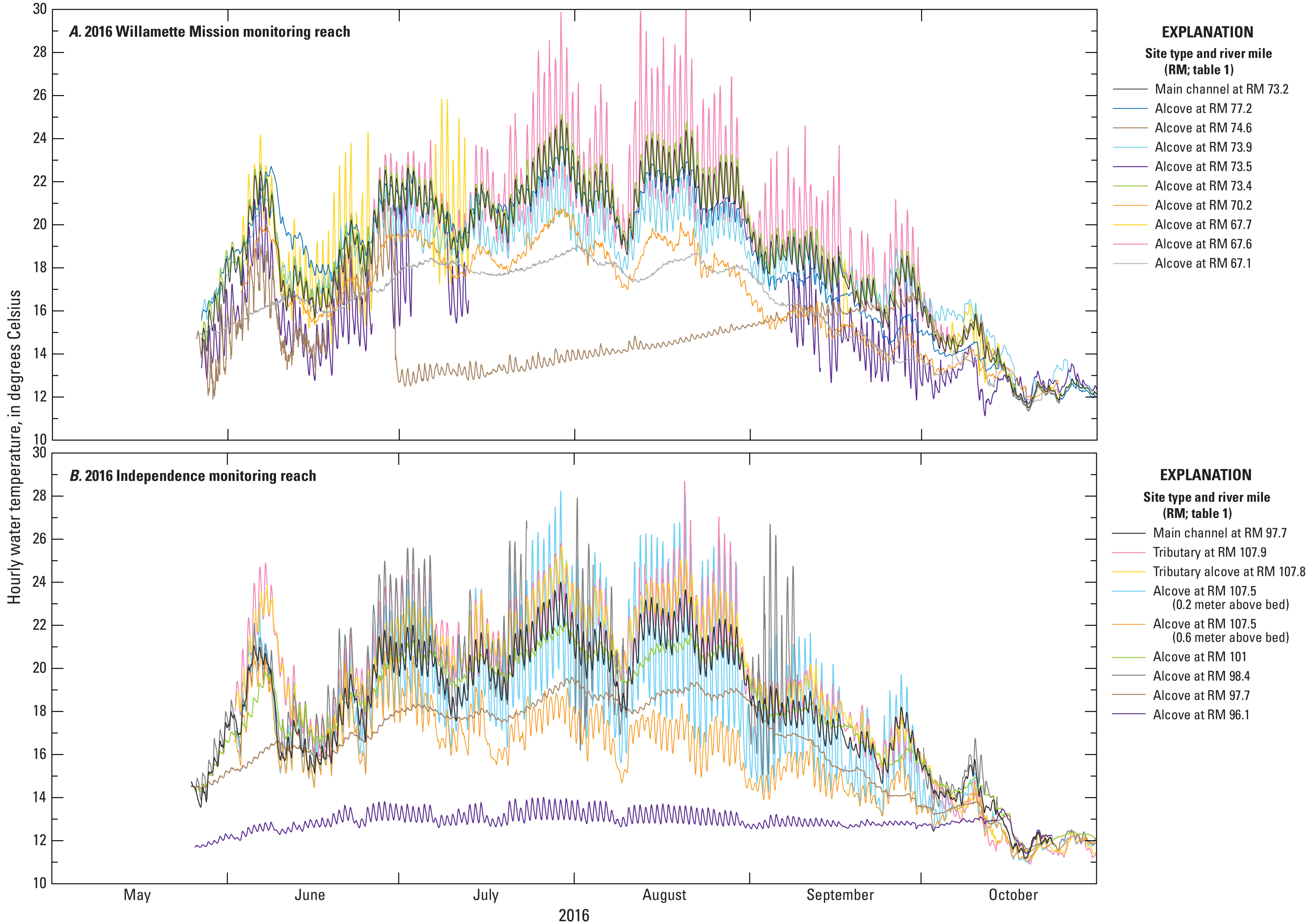


Figure 9. Hourly water-temperature measurements in monitored off-channel features of the Willamette River, Oregon, in summer 2016. *A*, Willamette Mission monitoring reach. *B*, Independence monitoring reach. *C*, Harrisburg monitoring reach. Note that some temperature records were deleted if data were suspect.

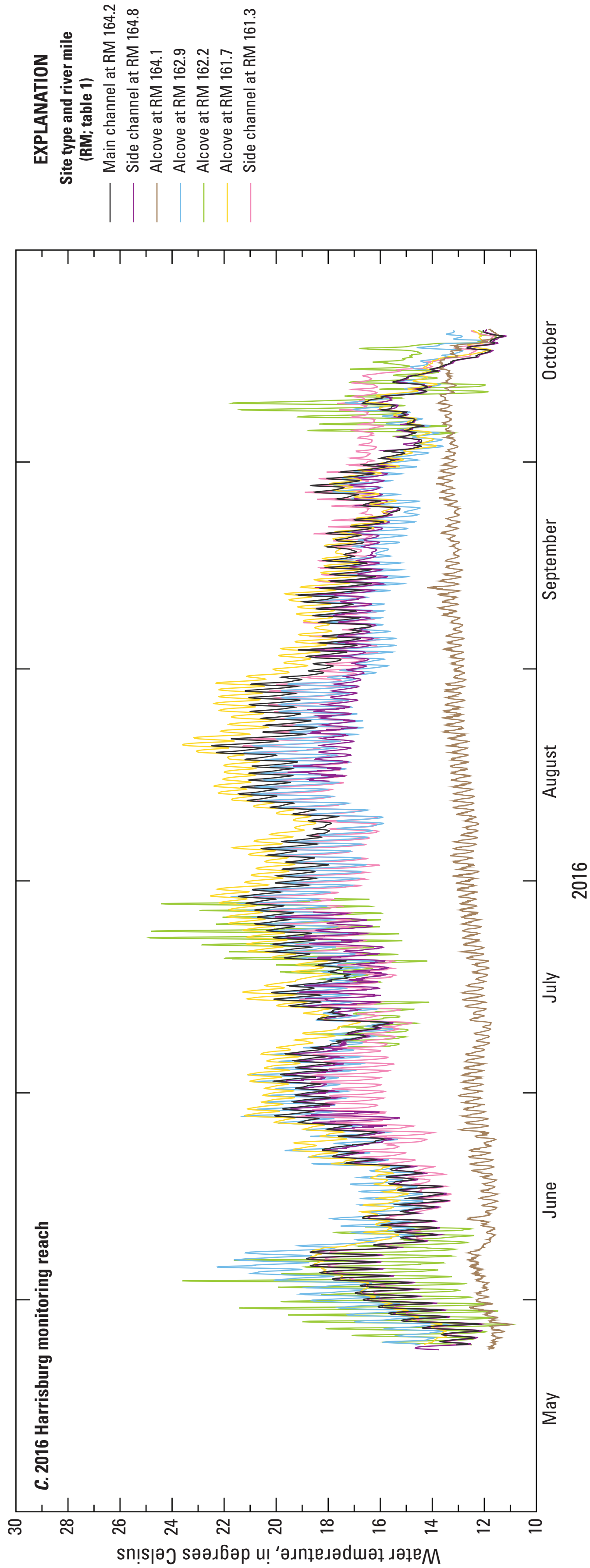


Figure 9. —Continued

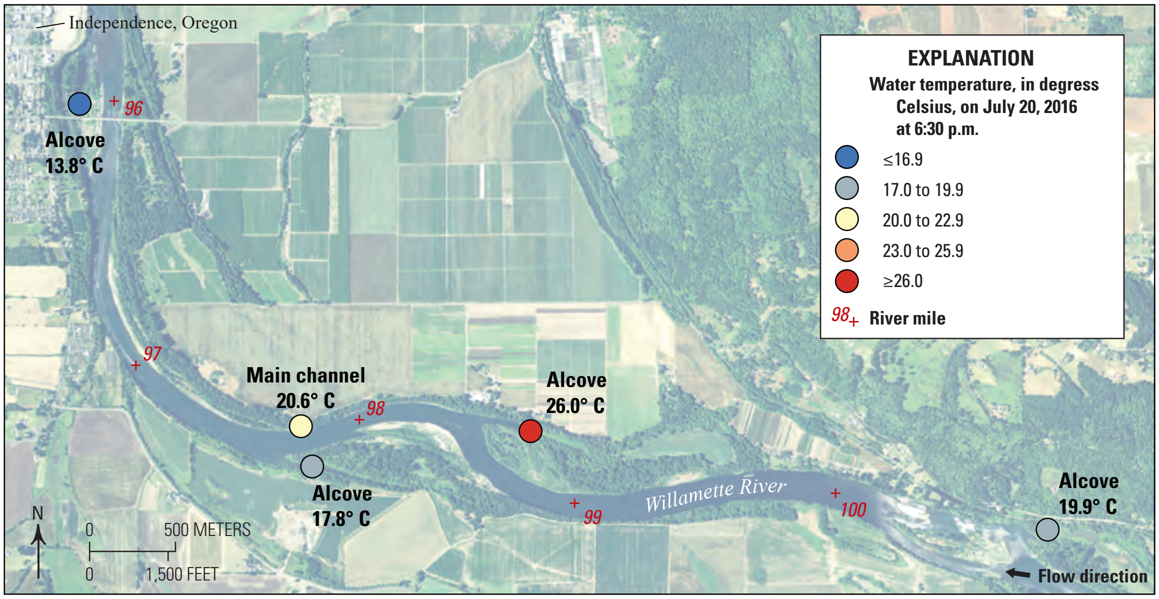


Figure 10. Water-temperature measurements on July 20, 2016, at 6:30 p.m. Pacific standard time in the Willamette River and select off-channel features near Independence, Oregon.

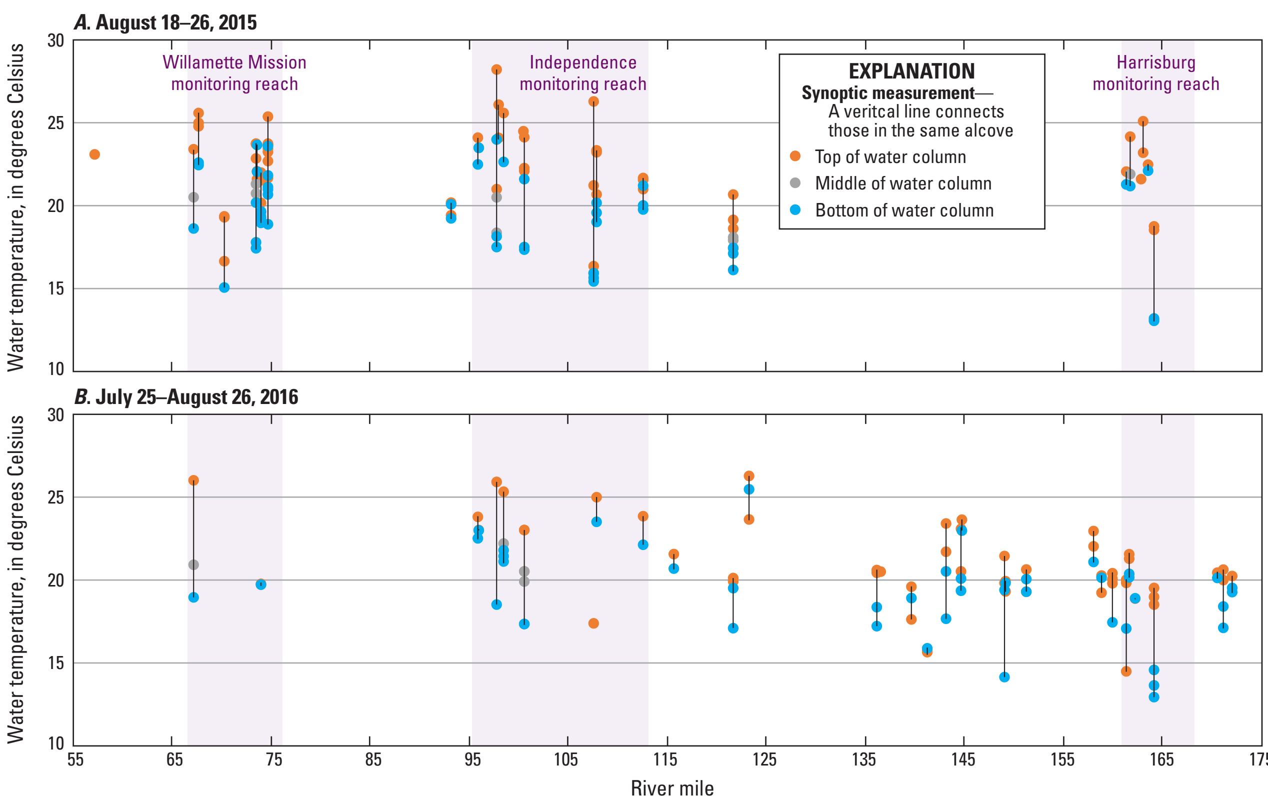


Figure 11. Water temperatures at the top, middle, and bottom of the water column in alcoves in the Willamette River, Oregon. *A*, August 18–26, 2015. *B*, July 15–August 26, 2016. Synoptic data shown are only from alcoves, which were disconnected from the main channel at the upstream end. Shallow alcoves were only measured with one top (near surface) measurement. Often, multiple top and bottom measurements were collected at different locations within a large alcove.

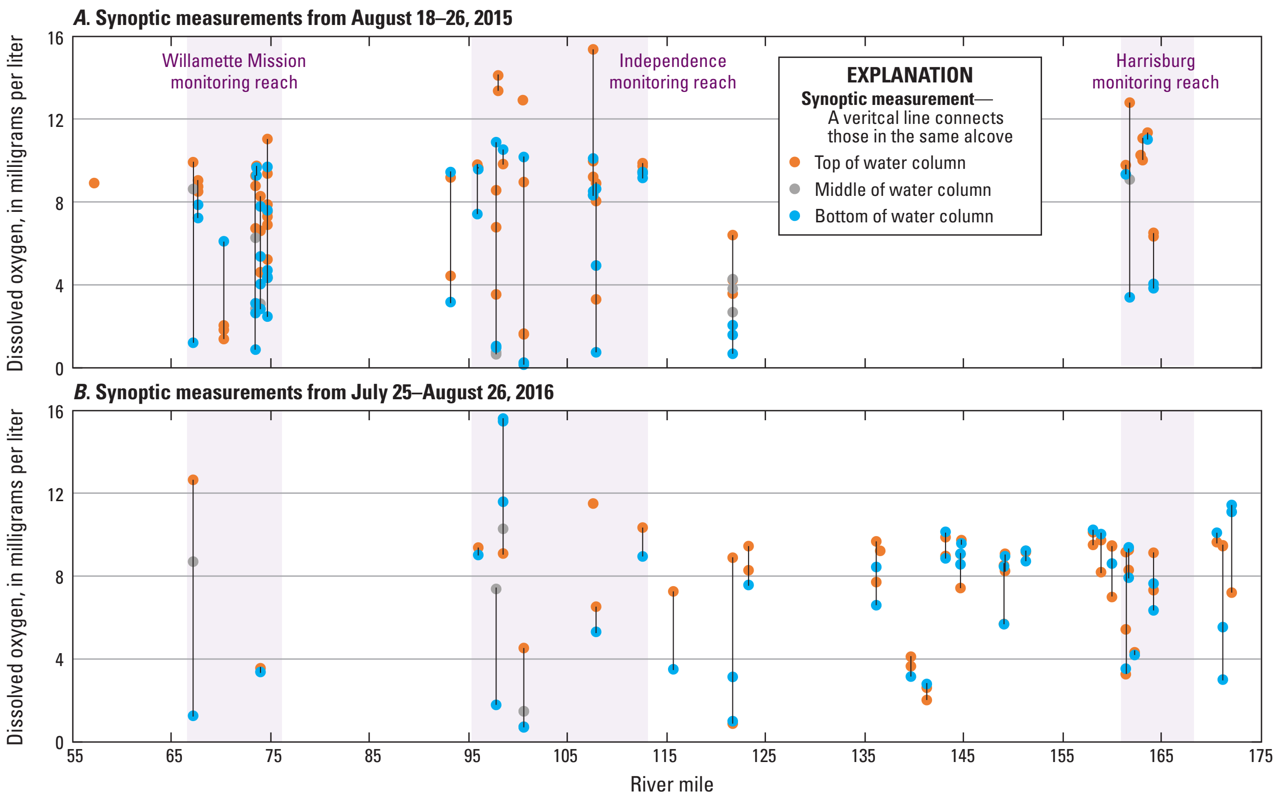


Figure 12. Dissolved-oxygen concentrations at the top, middle, and bottom of the water column in alcoves in the Willamette River, Oregon. *A*, August 18–26, 2015. *B*, July 25–August 26, 2016. Synoptic data shown are only from alcoves, which were disconnected from the main channel at the upstream end. Shallow alcoves were only measured with one top (near surface) measurement. Often, multiple top and bottom measurements were collected at different locations within a large alcove.

A longitudinal profile of water-quality synoptic measurements was collected to examine spatial heterogeneities in the alcove at RM 74.6 on August 27, 2015, at 2:00 p.m. PDT during low river-stage conditions (fig. 13). As shown by measurements collected from the main channel and progressing towards the upstream end of the alcove, water temperatures and specific conductance near the surface generally increased, whereas dissolved-oxygen concentrations near the surface generally decreased. In addition, the vertical heterogeneity (differences between surface and bottom measurements) of water temperature, dissolved oxygen, and specific conductance generally increased from the main channel to the upstream end of the alcove, with dissolved-oxygen concentrations becoming low near the bottom. In 2016, two continuous temperature sensors were installed in an alcove at RM 107.5 at different depths (0.2 m and 0.6 m above the bed). Comparing the readings from these sensors show that vertical heterogeneity can persist for many months in one alcove (fig. 9*B*).

Repeat longitudinal and vertical profiles of water-quality synoptic measurements were collected in the alcove at RM 97.7 on August 19, 2015, and October 7, 2015 (fig. 14). These profiles show overall cooler temperatures in the main channel and the alcove in autumn, yet vertical stratification still exists in both seasons. The difference between top and bottom measurements was less pronounced in October. For both example alcoves (figs. 13 and 14), the downstream portion of off-channel water (nearest the main channel) was likely mixing with water from the main channel, but differences became more pronounced at the upstream end because (1) water was isolated and less affected by water from the main channel and more affected by other factors such as weather conditions; (2) the depth of the feature decreased towards the upstream end, making the water more susceptible to environmental heat inputs and sediment oxygen demands; and (3) subsurface inputs may have been proportionately greater towards the upstream end of the alcove.

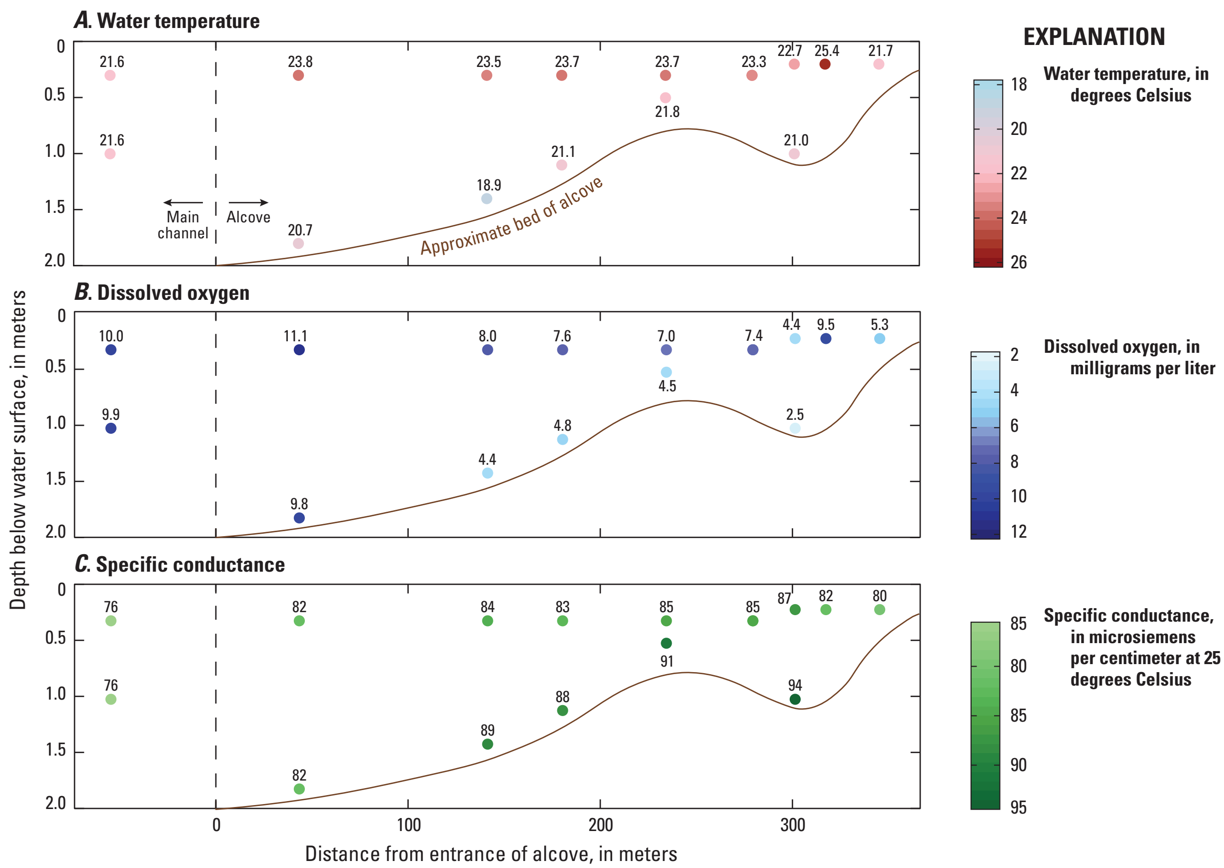


Figure 13. Longitudinal profiles of synoptic point measurements recorded in the alcove at river mile 74.6 along the Willamette River near Salem, Oregon, and adjacent main-channel readings on August 27, 2015, at 2:00 p.m. Pacific daylight time. *A*, water temperature. *B*, dissolved oxygen. *C*, specific conductance.

