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

Historical Changes to Channel Planform and Bed Elevations Downstream from Dams Along Fall Creek and Middle Fork Willamette River, Oregon, 1926–2016

Scientific Investigations Report 2023–5048

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

Cover. Middle Fork Willamette River, looking upstream from Jasper, Oregon, March 31, 2016. Photograph by Mackenzie K. Keith, U.S. Geological Survey.

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Heather D. Bervid

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)

Datums

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

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

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

Abbreviations

BiOp	Biological Opinion
fpkm	floodplain kilometer
lidar	light detection and ranging
rkm	river kilometer(s)
NGVD 29	National Geodetic Vertical Datum of 1929
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WVS	Willamette Valley System
WY	water year, defined as the 12-month period from October 1, for any given year, through September 30, of the following year. The water year is designated by the calendar year in which it ends.

Historical Changes to Channel Planform and Bed Elevations Downstream from Dams Along Fall Creek and Middle Fork Willamette River, Oregon, 1926–2016

By Mackenzie K. Keith, J. Rose Wallick, Gabriel W. Gordon, and Heather D. Bervid

Abstract

Operation of large, multipurpose dams within the Middle Fork Willamette River Basin, Oregon, including the Fall Creek sub-basin, have disrupted natural streamflow and sediment transport regimes and fish passage along the river corridors. Documenting channel morphology, including channel planform, landforms, vegetation cover, and river channel elevations at multiple points in time spanning the 20th and early 21st centuries, is useful for characterizing net changes occurring in response to construction and operation of these dams. The U.S. Geological Survey assessed historical channel changes that occurred within the past century in response to the construction and operation of flood-control dams by evaluating planimetric datasets (from 1926 plan and profile surveys and 1936 and 2016 aerial photographs) and elevation datasets (from 1926 plan and profile surveys and 2015 light detection and ranging [lidar]). This study specifically focuses on the lower 27.3 kilometers (km) of the Middle Fork Willamette River and the lower 11.5 km of Fall Creek, or the reaches downstream from the U.S. Army Corps of Engineers Dexter Dam and Fall Creek Dam, to the confluence with Coast Fork Willamette River. Altogether, compilation and evaluation of datasets for Fall Creek and the Middle Fork Willamette River downstream from the dams provide a foundation for understanding:

1. channel morphology and patterns of geomorphic stability prior to dam construction in 1926 and 1936;
2. channel morphology and patterns of lateral and vertical stability of the early 21st century that reflect present-day (post-dam) streamflow and sediment regimes as of 2015–16; and
3. geomorphic transformations of the river corridors in the decades following dam construction, including changes in planform and bed elevation (determined from water-surface elevations).

Findings from this study can be used to provide historical and geomorphic context for geomorphic responses to deep reservoir drawdowns on Fall Creek Lake that mobilize reservoir sediment downstream and informing other restoration and river-management activities; this report summarizes one component of a larger research effort to document the magnitude and spatial distribution of geomorphic responses to sediment releases from draining Fall Creek Lake.

As of 2016, the modern Fall Creek flows through a narrow, semi-alluvial channel that efficiently conveys water and sediment at typical streamflows downstream from Fall Creek Dam. This channel planform, including the positions and distributions of bars and secondary water features (side channels, alcoves, and ponds), generally reflects pre-dam conditions in 1936, suggesting relatively modest morphological adjustments resulted from reductions in sediment supply and alterations to peak streamflow after dam construction. The most substantial morphologic change detected over this period was a reduction in unvegetated gravel bars.

As of 2016, the modern Middle Fork Willamette River is a large, gravel-bed river that, despite substantial transformations in channel morphology and reduction in lateral dynamism following the construction of multiple upstream dams, remains a dominantly alluvial river. Prior to dam construction in 1926 and 1936, the reaches of the Middle Fork Willamette River downstream from Dexter Dam were laterally active with multi-thread and single-thread channels flanked by large, shifting gravel bars. Since streamflow regulation and other channel modifications in the mid-20th century, these reaches have become less laterally active and encompass a narrower floodplain corridor as abundant former gravel bars were converted to low-elevation floodplains colonized by young, dense forests. The Middle Fork Willamette River downstream from Dexter Dam has remained mostly vertically stable between 1926 and 2015, although localized segments possibly decreased in elevation as much as 2.3 meters.

Introduction

The Middle Fork Willamette River Basin drains 3,548 square kilometers (km^2) of western Oregon before joining the Coast Fork Willamette River to form the Willamette River near Eugene, and the Fall Creek Basin drains 653 km^2 of the Middle Fork Willamette River Basin (fig. 1). The Middle Fork Willamette River is a large, gravel-bed river, and historically, its lower reaches maintained a laterally active, multi-channeled, anastomosing planform sustained by flooding and voluminous inputs of gravel and large wood from upstream tributaries and local bank erosion (Dykaar, 2005; Wallick and others, 2013, 2018). This river and its tributaries provide habitat to two species of Endangered Species Act (ESA)-listed salmonids (*Onchorhyncus* spp.) and a diverse array of other native fish and wildlife species (National Marine Fisheries Service, 1999a, 1999b; U.S. Fish and Wildlife Service, 2008; White and others, 2022; Williams and others, 2022; table 1). In the mid-20th century, 4 high-head (greater than 28-meter [m] tall) flood-control dams were constructed in the basin by the U.S. Army Corps of Engineers (USACE) to provide flood protection for downstream communities as part of the Willamette Valley System (WVS) with 9 other dams (Lookout Point Dam, Dexter Dam and Fall Creek Dam shown in fig. 1 and Hills Creek Dam about 40 kilometers [km] east of the map area shown in fig. 1). Operation of these large, WVS dams (together with navigational improvements such as large wood removal and streambank stabilization) have resulted in substantial transformation of the downstream river channels and have interrupted natural streamflow and sediment transport regimes along several major river corridors of the Willamette River (Wallick and others, 2013; O'Connor and others, 2014; Gregory and others, 2019; table 1). In general, the physical and biological effects of large dams are well documented; for example, dams trap coarse sediment and modify streamflow patterns, resulting in altered geomorphic processes and consequent adjustments to channel morphology, substrates, and physical habitats in downstream reaches (for example, Williams and Wolman, 1984; Grant and others, 2003; Graf, 2006; Grant, 2012). However, assessments of historical geomorphic conditions between the pre-dam period and the present day are useful for understanding the site-specific historical patterns of channel landforms and decadal-scale changes, as well as the net changes in channel morphology that have occurred over the last century in response to the construction and operation of dams. Documenting historical channel conditions and long-term changes is also useful for identifying patterns of channel stability that result from natural and human-related controls on channel processes. Hence, the geomorphic context provided by historical channel change analyses of Fall Creek and Middle Fork Willamette River is informative for a wide range of restoration and floodplain-management activities.

At many large, regulated rivers in the western United States, changing societal values and requirements under ESA have motivated the USACE and other entities to develop strategies to mitigate some of the harmful effects of the dams and restore or re-naturalize some aspects of downstream river corridors to better support floodplain ecosystems and declining fish populations (for example, National Marine Fisheries Service, 2008). In the Middle Fork Willamette River Basin, those strategies include construction of fish passage facilities to transport adult salmon above the dams to their historical spawning grounds, lowering of reservoir lake levels to allow juvenile salmon to swiftly pass from reservoir to below-dam reaches, changes in dam operations to improve streamflows and thermal conditions in below-dam reaches, and implementation of river restoration activities to locally improve habitats downstream from dams (table 1). To inform these and other river-management decisions, a variety of fisheries and hydrological research studies have been implemented (for example, Buccola and others, 2016; Hansen and others, 2017; Kock and others, 2019; Keith and others, 2022, 2023). Repeated releases of reservoir sediments to reaches downstream from the dam have prompted questions about changes in channel morphology and aquatic habitats and quantifying the cumulative influence from effects of this management action (for example, see Grant and Lewis, 2015) compared with transformations imposed by dam construction. At Fall Creek Dam, detailed geomorphic assessments have been completed to evaluate responses to the annual temporary draining (streambed drawdowns; since 2011) that have resulted in the erosion and downstream export of reservoir sediments from the lake (Schenk and Bragg, 2014, 2015, 2021). To provide geomorphic and historical context for evaluating geomorphic responses to Fall Creek Lake streambed drawdowns, this study along Fall Creek and Middle Fork Willamette River assessed historical channel changes that occurred in the preceding century in response to the construction and operation of flood-control dams.

Purpose and Scope

This report documents channel morphology including channel planform, landforms, vegetation cover, and river channel elevations at multiple points in time spanning the 20th and early 21st centuries in the Middle Fork Willamette River Basin to characterize net changes occurring in response to construction and operation of USACE flood-control dams. Specifically, datasets from the early 20th century (1926 and 1936) were compared with more recent datasets (2005–16). Evaluation of these datasets provides a foundation for understanding:

1. channel morphology and patterns of geomorphic stability prior to dam construction;

2. channel morphology and patterns of lateral and vertical stability of the early 21st century that reflect present-day (post-dam) streamflow and sediment regimes; and

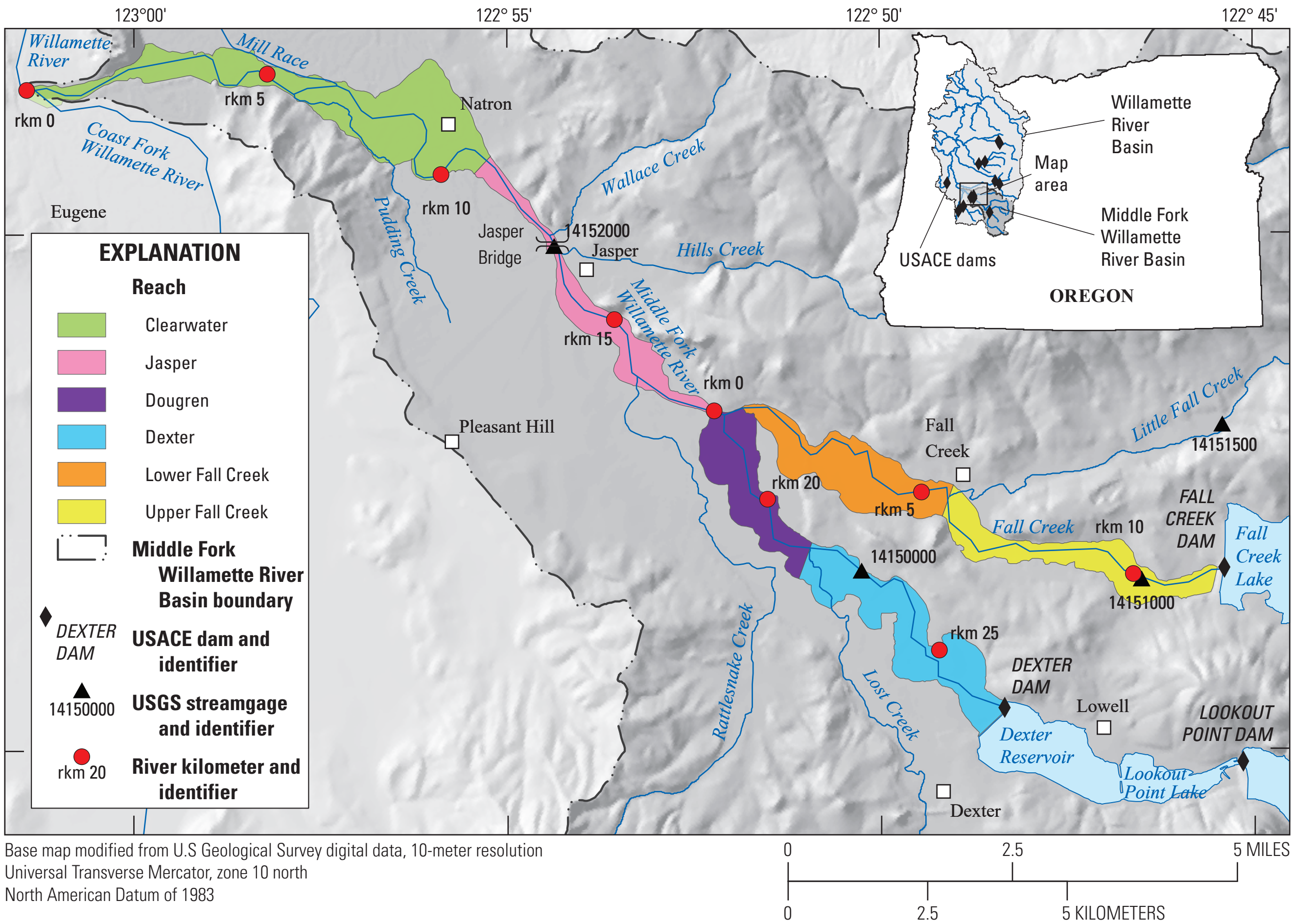

Figure 1. Study area with the stream network, basin boundary, study area, streamgages, and other features in the Fall Creek and Middle Fork Willamette River Basins, Oregon. Reach polygons show the floodplain mapping corridor (delineated by Wallick and others [2018] for the Middle Fork Willamette River and by Keith and Gordon [2019] for Fall Creek) and is narrower than the historical floodplain. Inset map shows the Willamette and Middle Fork Willamette River Basins and locations of Willamette Valley System dams operated by the U.S. Army Corps of Engineers. rkm, river kilometer; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey.

3. geomorphic transformations of the river corridors in the decades following dam construction, including changes in planform and bed elevation (assumed from water-surface elevations).

Assessments of historical channel conditions, net changes, and the ensuing spatial and temporal patterns of lateral and vertical channel stability that arise from this historical assessment are useful for informing restoration or management activities that may occur within the river corridors downstream from Fall Creek and Dexter Dams. The study area focuses on Fall Creek and Middle Fork Willamette River downstream from the lowermost USACE dams (Fall Creek and Dexter Dams) to the confluence with Coast Fork Willamette River. Mapping datasets created for this study are publicly available (Keith and Gordon, 2019).

Reporting Units and Locations

Values in this report primarily are reported in International System (SI) units; however, streamflow is presented in English units (cubic feet per second [ft^3/s]) to support floodplain managers in the Willamette Valley and provide consistency with data recorded at U.S. Geological Survey (USGS) streamgages. Locations along the Fall Creek and Middle Fork Willamette River study areas (fig. 1) in this report are given in river kilometers (rkm), measured along wetted-channel centerlines developed from 2009 (Watershed Sciences, 2009) and 2012 (Watershed Sciences Inc., 2012) light detection and ranging (lidar) datasets. Repeat mapping from aerial photographs also references floodplain kilometers (fpkm) measured along the mapping corridor centerlines developed from these lidar datasets to provide a static reference frame for large changes in channel locations that would affect channel lengths and historical changes in rkm. These locations and distances do not directly correspond with river miles depicted on USGS quadrangle maps.

Table 1. Summary of datasets used to evaluate channel planform and bed elevations along Fall Creek and Middle Fork Willamette River, Oregon, and historical events (excluding some natural events such as forest fires and landslides) influencing streamflow, sediment supply, and hydraulic conditions throughout the Willamette River Basin that may have affected geomorphic interpretations.

