Prepared in cooperation with the U.S. Army Corps of Engineers and The Nature Conservancy

Summary of Environmental Flow Monitoring for the Sustainable Rivers Project on the Middle Fork Willamette and McKenzie Rivers, Western Oregon, 2014–15

Open-File Report 2016–1186

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

Cover: Photographs of:

Top: Willows (*Salix* sp.) and black cottonwoods (*Populus trichocarpa*) at the Oxbow vegetation monitoring site on the McKenzie River, Oregon.

Bottom left: Black cottonwood growing from vegetative fragments at the Confluence Preserve on the Middle Ford Willamette River, Oregon.

Bottom right: Black cottonwood seedling at the Confluence Preserve on the Middle Fork Willamette River, Oregon.

All photographs by Krista Jones, U.S. Geological Survey, June 3–4, 2015.

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datums

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

Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

Abbreviations

EWEB	Eugene Water and Electric Board
FPKM	floodplain kilometer
FWS	U.S. Fish and Wildlife Service
NAIP	National Agriculture Inventory Program
OSU	Oregon State University
RKM	river kilometer
UO	University of Oregon
SRP	Sustainable Rivers Project
TNC	The Nature Conservancy
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WY	water year

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By Krista L. Jones[1], Joseph F. Mangano[1], J. Rose Wallick[1], Heather D. Bervid[1], Melissa Olson[2], Mackenzie K. Keith[1], and Leslie Bach[2,3]

Significant Findings

This report presents the results of an ongoing environmental flow monitoring study by The Nature Conservancy (TNC), U.S. Army Corps of Engineers (USACE), and U.S. Geological Survey in support of the Sustainable Rivers Project (SRP) of TNC and USACE. The overarching goal of this study is to evaluate and characterize relations between streamflow, geomorphic processes, and black cottonwood (*Populus trichocarpa*) recruitment on the Middle Fork Willamette and McKenzie Rivers, western Oregon, that were hypothesized in earlier investigations. The SRP can use this information to plan future monitoring and scientific investigations, and to help mitigate the effects of dam operations on streamflow regimes, geomorphic processes, and biological communities, such as black cottonwood forests, in consultation with regional experts. The four tasks of this study were to:

1. Compare the hydrograph from Water Year (WY) 2015 with hydrographs from WYs 2000–14 and the SRP flow recommendations,
2. Assess short-term and system-wide changes in channel features and vegetation throughout the alluvial valley section of the Middle Fork Willamette River (2005–12),
3. Examine changes in channel features and vegetation over two decades (1994–2014) for two short mapping zones on the Middle Fork Willamette and McKenzie Rivers, and
4. Complete a field investigation of summer stage and the growth of black cottonwood and other vegetation on the Middle Fork Willamette and McKenzie Rivers in summer 2015.

[1]U.S. Geological Survey.
[2]The Nature Conservancy.
[3]Northwest Power and Conservation Council.

Results of Task 1, a comparison of the hydrograph for WY 2015 with hydrographs for WYs 2000–14 and SRP flow recommendations, include the following:

- In WY 2015, the Middle Fork Willamette and McKenzie Rivers had winter bankfull flow events in late December 2014 that met the SRP winter bankfull flow recommendations. The magnitude of these events was sufficient to transport bed-material sediment, creating patches of bare gravel that formed recruitment sites for black cottonwood. Summer-like flow conditions started in late February, and were sustained throughout summer on both rivers as a result of the low winter and spring precipitation in western Oregon.
- During WYs 2000–15, flows on the Middle Fork Willamette River frequently met the SRP recommendations for small fall and spring flow pulses, but infrequently met the recommendations for winter bankfull flows, spring-to-summer transition flows, and summer baseflows. Flows on the McKenzie River infrequently met the winter bankfull, winter high-flow, small spring flow, and summer low-flow recommendations. Flow recommendations for small floods and large winter floods on the Middle Fork Willamette River, winter high flows and winter floods on the McKenzie River, and spring bankfull flows on both rivers were not met, partly because of the absence of natural flooding in western Oregon during this period.

Results of Task 2, an assessment of short-term and system-wide changes in channel features and vegetation throughout the alluvial section of the Middle Fork Willamette River from 2005 to 2012, include the following:

- Flow events that exceed the winter bankfull flow recommendation for multiple days, such as the January 2006 bankfull event that peaked at 22,800 cubic feet per second (ft^3/s) and lasted for 6.5 days, are successful at scouring unvegetated gravel bars, resetting shrubs and herbaceous vegetation, and triggering substantial but localized channel changes (such as avulsions in areas with existing side channels). In contrast, shorter duration bankfull events (such as the January 2009 event that peaked at 22,500 ft^3 and lasted 1.5 days) primarily affect the location and size of gravel bars and propagate meander migration.
- Geomorphically effective flows are achieved when flows exceed the SRP bankfull recommendation (19,000 ft^3) for a sustained duration, similar to the 2006 event. Based on the repeat mapping, the geomorphic effects of similar future bankfull events are likely to be localized, such as near floodplain kilometers (FPKMs) 21, 13–17, 3–6, and 0, where the Middle Fork Willamette River has a relatively wide active channel, unvegetated gravel bars, and side channels.
- Flow events that reconfigure gravel bars and secondary channels may provide important habitat benefits, such as increasing spawning and rearing habitats for salmonids, thermal diversity, and the complexity of instream and riparian habitats. They also may create recruitment sites for black cottonwood. Recruitment sites on active gravel bars are apt to be in the scour zone of future high-flow events, owing to the limited footprint of active geomorphic processes on the Middle Fork Willamette River.

Results of Task 3, an examination of changes in channel features and vegetation over two decades (1994–2014) for two short (less than 3 kilometers) mapping zones of the Middle Fork Willamette and McKenzie Rivers, include the following:

- Channel features in the Middle Fork Willamette and McKenzie mapping zones undergo frequent lateral adjustments, so these zones were considered ‘geomorphically dynamic’ compared with predominantly stable conditions elsewhere in the alluvial sections of these rivers.
- Over the last two decades, the Confluence mapping zone on the Middle Fork Willamette River (FPKMs 3–6 on Middle Fork Willamette River) has evolved primarily because of small avulsions and short sections of meander migration. In contrast, the McKenzie Oxbow mapping zone (FPKMs 23–25 on McKenzie River) has evolved because of a large-scale avulsion coupled with continued meander migration and floodplain erosion. Accordingly, the location of the channel and the mapped area of most features changed little in the Middle Fork Confluence zone, but changed greatly in the McKenzie Oxbow zone from 1994 to 2014.
- In the McKenzie Oxbow zone, cumulative channel and vegetation changes from 1994 to 2014 show how a large flood and subsequent smaller floods (such as that of February 1996 peaking at 51,600 ft^3, November 1996 peaking at 31,500 ft^3, and December 1998 peaking at 31,500 ft^3) can scour overflow channels and create conditions that allow even smaller magnitude flood events (such as those peaks ranging from 5,390 to 23,900 ft^3 between 2000 and 2005) to cause large-scale changes in channel planform, including avulsions. These channel changes resulted in an increase in bare gravel bars that are later colonized by herbaceous plants, shrubs, and trees as well as the creation of aquatic habitats. For instance, after the large channel avulsion, the abandoned mainstem channel became the McKenzie Oxbow that supports Oregon chub (*Oregonichthys crameri*) and other native fishes as of 2015.

Results of Task 4, a field assessment of summer stage and the growth of black cottonwood and other vegetation at two sites on the Middle Fork Willamette and McKenzie Rivers in summer 2015, include the following:

- Two monitoring sites were established on gravel bars that supported black cottonwood recruitment in summer 2015. One site was in the Middle Fork Confluence mapping zone and the second site was in the McKenzie Oxbow mapping zone). We observed 157 and 33 black cottonwoods in the monitoring plots at the Confluence and Oxbow sites, respectively, that were a mix of seedlings and clones from vegetative fragments (clones). Both seedlings and clones generally had good vigor over the summer. We observed 1 mortality at the Confluence site and 1 mortality at the Oxbow site. Continued monitoring would be needed to indicate the survivorship and maturation of the monitored cottonwoods.
- Invasive plants at both sites included reed canary grass (*Phalaris arundinacea*), marshpepper knotweed, white sweet clover (*Melilotus alba*), and bird’s-foot trefoil (*Lotus corniculatus*). These plants increased in cover over the summer, and often were found near black cottonwood seedlings and clones. The potential effects of these invasive plants on black cottonwood recruitment are unknown at this time.

Priority tasks that would benefit the implementation and monitoring of environmental flows in the Willamette River Basin include:

- **Additional analyses comparing observed streamflow against the SRP flow recommendations**. Analyses for Task 1 assessed whether streamflow magnitude met SRP flow recommendations for WYs 2000–15. These analyses did not thoroughly address flow duration, number of events per year, rate of change, spring flow recession, seasonal flow conditions, and other metrics pertinent to understanding geomorphic and vegetative responses to streamflows. Quantitatively examining these types of flow metrics and making those analyses publically available would support flow implementation and adaptive management.
- **Determination of geomorphically effective flow thresholds for the McKenzie River.** This study identified geomorphically effective flow thresholds for the Middle Fork Willamette River. We were unable to determine similar flow thresholds for the McKenzie River because repeat channel mapping was done for a small reach that is not representative of the streamflow, coarse sediment inputs, and channel stability conditions throughout the entire alluvial section of this river. Comprehensive repeat mapping and field observations of the alluvial section of the McKenzie River are needed to determine geomorphically effective flow thresholds for this river.
- **Delineation of channel and floodplain features from future aerial photographs.** In the future, additional mapping from aerial photographs taken before and after different types of flood events in low-flow and high-flow years would be helpful to document the range of geomorphic and vegetation responses to individual and sequential flow events, to refine the geomorphic thresholds for channel change and habitat creation, and to relate these changes with SRP flow implementation and success toward program goals.
- **Inventory of black cottonwoods and other plants in the alluvial sections of the Middle Fork Willamette and McKenzie Rivers.** An inventory of black cottonwoods would be helpful for identifying existing stand locations and age classes, relating stands with streamflow and channel conditions (past and present), and verifying whether vegetation mapped in Tasks 2 and 3 are primarily native or invasive plants. This inventory could be repeated over time to assess the persistence of younger black cottonwood stands and other plants in relation to SRP flow implementation.

Introduction

The Nature Conservancy (TNC) and U.S. Army Corps of Engineers (USACE) began their national Sustainable Rivers Project (SRP) in 2002 with the goal of identifying opportunities to adjust dam operations to provide ecologically beneficial flows for fishes, vegetation, and other river-dependent species throughout the year while meeting human needs and congressionally authorized purposes (Warner and others, 2014). The Willamette River Basin in western Oregon is one of eight demonstration sites in the SRP. Like the other demonstration sites, SRP efforts in the Willamette Basin have resulted in scientific assessments (called environmental flow frameworks; Gregory and others, 2007a; Risley and others 2010a; 2012) and flow recommendations resulting from an iterative process and input from regional experts (Gregory and others, 2007b; Risley and others, 2010b, Bach and others, 2013). Environmental flows can be defined as the streamflow needed to sustain ecosystems while continuing to meet human needs. Flow recommendations generally are evaluated for feasibility by dam operators, implemented where possible, and monitored by scientists to evaluate their effects on river ecosystems and dam operations (Tharme, 2003; Acreman and Dunbar, 2004; Richter and others, 2006; The Nature Conservancy, 2009). As of 2016, SRP efforts in the Willamette Basin have focused on the Middle Fork Willamette, Coast Fork Willamette, McKenzie, North Santiam, and South Santiam Rivers (fig. 1). Initial flow implementation started on the Middle Fork Willamette and McKenzie Rivers in 2015.

This study was done to help the SRP relate streamflow, geomorphic processes, and the recruitment of the native black cottonwood (*Populus trichocarpa*) on the Middle Fork Willamette and McKenzie Rivers. These rivers have many similar characteristics, including drainage area, geology, land cover, land use patterns, hydrographs, and the presence of revetments (table 1). The USACE operates dams on both rivers primarily for flood management with other authorized uses including hydropower, water quality, and recreation. The USACE operates Lookout Point and Dexter Dams on the mainstem Middle Fork Willamette River and the Fall and Hills Creek Dams on two of its tributaries (fig. 1; table 2). The USACE also manages the Blue River and Cougar Dams on two tributaries to the McKenzie River. The Eugene Water and Electric Board (EWEB), a local utility, operates the Carmen-Smith-Trail Bridge dam complexes, Leaburg Dam, and the Leaburg and Walterville diversion canals in the McKenzie River Basin.

Dam operations in the Middle Fork Willamette and McKenzie River Basins provide many human benefits, but they also alter streamflow regimes. Operations generally decrease the frequency, magnitude, and duration of peak flows and increase the magnitude of summer low flows (Gregory and others, 2007a; Risley and others, 2010a). Flow events exceeding the pre-dam 1.5 year recurrence interval flow on both rivers have been substantially decreased since the system of flood control reservoirs became fully operational in the 1960s (fig. 2; Gregory and others, 2007a; Risley and others, 2010a). The USACE flood regulation goal for the USGS streamflow gaging station at Jasper on the Middle Fork Willamette River is 19,833 cfs, which is slightly higher than the SRP winter bankfull target of 19,000 ft^3/s (National Marine Fisheries Service, 2008; Gregory and others, 2007b). High flows that approach the SRP winter bankfull flow recommendation on the Middle Fork Willamette River have longer durations but shorter frequencies compared to pre-dam conditions (Gregory and others, 2007a).

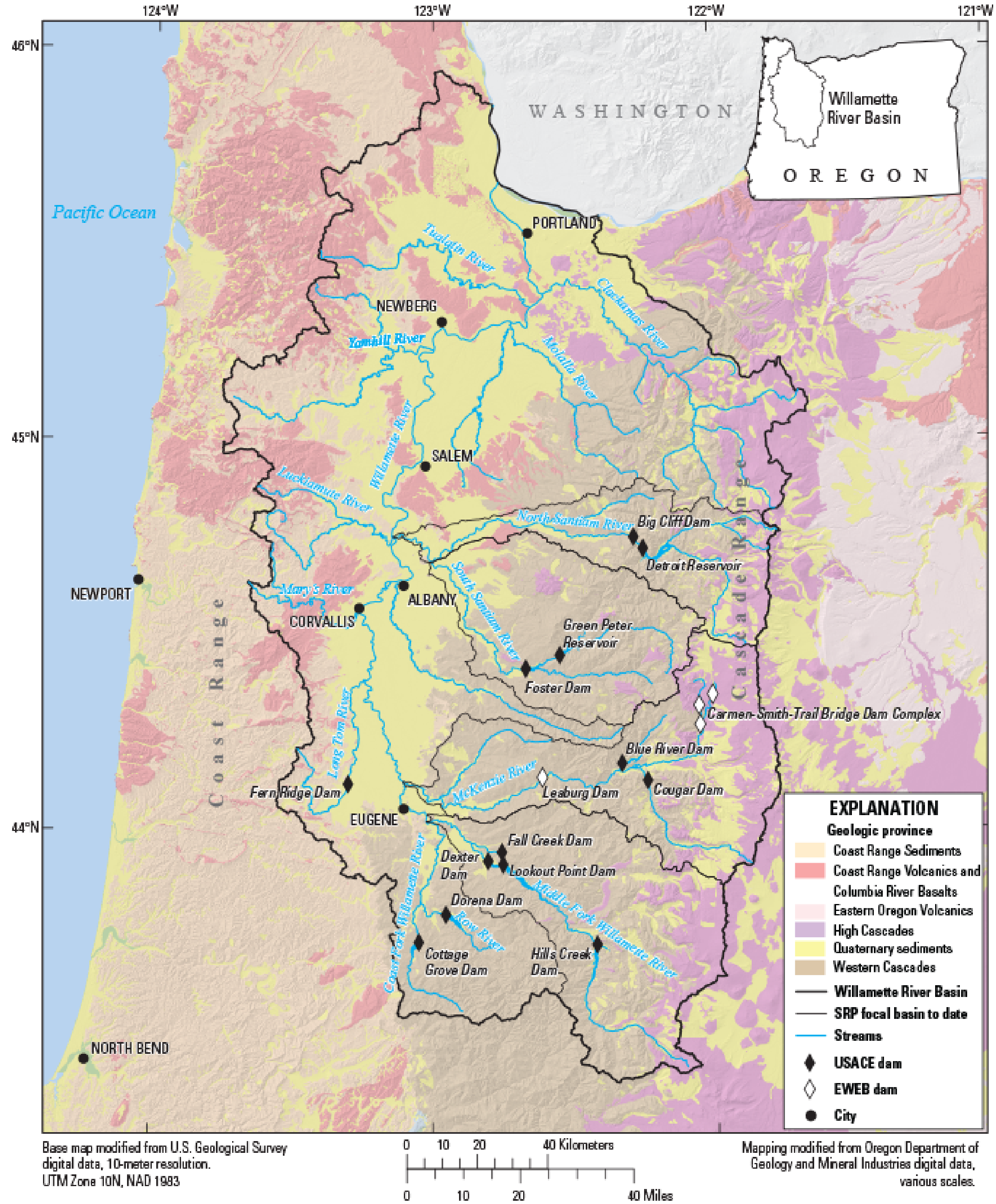


Figure 1. Map showing topography, geology, dams, major rivers, and focal basins of the Sustainable Rivers Project in the Willamette River Basin, western Oregon. [EWEB, Eugene Water and Electric Board; SRP, Sustainable Rivers Project; USACE, U.S. Corps of Engineers]

Table 1. Overview of characteristics of the Middle Fork Willamette and McKenzie River Basins, western Oregon.

[**Abbreviations:** km^2, square kilometers; mm/yr, millimeter per year]

Basin characteristic	Description
Drainage area	These adjacent basins flow westward to the main stem Willamette River. The Middle Fork Willamette River drains 3,530 km^2 before joining the Coast Fork Willamette River to form the main-stem Willamette River southeast of Eugene (fig. 1). Of similar size, the McKenzie River drains 3,450 km^2 before joining the main-stem Willamette River downstream northeast of Eugene (fig. 1).
Landcover	Both basins have about 90 percent forest cover, less than 0.5 percent urban land cover, and about 2 percent agricultural cover in the National Land Cover Database from 2011 (Jin and others, 2013).
Land use pattern	Urban and agricultural lands in both basins are primarily in the valley bottoms.
Geology	Both rivers drain the High Cascades and Western Cascades geologic provinces (Ma and others 2009; fig. 1). The Middle Fork Willamette and McKenzie Rivers are 20 and 30 percent in the High Cascades and 66 and 46 percent in the Western Cascades provinces, respectively, with the balance in the Quaternary sediments province.
Topography and channel form	The headwaters of the Middle Fork Willamette and McKenzie Rivers generally are underlain by porous Quaternary basalts of the low relief High Cascades (fig. 1). These rivers flow through the steep and highly dissected landscape of the Tertiary volcanic and volcaniclastic rocks of the Western Cascades. Here, streams are predominantly steep and confined by narrow canyon walls, and receive substantial inputs of coarse sediment from debris flows and landslides. Once the rivers exit the Western Cascades and enter the valley bottoms, stream gradient decreases and floodplains widen, resulting in ”wandering” rivers (Church, 2006) that alternate between single- and multi-thread segments.
Climate and hydrographs	The hydrographs of the Middle Fork Willamette and McKenzie River are shaped by cool and wet winters and warm and dry summers. In the winter, the Cascade Range receives as much as 2,600 mm of precipitation per year, which falls as rain and snow (Oregon State University, 2013). Peak flows are in winter, with major floods typically resulting from basin wide rain-on-snow events (Harr, 1981). Although precipitation is greatest along the Cascade Range crest, rainfall and snowmelt infiltrate through the young, porous volcanic rocks of the High Cascades, supporting steady year-round discharge at large spring complexes (Marshall, 1915; Stearns, 1928; Tague and Grant, 2004; Jefferson and others, 2006). Unlike the High Cascades, the older, less-permeable Western Cascades are steep and highly dissected, causing streamflow to be much more responsive to storm runoff.
Revetments	Banks on both rivers have been stabilized in places with revetments to protect infrastructure and agricultural fields from erosion and flooding.

Table 2. Dams and other flow regulation structures in the Middle Fork Willamette and McKenzie River Basins, western Oregon.

[Data from the U.S. Army Corps of Engineers and the Eugene Water and Electric Board. **Uses:** F, fisheries; FC, flood control; HP, hydropower; I, irrigation; N, navigation; QW, water quality; R, recreation. **Abbreviations:** NAVD 88, North American Vertical Datum of 1988; na, not applicable or available]

Basin	Dam name	River name	Year completed	Lake pool minimum (feet above NAVD 88)	Elevation maximum (feet above NAVD 88)	Upstream drainage areas (square mile)	Reservoir useable storage (acre-foot)	Reservoir surface area (hectares)	Uses	Maximum power output (kilowatt)
Middle Fork Willamette	Fall Creek	Fall Creek	1965	669	830	184	125,000	737	F, FC, I, N, QW, R	na
	Hills Creek	Middle Fork Willamette	1961	1,444	1,542	389	356,000	1,107	F, FC, HP, I, N, QW, R	30,000
	Lookout Point	Middle Fork Willamette	1953	821	930	991	453,000	1,765	F, FC, HP, I, N, QW, R	150,000
	Dexter	Middle Fork Willamette	1954	686	693	991	27,500	415	FC, HP, I, N, R	15,000
McKenzie	Carmen Diversion	McKenzie	1963	2,600	2,625	95	na	30	diversion for HP	na
	Smith River	Smith	1963	na	2,605	18	15,050	170	HP	108,000
	Trail Bridge	McKenzie	1963	na	2,092	184	2,100	73	re-regulation	10,000
	Cougar	South Fork McKenzie	1963	1,532	1,699	208	153,500	1,280	F, FC, HP, I, N, QW, R	25,000
	Blue River	Blue	1969	1,132	1,357	88	82,800	1,009	F, FC, I, N, QW, R	na
	Leaburg Dam and Canal	McKenzie	1930	na	na	1,020	na	na	diversion for HP	13,500
	Walterville Canal[1]	McKenzie	1910	na	na	1,080	na	na	diversion for HP	9,000

[1]Instead of a dam, chevrons (or rock weirs) are used to divert streamflow to the Walterville power canal.

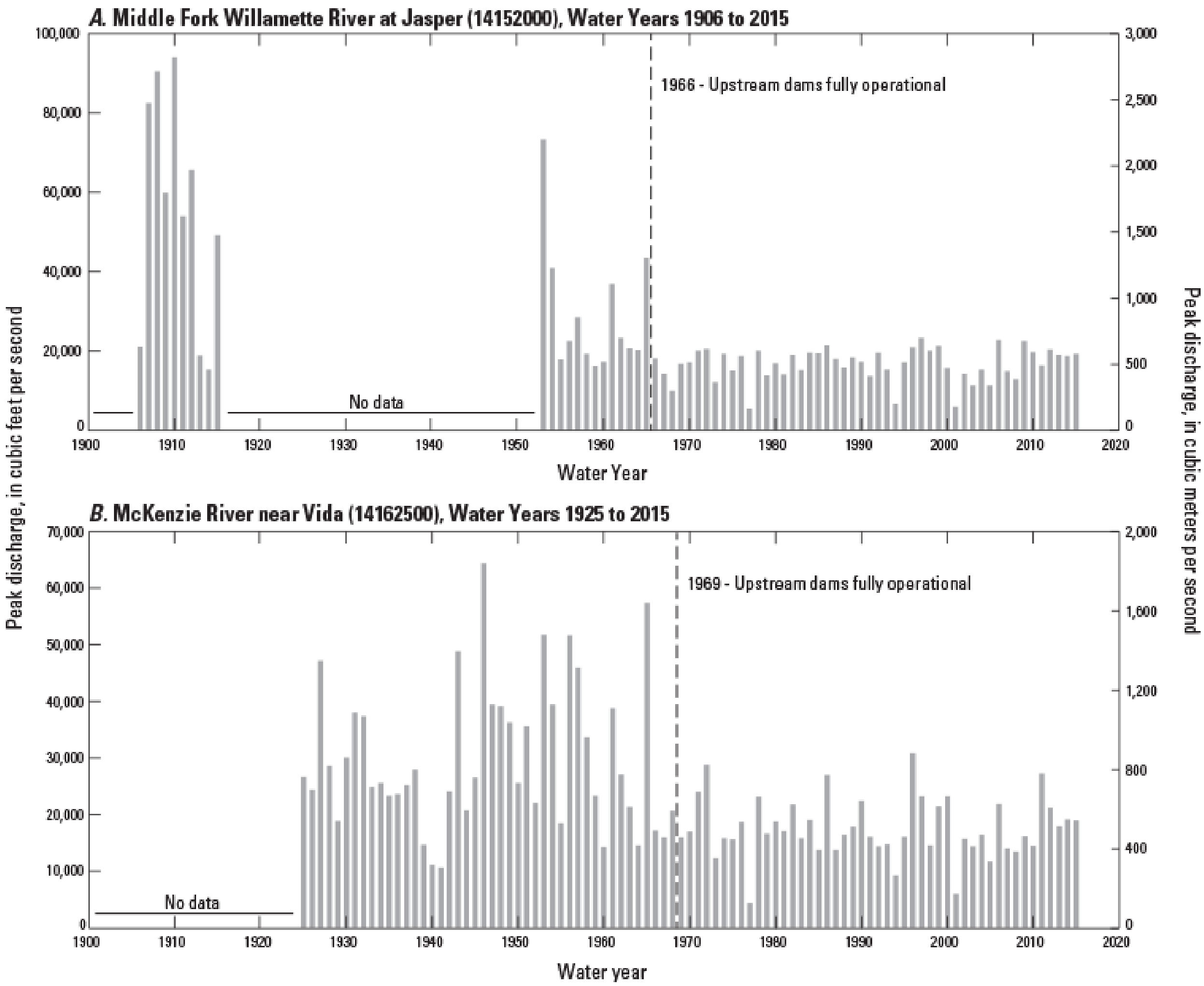


Figure 2. Graphs showing instantaneous peak streamflows for the (*A*) Middle Fork Willamette River at Jasper, Oregon (USGS streamgage 14152000), water years 1906–2015; and (*B*) McKenzie River near Vida, Oregon (USGS streamgage 14162500), water years 1925–2015.

On the McKenzie River, the EWEB Carmen-Smith-Trail Bridge Dam Complex in combination with USACE flood control Blue River and Cougar Dams on Blue and South Fork McKenzie Rivers, respectively, have decreased the frequency of large floods (greater than 10-year recurrence interval; Risley and others, 2010a). Downstream of the Cougar Dam on the South Fork McKenzie River, large floods have been eliminated and small floods (5–10 year recurrence interval) have decreased in frequency and magnitude (Risley and others, 2010a). Other flow alterations on the McKenzie River include decreases in the magnitude of high flows, increases in the magnitude of low flows, shifting of the lowest annual streamflow from September to March, decreases in monthly streamflows from February to May, and increases in monthly streamflows from July to November (Risley and others, 2010a). The USACE flood regulation goal for the USGS streamflow gage at Vida is 14,500 ft^3/s, which is lower than the SRP winter bankfull recommendation of 22,000 ft^3/s (National Marine Fisheries Service, 2008; Risley and others, 2010b). With the flood control reservoirs, USACE regulates streamflows at the Vida gaging station to be within the bankfull level to minimize flood damage; this regulation means that daily mean streamflows at the gaging station have exceeded the bankfull streamflow estimate of 20,000 ft^3/s (as determined using the USGS gaging station data and rating curves) in only 5 years during water years 1969–2008 (Risley and others, 2010a).

Dam operations and changes in the streamflow regimes of these rivers have resulted in substantial differences in channel forms and sediment regimes over time. The modern Middle Fork Willamette River has substantially less gravel bars and side channels than it did historically (Dykaar, 2005, 2008a, 2008b; Wallick and others, 2013) and a predominantly stable planform, owing to flood control, decreases in large wood and coarse sediment, and local bank stabilization (Wallick and others, 2013). O'Connor and others (2014) estimated that dams have decreased bed-material supply to the lower Middle Fork Willamette River by more than 90 percent (as estimated at the mouth of Middle Fork Willamette River). On the McKenzie River, decreases in the size of gravel bars and side channels have been reported downstream of Hayden Bridge from 1939 to 2005 (Risley and others, 2010a). Total trapping of coarse bed-material sediment by upstream dams on the McKenzie River is about 80 percent (as estimated at the mouth of the McKenzie River; O'Connor and others, 2014). These effects probably are greatest downstream of Leaburg Dam, and lessen downstream as unregulated tributaries, such as the Mohawk River, deliver bed material to the mainstem.

The cumulative effects of decreased peak flows and bed-material supply as well as increased channel stability dampen geomorphic processes, such as meander migration and channel avulsions, which historically created diverse aquatic and terrestrial habitats along these rivers. These types of geomorphic and habitat changes, in turn, influence the species that can thrive in and along these rivers. In particular, gallery forests of black cottonwood historically bordered these rivers. This iconic and native tree is one of the largest poplar species and "the tallest, fastest-growing hardwood in the western United States" (Niemiec and others, 1995). It starts flowering and producing seeds after 7 to 10 years, and can live for more than 100 years (Braatne and others, 1996). Black cottonwood offers nesting habitats for many birds, including bald eagles, woodpeckers, and owls (Steinberg, 2001), and helps to form habitat for fish and amphibians once it falls into rivers. Black cottonwood depends on specific flow regimes for its growth as well as dynamic channel processes that create freshly scoured sediments with open canopies where it can sprout from seeds (seedlings) or grow as clones from vegetative root and branch fragments (clones). Historically, different age classes of black cottonwood were found along these rivers because streamflow and geomorphic processes created the landforms and hydrologic conditions suitable for episodic recruitment events.