Factors Affecting Heterogeneity Within and Among Off-Channel Features

Water-quality heterogeneity occurred in off-channel features with various site characteristics. In off-channel features with abundant aquatic vegetation, biological processes greatly affected the water quality. Aquatic vegetation produces oxygen through photosynthesis, and the type of vegetation (submerged or emergent) affects how much dissolved oxygen from photosynthesis is released to the water column as opposed to directly to the atmosphere (Caraco and others, 2006). Large coverages of floating aquatic vegetation may inhibit reaeration of oxygen across the air/water interface. Emergent aquatic vegetation may shade the water underneath and decrease the incoming energy flux from sunlight, resulting in cooler water temperatures at depth. Additionally, an increased sediment oxygen demand due to an accumulation of large amounts of plant-derived organic matter would tend to decrease dissolved-oxygen concentrations near the substrate (Rounds and Doyle, 1997). Although determining the independent effects of plant assemblages (such as submerged, emergent, biofilms) on water quality were beyond the scope of this study, the combined effects often were observed.

Data collected in off-channel features with large quantities of emergent aquatic invasive plants (including *Ludwigia* spp.) revealed a steep vertical stratification in water temperature and dissolved-oxygen concentrations. The highest water temperature measured during a synoptic survey occurred on August 19, 2015, at 5 p.m. PDT in an off-channel feature at RM 97.7 that had abundant emergent aquatic vegetation (fig. 14). The water temperature and dissolved-oxygen concentration at the surface (0.2 m) were 28.2 °C and 6.9 mg/L, respectively (Mangano and others, 2017). At 0.8 m deep (near the bottom), the water temperature was 18.4 °C and the dissolved-oxygen concentration was 0.7 mg/L. In this off-channel feature, the water temperature decreased by about 10 °C and dissolved oxygen by 6 mg/L in 0.6 m of depth; the vertical gradient was similar when measured again in 2016. The cooler water temperatures and lower dissolved-oxygen concentrations may be attributed to decreased solar energy infiltration as the result of shading by aquatic macrophytes and the accumulated effect of respiration and sediment oxygen demand. In contrast, measurements collected in a nearby off-channel feature (RM 98.4; near Independence; fig. 15) on the same date and at a similar time (August 19, 2015, at 3:23 p.m. PDT) showed that water-temperature readings at

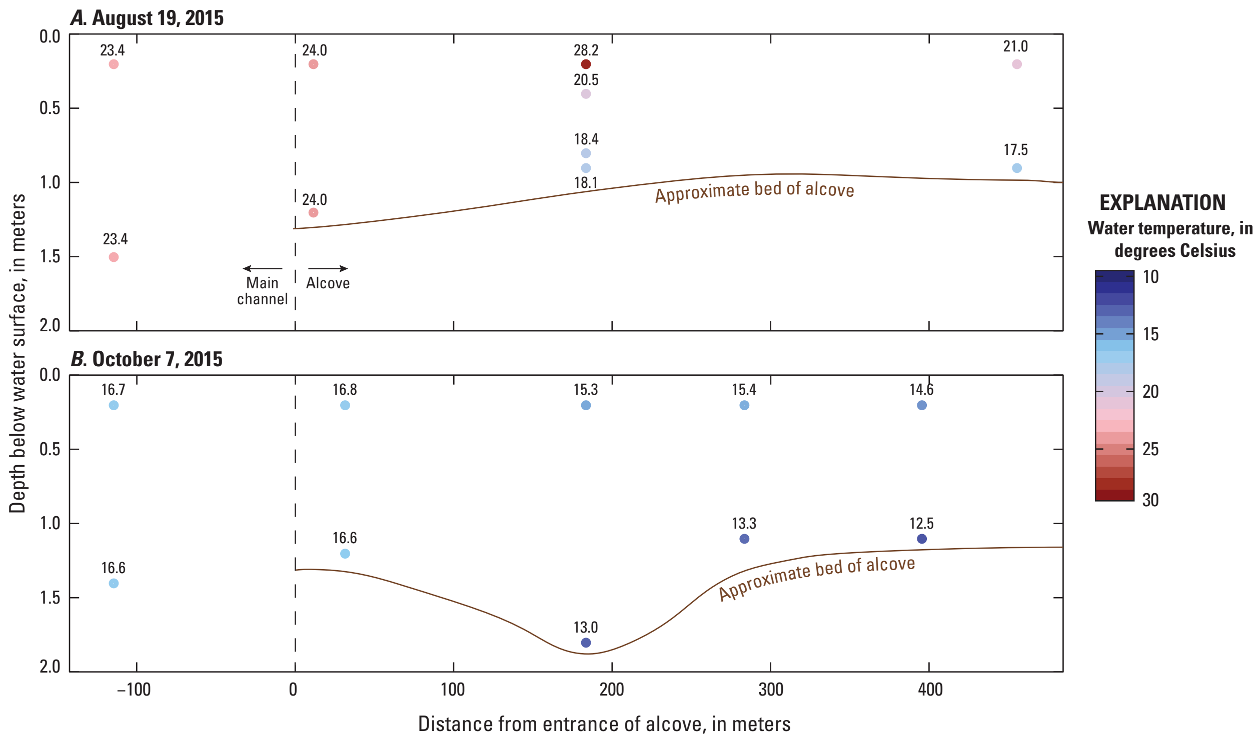


Figure 14. Longitudinal profiles of water-temperature synoptic point measurements recorded in the alcove at river mile 97.7 along the Willamette River near Independence, Oregon, and adjacent main-channel readings. *A*, August 19, 2015. *B*, October 7, 2015.

0.2 and 1.8 m depth differed by about 3 °C. Aerial photographs (taken in 2016) showed that the off-channel feature at RM 98.4 did not contain abundant aquatic vegetation on the surface, which may have contributed to the smaller vertical water-temperature gradient. The morphology of the two alcoves (including the feature's elevation at its upstream seasonal river-connection point) may be critical in determining the amount of aquatic vegetation that establishes in each, with more-frequent flushing flows passing through the alcove at RM 98.4 due to its lower and broader upstream connection point. Surface water passes less frequently through the relatively higher upstream end of the alcove at RM 97.7, which likely allows (or does not disrupt) the establishment of aquatic vegetation and the accumulation of sedimentary organic matter (fig. 15).

Vertical stratification and water-quality heterogeneity also are affected by factors other than aquatic vegetation. Measurements collected in the alcove at RM 164.1 near Harrisburg (on August 20, 2015) showed a 5.5 °C (water temperature) and 2.5 mg/L (dissolved oxygen) decrease between the top (0.1 m) and bottom (3.1 m). This feature did not contain large amounts of aquatic vegetation, and the vertical heterogeneity may have been caused by substantial depth or from subsurface inputs (cooler, with lower dissolved-oxygen levels) that might enter the feature at the bottom. Depth also can affect temperature and dissolved-oxygen concentrations due to decreased sunlight infiltration and a greater separation of bottom waters from the air/water interface. A large fraction of the solar energy flux is absorbed at the surface of the water column, which tends to heat the surface preferentially.

In some off-channel features, continuous temperature measurements clearly documented the presence and persistence of cool water that was largely unaffected by changing weather conditions (figs. 8 and 9). Whereas the water temperature in many off-channel features varied with consistent patterns that seemed to be in response to changes in weather conditions, measurements in alcoves at RMs 67.1, 70.2, 74.6, 96.1, 97.7, 101, 107.5, and 164.1 all showed a substantial disconnection from such weather patterns. Several of these alcoves were distinctly cooler than the main channel and had almost invariant or slowly varying temperatures, which may be indicative of a source of cool water entering the alcove, likely from subsurface inputs. Quantifying subsurface inputs was outside the scope of this study, but no other process can account for such cool water that persists for extended periods during summer.

The off-channel measurements from this study indicate that site-specific characteristics such as subsurface inputs, presence and abundance of aquatic and riparian vegetation, depth, and mixing at the air/water interface may all affect water temperature and dissolved-oxygen conditions in off-channel features of the Willamette River. Biological processes affected by those characteristics, such as photosynthesis and respiration, contribute to the measured heterogeneity. The

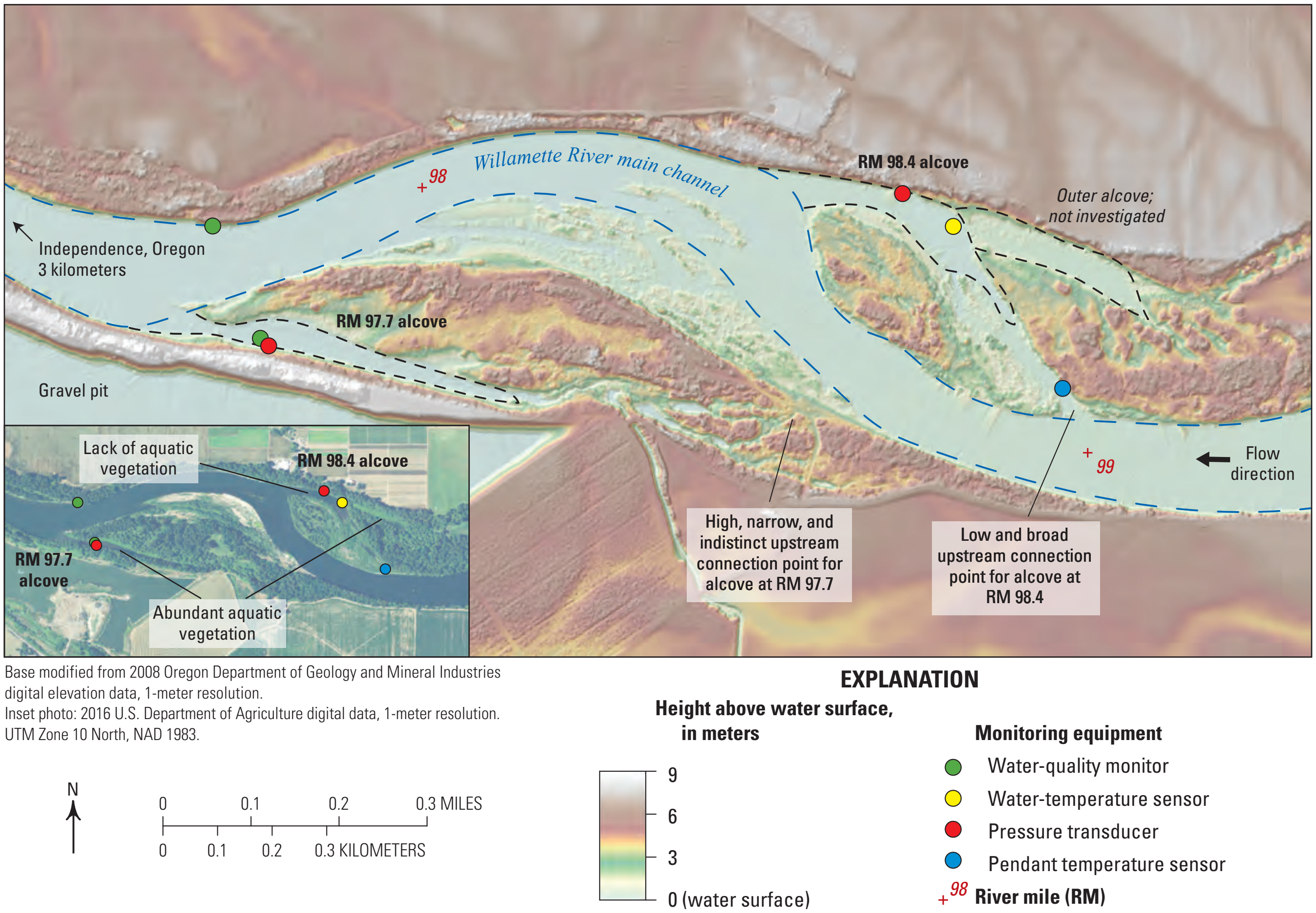


Figure 15. Schematic diagram showing 2008 lidar land-surface elevations and differences in size and height of upstream connection points for alcoves at river miles 97.7 and 98.4 near Independence, Oregon. Mean daily streamflow (discharge) of the Willamette River at Salem, Oregon (USGS gage 14191000) was 9,690 cubic feet per second during lidar acquisition.

relative effects of those characteristics and processes resulted in a wide variety of water-quality conditions found in off-channel features; the water-quality heterogeneity indicates that suitable regions, or microhabitats, within these features likely exist for fishes with various life-history requirements. Each off-channel feature is somewhat unique, but observations of site-specific characteristics, such as the presence or absence of shading, presence and abundance of aquatic plants, and the feature's morphology can help to explain the water-quality conditions occurring in each off-channel feature and categorize them in useful ways.

Comparing Off-Channel and Main-Channel Water Quality

Key result—Water temperatures in off-channel features can be warmer than, can be cooler than, or can fluctuate between warmer or cooler than main-channel temperatures in response to river stage and various site characteristics.

Water-quality conditions in off-channel features can differ from main-channel conditions at all temporal scales measured in this study. Water-quality parameters measured in the main-channel Willamette River serve as a reference for water quality measured in off-channel features. Representing the main-channel water temperature with a single measurement location for a reach is usually acceptable because of the relative homogeneity of temperature conditions in the main channel within each monitoring reach. However, conditions in off-channel features are heterogeneous, and reporting a water temperature from a single off-channel location is not an adequate characterization of off-channel conditions in the reach and may not even be an adequate representation of conditions within that single feature, which complicates data interpretation and the generalization of conclusions.

Synoptic measurements of water temperature and dissolved oxygen revealed substantial thermal diversity at various depths within alcoves and relative to the main channel. When multiple top (near surface) measurements were collected within one feature, the measured values were averaged so that a single "representative" top value could be compared to the closest main-channel synoptic measurement; multiple bottom measurements within one feature were also averaged for comparison (fig. 16). During the summers of 2015 and 2016 (July and August), water temperatures near the bottom of sampled alcoves were on average 1.7 °C cooler than the main channel. Water temperatures at the top of the water column of sampled alcoves were an average of 0.3 °C warmer than the main channel. The bottom water-column temperature was cooler in 77 percent of the features, and the top water-column temperature was cooler in 41 percent of the features compared to the main channel (fig. 16).

Dissolved-oxygen concentrations in the alcoves were often lower than or similar to those measured in the main channel near the feature. Dissolved-oxygen concentrations in the main channel generally fluctuated between 8 and 10 mg/L each day. Of the 60 alcoves with top dissolved-oxygen measurements, 38 percent were less than the main channel (<8 mg/L), 45 percent were similar to the main channel (8–10 mg/L), and 17 percent were greater than the main-channel dissolved-oxygen concentration (>10 mg/L). Of the 53 alcoves with bottom dissolved-oxygen measurements, 60 percent were less than, 27 percent were similar to, and 13 percent were greater than the main-channel dissolved-oxygen concentrations. Of the features with dissolved-oxygen concentrations lower than those in the main channel, many had concentrations less than 4 mg/L, a threshold used by Gregory and Wildman (2016) to indicate dissolved-oxygen levels in which native fish may survive but are still likely to be stressed (fig. 16).

Generally, main-channel water temperatures increased through July or August and then decreased, yet the many continuous temperature sensors deployed in off-channel features show a variety of temperatures compared to the main channel. Although limited to one location all season (on the bed of the feature in 2015 and mid-water column in 2016), the continuous monitors provide temporal patterns that cannot be discerned from the infrequent synoptic measurements. Comparisons between hourly off-channel and main-channel water temperatures revealed three broad categories in summer months: (1) off-channel features that were consistently cooler than the main channel, (2) off-channel features that were consistently warmer than the main channel, and (3) off-channel features with temperatures that fluctuated between warmer and cooler than the main channel, sometimes daily (figs. 17 and 18). Of the three types of off-channel features shown in figure 17, only the alcove at RM 107.5 had temperatures that were at least 2 °C cooler than the main channel at some point during the summer; cool features may act as CWRs for certain species of fish when stressful thermal conditions occur in the main channel.

Off-channel features ranged from about 10 °C warmer than the main channel to 10 °C cooler than the main channel, and patterns of temperature comparisons were diverse (appendix 1). Water-temperature patterns tended to change in autumn when river flows increased and air temperatures decreased. The Willamette Mission monitoring reach had the highest proportion of monitored off-channel features that were cooler than the main channel (fig. 18). Field observations of sampled off-channel features noted the highest occurrence of aquatic invasive *Ludwigia* spp. in that reach. Dense aquatic invasive vegetation was also present in some off-channel features in the Independence monitoring reach (for example, alcove at RM 97.7), and water temperatures in those features were also cooler than the main channel.

A total of 10 off-channel features monitored in this study were cooler than the main channel during July and August 2016 (fig. 18; appendix 1). Five of the 10 features (alcoves at RMs 67.1, 70.2, 73.5, 97.7, and 107.5) contained abundant emergent aquatic vegetation. Three of the 10 cool features (alcoves at RMs 74.6 and 96.1, and side channel at RM 161.3) were bordered by gravel bars that may have been supplying potentially cooler inputs from subsurface flow. Two of the features (alcove at RM 164.1 and side channel at RM 164.8) were bounded by gravel bars and revetments. Site-specific characteristics of these cool features (such as potential subsurface inputs, presence of revetments, and the presence of emergent aquatic vegetation) were not mutually exclusive, and multiple combinations likely could produce cool water in off-channel features.

Three out of the 21 off-channel features monitored in 2016 were warmer than the main channel in July and August (fig. 18; appendix 1). Water-temperature sensors deployed at RM 107.9 and 107.8 were placed in a small, slow-moving tributary and adjacent alcove, respectively. The off-channel feature at RM 161.7 was relatively shallow (2.1 m) and may (or may not) have been affected by runoff from gravel mining operations that bordered the site.

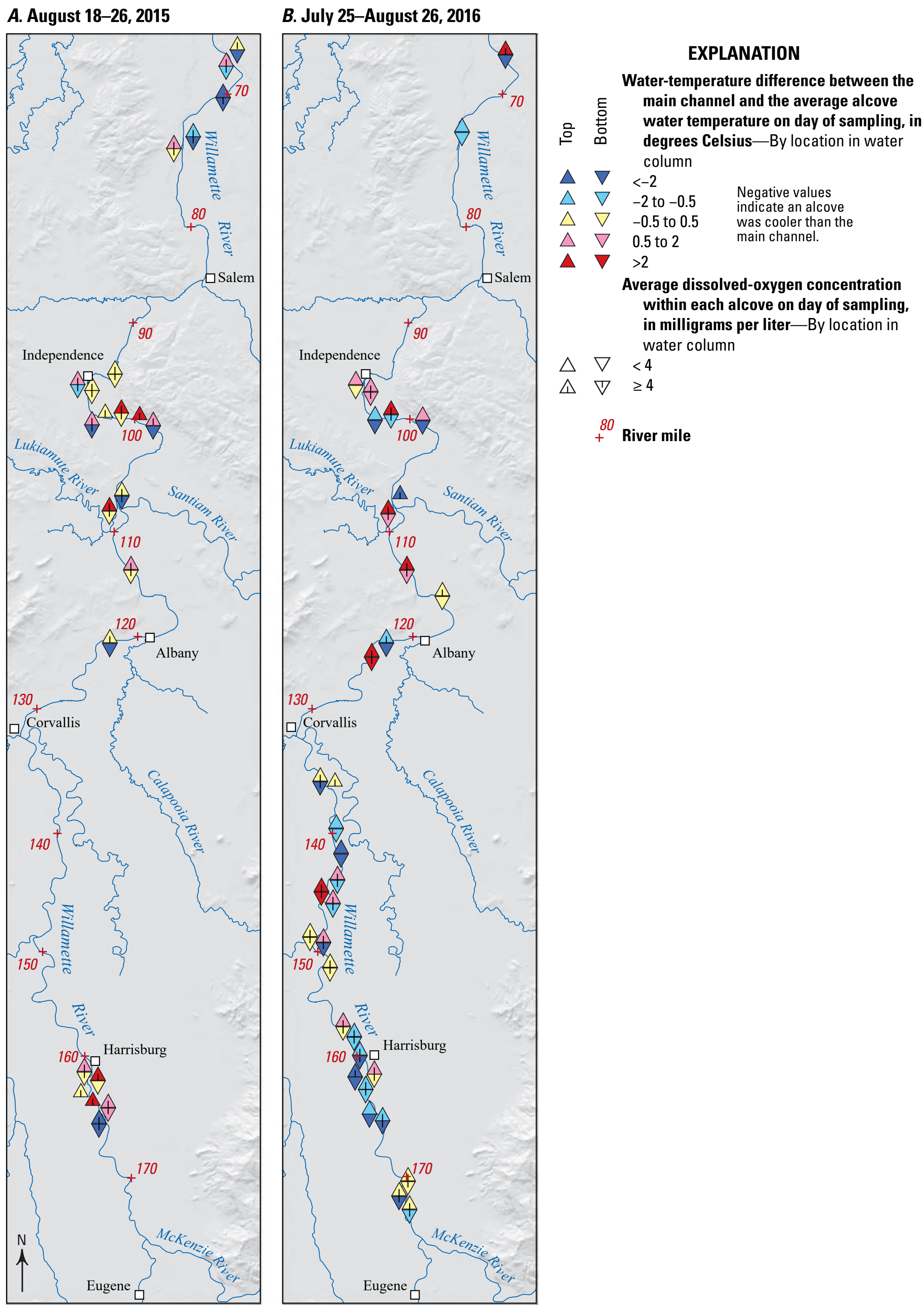


Figure 16. Average water-temperature differences between alcoves and the main channel, and averaged dissolved-oxygen concentrations in alcoves, measured at the top and bottom of the alcove's water column, in the Willamette River, Oregon. *A*, August 18–26, 2015. *B*, July 25–August 26, 2016.