[**Abbreviations:** NGVD 1929, National Geodetic Vertical Datum of 1929; BiOp, Biological Opinions; ft^3/s, cubic foot per second; lidar, light detection and ranging; rkm, river kilometer; USGS, U.S. Geological Survey; WY, water year]

Date	Activity or event type	Activity or event detail	Source
Time immemorial	Indigenous population	The southern Willamette Valley is the ancestral homeland of indigenous peoples from the Kalapuya, Yoncalla, Winefelly, Chelamela, and Molalla tribal bands, who lived in this region prior to Euro-American arrival. The descendants of these peoples are now recognized under the Confederated Tribes of the Grand Ronde Community of Oregon and the Confederated Tribes of Siletz Indians of Oregon.	https://www.grandronde.org/history-culture/history/; https://www.ctsi.nsn.us/introduction/; https://native-land.ca/
Mid-1800s	Growing Euro-American population	The first Euro-Americans settled in the southern Willamette Valley. The towns of Eugene and Springfield were settled in 1846 and 1848, respectively. Basin land use focused on agriculture and forestry.	Sedell and Froggatt, 1984; Dykaar, 2005; Dykaar, 2008a; Gregory and others, 2002a; Wallick and others, 2007; Wallick and others, 2013
1852	Mill Race	Mill Race constructed and used to diverted streamflow from the Middle Fork Willamette River near Clearwater Park to Springfield for grist and lumber mills.	Schall, 2017
Late-1800s	Historical survey	General Land Office maps showing houses and farms established in the southern Willamette Valley.	Bureau of Land Management, 2022
Late-1800s to mid-1900s	In-stream wood removal	Pre- and post-dam removal of instream wood debris.	Sedell and Froggatt, 1984; Benner and Sedell, 1997; Wallick and others, 2013; O'Connor and others, 2014; Gregory and others, 2019
Early 1900s	Splash damming	Fall Creek and Middle Fork Willamette River.	Miller, 2010
Early 1900s	Log drives	Fall Creek and Middle Fork Willamette River.	Miller, 2010
1906	Streamflow gaging	USGS streamgage station 14152000 at rkm 13.1 on the Middle Fork Willamette River at Jasper first began recording streamflow in WY 1906.	USGS, 2021
1909	Flood event	Maximum pre-dam peak streamflow of 94,000 ft^3/s recorded at Jasper streamgage on November 23, 1909 (WY 1910).	USGS, 2021
1926	Historical survey[1]	USGS hydrographic surveys of channel planform and water-surface elevations along the Middle Fork Willamette River in 1926 as part of a series of plan and profile maps of major tributaries to the Willamette River. These surveys were published at a scale of 1:31,680 and did not include Fall Creek.	USGS, 1927
1936	Streamflow gaging	USGS streamgage station 14151000 at rkm 10.1 on Fall Creek below Winberry Creek first began recording streamflow in WY 1936.	USGS, 2021
1936	Historical survey[1]	Black and white aerial photographs covering Fall Creek and the Middle Fork Willamette River downstream from the Fall Creek and Dexter Dams. These photographs were acquired on July 30, 1936, at a scale of 1:15,000.	USACE, 1936
1938	Historical survey	Habitat surveys completed by the Bureau of Fisheries (now National Marine Fisheries Service) in 1938 along Fall Creek.	McIntosh and others, 2009

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[**Abbreviations:** NGVD 1929, National Geodetic Vertical Datum of 1929; BiOp, Biological Opinions; ft^3/s, cubic foot per second; lidar, light detection and ranging; rkm, river kilometer; USGS, U.S. Geological Survey; WY, water year]

Date	Activity or event type	Activity or event detail	Source
1940s–1960s	Revetments	Revetments built in the study area pre- and post-date dam construction.	Gregory and others, 2002b; Gregory and others, 2007; Wallick and others, 2007; Institute for a Sustainable Environment Lab, 2017
1940s–1960s	Clearcutting	The practice of clearcutting timber harvest in the southern Willamette Valley started in 1940s and peaked in 1960s.	U.S. Forest Service, 1995; Miller, 2010
1940s–1970s	Dredging, navigational improvements	Pre- and post-dam changes made to river channel to improve waterway navigation.	Sedell and Froggatt, 1984; Benner and Sedell, 1997
1947	Streamflow gaging	USGS streamgage station 14150000 at rkm 22.5 on the Middle Fork Willamette River near Dexter, Oregon, first began recording streamflow in WY 1947.	USGS, 2021
1953	Flood event	Maximum pre-dam peak streamflow of 62,200 ft^3/s recorded at Dexter streamgage on January 18, 1953.	USGS, 2021
1954	Dam operation	Lookout Point Dam construction on the Middle Fork Willamette River began in 1948 and was completed in 1954.	https://www.nwp.usace.army.mil/Locations/Willamette-Valley/Lookout-Point/
1955	Dam operation	Dexter Dam construction on the Middle Fork Willamette River began in 1947 and was completed in 1955.	https://www.nwp.usace.army.mil/Locations/Willamette-Valley/Dexter/
1956	Flood event	Maximum pre-dam peak streamflow of 24,700 ft^3/s recorded at Fall Creek streamgage on December 11, 1956 (WY 1957).	USGS, 2021
1960s–1990s	Dam operation	Earlier reservoir drawdowns of Fall Creek Lake to a pool elevation of 700 ft (NGVD 1929) or lower began in the late 1960s and occurred nearly 40 times through the 1990s.	Smith and Korn, 1970; Downey and Smith, 1992
1961	Dam operation	Hills Creek Dam construction on the Middle Fork Willamette River began in 1956 and was completed in 1961.	https://www.nwp.usace.army.mil/Locations/Willamette-Valley/Hills-Creek/
1964	Flood event	Maximum peak streamflow event after upstream streamflow regulation by dams recorded at Dexter streamgage on December 26, 1964; 29,500 ft^3/s.	USGS, 2021
1965	Dam operation	Fall Creek Dam construction on Fall Creek began in 1964 and was completed in 1965.	https://www.nwp.usace.army.mil/Locations/Willamette-Valley/Fall-Creek/
1999	Endangered and threatened species listing	Threatened species status for Upper Willamette spring Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) in Oregon and Washington.	National Marine Fisheries Service, 1999a; National Marine Fisheries Service, 1999b
2005	Historical survey[1]	Four-band (red, green, blue, near infrared) aerial photographs collected as part of the National Agricultural Imagery Program covering the study area. This imagery was acquired on July 18 and August 4, 2005, at a 0.5-meter resolution.	U.S. Department of Agriculture, 2005

Table 1. Summary of datasets used to evaluate channel planform and bed elevations along Fall Creek and Middle Fork Willamette River, Oregon, and historical events (excluding some natural events such as forest fires and landslides) influencing streamflow, sediment supply, and hydraulic conditions throughout the Willamette River Basin that may have affected geomorphic interpretations.—Continued

[**Abbreviations:** NGVD 1929, National Geodetic Vertical Datum of 1929; BiOp, Biological Opinions; ft^3/s, cubic foot per second; lidar, light detection and ranging; rkm, river kilometer; USGS, U.S. Geological Survey; WY, water year]

Date	Activity or event type	Activity or event detail	Source
2008	Dam operation	Joint BiOp from the U.S. Fish and Wildlife Service and National Oceanic and Atmospheric Administration Fisheries were issued for the Willamette Valley Project including Middle Fork Willamette River Basin dams as part of the Endangered Species Act consultation.	National Marine Fisheries Service, 2008; U.S. Fish and Wildlife Service, 2008
2011–present (2022)	Dam operation	Annual streambed drawdowns of Fall Creek Lake to elevation 680 ft (NGVD 1929) near historical streambed in autumn 2011 (WY 2012) as part of the 2008 BiOp to facilitate the downstream passage of juvenile spring Chinook salmon. These operations were deemed successful in terms of fish passage, but large quantities of reservoir sediments were also passed downstream from the dam.	Nesbit and others, 2014; Northwest Fisheries Science Center, 2015; Hansen and others, 2017; Schenk and Bragg, 2014, 2015, 2021
2015	Historical survey[1]	Topo-bathymetric lidar data collected as part of the Oregon Lidar Consortium along Fall Creek and the Middle Fork Willamette River downstream from Fall Creek and Dexter Dams. These lidar data were acquired on September 14–15, 2015, with a 0.03–0.04-meter vertical accuracy and a raster cell size of 1 meter.	Quantum Spatial, 2016
2015	Dam operation	Implementation of the Sustainable Rivers Project environmental streamflow recommendations on the Middle Fork Willamette River at Lookout Point and Dexter Dams.	Warner and others, 2014; Gregory and others, 2007; Konrad, 2010
2016	Historical survey[1]	Four-band (red, green, blue, near infrared) aerial photographs collected as part of the National Agricultural Imagery Program covering the study area. This imagery was acquired on June 26, 2016, at a 1-meter resolution.	U.S. Department of Agriculture, 2016
2019	Flood event	Maximum peak streamflow event after upstream streamflow regulation by dams recorded at Fall Creek streamgage on April 10, 2019; 5,820 ft^3/s.	USGS, 2021
2019	Flood event	Maximum peak streamflow event after upstream streamflow regulation by dams recorded at Jasper streamgage on April 12, 2019; 24,400 ft^3/s.	USGS, 2021

[1]Primary datasets used to evaluate lateral and vertical channel stability for this study.

Study Area

The Middle Fork Willamette River drains 3,548 km^2 of northwest Oregon, before joining with the Coast Fork Willamette River near Eugene to form the Willamette River. The Fall Creek Basin (comprising 653 km^2 of the Middle Fork Willamette River Basin) and Fall Creek joins the Middle Fork Willamette River 17.9 km upstream from the river mouth. Hydrogeomorphic conditions along Fall Creek and Middle Fork Willamette River reflect the geology as well as past land uses and the hydro-climatology, streamflow, and regulation by dams.

Geology

The Fall Creek Basin is almost entirely within the older and less permeable Western Cascades (Tague and Grant, 2004; Jefferson and others, 2006), composed of steeply dissected Tertiary volcanic rocks. Although the headwaters of the Middle Fork Willamette River originate in the younger and more permeable High Cascades (Tague and Grant, 2004; Jefferson and others, 2006), most of the basin lies within the Western Cascades (66 percent), with the lowermost reaches extending to the low gradient floor of the Willamette Valley (Peck and others, 1964; and Sherrod, 1991, as cited in Smith and Roe, 2015). The Holocene floodplains of Fall Creek and the Middle Fork Willamette River downstream from the Fall Creek Lake and Dexter Dams are bordered by Pliocene to Pleistocene terrace gravels, upper Pleistocene Missoula Flood deposits, and Western Cascades volcanic rocks (O'Connor and others, 2001). The geology and steep terrain underlying the Western and High Cascades historically supported high rates of bed-material sediment entering the river corridors of the study area.

Human Influences on Fall Creek and the Middle Fork Willamette River Since the 1800s

The river corridors of Fall Creek and Middle Fork Willamette River have been influenced by Euro-American activities since the mid to late 19th century (table 1). Euro-American arrival and settlement in the southern Willamette Valley began in the mid-1800s, and by the late 1800s, General Land Office maps (available at Bureau of Land Management, 2022) show numerous houses and farms established on valley bottom surfaces. Timber was harvested from forested uplands and transported downstream, often facilitated by log drives and splash dams on the river channels (Miller, 2010; figs. 2–4). Instream gravel extraction, removal of large wood, various navigational improvements, and other activities also affected the river corridors of the Willamette River Basin (for example, Sedell and Froggatt, 1984; Benner and Sedell, 1997). One of the most substantial and persistent alterations to river morphology was perhaps the construction and operation of flood-control dams in the mid-20th century (Wallick and others, 2007). From 1941 to 1969, the USACE constructed 13 dams in the Willamette River Basin as part of the WVS, 3 of which are in the study area (fig. 1). Operation of these large, multipurpose dams has interrupted natural streamflow and sediment transport regimes along several major river corridors of the Willamette River Basin, including the Middle Fork Willamette River and Fall Creek (Wallick and others, 2013; O'Connor and others, 2014; Gregory and others, 2019). As part of the WVS, revetments were also constructed to stabilize streambanks throughout the major rivers of the Willamette River Basin (for example, Gregory and others, 2002b; Gregory and others, 2007; Wallick and others, 2007).

Figure 2. Log drive along Fall Creek, Oregon. Photograph taken about 1900 (date unknown) and provided by and used with permission from the Lane County History Museum.

Figure 3. Logs floating to a sawmill along the Middle Fork Willamette River at Jasper, Oregon. Photograph taken in 1905 from area near Jasper Bridge looking upstream and provided by and used with permission from the Lane County History Museum.

The culmination of direct and indirect effects on Fall Creek and the Middle Fork Willamette River have resulted in the channel simplification and stabilization.

Hydro-Climatology, Streamflow, and Regulation by Dams

The Middle Fork Willamette River Basin (fig. 1) is characterized by a temperate Mediterranean climate (Köppen-Geiger climate classification system) with warm dry summers and cool wet winters. Mean annual precipitation is 166 centimeters (cm; USGS, 2018, from PRISM 1971–2000 800-meter [m] grid). The mean annual maximum air temperature is 16.4 degrees Celsius (°C) and the mean annual minimum air temperature is 4.56 °C (USGS, 2018; from PRISM 1971–2000 800-m grid). In the Fall Creek Basin and much of the Middle Fork Willamette River Basin, most of the winter precipitation falls as rain, although a substantial amount of precipitation falls as snowfall along higher elevations of the Middle Fork Willamette River Basin. Prior to streamflow regulations, large floods occurring December through February and smaller floods occurring earlier in the autumn and later in the spring were typical of the Middle Fork Willamette River's characteristic Pacific Northwest wet-dry streamflow regimes (Gregory and others, 2007), reflecting seasonal precipitation and snowmelt patterns.

The USACE operates three major flood-control dams and one re-regulating dam within the Middle Fork Willamette River Basin that have altered sediment supply and streamflow to downstream river reaches since 1953 (table 1). Lookout Point (construction completed in 1954), Hills Creek (completed in 1961; about 40 km east of map area shown in fig. 1), and Fall Creek Dams (completed in 1965) impound waterbodies that are primarily operated as flood-control reservoirs. Dexter Dam (completed in 1955) is used to regulate power-generating water releases from Lookout Point Dam. Other authorized purposes include hydropower, recreation, irrigation, municipal and industrial water supply, fish and wildlife, and water quality. Since construction in the mid-20th century, USACE dams trap nearly all coarse sediment entering the lower reaches of Fall Creek and Middle

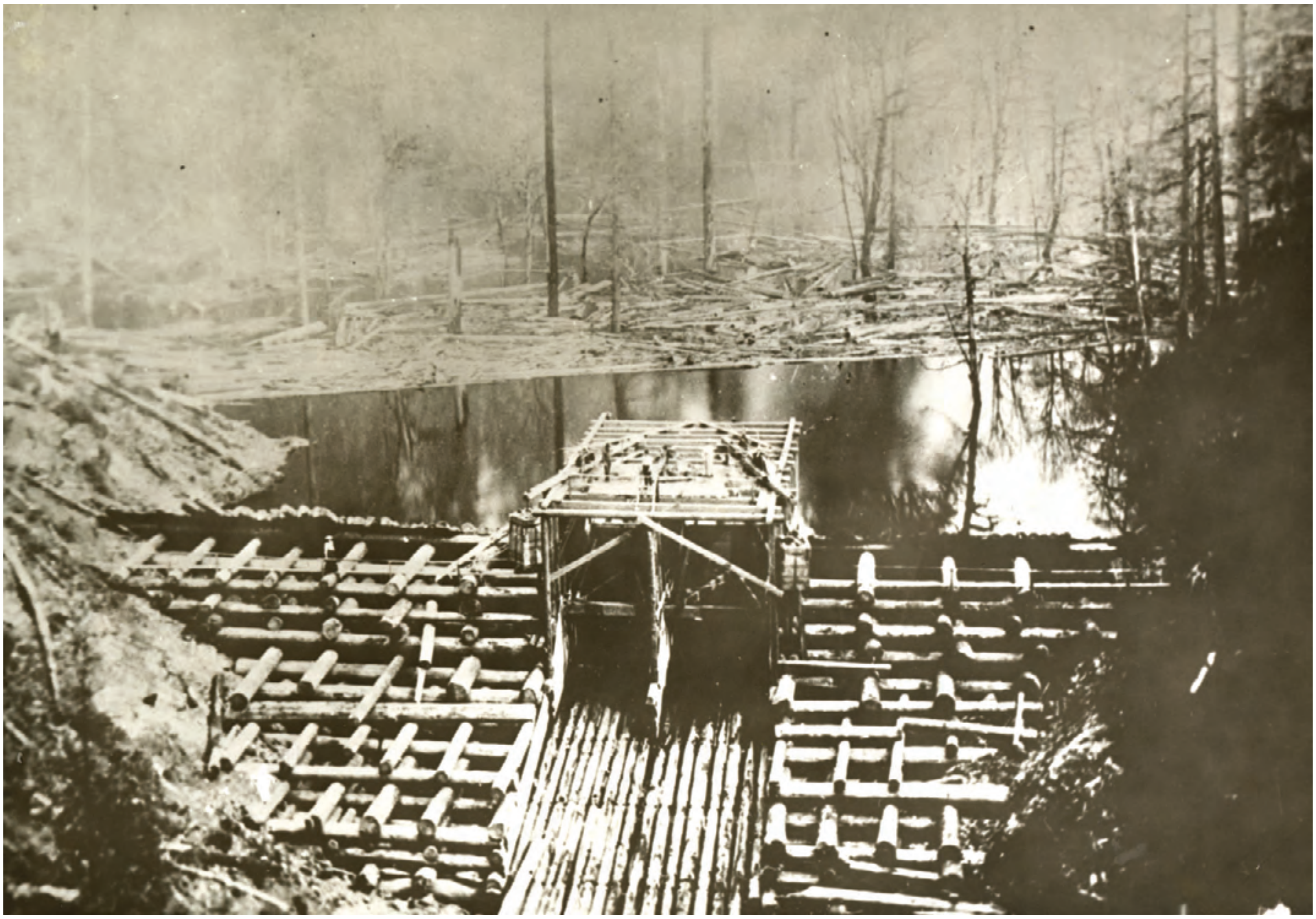


Figure 4. Splash dam along Fall Creek, Oregon. Photograph taken about 1900 (date unknown) and provided by and used with permission from the Lane County History Museum.