The environmental flow frameworks for the Middle Fork Willamette and McKenzie Rivers cited decreased recruitment of black cottonwood as concerns for both rivers (Gregory and others, 2007a, 2007b; Risley and others, 2010a, 2010b). Hypothesized limiting factors affecting black cottonwood along these modern river corridors include lack of gravel bars, rapid spring recession rates, inundation by high summer flows, competition with invasive species, and scouring by peak flows (table 3; Mahoney and Rood, 1998; Gregory and others, 2007a, 2007b; Risley and others, 2010a, 2010b). The overarching goal of this study is to characterize relations between streamflow, geomorphic processes, and black cottonwood recruitment on the Middle Fork Willamette and McKenzie Rivers. Results of this and future studies will help refine the limiting factors for black cottonwood so that the SRP can adaptively manage for flow regimes that create the habitats needed by black cottonwood in the Willamette River Basin.

Table 3. Five limiting factors possibly affecting black cottonwood (*Populus trichocarpa*) recruitment in the Willamette River Basin, western Oregon.

Limiting factor	Description of hypothesized impacts
Lack of gravel bars	The lack of gravel bars limits the number of sites where black cottonwood can germinate.
Rapid flow recession	Rapid flow recession rates in the spring dry out seedlings, leading to mortality.
High summer flows	High summer flows inundate and kill seedlings.
Invasive plants	Invasive plants out-compete black cottonwood seedlings.
Annual high flows	Annual high flows erode young seedlings and impede reach-scale recruitment.

Study Overview

The aim of this study is to address uncertainties in the Willamette SRP program related to streamflow, geomorphic processes, and black cottonwood so that the SRP has the information they need to manage for black cottonwood on the alluvial sections of the Middle Fork Willamette and McKenzie Rivers. The alluvial section of the Middle Fork Willamette River begins at the base of Dexter Dam (floodplain kilometer[4] [FPKM] 22; fig. 3; table 4) and extends to the confluence with the Coast Fork Willamette River. The McKenzie alluvial section begins near Deerhorn, Oregon (FPKM 35), about 12.6 FPKM downstream of the Leaburg Dam (fig. 4; table 4), and extends to the confluence with the Willamette River. The decreased peak flows at the U.S. Geological Survey (USGS) streamgages on the Middle Fork Willamette (14152000) and McKenzie Rivers (14163900) indicate the presence of upstream flood-risk management operations, although differences between years and river basins reflect operational decisions, inflows from unregulated tributaries, overall runoff patterns, and other factors (figs. 5 and 6). The Middle Fork Willamette and McKenzie River Basins are similar in size (3,530 and 3,450 km^2, respectively). The total unregulated area contributing to the rivers is 482 km^2 on the Middle Fork Willamette River between the mouth and Dexter Dam, and 803 km^2 on the McKenzie River between the mouth and Deerhorn, Oregon. These values indicate that the entire alluvial section of the McKenzie River has the potential to receive greater inputs of bed material and streamflow from unregulated tributaries than the entire alluvial section of the Middle Fork Willamette River.

[4]Locations along the alluvial sections are referenced to floodplain kilometers (FPKM; Wallick and others, 2013) because FPKM reference systems are stable over time, whereas river kilometer reference systems change when the length of a river increases or decreases. Numbering of the FPKM begins at the river mouths and continues up valley to the base of Dexter Dam on the Middle Fork Willamette River and town of Deerhorn on the McKenzie River.

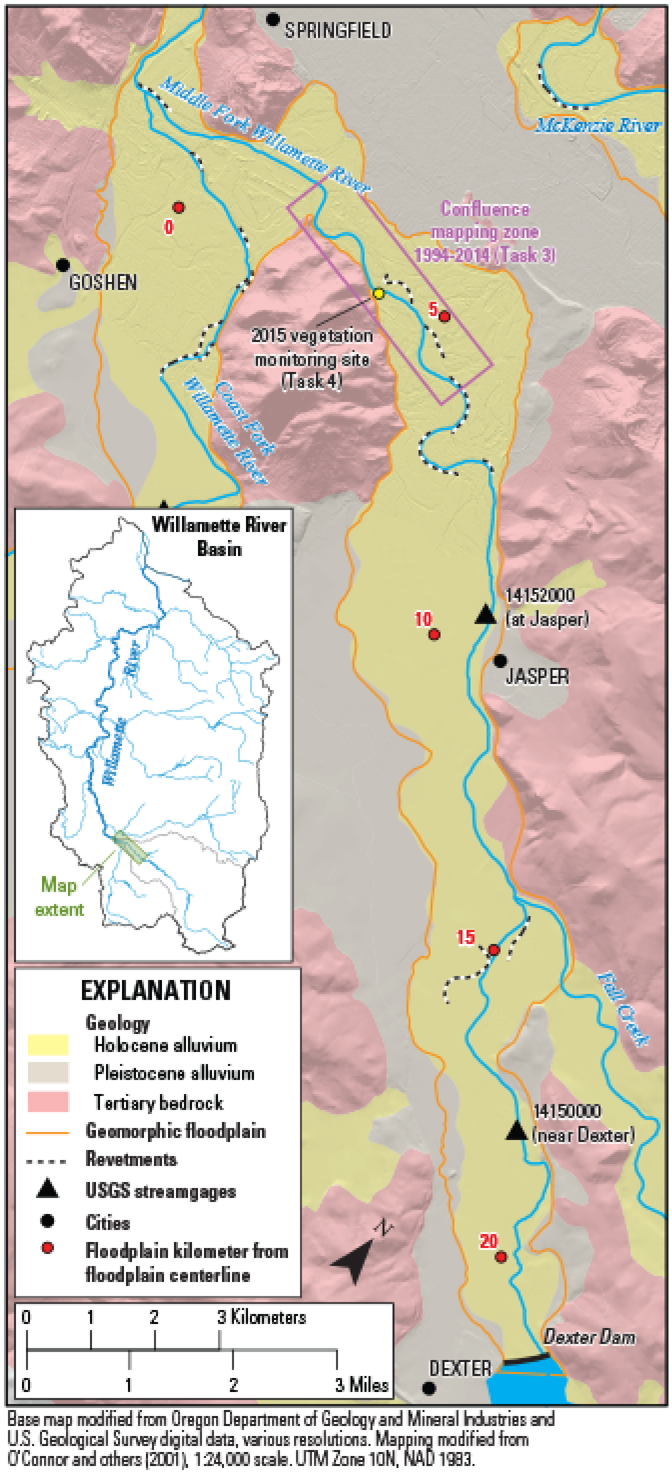


Figure 3. Schematic showing the alluvial section of the Middle Fork Willamette River, western Oregon. Geology simplified from O'Connor and others (2001).

Table 4. Features of the alluvial sections of the lower Middle Fork Willamette and McKenzie Rivers, western Oregon.

[**Abbreviations:** FPKM, floodplain kilometer; km, kilometer; km^2, square kilometer; m, meter; m/km, meter per kilometer]

Feature	Middle Fork Willamette River	McKenzie River
Alluvial section	FPKMs 0–22	FPKMs 0–35
Closest dam structure	Dexter at upper reach boundary	Leaburg (12.6 FPKM upstream of reach boundary)
Total basin drainage area (km^2)	3,530	3,450
Unregulated contributing area at downstream boundary of alluvial section (km^2)	482	803
Slope (percent)	0.22	0.19
Floodplain width (km)	1–2	0.1–3 (mostly 1.5)
Primary locations of bare gravel bars	FPKMs 0, 3–8, 13–17, and 20–21	FPKMs 0, 9, and 13.8–34
Multi-thread sections	FPKMs 15–17 and 20–22	FPKMs 14–34
Single-thread sections	FPKMs 0–14 and 18–19	FPKMs 0–13 and 35
Revetments	At confluence, FPKMs 3–9, and 14–16	At bends throughout alluvial section
Channel and bar trends	Reductions in gravel and side channels throughout alluvial section from 1939 to 1967	Reductions in gravel and side channels downstream of Hayden Bridge (FPKM 13.8) from 1939 to 2005

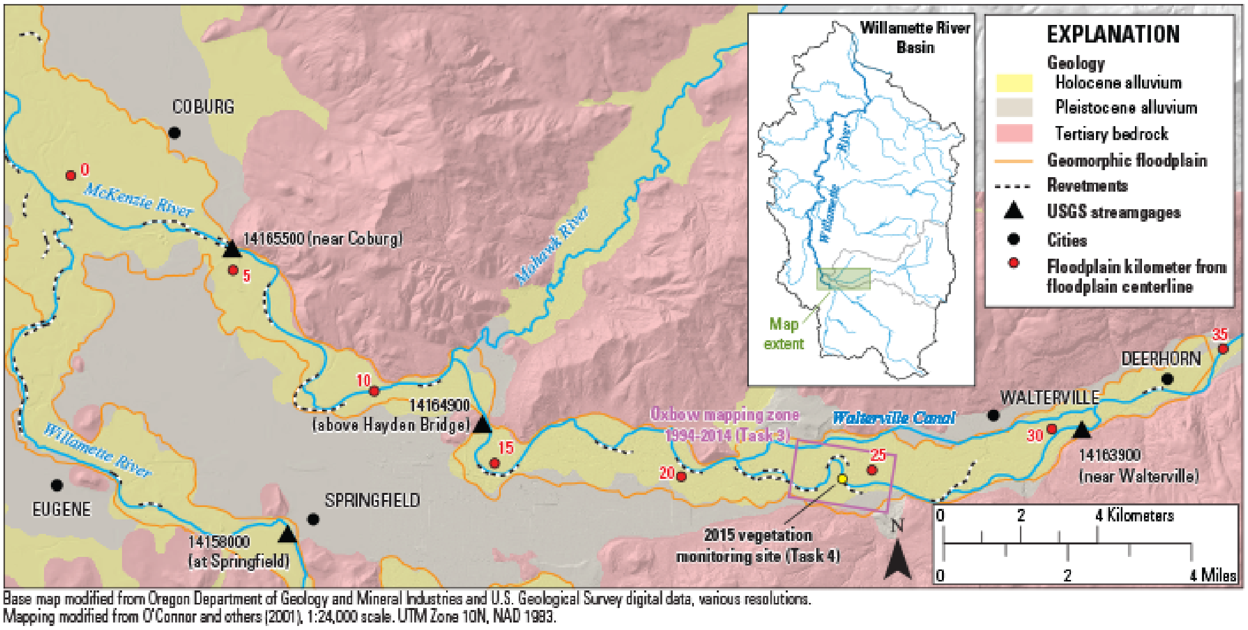


Figure 4. Schematic showing the alluvial section of the McKenzie River, western Oregon. Geology simplified from O'Connor and others (2001).

The alluvial sections of the Middle Fork Willamette and McKenzie Rivers have comparable slopes (0.22 and 0.19 percent, respectively) and floodplain widths (1–2 km on the Middle Fork Willamette River and 0.1–3 km on the McKenzie River; table 4). Bare gravel bars primarily are near FPKMs 0, 3–8, 13–17, and 20–21 on the Middle Fork Willamette River, and are near FPKMs 0, 9, and 13.8–34 on the McKenzie River. The length of multi-thread sections is shorter on the Middle Fork Willamette River (4 km) than on the McKenzie River (20 km). Likewise, revetments on the relatively straight, lower Middle Fork Willamette River are at the two multi-thread sections, whereas they are at the many bends throughout the meandering, lower McKenzie River. Sections with revetments historically were geomorphically dynamic, but now are relatively stable. Both rivers also have historically stable sections that flow against bedrock.

This study completed four analyses for different parts of these alluvial sections to relate aspects of streamflow, geomorphic processes, and black cottonwood. Those tasks were:

1. **A comparison of the hydrograph for WY 2015 with the hydrographs for WYs 2000–14 and SRP flow recommendations.** This analysis provides context for understanding the channel and vegetation mapping completed as part of Tasks 2–3 and the observations of black cottonwood made in summer 2015 for Task 4. Results also are helpful for evaluating current streamflows relative to the SRP flow recommendations and patterns of black cottonwood in the alluvial sections.
2. **An assessment of recent, system-wide changes in channel features and vegetation for the alluvial valley section of the Middle Fork Willamette River (2005–12).** Results of Task 2 help with understanding the character of the Middle Fork Willamette River from its mouth to Dexter Dam and its responses to bankfull events in 2005, 2011, and 2012. This assessment also identifies which types of recent flow events initiate channel avulsions and meander migration.

3. **An examination of changes in channel features and vegetation over two decades for two short mapping zones on the Middle Fork Willamette and McKenzie Rivers (1994–2014)**. This analysis examined changes in channel features and vegetation over a much longer time period than Task 2. It focused on one mapping zone on the Middle Fork Willamette River and one on the McKenzie River. These detailed snapshots help in examining how these geomorphically dynamic zones respond to flow events over a longer time period.
4. **A field investigation of the relations between summer stage and the growth of black cottonwood and other plants in summer 2015.** These site-specific observations of black cottonwood recruitment coincided with the exceptionally warm and dry summer of 2015. These results are helpful in examining the recruitment and vigor of black cottonwood and their potential interactions with invasive plants.

All tasks involve the use of high-resolution orthophotographs (or aerial photographs) to varying degrees. We used photographs collected in 1994, 2000, 2005, 2009, 2011, 2012, and 2014 by the USGS and U.S. Department of Agriculture (USDA) National Agriculture Inventory Program (NAIP; table 5). Individual photographs represent channel and vegetation conditions before and after different magnitudes and durations of peak flow events (figs. 5–7; table 6). For instance, photographs from 1994 capture the rivers during a period with low-magnitude peak flows (WYs 1990–94). The photographs from 2000 then capture the rivers after several bankfull events on both rivers (including nearly 45 days of bankfull flow over a 60-day period from November 1998 through January 1999 on the Middle Fork Willamette River) and three brief (1 day or less) events meeting the winter high-flow recommendation on the McKenzie River in WY 1996. Areas that did not have geomorphic changes in this time period may indicate that landforms are essentially stable in the present-day streamflow regime, owing to flow regulation and channel stability imposed by revetments or natural but non-erodible geologic features. The photographs from 2000 and 2005 capture how the river corridors changed during a period of dry conditions and relatively low peak flows. Vegetation encroachment in many streams in western Oregon has been observed for this period (Wallick and others, 2010, 2011; Jones and others, 2011, 2012a, 2012b, 2012c). Photograph pairs since 2005 are useful for evaluating geomorphic changes associated with more recent winter bankfull events.

Table 5. Aerial photographs and other digital mapping datasets reviewed in this study.

[**Dataset type:** lidar, light detection and ranging. **Year:** na, not applicable because mapping does not indicate specific year. **Source:** DOQ, Digital Orthophoto Quadrangle; NAIP, National Agriculture Inventory Program; DOGAMI, Department of Geology and Mineral Industries]

Dataset type	Year	Source	Scale
Orthophotograph	1994	DOQ	1 pixel = 1 meter
Orthophotograph	2000	DOQ	1 pixel = 1 meter
Orthophotograph	2005	NAIP	1 pixel = 1 meter
Orthophotograph	2009	NAIP	1 pixel = 1 meter
Orthophotograph	2011	NAIP	1 pixel = 1 meter
Orthophotograph	2012	NAIP	1 pixel = 1 meter
Orthophotograph	2014	NAIP	1 pixel = 1 meter
lidar	2008	DOGAMI	1 pixel = 1 meter
lidar	2011	DOGAMI	1 pixel = 1 meter
Fall Creek lidar	2012	DOGAMI	1 pixel = 1 meter
Geologic map	na	O'Connor and others (2001)	Mapped at 1:24,000
Geologic map	2009	Ma and others (2009)	Mapped at 1:12,000 to 1:500,000
Channel map	2005	McDowell and Dietrich (2012)	Mapped at 1:500 to 1:1,500
Channel map	2011	McDowell and Dietrich (2012)	Mapped at 1: 500 to 1:1,500
Geomorphic floodplain	na	McDowell and Dietrich (2012)	Mapped at 1:500 to 1:1,500
Geomorphic floodplain	na	Wallick and others (2013)	Mapped at 1:10,000

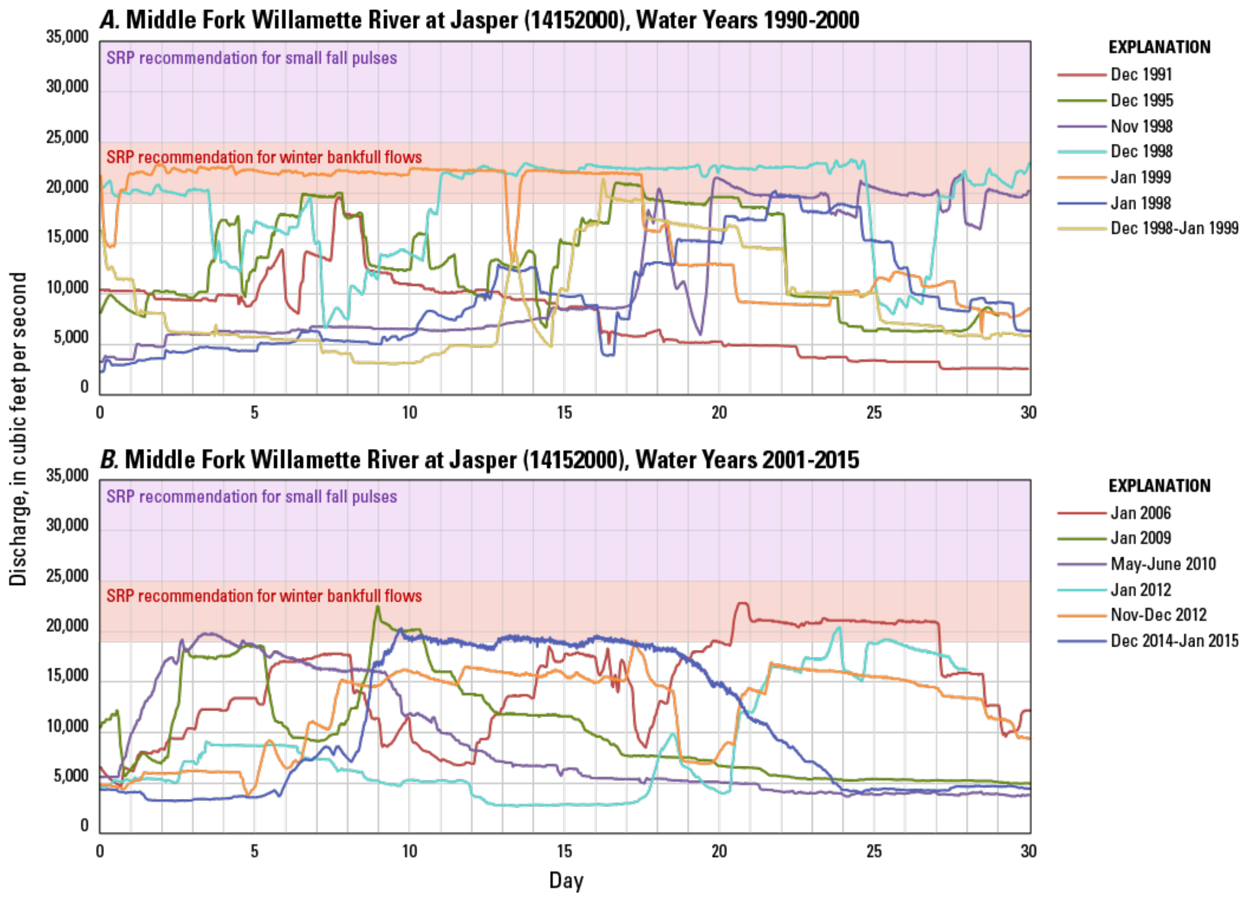


Figure 5. Graphs showing duration of flow events that exceeded bankfull discharge on the Middle Fork Willamette River at Jasper, Oregon (USGS streamgage 141520000), for (*A*) water years 1990–2000, and (*B*) 2001–15. Sustainable Rivers Project (SRP) flow recommendations are from Gregory and others (2007b).

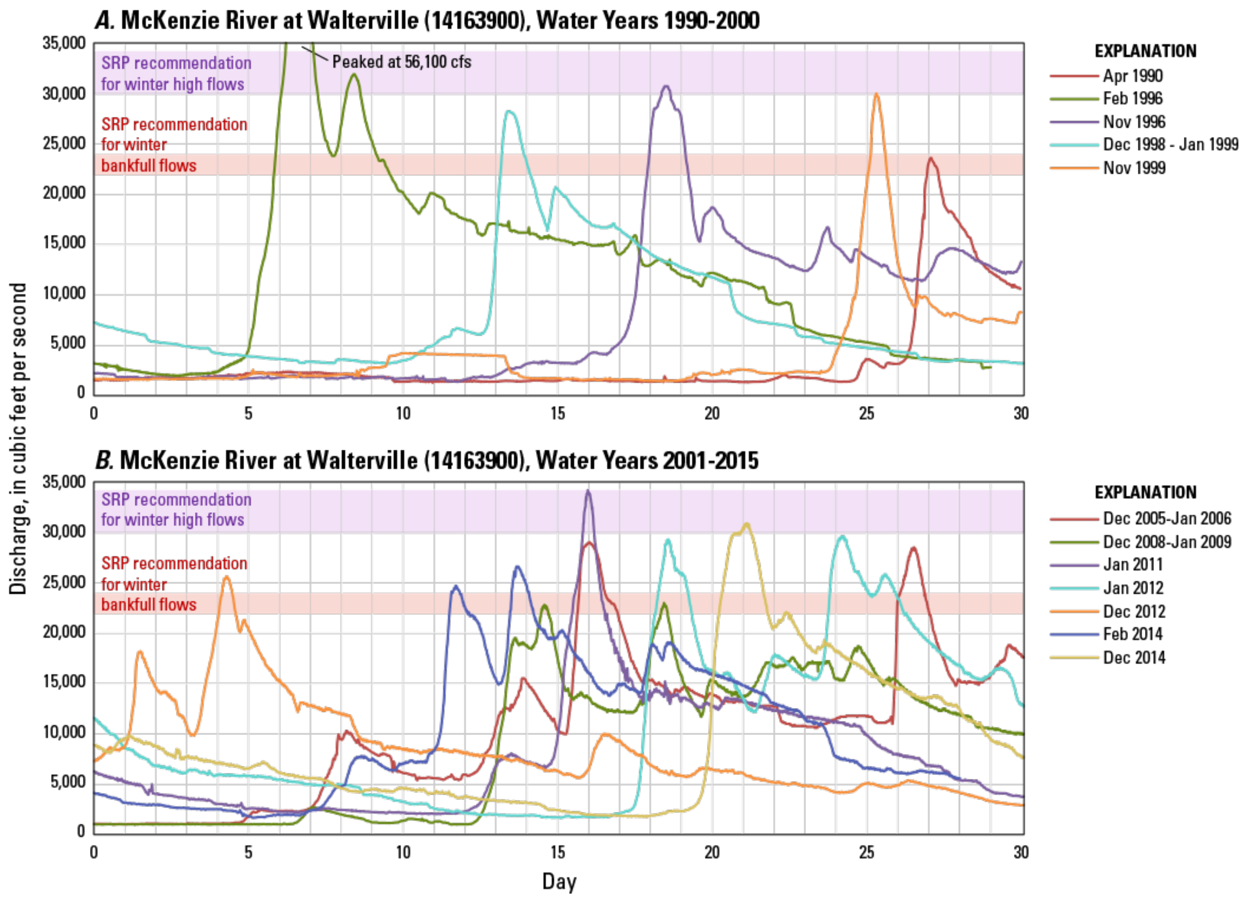


Figure 6. Graphs showing duration of flow events that exceeded bankfull discharge on the McKenzie River near Walterville, Oregon (USGS streamgage14163900), for (*A*) water years 1990–2000, and (*B*) 2001–15. Sustainable Rivers Project (SRP) flow recommendations are from Risley and others (2010b).

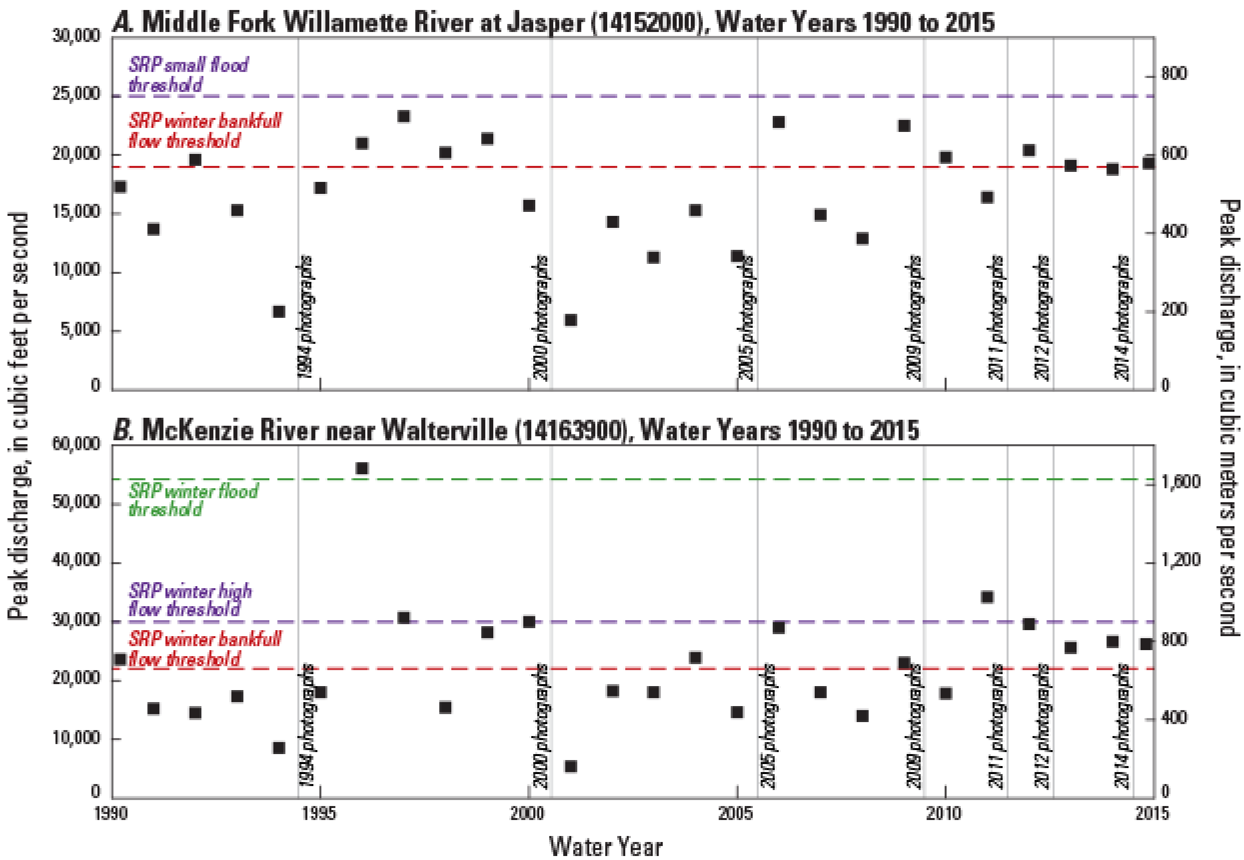


Figure 7. Graphs showing annual peak discharges and aerial photograph collections for water years 1990–15 on the (*A*) Middle Fork Willamette River at Jasper, Oregon (USGS streamgage 14152000), and (*B*) McKenzie River near Walterville (USGS streamgage 14163900). Fall flood and winter bankfull recommendations are from the Sustainable Rivers Project (SRP; Gregory and others, 2007b, Risley and others, 2010b). McKenzie River recommendations are for the canal reaches (Risley and others, 2010b).

Table 6. Description of annual peak flow conditions in time periods bounded by photograph pairs on the lower Middle Fork Willamette and McKenzie River Basins, western Oregon, water years 1990–2015.

[**Abbreviations:** WY, water year; ft^3/s, cubic foot per second]

Photograph pairs		Annual peak flow conditions bracketed by the photograph pair	Description
1994	2000	Floods of 1996–1997	Transition from a period with low peak flows (WYs 1990–94) to a period with several winter bankfull events[1] (including nearly 45 days of bankfull flow over a 60-day period in WY 1999 on the Middle Fork Willamette River) on both rivers and three brief (1 day or less), winter high flows[2] on the McKenzie River in WY 1996. Areas that did not have geomorphic changes in this time period may indicate landforms that are essentially stable in the present-day, regulated flow regime.
2000	2005	Period of peak flows with relatively low magnitudes	Period of relatively low peak flows and vegetation encroachment in many streams throughout western Oregon.
2005	2009	High flows of 2006–and 2009	Two winter bankfull events on the Middle Fork Willamette River (1.5 and 6.5 days long with peaks of 22,500 and 22,800 ft^3/s, respectively) and four winter bankfull events on the McKenzie River (each less than 1.5 days and peaks less than 29,000 ft^3/s) may have triggered local geomorphic changes such as erosion of sparsely vegetated surfaces and increases in bare gravel bars.
2009	2011	High flows of 2010 and 2011	Winter bankfull events on the Middle Fork Willamette River in WY 2010 (1 day with a peak of 19,800 ft^3/s) and McKenzie River in WY 2011 (1.5 days with a peak of 34,000 ft^3/s).
2011	2012	A single high-flow event in 2012	Winter bankfull event on the Middle Fork Willamette (1.5 days total over a 2.5-day period peaking at 20,400 ft^3/s) and McKenzie Rivers (2.5 days peaking at 29,600 ft^3/s) in January 2012; McKenzie River event almost exceeded the winter high-flow threshold.
2012	2014	High flows of 2012 and 2013	One winter bankfull (several hours peaking at 19,100 ft^3/s) and one near winter bankfull event (peak of 18,800 ft^3/s) on the Middle Fork Willamette River and two winter bankfull events (0.5 and 1.5 days peaking at 25,600 and 26,600 ft^3/s, respectively) on the McKenzie River.