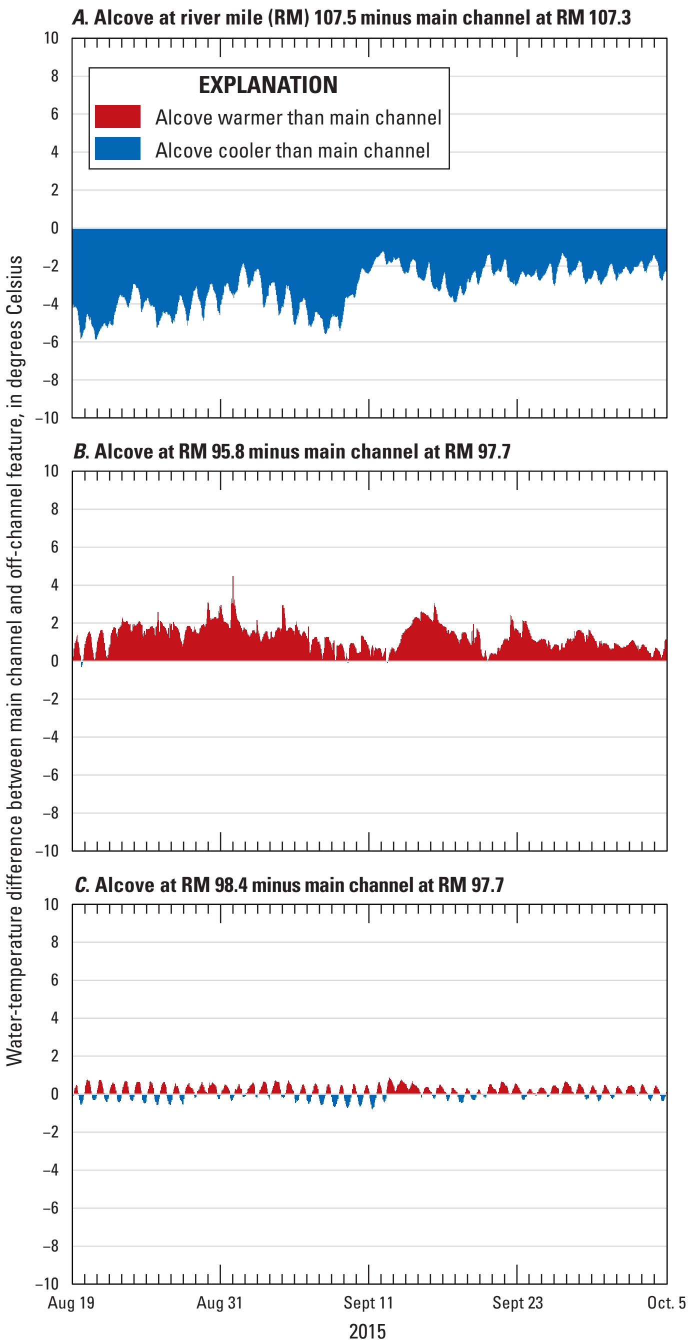


Figure 17. Examples of three types of patterns resulting from a comparison of water temperatures in the main channel and in several off-channel features of the Willamette River, Oregon. These data were collected in the Independence monitoring reach in 2015, and sensors were located at the bottom of the feature. *A*, alcove cooler than the main channel. *B*, alcove warmer than the main channel. *C*, alcove fluctuated between warmer and cooler than the main channel.

Many of the off-channel features that fluctuated between warmer and cooler than the main channel in July and August alternated daily, whereas others fluctuated at different intervals with no obvious pattern (appendix 1; figs. 8 and 9). Daily fluctuations in temperature differences may simply have been due to a larger diel temperature range in the off-channel feature relative to the main channel. The main channel typically is deeper and contains more water than the off-channel features per unit surface area. As a result, the heat content in the main channel relative to the heat flux across the air/water interface is larger than in off-channel areas, and main-channel temperatures will change less over the course of a day when exposed to the same environmental heat fluxes across the air/water interface. Alternatively, the fluctuations in temperature differences may be partly due to a lag in peak water temperature caused by subsurface flows moving through surrounding gravel bars on different time scales (Arrigoni and others, 2008). Water-temperature sensors were deployed on the bottom of off-channel features in 2015, potentially making them more susceptible to the effect of subsurface inputs through the substrate as compared to measurements collected in 2016. In 2015, more off-channel features with water-temperature differences that fluctuated daily between warmer and cooler than the main channel were found in the Independence and Harrisburg monitoring reaches compared to the Willamette Mission monitoring reach, which may be related to the importance of subsurface flows moving though the larger and more numerous active gravel bars found in the upper reaches of the Willamette River than are typically found in more-downstream reaches. Half of the fluctuating off-channel features measured water temperatures that were 2 °C cooler than the main channel for at least 1 hour in July or August (appendix 1); however, the length of time that the water temperature in the feature was 2 °C cooler than the main channel varied, and any potential value as a cold-water refuge to sensitive fish is unknown.

Effect of Upstream Morphology on Water Quality in Off-Channel Features

Off-channel water quality can change abruptly when upstream surface-water connection and disconnection occurs (effectively turning an alcove into a side channel, and back again), or when quick rises in river stage cause main-channel water to flow into an alcove from the downstream connection point (see fig. 3). The upstream end of an off-channel feature becomes connected by surface water to the main-channel flow when river stage reaches a critical height and overtops the landmass separating an alcove from the main channel. River stage and the geomorphology of the off-channel feature are key factors that dictate when

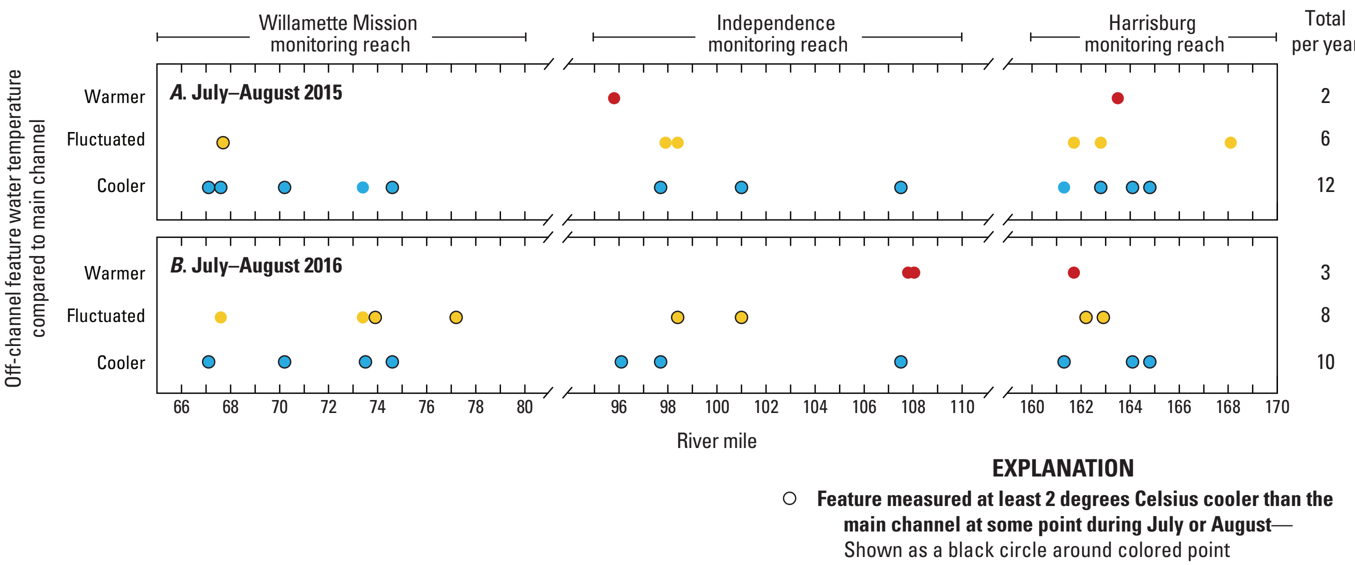


Figure 18. Categories of features based on water-temperature comparisons to the main channel in the three monitoring reaches of the Willamette River, Oregon. *A*, July–August 2015. *B*, July–August 2016. Water-temperature sensors were deployed on the bottom of the main channel and off-channel features in 2015 and in the middle of the water column in 2016. An off-channel feature was considered "cooler than the main channel" if it was cooler during the warmest months of the summer monitoring period (July–August; when Willamette River streamflow is at its lowest).

upstream connection/disconnection occurs, how much streamflow enters the off-channel feature, and how long that connection persists. Willamette River streamflow in the summer of 2015 and the late summer of 2016 was unusually low for the modern flow-management era (since 2000; fig. 4), so the timing and duration of any connection or disconnection in other years may be different from what was observed in this study.

In addition to the morphology and elevation of a feature's upstream connection point, other geomorphic characteristics, such as the composition of the substrate and landforms bounding a feature, are critical in determining the potential magnitude and flow paths of any subsurface inputs. Water can more easily travel through coarse gravel substrate than fine floodplain material or bedrock; thus, an alcove adjacent to landforms primarily composed of gravel (such as active bars and stable bars) may be more likely to receive substantial inputs of subsurface flows than features adjacent to landforms composed of less-permeable material (such as Pleistocene terraces, bedrock outcrops, or floodplains; Burkholder and others, 2008). Water color may indicate the potential paths of water inputs or the presence of organic matter present in off-channel features; for example, natural subsurface inputs are likely to be colorless (Chapelle and others, 2016) and may be visible in an alcove with highly colored water that has an accumulation of organic matter from aquatic or terrestrial plants. Colored subsurface inputs may indicate a dynamic exchange between surface and subsurface water (Regan and others, 2017).

Examples of the Relations Between Geomorphology, Surface-Water Connectivity, and Water Quality of Off-Channel Features

Key result—Upstream surface-water connection and disconnection, and related site characteristics, are important factors affecting water quality in off-channel features.

The patterns in the off-channel water temperatures collected in this study were the combined result of multiple processes and site characteristics, such as connections to the main channel, shading or lack of shading, stratification, presence or absence of submerged or emergent aquatic plants, and the magnitude and nature of any subsurface inputs. Using known site characteristics, some patterns in the data can be tied to certain processes, and strong hypotheses can be constructed to explain other patterns. Relying on water-temperature data alone, however, is insufficient to conclusively determine the processes that produce all patterns in the data. To better understand which processes are important, such as the timing and strength of upstream surface-water connection and disconnection, other datasets were needed. Data from dissolved-oxygen sensors, pendant temperature sensors, pressure transducers, and nearby streamgages were helpful in determining when upstream connection or disconnection may have occurred. Because multiple lines of evidence were needed, this analysis and discussion of upstream connections focuses on the five off-channel features where multiple types of equipment (specifically multiparameter water-quality monitors and, in some features, pendant temperature sensors and pressure transducers) were deployed in 2016 among the three monitoring reaches (fig. 19).

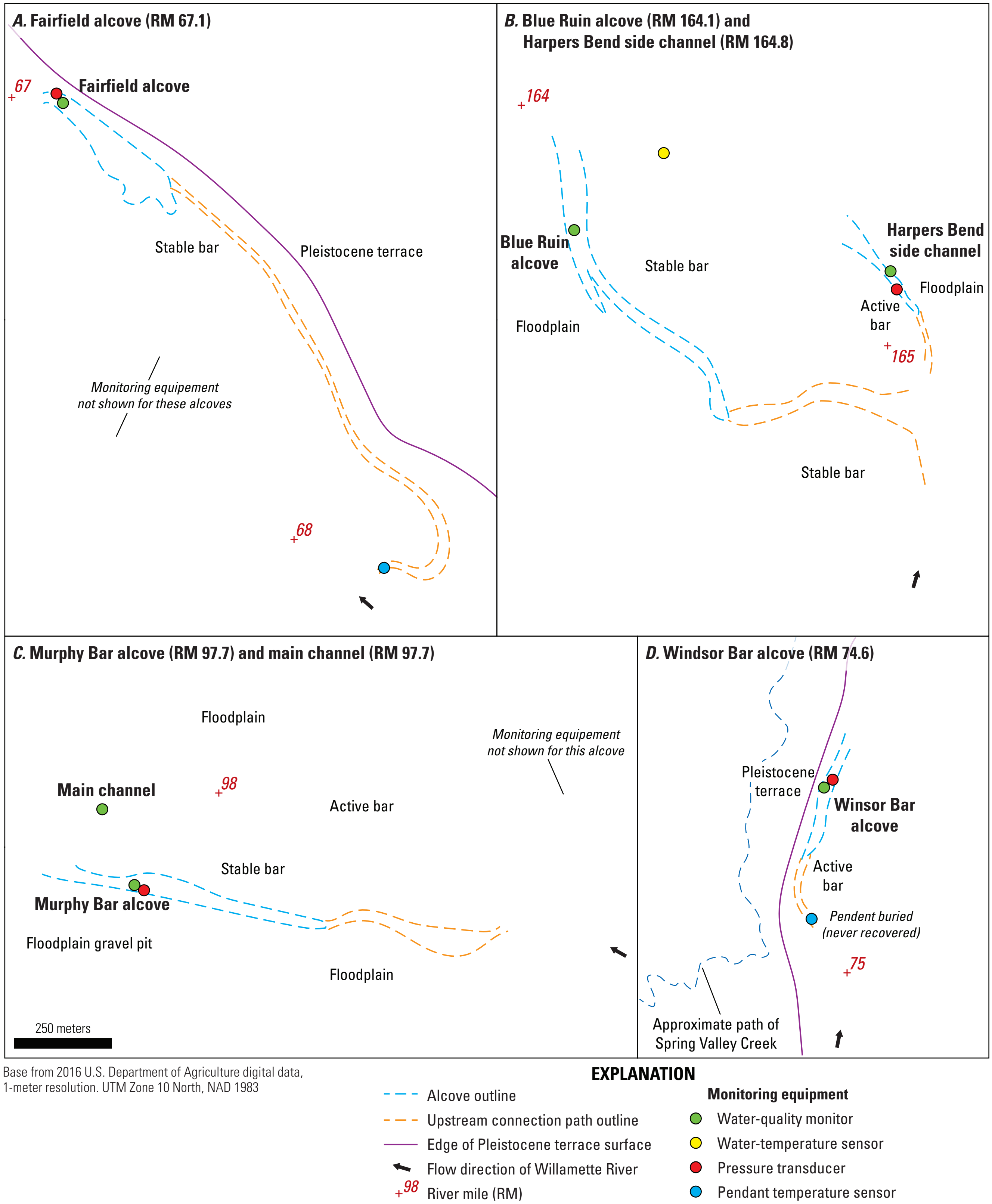


Figure 19. Location and important geomorphic features of five off-channel features and one main-channel location monitored with continuous water-quality monitors in summer 2016 along the Willamette River, Oregon. *A*, Fairfield alcove (river mile [RM] 67.1). *B*, Blue Ruin alcove (RM 164.1) and Harpers Bend side channel (RM 164.8). *C*, Murphy Bar alcove (RM 97.7) and main channel (RM 97.7). *D*, Windsor Bar alcove (RM 74.6).

Fairfield Alcove

The Fairfield alcove at RM 67.1 (fig. 19*A*) near Salem is a large off-channel feature between a stable bar and a tall Pleistocene terrace surface (O'Connor and others, 2001; fig. 19*A*; table 5). It functioned as an alcove during typical summer low flows in 2015–16 and connected to the main channel at the upstream end during moderate flows. To connect the upstream point of this feature with the main channel required an increase in stage of about 1 m compared to summer low-flow conditions, as estimated from field observations and from 2008 lidar data. This feature had narrow connection points at the upstream and downstream ends. Water in Fairfield alcove was highly colored (likely from tannins) compared to the main channel, and aquatic vegetation (*Ludwigia* spp., among others) was abundant. Maximum depth measured during low-flow synoptic visits was 1.3 m, and more than 0.5 m of soft, unconsolidated organic matter had accumulated at the bottom in many areas. Historical aerial photographs showed that this feature has remained stable since 1994 (appendix 2).

A water-quality monitor was deployed in this alcove in May 2016, and the upstream end of this off-channel feature was already disconnected from the main channel as observed in the field during equipment installation. Negligible dissolved-oxygen concentrations were measured during the study period until mid-October, when streamflow in the Willamette River (measured at the Salem streamgage; USGS station 14191000) increased from 10,000 to more than 40,000 ft^3/s in 6 days. Pendant temperature data collected at the upstream end of this off-channel feature revealed that the upstream end reconnected when streamflow at the Salem streamgage was around 25,000 ft^3/s. During this increase in flow, the river began flowing into the off-channel feature, first at the downstream end and then at the upstream end, flushing the feature with river water and increasing the dissolved-oxygen concentration from zero mg/L to about 9 mg/L and the water temperature from 12.5 °C to about 14.0 °C (similar to the main-channel dissolved-oxygen and water-temperature conditions at the time; fig. 20).

Increases in main-channel streamflow may affect off-channel water quality through an influx of water into the off-channel feature at its downstream end, even if the feature remains disconnected at its upstream end. Dissolved oxygen and water temperature in the Fairfield alcove responded to two short-duration flow increases in early October 2016. Streamflow at Salem increased twice from 7,000 to 13,000 ft^3/s between October 6 and October 8, 2016, which corresponded to a 0.6-m increase in stage at the Salem streamgage; pendant data revealed the stage increase was not enough to connect the upstream end of the alcove to the river. Main-channel water likely flowed into the feature at the downstream connection point due to a difference in stage between the main channel and alcove, indicated by the temporary increase in water temperature and dissolved-oxygen concentration in the alcove (fig. 20). Such water inputs at the downstream entrance of the alcove could also explain why the increase in dissolved-oxygen concentration started on October 14, 2 days before the pendant temperature data showed the upstream connection of the off-channel feature.

Windsor Bar Alcove

The Windsor Bar alcove is a relatively small off-channel feature at RM 74.6 that is between an active gravel bar and a tall Pleistocene terrace surface in a reach of the river that is straight and lacks channel complexity (O'Connor and others, 2001; fig. 19*D*; table 5). Spring Valley Creek is 150 m away, behind the Pleistocene terrace wall to the west of this feature and is 3 m higher in elevation than the side-channel water surface during the summer. The upstream end of the off-channel feature is connected to the main channel at all but unusually low flows; such unusual low flows did occur during this study, allowing data to be collected when this feature was an alcove. At moderate and high flows, surface water from the main channel overtops the bounding gravel bar and the feature is no longer separated from the main channel. Water in the feature is typically clear but has distinct areas of opaque, whitish water, possibly due to the erosion of sediment out of the silty, light-colored Pleistocene terrace wall. Aquatic vegetation in 2016 was minimal, perhaps because this off-channel feature often receives high river flows, and the bed is composed of hard, coarse-grained material. Maximum depths measured during low-flow synoptics were 1.8 m (fig. 13). Historical aerial photographs show that the gravel bar separating this feature from the main channel has transitioned from a stable bar with dense vegetation to an active bar with little vegetation between 1994 and 2016 (appendix 2).