Fork Willamette River and reduce the amount of fine-grained sediment transport (Wallick and others, 2013; O'Connor and others, 2014). Bed-material supply has been reduced by dams by about 94 percent near the mouth of the Middle Fork Willamette River (O'Connor and others, 2014).

The Middle Fork Willamette River and Fall Creek corridors downstream from Dexter and Fall Creek Dams have undergone substantial reductions in peak streamflows since the upstream dams became fully operational in the mid-19th century (table 1). Streamflow gaging on these rivers began prior to dam construction. Streamflow has been recorded at USGS streamgage stations since water year (WY) 1936 on Fall Creek (14151000; rkm 10.1), WY 1947 near Dexter on the Middle Fork Willamette River (14150000; rkm 22.5), and WY 1906 at Jasper on the Middle Fork Willamette River (14152000; rkm 13.1; USGS, 2021; fig. 1). Prior to the construction of Fall Creek Dam in 1965, the 0.5 annual exceedance probability flood (often referred to as the 2-year recurrence interval) at the Fall Creek streamgage was about 10,300 ft^3/s and the peak streamflow record was 24,700 ft^3/s (WY 1957); the maximum peak streamflow since dam construction is 5,820 ft^3/s (WY 2019) but annual peaks typically have not exceeded 5,000 ft^3/s during dam operations. At the Dexter streamgage on the Middle Fork Willamette River, the peak of record prior to streamflow regulation was 62,200 ft^3/s (WY 1953), and the peak streamflow for the regulated period (beginning in 1961 after Hills Creek, Lookout Point, and Dexter Dams were fully operational) is 29,500 ft^3/s (WY 1965). Farther downstream at the Jasper streamgage where peak streamflows have been regulated by all four dams since WY 1966, pre- and post-flow regulation period maximum annual peak streamflows were 94,000 ft^3/s (WY 1910) and 24,400 ft^3/s (WY 2019). For the Middle Fork Willamette River at the Jasper streamgage, Gregory and others (2007) found that the 0.5 annual exceedance probability event was 50 percent smaller in the post-dam period, compared to the pre-dam period.

Streamflows from each dam are operated to meet multiple seasonally varying streamflow objectives as described in the 2008 Biological Opinion (BiOp) for the WVS (National Marine Fisheries Service, 2008; table 1). Typical mean daily streamflows (since WY 2008) vary from about 1,200 to 8,000 ft^3/s at the Dexter streamgage on the Middle Fork Willamette River, although greater streamflows regularly occur in winter and spring. At the Fall Creek streamgage, base flows during July and August are typically 50–300 ft^3/s, but short-term operational releases have exceeded 3,000 ft^3/s nearly annually since WY 2008. In autumn and winter, from October to March, daily streamflows are typically greater than about 500 ft^3/s, with peak streamflows that typically range from 2,000 to 4,000 ft^3/s with maximum peak streamflow of 5,820 ft^3/s (April 10, 2019; USGS, 2021) since dam construction. Since 2011 (WY 2012), the USACE has temporarily drained Fall Creek Lake (fig. 1) to facilitate downstream passage of juvenile spring Chinook salmon (*Oncorhynchus tshawytscha*) by lowering lake levels to an elevation near the historical streambed. These streambed drawdowns have improved downstream fish passage and survival through the dam (Northwest Fisheries Science Center, 2015), but temporarily exposing reservoir sediments to fluvial erosion and transport has also increased the export of predominantly fine (less than 2 millimeters [mm]) sediment to the lower reaches of Fall Creek and the Middle Fork Willamette River (Schenk and Bragg, 2014, 2015, 2021).

Geomorphology of Fall Creek and the Middle Fork Willamette River

Within the study area, the modern-day channel and floodplain morphology vary substantially in relation to valley physiography, geology, sediment supply, sediment transport capacity, dam operations, and other factors. Fall Creek occupies a semi-alluvial channel that flows on a mixture of bedrock and coarse gravel substrate. In contrast, the Middle Fork Willamette River is a fully alluvial, single-thread sinuous river with intermittent side channels and gravel bars. Locally, the river flows against bedrock outcrops, but overall, the Middle Fork Willamette River mainly flows on a bed of cobble and gravel substrate, with more and larger gravel bars than along Fall Creek. Hence, the river corridors of the study area were divided into a series of contiguous, geomorphically distinct reaches to provide a framework for systematically evaluating channel and vegetation conditions and patterns of historical channel change. Geomorphic reaches were delineated on the basis of channel morphology, slope, and location of major tributaries as convenient segments for assessing geomorphic change. The study area is divided into six reaches (fig. 1; table 2):

Fall Creek

Upper Fall Creek is a mixed bed reach with bedrock and coarse alluvium and encompasses 5.9 km of Fall Creek between the base of Fall Creek Dam to the confluence of Little Fall Creek.

Lower Fall Creek is a dominantly alluvial reach with sections flowing on bedrock and includes the lowermost 5.6 km of Fall Creek from the confluence with Little Fall Creek to the mouth of Fall Creek.

Middle Fork Willamette River

Dexter is a multi-thread alluvial reach with large floodplain islands and encompasses 5.9 km of the Middle Fork Willamette River from the base of Dexter Dam to the confluence with Lost Creek.

Dougren is also a multi-thread alluvial reach with floodplain islands and includes 3.6 km of the Middle Fork Willamette River from the confluence of Lost Creek to the mouth of Fall Creek. The Dougren reach was designated as a

Table 2. Study reaches along Fall Creek and the Middle Fork Willamette River, Oregon.

[**Drainage area:** Drainage area at the downstream end of the reach as determined from StreamStats (U.S. Geological Survey, 2018). **Channel gradient:** Water surface gradient from 2015 lidar (Quantum Spatial, 2016). **Channel sinuosity:** Sinuosity calculated from 2016 wetted channel centerline and 2015 lidar floodplain centerline. **Average channel width:** Channel widths based on 2016 channel mapping by Keith and Gordon (2019). **Average floodplain width:** Floodplain widths determined from the floodplain mapping corridor delineated by Wallick and others (2018) and is narrower than the full historical floodplain. **Abbreviations:** rkm, river kilometer; km, kilometers; km^2, square kilometer; m, meter]

Reach	Upstream rkm	Downstream rkm	Length (km)	Drainage area (km^2)	Channel gradient	Channel sinuosity	Average channel width (m)	Average mapping corridor boundary width (m)
Upper Fall Creek	11.5	5.6	5.9	490	0.0029	1.08	37	481
Lower Fall Creek	5.6	0.0	5.6	653	0.0026	1.36	40	721
Dexter	27.3	21.4	5.9	2,616	0.0026	1.14	105	712
Dougren	21.4	17.9	3.6	2,745	0.0032	1.11	146	739
Jasper	17.9	10.7	7.2	3,596	0.0020	1.13	94	348
Clearwater	10.7	0.0	10.7	3,548	0.0019	1.21	104	679

separate reach from the Dexter reach because of the additional streamflow and sediment inputs provided by Lost Creek and other differences in floodplain characteristics (table 2).

Jasper reach consists of a dominantly alluvial, single-thread channel with a few large side channels, and includes 7.2 km of the Middle Fork Willamette River from the mouth of Fall Creek to rkm 10.7 where there is a change in channel and valley morphology.

Clearwater reach is a fully alluvial, primarily single-thread, sinuous reach with active gravel bars encompassing the lowermost 10.7 km of the Middle Fork Willamette River where the river and valley widen and flows to the Coast Fork Willamette River confluence.

Previous studies have described channel planform changes on the Middle Fork Willamette River (fig. 1) during the 20th century as well as channel and vegetation responses to environmental streamflows in the early 21st century, providing a basis for this study (for example, Dykaar, 2005, 2008a; McDowell and Dietrich, 2013; Jones and others, 2016). Prior to dam construction, the 10.5 km of the Middle Fork Willamette River downstream from Dexter Dam evolved through a combination of meander migration and avulsions whereby large meander bend cutoffs led to the creation of islands, numerous secondary channels, and large gravel bars (Dykaar, 2005, 2008a). Between the 1950s when dams were first constructed and 2004, river channel length and avulsions had decreased, exposed gravel patches had been reduced by 70 percent, and island area had decreased by 57 percent (Dykaar, 2005, 2008a). Previous and concurrent studies have also described channel conditions of the early 21st century, showing that the Middle Fork Willamette River downstream from Dexter Dam predominantly occupied a laterally inactive, single-thread channel with intermittent side-channels and gravel bars (Wallick and others, 2013; Jones and others, 2016). Geomorphic adjustments to regulated peak flows (for example, WY 2006) were typically modest and difficult to detect from aerial photography (Jones and others, 2016). Evaluation of the Middle Fork Willamette River in 2005 and 2011 by McDowell and Dietrich (2013) indicated that channels between this period underwent substantial geomorphic change, although most of that change was concentrated in sub-reaches of the river and not along the entire area studied. The lack of system-wide change was probably due to the combination of naturally stable geologic sections of the river and sections that had been stabilized by revetments or other bank protection. On Fall Creek, previous studies of historical channel changes are lacking. For both the Middle Fork Willamette River and Fall Creek, fisheries studies from the 1920s and 1930s provide insights into aquatic habitats and channel morphology in the decades prior to dam construction (for example, McIntosh and others, 2009).

Methods

This study uses historical datasets from the 1920s and 1930s, as well as more recent datasets from 2015 and 2016 (table 1), to characterize historical channel conditions and net changes to Middle Fork Willamette River and Fall Creek that occurred over the decades between these datasets. Datasets include USGS plan and profile surveys from 1926 (USGS, 1927) and aerial photography from 1936 (USACE, 1936; Keith and Gordon, 2019). These historical datasets were used to assess the channel morphology and geomorphic processes shaping Middle Fork Willamette River and Fall Creek prior to dam construction and were compared with 2015 lidar data (Quantum Spatial, 2016) and 2016 aerial photographs (U.S. Department of Agriculture, 2016) to describe transformations that occurred over the 20th century. The 1926 plan and profile surveys (along with specific streamgage analyses in Wallick and others, 2013) also provide a basis for evaluating the locations and magnitudes of elevation changes along the river, including channel-bed lowering or aggradation that can influence patterns of inundation, sediment transport, and other aspects of channel morphology.

Datasets and Processing

Plan and Profile Maps from 1926

Channel planform and water-surface elevations (a proxy for bed elevation) along the Middle Fork Willamette River in 1926 were characterized using historical plan and profile maps (USGS, 1927). These maps were part of a series of hydrographic surveys conducted along major tributaries of the Willamette River in the 1920s and 1930s, and although some smaller streams were surveyed as part of this effort, Fall Creek was not included in the map series. For this study, the plan maps of the river corridor were converted to digital maps by digitizing the outlines of the main wetted channels and side channels along the Middle Fork Willamette River from the confluence with the Coast Fork Willamette River to the North Fork Middle Fork Willamette River (upstream from the study area and about 4 km downstream from Oakridge, Oregon). The channel outlines depicted in the 1926 maps likely represent the low-flow wetted channel rather than the full active channel that would have encompassed larger gravel bars; however, the exact protocols used to create the original 1926 maps are unknown, so these maps are best used to represent overall channel position as opposed to being used for detailed analyses of features like wetted channel width or gravel bars area.

The 1926 plan and profile maps of the Middle Fork Willamette River between the Coast Fork Willamette River and North Fork Middle Fork Willamette River were georeferenced in ArcGIS using digital township and range lines and limited distinct topography that was apparent in both the 1926 dataset and 2015 lidar data. A more detailed description of georeferencing methods can be found in the published metadata (Keith and Gordon, 2019). When published in 1927, the historical maps were plotted on paper sheets at a scale of 1:31,680 and were released as "advanced sheets," indicating unquantified uncertainty in the data and mapping. One indication of this uncertainty is apparent when overlaying the georeferenced 1926 plan and profile maps with 2015 lidar data, revealing one side channel on the Middle Fork Willamette River near the current location of Dexter Dam that was originally mapped on a hillslope. The main channel boundary georeferenced maps were manually digitized at a scale of 1:5,000 throughout the study area to overlay and compare with planform and active channel location produced with geomorphic mapping from the 1936 and 2016 aerial photographs.

To assess vertical changes in the river profile, elevations along the 1926 channel were compared with channel elevations from lidar datasets (see section, "Lidar from 2015"). The 1926 elevations were aligned with a river kilometer referencing system that denoted the distance of that point from the river's mouth along the center of the channel. Elevations from the 1926 survey are assumed to be water-surface elevations (as opposed to channel-bed elevations) that reference mean sea level (MSL), which we approximate as close to the National Geodetic Vertical Datum of 1929 (NGVD 29) for this study. The vertical difference between NGVD 29 and the North American Vertical Datum of 1988 (NAVD 88, the datum used in this study) within the study area is typically about 1.1 m (plus or minus [±] 0.05 m; National Oceanic and Atmospheric Administration, 2020); therefore, a constant correction (plus [+] 1.1 m) was applied to all 1926 profile elevations to adjust to the NAVD 88 datum. Further shifting elevations to account for the difference from the older MSL datum in use at the time of creation of the 1926 map (MSL likely referencing the General Adjustment of 1912) to NGVD 29 would likely result in an adjustment of about 0.15 m or less (Rappleye, 1932). This additional vertical adjustment is challenging to determine and likely within the uncertainty introduced by unknown survey error and unknown streamflow at the time of the 1926 survey relative to comparison datasets. For example, although streamflow data on the Middle Fork Willamette River are limited in the period before dam construction, the differences in stage for a given discharge for the recent rating relation at the Jasper streamgage provide insights into the potential magnitude of uncertainty introduced by comparing the 1926 water surface profile at an unknown discharge with the 2015 profile. Although the current rating is an imperfect predictor of the rating in 1926, it is still informative because (1) the mapping and observations of this study show that the location of the Jasper streamgage has been laterally stable since the 1926 and (2) the channel-bed elevations have been relatively stable from 1975 to 2021 (Wallick and others, 2013). The difference in stage for the current rating between 1,000–2,000, 2,000–3,000, and 3,000–4,000 ft^3/s is about 0.27, 0.21, and 0.18 m, respectively—all greater than 0.15 m that would be introduced with estimated pre-1929 datum adjustment. Evaluation of stage-discharge relations at the Jasper streamgage on the Middle Fork Willamette River (since 1953) suggest that bed-elevation changes since dam construction have been about 0.3 m or less (Wallick and others, 2013), which is twice what would be incorporated assuming a pre-1929 datum shift. (Current ratings available at WaterWatch [https://waterwatch.usgs.gov/?id=mkrc]; current and historical ratings available by contacting the USGS.) Additionally, the vertical adjustment from MSL to NGVD 1929 is about an order of magnitude less than the adjustment to convert from NGVD 29 to NAVD 88, and therefore was not applied.

Aerial Photographs from 1936

Black and white, 1:15,000-scale aerial photographs were acquired on July 30, 1936 (USACE, 1936; Keith and Gordon, 2019), covering Fall Creek and the Middle Fork Willamette River downstream from the Fall Creek and Dexter Dams, respectively. These 1936 photographs were scanned and georeferenced to provide a basis for mapping channel features and characterizing channel conditions prior to construction of USACE flood-control dams. The photographs were georeferenced in ArcGIS using spatially registered 2005 aerial photographs (U.S. Department of Agriculture, 2005) as a base layer. The georeferencing process resulted in root-mean square errors (RMSE) ranging from 1.25 to 4.27 m for individual frames (overall 2.32-m mean RMSE); although locally, photograph offset on adjacent photographs can be as high as 15 m, primarily in locations farther from the river. Photographs also were clipped and mosaicked in ArcGIS. The 1936 imagery provided a base for creating the 1916 digital geomorphic maps, and detailed methodology for photograph georeferencing, mosaicking, and mapping is documented in the published metadata (Keith and Gordon, 2019). Streamflow at the time of aerial photograph acquisition was 61 ft^3/s on Fall Creek, but unknown for the Middle Fork Willamette River.