[1]Winter bankfull flow recommendations from the Sustainable Rivers Project are 19,000 ft^3/s on the lower Middle Fork Willamette River (Gregory and others, 2007b) and 22,000 ft^3/s for the canal reaches of the McKenzie River (Risley and others, 2010b).

[2]The small flood recommendation from the Sustainable Rivers Project is 25,000 ft^3/s on the lower Middle Fork Willamette River (Gregory and others, 2007b). The McKenzie River has a comparable recommendation for winter high flows (30,000 ft^3/s) in its canal reaches (Risley and others 2010b).

Analysis Tasks

Task 1—Compare Hydrograph for Water Year 2015 with Hydrographs for Water Years 2000–14 and the SRP Flow Recommendations

The objective of Task 1 was to compare the observed streamflow conditions for WY 2015 with conditions for WYs 2000–14 and the SRP flow recommendations. Results of this task provide context for understanding the channel and vegetation mapping completed as part of Tasks 2–3 and the observations of black cottonwood made in summer 2015 for Task 4. Results also are helpful for evaluating current streamflows relative to the SRP flow recommendations and patterns of black cottonwood in the alluvial sections.

Methods

For this task, we compiled daily mean discharge data from the USGS streamgages on the Middle Fork Willamette River at Jasper (14152000; period of record 1905-2015) and McKenzie River near Walterville (14163900; period of record 1989-2015). Analyses focused on WYs 2000–15 because these years indicate recent flow management in accordance with the Willamette Biological Assessment (U.S. Army Corps of Engineers, 2000) and Biological Opinion (National Marine Fisheries Service, 2008). Observed streamflows were compared with the river-specific SRP flow recommendations (table 7). The SRP flow recommendations for the Middle Fork Willamette and McKenzie Rivers differ, owing to workshop perspectives, congressional authorizations for flood risk reduction and other uses, and streamflow conditions (Gregory and others, 2007b; Risley and others, 2010b). Initial SRP flow implementation started on the Middle Fork Willamette and McKenzie Rivers in 2015.

Results

Flow Conditions for Water Year 2015

In October to mid-November, the Middle Fork Willamette River was near its magnitude for the small fall pulses recommendation (fig. 8; table 7). During this period, the McKenzie River had flows that generally were less than its fall flows recommendation except for during three flow events in November (fig. 9). Both rivers, then, had flow events in late December 2014 that exceeded their SRP winter bankfull recommendations. The bankfull event on the Middle Fork Willamette River surpassed the SRP bankfull recommendation of 19,000 ft^3/s for four days during the seven day high-flow period from December 25 to 31, 2014. The bankfull event on the McKenzie River lasted two days, and peaked at 26,200 ft^3/s on December 22, 2014.

Table 7. Environmental flow recommendations from the Sustainable Rivers Project (SRP) for the Middle Fork Willamette and McKenzie Rivers, western Oregon.

[Flow recommendations are from Gregory and others (2007b) and Risley and others (2010b). Initial SRP flow implementation started in 2015 on Middle Fork Willamette and McKenzie Rivers. **Magnitude range**: ft^3/s, cubic foot per second. **Symbols:** <, less than; > greater than; –, unspecified]

River	Name of flow recommendation from workshop summaries	Short name of flow recommendation	Timing	Magnitude range (ft3/s)	Duration	Events per year	Frequency	Intended flow benefits identified at workshops	Magnitude achieved	
									WY 2000–14	WY 2015
Middle Fork Willamette	Small fall pulses	–	October 1–November 15	1,500–3,000	<5 days based on unregulated record	1–4 based on precipitation events	–	Avoid flushing of warm water from reservoir; assist with fish migrations; prevent stranding and redd dewatering/scouring	Achieved or exceeded all years	Achieved or exceeded, but no pulses
	Winter bankfull flow pulses	Winter bankfull flow	November 15–March 15	19,000–25,000	Mimic duration of unregulated events	1–5 based on precipitation events	–	Assist with fish migration; create lateral, aquatic, and floodplain habitats; transport sediment; prevent stranding	2006, 2009, 2012	Achieved minimum threshold for 4 days
	Small floods above bankfull flow	Small flood	November 15–March 15	25,000–40,000	–	–	–	Transport sediment; create floodplain surfaces and sites for black cottonwood regeneration	None	None
	Large winter floods	–	November 15–March 15	40,000–80,000	–	–	–	Create floodplain surfaces; trigger channel avulsions; create sites for black cottonwood regeneration	None	None
	Spring flow pulses	–	March 1–July 1	4,000–15,000	Mimic duration of unregulated events	1–5 based on precipitation events	–	Assist with fish migrations; prevent fish stranding; create lateral habitats; disperse seeds and establish cottonwood seedlings	Achieved or exceeded all years	First time in 15 years to not achieve minimum threshold
	–	Spring bankfull flow	March 15–May 15[a]	[1]19,000–25,000	–	–	–	–	None	None
	Spring-to-summer transition flow	–	March 1–July 1	5,000 down to 1,500	–	–	–	Disperse seeds and establish cottonwood seedlings; prevent stranding	2003?, 2012?, 2014?[2]	None

River	Name of flow recommendation from workshop summaries	Short name of flow recommendation	Timing	Magnitude range (ft3/s)	Duration	Events per year	Frequency	Intended flow benefits identified at workshops	Magnitude achieved	
									WY 2000–14	WY 2015
	Summer baseflow	—	June 1–October 1	1,000–2,000	—	—	—	Protect habitats for many species including riparian plant seedling nesting shorebirds that may be inundated	2001 (all other years exceed maximum threshold)	Achieved
McKenzie	Fall flows to protect Chinook redds and benefit fish outmigration	Fall flows	October 15–November 30	6,000–20,000	<5 days	2 to 3	Annually for smaller, every 3 years for larger	Assist with fish migrations; prevent stranding and redd dewatering/scouring	2006, 2007, 2009, 2013	Achieved for 2 days in mid-November
	Winter bankfull flow for gravel movement	Winter bankfull flow	December 15–March 31	22,000–24,000	<5 days	1	Once every year	Transport sediment to move gravel and flush out fine sediment	2006, 2011, 2012	Achieved for 2 days
	Winter high flow for reconnecting off-channel habitat	Winter high flow	December 15 – February 28	30,000–34,000	<5 days	1	Once every 5 years	Transport sediment; reconnect off-channel habitats; create new lateral habitats	None	None
	Winter flood for channel/floodplain habitat enhancement	Winter flood	December 15–February 28	>54,000	Based on upstream inflow conditions	1	Once every 10 years	Create and enhance channel and floodplain habitats; recruit large wood; trigger bank erosion and sediment transport	None	None
	Small spring flows for fish outmigration and riparian vegetation enhancement	Small spring flows	March 1–May 15	10,000–12,000	<5 days	1 to 2	Annually	Assist with fish migrations; create lateral habitats; create sites for black cottonwood regeneration	2002, 2003, 2011, 2012, 2014	None
	Spring bankfull flow for flushing and scouring	Spring bankfull flow	April 1–May 15	22,000–24,000	<5 days	1	Once every 3 years	Assist with fish migrations; transport sediment; create lateral and aquatic habitats; flush fine sediment; disperse seeds and establish black cottonwood seedlings	None	None
	Summer low flow for vegetation development and fish rearing	Summer low flow	July 1–September 30	>1,500	—	—	—	Protect habitats for black cottonwood and alders and spring Chinook rearing	2002, 2010, 2011 (all other years below minimum threshold)	None; below minimum threshold

[1]Middle Fork spring bankfull not specified in report; magnitude mimics winter bankfull, timing derived from end of winter floods to end of McKenzie spring bankfull.

[2]Transition rates appear appropriate, but further review and specifications needed to determine if achieved.

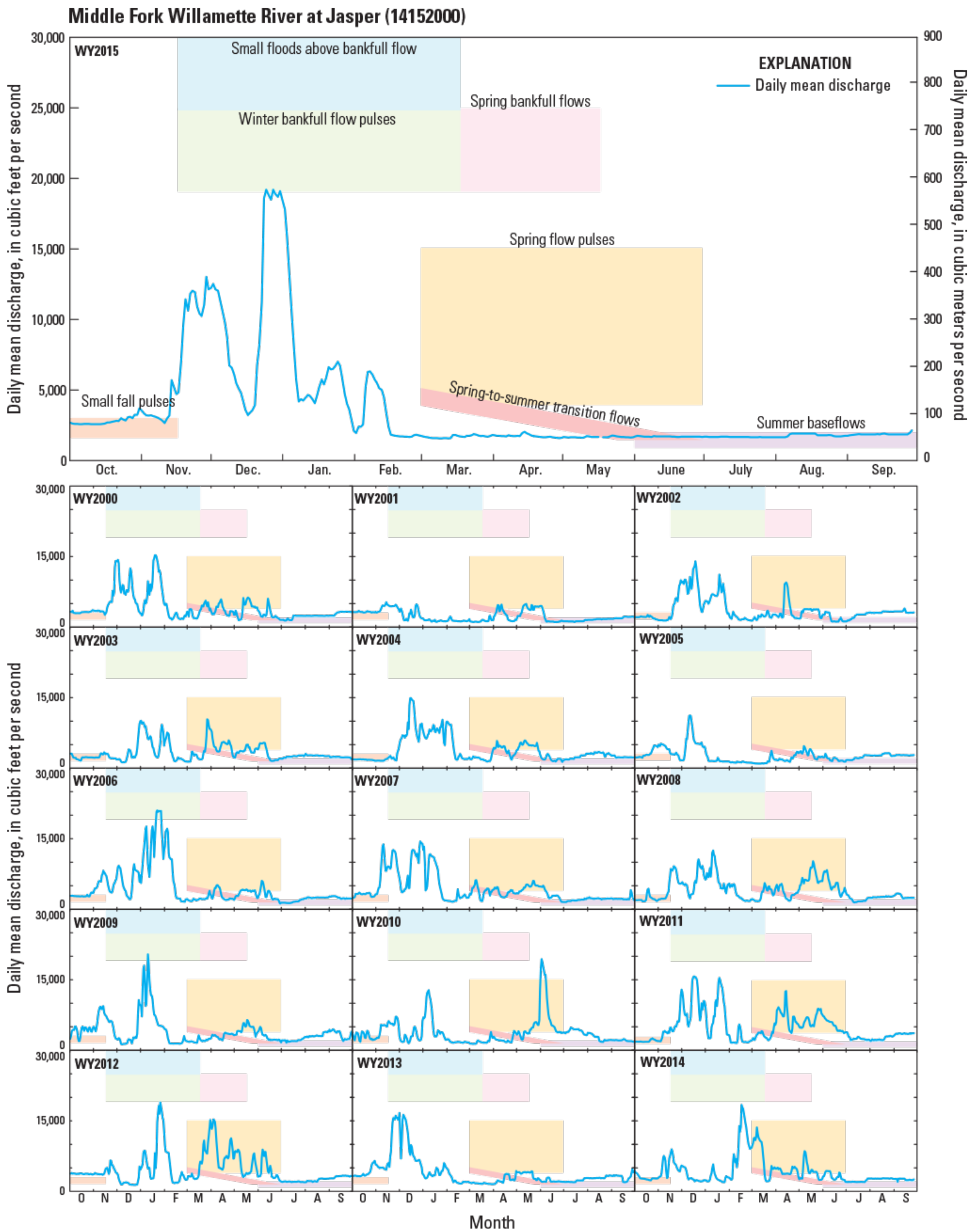


Figure 8. Hydrographs showing daily mean discharge on the Middle Fork Willamette River at Jasper, Oregon (USGS streamgage 14152000), water years 2000–15. Flow recommendations are from the Sustainable Rivers Project (SRP; Gregory and others, 2007b).

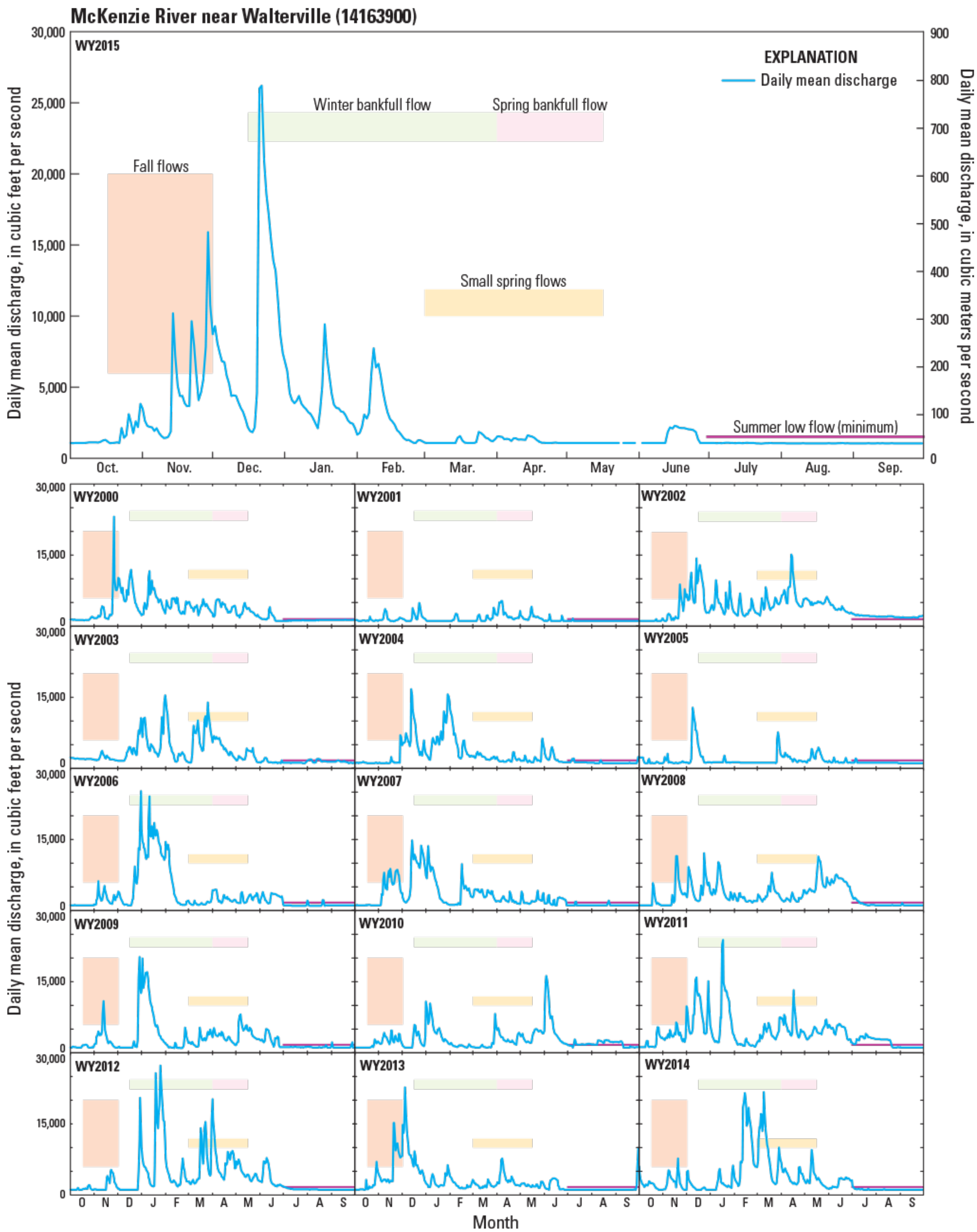


Figure 9. Hydrographs showing daily mean discharge on the McKenzie River near Walterville, Oregon (USGS streamgage 14163900). Flow recommendations are from the Sustainable Rivers Project (SRP) for the canal reaches (Risley and others, 2010b).

In calendar year 2015, the state of Oregon had its warmest year to date (National Oceanic and Atmospheric Administration, 2016). These warm and dry conditions, in addition to near-record and record low snowpack at higher elevations (Natural Resources Conservation Service, 2015), influenced streamflow conditions. Summer-like flow conditions started in late February on both rivers (figs. 8 and 9). These low-flow conditions were sustained throughout the summer. The lack of spring flow events made determining spring–to-summer transition rates unfeasible for WY 2015. The highest spring and summer flow on the Middle Fork Willamette River was 2,060 ft^3/s in mid-April, well below the 4,000 ft^3/s minimum SRP recommendation for spring flow pulses (table 7). This makes WY 2015 the only year between 2000 and 2015 that the minimum SRP recommendation for spring flow pulses was not met on the Middle Fork Willamette River. The SRP recommendation for summer baseflow was met from June through September as flows stayed below 2,000 ft^3/s. The increase in summer baseflow in early August is associated with water releases from the Lookout Point Reservoir. The McKenzie River also had a lack of small spring flows in WY 2015. The highest spring and summer flows on the McKenzie River were in June, when discharge increased to 2,000–2,250 ft^3/s for nearly 2 weeks, when EWEB closed the Walterville Power Canal for maintenance. After the canal reopened, flow on the McKenzie River remained at 1,050 ft^3/s, well below the minimum SRP recommendation for summer low flows (1,500 ft^3/s) reached most summers from 2000 to 2014.

Flow Conditions for Water Years 2000–15 Relative to the SRP Flow Recommendations

Flows for WYs 2000–15 were compared with the SRP flow recommendations for the Middle Fork Willamette and McKenzie Rivers to provide context for how often flows met SRP flow recommendations prior to environmental flow implementation in 2015. For context, the magnitudes for bankfull events as well as small and large flood events were met more frequently prior to flow regulation on both rivers (fig. 2) (Gregory and others, 2007a; Risley and others, 2010a). The duration of higher magnitude flood events also was greater prior to regulation on the Middle Fork Willamette River (Gregory and others, 2007a). Similar analyses are not available for the McKenzie River.

Hydrograph analyses for the Middle Fork Willamette River (fig. 8; table 7) show that the recommendation for small fall pulses developed to assist with fish migrations, prevent fish stranding, and the scouring and dewatering of redds was met in terms of magnitude each year for WYs 2000–15. Spring flow pulses were achieved or exceeded in all years, except in WY 2015. The intent of this flow recommendation is to assist with fish migrations, prevent fish stranding, create lateral habitats, and help with the dispersal and regeneration of black cottonwood. Three other recommendations were met less frequently. The winter bankfull flow pulses recommendation was exceeded in magnitude four times in the last 15 years. WYs 2006 and 2015 were the only water years that exceeded the winter bankfull flow pulses recommendation (19,000 ft^3/s) for more than a couple days on the Middle Fork Willamette. Flows in WYs 2009 and 2012 exceeded the recommendation with peaks of 22,500 and 20,400 ft^3/s and durations of 1.5 and 0.5 days, respectively. The spring-to-summer transition recommendation may have been met in WYs 2003, 2012, and 2013, but warrants further investigation because this flow recession component is important for black cottonwood recruitment and providing habitat for other flora and fauna. Finally, the summer baseflow recommendation was met in WYs 2001 and 2015 as a result of prolonged summer-like flow conditions, starting in June in WY 2001 and February in WY 2015. Summer low flows in other years typically exceeded the SRP recommendation. Flows did not meet recommendations for small and large floods and spring bankfull flows during WYs 2000–

15 because climate conditions did not produce these types of big floods during this period. The recommendation for large winter floods (40,000–80,000 ft^3/s) is not shown in fig. 8 because flows were substantially less than this magnitude during the analysis period.

Hydrograph analyses for the McKenzie River (fig. 9; table 7) show that four flow recommendations were met in some years. The fall flows recommendation, intended to help with fish migrations and redd protection, was met five times in the last 15 years, including WYs 2006, 2007, 2009, 2013, and 2015. Fall flows reached 8,760 ft^3/s for 8 days in WY 2007, 10,900 ft^3/s for 3 days in WY 2009, and 10,200 ft^3/s for 2 days in WY 2015. Peaks were smaller, reaching 6,200 for 1 day in WY 2006 and 6,990 ft^3/s for 1 day in WY 2013. The winter bankfull recommendation was met in 4 years (WYs 2006, 2011, 2012, and 2015). The highest event was the January 2012, one that lasted for 4 days over an 8-day period and peaked at 27,300 ft^3/s. WY 2015 had a bankfull event that reached 26,200 ft^3/s, making it the second highest peak during this period. The spring pulse recommendation was met in five water years (2002, 2003, 2011, 2012, and 2014). This spring pulse was proposed to help assist with fish migrations, and the creation of lateral habitats and sites for black cottonwood regeneration. Finally, the summer low-flow recommendation, intended to help protect habitats for black cottonwood, alders (*Alnus* spp.), and spring Chinook salmon (*Oncorhynchus tshawytscha*) rearing, was met in 2002, 2010, and 2011. Flows did not meet the recommendations for winter high flows, winter floods, and spring bankfull flows during WYs 2000–15. Because flows never approach the recommendations for winter high flows (30,000–34,000 ft^3/s; table 7) and winter floods (>54,000 ft^3/s), those recommendations are not shown on fig. 9.

Discussion

WY 2015 was different from WYs 2000–14 because streamflow exceeded the SRP winter bankfull flow recommendations on both rivers and then dropped to summer flow conditions in February, resulting in no spring bankfull or pulse events (figs. 8 and 9; table 7). WY 2015 is the only year when the spring flow pulse recommendation was not met on the Middle Fork Willamette River.

The recruitment of black cottonwood is shaped partly by these flow conditions. Field observations suggest that the winter bankfull flows likely scoured vegetation as well as deposited new landforms at the vegetation monitoring sites, burying older vegetation (Task 4). In particular, sediment deposition substantially increased the overall downstream area of the Confluence mapping zone on the Middle Fork Willamette River where we monitored vegetation in summer 2015 (fig. 3). The channel flanking bars then were exposed during the prolonged low-flow conditions, providing sites for the germination and recruitment of black cottonwood, in some cases down to the edge of the low-flow channel. Given the lack of spring flows and recession in WY 2015, black cottonwood seedlings and clones from vegetative fragments (clones) probably established in locations with sufficient access to the water table early in the summer and thus were less sensitive to drawdown rates than cohorts in other years. The WY 2015 cohort, however, likely will be vulnerable to scour by winter flow events, owing to their proximity to the low-flow channel because spring flows were exceptionally low in spring 2015. In contrast, other years with relatively low flows, such as WYs 2001–05, lacked bankfull flow events on both rivers, limiting the scour of vegetation and the area of bare surfaces where new vegetation could establish.

Preliminary analysis suggests that spring-to-summer transition rates were within the SRP recommendations for the Middle Fork Willamette River in 2003, 2012, and 2014. The rate of river drawdown during the spring-to-summer transition is critical for seed dispersal and vegetation seedling recruitment (Gregory and others, 2007a). Seedlings of other *Populus* species have the greatest survival and root elongation when recession is 0–2 cm/d and 1 cm/d, respectively (Mahoney and Rood, 1991). When recession rates exceed the rate of root growth by black cottonwood seedlings, the seedlings lose access to their primary water source during summer. More detailed analyses are warranted to examine recession rates on these rivers as well as root elongation rates of black cottonwood. We suspect that the sensitivity of new cottonwood cohorts to spring recession rates probably is more pronounced in other years than it was WY 2015, owing to the prolonged low flows and black cottonwood growth in locations with sufficient access to the water table.

Hydrographs in figs. 8 and 9 show that some SRP flow recommendation were met less frequently than other recommendations during WYs 2000–15 (table 7). Flows generally met the recommendations for small fall and spring flow pulses on the Middle Fork Willamette River. Flows on the Middle Fork met the recommendations for winter small floods, spring-to-summer transition, and summer baseflow for 5 or less years. Flows on the McKenzie River met the winter bankfull, winter high flow, spring pulse flow, and summer low-flow recommendations for 5 or less years. Flows on both rivers did not meet the recommendations for winter flows exceeding bankfull and spring bankfull events.

Task 2—Assess Short-Term, System-Wide Changes in Channel Features and Vegetation for the Alluvial Valley Section of the Middle Fork Willamette River (2005–12)

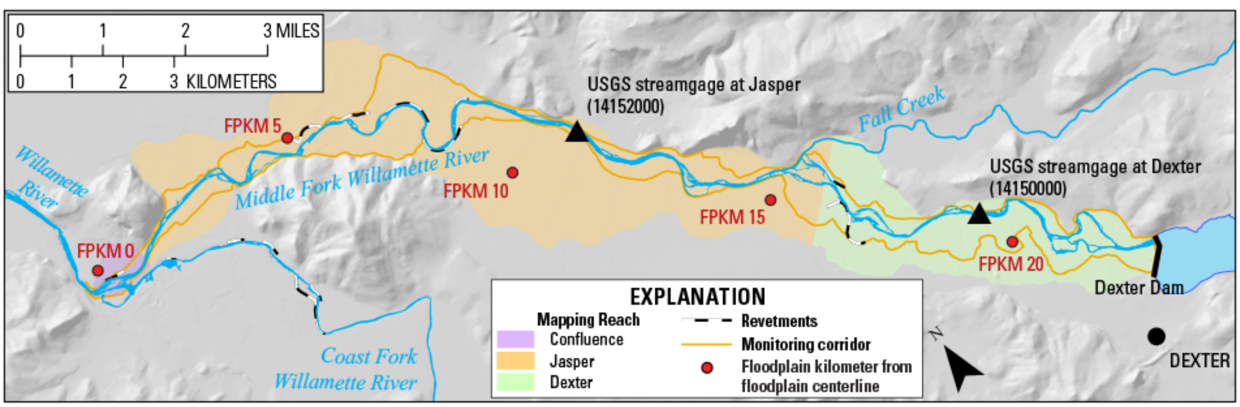
The objective of Task 2 was to summarize recent changes in active channel features and vegetation throughout the entire alluvial section on the Middle Fork Willamette River from 2005 to 2012. Assessing these changes is helpful for determining which types of flood events shape channel morphology and vegetation, specifically black cottonwood, along the modern Middle Fork. Specific elements for this task include the following:

1. Map active channel landforms from orthophotographs taken in 2012, and differentiate bar landforms by vegetation cover;
2. Make revisions to the 2005 and 2011 landform datasets from McDowell and Dietrich (2012) so that datasets from their study and this study could be compared;
3. Normalize the channel mapping datasets for 2005, 2011, and 2012 to account for differences in streamflow at the time of photograph acquisition; and
4. Summarize spatial patterns in the distribution of active channel landforms, temporal changes in channel morphology, and overall trends in vegetation density.

Mapping Reaches

The area for Task 2 encompassed the entire alluvial valley section of the Middle Fork Willamette River downstream of Dexter Dam (FPKMs 0–22; fig. 3). Systematic mapping of the entire reach is needed to inform and adaptively manage SRP flow implementation and to define geomorphically effective flows—or flows with the optimal combination of magnitude and duration to produce the most geomorphic change (Costa and O'Connor, 1995). Owing to resource constraints, this mapping effort focused only on the Middle Fork Willamette River, not the McKenzie River, because the Middle Fork Willamette River has existing channel mapping datasets (McDowell and Dietrich, 2012). As of 2016, similar comprehensive mapping datasets remain unavailable for the entire alluvial section of the McKenzie River.

This study divided the alluvial valley reach of the Middle Fork Willamette River into three mapping reaches to relate channel and vegetation changes with streamflow (fig. 10). The Confluence Reach is a short reach, extending from the mouth of the Middle Fork Willamette River (FPKM 0) to FPKM 1. This short section of river was treated as a separate reach because its aerial photographs were acquired at different discharges than upstream reaches in 2005 and 2011 (table 8). The Jasper Reach extends from FPKM 1 to the mouth of Fall Creek (FPKM 15). The Confluence and Jasper Reaches correspond to the "lower" Middle Fork Willamette Reach described in the SRP monitoring framework (Rose Wallick, USGS, verbal commun., May 18, 2015). The Dexter Reach extends from FPKM 16 to the base of Dexter Dam. Streamflows in the Jasper and Confluence Reaches are characterized by the USGS streamgage at Jasper (14152000), which accounts for contributions from Fall Creek. The USGS streamgage near Dexter (14150000) was used for discharge data in the Dexter Reach.



Base map modified from U.S. Geological Survey digital data, 10-meter resolution. UTM Zone 10 N, NAD 83.

Figure 10. Schematic showing the study reaches for assessing recent changes in active channel features and vegetation in the alluvial valley section of the Middle Fork Willamette River, western Oregon, 2005–12.

Table 8. Flight dates and stream discharges for aerial photographs used for repeat mapping of channel features, Middle Fork Willamette River, western Oregon.

[**Abbreviations:** FPKM, floodplain kilometers; ft^3/s, cubic foot per second]

Reach	USGS streamgage used to determine photograph discharge	Year	Flight date	Photograph discharge (ft^3/s)	Average mean annual discharge at streamgage,1970–2013 (ft^3/s)	Ratio of photograph discharge to average mean annual discharge
Dexter	Dexter	2005	August 4	2,290	3,046	0.75
FPKMs 16-22	(14150000)	2011	July 2	3,430	3,046	1.13
		2012	July 7	1,840	3,046	0.60
Jasper	Jasper	2005	August 8	2,810	4,126	0.68
FPKMs 1–15	(14152000)	2011	July 2	3,830	4,126	0.93
		2012	July 7	2,160	4,126	0.52
Confluence	Jasper	2005	July 18	2,240	4,126	0.54
FPKM 0	(14152000)	2011	July 1	3,760	4,126	0.91
		2012	July 7	2,160	4,126	0.52

Methods

Landforms and vegetation density on gravel bars were mapped from publicly available, high-resolution orthophotographs from USDA NAIP (fig. 11; table 5). Photographs from 2012 were used to map geomorphic features in the active channel and floodplains. Mapping was confined to the low-elevation, channel-flanking floodplain areas and the active channel (defined as the area typically inundated during annual high flows as determined by the presence of water and flow-modified surfaces; Church, 1988). The mapping corridor was developed to provide a static reference frame from which to compare geomorphic maps from different time periods. Higher-elevation floodplain areas away from the main channel were excluded from the mapping corridor because they are unlikely to be inundated during floods in the modern flow regime.