Data from this site illustrate that rapid, distinct changes in water-quality parameters occurred within the alcove when the upstream end of the feature became disconnected from main-channel surface flow. When the monitoring equipment was installed in late May 2016, the upstream end of this feature was connected to the main channel. It is likely that the upstream end of the feature became disconnected on June 30 when streamflow at the Salem streamgage was approximately 8,200 ft^3/s; the disconnection was visually confirmed during a site visit in late July. Over the course of only 1 hour, water temperature in this feature decreased by 5 °C, dissolved oxygen decreased by 5 mg/L, and specific conductance increased by 10 microsiemens per centimeter at 25 °C (fig. 21). Subsurface inputs with long flow paths (about >100 m) are often cool in summer and tend to have a steady temperature (Poole and others, 2008), with low dissolved-oxygen concentrations and elevated specific conductance (Ebersole and others, 2003; Hinkle and others, 2014). Subsurface inputs were likely a contributing source to this off-channel feature, which became apparent when it transitioned from a side channel to an alcove. Although the subsurface inputs were likely contributing when the feature was both a side channel and an alcove, these water-quality changes suggest that subsurface flows have a more dominant effect on this feature's water quality when it is an alcove.

Table 5. Observational data collected at five off-channel features along the Willamette River, Oregon, where water-quality monitors were deployed in summer 2016.

[**Maximum depth:** Maximum depth during summer low flow synoptic point measurements. **Feature type at different flow conditions:** See section, "Terminology" for definitions of relative flow terms. **Abbreviation:** RM, river mile]

Site name and river mile (fig. 19)	Wetted area during summer low flows (square meters)	Maximum depth (meters)	Open water aquatic vegetation	Dominant bed texture and substrate	Water clarity	Upstream connection	Feature type at different flow conditions
Fairfield alcove RM 67.1	32,000	1.3	Abundant	Soft; unconsolidated fine sediments and organic matter	Highly colored (tannins) and low transparency	Relatively narrow connection point; distinct channel over stable floodplain	Unusually low: alcove Low: alcove Moderate: side channel High: side channel
Windsor Bar alcove RM 74.6	9,000	1.8	Sparse	Hard; sand and gravel	Clear with localized light-colored opaque (silty) areas	Flow over an active gravel bar	Unusually low: alcove Low: side channel Moderate: main channel High: main channel
Murphy Bar alcove RM 97.7	23,000	1.2	Abundant	Soft; unconsolidated fine sediments and organic matter	Highly colored (tannins) and low transparency	Narrow connection points; flow over densely vegetated stable bar	Unusually low: alcove Low: alcove Moderate: unknown High: side channel
Blue Ruin alcove RM 164.1	35,000	3.1	Sparse	Hard; sand and gravel	Clear, high transparency	Wide and low connection points; flows over stable and active gravel bar	Unusually low: alcove Low: likely alcove Moderate: side channel High: side channel
Harpers Bend side channel RM 164.8	6,000	2.4	Moderate	Hard; sand and gravel	Clear, moderate transparency	Flow behind active gravel bar (continuously connected through this study)	Unusually low: side channel Low: side channel Moderate: main channel High: main channel

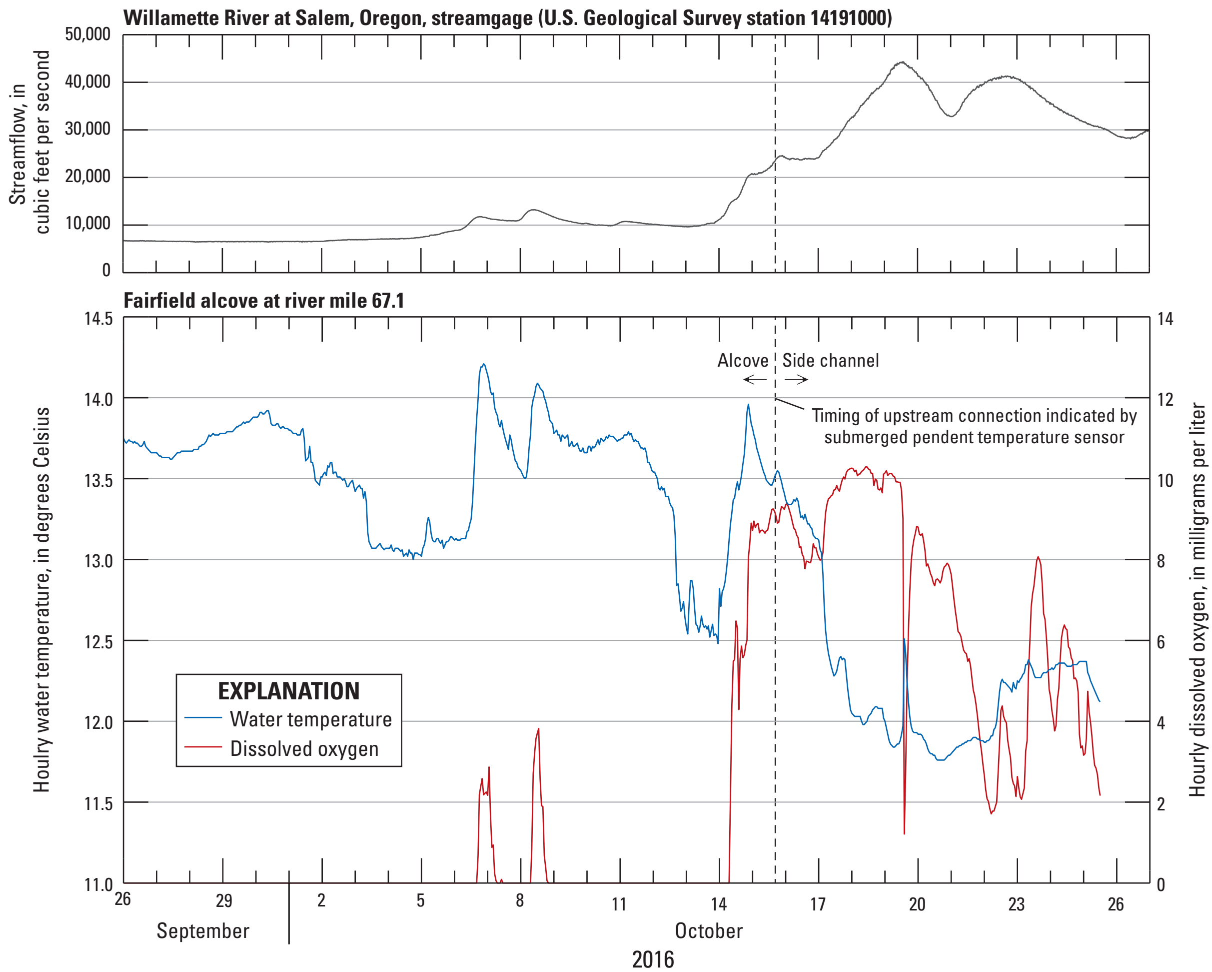


Figure 20. Hourly water-temperature and dissolved-oxygen measurements in the Fairfield alcove at river mile 67.1 along the Willamette River, Oregon, and streamflow at the Willamette River at Salem, Oregon, streamgage (U.S. Geological Survey station 14191000) in September and October 2016.

Murphy Bar Alcove

The Murphy Bar alcove at RM 97.7 sits between a stable bar with mature trees and a floodplain berm with a gravel pit behind it (fig. 19*C*; table 5). This alcove has a narrow upstream connection that is overtopped at high flows; however, even then, main-channel flow into the alcove likely would be minimal and have reduced velocity because of the constricted connection (fig. 15). Water in the alcove is highly colored, and abundant aquatic vegetation (*Ludwigia* spp., among others) is present, especially along the north end of the feature. Mature trees surround the alcove, and the substrate is composed of a thick (about 1-m) layer of unconsolidated organic matter. Maximum depths measured during low-flow synoptics were 1.2 m. Historical aerial photographs show that this feature has remained stable since 1994 (appendix 2).

This off-channel feature functioned similarly to Fairfield alcove during the 2016 monitoring period and showed that water quality can change because of main-channel surface-water inputs from the upstream and downstream ends of the feature. Murphy Bar alcove had been recently connected to the main channel when the water-quality monitor was installed, but dissolved-oxygen concentrations (measured 0.6 m above the substrate) decreased after installation and began approaching zero mg/L. The patterns observed in the dissolved-oxygen data suggested that oxygen consumption occurred; given the observed conditions in the alcove discussed above, consumption is probably the result of respiration and organic-matter decomposition and a lack of oxygenated upstream surface-water input. The dissolved-oxygen concentrations remained low (generally around zero mg/L) all summer until river flows increased in October (fig. 22). The months of anoxic conditions measured at this site were likely due to a high sediment oxygen demand derived from the large accumulation of sedimentary organic matter observed in the alcove.

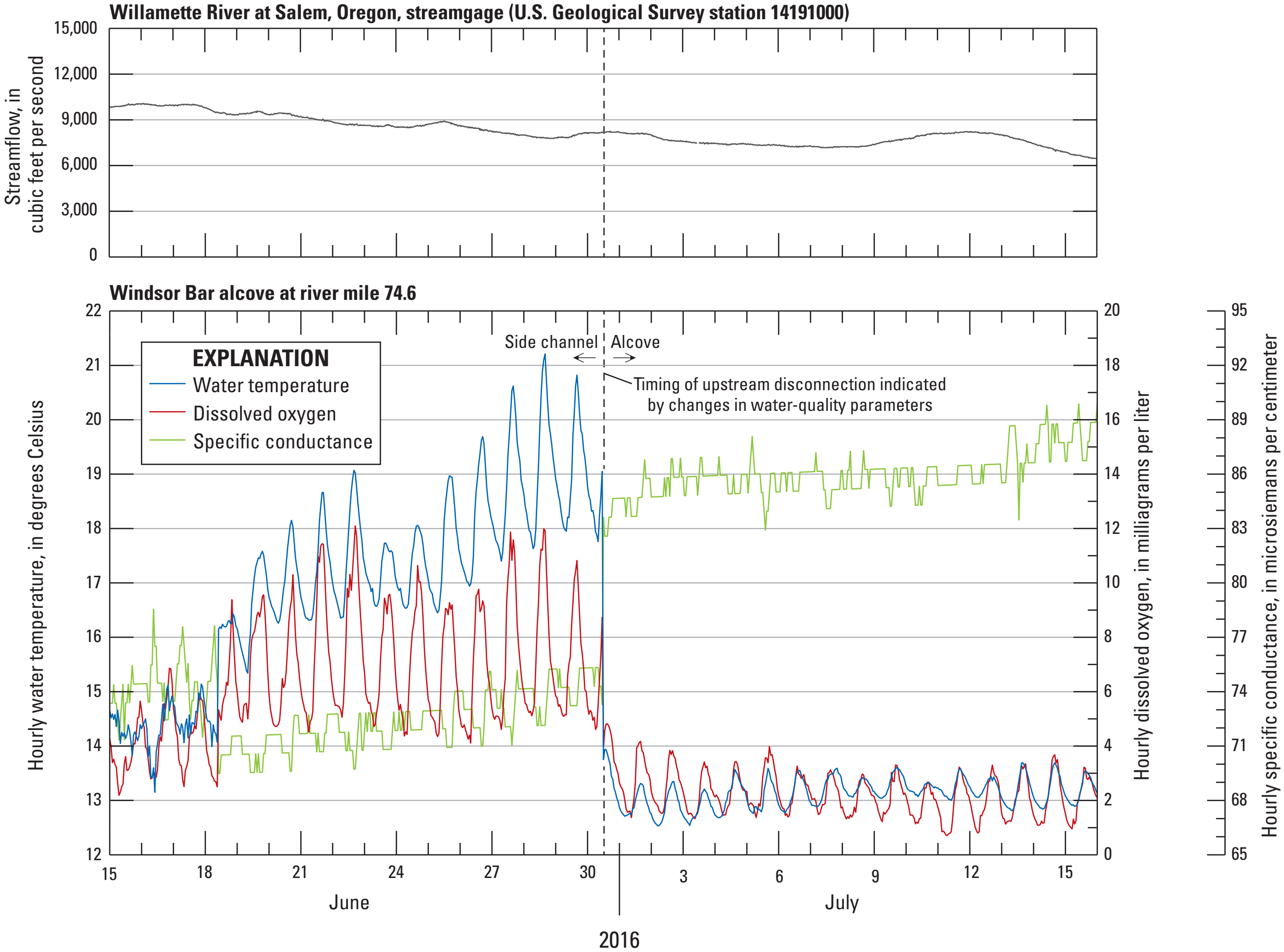


Figure 21. Hourly water-temperature, dissolved-oxygen, and specific-conductance measurements in Windsor Bar alcove at river mile 74.6 along the Willamette River, Oregon, and streamflow at the Willamette River at Salem, Oregon, streamgage (U.S. Geological Survey station 14191000) in June and July 2016.

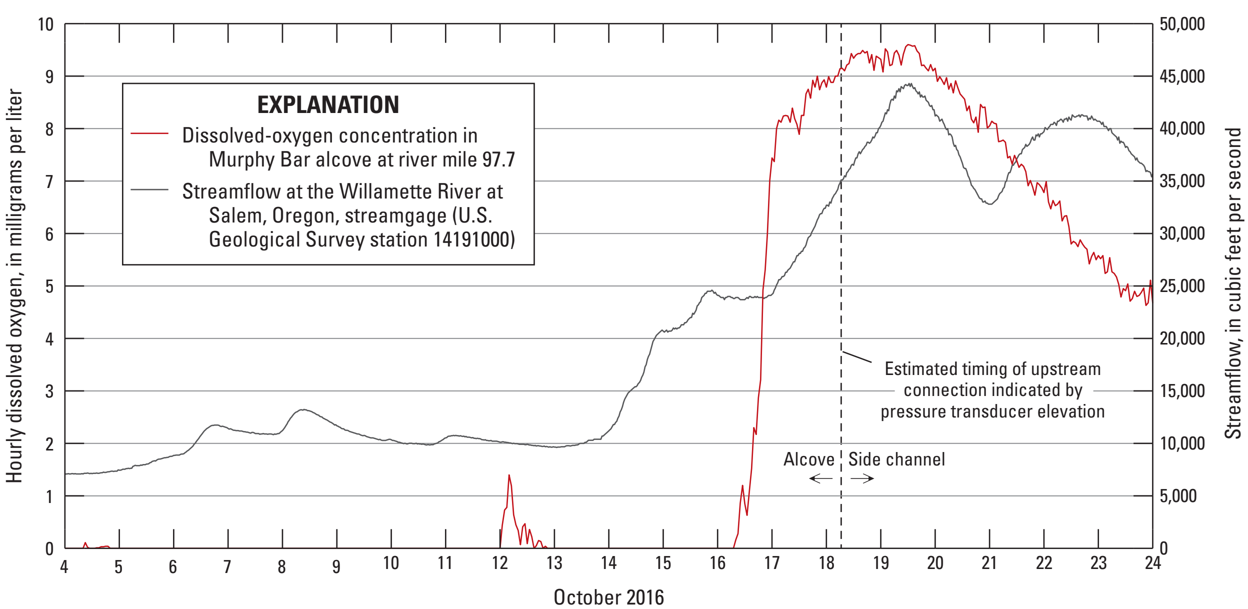


Figure 22. Hourly dissolved-oxygen concentrations in Murphy Bar alcove at river mile 97.7 (near Independence) along the Willamette River, Oregon, and streamflow at the Willamette River at Salem, Oregon, streamgage (U.S. Geological Survey station 14191000) in October 2016.

The high elevation of the upstream connection point of this feature and the quick rise in stage in October 2016 prevented an exact determination of when this alcove became reconnected. Comparing pressure-transducer data to the site's lidar topography suggests that river stage must rise about 3 m from 2016's summer low-flow stage (about 6,000 ft^3/s at Salem) before the upstream connection point would be overtopped (fig. 15). By comparing sensor-depth data from a pressure transducer deployed in this alcove to streamflow changes at the Salem streamgage, it is estimated that an upstream connection might occur in this alcove when streamflow at the Salem streamgage is about 35,000 ft^3/s; increases in dissolved-oxygen concentration at streamflows less than 35,000 ft^3/s probably were the result of river water entering at the downstream end of the feature (fig. 22). The slow decline in dissolved-oxygen concentrations in the alcove after the stage increased in October 2016 suggests that oxygen demands in the alcove are greater than the rate at which the alcove was being supplied with well-oxygenated water. This pattern is likely due to the high and narrow upstream connection point; additional inputs of water with lower oxygen concentrations (subsurface input) also may have contributed to the decline.

Water temperature in this feature remained below 20 °C, and its temperature patterns tracked somewhat with those in the main channel in 2016, but with cooler temperatures and more muted variations (fig. 23). The similarity in summertime temperature patterns between the alcove and main channel, with alcove temperature patterns that lagged and were muted relative to main-channel temperatures, suggests that inputs of radiative heat and cool subsurface flows existed in this alcove. The lagged and muted patterns could be partly indicative of the time scales of subsurface flow through the upstream gravels. As with Fairfield alcove, water temperature in Murphy Bar alcove was likely buffered by riparian shading and the emergent aquatic vegetation on the surface and in the water column. Diel temperature fluctuations were about 0.3 °C in the off-channel feature versus 2.0 °C in the main channel.

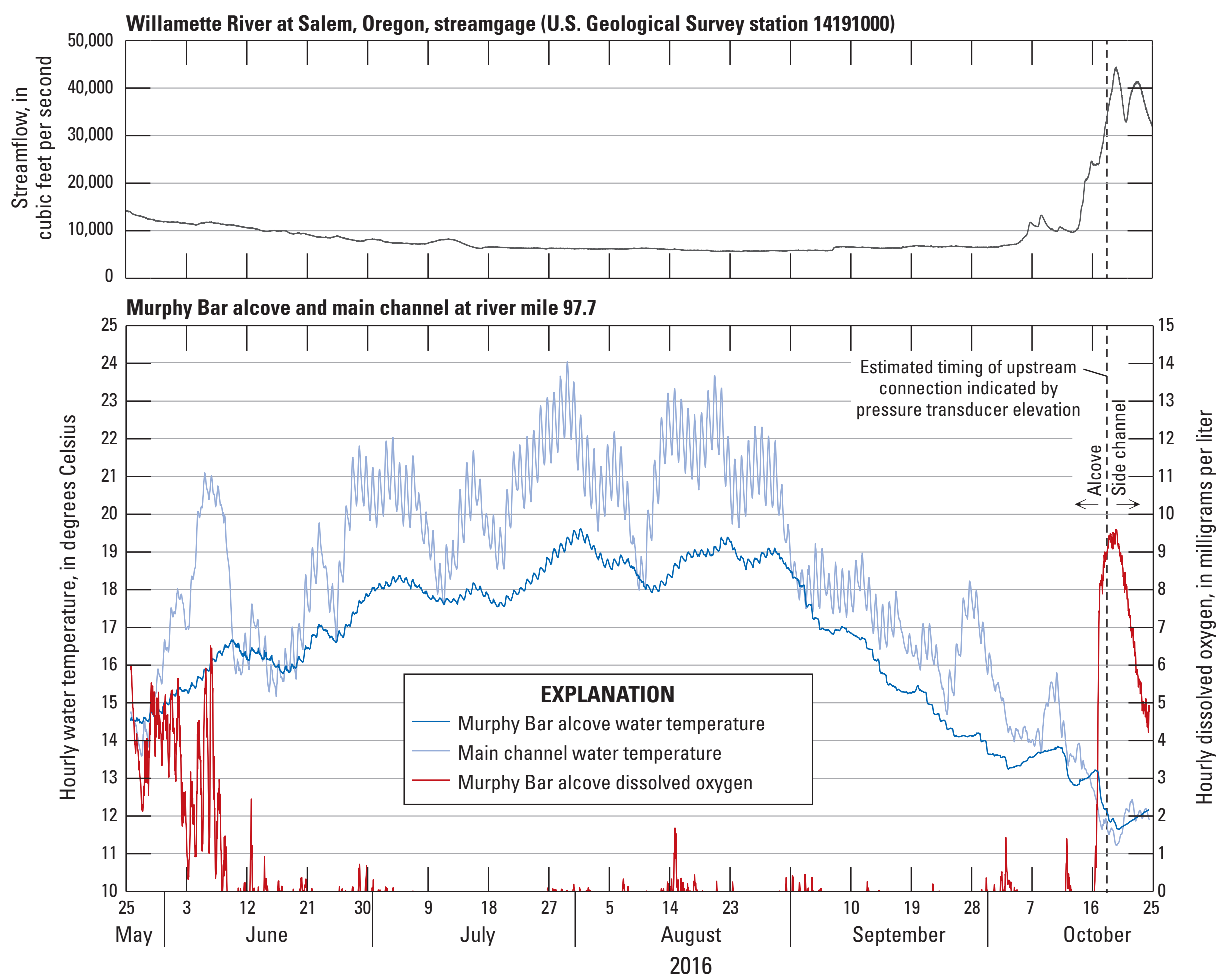


Figure 23. Hourly water-temperature measurements in the main-channel Willamette River, Oregon, at river mile 97.7, hourly water-temperature and dissolved-oxygen measurements in Murphy Bar alcove at river mile 97.7, and streamflow at the Willamette River at Salem, Oregon, streamgage (U.S. Geological Survey station 14191000) from May through October 2016.