Aerial Photographs from 2005

Aerial photographs were acquired on July 18 and August 4, 2005, for the National Agricultural Imagery Program (U.S. Department of Agriculture, 2005) consisting of four-band imagery (red, green, blue, near infrared) at a 0.5-m resolution with full coverage of the study area. These publicly available images were formatted as digital orthophotos. The imagery provided a base for geospatially registering the 1936 aerial photography and creating the 2005 centerline discussed in this report. The 2005 aerial photographs were used to produce geomorphic maps of the study area (along with maps from 2011, 2012, and 2014; Keith and Gordon, 2019) to address more in-depth analyses of channel responses related to streambed drawdowns and will be described in future reports. Streamflow at the time of the 2005 aerial photograph acquisition was 222 ft^3/s at the Fall Creek streamgage, 3,300 ft^3/s at the Dexter streamgage, and 3,640 ft^3/s at the Jasper streamgage for the Middle Fork Willamette River.

Lidar from 2015

Topo-bathymetric lidar data were acquired September 14–15, 2015, for the Oregon Lidar Consortium, along Fall Creek and the Middle Fork Willamette River downstream from Fall Creek and Dexter Dams. Overall project vertical accuracy RMSE reported for the lidar datasets ranges from 0.03 to 0.04 m for the topo-bathymetric lidar (Quantum Spatial, 2016). This study utilized bare earth raster datasets, which had a cell size of 1 m publicly available from the Oregon Department of Geology and Mineral Industries to extract longitudinal profiles of the channel-bed and water-surface elevations for comparison with 1926 plan and profile water-surface elevations. Streamflow at the time of the 2015 lidar acquisition was 203 ft^3/s at the Fall Creek streamgage, 1,470–1,510 ft^3/s at the Dexter streamgage, and 1,860–1,910 ft^3/s at the Jasper streamgage for the Middle Fork Willamette River.

Aerial Photographs from 2016

Aerial photographs were acquired June 26, 2016, for the National Agricultural Imagery Program (U.S. Department of Agriculture, 2016) consisting of four-band imagery (red, green, blue, near infrared) at a 1-m resolution with full coverage of the study area. These publicly available images were formatted as digital orthophotos. The imagery provided a base for creating the 2016 digital geomorphic maps (Keith and Gordon, 2019). Streamflow at the time of the 2016 aerial photograph acquisition was 225 ft^3/s at the Fall Creek streamgage, 1,930 ft^3/s at the Dexter streamgage, and 2,340 ft^3/s at the Jasper streamgage for the Middle Fork Willamette River.

Geomorphic Mapping, 1936 and 2016

Geomorphic maps of the active channel and adjacent floodplain of Middle Fork Willamette River and Fall Creek were developed from 1936 and 2016 aerial photograph datasets, respectively, to characterize spatial and temporal patterns of landforms, such as gravel bars, side channels, bedrock outcrops, and other features, which are all indicative of the geomorphic processes shaping these river corridors. Because of upstream regulation by flood-control dams, areas adjacent to the channel that historically functioned as floodplains have been rarely inundated, so mapping focused on delineating features within the active channel, or the "channel of an alluvial stream subject to change by prevailing discharges" (Goudie, 2014). For this study, the active channel was defined as the area typically inundated annually as determined by the presence of water and flow-modified surfaces (Church, 1988) and included features such as the low-flow channel, side channels, and both vegetated and unvegetated gravel bars. Floodplain features, such as floodplain islands surrounded by (or nearly surrounded by) active channel features, were also mapped. Historical and recent floodplain features within the mapping corridor but outside the active channel were not systematically mapped; however, an attempt was made to map secondary water features within the mapping corridor floodplain (Keith and Gordon, 2019). Prior to dam construction, these active channel features likely evolved through frequent bed-material transport (Church, 2006) but are presently more stable owing to reductions in coarse sediment supply and peak flow magnitudes, as indicated by presence of dense young forests that have colonized formerly unvegetated gravel bars (Wallick and others, 2013).

The Holocene floodplain of the Middle Fork Willamette River downstream from Dexter Dam is broad (greater than about 1.5 km wide in places) and merges with the floodplain of the Coast Fork Willamette River toward its mouth, making it difficult to clearly distinguish among fluvial surfaces specific to the Middle Fork Willamette River, especially considering present-day patterns of land use that have obscured former floodplain features. Within the historical (or Holocene) floodplain is a corridor of low-elevation, channel flanking surfaces that border the Middle Fork Willamette River and have distinct floodplain topography that extend laterally beyond the active channel (referred to as "mapping corridor" for this study). The mapping corridor boundary—delineated along Fall Creek for this study and modified from Jones and others (2016) along the Middle Fork Willamette River—varies in width from about 350 to 740 m (table 2). Inset within the floodplain of the Middle Fork Willamette River is the river channel, where reach-average, low-streamflow channel widths typically vary from about 90 to 150 m (table 2). In contrast, Fall Creek is much smaller, with reach average mapping corridor boundary widths ranging from about 480 to 720 m and average channel widths of about 40 m (table 2).

Geomorphic mapping of the 1936 and 2016 aerial photographs followed protocols developed specifically for Fall Creek and the Middle Fork Willamette River to evaluate geomorphic responses to streambed drawdown operation at Fall Creek Dam (Keith and Gordon, 2019). The aerial photograph mapping methods used for this study have hierarchy and protocols like those of previous channel mapping studies for other gravel-bed rivers in Oregon, including the Chetco, Umpqua, and Sprague Rivers (Wallick and others, 2010; Wallick and others, 2011; O'Connor and others, 2014), and expand upon mapping frameworks developed specifically for the Middle Fork Willamette River in previous studies (Dykaar, 2008a; McDowell and Dietrich, 2013; Jones and others, 2016) with increased spatial, temporal, and mapping unit resolution to characterize potentially subtle planform changes. The mapping datasets produced for each period include information on reaches, large-scale process domains, landforms, water-feature types (if applicable), cover types (if applicable), and vegetation density (table 3).

All features within the mapping corridor boundary of Middle Fork Willamette River and floodplain of Fall Creek were digitized at 1:2,500 scale in ArcGIS with a minimum mapping unit of 200 square meters (m^2). Additionally, wetted channel centerlines were mapped for the 1936 and 2016 (as well as 2005) periods to aid in documenting changes in channel length. Streamflow at the time of the 1936 aerial photograph acquisition is unknown for the reaches of the Middle Fork Willamette River and was relatively low for Fall Creek (61 ft^3/s) compared with streamflow during the 2016 aerial photograph acquisition, which ranges from 225 ft^3/s on Fall Creek to 1,930–2,340 ft^3/s on the Middle Fork Willamette River.

Geomorphic mapping and interpretation of mapping results can be influenced by multiple sources of uncertainty. The area of water features and gravel bars is influenced by streamflow and inundation during aerial photograph acquisition (for example, see analyses on the Chetco and Umpqua Rivers [Wallick and others, 2010, 2011; Curtis and Guerrero, 2015; Curtis and others, 2015]). The lack of streamflow information for the Middle Fork Willamette River in 1936 precluded attempts to normalize the bar area for discharge. Other sources of uncertainty in mapping derived from image quality or view obstruction included glare, shadows, or overhanging vegetation that obscured underlying landforms and resulted in inaccurate feature mapping. For the Fall Creek and Middle Fork Willamette River mapping, this is most common where the edge of water and back edges of bars are obscured by vegetation or its shadows. Mapping errors were reduced through multiple quality assurance and control by multiple study team members. Curtis and Guerrero (2015) analyzed uncertainties related to repeat geomorphic mapping on the Trinity River, California, and found that digitizing precision was greater for smooth, visible boundaries and poorer for features obscured by shadows or canopy cover. Misalignment of features during the 1936 photograph georeferencing process also introduced errors. However, error from photograph offset was deemed modest because (1) imagery offset in this study likely results in errors smaller than those from other sources of uncertainty and (2) mapping analyses focused on changes in area and not morphologic changes through overlay analyses. Aggregating landform areas over one or more kilometers or at the reach scale is appropriate for change analyses given the uncertainty from these sources. On Fall Creek, where landforms are relatively smaller, persistent in size and location over time, and more likely to be obscured by shadows or vegetation, overlay analyses to evaluate a single gravel bar would have a greater level of uncertainty than comparisons of larger, relatively dynamic, and clearly visible bars along the Middle Fork Willamette River.

Results

Changes in Channel Planform, 1926–36

Geomorphic maps of the Middle Fork Willamette River developed from the 1926 plan and profile maps and 1936 aerial photographs (Keith and Gordon, 2019) document channel planform in both periods as well as planimetric changes that occurred in the intervening decade. Both maps depict the river channel as having single-thread and multi-thread sections. The 1936 map is much more detailed than the 1926 map, owing to the detail in the underlying aerial photographs that permitted delineation of features within the active channel domain (table 3) such as forested islands

Table 3. Mapping units for Fall Creek and Middle Fork Willamette River, Oregon.

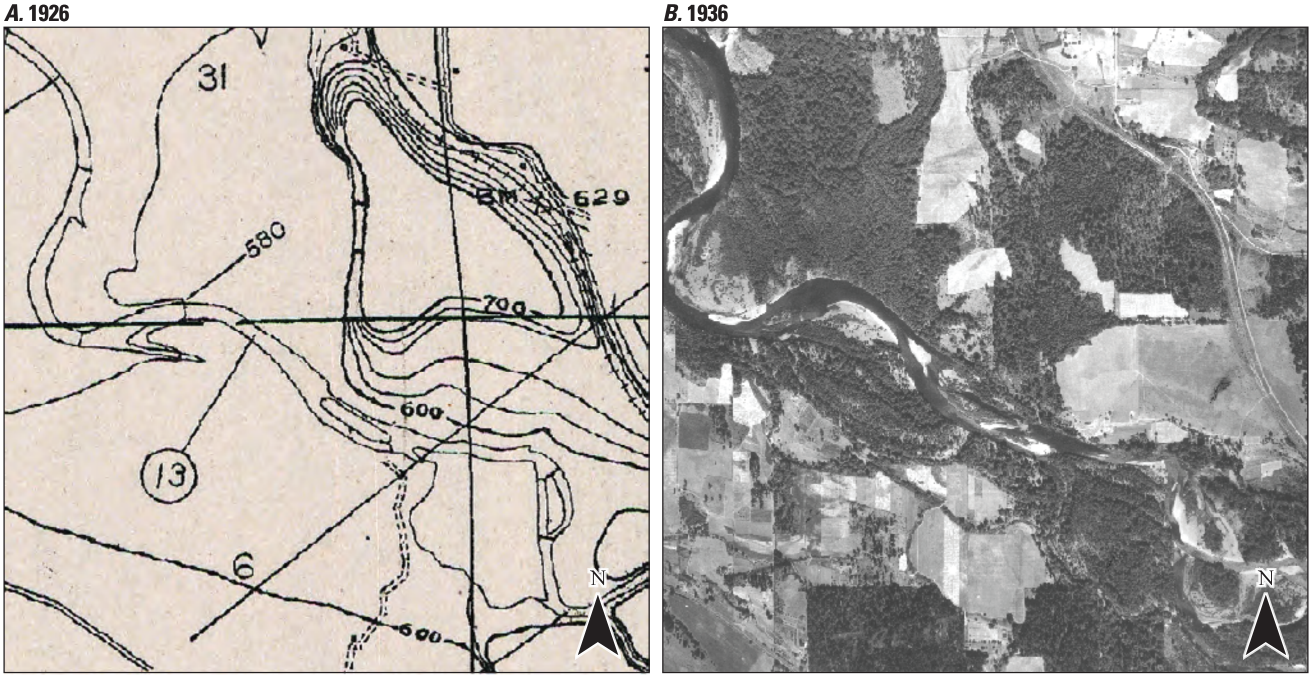
[Geomorphic mapping from aerial photographs. Terminology modified from Keith and Gordon (2019). **Abbreviation:** NA, not applicable]

Process domain	Landform	Water-feature type	Cover type	Vegetation density
Active channel	Main wetted channel	Main wetted channel	Water	NA
	Bar	NA	Herbaceous	Dense
			Woody	Dense
			Unvegetated	Unvegetated
	Bedrock	NA	NA	NA
	Secondary water feature	Side channel	Water	NA
		Alcove		
		Pond		
		Other		
Floodplain	Secondary water feature	Water feature, not in the active channel	Water	NA
	Floodplain island	NA	(Same as bars)	(Same as bars)

and gravel bars, whereas the 1926 map only depicts the channel outlines (fig. 5). In 1936, the Middle Fork Willamette River was flanked by large (several-thousand-square-meter) unvegetated gravel bars, with floodplain areas having mature forest and agriculture. In some locations, the low-streamflow wetted channel was separated by large, forested islands into channels bordered by mature forest, such as in the Dexter reach. In other areas, flow in the 1936 channel was divided into multiple channels that were each flanked by broad swaths of unvegetated gravel bars, indicating that these channels and bars were subject to frequent lateral adjustments more typical of a “wandering gravel bed river” (Church, 1983; fig. 6). Segments of the 1936 channel in the Jasper reach flowed along the base of a hillslope, where bedrock is apparent in the present-day channel (for example, near rkm 15.3 and 13.4).

Comparison of the 1926 and 1936 maps for Middle Fork Willamette River revealed river segments that underwent avulsions or meander migration and other segments with minimal lateral adjustments over the 10-year period between the mapping datasets. The most substantial channel changes were several large-scale avulsions (spanning 1–3 km of the floodplain) where secondary channel features in the 1926 maps were either abandoned or occupied by the main channel by 1936. Examples of channel abandonment or re-occupation were mainly observed in the Dexter, Dougren, and Clearwater reaches, whereas the Jasper reach was more laterally inactive (fig. 6*C*–6*F*). Also apparent in each reach were long (2–10 km) channel segments that underwent meander migration (including bend growth and elongation, as indicated on Dexter, Dougren and Clearwater reaches) and lateral shifting (typically straight sections that shifted laterally, often more than 100 m; fig. 6*C*–6*D*, 6*F*). Each reach also had laterally inactive sections where channel position remained similar, although lateral stability between 1926 and 1936 was most extensive along the Jasper reach and lower segments of the Clearwater reach (fig. 6*E*–6*F*). From field observations and geologic mapping (Smith and Roe, 2015), these laterally inactive segments coincide with areas where the channel flows along or over bedrock.

***A.* 1926** ***B.* 1936**



Base maps modified from USGS plan and profile maps from 1926 (1:24,000; USGS, 1927) and aerial photographs from 1936 (1:15,000; USACE, 1936; Keith and Gordon, 2019).