Features in the mapping corridor were divided into five landform mapping units:

1. The primary, low-flow channel;
2. Secondary channel features;
3. Gravel bars;
4. Floodplains; and
5. Floodplain water bodies (table 9).

These mapping units capture the primary types of historical and modern landforms along the Middle Fork Willamette River. All features larger than about 250 m^2 were digitized at a scale of 1:2,500. Gravel bars were subdivided into bare bars where vegetation cover was less than 10 percent and vegetated bars where vegetation cover was greater than 10 percent, matching the methods of McDowell and Dietrich (2012). Vegetation growing on the bars was not identified to species, and may include native or invasive herbaceous plants, shrubs, or older forests. Consistency between mapped reaches and years was achieved with an iterative review process wherein all line work was reviewed and verified by multiple members of the project team before it was finalized.

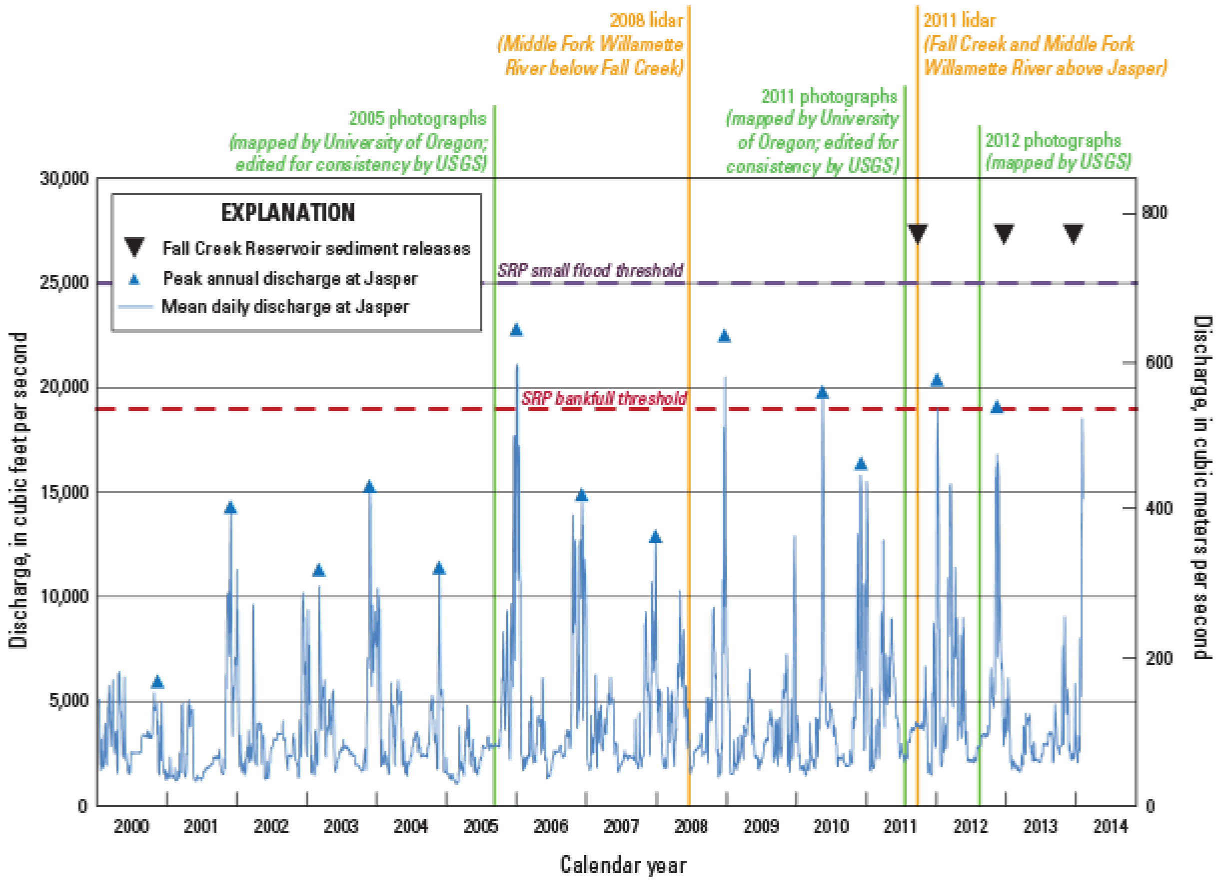


Figure 11. Graph showing peak and mean daily discharge on the Willamette River at Jasper, Oregon (USGS streamgage 14152000), with dates of aerial photograph and lidar acquisition and releases from the Fall Creek Reservoir.

This study also revised existing digital channel maps from 2005 and 2011 (McDowell and Dietrich, 2012) to create a single, compatible dataset for evaluating changes in channel features in relation to streamflow. Revisions to the 2005 and 2011 datasets included minor refinement of line work and reclassification of mapped features to ensure consistency with the mapping protocols of this study. For example, landforms classified as “floodplain islands” by McDowell and Dietrich (2012) from the University of Oregon were reclassified as vegetated bars because mapping protocols for this study classified islands as bar landforms. The USGS also checked to ensure that all bar areas greater than 250 m^2 with little or no vegetation were mapped as “bare bars,” which in some cases entailed dividing areas originally mapped as “floodplain islands” into smaller units based on vegetation density.

Table 9. Mapping units, descriptions, and subclasses for landform mapping along the alluvial valley section of the Middle Fork Willamette River, western Oregon.

[**Abbreviation:** na, not applicable]

Landform mapping unit	Description	Subclasses
Primary, low-flow channel	Main thread of surface water flow in the active channel; conveys most of the flow in multi-thread reaches	na
Secondary channel features	Features in the active channel that are not the primary channel, including sloughs, alcoves, and side channels	na
Gravel bars	Deposits of coarse sediment in the active channel that are created from bed-material transport; delineated based on overall morphology and surface texture (Wallick and others, 2010, 2011; Jones and others, 2011; 2012a, 2010b, 2010c)	Vegetated bars (cover more than10 percent); bare bars (cover less than 10 percent); vegetation can include herbaceous plants, shrubs, and mature forests
Floodplain	Channel flanking areas extending from the wetted channel to the edge of the monitoring corridor that appear stable in the aerial photographs (or do not have signs of fluvial activity); predominantly characterized by mature forest canopy	na
Floodplain water bodies	Water bodies in floodplain that do not have surface water connections with the river in the aerial photographs; mapped area of these features probably is less than actual area, owing to dense canopy cover obscuring some features	Natural features created and maintained by fluvial processes; artificial features including gravel pits that are created by other land uses

Normalization of Mapped Landform Areas

Imprecise line placement, canopy cover, and differences in stream discharge at the time of aerial photograph acquisition are the key sources of mapping error in this study because they can cause differences in the areas and boundaries of actual and mapped features. Of these error sources, error from line placement is small (typically less than 9 m), and error related to canopy cover primarily affects the outer boundaries of small and narrow wetted features often obscured by dense canopy cover, such as sloughs and secondary channels. The most systematic error in the mapping datasets comes from the aerial photographs being taken at different discharges (“photograph discharge”) even though they were all collected in summer. Photograph discharge generally was least in 2012, slightly greater in 2005, and much greater in 2011 (table 8). This means mapping datasets will have less wetted channel areas and greater bar areas in 2012 (owing to low stage), but greater wetted channel areas and less bar areas in 2005 and 2011 (as channel widens and submerges low elevation bars with increasing discharge; fig. 12).

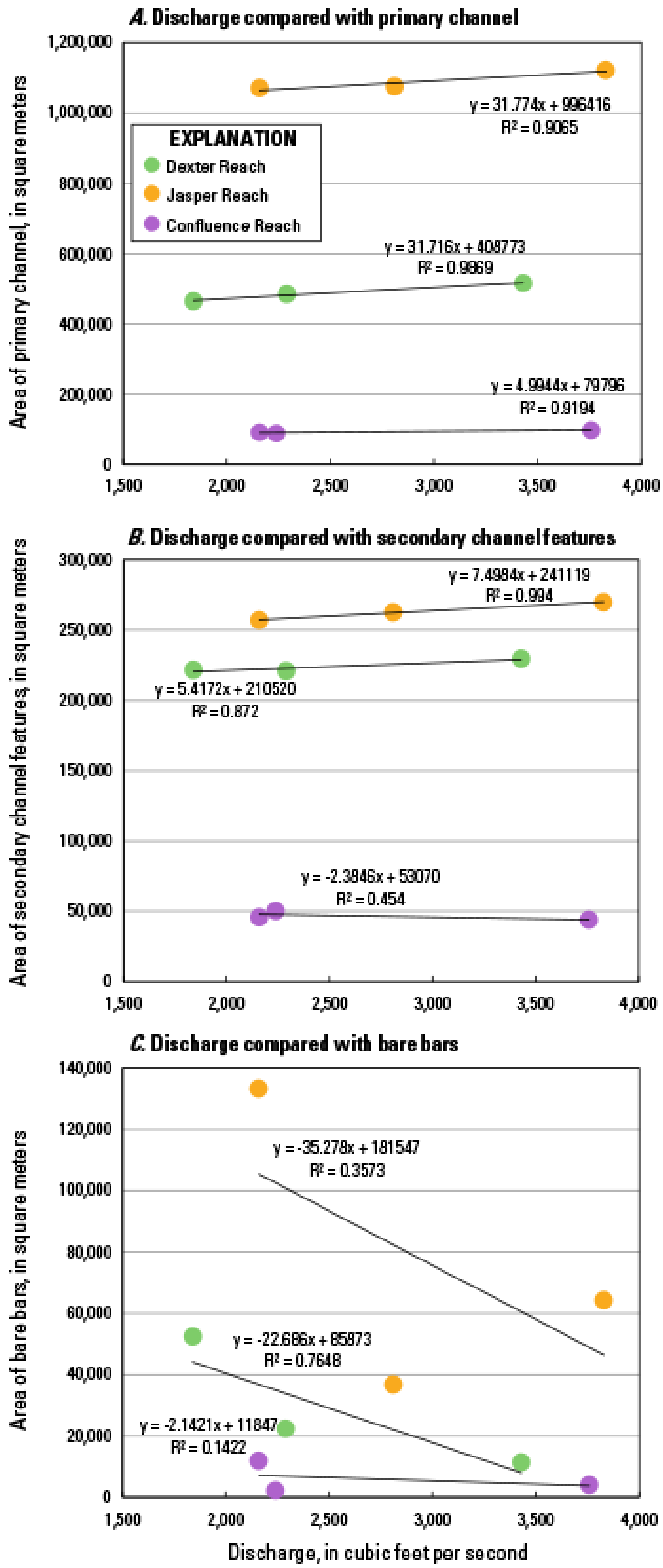


Figure 12. Graphs showing discharge at the time of aerial photograph collection compared with the mapped area of the (*A*) primary channel, (*B*) secondary channel features, and (*C*) bare bars in the alluvial section of the Middle Fork Willamette River, western Oregon, 2005–12.

This study applied an equation similar to Wallick and others (2011) to normalize the area of features mapped in 2005 and 2011 to the lowest photograph discharge of 2012. The normalization equation is:

$$A_{Qi} = A_M - b(Q_i - Q_m) \tag{1}$$

where

A_{Qi}	is the mapped area of an individual feature class for year *m* normalized by the lowest photograph discharge year (or index discharge year; here, 2012) in a reach;
Q_i	is defined as the lowest discharge for which the reach has channel measurements (here, 2012);
A_M	is the mapped area of an individual feature class for a particular set of photographs from year *m* for which the discharge was Q_m (or greater than the index discharge; here, years 2005 and 2011); and
b	is the regression coefficient for the reach-specific relation between a mapped feature class (fig. 12).

This normalization equation was applied to the areas of primary channel, secondary channel features, and bare bars in the Dexter and Jasper Reaches as mapped from the 2005 and 2011 photographs (fig. 12*A*-*C*). The equation was not applied to the Confluence Reach because of the poor relationships between photograph discharge and mapped feature area, which perhaps is partly due to the small sample size of mapped features in this short reach (fig. 12).

Results

Landforms of the Alluvial Section of the Middle Fork Willamette River in 2012

The monitoring corridor, encompassing the alluvial section of the Middle Fork Willamette River, has a narrow active channel and a relatively straight primary channel (sinuosity of 1.18 m/m) that are inset in a floodplain that is broad, forested, and predominately stable (fig. 13). Floodplain features in 2012 made up 70 percent of the mapping corridor (table 10). The remainder was 12 percent primary channel, 4 percent secondary channel features, 1 percent bare gravel bars, 9 percent vegetated gravel bars, 2 percent natural floodplain water bodies, and 3 percent artificial floodplain water bodies (fig. 14*A*; table 10). Unit bar area, or the total area of bars per meter of channel length (m^2/m), was 45.7 m^2/m for vegetated bars and 7.3 m^2/m for bare gravel bars in 2012.

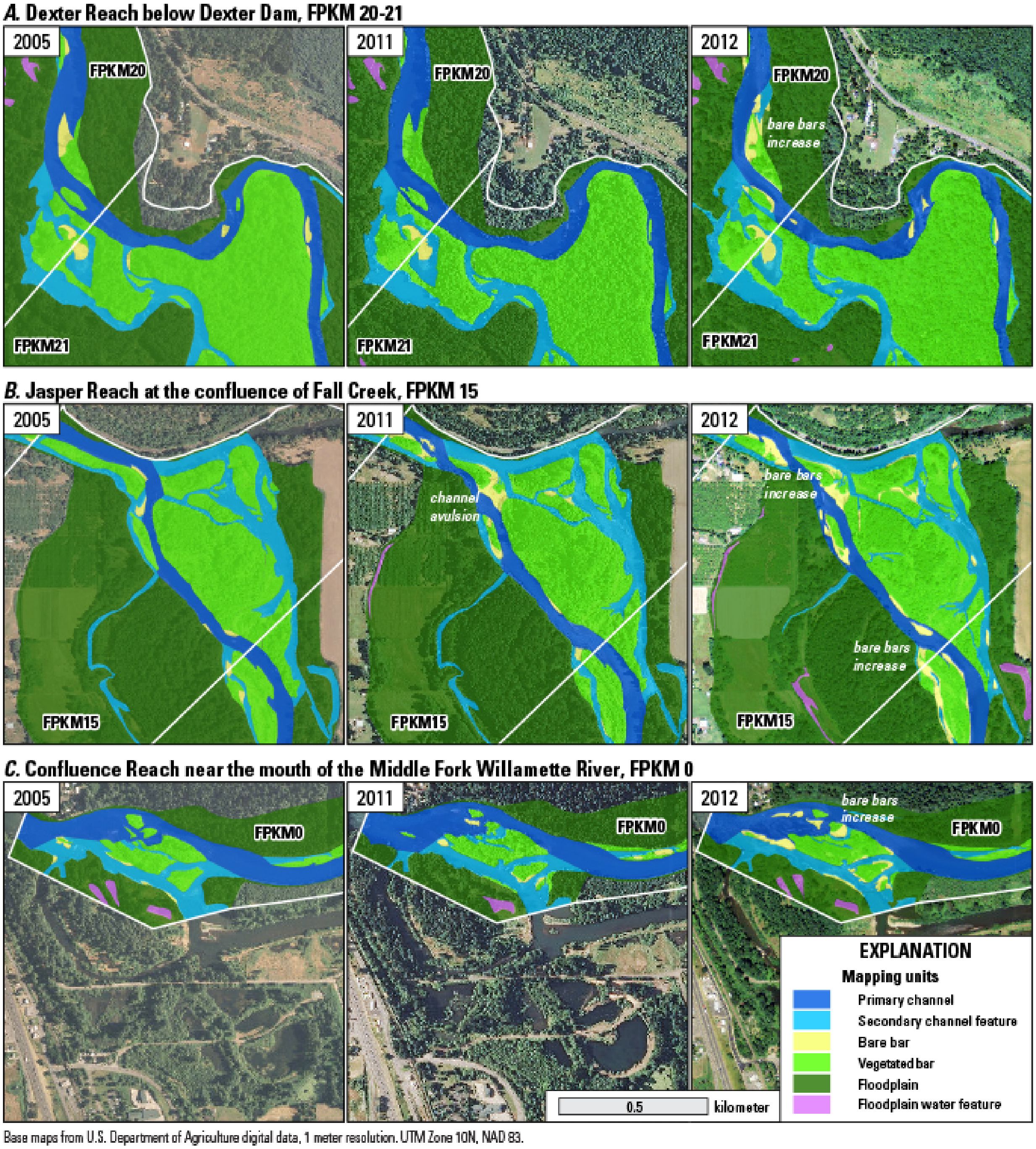


Figure 13. Aerial photographs showing examples of active channel features and channel change near floodplain kilometers (FPKM) (*A*) 20–21, (*B*) 15, and (*C*) 0 on the Middle Fork Willamette River, western Oregon, 2005–12.

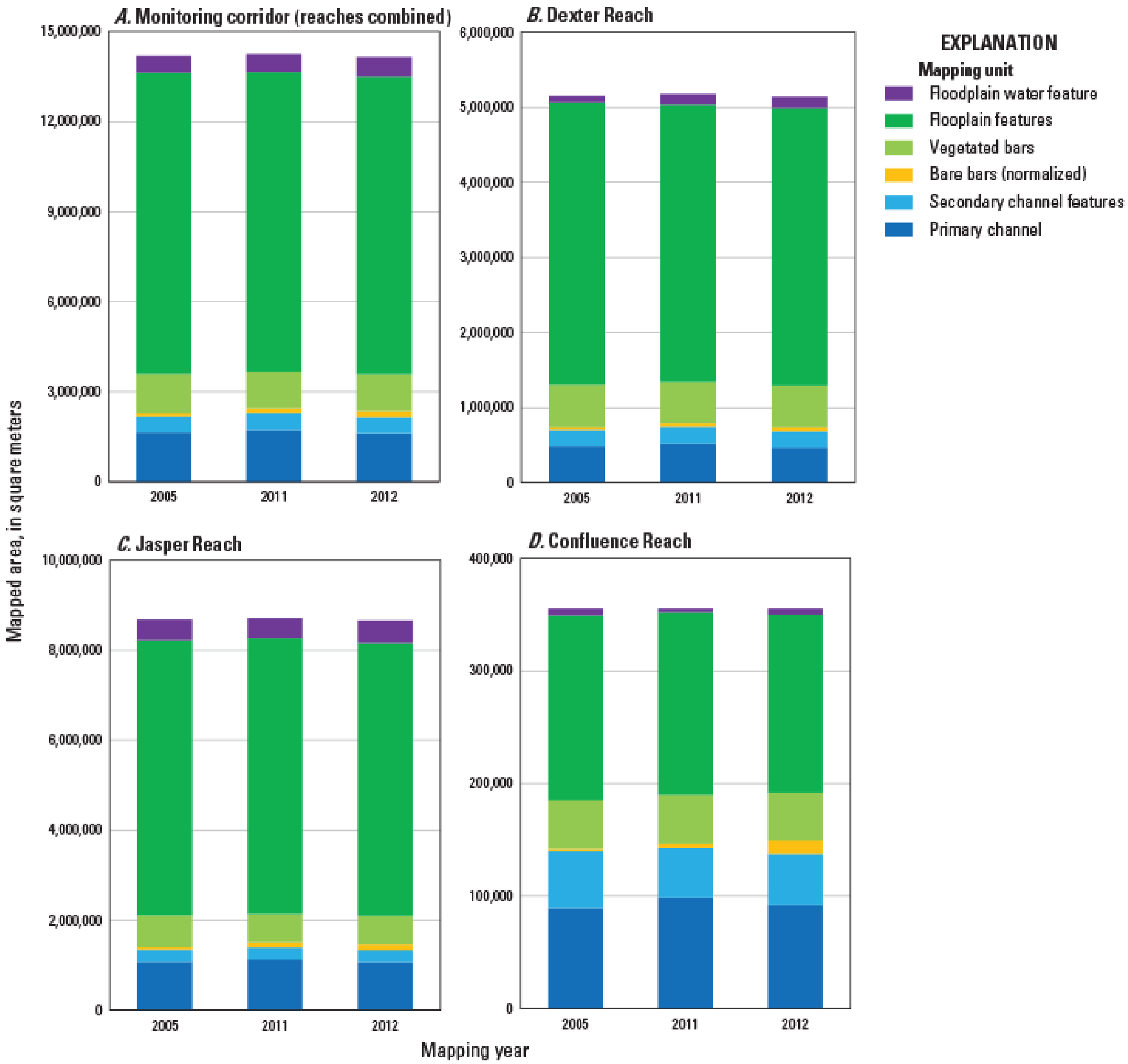


Figure 14. Graphs showing areas of active channel and floodplain features for the monitoring corridor (reaches combined) (A), and Dexter (B), Jasper (C), and Confluence (D) study reaches, Middle Fork Willamette River, western Oregon, 2005, 2011, and 2012.

Table 10. Summary of mapped and normalized channel and floodplain features on the Middle Fork Willamette River, western Oregon, 2005, 2011, and 2012.

[**Reach:** FPKM, floodplain kilometer. **Abbreviations:** na, not calculated; m, meter; m^2, square meter; m^2/m, square meter per meter; %, percent]

			Primary channel			Secondary channel features			Bare gravel bars		
Reach	Year	Primary channel centerline length in 2012 (m)	Mapped area (m^2)	Normalized mapped area[1] (m^2)	Unit bar area[2] (m^2/m)	Mapped area (m^2)	Normalized mapped area[1] (m^2)	Unit bar area[2] (m^2/m)	Mapped area (m^2)	Normalized mapped area[1] (m^2)	Unit bar area[2] (m^2/m)
Monitoring corridor (FPKMs 0–22)	2005	27,000	1,650,200	na	61.1	533,900	na	19.8	61,400	na	2.3
	2011	27,000	1,737,200	na	64.3	543,200	na	20.1	79,600	na	2.9
	2012	27,000	1,627,700	na	60.3	524,400	na	19.4	197,500	na	7.3
Percent of mapped area (2012)			12%			4%			1%		
Confluence (FPKM 0)	2005	1,300	89,600	na	68.9	50,100	na	38.5	2,200	na	1.7
	2011	1,300	98,600	na	75.8	44,000	na	33.8	4,000	na	3.1
	2012	1,300	91,900	na	70.7	45,700	na	35.1	11,800	na	9.1
Jasper (FPKMs 1–15)	2005	17,400	1,075,900	1,055,200	60.6	262,800	257,900	14.8	36,800	59,700	3.4
	2011	17,400	1,121,900	1,068,900	61.4	269,600	257,100	14.8	64,200	123,100	7.1
	2012	17,400	1,071,100	na	61.6	257,000	na	14.8	133,200	na	7.7
Dexter (FPKMs 16–22)	2005	8,300	484,800	470,500	56.7	221,000	257,900	31.1	22,400	32,600	3.9
	2011	8,300	516,600	466,200	56.2	229,600	221,000	26.6	11,300	47,400	5.7
	2012	8,300	464,700	na	56.0	221,900	na	26.7	52,400	na	6.3

Reach	Year	Vegetated gravel bars		Floodplain features		
		Mapped area (m^2)	Unit bar area[2] (m^2/m)	Mapped area of floodplain features (m^2)	Mapped area of floodplain water bodies (natural) (m^2)	Mapped area of floodplain water bodies (artificial) (m^2)
Monitoring corridor (FPKMs 0–22)	2005	1,316,600	48.8	10,038,400	194,200	357,400
	2011	1,211,600	44.9	9,989,700	224,100	366,700
	2012	1,233,400	45.7	9,908,400	294,400	366,200
Percent of mapped area (2012)		9%		70%	2%	3%
Confluence (FPKM 0)	2005	43,300	33.3	164,000	6,000	0
	2011	43,200	33.2	162,200	3,200	0
	2012	42,600	32.8	158,000	5,300	0
Jasper (FPKMs 1–15)	2005	707,600	40.7	6,109,900	108,800	354,200
	2011	624,100	35.9	6,128,400	85,000	362,700
	2012	638,300	36.7	6,054,900	138,800	362,700
Dexter (FPKMs 16–22)	2005	565,700	68.2	3,764,400	79,400	3,200
	2011	544,300	65.6	3,699,000	136,000	4,000
	2012	555,300	66.9	3,692,800	150,300	3,500

[1]Equation 1 was applied to normalize the areas of primary channel in all reaches, secondary water features in the Jasper and Dexter Reaches, and bare bars in the Jasper and Dexter Reaches. Normalization was done to account for higher discharge in the aerial photographs from 2005 and 2011 compared with 2012 photographs.

[2]When reach was not normalized, the measured area was used for unitization.

The area of mapped channel features in 2012 varied along the alluvial section of the Middle Fork Willamette River according to differences in overall channel planform and the locations of tributary confluences (fig. 15*A–C*; table 10). For instance, the area of the primary channel was greatest near FPKM 8 because the floodplain transect included a large bend and nearly 2 km of primary channel. Secondary channel features were the most abundant near FPKMs 21, 15, 13, and 0. Large, forested bars and bare bars separated the Middle Fork Willamette River at FPKMs 21, 15, 13, and 0, resulting in a network of numerous secondary channels (figs. 13 and 16). Natural and artificial floodplain water bodies were most numerous in the Jasper Reach (fig. 16). FPKMs 21 and 15 have examples of natural floodplain water features, including seasonally disconnected ponds, and secondary channel features. Both sets of features are important habitats supporting Oregon chub (*Oregonichthys crameri*), salmonids, and lamprey (*Lampetra* spp. and *Entosphenus tridentatus*).

The alluvial section of the Middle Fork Willamette River also has small and intermittent bare gravel bars. Bare gravel bars were near FPKMs 20–21 and 16–17 in the Dexter Reach, FPKMs 13–15 (near the Fall Creek Confluence) and 3–8 in the Jasper Reach, and near FPKM 0 in the Confluence Reach. These relatively gravel-rich areas predominately were located near tributary confluences. Few bare bars are present between FPKMs 8 and 12, where the channel flows against foothills of the Western Cascades. The area of individual bare bars ranged from 300 to 6,000 m^2 in the Dexter Reach, 1,000 to 6,000 m^2 in the Jasper Reach, and 300 to 1,400 m^2 in the Confluence Reach.

Finally, the alluvial Middle Fork Willamette River has large and nearly continuous vegetated gravel bars along its entire length. The area of vegetated bars within the mapping corridor was more than six times greater than the total area of bare bars in 2012 (fig. 14; table 10). Most vegetated bars are channel flanking bars that are adjacent to floodplain surfaces and have moderate to dense shrubs and mature forests. The area of most individual vegetated gravel bars exceeded 10,000 m^2.

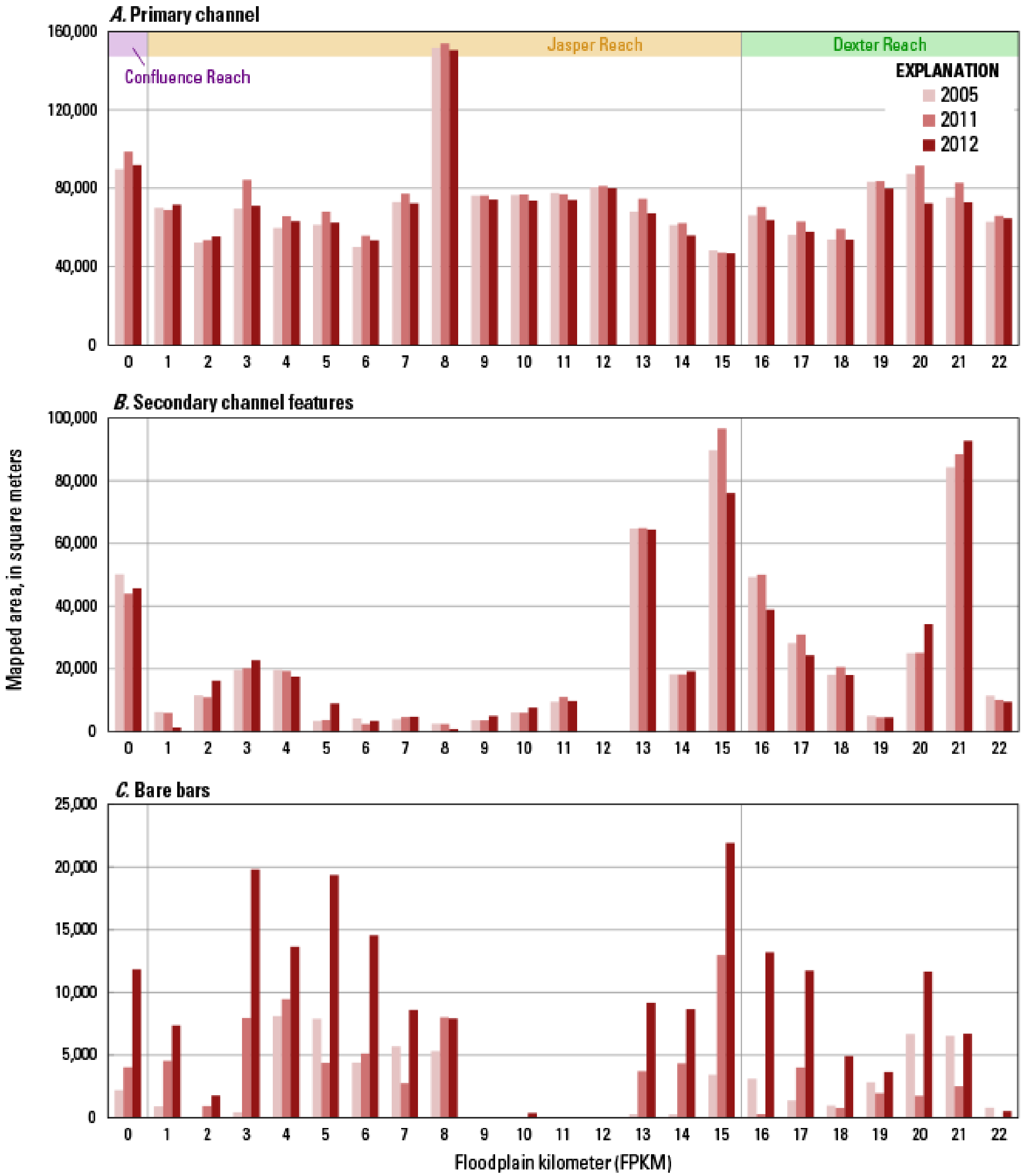


Figure 15. Graphs showing sizes of mapped areas, by floodplain kilometer (transect), of (*A*) primary channel, (*B*) secondary channel features, and (*C*) bare bars in the alluvial section of the Middle Fork Willamette River, western Oregon, in 2005, 2011, and 2012. Areas shown for each floodplain kilometer represent mapped areas that are not normalized by discharge.