Blue Ruin Alcove

The Blue Ruin alcove at RM 164.1 is a large and deep off-channel feature that was part of the main channel as recently as 1994 (fig. 19*B*; table 5; appendix 2). The feature is between a stable bar and a low floodplain surface, and the western bank is stabilized by revetments. The upstream connection point for this feature is complex, with multiple long, low channels cutting into an old gravel bar. A stage increase of about 1 m above summer low-flow stage (based on 2008 lidar) is required to connect the upstream end of this alcove to the river. The downstream connection point with the main channel is wide, and the off-channel feature is likely scoured during high-flow conditions. The alcove has minimal aquatic vegetation (mostly submerged), and the water is clear in summer, making it possible to see the gravel and sand bottom of the alcove; the maximum depth during low-flow synoptic measurements was 3.1 m.

Patterns and magnitudes of water temperature and dissolved-oxygen concentration in Blue Ruin alcove were markedly different from main-channel water-quality conditions from May through October 2016 (alcove at RM 164.1 in fig. 9). The Blue Ruin alcove was disconnected at its upstream end when water-quality monitoring equipment was installed 0.6 m above the substrate on May 24, 2016. Dissolved-oxygen concentrations and fluctuations in this feature were characteristic of photosynthesis and respiration by algae and the few benthic aquatic plants, with limited sediment oxygen demands due to a lack of any substantial accumulation of organic matter in the sediments. Anoxic conditions were not observed, but dissolved-oxygen concentrations were below 4 mg/L for a large part of the monitoring period (fig. 24). Blue Ruin alcove is deep with sand and gravel substrate and may have had subsurface inputs, which could supply cool water with minimal diel water-temperature fluctuation. Water temperature at 0.6 m above the bed was often at least 5 °C cooler than the main-channel water temperature and remained below 14.3 °C all summer (fig. 24). The increase in Willamette River streamflow

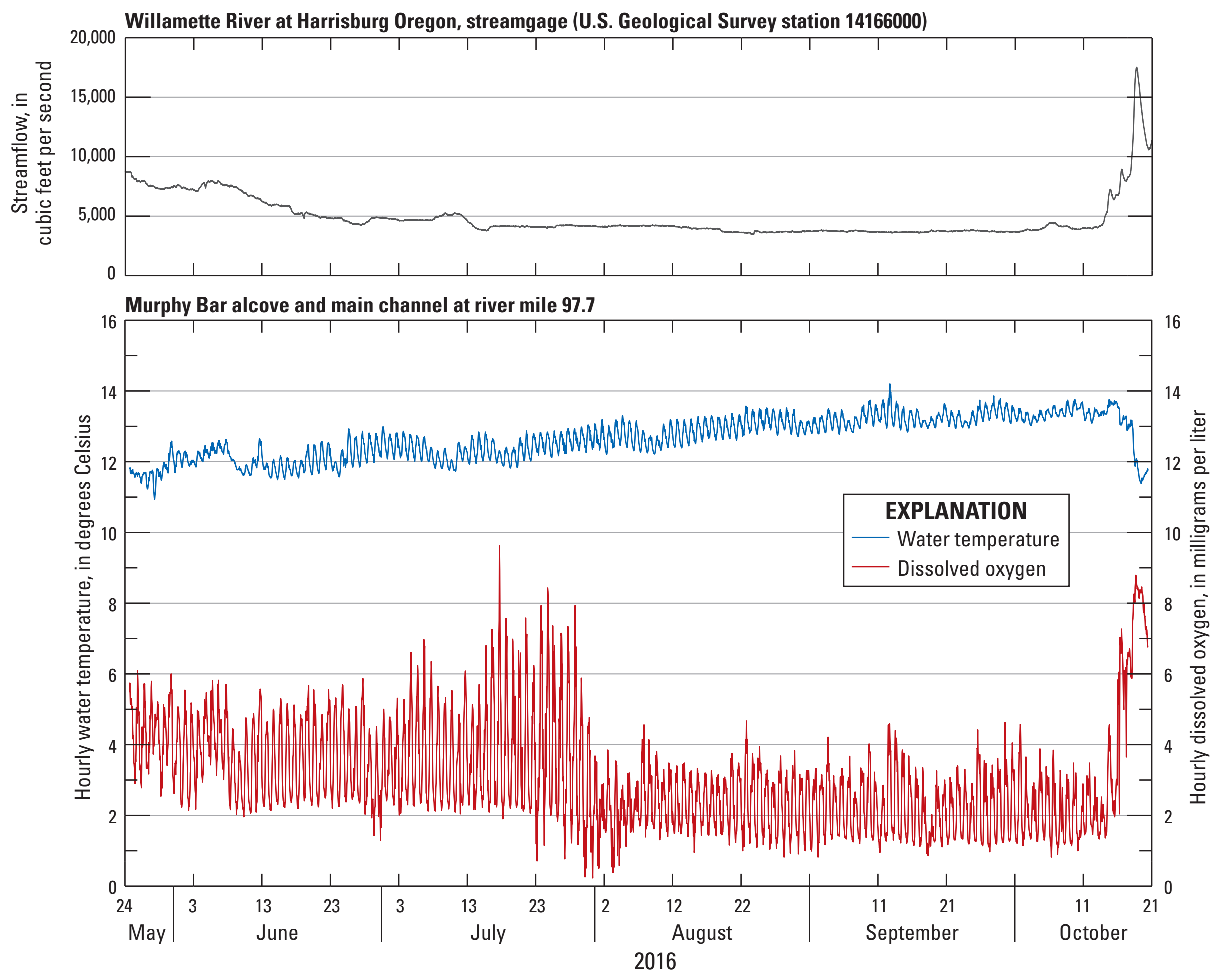


Figure 24. Hourly water-temperature and dissolved-oxygen measurements in Blue Ruin alcove at river mile 164.1, and streamflow at the Willamette River at Harrisburg, Oregon, streamgage (U.S. Geological Survey station 14166000) during 2016.

that occurred in October 2016 caused an increase in the feature's dissolved-oxygen concentration and a decrease in water temperature, indicating an influx of water from the main channel at either the upstream or downstream end; this feature did not contain a pressure transducer or a pendent, so determining when the upstream connection occurred was not possible. The water-quality characteristics of this off-channel feature are likely affected by minimal aquatic vegetation, frequent scouring during winter high flows (and the associated absence of an accumulation of sedimentary organic matter), depth, and potential subsurface inputs.

Harpers Bend Side Channel

The active gravel bar bordering the Harpers Bend side channel at RM 164.8 near Harrisburg is completely inundated by main-channel flow during moderate- and high-flow conditions. During low-flow summer conditions, this feature is a side channel with a small input of main-channel surface-water flow all summer (fig. 19*B*; table 5). This feature is between a low floodplain surface stabilized with revetments and an active gravel bar that has been growing annually due to erosion of the riverbank on the opposite side of the main channel (appendix 2). The downstream connection point is wide during high flows but becomes narrower as flow decreases through the summer; the upstream connection point is a distinct, narrow channel. Terrestrial vegetation was sparse on both sides of the off-channel feature, and moderate amounts of submerged aquatic vegetation were found near the downstream end. The water was clear, providing a view of the cobble substrate about 2.4 m below the water surface during summer.

Based on the dissolved-oxygen dataset and observations during several field visits, this off-channel feature did not completely disconnect from the main channel at the upstream end during the 2016 data-collection period. Dissolved-oxygen concentrations in the side channel (measured 0.6 m above the substrate) were characteristic of main-channel solubility-driven concentrations and patterns until the diel fluctuations increased in late June and July (fig. 25); main-channel dissolved-oxygen conditions were not monitored in this reach, but the data from RM 97.7 provide a useful comparison from a main-channel site where dissolved-oxygen concentrations were mostly a function of oxygen solubility. The increased dissolved-oxygen diel fluctuations in Harpers Bend side channel relative to main-channel conditions, along with changes in the specific conductance (not shown), corresponded to a decrease in stage in the feature recorded from a pressure transducer. The decreased stage and increased dissolved-oxygen fluctuations indicated that biological activity (photosynthesis and respiration) was having more of an effect on dissolved oxygen than the limited upstream surface-water inputs during periods of lower water level in the main channel. The dissolved-oxygen pattern from July through September likely was indicative of an increased residence time and an associated increase in primary production. Anoxic dissolved-oxygen concentrations were not measured during the summer of 2016, which could indicate that main-channel water inputs probably continued to affect the site throughout the season, and that the site had small oxygen demands that were insufficient to overcome other oxygen inputs.

The water-temperature pattern in this feature also supports the interpretation that a small amount of water from the main channel was flowing into the feature throughout the 2016 study period, and some cooler subsurface inputs were also present. The main-channel and side-channel water-temperature patterns and diel fluctuations were nearly identical through early July, but the side-channel water temperature was cooler than main-channel temperatures from July through September, indicating that the small main-channel inputs were not dictating the temperature in the off-channel feature (fig. 25). Given the presence of the gravel substrate and the adjacent active gravel bar, cooler subsurface inputs likely were important in affecting the feature's water temperature. The absence of emergent aquatic vegetation may be due to periodic and wintertime high-flow velocities that probably are strong enough to flush out weakly rooted vegetation and prevent a heavy accumulation of organic material in the sediments.

Importance of Upstream Connections on Water Quality of Off-Channel Features

Data from this study revealed a strong relation between site geomorphology and the water quality of the river's off-channel features. An analysis of multiple datasets (water temperature, dissolved oxygen, pressure transducer, pendant, and stage) collected in the main channel and in the off-channel features revealed how water quality in an off-channel feature is affected by several factors, especially the nature of surface-water connections at the upstream (and downstream) end of the feature. The five off-channel features that were intensively monitored in 2016 differed substantially in their geomorphological characteristics such as their size, adjacent landforms, and height of their upstream connection location, which together with other factors contributed to different water-quality patterns and conditions.

The surface-water connection between the main channel and the upstream part of these five off-channel features varied with streamflow, resulting in a range of connection/disconnection dates and duration of connectivity during the 2016 monitoring period. Murphy Bar, Blue Ruin, and Fairfield alcoves became disconnected from the main channel at their upstream ends at typical summer low flows, Windsor Bar alcove became disconnected at unusually low summer flows, and the upstream end of Harpers Bend side channel never completely disconnected during the flow conditions in 2016. The occurrence and duration of disconnection was highly variable among the studied features and depended on the height of their upstream connection point relative to local main-channel stage. Reconnection to the river at the upstream end was rapid and somewhat coincident for most of these features because the river stage increased quickly in 2016 in response to rains in October.

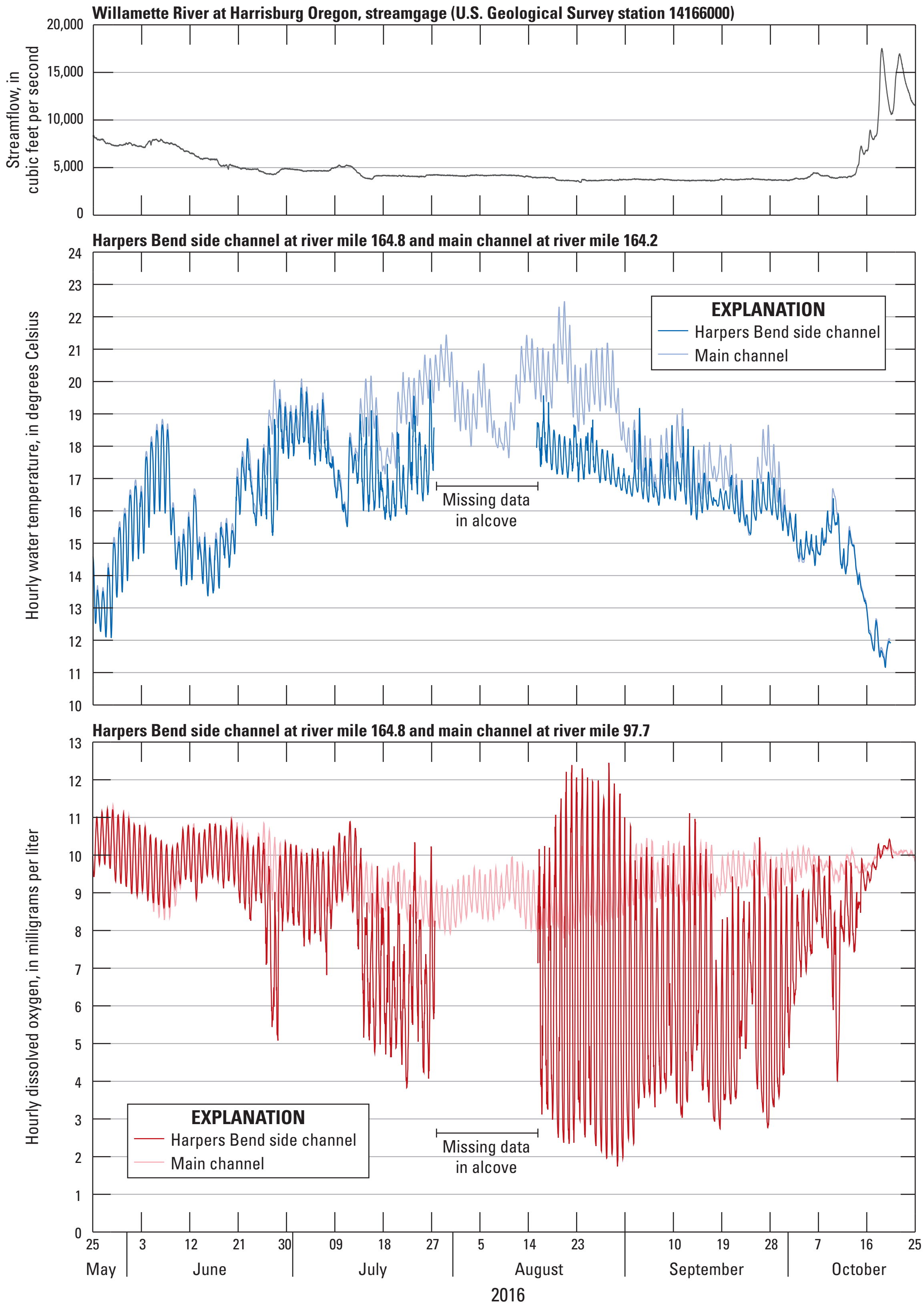


Figure 25. Hourly water-temperature and dissolved-oxygen measurements in Harpers Bend side channel at river mile (RM) 164.8 (near Harrisburg, Oregon), plotted with water-temperature data from the main channel at RM 164.2 and dissolved-oxygen data from the main channel at RM 97.7; and streamflow at the Willamette River at Harrisburg, Oregon, streamgage (U.S. Geological Survey station 14166000).

When these off-channel features were disconnected from the river at their upstream end, their water-quality conditions began to diverge from and in some cases became extremely different from main-channel conditions. Similarly, reconnection quickly changed the water quality of these features, making it more like main-channel conditions. The morphology of an off-channel feature may also be correlated to other site-specific characteristics that can affect water-quality conditions. For example, off-channel features that were connected at the upstream end during low flows did not contain large amounts of emergent aquatic vegetation. Infrequent high, scouring streamflows and frequent moderate streamflows may affect the feature's depth, any accumulation of fine sediment, and the establishment of emergent aquatic vegetation.

Linking Site Characteristics and Water-Quality Processes in Off-Channel Features

Data collection for this study encompassed two summers and dozens of sites, included quantitative and qualitative measurements, and focused on off-channel and main-channel water-quality conditions of a major river system. Analysis of the various datasets revealed many commonalities and provided insights into the many factors that affect water quality in off-channel features. Using those insights, a site classification scheme and a theoretical process matrix were created to help distill and organize the key findings. The site classification scheme is an organizational aid that summarizes common or contrasting outcomes among the intensively measured off-channel sites, using measured water-quality patterns and ranges and site-specific characteristics to create four broad categories of water-quality conditions measured in this study. The theoretical process matrix extends the site classification scheme to more generally list the processes and site-specific characteristics that are likely to combine to create the various water-quality conditions that occur in off-channel features.

Site Classification Scheme

Despite the fact that each off-channel feature along the Willamette River is unique in its shape, size, connection to the river, or in its water-quality patterns over the course of the summer, the various data collected in this study revealed enough similar and contrasting patterns to allow the creation of a site classification scheme organized around general site characteristics and categories of water-quality outcomes. The scheme relies on all the continuous water-temperature datasets, dissolved-oxygen datasets, and synoptic measurements collected in off-channel features of the Willamette River in summers 2015–16, but draws particularly from the datasets collected at the intensively monitored sites in 2016. The site classification scheme categorizes sites first as alcoves or side channels and then further categorizes expected water-quality conditions based on a set of site characteristics (table 6). The scheme is applicable during typical summer low flows, when many off-channel features adjacent to the Willamette River function as alcoves.

Potentially the most important characteristic of an off-channel feature that affected water-quality conditions was the presence or absence of an upstream connection to the main channel during summer low flows (represented in the first column of the site classification scheme; table 6). These features have upstream connection points with different bed elevations, which dictate the timing and duration of connection with the main channel. When connected at the upstream end, the alcove becomes a side channel and its water quality is more likely to reflect conditions in the main channel. Other site-specific characteristics that were important in determining water-quality conditions in the off-channel features included the presence of aquatic invasive plants, any accumulation of sedimentary organic matter, water transparency (turbidity), shading, and depth. Sites could be categorized according to their resulting water-quality conditions, as follows:

1. *Features with cool water temperatures and depleted dissolved oxygen*—Such features tended to contain abundant emergent aquatic vegetation, highly colored water with low transparency, some accumulation of sedimentary organic material, some shading from aquatic or riparian vegetation, a relatively high-elevation upstream connection point, and typically were disconnected at the upstream end during summer low flows (table 6).

2. *Features with cool water temperatures and oxygenated water*—This type of feature lacked emergent aquatic vegetation or much sedimentary organic matter, had high transparency and a moderately high-elevation upstream connection point, and typically was disconnected at the upstream end during summer low flows. The features were deep and not shaded by vegetation (table 6), possibly due to nearby active gravel bars and (or) high-energy flushing flows during winter.

3. *Features with cool, fluctuating water temperatures and variable, but oxygenated, water*—Such features contained submerged aquatic vegetation, transparent water, a low-elevation upstream connection point, and remained connected at the upstream end during summer. The features were moderately deep and not shaded by vegetation (table 6).

4. *Features with warm water temperatures and unknown dissolved-oxygen concentrations*—These features typically were shallow, with a high or moderately high upstream connection point, and were not shaded by vegetation (table 6).

Table 6. A site classification scheme linking broad patterns of measured water-quality conditions to site characteristics of off-channel features along the Willamette River, Oregon, in the low-flow summer periods of 2015 and 2016.

Upstream connection to the main channel during typical summer low flows	Relevant site-specific characteristics observed	Typical water-quality conditions
Disconnected from main-channel surface flow at the upstream end (an alcove)	Large quantities of emergent aquatic plants Low transparency An accumulation of organic-rich sediments Shaded by vegetation	Consistently cool water temperatures below surface Depleted oxygen concentrations in the middle and lower water column
	Small quantities of emergent aquatic plants, or none Little to no accumulation of organic matter in sediments Not shaded by vegetation High transparency Deep	Consistently cool water temperatures below surface Oxygenated water below surface
	Not shaded by vegetation Shallow	Consistently warm water temperatures below surface Unknown oxygen conditions
Connected to main-channel surface flow at the upstream end (a side channel)	Presence of submerged aquatic vegetation Not shaded by vegetation High transparency Moderately deep	Cool and variable water temperatures below surface Oxygenated water below surface with potential for large diel variations

This site classification scheme, and the water-quality categories created during typical summer low flows, likely apply to other off-channel features along the Willamette River that were not measured. This scheme is a first attempt at identifying the dominant mechanisms and processes affecting water-quality conditions in off-channel features and is only intended to broadly characterize the features monitored in this study by linking monitoring data to site characteristics. It is possible that additional factors, not measured or identified in this study, also are important in determining water-quality conditions in off-channel features. Additional data collection would be helpful in identifying any other relevant site-specific characteristics that could be used to refine the site classification scheme.

Theoretical Process Matrix

The site classification scheme is limited by sample size and the methods used in this study and may not fully represent the complexity of the Willamette River system or the diversity of water-quality conditions that occur in its off-channel features. Another useful approach to organizing the results and insights from this study is embodied in a proposed "theoretical process matrix," which lists the water-quality conditions commonly observed in off-channel features and links them to a suite of processes and site-specific characteristics that are likely to combine to create such conditions (table 7). This matrix draws insights not just from this study, but also from a general knowledge of the principles of physics, chemistry, limnology, geology, and stream ecology.

The theoretical process matrix can be applied when researching the conditions occurring in any off-channel feature. For example, Blue Ruin alcove at RM 164.1 had cool water that was likely a function of depth (affecting vertical stratification) and the presence of sand and gravel substrate (affecting subsurface inputs). The Fairfield alcove at RM 67.1 was anoxic while it was disconnected at the upstream end. The anoxic conditions probably resulted from a combination of shading (by riparian and emergent vegetation) and a high accumulation of organic matter decomposing in the sediments. Such site characteristics reduce the light available for photosynthesis in the water column and cause sediment oxygen demands that exceed photosynthetic production.

Table 7. Theoretical process matrix linking water-quality outcomes or conditions for water temperature and dissolved oxygen with processes and site characteristics that can combine to create the outcomes in off-channel features of the Willamette River, Oregon.