0 1,500 3,000 FEET
0 500 1,000 METERS

Figure 5. Images showing examples of the (*A*) 1926 plan and profile map and (*B*) 1936 aerial photograph along the Middle Fork Willamette River, Oregon, downstream from the confluence with Lost Creek (river kilometers 22.4–19.2). [USGS, U.S. Geological Survey; USACE, U.S. Army Corps of Engineers]

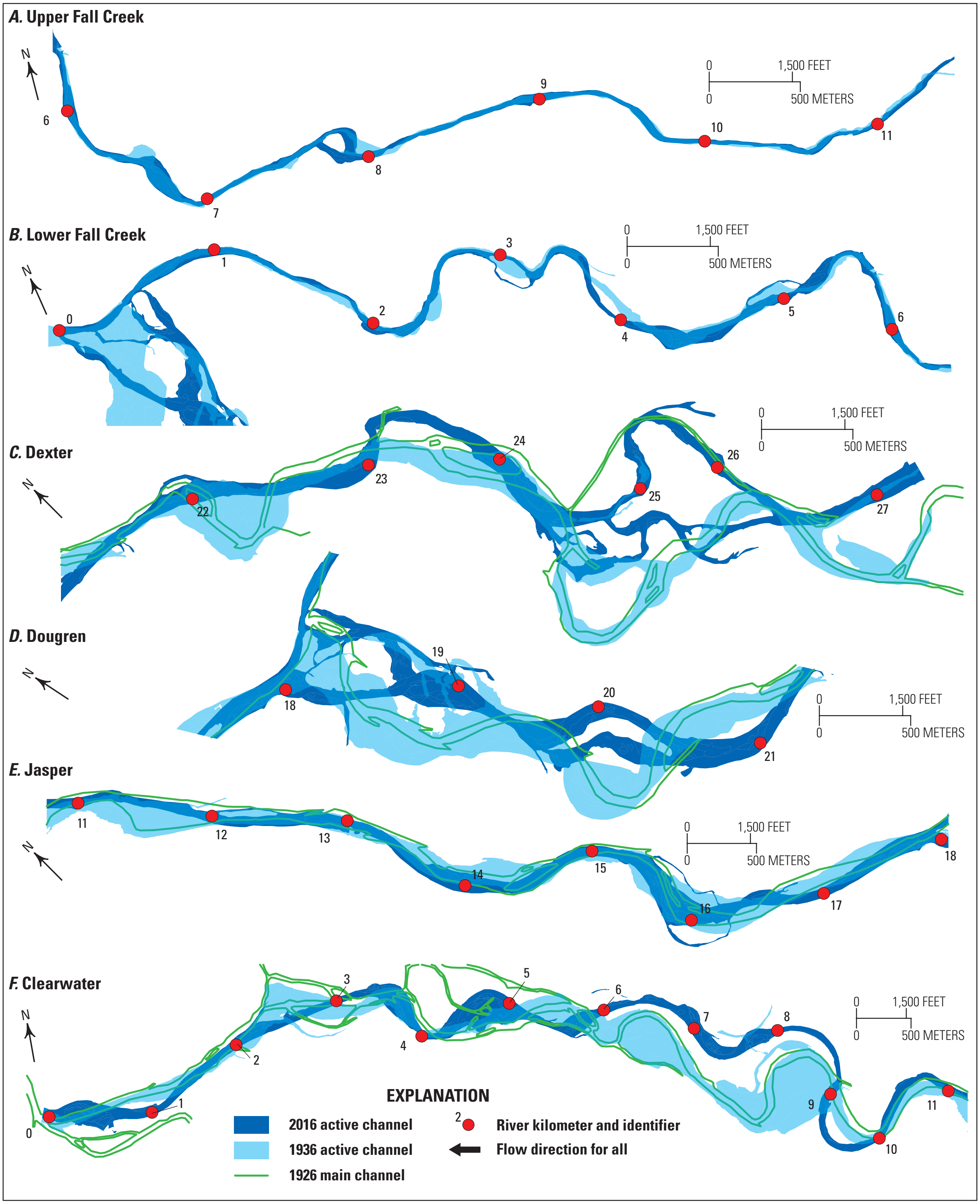


Figure 6. Planiform of reaches in the study for Fall Creek and the Middle Fork Willamette River, Oregon. The 1926 outline represents the wetted channel boundary, whereas the 1936 and 2016 channel footprints depict the active channel boundary encompassing the main wetted channel, gravel bars, and secondary water features for the (*A*) Upper Fall Creek, (*B*) Lower Fall Creek, (*C*) Dexter, (*D*) Dougren, (*E*) Jasper, and (*F*) Clearwater reaches.

Landforms Along Fall Creek and the Middle Fork Willamette River, 2016

Bars

Bars mapped along Fall Creek and the Middle Fork Willamette River (fig. 7) were fluvially deposited landforms that indicate a continuum of sediment and vegetation characteristics representing hydrogeomorphic and vegetation processes. On bar surfaces that have undergone recent bed-material transport and scour, large areas of unvegetated sands and gravel were abundant, whereas vegetation (ranging from herbaceous vegetation dominated by grasses to woody shrubs and young trees) signified different degrees of geomorphic stability (similar to findings by Dykaar, 2008a, 2008b; McDowell and Dietrich, 2013; Jones and others, 2016). Throughout the study area, unvegetated gravel bars were most commonly mapped as elongated channel-flanking patches of gravel, parallel to the margin of the low-flow wetted channel along channel margins or as point bars on the inside of meander bends. Unit bar area (mapped area for a reach divided by reach length) in 2016 varied across the study area from 11.7 meters squared per meter (m^2/m) in the Upper Fall Creek reach to 57.7 m^2 in the Dougren reach (table 4).

On Fall Creek in 2016, unvegetated bars were sparse, whereas vegetated bars typically densely vegetated with mature woody vegetation were more frequent (figs. 7*C*, 8; table 3). The Upper Fall Creek and Lower Fall Creek reaches had the smallest mapped bar areas and unit bar areas throughout the study area. Unvegetated bars were mapped at fpkm 0.5 and between about fpkm 5.0 and 2.5 in 2016 (figs. 7*C*, 8, 9*C*–9*D*) coinciding with the confluence with the Middle Fork Willamette River and the Little Fall Creek confluence, respectively. Vegetated bars along both reaches of Fall Creek were dominantly covered in woody vegetation, although some bars with herbaceous cover were also present (figs. 7*C*, 8*A*).

Like Fall Creek, unvegetated bars on the Middle Fork Willamette River in 2016 were also sparse, particularly in the Dexter and Jasper reaches (figs. 7*A*, 8*A*, 10*B;* unvegetated unit bar area of 2.5 and 2.9 m^2/m; table 4;), and most of the mapped bar landforms were densely vegetated (figs. 7*A*, 8*A*). Although bar area and unit bar area were greater on the Middle Fork Willamette River than on Fall Creek (table 4), that probably relates to differences in channel streamflows and drainage area, geology and sediment supply, and local channel morphology.

The greatest total unit bar area for all bars in the study area (57.7 m^2/m) was downstream from Lost Creek in the Dougren reach. This reach also had the second greatest unvegetated unit bar area (8.1 m^2/m), with these features increasing with distance downstream along the reach (table 4; figs. 7*A*, 8*A*, 10*C*–10*D*). Mapped bars were sparse in the Jasper reach, with unvegetated bar presence primarily limited to a few kilometers downstream from the confluence with Fall Creek (fpkm 15.0 and 13.5) and some intermittent, mostly vegetated, bars mapped through the rest of the reach (figs. 7*A*, 8, 11*A*–11*B*). Bar area along the Middle Fork Willamette River in 2016 was greatest at fpkm 4.5–5.0 in the Clearwater reach where a very large (greater than 100,000 m^2), densely vegetated bar was mapped, parts of which could have probably been also mapped as a floodplain island. The overall mapping from 2016 showed considerably greater mapped areas of unvegetated and vegetated bars throughout the Clearwater reach relative to any other reach, although unit bar area for all bars (30.4 m^2/m) was substantially less than that mapped for the Dougren reach (table 4; figs. 7*A*, 11).

Secondary Water Features

Secondary water features encompass off-channel water features connected to the main stem Fall Creek or Middle Fork Willamette River as side channels and alcoves or disconnected as ponds. On Fall Creek, the dominant type of secondary water feature mapped in 2016 was side channels. The side channels mapped along Fall Creek were relatively short (less than 400 m in length) compared to those mapped along the Middle Fork Willamette River, which could extend greater than 1 km in length. Along Fall Creek, a few small (less than about 1,620 m^2) areas were mapped as alcoves or side channels in the Upper Fall Creek reach in 2016 (figs. 7*D*, 8*B*, 9*A*–9*B*; table 4), although field observations confirmed the presence of other small unmapped secondary water features (such as at rkm 6.4) that were not mapped owing to photograph resolution, mapping scale, or overhanging vegetation. Secondary water features were more abundant and larger in the Lower Fall Creek reach in 2016 than in the Upper Fall Creek reach (figs. 7*D*, 8*B*, 9*C*–9*D*; table 4). Similar to the greater abundance of gravel bars on the Middle Fork Willamette River than Fall Creek in 2016, there were also more secondary water features (fig. 7*B*, 7*D*). Within the Dexter reach, the dominant type of secondary water features were alcoves ranging in size from about 360 to more than 12,000 m^2 (figs. 7*B*, 8*B*, 10*A*–10*B*). The greatest area of secondary water features in the 2016 mapping of Middle Fork Willamette River occurred at fpkm 17.5 in the Dougren reach, which had more frequent spacing of secondary water features compared with other reaches (figs. 7*B*, 10*C*–10*D*). In the Jasper and Clearwater reaches, side channels were the dominant type of secondary water feature in 2016 (figs. 8*B*, 11); however, these features were spatially intermittent and highly variable in size, with some fpkm transects having no secondary water features and others having large (as much as 32,000 m^2) areas of secondary water features (fig. 7*B*).

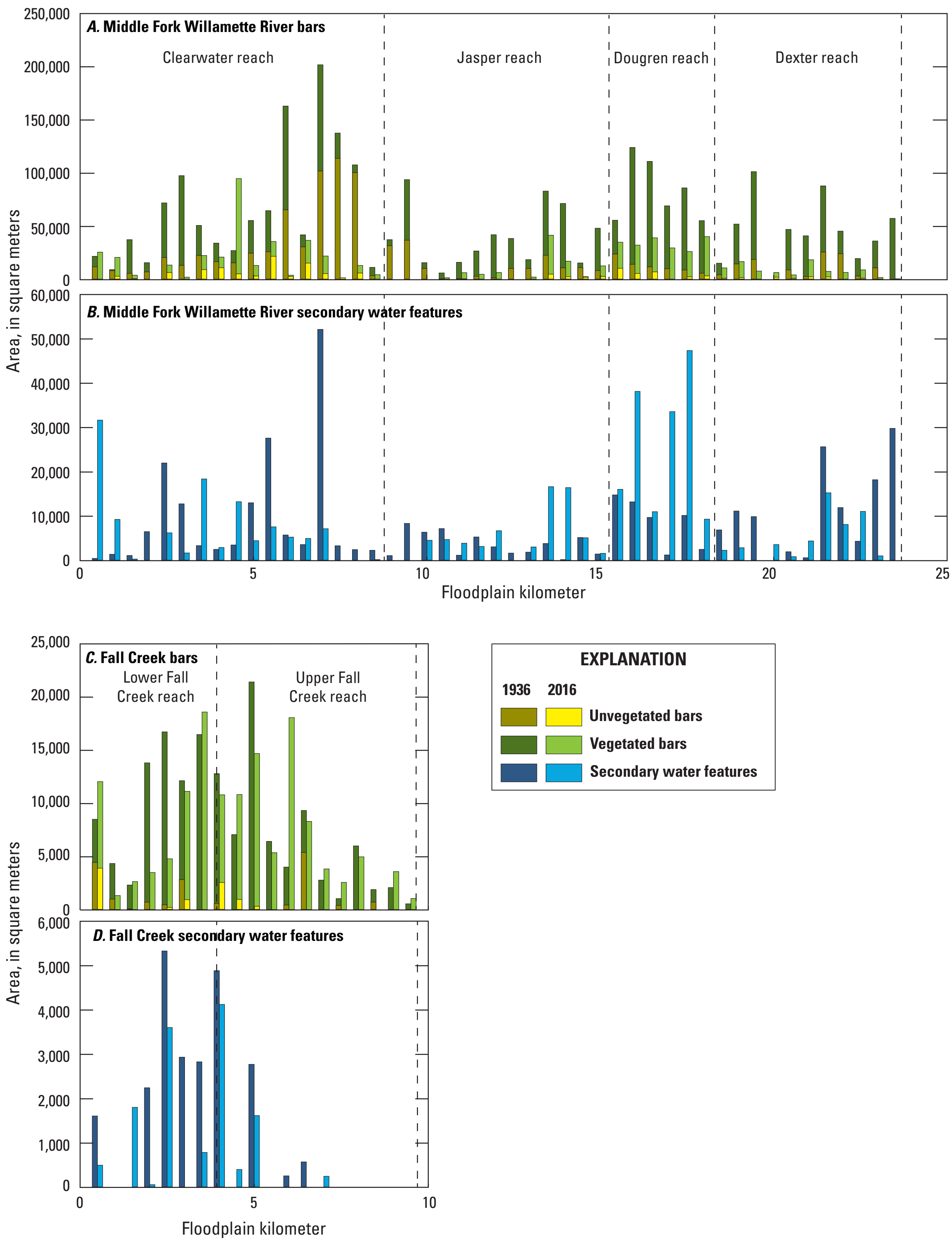


Figure 7. Bar and secondary water feature area by floodplain kilometer along the Middle Fork Willamette River (*A*, *B*) and Fall Creek (*C*, *D*), Oregon, mapped from 1936 and 2016 aerial photographs (mapping from Keith and Gordon, 2019).

Table 4. Mapped areas by landform and reach for Fall Creek and the Middle Fork Willamette River, Oregon, 1936 and 2016.

[Areas are in square meters and are rounded to three significant digits. Unit bar area in square meters is the mapped area divided by reach centerline length. Repeat geomorphic mapping data available in Keith and Gordon (2019).]

Reach	Total main wetted channel area		Total bar area (vegetated and unvegetated)		Total unvegetated bar area		Secondary water features		Bedrock		Floodplain island	
	1936	2016	1936	2016	1936	2016	1936	2016	1936	2016	1936	2016
Area, in square meters												
Upper Fall Creek	132,000	141,000	61,400	70,400	7,000	412	3,620	1,880	10,8000	5,460	13.800	17,900
Lower Fall Creek	119,000	138,000	88,700	68,100	12,600	4,460	19,800	11,300	5,200	3,980	0	32,900
Dexter	267,000	457,000	492,000	88,800	113,000	15,000	117,000	48,900	0	792	248,000	333,000
Dougren	249,000	198,000	511,000	202,000	79,300	28,200	55,400	118,000	0	0	168,000	372,000
Jasper	460,000	495,000	507,000	106,000	147,000	19,200	44,500	65,900	5,680	511	0	105,000
Clearwater	573,000	673,000	1,170,000	341,000	610,000	101,000	159,000	111,000	8,760	1,590	134,000	92,400
Total	**1,800,000**	**2,100,000**	**2,830,000**	**876,000**	**969,000**	**169,000**	**399,000**	**357,000**	**30,400**	**12,300**	**564,000**	**952,000**
Unit landform area, in square meters per meter												
Upper Fall Creek	22.0	23.5	10.2	11.7	1.2	0.1	0.6	0.3	18.0	0.9	0.0	3.0
Lower Fall Creek	23.3	27.1	17.4	13.4	2.5	0.9	3.9	2.2	1.0	0.8	0.0	6.5
Dexter	45.3	77.5	83.4	15.1	19.2	2.5	19.8	8.3	0.0	0.1	42.0	56.4
Dougren	71.1	56.6	146.0	57.7	22.7	8.1	15.8	33.7	0.0	0.0	48.0	106.3
Jasper	68.7	73.9	75.7	15.8	21.9	2.9	6.6	9.8	0.8	0.1	0.0	15.7
Clearwater	51.2	60.1	104.5	30.4	54.5	9.0	14.2	9.9	0.8	0.1	12.0	8.3

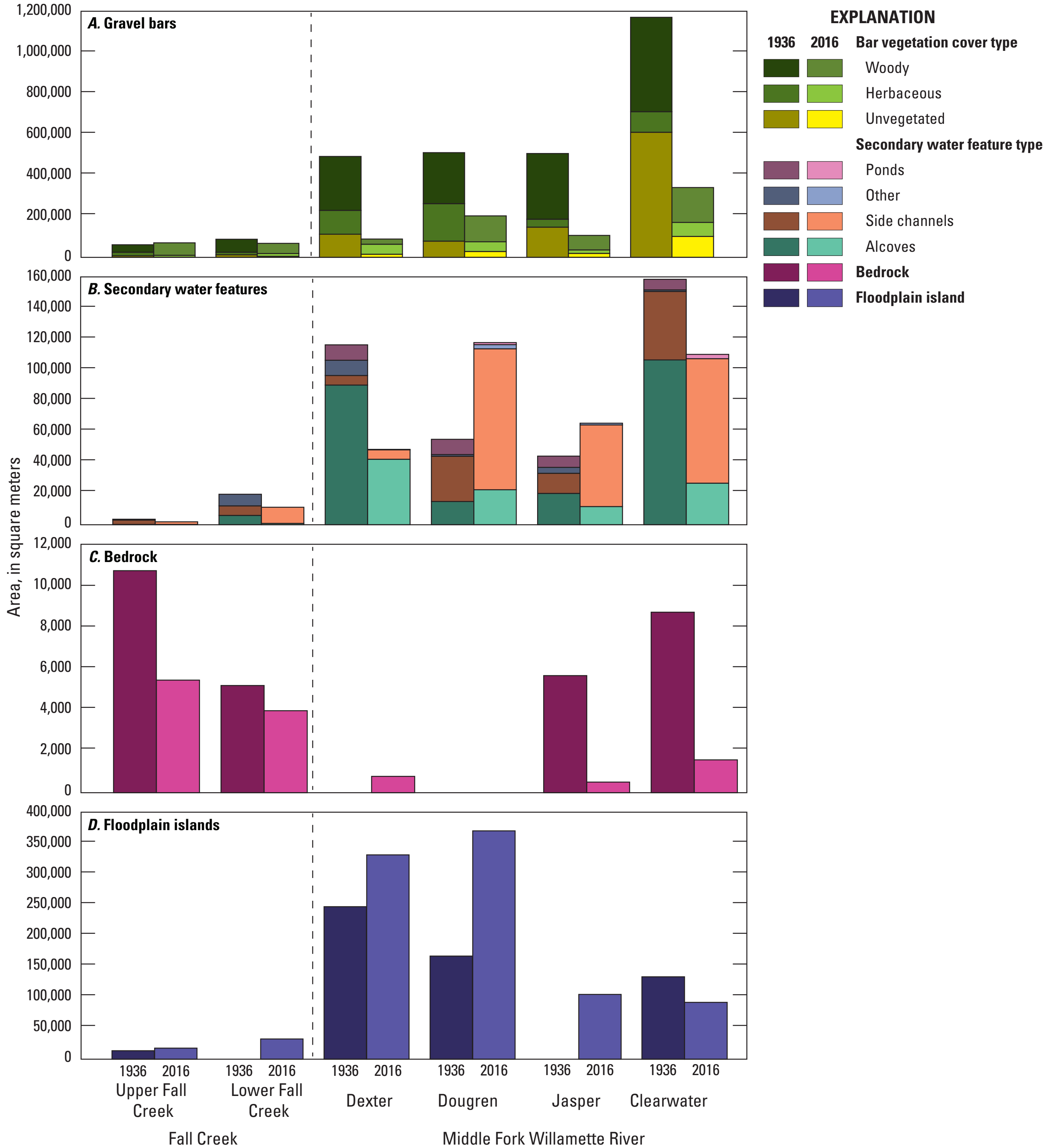


Figure 8. Gravel bars by vegetation type (*A*), secondary water features by type (*B*), bedrock(*C*), and floodplain island (*D*) for reaches along Fall Creek and the Middle Fork Willamette River, Oregon, 1936 and 2016 mapped area.