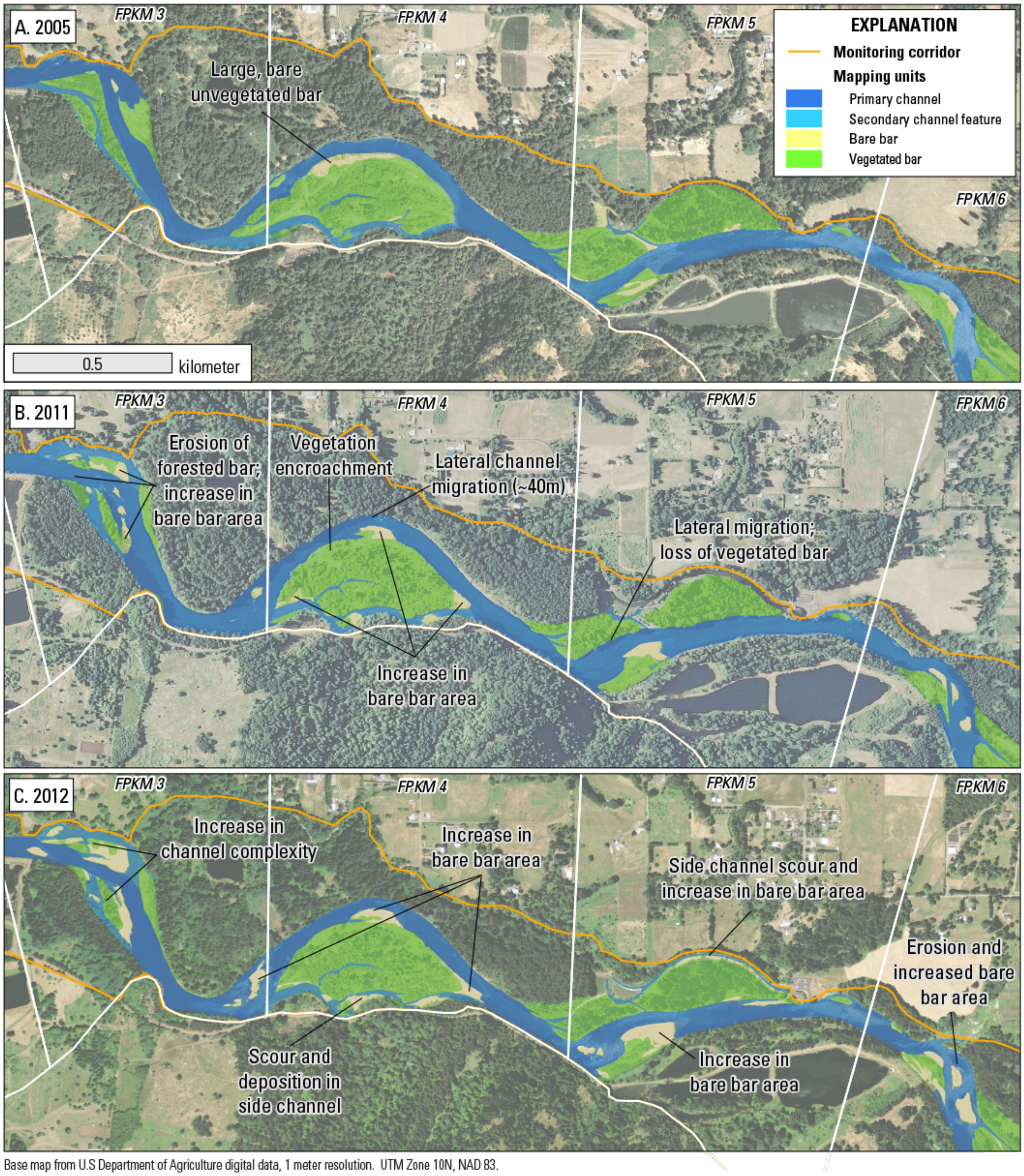


Figure 16. Aerial photographs showing examples of channel change near floodplain kilometer (FPKMs) 3–6 in the Jasper Reach on the Middle Fork Willamette River, western Oregon, in (*A*) 2005, (*B*) 2011, and (*C*) 2012.

Changes in the Planform and Area of Landforms on the Alluvial Section of the Middle Fork Willamette River, 2005–12

The Middle Fork Willamette River transitioned from a period of low flows and no bankfull events (WYs 2000–05) to a period with three events exceeding the SRP winter bankfull flow recommendation between 2005 and 2011, as well as one single event exceeding this same recommendation between 2011 and 2012 (fig. 7*A*; table 6). The primary landform trends in response to these flows were as follows:

- **The area mapped as floodplain was relatively stable** (fig. 14; table 10). Localized decreases in floodplain area were observed, such as near FPKM 4 (fig. 16), but these local changes did not affect the overall floodplain trends.
- **The area of mapped floodplain water bodies fluctuated between time periods** (table 10). The changes in the total area of floodplain water bodies likely indicate mapping uncertainties associated with dense forest canopy rather than actual geomorphic changes. Inundation of these disconnected features also is likely influenced in part by subsurface flows between the mainstem channel and floodplain areas.
- **The primary channel was relatively stable in terms of normalized area (table 10) and planform in all reaches. Exceptions to the stable planform were locations with active meander migration and channel avulsions.** For example, the channel toward the middle of FPKM 4 had rapid meander migration of about 7 m/yr between 2005 and 2011, resulting in a total of about 40 m of lateral channel movement to the north (fig. 16*A–B*). Less rapid meander migration occurred on the north bank near the downstream boundary of FPKM 5 between 2005 and 2012, resulting in 1–3 m/yr of bank erosion (fig. 16*A–C*). The channel moved less than 200 m laterally through vegetated bars near FPKMs 3 and 15, creating new channels and increasing channel complexity from 2005 to 2011 and then from 2011 to 2012 (figs. 13 and 16).
- **Secondary channel features had overall stable planform, except in locations with increasing areas of shifting, bare gravel bars.** For instance, secondary channel features shifted their location from 2005 to 2011 and from 2011 to 2012 in response to changes in the area and location of bare gravel bars near FPKMs 0, 3, 15, and 21 (figs. 13 and 16). Our study did not indicate areas where new side channels were scoured in previously stable areas.
- **The area of secondary channel features was relatively stable in all reaches from 2005 to 2012** (fig. 14; table 10). Localized planform changes in secondary features occurred between years, but did not affect overall area trends.
- **The area of bare gravel bars was the lowest in 2005, but increased substantially in 2011 and then remained similar, or slightly increased in 2012** (fig. 14; table 10). Bar area was low in 2005, in large part owing to the preceding 6 years without bankfull events (fig. 7*A*). The normalized area of bare gravel bars in the Jasper Reach increased from 59,700 to 123,100 m^2 (106 percent) from 2005 to 2011, and then to 133,200 m^2 (8 percent) in 2012. Increases in the Dexter Reach were smaller; bare bar area increased from 32,600 to 47,400 m^2 (45 percent) from 2005 to 2011, and then to 52,400 m^2 (11 percent) in 2012. The actual increase in bare bar area from 2011 to 2012 likely is minimal in the Jasper and Dexter Reaches, owing to multiple sources of mapping error and uncertainty introduced by normalizing mapped bare bar area by photograph discharge. The 2011 and 2012 photographs also bracket the release of substantial fine sediment (predominantly sand) from the Fall Creek Lake that winter (fig. 11). The repeat mapping

from this study, USGS sediment data collection, Oregon Department of Fish and Wildlife studies, and anecdotal observations indicate that fine sediment from Fall Creek Lake did not substantially contribute to increases in bar area. The large apparent increases in the un-normalized area of bare bars in the Confluence Reach between 2011 and 2012 may be partly attributable to the low photograph discharge of the 2012 photographs.

- **The locations of bare gravel bars changed greatly between time periods, especially in FPKMs with increasing bar area**. For example, newly formed bare gravel patches (generally smaller than 1,000 m^2) appeared in the 2011 photographs near the Fall Creek confluence (FPKM 15) and FPKM 13. In some places, these new bars were in different locations in the 2012 photographs, corresponding to changes in adjacent secondary channel features (fig. 13).
- **The area of mapped vegetated bars primarily was stable, but fluctuated slightly from 2005 to 2012** (table 10). From 2005 to 2011, their area decreased by about 4 percent in the Dexter Reach, about 12 percent in the Jasper Reach, and less than 1 percent in the Confluence Reach. From 2011 to 2012, vegetated bars increased by 2 percent in the Dexter and Jasper Reaches, but decreased by about 1 percent in the Confluence Reach. Actual changes in vegetated bars likely were small when mapped net changes were small, owing to multiple sources of mapping error. However, the net 10 percent decrease in the Jasper Reach between 2005 and 2012 likely indicates actual losses in vegetated bars because of erosion. For example, noticeable decreases in vegetated bars included scouring near FPKM 6 between 2011 and 2012, as well as the erosion of densely vegetated bars near FPKMs 3 and 15 as a result of channel avulsions between 2005 and 2011 (figs. 13 and 16).

Discussion

Comparison of the landform mapping datasets from 2005, 2011, and 2012 are helpful for considering historical and ongoing geomorphic processes and evaluating reach-wide changes in channel planform and landforms relative to recent flood events. Prior to dam construction, the alluvial section of the Middle Fork Willamette River was a geomorphically dynamic, multi-thread river (Dykaar, 2005, 2008a, 2008b; Wallick and others, 2013). The locations of its primary channel, secondary channel features, and gravel bars changed frequently in response to large floods as well as substantial inputs of large wood and coarse sediment (Wallick and others, 2013). Since dam construction began in the early 1950s, floods with the energy to do substantial geomorphic work and the supply of sediment to this alluvial section have decreased. As such, channel-forming processes, such as channel avulsions and meander migration, have been substantially dampened, resulting in the stable locations of the primary channel and secondary channel features. The lack of channel shifting and diminished peak flows have allowed vegetation to stabilize channel-flanking gravel bars that historically were scoured more frequently as well as decreased “floodplain recycling,” whereby wood and coarse sediment are eroded but reused downstream to form new bars and habitats. Continued channel stability and resulting vegetation colonization of formerly bare gravel bars account for the expansive vegetated bars throughout the study area and relative absence of bare gravel bars in recent years.

Combining the recent landform mapping with streamflow hydrographs shows how the Middle Fork Willamette River responded to bankfull events from 2005 to 2012 in the context of the modern system of flood control and revetments. The alluvial section primarily was stable over this time period. However, it did have some substantial but localized changes from 2005 to 2011 in response to three events that exceeded the winter bankfull recommendation for 1–7 days (figs. 5 and 7*A*). These events scoured the vegetation that had established on previously bare gravel bars during the low-flow period of 2000–05, resulting in substantial increases in bare gravel bars in 2011 (fig. 14; table 10). These events also triggered meander migration and short avulsions (figs. 13 and 16). The erosion of sediment from vegetated bars, channel edges, and avulsions is the likely source of the new bare gravel bars because the alluvial Middle Fork Willamette River receives minimal bed-material inputs from upstream sources (O'Connor and others, 2014). In contrast, from 2011 to 2012, landforms had minor changes, such as the location and size of bare gravel bars, following a bankfull event that peaked at 20,100 ft^3/s and lasted for only one day.

These findings indicate that the winter bankfull flow pulse recommendation of 19,000 ft^3/s at the USGS streamgage at Jasper probably is a suitable minimum threshold for geomorphically effective flows. Flows of this magnitude may need to be held for multiple days (such as the 2006 event) to cause substantial geomorphic changes. Other flow events with varying magnitudes and durations move different sizes and volumes of sediment and scour different types and ages of vegetation. However, for the monitoring and evaluation purposes of the SRP, the bankfull threshold seems to capture the flow events that cause the principal geomorphic changes visible from the aerial photographs on the Middle Fork Willamette River.

Most of the geomorphic change on the alluvial Middle Fork Willamette River between 2005 and 2012 occurred between 2005 and 2011. Separating the geomorphic effects of the individual bankfull events during this period is challenging because the landform datasets from 2005 and 2011 bracket three bankfull events. Therefore, we did a qualitative review of the aerial photographs from Google Earth™ for 2006, 2008, and 2010. Two short avulsions, scour of sparsely vegetated bars, and at least one location of lateral migration into forested floodplain surfaces were visible after the large magnitude, long-duration January 2006 event. The bankfull flows of 2008–09 and 2010 continued the lateral migration and bar formation that were initiated by the 2006 event, but did not trigger avulsions or substantially scour vegetated surfaces. From these observations, it seems that bankfull flows of many days in duration, such as the 2006 event that peaked at 22,800 ft^3/s and lasted for 6.5 days, are needed to initiate substantial channel change and scour vegetated bars on the alluvial section of Middle Fork Willamette River downstream of Dexter Dam. At this time, it also is challenging to distinguish between the effects of flow magnitude and duration on geomorphic processes. Observations from this qualitative review suggest the January 2009 event that peaked at 22,500 ft^3/s and lasted for about 1.5 days did not cause changes comparable to the 2006 bankfull event that had slightly higher magnitude and longer duration (22,800 ft^3/s for 6.5 days).

Implications for Ecosystems along the River Corridors and Sustainable Rivers Project

The SRP program on the Middle Fork Willamette River aims to manage for streamflows that meet authorized uses as well as to create and sustain habitats for native fauna and flora, including Oregon chub, endangered salmonids, and black cottonwood. Findings from this task indicate that events exceeding the winter bankfull recommendation for multiple days (such as the 2006 bankfull event) are successful at scouring bars, resetting vegetation, and triggering substantial but localized channel change, whereas shorter-duration bankfull events primarily affect the location and size of gravel bars and propagate meander migration (such as the 2008–09 event). The geomorphic effects of future bankfull events are likely to be localized in areas, such as near FPKMs 21, 13–17, 3–6, and 0, where the Middle Fork Willamette River has a relatively wide active channel, bare gravel bars and erodible bank materials. Although localized, the erosion and redeposition of sediment result in the reconfiguration of gravel bars and secondary channels, in some cases increasing spawning habitat, channel complexity, hyporheic exchange, and thermal diversity. Such changes may help support the creation of coldwater refuges, a limiting factor for migrating salmon in the Willamette River Basin (Hulse and others, 2007; National Marine Fisheries Service, 2008), by enhancing hyporheic exchange (Fernald and others, 2001; Poole and others, 2006; Arrigoni and others, 2008; Burkholder, 2008). Additionally, spawning of spring Chinook salmon in the alluvial Middle Fork Willamette River occurs primarily directly downstream of Dexter Dam where suitable gravels for redd building are sparse (National Marine Fisheries Service, 2008; Greg Taylor, U.S. Army Corps of Engineers, oral commun., September 20, 2012). The modest increases in bare gravel bars from 2011 and 2012 could signify increases in spawning habitat. Gravel bars are also key areas utilized by juvenile spring Chinook salmon during summer months (Tom Freisen and Luke Whitman, ODFW, oral commun., September 29, 2016), so increases in these features could lead to overall increases in the availability of summer rearing habitats. Channel complexity and bare gravel bars along the primary channel also will provide germination sites for black cottonwood. However, these sites are susceptible to being reset or reshaped by the next bankfull event, owing to the narrow active channel zone of the Middle Fork Willamette River.

Reinstating geomorphic change farther away from the primary channel probably will require flow events of greater magnitude and duration than events that occurred between 2005 and 2012. For example, widespread meander migration and large-scale channel avulsions typically are required to create new secondary channels, floodplain ponds, and protected germination sites for black cottonwood that are away from the primary channel. Such types of channel change were not observed from 2005 to 2012. Without higher flow events, existing floodplain sloughs and secondary channels probably will fill gradually with fine sediment, resulting in a long-term decrease in these important off-channel habitats for Oregon chub, juvenile salmonids, and lamprey. Likewise, scouring forested islands or bars will require greater flows, as we did not detect many areas where forested islands or bars were substantially eroded by the bankfull flows during 2005–12. Until such flows occur on the Middle Fork Willamette River, the geomorphic effects of bankfull flow releases will be limited to the narrow active channel that is inset in the broad floodplain corridor.

Task 3—Examine Changes in Channel Features and Vegetation over Two Decades (1994–2014) for Two Short Mapping Zones on the Middle Fork Willamette and McKenzie Rivers

Task 2 involved an assessment of the entire alluvial section of the Middle Fork Willamette River from 2005 to 2012. In contrast, Task 3 focused on two short mapping zones on the Middle Fork Willamette and McKenzie Rivers, and involved an assessment of seven sets of aerial photographs, spanning two decades on these rivers. Applying Task 3 to the entire alluvial sections of both rivers was beyond the scope of this study. The long-term assessments resulting from Task 3 are helpful in examining how geomorphically dynamic zones of these rivers respond to a broader range of flow events. Specific work elements for this task include the following:

1. Map active channel landforms and their vegetation coverages for two mapping zones from publicly available aerial photographs taken in 1994, 2000, 2005, 2009, 2011, 2012, and 2014.
2. Summarize spatial patterns in the distribution of active channel landforms, temporal changes in channel morphology, and overall trends from channel features mapped from 1994 to 2014.

Mapping Zones

We focused repeat mapping of channel features and vegetation coverage in two mapping zones, one on the Middle Fork Willamette River (fig. 17*A*) and one on the McKenzie River (fig. 17*B*). These mapping zones correspond with the monitoring zones identified in the forthcoming SRP monitoring framework as critical river segments to focus future monitoring efforts for the Sustainable Rivers Program (Rose Wallick, USGS, verbal commun., May 18, 2015). The mapping zones for this study were identified as geomorphically dynamic segments with actively shifting gravel bars, side channels and flanking low elevation floodplains, and young stands of woody vegetation that were more likely to respond to environmental flows than other, more intrinsically stable sections of each river corridor. The mapping zones used in this study have comparable water surface slopes when measured from lidar, ranging from 0.225 percent in the Middle Fork Willamette River zone to 0.204 and 0.255 percent in the McKenzie zone before and after the channel avulsion. The selected zones encompass the TNC Willamette Confluence Preserve on the Middle Fork Willamette River (FPKMs 3–6) and the McKenzie Oxbow Conservation Area (FPKMs 23–25), where we set up two sites for monitoring black cottonwood and other vegetation for Task 4. Historically, these zones were shaped by similar geomorphic processes, including avulsions and meander migration.

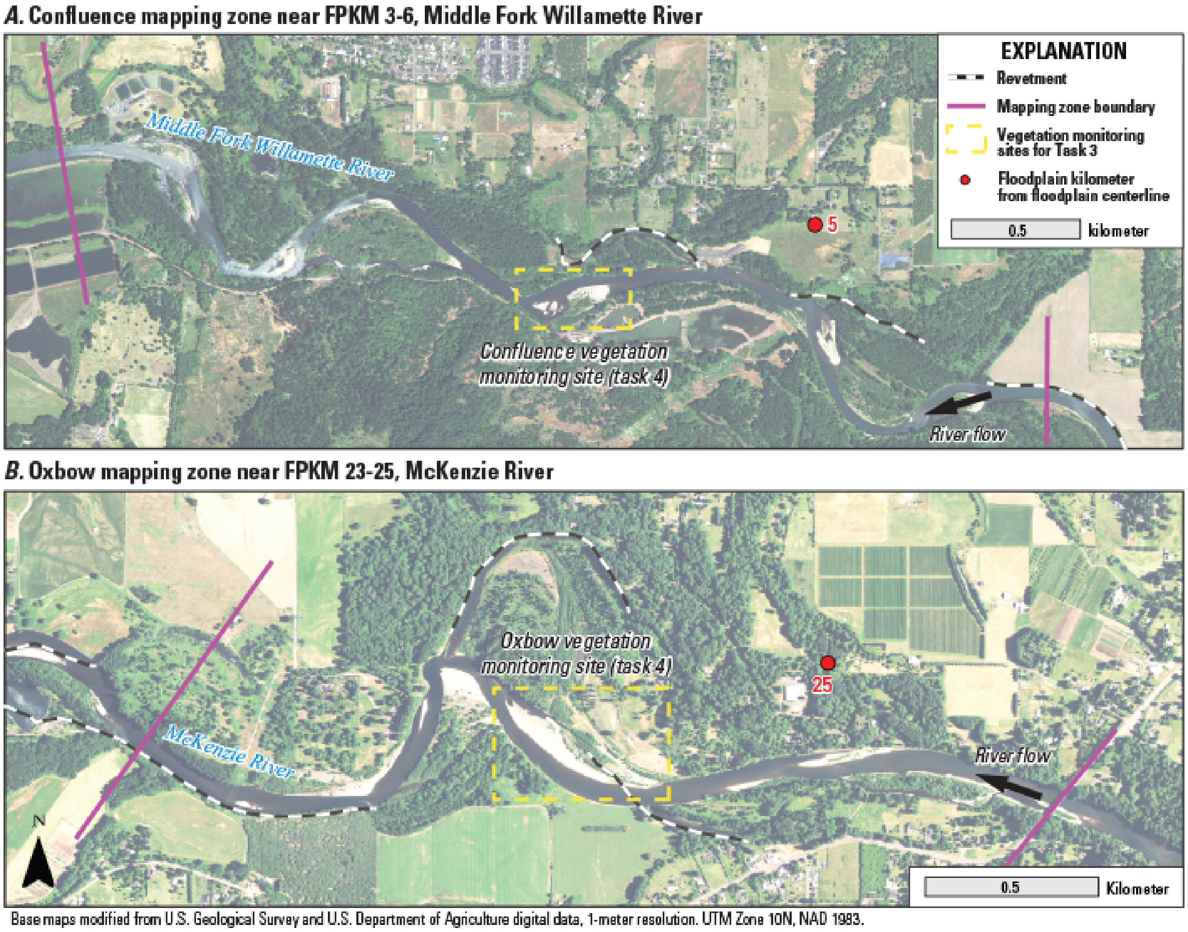


Figure 17. Aerial photographs showing mapping zones for mapping channel features and vegetation on the (*A*) Middle Fork Willamette River near floodplain kilometers (FPKMs) 3–6, and (*B*) McKenzie River near FPKMs 23–25, western Oregon, 1994–2014. Photographs also show the locations of two vegetation monitoring sites located in these mapping zones.

Methods

Like the mapping for Task 2, four broad classes of landforms—the primary channel, secondary channel features, bars, and floodplain—were mapped from high-resolution orthophotographs from USGS and USDA NAIP (tables 5 and 6). Mapping and analyses for Task 3 had four key differences from those for Task 2. First, mapping for Task 3 used photographs spanning two decades (1994, 2000, 2005, 2009, 2011, 2012, and 2014), whereas Task 2 only used photographs for 2005, 2011, and 2012. Second, analyses for Task 3 did not account for differences in photograph discharge as was done for Task 2, owing to scope limitations. This means that some of the inter-annual differences in the mapped primary channel, secondary channel features, and bars may be related to streamflow at the time of aerial photograph collection rather than actual physical change. In particular, photographs in 2011 were collected at greater discharges than those collected in other years, whereas photographs in 1994 were collected at lower discharges than the other photographs (table 11). Third, the floodplain mapping for Task 3 was limited to features near the active channel and transitioning from the active channel to floodplain over the mapping period. Fourth, a dominant vegetation class and density was assigned to each bar and floodplain landform. The four vegetation classes were:

1. Bare—no apparent vegetation;
2. Herbaceous plants—a mixture of annual and perennial plants, including grasses, sedges, and rushes;
3. Shrub—woody shrub cover, typically willows (*Salix sp.)*; and
4. Shrubs and trees—typically willow with some larger trees in the canopy.

These broad vegetation classes capture general vegetation communities similar to the mapping of McDowell and Dietrich (2012), but do not capture individual species. The three vegetation densities were:

1. Low—less than 10 percent;
2. Moderate—10–50 percent cover; and
3. Dense–greater than 50 percent cover, matching the existing datasets of McDowell and Dietrich (2012).

Table 11. Flight dates and stream discharges for aerial photographs used for repeat mapping of channel features in the Confluence mapping zone on the Middle Fork Willamette River and the Oxbow mapping zone on the McKenzie River, western Oregon.

[**Abbreviation:** ft^3/s, cubic foot per second]

Mapping zone	Floodplain kilometer	USGS streamgage used to determine photograph discharge	Year	Flight date	Photograph discharge (ft^3/s)	Mean annual discharge at streamgage (ft^3/s)	Ratio of photograph discharge to mean annual discharge
Confluence (Middle Fork Willamette River)	3–6	Jasper (14152000)	1994	May 24	1,410	2,329	0.61
			2000	July 24	2,530	4,203	0.60
			2005	August 4	2,810	2,759	1.02
			2009	June 29	2,340	3,994	0.59
			2011	July 1	3,760	4,919	0.76
			2012	July 7	2,160	4,754	0.45
			2014	June 19	2,600	4,294	0.61
Oxbow (McKenzie River)	23–25	Walterville (14163900)	1994	June 29	1,110	1,653	0.67
			2000	August 6	1,190	3,179	0.37
			2005	August 4	1,140	1,678	0.68
			2009	June 29	1,150	2,912	0.39
			2011	July 2	2,000	4,102	0.49
			2012	July 7	1,410	3,795	0.37
			2014	June 11	1,560	3,407	0.46

Results

Confluence Mapping Zone on the Middle Fork Willamette River

As seen in Task 2 and fig. 16, the Middle Fork Willamette River in the Confluence mapping zone has a narrow active channel (alternating between an average of 65 and 120 m wide, and 360 m at the widest point in 2014) that is inset in a forested floodplain (fig. 18). The mapping zone had a generally stable planform from 1994 to 2014, except upstream and downstream of most river bends. In these short sections, the location of the primary channel as well as the location, area, and vegetation of bars fluctuated over time, indicating the cyclical nature of scour, erosion, deposition, and vegetation recruitment. Despite these local changes, most mapped features had modest net changes (less than 20 percent) from 1994 to 2014 (fig. 19*A*; table 12). The exceptions were secondary channel features that increased from 48,000 to 73,100 m^2 (52 percent) and bars with shrubs that increased from 77,000 to 92,900 m^2 (21 percent) from 1994 to 2014. Some area increases for secondary channel features may owe to photograph discharge being greater in 2014 than in 1994 (table 11). The following is a timeline of changes in the Confluence mapping zone from 1994 to 2014:

- Between 1994 and 2000, two substantial channel changes occurred. First, the primary channel at the boundary of FPKMs 3 and 4 avulsed 125 m across shrubs and trees to occupy a side channel. Second, meander migration eroded bars vegetated with trees, shrubs, and herbaceous vegetation near the middle of FPKM 3 and the two large bars in FPKM 6. Changes in channel planform and scouring of landforms correspond with the area of bare gravel bars increasing from 34,400 to 52,200 m^2 (52 percent; table 12) from 1994 to 2000.
- Between 2000 and 2005, the primary channel migrated into trees and shrubs near the downstream boundary of FPKM 4. The most substantial change in mapped area was the shift from bare gravel bars to vegetated bars, corresponding to a nearly 90 percent decrease (52,200 to 5,800 m^2; table 12) in the area of bare gravel bars along the primary and secondary channels throughout the mapping zone. Given the similar photograph discharges for the 2000 and 2005 photographs, the decrease in bare gravel bars indicates a substantial change during this period. The conversion from bare to herbaceous bars makes sense given the low-flow period of WYs 2000–05 (fig. 7*A*) and similar observations from other rivers in western Oregon (Wallick and others, 2010; 2011; Jones and others, 2011; 2012a, 2012b, 2012c).
- From 2005 and 2009, the primary channel had two planform changes. First, an avulsion cut 100 m in the middle of FPKM 3, forming as a chute-cutoff along the inside of the meander bend and splintering flow into multiple channels. Upstream, the channel meandered through floodplain areas with shrubs and trees at FPKMs 4 and 6, resulting in the scouring of these vegetated surfaces. Bare bars also increased along the secondary channel running along the southern end of the mapping zone in FPKM 4, indicating scour of these surfaces between 2005 and 2009. Collectively, these channel changes, scouring of vegetation along the primary channel in FPKM 4, and the smaller photograph discharge in 2009 relative to 2005 culminate in the area of bare gravel bars increasing from 5,800 to 44,400 m^2, or more than 600 percent, from 2005 to 2009 (table 12). Correspondingly, the area of bars with herbaceous vegetation decreased from 91,600 to 62,600 m^2 (about 32 percent).