Water-quality condition	Process affecting the condition	Site characteristic affecting the process
	Water temperature	
Cool water	Reduced solar insolation	Shaded (by riparian vegetation, emergent aquatic vegetation, or topography)
	Vertical stratification	Sufficient depth for stratification to occur
		Insufficient mixing (by wind and [or] turbulence) to disrupt stratification
		Low transparency (high turbidity or color)
	Cool water input (often groundwater or hyporheic input)	Location in the floodplain and active channel
		Presence and abundance of gravel
Warm water	High solar insolation	Not shaded (by riparian vegetation, emergent aquatic vegetation, or topography)
	Absence of vertical stratification	Shallow (insufficient depth for stratification to occur)
		Mixing by wind or flow does not allow for vertical stratification
	Warm water input	Upstream connection with the main channel during summer low flows
		Strong inflow at downstream connection point due to river stage increase
		Presence of point source or warm tributary input
Daily fluctuations in water temperature	Ambient air-temperature fluctuations and solar insolation	High surface area to volume ratio plus exposure to sunlight plus moderate to long residence time
	Fluctuating water input	Presence of point source or tributary input with fluctuating temperature
		Small upstream connection with the main channel during summer low flows plus high surface area to volume ratio plus exposure to sunlight plus moderate to long residence time
	Dissolved oxygen	
Oxygenated	Photosynthetic production exceeds oxygen demands	Not shaded plus presence of submerged aquatic plants and (or) algae
		Low oxygen demands (lack of organic matter in sediments)
	Oxygenated water input (often main-channel input or point source)	Upstream connection with the main channel during summer low flows
		Strong inflow at downstream connection point due to river stage increase
		Presence of oxygenated point sources or tributary inputs
	Aeration	Sufficient mixing by wind or flow
Low dissolved oxygen	Reduced solar insolation causing reduced photosynthetic oxygen production	Shaded (by riparian vegetation, emergent aquatic vegetation, or topography)
	Vertical stratification causing a greater chance for hypolimnetic oxygen depletion	Sufficient depth for stratification to occur
		Insufficient mixing (by wind and [or] turbulence) to disrupt stratification
		Low transparency (high turbidity or color)
	Oxygen demands exceed photosynthetic production	High accumulation of organic matter being broken down by microbial respiration
		A lack (or recent senescence) of algae or plants that photosynthesize
	Low-oxygen water input (often groundwater or hyporheic input)	Location in the floodplain and active channel
		Presence and abundance of gravel
		Length (time scale) of flow path for the groundwater or hyporheic input
Daily fluctuations in dissolved-oxygen concentrations	Photosynthesis and respiration and solar insolation	Not shaded plus presence of aquatic plants and (or) algae plus moderate to long residence time

Certain water-quality outcomes in off-channel features could be caused by one or more combinations of processes and site characteristics. Therefore, this theoretical process matrix lists multiple factors that could affect water-quality conditions. For example, cool water temperatures at a location could reflect reduced solar insolation, vertical stratification, a cool water input, or a combination of these factors. A site-specific characteristic that could contribute to vertical stratification includes sufficient depth for stratification to occur, insufficient wind- or flow-induced mixing, low transparency (high turbidity or color), or a combination of these characteristics. The matrix can be used to better understand the various combinations of water temperature and dissolved-oxygen conditions that may exist (for example, warm water temperatures and daily fluctuations in dissolved-oxygen concentrations). Alternatively, the site-specific characteristics and processes identified in the matrix can be used by researchers and flow managers to gain a general understanding of the causes of certain water-quality conditions and to infer potential conditions in an off-channel feature without having to monitor that feature intensively.

Competing processes in the theoretical process matrix also introduces several questions:

1. Would the water temperature in an off-channel feature be cool or warm if it had a warm water input and reduced solar insolation?

2. How would the addition of subsurface inputs affect the dissolved oxygen in a feature with high photosynthetic production?

3. Would increasing summer flows in the Willamette River result in warm temperatures in off-channel features (by connecting them to the main channel and flushing them with warm surface water, and potentially pushing out emergent aquatic vegetation), or would the increased surface flows lead to increased cool subsurface inputs, or both?

4. How would infrequent moderate or high summer streamflows affect water temperature in a feature with an established emergent aquatic vegetation community?

In such situations, actual water-quality conditions would depend on the strength of the individual and competing processes. In other situations, processes may reinforce each other to strengthen a result. For example, the presence of large amounts of decomposing organic matter could lead to low oxygen conditions through an enhanced sediment oxygen demand, whereas the concomitant input of subsurface water (typically with low dissolved oxygen) would reinforce the resulting low-oxygen condition. With additional data collection and modeling, it may be possible to determine the relative importance of each of the site-specific characteristics and processes. More information is needed to begin to quantify the effects of these site-specific characteristics and processes controlling water-quality conditions in off-channel features of the Willamette River system.

Conclusions and Implications for Research and Management

Summer water temperatures in the main channel of the Willamette River are warm (>18 °C) and may cause stress to cold-water fishes. Warm main-channel conditions emphasize the importance of understanding water-quality conditions in off-channel features and their relation to streamflow, which was the objective of this study. The number of off-channel features that function as CWRs for fishes depends on the local geomorphology, hydrology, and ecology of a river reach or feature. This study identified geomorphic characteristics, such as the relative height of an upstream connection necessary for main-channel water to enter an off-channel feature, as important effects on the hydrology and water quality of off-channel features. The timing, duration, and quantity of surface-water inputs to off-channel features affect the local ecology (the presence or absence of aquatic vegetation) and the substrate (the presence or absence of accumulations of organic matter), both of which in turn affect the water temperature and dissolved-oxygen concentration in off-channel features.

Certain site-specific characteristics of an off-channel feature may be important indicators of the water-quality conditions and the potential relation between water quality and the site's geomorphology. Water-quality heterogeneity exists within and among off-channel features, but the predominant water-quality conditions measured in this study were used to make useful generalizations. Four categories of water-quality conditions were measured and classified in this study, although others likely exist:

1. Features with cool-water temperatures and depleted dissolved oxygen.

2. Features with cool-water temperatures and oxygenated water.

3. Features with cool, fluctuating water temperatures and variable, but oxygenated, water.

4. Features with warm-water temperatures and unknown dissolved-oxygen concentrations.

Based on observational and measured data from this study, off-channel features in category 1 tended to have large quantities of emergent aquatic vegetation, thick accumulations of decomposing organic matter, a steep vertical gradient of water temperature and dissolved oxygen, and a relatively high-elevation upstream connection point that kept the feature disconnected at the upstream end and prevented the throughput of river water during the low-flow summer period. Off-channel features in category 2 typically were controlled by a moderately high-elevation upstream connection point and lacked abundant emergent aquatic vegetation. Off-channel features in category 3 remained connected at the upstream end throughout the summer, and biological activity likely contributed to any pronounced diel fluctuations of dissolved oxygen. Dissolved-oxygen concentrations and patterns are unknown for off-channel features in category 4 because only water temperature was measured in this type of feature. Both water temperature and dissolved-oxygen concentration are critical factors for supporting healthy and diverse aquatic ecosystems; therefore, it is important to measure and study both to better understand the role and ecological function of these off-channel features.

Because of the various elevations of upstream connection points and other factors affecting water-quality conditions in off-channel features, not all features will respond the same way or at the same time in response to flow changes. Flow management using upstream storage reservoirs in the Willamette River Basin may be able to affect the conditions in off-channel features and the quality of habitat in those features for target aquatic species. For example, managed releases of water from upstream reservoirs during summer could temporarily connect the upstream ends of certain off-channel features, thereby flushing well-oxygenated, but potentially warm, main-channel water through those features. These managed flow releases might also disrupt the establishment of invasive aquatic vegetation and the buildup of organic matter, which in turn might minimize the oxygen demand from organic-matter decomposition. Increasing streamflows so that water enters an off-channel feature at its downstream end (but not the upstream end), may affect water-quality within an off-channel feature without requiring substantial flow increases. Using summer flow operations to disconnect features at the upstream end may result in localized cool-water temperatures in some features; however, a negative effect on dissolved-oxygen concentrations could also occur.

In addition to flow management, restoration practices can affect water quality in off-channel features. For example, excavating channels or reducing the elevation of the upstream ends of targeted off-channel features could allow main-channel surface water to flow freely through those off-channel features at lower streamflows. It is possible that increasing the frequency and amount of surface flows through off-channel features that are often disconnected at the upstream end might reduce the establishment of aquatic invasive plant communities, which in turn could reduce the abundance of decomposing organic matter and prolonged anoxic conditions. Current practices of manually removing emergent aquatic plant communities may also lead to a lower oxygen demand from decomposition but could result in a greater influx of heat by removing floating plants that block solar insolation; however, chemically treating emergent aquatic plant communities may increase the available organic matter for decomposition. Allowing or enhancing the channel migration process that creates and maintains active gravel bars in certain river reaches may promote cool subsurface inputs to wetted off-channel features. Many factors affect temperature (shading, depth, subsurface flows, and main-channel throughput) and dissolved oxygen (photosynthesis, respiration, decomposition of sedimentary organic matter, and inputs from various water sources) in the off-channel features of the Willamette River. Reconciling how flow management and restoration activities affect water temperature and dissolved oxygen (and therefore, fish habitat) in off-channel features is complex, and the site classification scheme and theoretical process matrix introduced in this report can assist with better understanding the interaction of potentially confounding variables influencing water-quality processes.

Quantifying the effects of site-specific characteristics and the relative inputs of subsurface flow into off-channel features is a logical next step to strengthen the site classification scheme and theoretical process matrix outlined here. Currently, it is unclear how increasing or decreasing summer flows will affect the quantity of subsurface flows into off-channel features. To fill current data gaps and provide more information and insights for research and management, water quality in specific off-channel features could be monitored over a wide range of conditions, such as during gradual decreases in river stage, gradual increases in river stage, and during intermittent high flows in the Willamette River. Comprehensive studies of water-quality conditions in off-channel features with various types (emergent and submerged) and abundance of vegetation would strengthen the site classification scheme. Future monitoring could target the collection of continuous vertical and longitudinal (three-dimensional) water-quality data, which may reveal regions within off-channel features that function as CWRs during climatic extremes. In addition, supplementary data could be used to develop models to better understand and predict water quality in off-channel features in response to numerous scenarios. The off-channel features of the Willamette River are diverse and dynamic and respond to a wide variety of processes and factors. A better understanding of those factors and processes should lead to a better means of predicting and managing the water-quality conditions that occur there.

References Cited

Arismendi, I., Dunham, J.B., Heck, M.P., Schultz, L.D., and Hockman-Wert, D., 2017, A statistical method to predict flow permanence in dryland streams from time series of stream temperature: Water (Basel), v. 9, no. 12, p. 946. [Also available at https://doi.org/10.3390/w9120946.]

Arrigoni, A.S., Poole, G.C., Mertes, L.A.K., O'Daniel, S.J., Woessner, W.W., and Thomas, S.A., 2008, Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels: Water Resources Research, v. 44, no. 9, 13 p. [Also available at https://doi.org/10.1029/2007WR006480.]

Benton Soil and Water Conservation District, 2014, Water weeds—Guide to aquatic weeds for Benton County: Benton Soil and Water Conservation District, p. 28, accessed November 20, 2018, at https://www.bentonswcd.org/assets/BSWCDAquaticWeedGuidebklt15.pdf.

Brett, J.R., 1952, Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*: Journal of the Fisheries Research Board of Canada, v. 9, no. 6, p. 265–323. [Also available at https://doi.org/10.1139/f52-016.]

Buccola, N.L., Turner, D.F., and Rounds, S.A., 2016, Water temperature effects from simulated dam operations and structures in the Middle Fork Willamette River, western Oregon: U.S. Geological Survey Open-File Report 2016–1159, 39 p. [Also available at https://doi.org/10.3133/ofr20161159.]

Bunch, A.J., Allen, M.S., and Gwinn, D.C., 2010, Spatial and temporal hypoxia dynamics in dense emergent macrophytes in a Florida lake: Wetlands, v. 30, no. 3, p. 429–435. [Also available at https://doi.org/10.1007/s13157-010-0051-9.]

Bureau of Reclamation, 2012, Agrimet: Bureau of Reclamation cooperative agricultural weather network, digital data, accessed October 2016, at https://www.usbr.gov/pn/agrimet/.

Burkholder, B.K., Grant, G.E., Haggerty, R., Khangaonkar, T., and Wampler, P.J., 2008, Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA: Hydrological Processes, v. 22, no. 7, p. 941–953. [Also available at https://doi.org/10.1002/hyp.6984.]

Caldwell, J.M., and Doyle, M.C., 1995, Sediment oxygen demand in the lower Willamette River, Oregon, 1994: U.S. Geological Survey Water-Resources Investigations Report 95–4196, 14 p. [Also available at https://doi.org/10.3133/wri954196.]

Caraco, N., Cole, J., Findlay, S., and Wigand, C., 2006, Vascular plants as engineers of oxygen in aquatic systems: Bioscience, v. 56, no. 3, p. 219–225. [Also available at https://doi.org/10.1641/0006-3568(2006)056[0219:VPAEOO]2.0.CO;2.]

Carter, K., 2005, The effects of dissolved oxygen on steelhead trout, coho salmon, and Chinook salmon biology and function by life stage: California Regional Water Quality Control Board North Coast Region, accessed November 20, 2019, at https://pdfs.semanticscholar.org/f75d/8e52325eb618e8fa73fe04a28df34bbae8f2.pdf.

Chapelle, F.H., Shen, Y., Strom, E.W., and Benner, R., 2016, The removal kinetics of dissolved organic matter and the optical clarity of groundwater: Hydrogeology Journal, v. 24, no. 6, p. 1413–1422. [Also available at https://doi.org/10.1007/s10040-016-1406-y.]

Church, M., 1983, Patterns of instability in a wandering gravel bed channel, *in* Collinson, J.D., and Lewin, J., eds., Modern and ancient fluvial systems—Lewin International Association of Sedimentology, Special Publication 6 p. 169–180. [Also available at https://doi.org/10.1002/9781444303773.ch13.]

Davis, J.C., 1975, Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species—A review: Journal of the Fisheries Research Board of Canada, v. 32, no. 12, p. 2295–2332. [Also available at https://doi.org/10.1139/f75-268.]

Davison, R.C., Breese, W.P., Warren, C.E., and Doudoroff, P., 1959, Experiments on the dissolved oxygen requirements of cold-water fishes: Sewage and Industrial Wastes, v. 31, no. 8, p. 950–966. [Also available at https://www.jstor.org/stable/25033954.]

Doudoroff, P., and Shumway, D.L., 1970, Dissolved oxygen requirements of freshwater fishes: Food and Agriculture Organization of the United Nations, Fisheries Technical Paper no. 86, accessed October 2018, at https://ir.library.oregonstate.edu/concern/administrative_report_or_publications/xw42n891s.

Ebersole, J.L., Liss, W.J., and Frissell, C.A., 2003, Cold water patches in warm streams—Physicochemical characteristics and the influence of shading: Journal of the American Water Resources Association, v. 39, no. 2, p. 355–368. [Also available at https://doi.org/10.1111/j.1752-1688.2003.tb04390.x.]

Esri, 2014, USGS Historical Topographic Map Explorer: Esri web application, historical topographic map collection courtesy of the U.S. Geological Survey, accessed June 2015, at https://livingatlas.arcgis.com/topoexplorer/.

Fernald, A.G., Wigington, P.J., Jr., and Landers, D.H., 2001, Transient storage and hyporheic flow along the Willamette River, Oregon—Field measurements and model estimates: Water Resources Research, v. 37, no. 6, p. 1681–1694. [Also available at https://doi.org/10.1029/2000WR900338.]

Fryer, J.L., Pilcher, K.S., Sanders, J.E., Rohovec, J.S., Zinn, J.L., Groberg, W.J., and McCoy, R.H., 1976, Temperature, infectious diseases, and the immune response in salmonid fish: U.S. Environmental Protection Agency Ecological Research Series EPA–600/3–76–021, 81 p.

Gregory, S.V., Haggerty, R., and Hulse, D., 2008, Final report—Harnessing the hydrologic disturbance regime—Sustaining multiple benefits in large river floodplains in the Pacific Northwest: U.S. Environmental Protection Agency, accessed October 1, 2018, at https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/7544/report/F.

Gregory, S., and Wildman, R., 2016, Cold water refuges—Technical details: University of Oregon, Institute for a Sustainable Environment, accessed November 19, 2018, at https://oe.oregonexplorer.info/ExternalContent/willamette_slices/cold_water_refuge_TD.pdf and https://oregonexplorer.info/places/basins/willamette?qt-basin_quicktab=1.

Gregory, S., Wildman, R., Hulse, D., Ashkenas, L., and Boyer, K., 2019, Historical changes in hydrology, geomorphology, and floodplain vegetation of the Willamette River, Oregon: River Research and Applications, v. 35, no. 8, p. 1279–1290. [Also available at https://doi.org/10.1002/rra.3495.].

Hinkle, S.R., Bencala, K.E., Wentz, D.A., and Krabbenhoft, D.P., 2014, Mercury and methylmercury dynamics in the hyporheic zone of an Oregon stream: Water, Air, and Soil Pollution, v. 225, no. 1, p. 1694. [Also available at https://doi.org/10.1007/s11270-013-1694-y.]

Jeffries, K.M., Hinch, S.G., Martins, E.G., Clark, T.D., Lotto, A.G., Patterson, D.A., Cooke, S.J., Farrell, A.P., and Miller, K.M., 2012, Sex and proximity to reproductive maturity influence the survival, final maturation, and blood physiology of Pacific salmon when exposed to high temperature during a simulated migration: Physiological and Biochemical Zoology, v. 85, no. 1, p. 62–73. [Also available at https://doi.org/10.1086/663770.]

Mangano, J.F., Buccola, N.L., Piatt, D.R., Smith, C.D., and White, J.S., 2017, Point measurements of temperature and water quality in main-channel and off-channel features of the Willamette River, 2015–16: U.S. Geological Survey data release, accessed May 2019, at https://doi.org/10.5066/F7VQ315.

Mangano, J.F., Piatt, D.R., Buccola, N.L., and Smith, C.D., 2018a, Water surface elevations recorded by submerged water level loggers in off-channel features of the middle and upper Willamette River, Oregon, summer, 2016: U.S. Geological Survey data release, accessed May 2019, at https://doi.org/10.5066/F77M06D.

Mangano, J.F., Piatt, D.R., Jones, K.L., and Rounds, S.A., 2018c, Water temperature in tributaries, off-channel features, and main channel of the lower Willamette River, northwestern Oregon, summers 2016 and 2017: U.S. Geological Survey Open-File Report 2018–1184, 33 p., accessed May 2019, at https://doi.org/10.3133/ofr20181184.

Mangano, J.F., Smith, C.D., Buccola, N.L., and Piatt, D.R., 2018b, Continuous temperature measurements to assess upstream connection of off-channel features of the middle and upper Willamette River, Oregon, summer, 2016: U.S. Geological Survey data release, accessed May 2019, at https://doi.org/10.5066/F73T9FPK.

Martins, E.G., Hinch, S.G., Patterson, D.A., Hague, M.J., Cooke, S.J., Miller, K.M., Lapointe, M.F., English, K.K., and Farrell, A.P., 2011, Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (*Oncorhynchus nerka*): Global Change Biology, v. 17, no. 1, p. 99–114. [Also available at https://doi.org/10.1111/j.1365-2486.2010.02241.x.]

Mote, P.W., Rupp, D.E., Li, S., Sharp, D.J., Otto, F., Uhe, P.F., Xiao, M., Lettenmaier, D.P., Cullen, H., and Allen, M.R., 2016, Perspectives on the causes of exceptionally low 2015 snowpack in the western United States: Geophysical Research Letters, v. 43, no. 20, p. 10980–10988. [Also available at https://doi.org/10.1002/2016GL069965.]

Murray, C.B., and McPhail, J.D., 1988, Effect of incubation temperature on the development of five species of Pacific salmon (*Oncorhynchus*) embryos and alevins: Canadian Journal of Zoology, v. 66, no. 1, p. 266–273. [Also available at https://doi.org/10.1139/z88-038.]

National Marine Fisheries Service, 2008, Executive summary—2008 Willamette Project biological opinion: National Oceanic and Atmospheric Administration Fisheries Archive, 17 p., accessed December 19, 2018, at https://www.westcoast.fisheries.noaa.gov/publications/hydropower/willamette/will-exsum.pdf.

O’Connor, J.E., Mangano, J.F., Anderson, S.W., Wallick, J.R., Jones, K.L., and Keith, M.K., 2014, Geologic and physiographic controls on bed-material yield, transport, and channel morphology for alluvial and bedrock rivers, western Oregon: Geological Society of American Bulletin, v. 26, nos. 3–4, 21 p., accessed January 2019, at https://doi.org/10.1130/B30831.1.

O'Connor, J.E., Sarna-Wojcick, A., Woznikak, K.C., Polette, D.J., and Fleck, R.J., 2001, Origin, extent, and thickness of Quaternary geologic units in the Willamette Valley, Oregon: U.S. Geological Survey Professional Paper 1620, 51 p. [Also available at https://doi.org/10.3133/pp1620.]