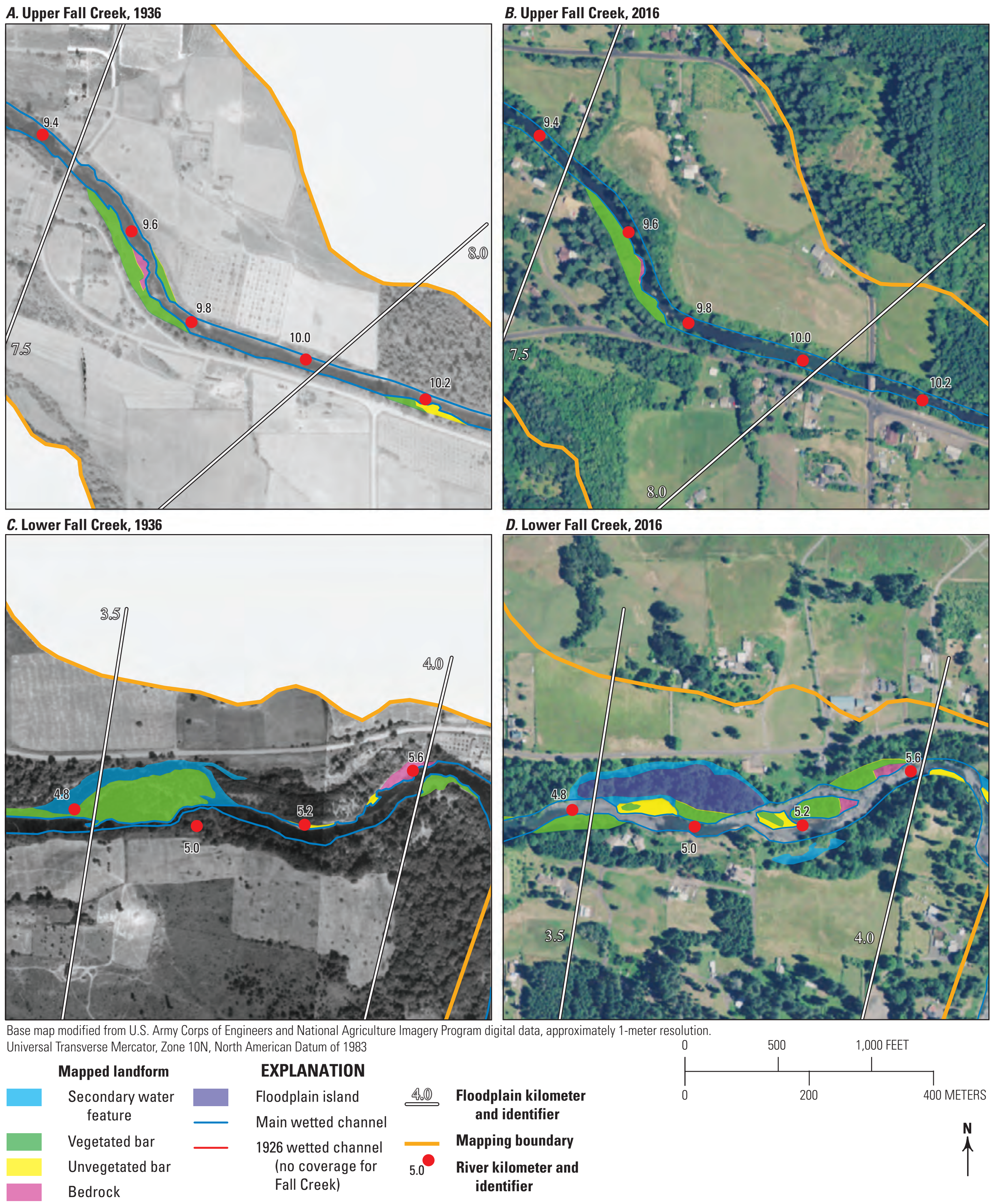


Figure 9. Repeat geomorphic mapping from aerial photographs for the Upper Fall Creek reach (river kilometers [rkm] 11.5–5.6, showing segment rkm 10.2–9.4) and the Lower Fall Creek reach (rkm 5.6–0.0; showing segment rkm 5.6–4.8), Oregon, 1936 (*A* and *C*) and 2016 (*B* and *D*). Repeat geomorphic mapping data are available from Keith and Gordon (2019).

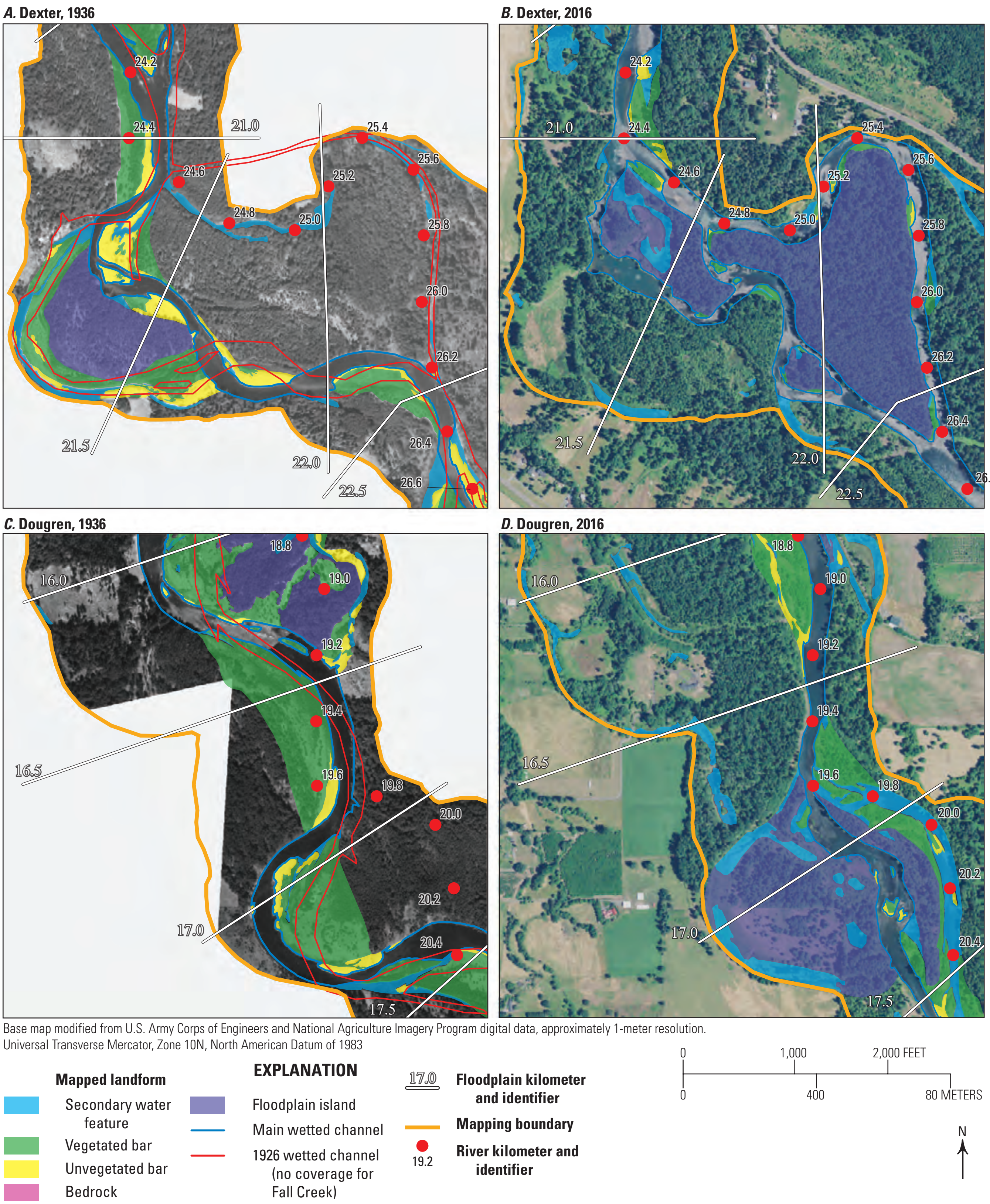


Figure 10. Repeat geomorphic mapping from aerial photographs for the Dexter reach (river kilometers [rkm] 27.3–21.4, showing segment rkm 26.6–24.2) and the Dougren reach (rkm 21.4–17.9; showing segment rkm 20.4–18.8) along the Middle Fork Willamette River, Oregon, 1936 (*A* and *C*) and 2016 (*B* and *D*). Repeat geomorphic mapping data are available from Keith and Gordon (2019).

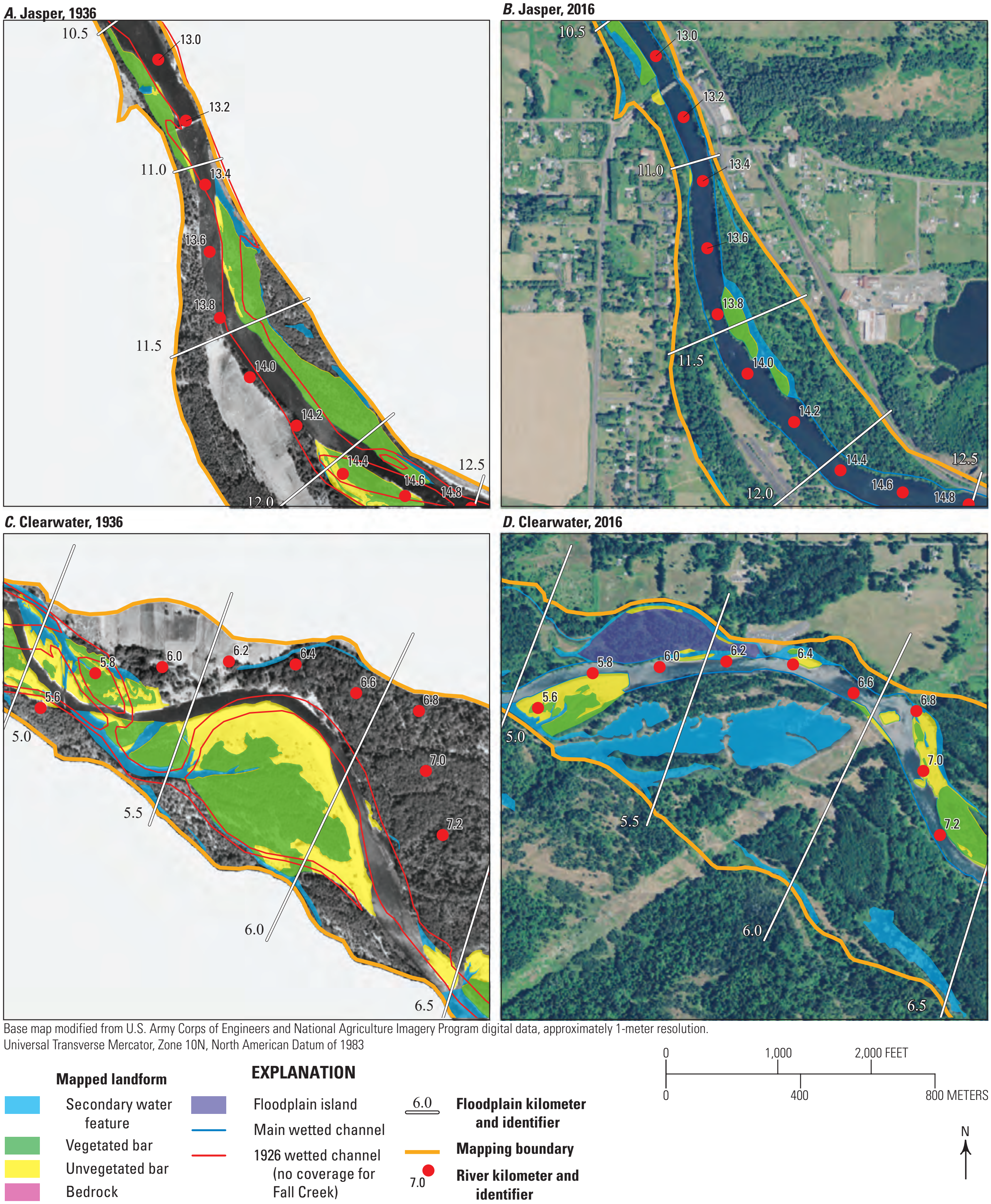


Figure 11. Repeat geomorphic mapping from aerial photographs for the Jasper reach (river kilometers [rkm] 17.9–10.7; showing segment rkm 14.8–13.0) and the Clearwater reach (rkm 10.7–0.0; showing segment rkm 7.2–5.6) along the Middle Fork Willamette River, Oregon, 1936 (*A* and *C*) and 2016 (*B* and *D*). Repeat geomorphic mapping data are available in from Keith and Gordon (2019).

Floodplain Islands

Compared with mapped gravel bars in the study area, floodplain islands were generally much larger and covered with dense, mature woody vegetation, representing geomorphically stable alluvial features (similar to findings by Dykaar, 2008a, 2008b; Wallick and others, 2013; and McDowell and Dietrich, 2013). As mapped, some floodplain islands were only partially surrounded by water because of low streamflows or overhanging vegetation that obscured adjacent channels in the aerial photographs. Floodplain islands were distinguished from areas mapped as floodplain surfaces by their lobate form in comparison with broader floodplain surfaces and were entirely or partially bound by side channels, alcoves, or swales, indicating that they were surrounded by streamflow during high-streamflow events. In 2016, floodplain islands were present along Fall Creek (figs. 8*D*, 9*D*) between fpkm 6.0–2.5, with the largest mapped area within fpkm 2.5 (just under 20,000 m^2). Large floodplain islands (1,580–245,000 m^2) were present throughout the Middle Fork Willamette River but were most abundant in the Dexter and Dougren reaches (figs. 10, 8*D*). Floodplain islands were also present at fpkm 14.0–13.5 and 10.5–10.0 in the Jasper reach, at fpkm 6.0–5.5 in the Clearwater reach (fig. 11*C*), and at 1.0–0.5 in the Clearwater reach but were typically smaller than those on the Middle Fork Willamette River upstream from the Fall Creek confluence (fig. 8*D*). Areas mapped as floodplain islands in 2016 aerial imagery most likely represent former alluvial features that now function as floodplains or terraces with little to no inundation or accumulation of fine-grained sediment under current streamflow management.