- From 2009 to 2011, the Middle Fork Willamette River had predominantly stable planform with fewer gravel bars in FPKM 3. The area of mapped bare bars decreased from 44,400 to 25,900 m^2 (about 42 percent), and that for herbaceous bars decreased from 62,64600 to 44,900 m^2 (about 28 percent). The greater photograph discharge in 2011 probably decreased the mapped area of bare gravel bars, bars with herbaceous vegetation, and bars with shrubs while increasing the mapped area of secondary channel features, particularly in FPKMs 3 and 4.
- From 2011 to 2012, meander migration at the boundary of FPKMs 4 and 5 continued and the channel consolidated into one primary channel in FPKM 3. The mapping zone had more bare gravel bars in FPKMs 3, 5, and 6 and near the boundary of FPKMs 3 and 4. Some of these changes may have been caused by the lesser photograph discharge in 2012 compared to 2011; however, we suspect that the increased area of bare bars in FPKMs 6, 5, and 3 are associated with the scouring of vegetation from landforms near the primary channel. Bar coverage with shrubs increased in FPKM 6.
- From 2012 to 2014, the channel migrated 35 m into trees and shrubs in FPKM 6, leaving behind secondary channel features and bare bars. It also migrated 20 m at the boundary of FPKMs 4 and 5, creating new secondary channel features and bare bars. The mapped area of secondary channel features increased from 58,000 to 73,1005 m^2 (about 26 percent)

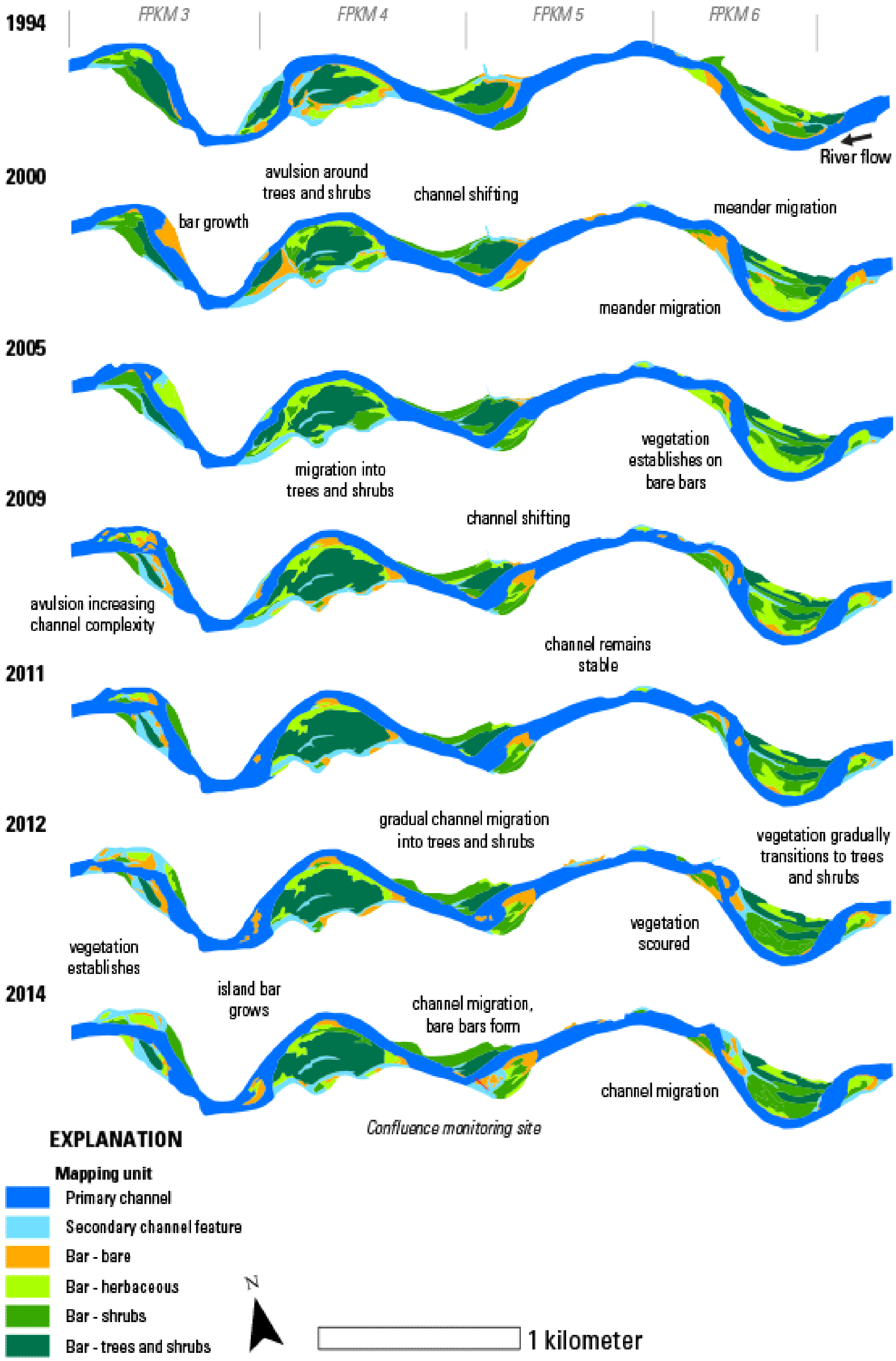


Figure 18. Diagrams showing mapped channels and vegetation features near floodplain kilometers (FPKMs) 3–6 in the Confluence mapping zone of the Middle Fork Willamette River, western Oregon, 1994–2014.

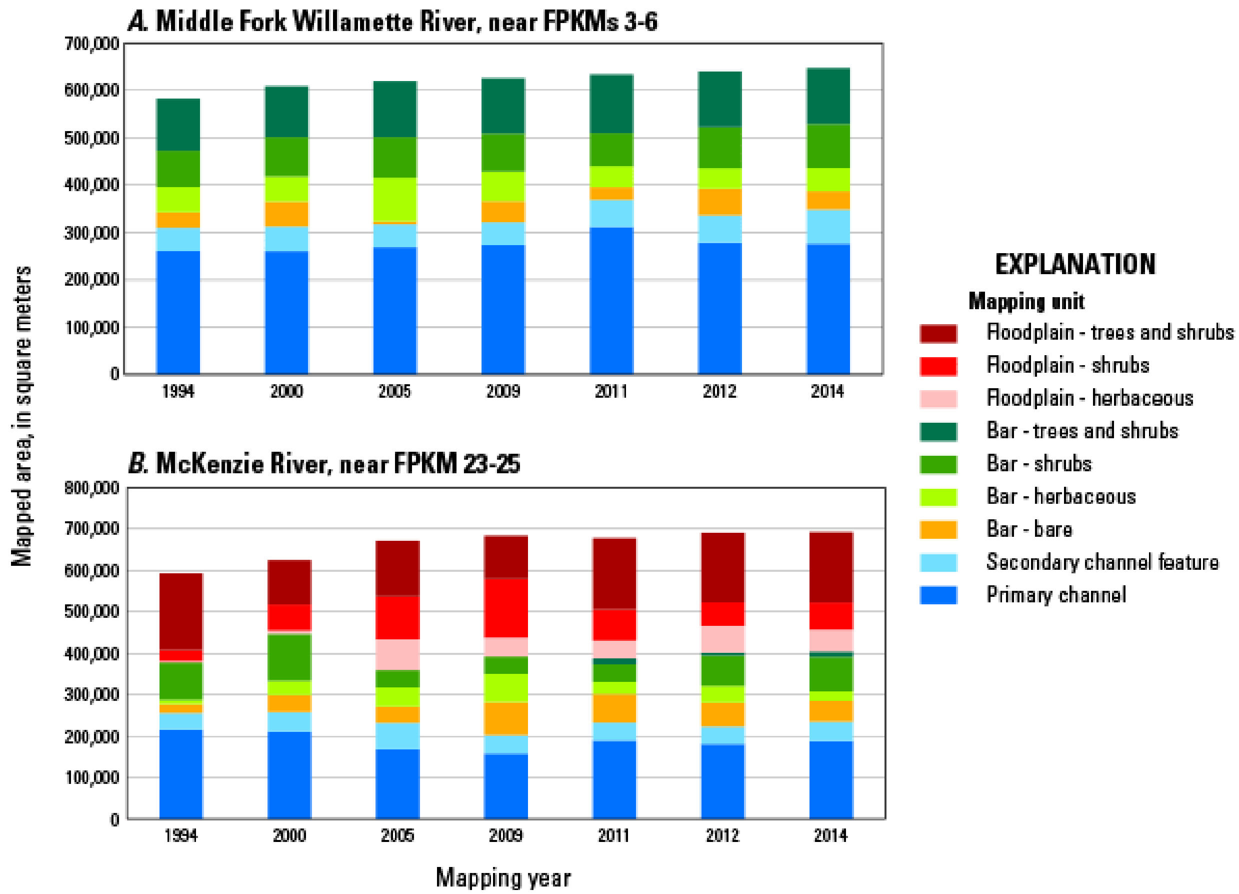


Figure 19. Graph showing relative sizes of mapped areas of primary channel, secondary channel features, and gravel bars in each floodplain transect for the (*A*) Confluence mapping zone of the Middle Fork Willamette River, and (*B*) Oxbow mapping zone of the McKenzie River, western Oregon, 1994–2014.

Table 12. Channel and floodplain features mapped from aerial photographs for the Confluence mapping zone of the Middle Fork Willamette River and the Oxbow mapping zone of the McKenzie River, western Oregon, 1994–2014.

[All numbers are in square meters, except as otherwise indicated. Percentages in parentheses indicate minus percentages. **Symbol:** %, percent change; <, less than; –, none mapped]

Mapping zone	Year	Wetted channel		Bar features				Floodplain features		
		Primary channel	Secondary channel features	Bare	Herbaceous	Shrubs	Trees and shrubs	Herbaceous	Shrubs	Trees and shrubs
Confluence (FPKMs 3–6)	1994	261,100	48,000	34,400	52,000	77,000	110,100	–	–	–
	2000	260,000	52,400	52,200	53,500	82,600	108,300	–	–	–
	1994–2000	(<1%)	9%	52%	3%	7%	(2%)			
	2005	268,300	49,300	5,800	91,600	85,800	118,100	–	–	–
	2000–05	3%	(6%)	(89%)	71%	4%	9 %			
	2009	273,100	48,200	44,400	62,600	79,600	116,800	–	–	–
	2005–09	2%	(2%)	663%	(32%)	(7%)	(1%)			
	2011	311,400	57,600	25,900	44,900	69,200	125,100	–	–	–
	2009–11	14%	20%	(42%)	(28%)	(13%)	7%			
	2012	277,700	58,000	56,100	43,600	87,100	117,700	–	–	–
	2011–12	(11%)	1%	116%	(3%)	26%	(6%)			
	2014	275,600	73,100	38,000	49,300	92,900	118,200	–	–	–
	2012–14	(1%)	26%	(32%)	13%	7%	<1%			
Net change	1994–2014	6%	52%	10%	(5%)	21%	7%			

Mapping zone	Year	Wetted channel		Bar features				Floodplain features		
		Primary channel	Secondary channel features	Bare	Herbaceous	Shrubs	Trees and shrubs	Herbaceous	Shrubs	Trees and shrubs
Oxbow (FPKMs 23-25)	1994	216,200	39,600	21,600	9,900	90,000	–	3,700	26,600	184,900
	2000	211,300	46,600	42,200	33,800	112,300	–	8,200	62,500	107,400
	1994–00	(2%)	18%	94%	241%	25%		121%	135%	(42%)
	2005	168,300	64,300	39,500	45,700	41,000	–	75,000	103,400	134,300
	2000–05	(20%)	38%	(6%)	35%	(64%)		816%	66%	25 %
	2009	157,500	45,200	79,200	68,500	40,900	–	46,700	141,000	103,900
	2005–09	(6%)	(30%)	101%	50%	(<1%)		(38%)	36%	(23%)
	2011	189,800	43,400	68,800	29,700	41,600	13,900	43,400	75,300	171,700
	2009–11	20%	(4%)	(13%)	(57%)	2%		(7%)	(47%)	65%
	2012	180,800	42,300	58,000	39,600	73,500	8,100	64,200	56,000	167,600
	2011–12	(5%)	(3%)	(16%)	33%	77%	(42%)	48%	(26%)	(2%)
	2014	187,900	47,200	50,200	22,900	82,300	14,200	51,500	65,300	170,000
	2012–14	4%	12%	(13%)	(42%)	12%	75%	(20%)	16%	1%
Net change	1994–2014	(13%)	19%	131%	131%	(9%)	2%	1,292%	145%	(8%)

Oxbow Mapping Zone on the McKenzie River

The Oxbow mapping zone near FPKMs 23–25 on the McKenzie River has an active channel that generally is 80–120 m wide, but more than 360 m wide at its widest point in 2009 (fig. 20). The active channel is set in a floodplain as wide as 850 m following the large avulsion between 2000 and 2005. In 1994, the McKenzie River from FPKMs 23 to 25 was nearly 4 km long, owing to the large-amplitude bend near FPKM 24. The river corridor changed greatly from 1994 to 2014, with substantial net changes in channel planform and the area of bare gravel bars, bars with herbaceous vegetated, and floodplain features with herbaceous plants and shrubs (fig. 19*B*; table 12). The following is a timeline of changes in the Oxbow mapping zone from 1994 to 2014:

- Between 1994 and 2000, a narrow (40-m wide) overflow channel had been scoured across the neck of the meander bend at the boundary of FPKMs 23 and 24. Meander migration moved the primary channel northward near the FPKM 23-24 boundary into floodplain trees and southward in FPKM 23 into a mix of vegetated landforms. These channel changes corresponded in bare gravel bars increasing from 21,700 to 42,200 m^2 (about 94 percent), and bars with herbaceous cover increasing from 9,900 to 33,800 m^2 (241 percent), particularly along the meander bend. Floodplain vegetation at the boundary of FPKMs 23 and 24 changed from a trees and shrubs to shrubs and herbaceous cover between years, indicating scour of floodplain landforms with the creation of the overflow channel.
- From 2000 to 2005, a major avulsion occurred near the boundary of FPKMs 23 and 24. The main channel abandoned its meander bend, occupied the scoured area slightly north of the overflow channel, and then widened and moved northward to its location in the 2005 photographs. The avulsion decreased the length of the primary channel, decreasing its mapped area from 211,300 to 168,300 m^2 (about 20 percent) while increasing the area of secondary channels from 46,600 to 64,300 m^2 (about 38 percent). It is noteworthy that the avulsion was responsible for creating the secondary channel feature referred to as the McKenzie Oxbow. Large gravel bars that replaced parts of the floodplain forest flanked the newly carved primary channel. Trees and shrubs become stable in the center of the avulsed bend. The former McKenzie River channel likely was disconnected from the main channel, allowing herbaceous plants and shrubs to establish in the abandoned channel.
- From 2005 to 2009, vegetation transitioned from herbaceous plants to primarily shrubs in the abandoned channel. Changes along the primary channel included channel shifting and corresponding increases in bare bars (39,500–79,200 m^2, about 101 percent) and bars with herbaceous vegetation (45,700–68,500 m^2, about 50 percent), as well as meander migration at the apex of a bend in the newly created main channel near FPKM 23.
- From 2009 to 2011, the primary channel had a stable planform. The much greater photograph discharge for 2011 compared to 2009 probably accounts for some of the increases in the mapped area of primary channel and decreases in the mapped area of bare gravel bars (table 11). Vegetation transitioned to trees and shrubs along the overflow channel.

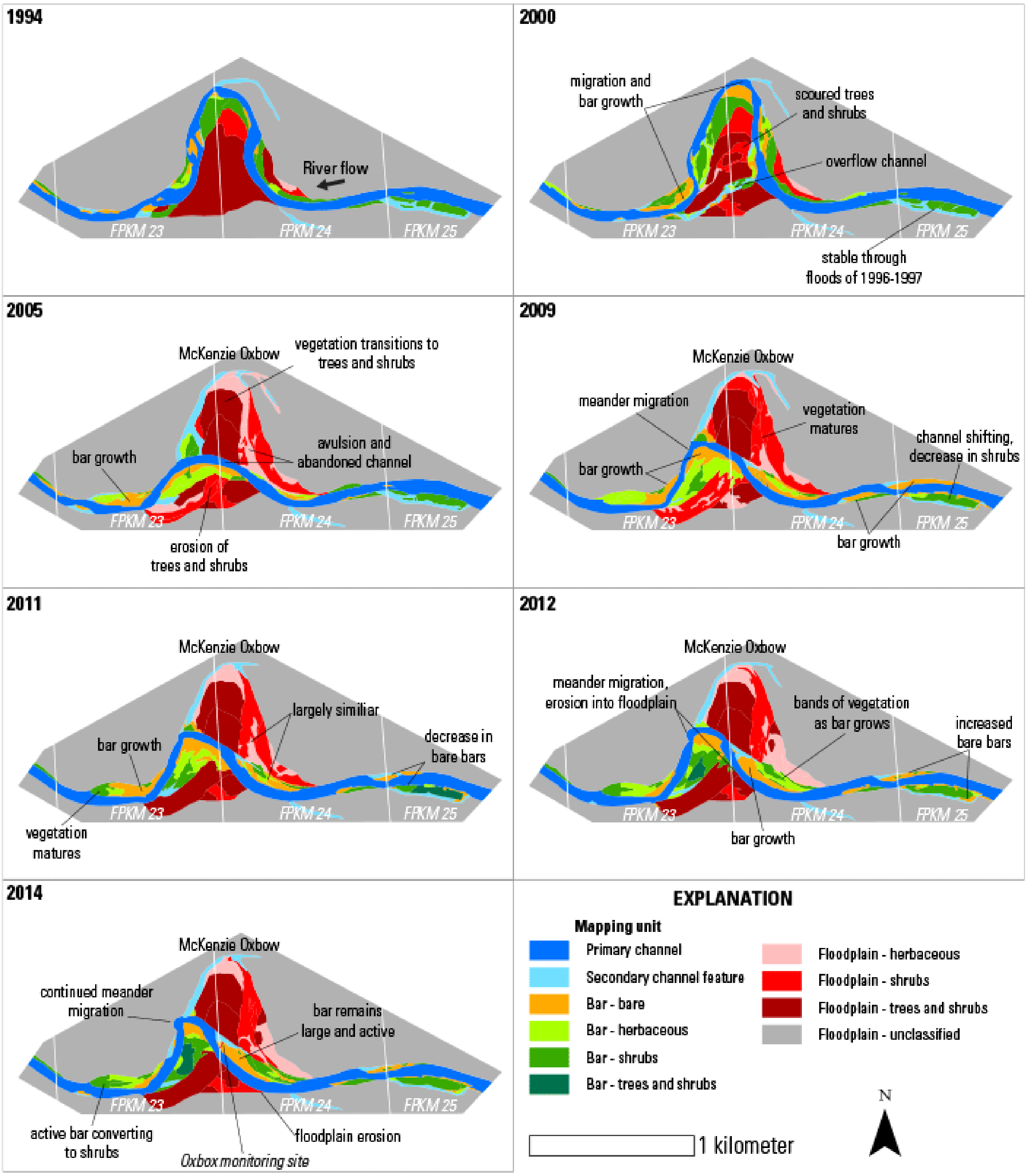


Figure 20. Diagrams showing mapped channels and vegetation features near floodplain kilometers (FPKMs) 23–25 in the Oxbow mapping zone of the McKenzie River, western Oregon, 1994–2014.

- From 2011 to 2012, the apex of the meander bend continued to erode into the floodplain. Bars elongated in FPKM 24, particularly at the head of the overflow channel, and in FPKM 25. Meander migration in two locations opposite the bare bars eroded into floodplain landforms. Other changes included increases in bars with herbaceous plants and shrubs, and in floodplain landforms with herbaceous plants.
- From 2012 to 2014, the meander migration of the large bend continued into the floodplain and some floodplain erosion occurred in FPKM 23. Vegetation on the bar on river left downstream of the bend continued to transition from herbaceous plants (as mapped in 2009) to shrubs and trees by 2014.

Discussion

The mapping zones of the Middle Fork Willamette and McKenzie Rivers historically were geomorphically dynamic, with both zones evolving because of substantial meander migration, avulsions, and cycles of scour, sediment deposition, and vegetation shifts. These zones have continued to show some channel dynamism over the last two decades, but of different magnitudes. The Middle Fork zone has evolved primarily because of small avulsions and short sections of meander migration (fig. 18). This is partly because the zone has several low-amplitude bends, and is confined by bedrock to the south and some revetments to the north (fig. 3). Overall, this zone had little changes in channel planform and the mapped area of most features (table 12). As noted for Task 2, geomorphically effective flows, exceeding the SRP bankfull recommendation of 19,000 ft^3/s on the Middle Fork Willamette River, are responsible for the main channel changes observed from 1994 to 2014. For instance, several bankfull events (for 45 days and peaking at 23,000 ft^3/s) probably triggered the avulsion near FPKM 4 and meander migration near FPKM 6 between 1994 and 2000 (figs. 7*A* and 18; table 6). Later, two bankfull events between 2005 and 2009 (peaking near 23,000 ft^3/s for two and six days), probably triggered the avulsion near FPKM 3 and meander migration at FPKM 4 and 6.

In contrast, the McKenzie zone has evolved because of a large-scale avulsion coupled with continued meander migration and floodplain erosion (fig. 20). These geomorphic changes resulted in substantial changes in channel planform and the mapped area of most features in the McKenzie Oxbow zone from 1994 to 2014 (fig. 19; table 12). These changes occurred partly because the high-amplitude bend of the channel in 1994 created favorable conditions for channel avulsion. The resulting, cumulative channel and vegetation changes from 1994 to 2014 in the McKenzie mapping zone demonstrates how (1) a large flood and subsequent smaller floods can trigger a cascade of channel and vegetation changes, and (2) small floods can trigger meander migration and bar growth. The flood of February 1996 peaked at 56,100 ft^3/s (meeting the SRP large flood recommendation) and persisted for one day above the winter flood recommendation and four days above the winter bankfull recommendation. It likely carved an overflow channel through mature floodplain forest that ultimately became the new primary channel by 2005 (fig. 20). Events on November 19, 1996, and December 28, 1998, peaked at 31,500 and 30,500 ft^3/s, respectively, met the SRP winter high-flow recommendation for 1 day each, and probably contributed to the scouring of the overflow channel. The McKenzie River abandoned its former large-amplitude bend, and occupied the small overflow channel between 2000 and 2005. Antecedent scouring of the overflow channel set the stage for the avulsion, which occurred during a period without bankfull events and when overbank stream power probably was insufficient to trigger this avulsion on its own. This sequence of flow events and geomorphic changes indicates that relatively large-magnitude floods may be needed to generate high overbank shear stresses and to initiate avulsions in areas with floodplain forests, as reported previously for the Willamette Valley by Wallick and others (2006), and for the Waitaki River in New Zealand and Platte River in Nebraska by Tal and others (2004). High-flow events, thus, can establish conditions that allow smaller-magnitude flood events to be geomorphically effective and create a diversity of channel features and vegetation classes.

Small floods also seem sufficient to trigger meander migration and bar growth in the McKenzie Oxbow mapping zone, as shown by the mappings for 2009–11 and 2011–12 (figs. 7*B* and 20). These periods span the January 16, 2011, flood event of 35,200 ft^3/s and January 19, 2012, flood event of 26,700 ft^3/s that meet the SRP small flood and bankfull recommendations, each for 1.5 days. From 2009 to 2012, the channel shifted in several locations, eroding shrubs and creating new bare gravel bars on opposite banks. From 2012 to 2014, peak flows were about 25,000 ft^3/s for 0.5 and 1.5 days. The main geomorphic response during this period was continued channel shifting through vegetated bars near the apex of the meander bend at FPKM 23.

Streamflow and geomorphic processes influenced vegetation in both zones, which is expected for these alluvial rivers. Bankfull floods seem capable of carrying bed-material sediment and scouring herbaceous vegetation that grows on bare bars during summer months (figs. 7, 18, and 20). Periods with frequent bankfull events, small flood events, and active geomorphic processes tended to have a more diverse assemblage of channel and bar features as well as vegetation (figs. 7, 18, and 20). As seen in Task 2, the area of bare bars decreased in the Middle Fork Confluence mapping zone, owing to vegetation establishment between 2000 and 2005, when peak flows had low magnitudes. Bankfull events in subsequent years have triggered an avulsion and vegetation scour in FPKM 3 and channel migration near the boundary of FPKMs 4 and 5. Likewise, flow events and geomorphic processes shape vegetation in the McKenzie Oxbow mapping zone (fig. 20). Higher peak flows (especially the flood of 1996) triggered lateral migration and avulsions that eroded older trees and shrubs from floodplain surfaces, and shrubs and other vegetation from bar surfaces. Herbaceous plants and shrubs later colonized the bars created by meander migration and the 1-km-long, abandoned mainstem channel, as seen in the mapping from 2000 to 2014. The new vegetation persists as of 2014 because it is now outside the area of active meander migration and erosion.

In the mapping zones of the Middle Fork Willamette and McKenzie Rivers, meander migration is an important geomorphic process that erodes landforms and vegetation communities on the advancing bank while depositing sediment that can support vegetation succession on the opposite bank. The presence of large patches of herbaceous plants transitioning to shrubs and trees along the meander bends suggests that many of the hydrologic and vegetation processes for native vegetation likely are in-place in some locations of the mapping zones, at least for certain years. The presence of these large transitional patches also suggests that spring and summer streamflow hydrographs likely are suitable for the establishment of vegetation that can persist during high flows in subsequent winters. For instance, vegetation on the large landforms in FPKMs 4 and 6 in the Middle Fork zone and FPKM 24 in the McKenzie zone were first colonized by herbaceous plants and then by shrubs and trees over the following 5–15 years. If black cottonwoods are growing in these stands, then they would be old enough to reproduce in 2014. Field investigations are warranted to verify that the plants in these mapping zones are those desired by the SRP and regional stakeholders because this mapping analysis cannot identify plant species reliably from the aerial photographs.

Implications for Ecosystems along the River Corridors

Channel changes observed in the mapping zones also help create new, large aquatic habitats. Meander migration helps create gravel bars and the associated downstream alcove habitats, such as near FPKM 6 and the boundary of FPKMs 4 and 5 on the Middle Fork Willamette River (fig. 18) and near the boundary of FPKMs 23 and 24 on the McKenzie River (fig. 20). Avulsions also can help create large secondary channel features. After the avulsion of the McKenzie River between 2000 and 2005, the former mainstem channel became a secondary channel feature that was connected to a preexisting secondary channel feature (fig. 20).This secondary channel feature, known as the McKenzie Oxbow, supports the largest known population of Oregon chub in the McKenzie River Basin (Bangs and others, 2014). Likewise, the large secondary channel feature along the southern edge of the Middle Fork zone in FPKM 4 probably was created by historical channel movements between floodplain forests to the north and bedrock to the south (fig. 3). With the modern flow regimes, aquatic habitats probably will be created mostly by meander migration and small avulsions in the Middle Fork zone, whereas they probably will be created by large-scale avulsions in the McKenzie zone. The resetting of some aquatic habitats may disrupt habitat distributions in the short term, but it is an important process that provides many benefits, such as flushing out fine sediments that can decrease hydraulic connectivity and hyporheic exchange (for example, Brunke and Gonser, 1997) and introducing large wood into the channels.

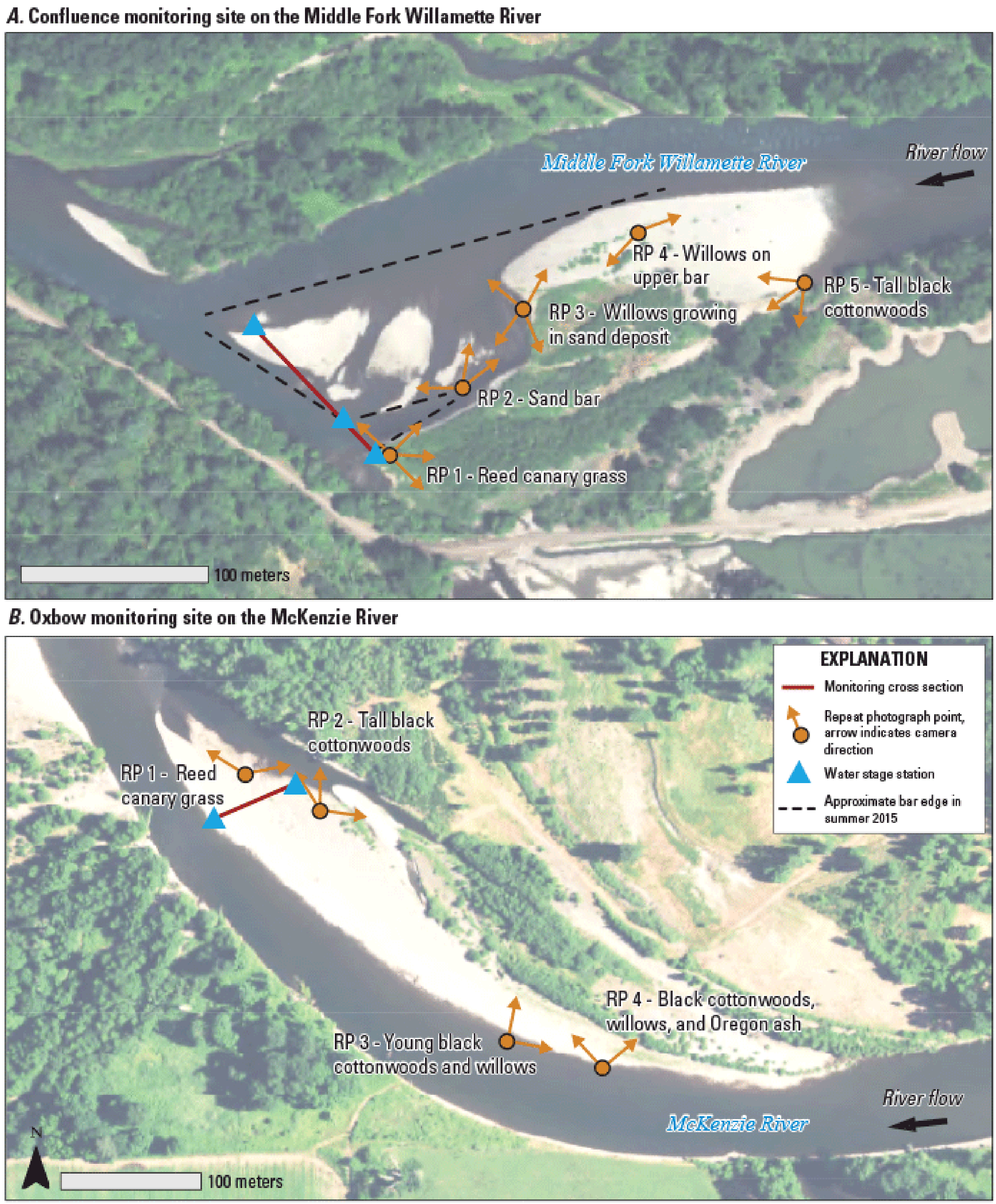
Task 4: Complete a Field Investigation of Stage and the Growth of Black Cottonwood and Other Vegetation on the Middle Fork Willamette and McKenzie Rivers in Summer 2015

The objective of Task 4 was to develop a baseline for the relations between streamflow and black cottonwood recruitment during summer 2015. Work elements were to:

1. Relate water stage observations made at the monitoring sites to discharge recorded at nearby upstream USGS streamgages to develop a baseline for evaluating stage-discharge relations at the sites; and
2. Collect data on particle size, soil moisture, black cottonwood vigor, as well as the vigor, cover, and occurrence of other native and invasive plants.