Oregon Department of Environmental Quality, 2003, Figure 340A—Fish use designations—Willamette Basin, Oregon: State of Oregon Department of Environmental Quality map, accessed October 5, 2019, at https://www.oregon.gov/deq/Rulemaking%20Docs/figure340a.pdf.

Oregon Department of Environmental Quality, 2005, Figure 340B—Salmon and steelhead spawning use designations, Willamette Basin, Oregon: State of Oregon Department of Environmental Quality map, accessed October 5, 2019, at https://www.oregon.gov/deq/Rulemaking%20Docs/figure340b.pdf.

Oregon Department of Environmental Quality, 2016a, Water quality standards—Beneficial uses, policies, and criteria for Oregon—Temperature: Oregon Administrative Rule 340–041–0028(4): Oregon Department of Environmental Quality, accessed August 28, 2018, at https://secure.sos.state.or.us/oard/viewSingleRule.action?ruleVrsnRsn=244176.

Oregon Department of Environmental Quality, 2016b, Water quality standards—Beneficial uses, policies, and criteria for Oregon—Definitions: Oregon Administrative Rule 340-041-0002(10): Oregon Department of Environmental Quality, accessed August 28, 2018, at https://secure.sos.state.or.us/oard/displayDivisionRules.action?selectedDivision=1458.

Oregon Department of Environmental Quality, 2016c, Water quality standards—Beneficial uses, policies, and criteria for Oregon—Dissolved oxygen: Oregon Administrative Rules 340–041–0016: Oregon Department of Environmental Quality, accessed November 15, 2018, at https://secure.sos.state.or.us/oard/viewSingleRule.action?ruleVrsnRsn=256028.

Pogue, T.R., Jr., and Anderson, C.W., 1995, Processes controlling dissolved oxygen and pH in the upper Willamette River basin, Oregon, 1994: U.S. Geological Survey Water-Resources Investigations Report 95–4205, 71 p. [Also available at https://pubs.er.usgs.gov/publication/wri954205.]

Poole, G.C., O'Daniel, S.J., Jones, K.L., Woessner, W.W., Bernhardt, E.S., Helton, A.M., Stanford, J.A., Boer, B.R., and Beechie, T.J., 2008, Hydrologic spiralling—The role of multiple interactive flow paths in stream ecosystems: River Research and Applications, v. 24, no. 7, p. 1018–1031. [Also available at https://doi.org/10.1002/rra.1099.]

Quinn, T.P., and Adams, D.J., 1996, Environmental changes affecting the migratory timing of American shad and sockeye salmon: Ecology, v. 77, no. 4, p. 1151–1162. [Also available at https://doi.org/10.2307/2265584.]

Regan, S., Hynds, P., and Flynn, R., 2017, An overview of dissolved organic carbon in groundwater and implications for drinking water safety: Hydrogeology Journal, v. 25, no. 4, p. 959–967. [Also available at https://doi.org/10.1007/s10040-017-1583-3.]

Rounds, S.A., 2010, Thermal effects of dams in the Willamette River basin, Oregon: U.S. Geological Survey Scientific Investigations Report 2010–5153, 64 p. [Also available at https://doi.org/10.3133/sir20105153.]

Rounds, S.A., and Doyle, M.C., 1997, Sediment oxygen demand in the Tualatin River Basin, Oregon, 1992–96: U.S. Geological Survey Water-Resources Investigations Report 97–4103, 19 p. [Also available at https://pubs.er.usgs.gov/publication/wri974103.]

Runkel, R.L., McKnight, D.M., and Rajaram, H., 2003, Modeling hyporheic zone processes: Advances in Water Resources, v. 26, no. 9, p. 901–905. [Also available at https://doi.org/10.1016/S0309-1708(03)00079-4.]

Sauter, S.T., Crawshaw, L.I., and Maule, A.G., 2001, Behavioral thermoregulation by juvenile spring and fall chinook salmon, *Oncorhynchus tshawytscha*, during smoltification: Environmental Biology of Fishes, v. 61, no. 3, p. 295–304. [Also available at https://doi.org/10.1023/A:1010849019677.]

Sedell, J.R., and Froggatt, J.L., 1984, Importance of streamside forests to large rivers—The isolation of the Willamette River, Oregon, U. S. A., from its floodplain by snagging and streamside forest removal: SIL Proceedings, 1922–2010, v. 22, no. 3, p. 1828–1834, https://doi.org/10.1080/03680770.1983.11897581.

Takamura, N., Kadono, Y., Fukushima, M., Nakagawa, M., and Kim, B.-H.O., 2003, Effects of aquatic macrophytes on water quality and phytoplankton communities in shallow lakes: Ecological Research, v. 18, no. 4, p. 381–395. [Also available at https://doi.org/10.1046/j.1440-1703.2003.00563.x.]

Torgersen, C.E., Ebersole, J.L., and Keenan, D.M., 2012, Primer for identifying cold-water refuges to protect and restore thermal diversity in riverine landscapes: U.S. Environmental Protection Agency Water Division EPA 910–C–12–001, 91 p.

U.S. Army Corps of Engineers, 2019, The Willamette Valley project: U.S. Army Corps of Engineers Portland District web page, accessed July 25, 2019, at https://www.nwp.usace.army.mil/Locations/Willamette-Valley/.

U.S. Geological Survey, 2018, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed September 10, 2018, at https://doi.org/10.5066/F7P55KJN.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods, book 1, chap. D3, accessed September 10, 2018, at https://pubs.water.usgs.gov/tm1d3.

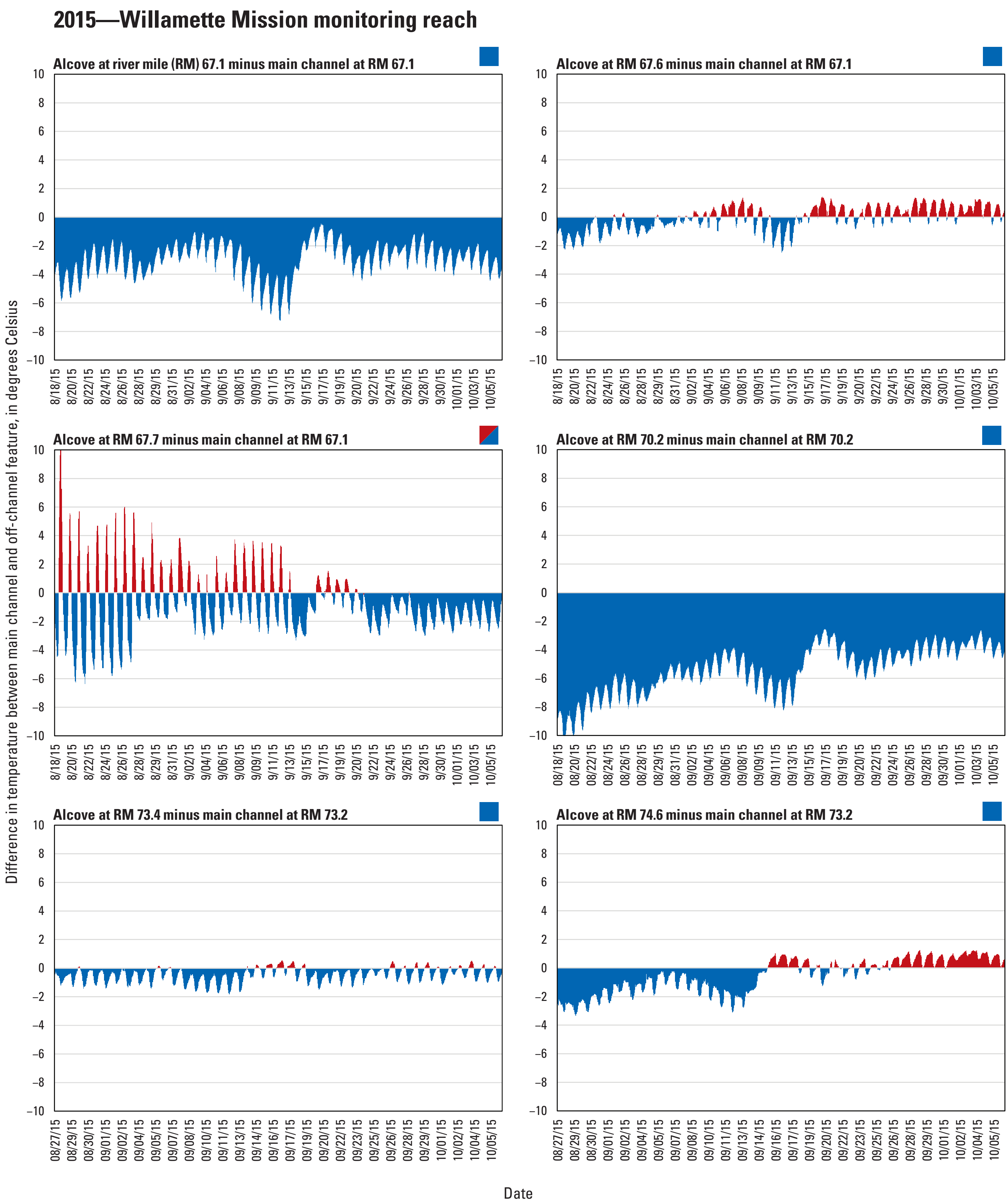
Wallick, J.R., Jones, K.L., O'Connor, J.E., Keith, M.K., Hulse, D., and Gregory, S.V., 2013, Geomorphic and vegetation processes of the Willamette River floodplain, Oregon—Current understanding and unanswered questions: U.S. Geological Survey Open-File Report 2013–1246, 70 p. [Also available at https://doi.org/10.3133/ofr20131246.]

Williams, J.E., Giannico, G.R., and Withrow-Robinson, B., 2014, Field guide to common fish of the Willamette Valley floodplain: Corvallis, Oregon, Oregon State University Extension Services, 44 p.

This page intentionally left blank.

Appendix 1. Comparison of Off-Channel to Main-Channel Water Temperatures for Continuously Monitored Sites

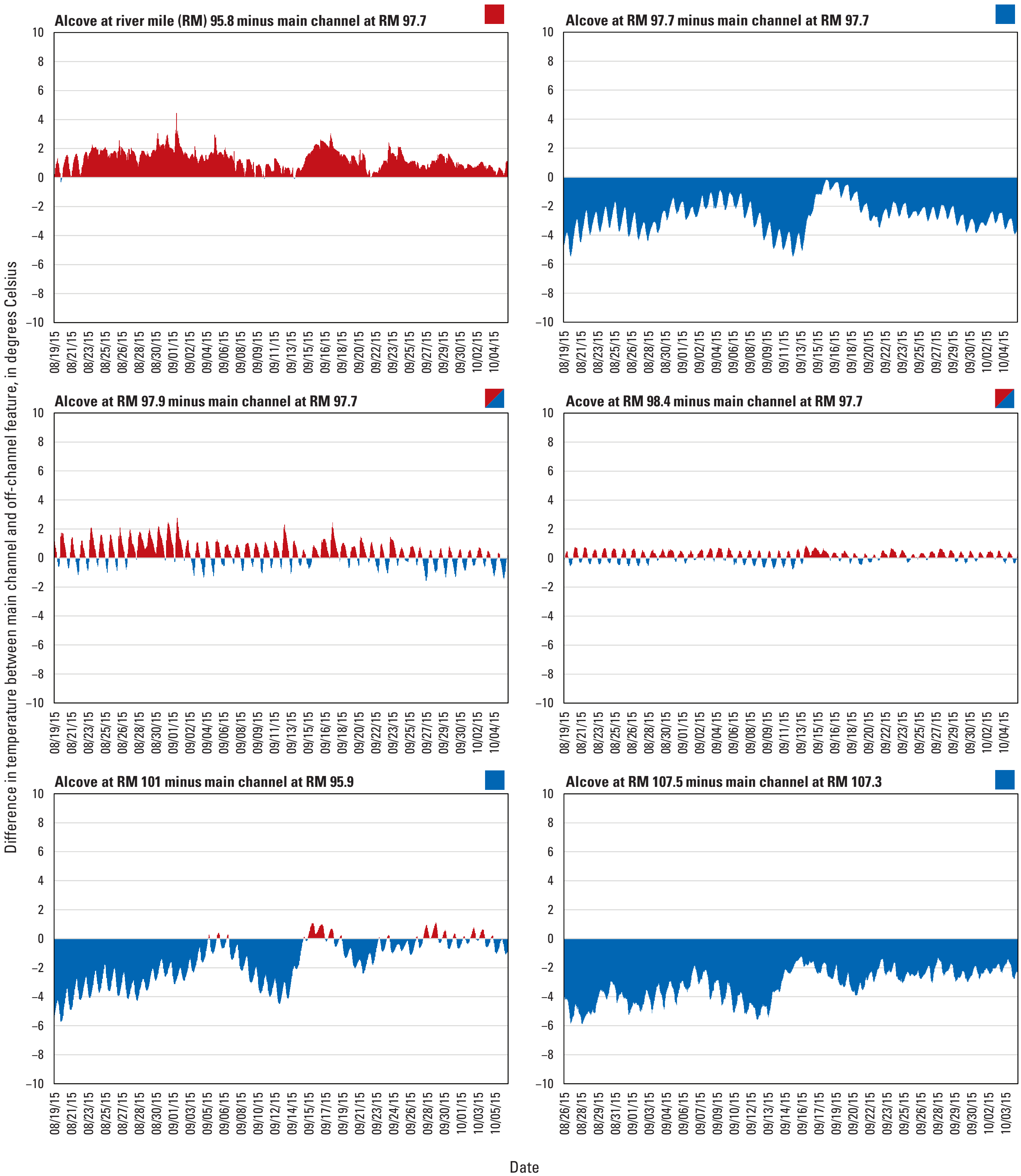
Patterns resulting from a comparison of off-channel water temperatures to temperatures in the main channel are presented in this appendix for all continuously monitored sites. For each graph, the hourly main-channel water temperature was subtracted from the hourly off-channel temperature. Values greater than zero show that the off-channel feature was warmer than the main channel, whereas values less than zero show that the off-channel feature was cooler than the main channel. Graphs with a blue box in the top right corner indicate that the off-channel water temperature generally was cooler than the main-channel water temperature during July and August. Red boxes indicate that the off-channel water temperature generally was warmer than the main-channel water temperature during July and August. Red/blue boxes indicate that the off-channel water temperature fluctuated between warmer and cooler than the main-channel water temperature during July and August. Off-channel features and main-channel sites are referred to by their river mile location (tables 1 and 2).



EXPLANATION

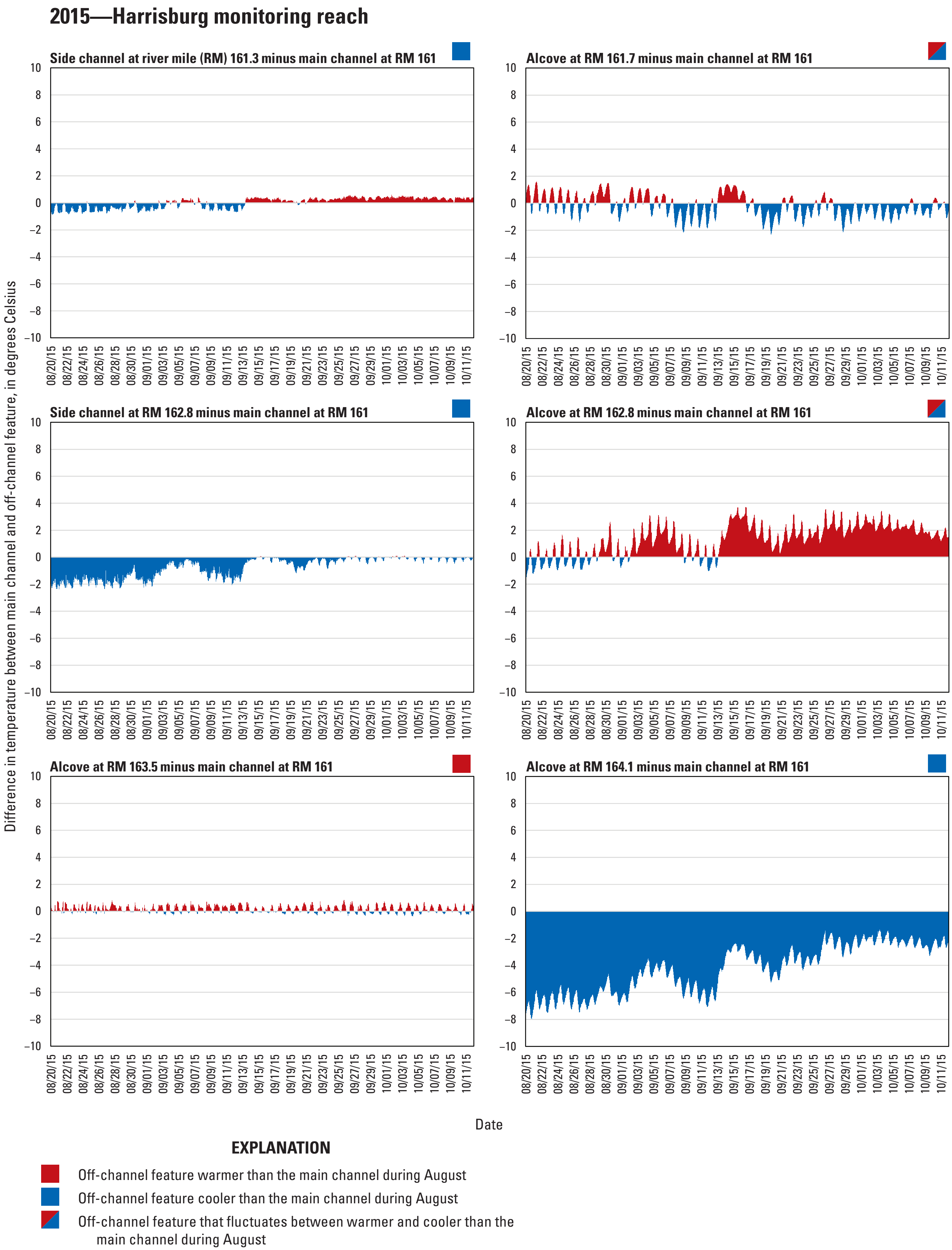
- Off-channel feature cooler than the main channel during August
- Off-channel feature that fluctuates between warmer and cooler than the main channel during August

2015—Independence monitoring reach

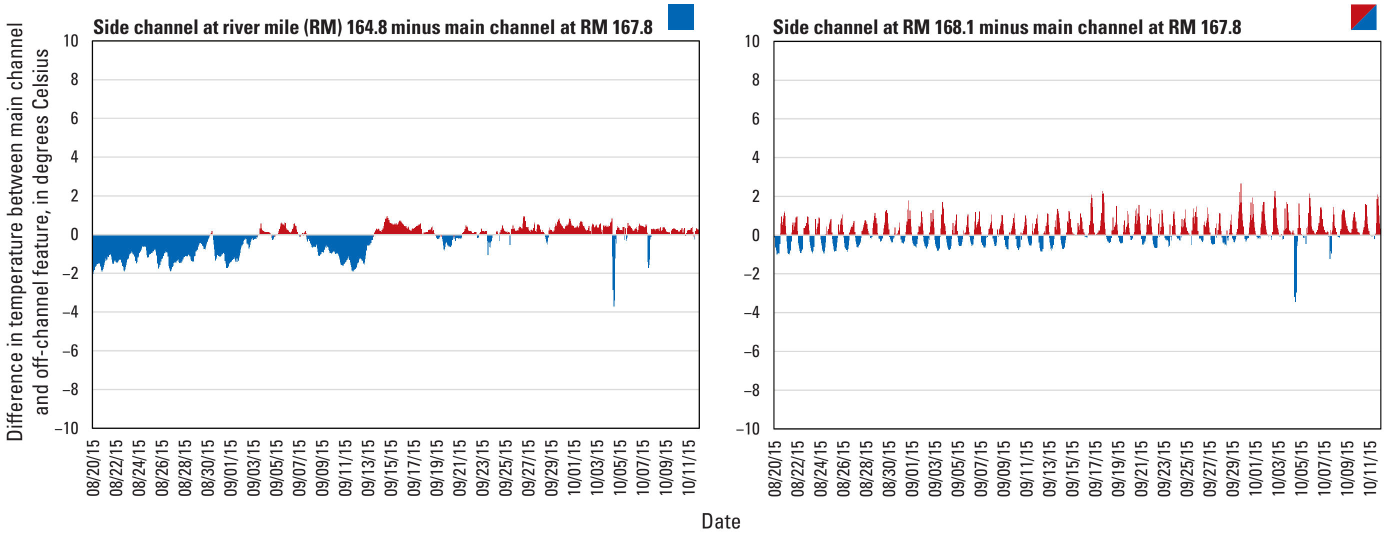


EXPLANATION

- Off-channel feature warmer than the main channel during August
- Off-channel feature cooler than the main channel during August
- Off-channel feature that fluctuates between warmer and cooler than the main channel during August