Bedrock

Bedrock exposed within or flanking the main channels of Fall Creek and the Middle Fork Willamette River indicate areas where streamflows were capable of transporting bed-material sediment, precluding the development of alluvial mantle (O’Connor and others, 2014). Bedrock outcrops often showed parallel ridges or cracks with a more jagged outline compared with the smooth texture and streamlined perimeter of bars. The extent of mappable bedrock visible from the 2016 aerial photographs was much smaller than bars, and the greatest mapped concentration of bedrock outcrops was at fpkm 9.5–9.0 in the Upper Fall Creek reach (5,460 m^2; fig. 8*C*). Mapped bedrock outcrops along the Middle Fork Willamette River in 2016 were typically smaller and less abundant than along Fall Creek for the same period (fig. 8*C*), with only 5 mapped patches ranging from 374 to 972 m^2 and with no bedrock mapped in the Dougren reach. Although in-channel bedrock was apparent in our field surveys throughout Fall Creek and Middle Fork Willamette River, this unit was underrepresented in the mapping because water and overhanging vegetation obscured bedrock and because many exposed outcrops were smaller than the minimum mapping unit.

Changes in Landforms and Planform, 1936–2016

Comparison of channel conditions from 1936 and 2016 for Fall Creek and Middle Fork Willamette River revealed that although the main channels of these rivers have remained in largely similar locations since the early 20th century, there were major reductions in unvegetated gravel bars and local losses and gains of secondary water features (figs. 6–11). Considering all reaches along Fall Creek and the Middle Fork Willamette River mapped downstream from the USACE dams, the total area of vegetated and unvegetated bars encompassed more than 2.83 million m^2 in 1936, which decreased by 69 percent to 876,000 m^2 in 2016 (fig. 8*A*; table 4). Patterns and magnitudes of channel transformations varied among reaches, but overall, the Middle Fork Willamette River underwent much a greater suite of transformations between 1936 and 2016 than Fall Creek. The change in unit total bar area for reaches on Fall Creek ranged from a decrease of 4.0 m^2/m to an increase of 1.5 m^2/m, whereas changes on reaches of the Middle Fork Willamette River ranged from losses of 59.9 to 88.3 m^2/m. The areal changes in total bars between these two periods was attributable to the conversion of unvegetated bars to vegetated bars and the conversion of formerly vegetated bars to floodplain islands or other surfaces falling outside the 2016 active channel mapping. On Fall Creek, the river channel in 1936 and 2016 flowed on a mix of bedrock and gravel, and channel position has varied minimally in the 80-year mapping interval (figs. 6, 9). The greatest geomorphic changes on Fall Creek detected through the repeat mapping have been a 65–94 percent (6,590–8,140 m^2) reduction in reach-aggregated unvegetated gravel bars and a 43–48 percent (1,740–8,500 m^2) reduction in the area of reach-aggregated secondary water features (figs. 8*A*, 9; table 4). In contrast, geomorphic transformations on the Middle Fork Willamette River have been more substantial even though the percent changes in unvegetated gravel bars were similar, with a 64–87 percent (51,100–509,000 m^2) reduction in reach-aggregated unvegetated bars and both (depending on the reach) increases (21,400–62,600 m^2) and decreases (48,000–68,100 m^2) in reach aggregated secondary water features (figs. 8*A*–8*B*, 10, 11; table 4). Despite major losses in mapped bars, fewer substantial losses have occurred in secondary water features across the whole study area and only minor changes have occurred in wetted channel length between the 1936 and 2016 (1.2 percent increase on Fall Creek and 1.8 percent reduction on the Middle Fork Willamette River; fig. 12).

Fall Creek

Fall Creek was historically, and is presently, a narrow (table 1), semi-alluvial river with intermittent gravel bars (fig. 9). In 1936, the Upper Fall Creek reach had fewer total gravel bars and lowest total bar area (vegetated and unvegetated) than other reaches in the study area (61,400 m^2; table 4; figs. 8, 9*A*). By 2016, nearly all the unvegetated bars in the Upper Fall Creek reach (fig. 9*B*) had either been eroded

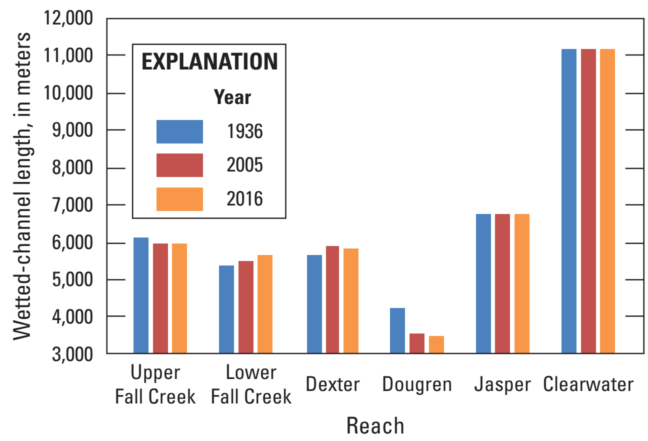


Figure 12. Total wetted-channel centerline length by reach and year from repeat geomorphic mapping of aerial photography for Fall Creek and the Middle Fork Willamette River, Oregon, 1936, 2005, and 2016.

(and therefore, were not apparent in the aerial photographs), colonized with vegetation, or obscured by greater streamflow at the time of the aerial photograph, causing a near complete elimination (94 percent; 6,590 m^2) of unvegetated gravel bars from this section of the river and an expansion of bars with woody cover (increase of 66 percent). For example, at rkm 6.4 on Fall Creek, a relatively large patch of unvegetated gravel apparent in 1936 was subsequently colonized by woody vegetation and densely forested by 2016 (fig. 7*C*). Likewise, the mapped area of secondary water features decreased by 48 percent (1,740 m^2) on the Upper Fall Creek reach and was primarily attributable to reductions in mappable side channels (fig. 8*B*; table 4). In 1936, the Lower Fall Creek reach (fig. 9*C*) had a total reach-aggregated bar area of 88,700 m^2, but a 23 percent (20,600 m^2) reduction in all bars and 65 percent (8,140 m^2) reduction in unvegetated gravel bars by 2016 (fig. 8*A*; table 4) resulted in present-day patches of unvegetated gravel that were sparser and smaller than in 1936 (fig. 9*D*). The Lower Fall Creek reach also had a 43 percent (8,500 m^2) loss in secondary water features between 1936 and 2016 (figs. 9*C*–9*D*; table 4), which primarily occurred through loss of areas mapped as alcoves (85 percent/5,170 m^2 reduction) that were primarily incorporated into floodplain in later periods (fig. 8*B*). Although overall losses in secondary water features were documented, increases (68 percent, 4,210 m^2) in side-channel area were also mapped (fig. 8*B*). The locations of exposed bedrock were similar in the 1936 and 2016 aerial imagery for both the Upper Fall Creek and Lower Fall Creek reaches, and reductions (95 and 23 percent, respectively) in the areal extent of mapped bedrock primarily related to the greater streamflows represented in the 2016 aerial photograph (in which inundated outcrops along the channel margins and instances where local bedrock patches may have been buried in sediments that were then colonized by vegetation; figs. 8, 9; table 3). Although many of the reach-scale patterns of channel change are supported with visual inspection of the photographs and observations of actual channel transformation, some of the decreases in unvegetated gravel bars, secondary water features, and bedrock resulted from much lower streamflow at the time of 1936 aerial photograph acquisition (61 ft^3/s at the Fall Creek streamgage) compared with streamflow during the 2016 photograph acquisition (225 ft^3/s at the Fall Creek streamgage).

Middle Fork Willamette River

Although Fall Creek downstream from Fall Creek Dam was historically and more recently (2016) laterally inactive, comparison of 1936 and 2016 channel maps of the Middle Fork Willamette River downstream from Dexter Dam revealed historical lateral dynamism and substantial transformations in channel planform (fig. 6). Comparison of these maps indicated an overall increase in geomorphic stability along the Middle Fork Willamette River, although the magnitudes of channel transformation vary by reach (figs. 10, 11). The Dexter reach (immediately downstream from Dexter Dam) underwent the greatest suite of transformations to unvegetated bars, channel position, and wetted channel length of any reach on the Middle Fork Willamette River between 1936 and 2016 (figs. 6, 8, 10*A*, 12; table 4). In 1936, broad vegetated and unvegetated bars were frequent and accounted for 44 percent of the mapped active channel area in this reach, but by 2016 unvegetated gravel bars were mostly absent and total vegetated and unvegetated bar area accounted for about 9.6 percent of the active channel area in the Dexter reach. Much of the 2016 channel was flanked by surfaces with mature forest (gravel bars with woody vegetation or other mapping categories) and occasional small patches of stable, unvegetated gravel where frequent scouring streamflows preclude vegetation growth (fig.10*B*). The overall area mapped as active channel decreased between 1936 and 2016 by 24 percent with an 87 percent decrease in unvegetated gravel bars and a 58 percent decrease in secondary water features (figs. 7, 8*A*).

The Dougren reach also underwent substantial planform simplification during this period; however, the overall total area mapped as active channel between 1936 and 2016 remained similar (figs. 6, 10*C*–10*D*). The most substantial changes in the Dougren reach consisted of a 64 percent decrease in the area of unvegetated gravel bars and a twofold increase in the area of secondary water features (fig. 8; table 4). In 1936, the reach was nearly continuously flanked by unvegetated bars but by 2016, although bars were still relatively abundant in comparison with other reaches, they were narrower, woodier, and less spatially continuous, and in many cases had evolved into floodplain or floodplain islands (figs. 6, 8*A*, 10*C*–10*D*). The large increase (121 percent) in floodplain island area near the confluence with Fall Creek and farther upstream at rkm 20.5–19.5 corresponded with the increase of mapped of secondary water features, because island growth led to creation and elongation of secondary water features (fig. 8*B*, 8*D*).

Downstream from the Fall Creek confluence, the Middle Fork Willamette River, along the Jasper and Clearwater reaches, also underwent major reductions in unvegetated gravel bars. The Clearwater reach (the lowermost reach of the Middle Fork Willamette River) retained a greater area of actively shifting gravel bars in the 2016 period than other reaches in the study (figs. 6, 8, 11; table 4). The Jasper and Clearwater reaches underwent 87 and 83 percent decreases (respectively) in unvegetated gravel bars, as large expansive gravel bars in 1936 were lost to erosion or colonized by vegetation. Small amounts of bedrock present in the 1936 mapping in theses reaches (5,680–8,760 m^2) were reduced by 2016, although the mapped bedrock only accounted for a very small part (0.6 percent or less) of the total reach-aggregated active channel area for any mapped period within the Jasper and Clearwater reaches (fig. 8*C*; table 4).

The 1936 channel maps may be biased toward greater mapped area of exposed unvegetated gravel bars and bedrock and less mapped area of wetted channel features compared to the 2016 images due to the streamflows depicted in the 1936 aerial photographs. Although streamflow at the time of 1936 aerial photograph acquisition on the Middle Fork Willamette River is unknown, streamflows in 2016 were augmented in summer by releases from upstream USACE dams (Gregory and others, 2007) and streamflow along Fall Creek in the 1936 aerial photographs was substantially lower than that for later (regulated) periods, including 2016. Despite uncertainty from the aerial photograph mapping, the major losses in unvegetated gravel bars, coupled with field observations and close inspection of the aerial photographs indicating erosion and vegetation colonization of unvegetated gravel bars between 1936 and 2016, the overall pattern in bar loss almost certainly indicated actual channel change and planform simplification. Likewise, the increases in mapped area of side channels for the Dougren, Jasper, and Clearwater reaches may have partly reflected higher streamflow in 2016 compared with 1936, but likely also reflected the development of secondary water features within and around historically unvegetated bars that became stable woody bars or floodplain islands.

Changes in Bed and Water-Surface Elevations, 1926–2015

Comparison of longitudinal water-surface profiles of the Middle Fork Willamette River extending from Dexter Dam to the confluence with the Coast Fork Willamette River (fig. 13) derived from 1926 plan and profile maps (USGS, 1927) and 2015 bathymetric lidar (water-surface and channel-bed elevations; Quantum Spatial, 2016) showed that the water-surface profile along much of the 27-km channel segment has remained largely similar over the 90-year period between surveys. Observed changes in water-surface elevation were used to indicate bed elevation changes, particularly when evaluating profiles over distances greater than 1 km. The magnitude and spatial extent of divergences between historical and recent profile elevations were the smallest along the Jasper reach, where water-surface profiles were largely similar although slightly greater (0.05–0.84 m higher) in 2015 than in 1926 at comparable locations. Areas with the most apparent lowering of water-surface elevations from 1926 to 2015 were along localized segments of the Dexter, Dougren, and Clearwater reaches. By reach, the locations with greatest decrease in water-surface elevation were rkm 24.8 in the Dexter reach (1.9 m lower), rkm 20.4 in the Dougren reach (0.7 m), and rkm 7.6 in the Clearwater reach (2.3 m; fig. 13). This lowering encompassed 2–10-km-long segments of the river, coinciding with knickpoint-like features (abrupt change in slope along the profile) and areas where the channel flows along steep (greater than about 2-m) channel banks. This study did not identify channel segments (greater than about 2 km in length) with substantial increases (more than 1 m) in the profile elevations between 1926 and 2015 that would indicate any systematic aggradation in the study area. However, at the downstream end of the Dougren reach, there was one instance where the 2015 water-surface profile was higher than 1926 by as much as 1.7 m (fig. 13). The water-surface elevations in both 1926 and 2015 reflect discharge at the time of the surveys; streamflows were not monitored in 1926, so the actual error associated could be quite large, particularly as streamflows increase for the Middle Fork Willamette River as indicated by current streamflow-stage relations (see discussion of error in section, “Plan and Profile Maps from 1926”). Overall, these findings show that, whereas much of the Middle Fork Willamette River downstream from Dexter Dam was vertically stable from 1926 to 2015, some segments likely have undergone bed-level lowering and incision.

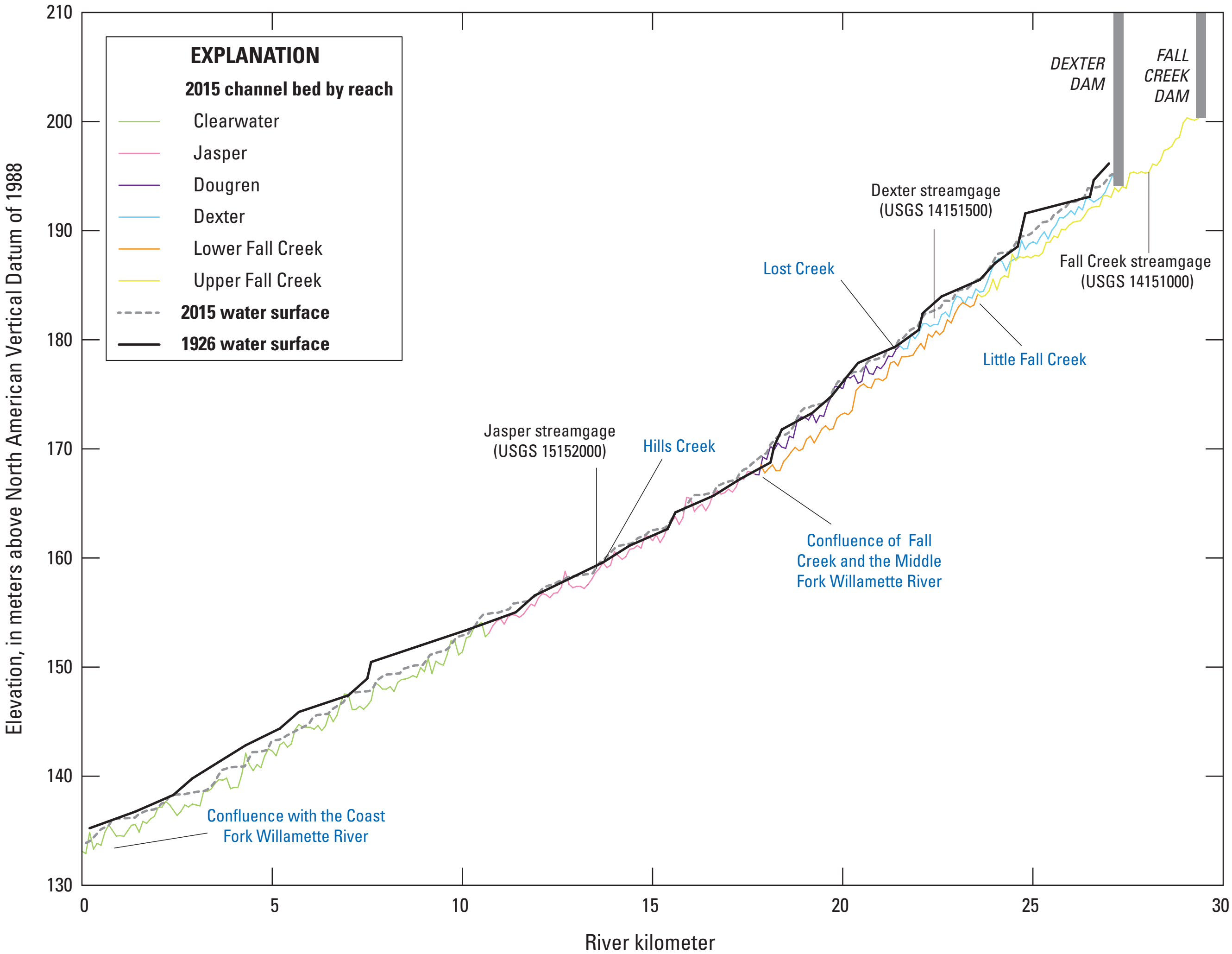


Figure 13. Recent longitudinal profiles for Fall Creek and the Middle Fork Willamette River, Oregon, from 2015 bathymetric lidar channel-bed and water-surface elevations (Quantum Spatial, 2016). Historical longitudinal profile for the Middle Fork Willamette River, Oregon, from from 1926 water-surface elevation (U.S. Geological Survey, 1927).