Sites of Streamflow and Black Cottonwood Observations

Field observations and vegetation monitoring for Task 4 focused on dynamic gravel bars at the TNC Willamette Confluence Preserve on the Middle Fork Willamette River (FKM 5; fig. 21*A*) and the McKenzie Oxbow Conservation Area on the McKenzie River (FPKM 25; fig. 21*B*). Sites for this task were located in the Confluence and Oxbow mapping zones referenced in Task 3.



Base maps modified from U.S. Department of Agriculture digital data, 1-meter resolution. UTM Zone 10N, NAD 1983.

Figure 21. Aerial photographs showing locations of monitoring cross sections, water stage measurements, and repeat photograph points at (*A*) The Nature Conservancy Willamette Confluence Preserve site on Middle Fork Willamette River, and (*B*) McKenzie Oxbow Conservation Area on McKenzie River, western Oregon. Aerial photographs of the Middle Fork Willamette and McKenzie Rivers were collected on June 19, 2014 and June 11, 2014, respectively, by the National Agriculture Inventory Program.

Methods

Data collection at the Confluence and Oxbow vegetation monitoring sites involved establishing cross sections, monitoring water stage, collecting data on black cottonwood and other vegetation, taking repeat photographs, and making particle measurements. Vegetation was monitored about every 3 weeks from June to August (June 3–4, June 25, July 15, and August 6–7, 2015). Water stage observations were taken on these trips as well as on the site reconnaissance trip on May 18, 2015.

Monitoring Cross Sections

Monitoring cross sections (or transects) were established at the downstream ends of the bars perpendicular to flow (fig. 21*A*–*B*), where both bars had alcoves connected to the mainstem. The cross sections then were divided into landforms on the basis of dominant particle size and geomorphic processes (table 13). Landform boundaries, locations of the water edge, and topography were surveyed using a survey-grade Real Time Network-Global Positioning System. Survey equipment accuracy was verified to a local benchmark near each site. Survey accuracy was 0.04 m (1.57 in.) vertical and 0.03 m (1.18 in.) horizontal at the Confluence site, and 0.05 m (1.97 in.) vertical and 0.04 m (1.57 in.) horizontal at the McKenzie Oxbow site.

Water Stage Observations

Distances from the water edge to surveyed stations were measured during each monitoring visit ("water stage stations;" fig. 21*A*–*B*). Measurements were made on the mainstem and alcoves sides of the cross sections as near in time as possible and recorded to the nearest hour. Measured distances were plotted on the surveyed cross sections to determine water stage elevations. Stage observations were compared against discharge readings at nearby USGS streamgages (Middle Fork Willamette at Jasper [14152000] and McKenzie River near Walterville [14163900]). Preliminary stage-discharge relations were developed only for the mainstem sides of the cross sections because flow varied little between the two ends of the cross sections.

Vegetation Monitoring

Vegetation data were collected along the monitoring cross sections using plot and census collection methods. We used plot methods to collect observations and measurements at randomly selected locations that were revisited over the summer, and used census methods to capture overall conditions along the cross sections that may have been missed by the unbiased plot methods.

For vegetation plots, we first established monitoring locations along the cross sections at predetermined, randomly generated locations that were stratified by landform so that plots did not straddle landforms. We placed one plot (1 m^2) per every 5 m of landform length (maximum number of plots = 3). At the Oxbow site, black cottonwood was not initially observed in the randomly placed plots, so we intentionally added two more plots in landforms 1 and 6 where black cottonwood was initially present (table 13). All plot locations were marked with rebar and surveyed, and then revisited during each sampling trip.

Table 13. Landforms, monitoring plots, and black cottonwood presence along the monitoring cross sections at The Nature Conservancy Willamette Confluence Preserve site on Middle Fork Willamette River and the McKenzie Oxbow Conservation Area site on the McKenzie River, western Oregon.

[**D_{50}:** D_{50}, median particle size; mm, millimeter]

Site	Landform				Monitoring plots	
	Number	Description	D_{50} (mm)	Sediment class	Number	Black cottonwood seedling and (or) clone from vegetative fragments, if found
Confluence	1	Active bar to main channel	32	Very coarse gravel	1	Seedling
					2	Seedling
	2	Gravel ridge 1	28.2	Coarse gravel	3	Clone
					4	None
	3	Gravel ridge 2	22.9	Coarse gravel	5	None
					6	None
					7	Clone
	4	Sand ridge 1	0.4	Medium sand	8	Both
					9	Both
					10	None
	5	Sand-gravel swale	0.6	Coarse sand	11	Clone
					12	Seedling
	6	Gravel ridge 3	24.5	Coarse gravel	13	Clone
					14	Seedling
	7	Wet sand to alcove	0.4	Medium sand	15	Both
Oxbow	1	Active bar to main channel	57.2	Very coarse gravel	1	Seedling
					Extra 1	Both
					2	None
	2	Gravel ridge 1	59.8	Very coarse gravel	3	None
					4	None
					5	None
	3	Gravel swale	36.5	Very coarse gravel	6	None
					7	None
	4	Gravel ridge 2	45.9	Very coarse gravel	8	None
					9	None
	5	Sand-gravel mix	0.5	Coarse sand	10	None
					11	None
	6	Wet sand to alcove	0.4	Medium sand	12	None
					Extra 2	Clone

Many observations were made at each surveyed rebar marker during each sampling trip. First, the bottom-center of the plots was aligned with the rebar for consistent monitoring. We then counted the number of black cottonwood (*P. trichocarpa*), willows (*Salix sp.),* bigleaf maple (*Acer macrophyllum*), and Oregon ash (*Fraxinus latifolia*). Stem counts were made for black cottonwood but not for willows. We recorded presence and estimated total aerial cover for all other plants in the plots using cover classes (<1, 1–5, 5–25, 25–50, 50–75, or 75–100 percent). We identified plants in the "other" category to species when possible. Each tree species and "other" plant category were assigned scores for browsing stress, pest damage, drought stress, inundation stress, and overall plot sediment erosion or deposition, with scores ranging from 0 (none) to 3 (high). We removed the armor layer, and estimated the depth to soil moisture near the rebar marker of each plot (0, <0.5, 0.5–1, and >1 cm). Depth to soil moisture is a qualitative indictor of where the observer felt moisture in the soil matrix. For black cottonwood seedlings, we assigned each seedling a number, recorded seedling height and likely reproduction mode (seed or vegetative fragment). Reproductive mode probably was best identified for small (<2 mm) seedlings and vegetative fragments with 1 year of growth. Plants were not excavated to verify reproduction mode. Finally, we took repeat photographs so that individual seedlings and plants in each plot could be tracked over the summer. In some cases, repeat photographs of bigleaf maple, Oregon ash, alder, and red-osier dogwood (*Cornus stolonifera*) individuals also were taken to show changes in these plants over the summer.

For the census monitoring, we established a 3-m-wide buffer on each side of the cross section (6 m across total). For each landform, we estimated the number of black cottonwood, willow, bigleaf maple, and Oregon ash (<25, 25–50, 50-75, 75–100, and >100), and assigned scores data on vegetation health, including browsing, pest, drought, and inundation stress with scores ranging from 0 (none) to 3 (high).We also recorded the names and approximate coverage of other plants by landform. Coverage categories were low, moderate, and high.

Particle Size Measurements

We made two sets of particle measurements at the two monitoring cross sections during the last sampling trip on August 6. We measured the median size of 100 particles along each landform. We also measured particle sizes in each vegetation-monitoring plot by taking the median size of five particles (four corners and center of plot). Both sets of measurements were made using a gravelometer measurement template (Federal Interagency Sediment Project, US SAH–97™ Gravelometer).

Repeat Photographs

Photographs were taken at marked, surveyed locations during each trip to capture changes that were not observed in the monitoring cross sections over the summer (fig. 21*A*–*B*). We established five repeat photograph sites at the Confluence site to capture reed canary grass (*Phalaris arundinacea*) at the southern end of cross section, a high-elevation sand bar at the upstream end of the alcove, willows growing in sand deposited in the middle of the bar, willows on the upper bar, and mature black cottonwoods at the upstream end of the bar. At the Oxbow site, we set up four repeat photograph points to document reed canary grass growing near the alcove outlet, mature black cottonwoods growing above the cut bank at the northeastern end of cross section, young black cottonwood and willows near the middle of the gravel bar, and black cottonwood, willows, and Oregon ash near the upstream end of the gravel bar.

Results

Stage-Discharge Observations

At the Confluence site, stage changed very little from June to August (less than 0.1 ft), indicating the stable discharge at the Jasper streamgage (fig. 22*A*, 22*C*). In contrast, stage varied by about 0.9 ft at the Oxbow site because discharge increased slightly when EWEB closed the Walterville canal for maintenance work (fig. 22*B*, 22*D*). As expected, the site-specific stage measurements and discharge collected at the upstream streamgages have positive linear relations (fig. 22*B*). These relations are preliminary; additional measurements at a wider range of flows are needed to develop robust stage and discharge relations for the SRP program.

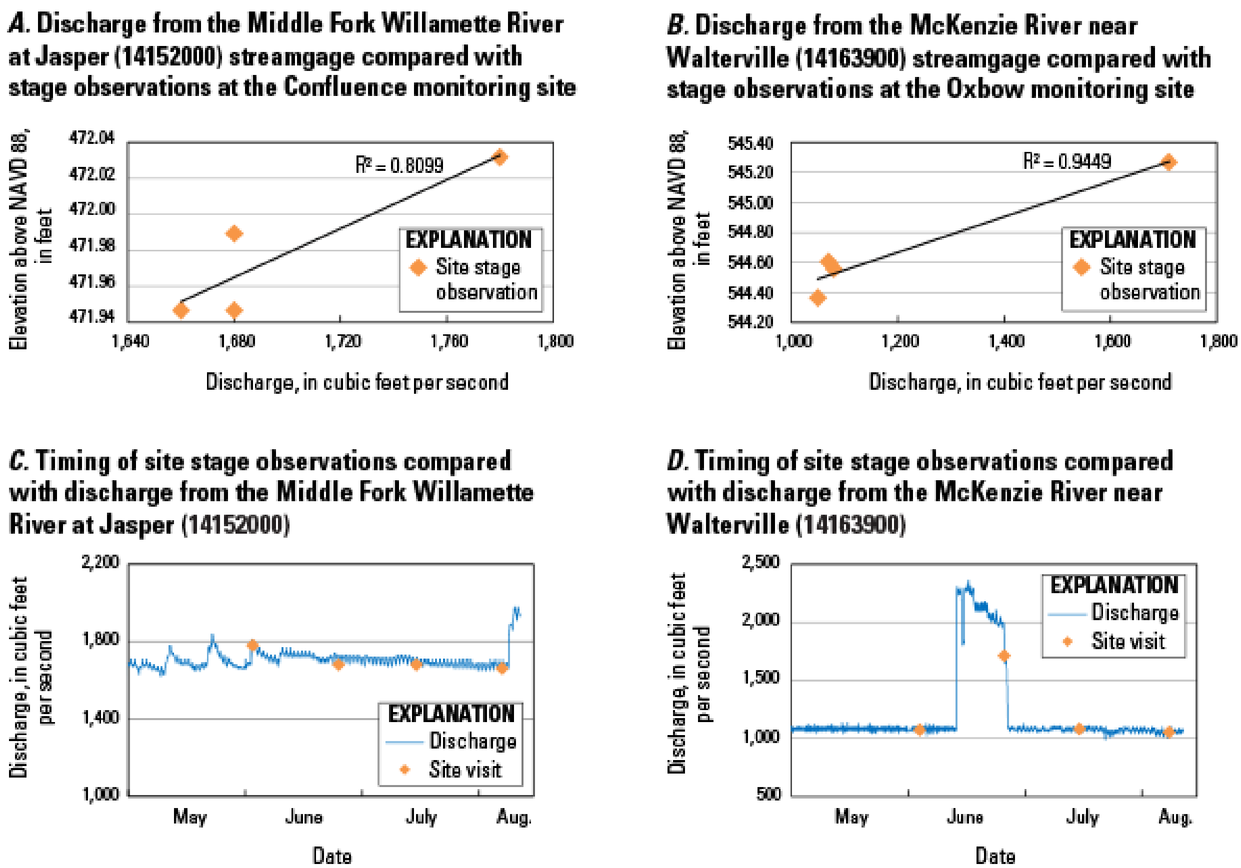


Figure 22. Graphs showing instantaneous discharge at USGS streamgages (Middle Fork Willamette at Jasper [14152000] and McKenzie River near Walterville [14163900]) and stage observations at the Confluence monitoring site on Middle Fork Willamette River (*A*,*C*) and Oxbow Monitoring site on the McKenzie River (*B*,*D*), western Oregon.

Vegetation Monitoring Cross Sections

Monitoring cross sections at the two sites were of similar length, but had different elevations and topography (fig. 23*A–B*). The Confluence site was lower in absolute elevation, had less of an elevation range (0.9 compared to 1.5 m), and had muted topography compared to the Oxbow site. The sites had similar numbers of landforms (7 and 6 at the Confluence and Oxbow sites, respectively) and plots (15 and 14 at the Confluence and Oxbow sites, respectively). The Confluence site had more landforms with sand, especially from the middle of the cross section toward the alcove, whereas the Oxbow site generally had coarser landforms with sand landforms only near the alcove (fig. 23; table 13). Likewise, Oxbow plots generally had coarser surface sediments than the Confluence plots (fig. 24*A–B*; table 13). Subsurface observations for plots near the water edge indicated subsurface materials generally were larger near the mainstem (average subsurface particle sizes of 8 and 11–16 mm for the Confluence and Oxbow sites, respectively) and were less than 2 mm near the alcoves at both sites.

Black Cottonwood Observations

From early June to early August, black cottonwood was observed in 11 of the 15 Confluence plots and 3 of the 14 Oxbow plots (figs. 25 and 26; table 13). Both sites had a mixture of seedlings and vegetative clones. Overall, black cottonwood plants were more numerous and taller in the Confluence plots than in the Oxbow plots. Seedlings and clones in the Confluence plots nearly doubled in height between the first and last sampling trips (fig. 25*B*). Black cottonwood growth in the Oxbow plots was less substantial, but new seedlings were found in Plot 1 and Extra Plot 1 during the last two monitoring trips (fig. 26*A–B*).

During the first monitoring trip, the observer felt moisture in the soil near the surface in nearly one-half of the Confluence plots (fig. 25*C*), but only in the Oxbow plots near the mainstem and alcove (fig, 26*C*). Some of the soil moisture at the Confluence site may be attributable to some rainfall the day and night before the June 3 trip. As expected, depth to soil moisture generally decreased over the summer at both sites. Exceptions were plots near the mainstem and alcoves at both sites.

Over the summer, black cottonwoods in the monitoring plots experienced some browsing and pest stress at these sites (figs. 27*A–B* and 28*A–B*). Based on scat and track observations, deer were the likely browsers, decreasing the heights of some plants to a few centimeters (fig. 29). Pests included larval and adult forms of beetles, such as possibly striped willow leaf beetle (*Disonycha alternata*). Pest damage resulted in skeletal, dry leaves on black cottonwoods and willows across the Confluence plots and primarily at the Oxbow plots near the mainstem. Pest damage generally seemed to diminish somewhat over the summer, and plants tended to rebound from browsing and pest damage (fig. 29).

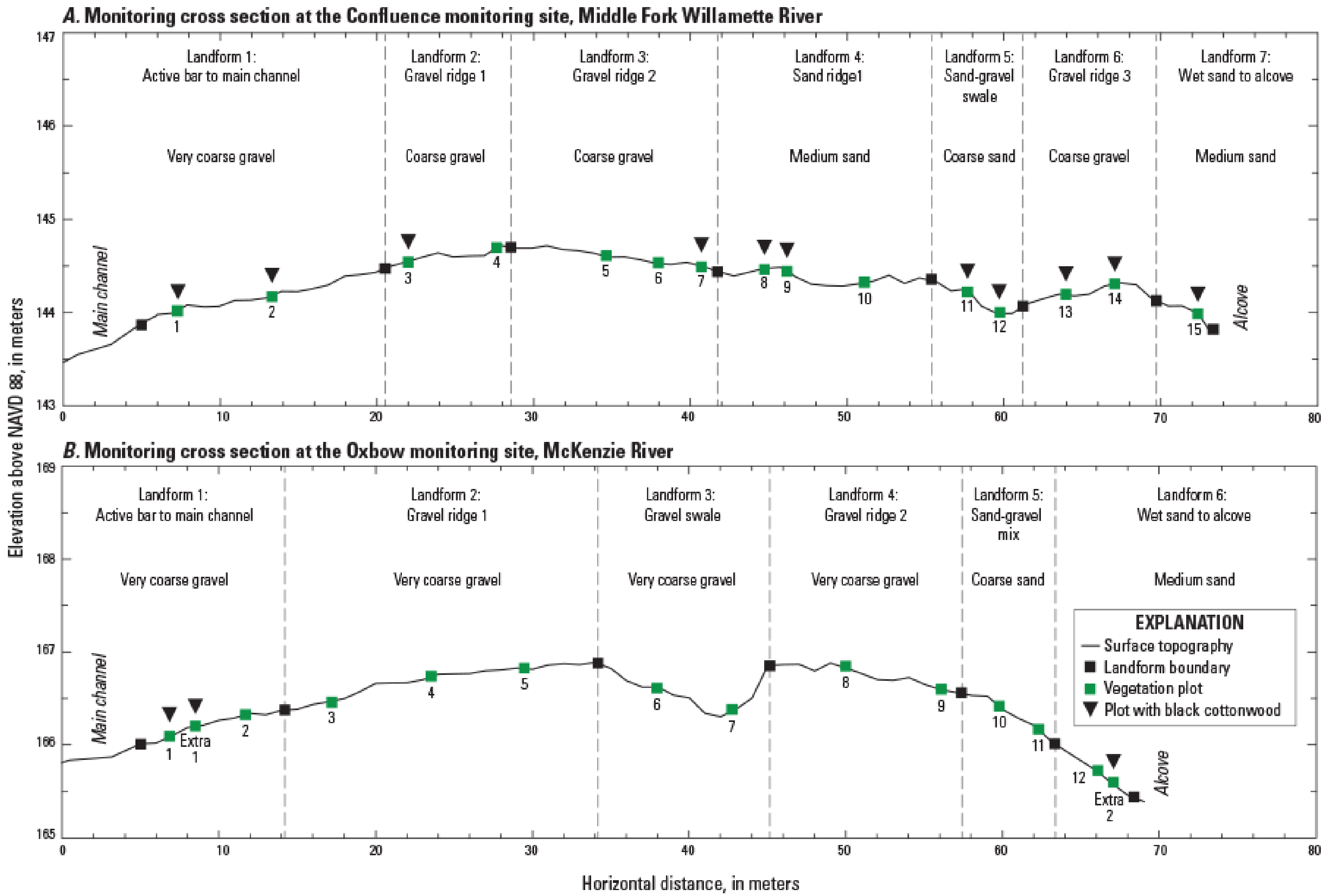


Figure 23. Graphs showing landforms and vegetation plots along monitoring cross sections at (*A*) The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, and (*B*) McKenzie Oxbow Conservation Area site on the McKenzie River, western Oregon.

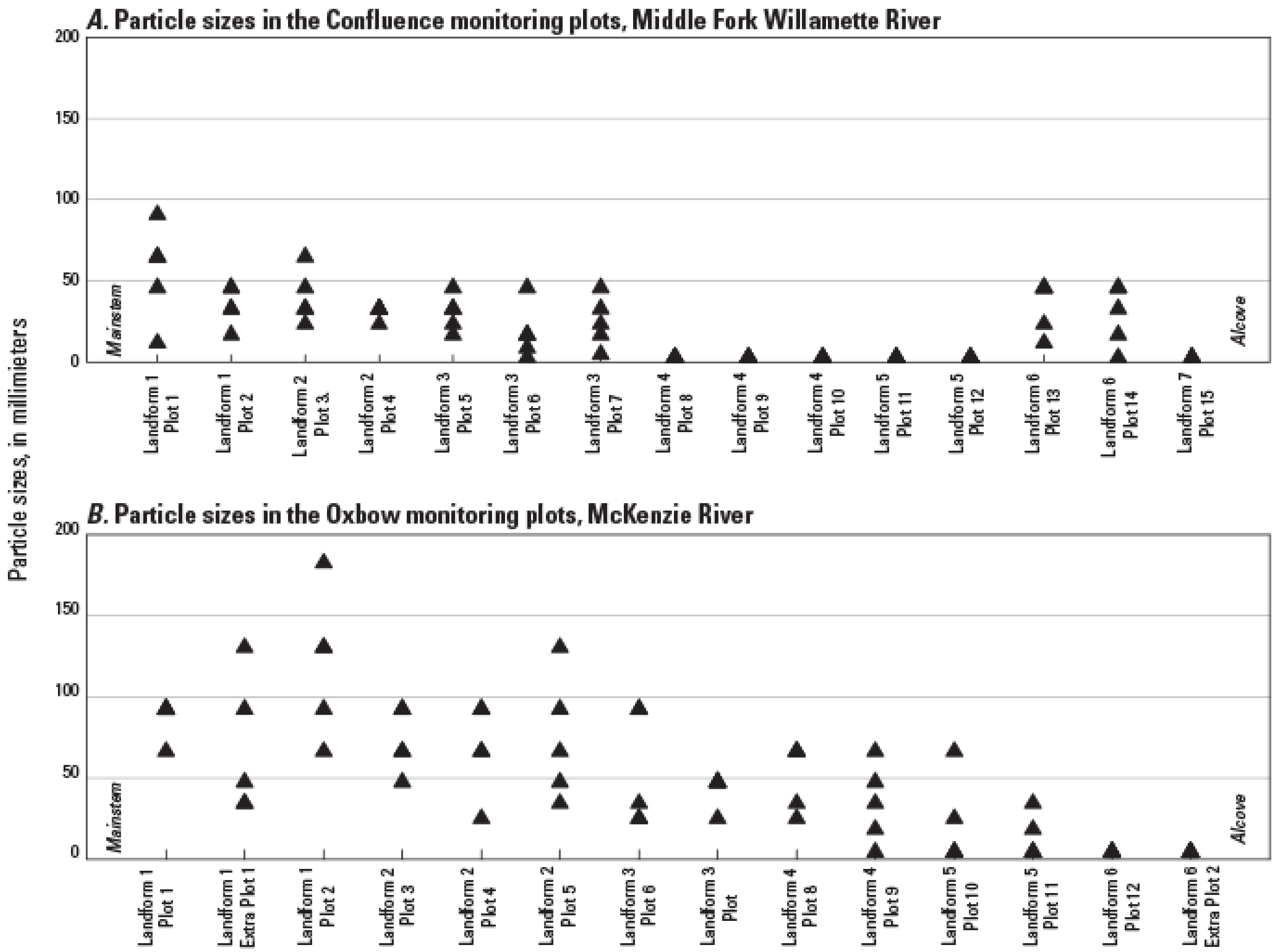


Figure 24. Five particle measurements made in plots along monitoring cross sections at (*A*) The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, and (*B*) McKenzie Oxbow Conservation Area site on the McKenzie River, western Oregon. Particle size measurements overlapped for plots where five points are not visible.

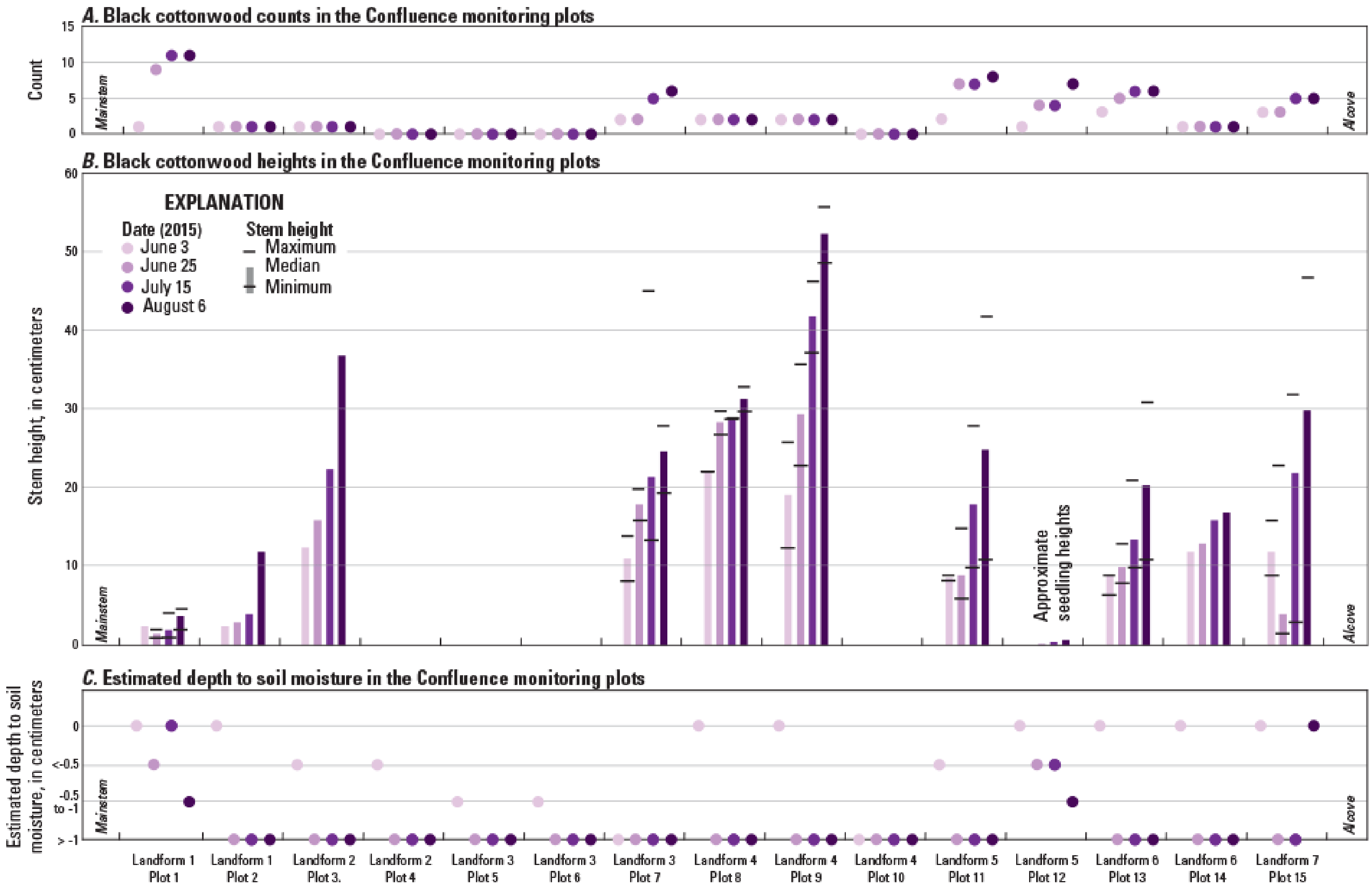


Figure 25. Graphs showing observations of (*A*) black cottonwood counts, (*B*) black cottonwood heights, and (*C*) depth to soil moisture over the monitoring season at The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, western Oregon.