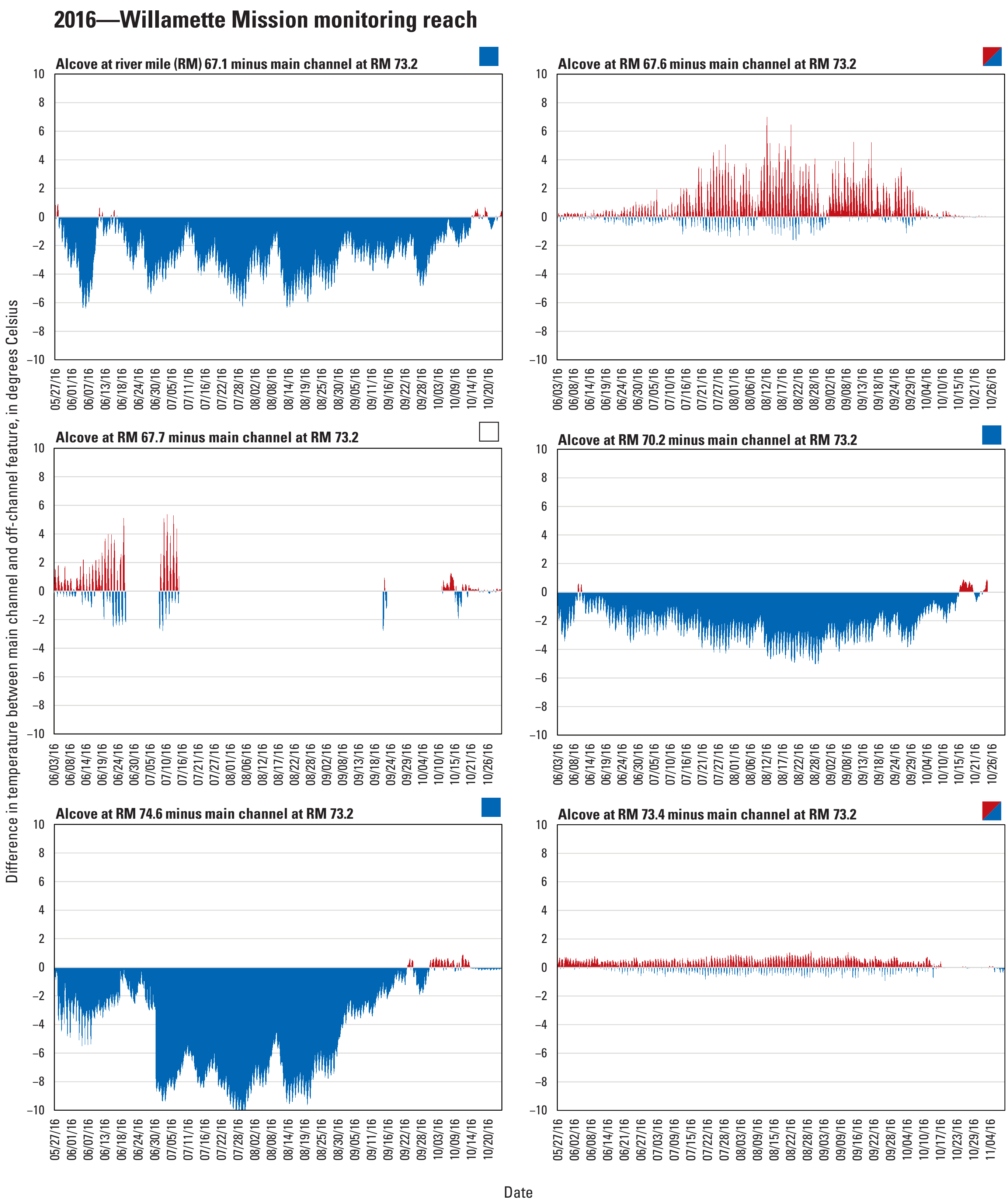

2015—Harrisburg monitoring reach
Side channel at river mile (RM) 161.3 minus main channel at RM 161
Alcove at RM 161.7 minus main channel at RM 161
Side channel at RM 162.8 minus main channel at RM 161
Alcove at RM 162.8 minus main channel at RM 161
Alcove at RM 163.5 minus main channel at RM 161
Alcove at RM 164.1 minus main channel at RM 161
Difference in temperature between main channel and off-channel feature, in degrees Celsius
10
8
6
4
2
0
−2
−4
−6
−8
−10
08/20/15
08/22/15
08/24/15
08/26/15
08/28/15
08/30/15
09/01/15
09/03/15
09/05/15
09/07/15
09/09/15
09/11/15
09/13/15
09/15/15
09/17/15
09/19/15
09/21/15
09/23/15
09/25/15
09/27/15
09/29/15
10/01/15
10/03/15
10/05/15
10/07/15
10/09/15
10/11/15
Date
EXPLANATION
Off-channel feature warmer than the main channel during August
Off-channel feature cooler than the main channel during August
Off-channel feature that fluctuates between warmer and cooler than the main channel during August

2015 – Harrisburg monitoring reach (continued)



EXPLANATION

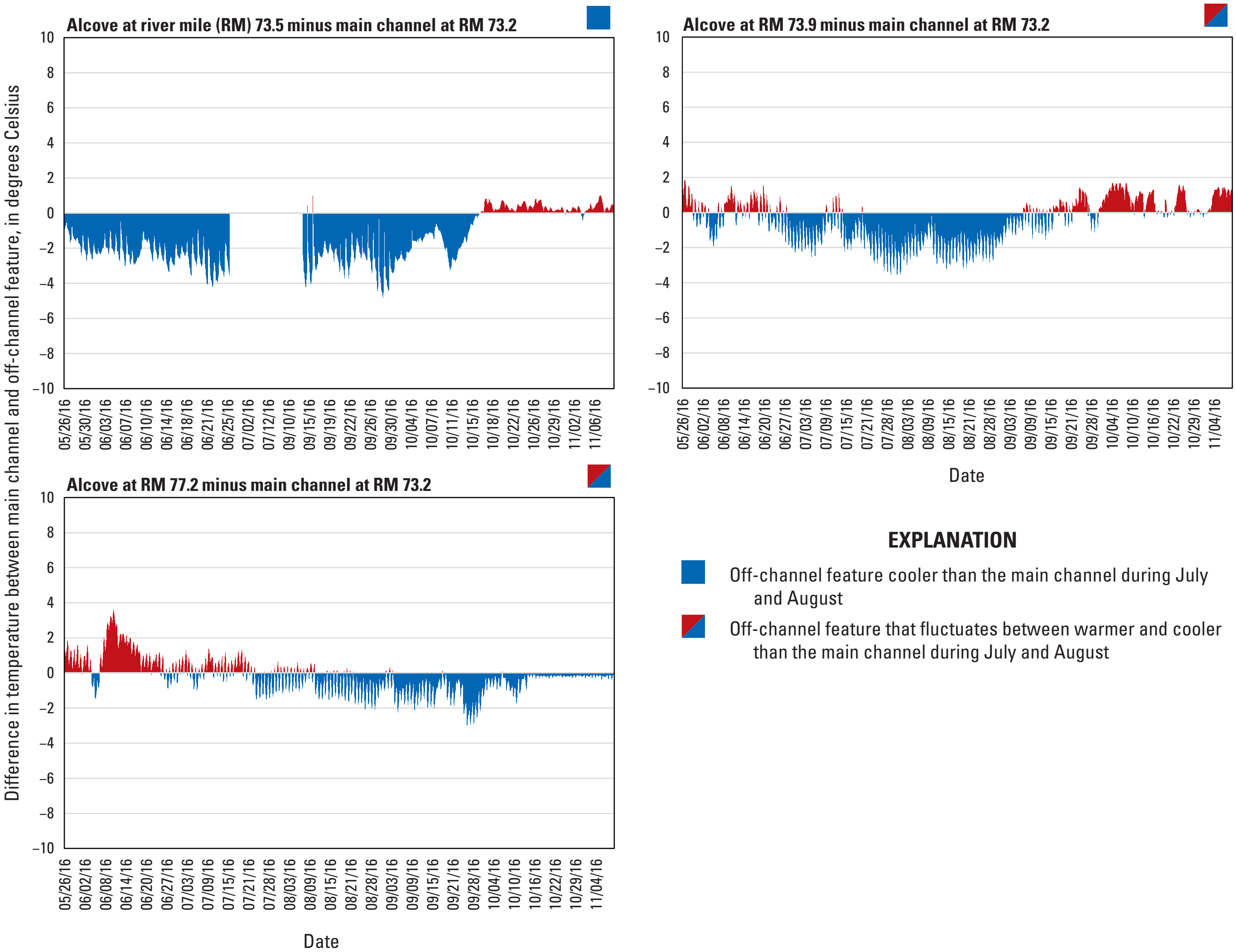
- Off-channel feature cooler than the main channel during August
- Off-channel feature that fluctuates between warmer and cooler than the main channel during August



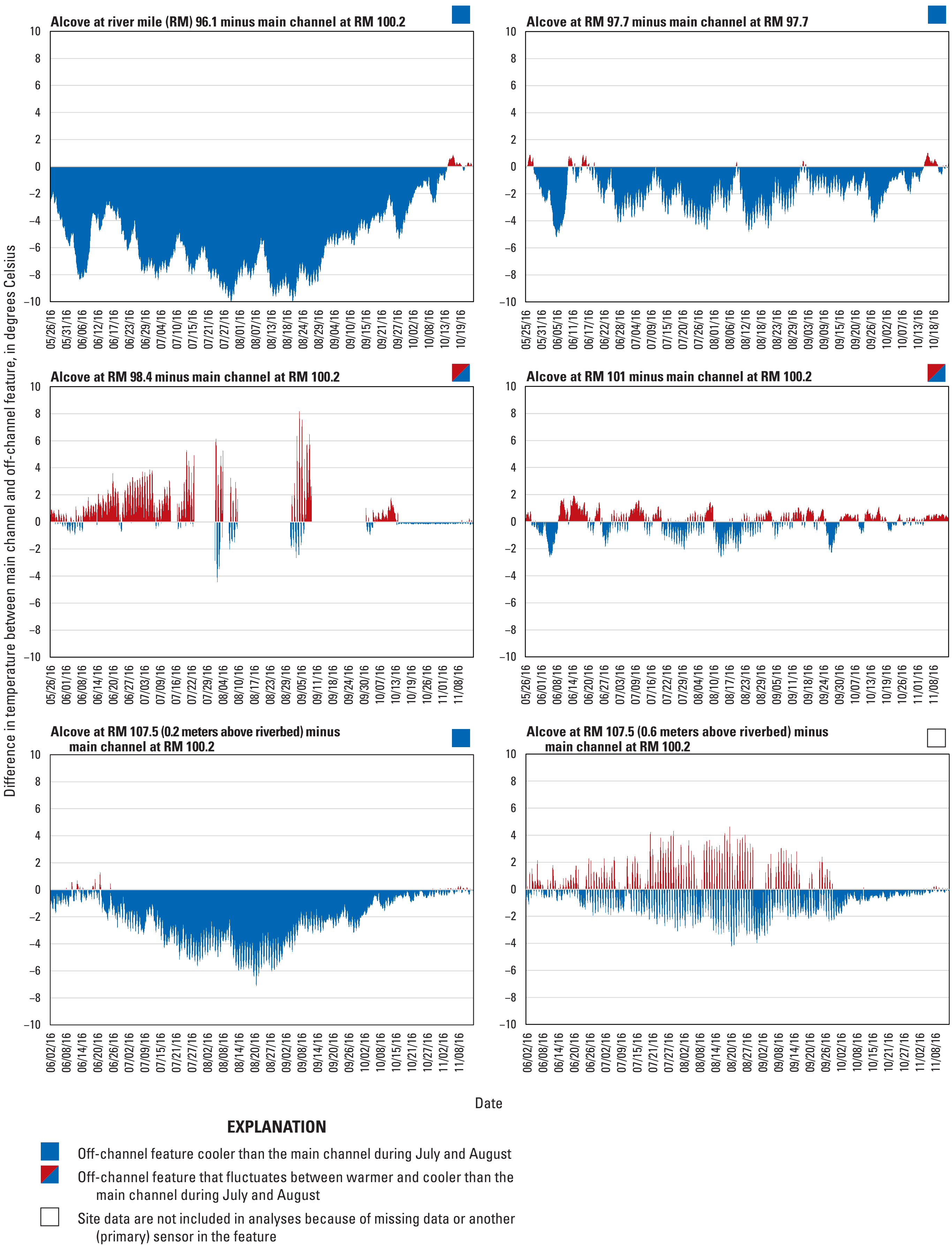
EXPLANATION

- Off-channel feature cooler than the main channel during July and August
- Off-channel feature that fluctuates between warmer and cooler than the main channel during July and August
- Site data are not included in analyses because of missing data or another (primary) sensor in the feature

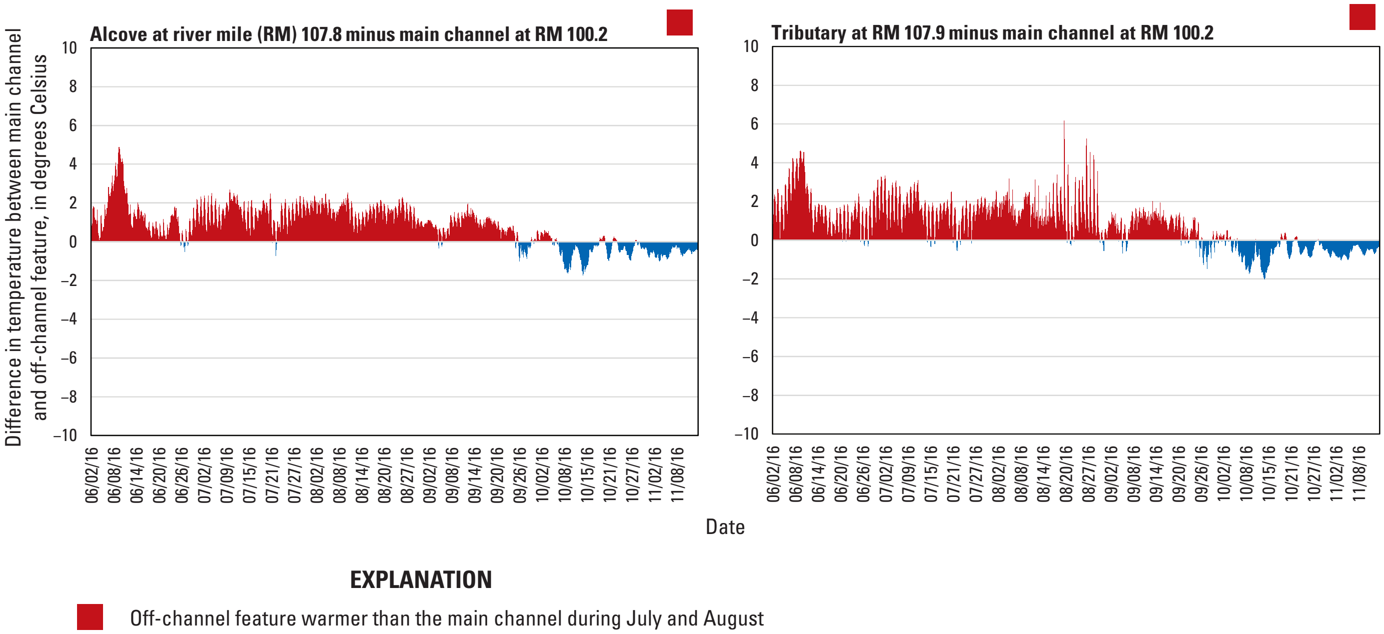
2016—Willamette Mission monitoring reach (continued)

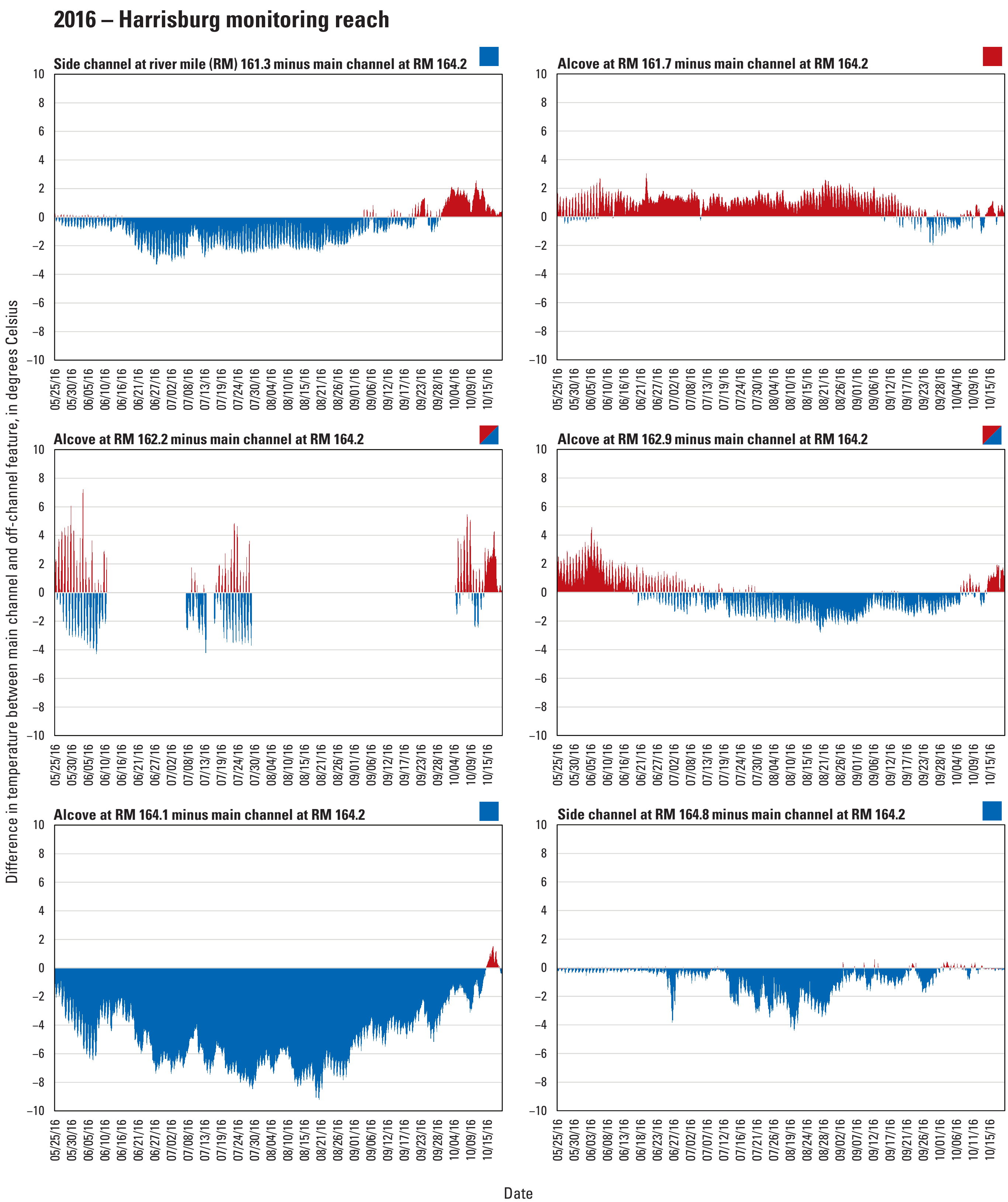


2016—Independence monitoring reach



2016—Independence monitoring reach (continued)





EXPLANATION

- Off-channel feature warmer than the main channel during July and August
- Off-channel feature cooler than the main channel during July and August
- Off-channel feature that fluctuates between warmer and cooler than the main channel during July and August

Appendix 2. Aerial Imagery from 1994 and 2016 for Select Off-Channel Features

This appendix shows aerial imagery from 1994 and 2016 for the five off-channel features that were intensively monitored in 2016. Such imagery is useful in ascertaining the stability of the channel and its gravel bars and features, as well as the presence and absence of vegetation over time.

Base map data from Google, 2018

0 500 METERS
0 1,000 FEET


June 18, 1994
July 23, 2016
Willamette River
flow direction
Location of water-quality monitor at
Windsor Bar side channel
(river mile 74.6)
River mile 75
N
Base map data from Google, 2018
0
250 METERS
0
500 FEET

Base map data from Google, 2018


May 6, 1994
May 29, 2016
River mile 164
Location of water-quality monitor
at Blue Ruin alcove
(river mile 164.1)
Location of water-quality monitor at
Harpers Bend side channel
(river mile 164.8)
River mile 165
Willamette River
flow direction
N
Base map data from Google, 2018
0
500 METERS
0
1,000 FEET

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma and Rolla
Publishing Service Centers

For more information concerning the research in this report, contact the
Director, Oregon Water Science Center
U.S. Geological Survey
2130 SW 5th Avenue
Portland, Oregon 97201
https://www.usgs.gov/centers/or-water

USGS

Smith and Others—**Temperature and Water-Quality Diversity and Effects of Surface-Water Connection, Willamette River, Oregon, 2015–16**—SIR 2020–5068

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20205068