Discussion

Channel conditions along Fall Creek and the Middle Fork Willamette River, Oregon, in 2015–16 were compared with historical (pre-dam) maps and surveys from 1926 and 1936 to characterize net changes occurring in response to construction and operation of USACE flood-control dams and other land-use changes over the nearly 8 decades between the datasets (table 1). This comparison of historical and present-day conditions specifically sought to identify patterns of geomorphic stability prior to dam construction and transformations of the river corridors that resulted mainly from dam construction. Changes in channel planform and bed elevations were assessed using datasets from the early 20th century that pre-date the 1954–66 construction of upstream USACE dams in the Fall Creek and Middle Fork Willamette River Basins. These historical datasets provide a basis for evaluating historical conditions and long-term patterns of lateral and vertical stability, as well as providing historical geomorphic context for responses to streambed drawdown at Fall Creek Lake and informing other restoration and river-management activities.

The geomorphic maps developed for this study from 1936 aerial photography provide insights into channel planform and channel features of the early 20th century prior to construction of upstream flood-control dams and other channel modifications and land-use changes (table 1). The lower 11.5 rkm of Fall Creek (downstream from what is now Fall Creek Dam) occupied a relatively straight and narrow mixed bed (bedrock and alluvium) channel with intermittent unvegetated gravel bars, side channels, and alcoves. The lower 27.3 rkm of Middle Fork Willamette River (downstream from what is now Dexter Dam) was a fully alluvial, gravel-bed channel that flowed locally on bedrock, with single-thread and multi-channeled sections. In 1936, the Middle Fork Willamette River was flanked by large actively shifting gravel bars, and in many areas, streamflow was separated into multiple channels by forested islands and mid-channel bars.

The geomorphic maps developed for this study from 1926 plan and profile maps provide insights into channel planform in the decade-prior maps developed from the 1936 aerial photographs. The presence of large unvegetated bars and numerous secondary channel features along the Middle Fork Willamette River in 1936, together with the channel changes noted between 1926 and 1936, are indicative of lateral dynamism whereby the channel frequently shifted position through avulsions and meander migrations. These and other indications of frequent channel change prior to dam construction have also been documented in previous studies along the Middle Fork Willamette River (Dykaar, 2005, 2008a), Willamette River (Gregory and others, 2002a; Wallick and others, 2007), and for other unregulated western Oregon rivers (O'Connor and others, 2014). In the mid-20th century, the construction and operation of flood-control dams in the Fall Creek and Middle Fork Willamette River watersheds substantially reduced peak streamflows and trapped all coarse sediment and most fine sediment that was historically supplied to downstream reaches (O'Connor and others, 2014). Despite major alterations to flow and sediment regimes, the inherent geomorphic stability of Fall Creek (as indicated by bedrock outcrops, substrate conditions, and minimal channel change from 1936 to 2016) resulted in relatively modest post-dam geomorphic changes compared with those of the Middle Fork Willamette River. However, 30 years of pre-dam land-use change and other natural events in Fall Creek and about 20 years along the Middle Fork Willamette River (table 1) that are encompassed in the period between aerial photograph mapping likely also affected these river corridors, as well as legacy effects of land-use changes that occurred before 1936. The period between 1936 and the 1950–60s was a time of land-use change in these watersheds, particularly logging and road building. Additionally, large floods such as the peak of record on Fall Creek (WY 1957; 24,700 ft^3/s at the Fall Creek streamgage) and the WY 1953 event on the Middle Fork Willamette River (73,400 ft^3/s) would have influenced channel morphology within the study reaches.

The primary transformation in mapped channel features between 1936 and 2016 from aerial photographs on Fall Creek was a loss in unvegetated gravel bars (94 percent along Upper Fall Creek reach and 63 percent along Lower Fall Creek reach), although these features were small and sparse even in the historical datasets (figs. 7–9). The 1926 survey does not encompass Fall Creek, so there is no basis for systematic comparison of water-surface profiles and identification of reach-scale patterns of vertical stability, but reach-scale vertical adjustments likely were minimal between 1926 topographic surveys and 2015 lidar data given the persistence of mapped bedrock and that limited planimetric changes measured change between 1936 and 2016.

Altogether, the extent of exposed, in-channel bedrock and limited number of alluvial landforms (gravel bars, secondary water features, and floodplain islands) in 1936 and 2016 provide two major insights about the historical and present-day geomorphic conditions in Fall Creek. First, Fall Creek has both historically and presently been a semi-alluvial channel since at least the early 20th century, which is corroborated by early fisheries surveys (McIntosh and others, 2009) and other anecdotal accounts, and likely has supported a high transport capacity relative to bed-material supply. Although various human alterations to the river channel in the late 1800s and early 1900s (such as log drives and splash damming; Miller, 2010; figs. 2–4) may have scoured available gravel and contributed to extensive-in-channel bedrock by 1936, the overall morphology and character of Fall Creek is typical of other western Oregon rivers that have an inherently low supply of coarse sediment (relative to transport capacity) owing to geological control (Wallick and others, 2011; O'Connor and others, 2014). Second, the construction of Fall Creek Dam in 1965 has further diminished bed-material supply by trapping gravel upstream from the dam and reducing erosive peak streamflows that would have historically liberated stored gravel from bars and floodplains in reaches downstream from the dam. Reduction in peak streamflows has also permitted vegetation colonization and encroachment on historically unvegetated gravel bars, which has stabilized these landforms and lessened the likelihood that this alluvium could be eroded and transported by present-day regulated streamflows. The construction and operation of Fall Creek Dam has led to modifications in the overall pattern of landforms and vegetation, whereby historical (pre-dam) patches of unvegetated gravel have either been lost through erosion or colonized by woody vegetation. These and other modifications may have increased the efficiency of the transport of suspended sediments during streambed drawdown operations at low to moderate streamflows. At higher streamflows, the additional woody vegetation in the active channel and on formerly unvegetated gravel bars may reduce the streamflow and sediment conveyance by increasing floodplain roughness. However, detailed hydraulic modeling would be needed to evaluate effects of the relation more fully between historical channel transformations and streamflow and sediment conveyance.

Geomorphic transformation of the fully alluvial Middle Fork Willamette River during the 20th century was much more substantial than along Fall Creek, as this formerly laterally active river corridor with numerous, large (tens of thousands of square meters) actively shifting gravel bars became laterally inactive. Over the 10-year period between 1926 and 1936, some dynamic river segments underwent avulsions spanning 1–3 km of the floodplain where secondary channel features in 1926 were either abandoned or occupied by the main channel by 1936; other segments underwent minimal lateral adjustments. Changes over the 20th century spanning dam construction and other channel modifications are evidenced by river-wide reduction in unvegetated bars and encroachment of stabilizing vegetation between 1936 and 2016, as well as minimal channel change detected since about 2005 (McDowell and Dietrich, 2013; Jones and others, 2016; Keith and Gordon, 2019; figs. 6, 8, 10, 11; table 4). Overall, comparison of the 1926, 1936, and 2016 channel maps for the Middle Fork Willamette River indicate that (1) the Dexter and Dougren reaches, closest downstream from Dexter Dam, underwent substantial changes in channel location and landforms that led to the greatest increases in geomorphic stability, as indicated by a lack of features and processes (such as unvegetated gravel bars and bank erosion) that would typically signify bed-material transport; and (2) despite nearly a 90-percent decrease in unvegetated gravel bars in the Clearwater and Jasper reaches (figs. 8*A*, 11), the net losses did not eliminate gravel (through erosion or vegetation colonization) because these reaches had a substantial area of bars in 1936 and small unregulated tributaries and local bank erosion downstream of the dam's supply gravel (figs. 9*A*–9*B*, 10*A*–10*B*). The increase in the area of side channels mapped between 1936 and 2016 in the Dougren, Jasper, and Clearwater reaches (fig. 8*B*) likely, in part, reflects greater streamflow in the aerial photographs during 2016. However, other river corridor transformations in the study area seem likely to have affected the size and distribution of side channels; for example, stabilization of former unvegetated bars that were converted to woody bars and floodplain islands are associated with increasing area and elongations of side channels (figs. 10*C*–10*D*). Comparison of pre-dam maps from 1926 and 1936 shows large-scale avulsions (spanning 1–3 km of the floodplain) and 2–10 km channel segments that underwent meander migration and lateral shifting (figs. 6*C*–6*D*, 6*F*). Laterally inactive sections were also documented in each reach, although most extensively along the Jasper reach and downstream sections of the Clearwater reach (fig. 6*E*–6*F*), often coinciding with areas of stable bedrock.

Major losses in unvegetated gravel bars and vegetation colonization between 1936 and 2016 along all reaches of the Middle Fork Willamette River are indicative of river-wide channel simplification (fig. 8*A*). Across the study area, the area of unvegetated bars was reduced by 83 percent and the total bar area was reduced by 69 percent. The Dexter and Dougren reaches underwent substantial changes in channel location and landforms that led to the greatest increases in geomorphic stability, as indicated by a strongly reduced area of unvegetated gravel bars in 2016 (figs. 6, 8, 10). The Clearwater and Jasper reaches also underwent major decreases in gravel bars, but the net losses did not result in the elimination of nearly all unvegetated gravel bars from these reaches as they did for the reaches directly downstream from the dams. Increases in side channel area during this same period in Dougren, Jasper, and Clearwater reaches (figs. 8, 10*C*–10*D*, 11; table 4) may partly reflect higher streamflow in 2016 compared with 1936 (inferred from differences of streamflow of 61 and 225 ft^3/s at the Fall Creek streamgage during these periods), but in some areas the local differences in geomorphic maps confirm that side channels were formed in conjunction with the evolution of large unvegetated bars into more stable bars (woody cover) or floodplain islands.

The Middle Fork Willamette River has both vertically stable sections and sections that may have undergone bed-level changes between 1926 and 2015. Water-surface longitudinal profiles, assumed to be broadly representative of channel-bed elevations over distances of about 1 km and derived from 1926 maps and 2015 bathymetric lidar, show that much of the Middle Fork Willamette River downstream from Dexter Dam has remained vertically stable, with mostly similar bed elevations over the 90-year period between surveys, which spans the construction and subsequent operation of upstream USACE dams (fig. 13). The key differences between the 1926 and 2015 water-surface profiles are select areas where water-surface elevations in 2015 are lower than in 1926 within the Dexter, Dougren, and Clearwater reaches (fig. 13).

Maximum local lowering in each reach ranged from about 0.7 to 2.3 m. Areas of potential bed lowering each encompass 2- to 10-km-long segments of the river, are coupled with knickpoint-like profile features (immediately upstream from apparent bed-level lowering) and coincide with areas where the channel flows along steep channel banks that can exceed 2 m in height. The segments with apparent bed lowering also occur in fully alluvial, laterally mobile channel segments that had lateral channel shifting both prior to and after dam construction (as evident from repeat channel mapping 1936–2016 and field observations). Although the exact amount of incision is not known because of uncertainty in water level, unknown survey error and datum adjustments, and channel migration, substantial lowering in the water-surface profiles in multiple locations of more than 1 m that is not systematically tracked across the study area suggests that localized lowering of channel-bed elevations may reflect actual decreases in bed elevations.

Other human alterations to the river channel, such as splash dams and log drives (figs. 2–4; Miller, 2010), tree clearing, and commercial gravel extraction may have also contributed to bed-level lowering before the implementation of large flood-control projects (dams and revetment), as has been suggested for other gravel-bed rivers in the Willamette River Basin (Klingeman, 1973; Sedell and Froggatt, 1984). Although the Dexter, Dougren, and Clearwater reaches were mainly vertically stable with local areas of lowering between 1926 and 2015, the entire Jasper reach was vertically stable. The only area with potential aggradation was the downstream end of the Dougren reach where water-surface elevations increased locally by as much as 1.7 m, which corresponds with the confluence of Fall Creek and the growth in mid-channel bars in this area (fig. 13). These patterns of vertical stability largely relate to geological controls and the distribution of bedrock versus alluvium observed in the present-day channel, which indicates the sensitivity of a particular reach to incision following reductions in bed-material supply that occurred after dam construction in the mid-20th century. Only short (less than 2-km) segments showed potential aggradation (more than 1 m). Nearly all locations of apparent aggradation or incision coincide with locations along the river where meander migration and changes in channel planform have resulted in longitudinal shifting and alignment of channel-bed features and thereby may not be representative of real aggradation or incision. However, assessment of apparent incision spanning segments longer than 2 km minimizes uncertainty. For example, locations of apparent aggradation might be associated with former pool features that have shifted to a shallow bar or riffle features. However, the reach-scale patterns of bed-lowering (along the Dexter reach) and vertical stability (for the Jasper reach) inferred from the longitudinal profiles of pre-dam (1926) and post-dam (2015) conditions are consistent with the local patterns of bed elevation changes documented at the Dexter and Jasper streamgages from specific streamgage analyses (Wallick and others, 2013).

Conclusions

Altogether, evaluation of datasets for Fall Creek and the Middle Fork Willamette River, Oregon, downstream from U.S. Army Corps of Engineers dams constructed during 1954–1965 provides a foundation for understanding:

1. channel morphology and patterns of geomorphic stability prior to dam construction (1926–1936);
2. channel morphology and patterns of lateral and vertical stability of the early 21st century that reflect post-dam (2016) streamflow and sediment regimes; and
3. geomorphic transformations of the river corridors in the decades following dam construction, including changes in planform (1936–2016) and bed elevation (1926–2015).

These historical datasets provide a basis for evaluating historical conditions and long-term patterns of lateral and vertical stability, as well as providing historical geomorphic context for evaluating geomorphic responses to streambed drawdowns at Fall Creek Lake and informing other restoration and river-management activities.

As of 2016, Fall Creek flows through a narrow, semi-alluvial channel that efficiently conveys water and sediment at typical low-to-moderate streamflows downstream from Fall Creek Dam. This channel planform, including the positions and distributions of bars and secondary water features (side channels, alcoves, and ponds), generally reflects pre-dam conditions in 1936, suggesting relatively modest morphological adjustments resulting from reductions in sediment supply and alterations to peak streamflow after dam construction. The most substantial morphologic change detected for Fall Creek over this period was a reduction in unvegetated gravel bars. The persistence of in-channel bedrock and lack of full alluvial cover in both 1936 and 2016 datasets suggest transport capacity along Fall Creek has historically and recently exceeded sediment supply.

The reaches of the Middle Fork Willamette River downstream from Dexter Dam were historically (1936) laterally active with multi-thread and single-thread channels flanked by large, shifting gravel bars. As of 2016, the Middle Fork Willamette River is a large, gravel-bed river that, despite substantial transformations in channel morphology and reduction in lateral dynamism following the construction of three upstream dams, remains a fully alluvial river. Since streamflow regulation and other channel modifications in the mid-20th century, these reaches have become more laterally stable and encompass a narrower floodplain corridor as former gravel bars were converted to low-elevation floodplains colonized by young, dense vegetation. Reaches between Dexter Dam and the Fall Creek confluence are slightly more laterally inactive than those farther downstream to the mouth of the Middle Fork Willamette River where gravel bars are larger, more abundant, and subject to annual scour that inhibits vegetation cover. Changes in water-surface profiles in the 27-kilometer (km) segment of the Middle Fork Willamette River downstream from Dexter Dam greater than 1 meter (m) for more than 2 km were not present along the Jasper reach and were localized in other reaches, reaching a maximum (2.3 m lowering) in the Clearwater reach. Channel segments greater than about 2 km in length with substantial increases in profile elevations that would indicate aggradation were not identified.

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