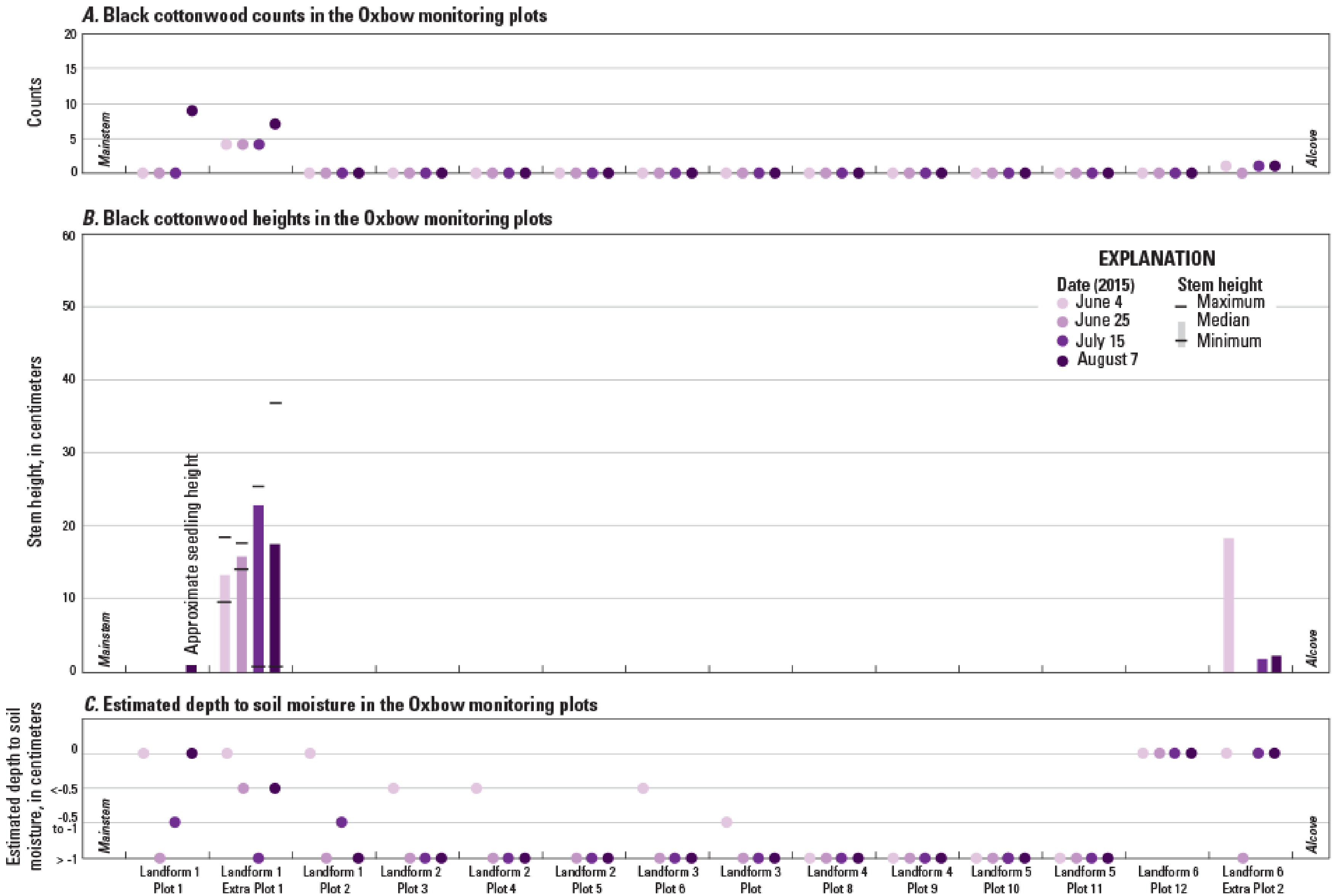


Figure 26. Graphs showing observations of (*A*) black cottonwood counts, (*B*) black cottonwood heights, and (*C*) depth to soil moisture over the monitoring season at the McKenzie Oxbow Conservation Area site on the McKenzie River, western Oregon.

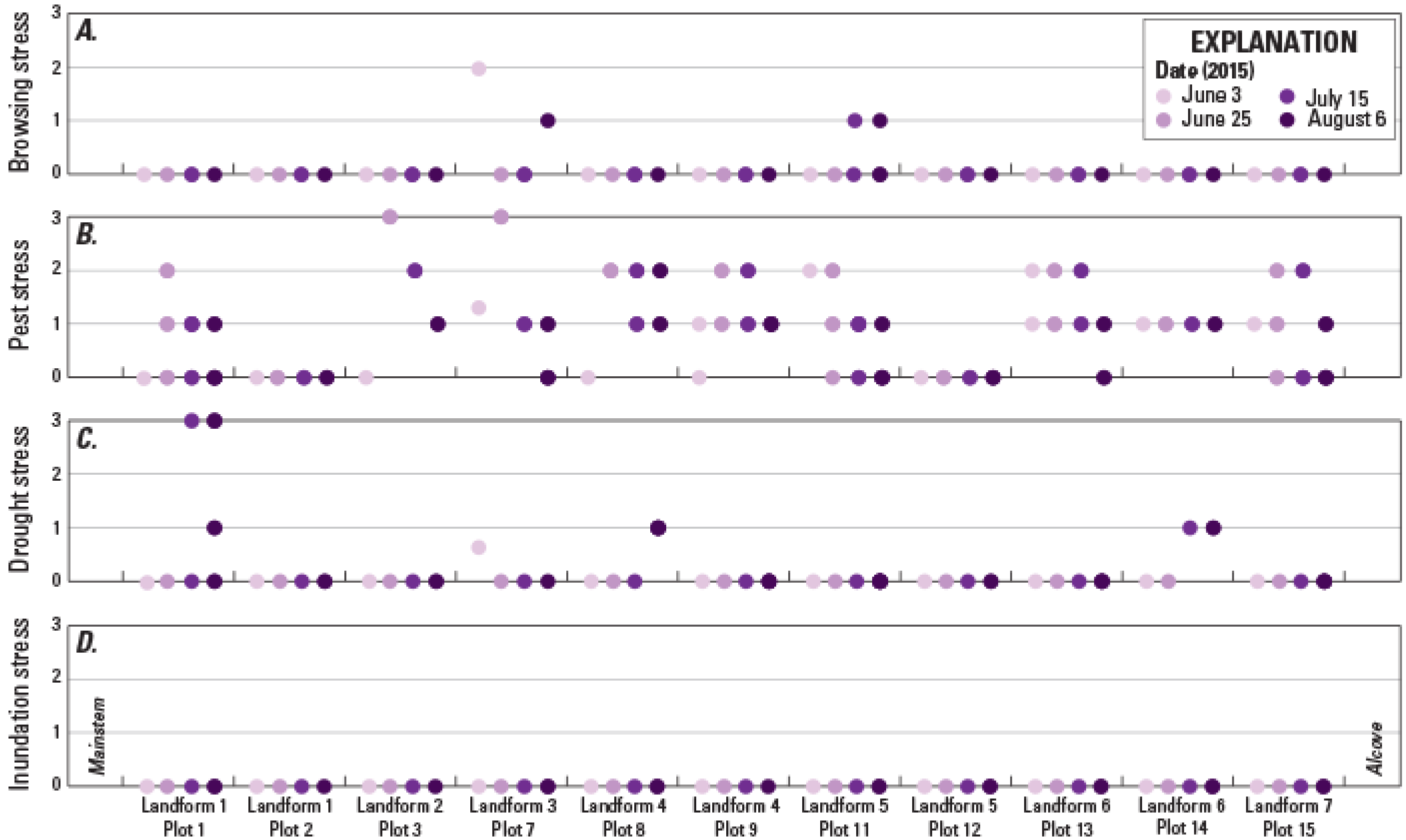


Figure 27. Graphs showing observations of (*A*) browsing, (*B*) pest, (*C*) drought, and (*D*) inundation stress for black cottonwood over the monitoring season at The Nature Conservancy Willamette Confluence Preserve site, Middle Fork Willamette River, western Oregon. Only monitoring plots with black cottonwood are shown. Stress levels were ranked qualitatively in the field from 0 (none) to 3 (high).

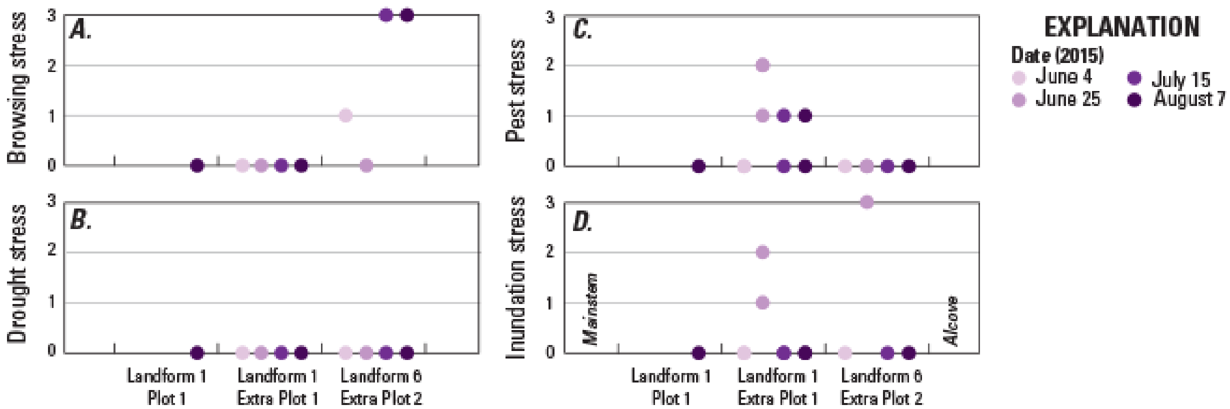


Figure 28. Graphs showing observations of (*A*) browsing, (*B*) pest, (*C*) drought, and (*D*) inundation stress for black cottonwood over the monitoring season at the McKenzie Oxbow Conservation Area site, McKenzie River, western Oregon. Only monitoring plots with black cottonwood are shown. Stress levels were ranked qualitatively in the field from 0 (none) to 3 (high).

A. **June 3, 2015**
Heavy browsing on the left stem of a black cottonwod vegetative clone

B. **June 25, 2015**
Pest damage contributes to a dry black cottonwood clone with skeletal leaves; the invasive bird's-foot trefoil with yellow flowers grows around the clone

C. **July 15, 2015**
Stems of the vegetative clone recovered from the browsing and pest damage

D. **August 6, 2015**
Vegetative clone continues to grow and appears healthy

Figure 29. Photographs of repeat plot showing black cottonwood with browsing and pest damage and subsequent recovery in Plot 7 at The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, western Oregon, (*A*) June 3, (*B*), June 25, (*C*), July 15, and (*D*), August 6, 2015.

Some black cottonwoods in the monitoring plots showed signs of drought or inundation stress (figs. 27*C*–*D*, and 28*C*–*C*). At the Confluence site, drought stress was noted in Plots 1and 14 on the third monitoring trip, and in Plots 1, 8, and 14 on the last monitoring trip. Some of these plants were dried and shriveled on the third trip, and one seedling in Plot 1 had died by the third trip. In contrast, the two Oxbow plots with black cottonwood throughout the summer (Extra Plots 1 and 2) did not have any observed drought stress, but were inundated during the second trip (fig. 30*A*–*H*). Three of the four black cottonwoods in Extra Plot 1 survived the inundation and recovered by the fourth trip. One stem was lying flat and completely underwater during the second trip, and then appeared dead on following trips. The one black cottonwood in Extra Plot 2 that survived inundation was found browsed to a stub on the third trip and then still low in height with a small new stem growth on the fourth trip. This plant probably was browsed down before the inundation because the field crew was unable to find the plant when searching the plot. The increased soil moisture after the period of inundation likely allowed seedling growth observed during the last trip in Oxbow Plot 1. Owing to the limited inundation observed during summer 2015, we did not observe any indications of sediment erosion or deposition in any plots.

Black cottonwood seedlings and clones often grew alongside other plants in the monitoring plots. The coverage of plants in the "other" category increased substantially over the summer throughout the Confluence site, especially in Plots 8–15 that were dominated by sand and near the alcove (fig. 31*A*). At the Oxbow site, substantial increases in plant cover seemed to occur primarily near the mainstem in Plots 1, 2, and Extra Plot 1 as well as in Extra Plot 2 and Plot 12 near the alcove (fig. 31*B*).

Figure 30. Photographs of repeat plot showing black cottonwood with some inundation in Extra Plots 1 (*A–D*) and 2 (*E–H*) at the McKenzie Oxbow Conservation Area site on the McKenzie River, western Oregon, 2015.

Figure 31. Graphs showing coverage of non-black cottonwood plants in monitoring plots at (*A*) The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, and (*B*) McKenzie Oxbow Conservation Area on the McKenzie River, western Oregon, June 3–August 7, 2015.

The plants observed alongside black cottonwood varied along the monitoring cross sections. At the Confluence site, some plots had few plants other than black cottonwood and willow seedlings, such as Plot 1. Other Confluence plots had greater coverage of other plants. For instance, Confluence Plots 7 and 11 had large coverage of two invasive species, bird’s-foot trefoil (*Lotus corniculatus*) and white sweet clover (*Melilotus alba*; figs. 29 and 32). Compared to the Confluence plots, the three Oxbow plots with black cottonwood generally had less coverage of other plants. Oxbow Extra Plot 1 had some marshpepper knotweed (*Persicaria hydropiper*), reed canary grass (*P. arundinaceae*), foxglove (*Digitalis purpurea*), and bird’s-foot trefoil (fig. 30*A–D*). Oxbow Extra Plot 2 had greater coverage of plants, including willow seedlings, marshpepper knotweed, reed canary grass, bird’s-foot trefoil, and unidentified grasses (figs. 30*A–H*). Oxbow Plot 1 had some black cottonwood seedlings during the fourth monitoring trip, as well as bird’s-foot trefoil and reed canary grass.

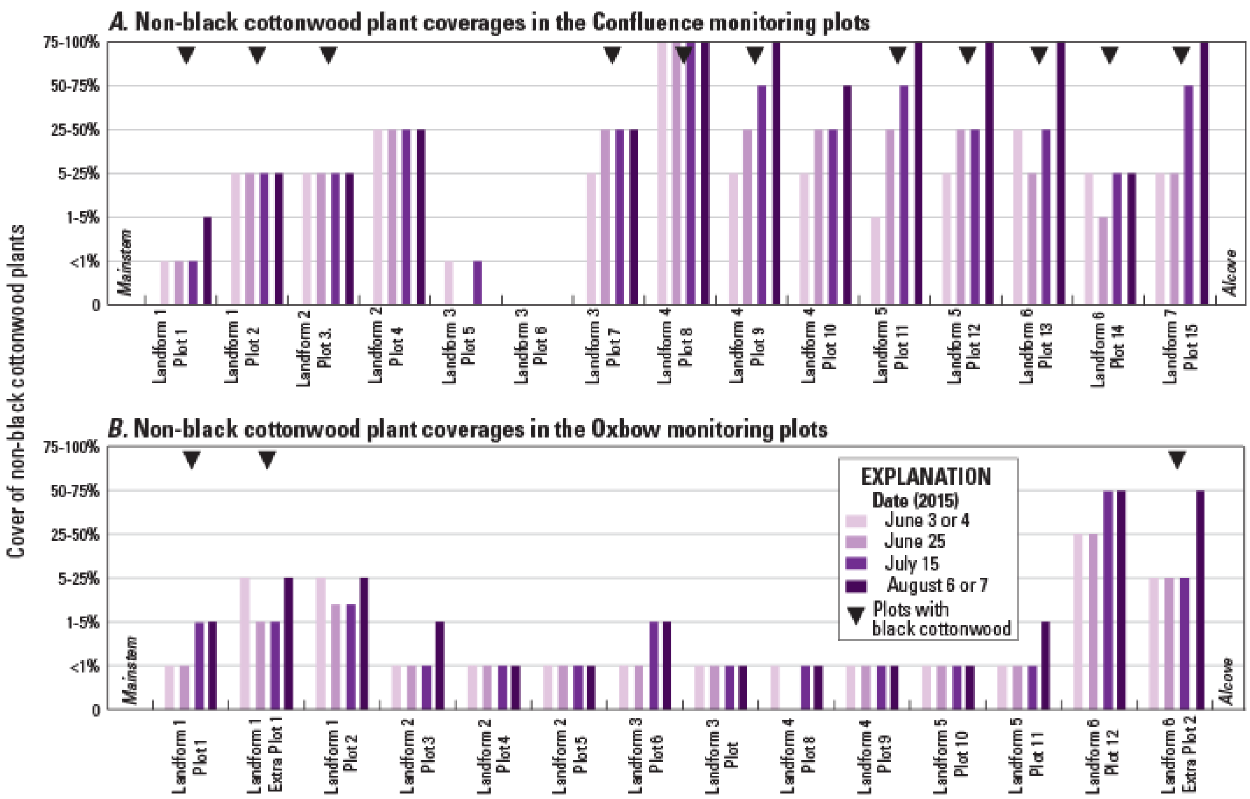


Figure 32. Photographs of repeat plot showing black cottonwood with other plants in Plot 11 at The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, western Oregon, (*A*) June 3, (*B*), June 25, (*C*), July 15, and (*D*), August 6, 2015.

Census monitoring across the entire monitoring cross section showed that common plants included native willows, bigleaf maple, and red-osier dogwood, as well as invasive marshpepper knotweed, white sweet clover, bird's-foot trefoil, and reed canary grass. Field observations indicate that parts of the Oxbow site, such as near the alcove, had different willow species than the Confluence site. Less common plants included white alder (*Alnus rhombifolia*), Douglas- fir (*Pseudotsuga menziesii*), foxglove (*Digitalis spp.),* and lupine (*Lupinus spp.).* As seen in the monitoring plots, coverage by these other plants increased in the landforms near the alcoves and mainstem over the summer (figs. 33*A*–*B*). Additionally, Confluence landforms 4 and 5 were partially within a small swale with medium and coarse sand, respectively. These two landforms had moderate–to-high coverage by other plants throughout the summer.

Outside the monitoring plots, we observed black cottonwoods at the sites and on adjacent landforms (fig. 34). For instance, black cottonwoods (about 10–15 m tall) were in a thicket of willows near the middle of the Oxbow bar. We did not see similar black cottonwoods emerging from a willow thicket near repeat photograph point 3 at the Confluence site. This surface was deposited between 1994 and 2000 (fig. 18). Other locations of older black cottonwoods, with heights ranging from about 30 to 60 m, were observed in multiple locations at both sites. For instance, most of the older black cottonwood stands near the Confluence and Oxbow sites were established prior to 1994 (figs. 18 and 34).

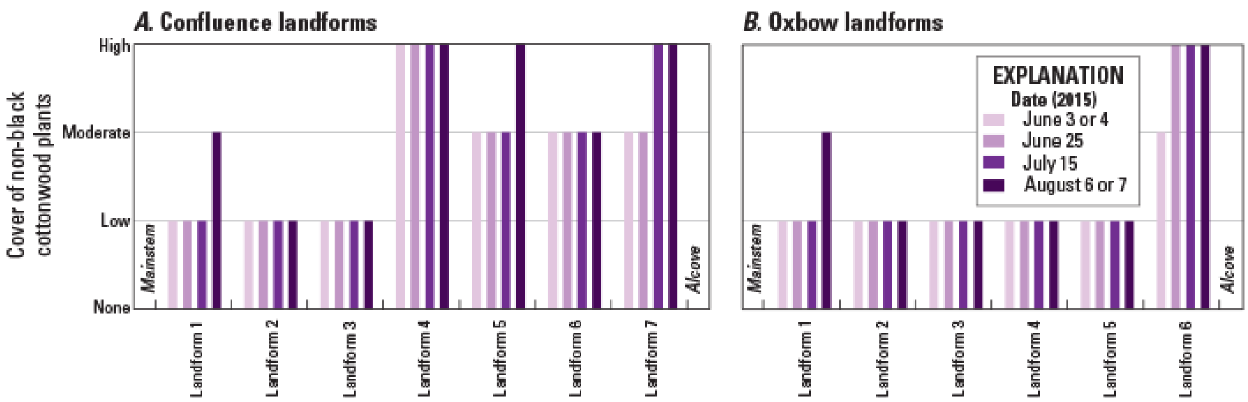


Figure 33. Graphs showing coverage of non-black cottonwood plants recorded during census surveys at (*A*) The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, and (*B*) McKenzie Oxbow Conservation Area on the McKenzie River, western Oregon, June 3–August 7, 2015.

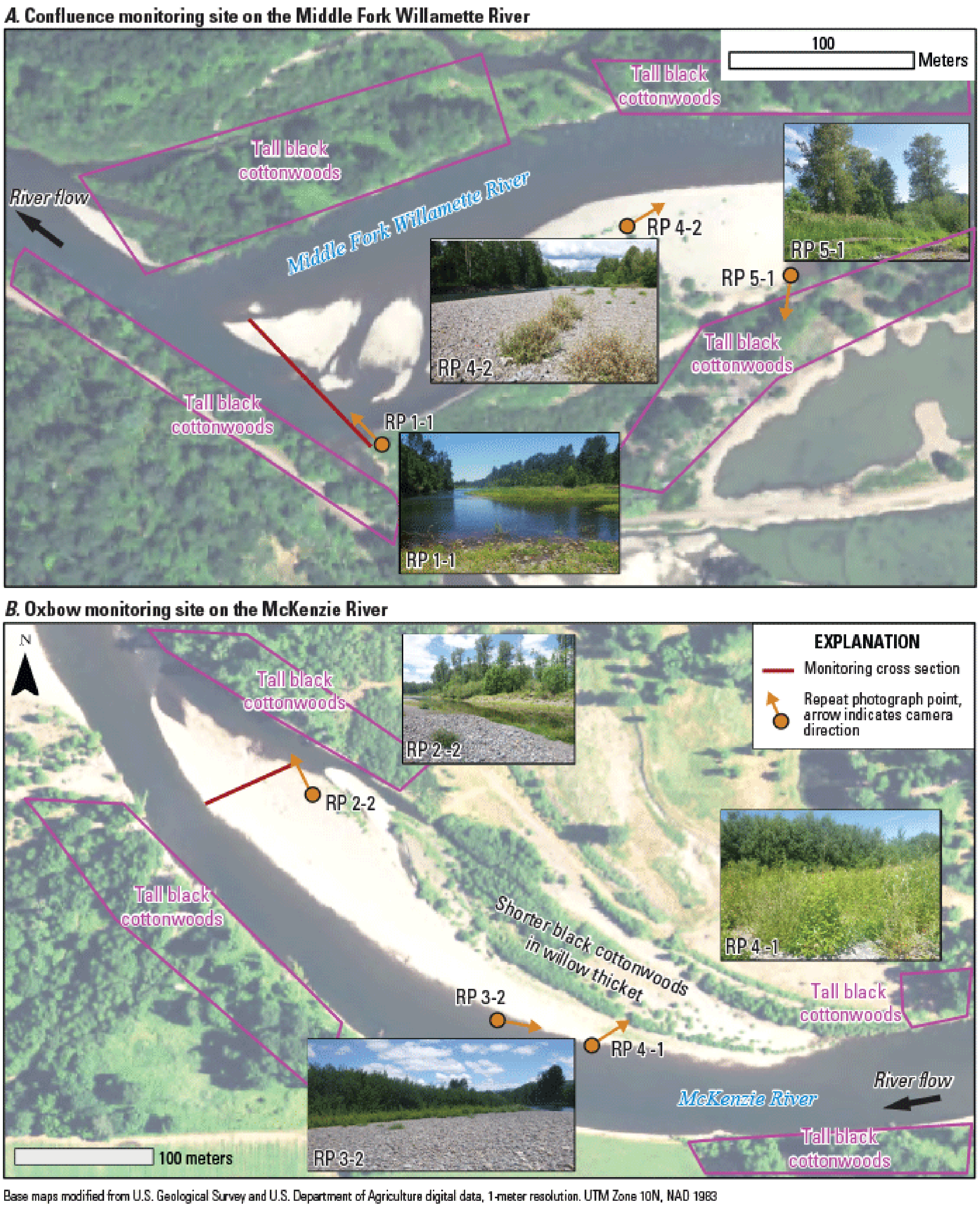


Figure 34. Aerial and ground photographs showing approximate locations of older black cottonwoods observed at the monitoring sites and on adjacent landforms at (*A*) The Nature Conservancy Willamette Confluence Preserve site on the Middle Fork Willamette River, and (*B*) McKenzie Oxbow Conservation Area on McKenzie River, western Oregon. Aerial photographs of the Middle Fork Willamette and McKenzie Rivers were collected on June 19, 2014 and June 11, 2014, respectively, by the National Agriculture Inventory Program. Field photographs were taken from June 3, 2015.

Discussion

Vegetation monitoring provides multiple snapshots of black cottonwood and their vigor for summer 2015. Conditions during this summer included low streamflow, air temperature exceeding 90°F for prolonged periods, and limited snowmelt water for summer flow releases from the dams. As such, the flow regime of this summer deviates from that of other years where decreased spring flows and elevated summer flows typically pose challenges for black cottonwood recruitment (Gregory and others, 2007a; Risley and others 2010a). For instance, if this sampling had occurred in an average or large flow year, we probably would have observed more pronounced effects of the spring recession rates on black cottonwood as well as higher summer flows and more inundation of plants at the Confluence and Oxbow sites.

Stage Observations in Relation to Discharge

In summer 2015, streamflow changed little at USGS streamgages upstream of the Confluence and Oxbow sites. Accordingly, site-specific stage measurements varied by less than 1 ft in elevation. The one exception to this low-flow regime was when flows temporarily increased in mid-to-late June at the Oxbow site (fig. 22*D*) because of maintenance closure at the Walterville Canal. Four of the Oxbow plots were fully or partially submerged during this trip (fig. 30). Despite this change in discharge, only the soil moisture measurements in the inundated plots seemed to follow the streamflow changes. Depth to soil moisture in all other Oxbow plots continued to increase over the summer (fig. 26*C*). Collection of future stage data could be improved by recording the time of collection to the nearest one-fourth hour to match the interval of instantaneous discharge collection at USGS streamgages. In some cases, the instantaneous discharge data shows variations on the order of 10–20 ft^3/s within 15 min of our recorded stage measurement time.

Black Cottonwood and Other Vegetation Observations

Young seedlings and clones from vegetative fragments were more numerous at the Confluence site than the Oxbow site (figs. 25 and 26), likely owing to lower bar elevation (fig. 23*A*) and fine sediment deposits that probably are sourced from the releases of Fall Creek Dam at the Confluence site. The low-elevation setting of the Confluence bar allowed some plots, such as Confluence Plot 12, to support seedling growth throughout the monitoring window (fig. 25). In contrast, the Oxbow monitoring cross section was higher elevation (fig. 23*B*) and primarily coarse sediments lacking an overlay of fine sediment. Only Extra Plots 1 and 2 and later Plot 1 at the Oxbow site supported black cottonwood, probably owing to their closer proximity to the water table than the remaining Oxbow plots and transect (fig. 26*A–C*).

Overall, most cottonwood clones and seedlings in the monitoring plots appeared in good condition over the summer, increasing in height and number of stems and rebounding from pest damage (figs. 27, 28, and 29). We observed a total of 157 and 33 black cottonwoods at the Confluence and Oxbow sites, respectively, and only 1 mortality per site. The mortality in Confluence Plot 1 probably was related to drought stress, whereas the 1 mortality at the Oxbow site occurred after the period of inundation. At this time (2016), it remains unknown whether the remaining 190 black cottonwoods will survive the remainder of the growing season and winter high flows. A probable outcome is that most black cottonwood seedlings and clones near the mainstem channels likely will be scoured during the subsequent winter because these plants established on surfaces exposed since February 2015. The survivorship of black cottonwoods that are further away from the mainstem channel will depend on the magnitude and duration of flows in subsequent years.

Along the monitoring cross sections, we observed other native plants, such as willows and bigleaf maple, and invasive plants, such as reed canary grass, marshpepper knotweed, white sweet clover, and bird's-foot trefoil. Throughout the monitoring plots and cross sections, these four invasive plants were the most ubiquitous plants, increasing in coverage over the summer. These four plants have the potential to limit the germination and recruitment of black cottonwood through several mechanisms. For instance, reed canary grass tends to form a monoculture with tall foliage and dense rhizomatous mats, excluding most other vegetation except previously established tall, woody vegetation. We generally did not observe dense stands of reed canary grass in our monitoring plots, but did observe these types of stands near Confluence Repeat Photograph Point 1 and Oxbow Repeat Photograph Point 1. In the monitoring plots, we generally observed more marshpepper knotweed, white sweet clover, and bird's-foot trefoil. These three plants can grow rapidly, cover bare surfaces, and compete with black cottonwood for resources such as sunlight, water, and nutrients. Some species may shade seedlings with their height (such as white sweet clover) or sprawling form (such as bird's-foot trefoil and marshpepper knotweed). During this study, we observed black cottonwood clones and seedlings in Confluence Plots 2, 11, and 12 persisting over the summer, despite some shade and increasing coverage by bird's-foot trefoil and marshpepper knotweed (fig. 32). Field observations suggest the canopy provided by these invasive plants may have helped maintain soil moisture, creating a cool and humid microclimate for the young black cottonwoods, although the effects of competition for water and nutrients is unknown. These preliminary observations suggest that invasive plants are not entirely preventing black cottonwood growth, but the overall effect on recruitment is unknown. From this initial set of observations, we hypothesize that interspecies plant competition may be greatest in sand landforms near sheltered alcoves and less in gravel landforms near the primary channel that are subject to annual scouring and active bedload transport.

To date (2016), environmental flow efforts in the Willamette River Basin have tended to emphasize the importance of black cottonwood recruitment by seedlings (Gregory and others 2007a, 2007b; Risley 2010a, 2010b). However, seedlings and clones from vegetative fragments—two different recruitment pathways for black cottonwood—were observed at both monitoring cross sections. Seedlings were more numerous than clones, and generally were present near the water edge or where shade helped maintain soil moisture. This is because seedlings require moist, bare soils for germination. In contrast, clones tended to be less numerous than seedlings, but were present farther away from the water edge where they are possibly less exposed to scouring flows. Clones tend to be larger and able to grow where moisture is limiting because they can draw on the stored energy and moisture in their vegetative fragments (Wilson, 1970; Rood and others, 2003). For example, we found that seedlings typically were less than 1 cm tall and apparent clones were more than 5 cm tall at the beginning of the monitoring season (figs. 25 and 26; table 13). Clones were observed along the monitoring cross sections at a range of elevations, emerging from the canopy of invasive plants, and rebounding from drought, browsing, and pest stress. One hypothesis is that clones may have a temporal and height advantage over seedlings because clones may establish earlier in the season and gain height before invasive plants. However, seedlings maintain the genetic diversity of the cottonwood population. Further investigation is warranted to examine the relative advantages of these black cottonwood reproductive strategies in the modern Middle Fork Willamette and McKenzie Rivers.

Synthesis of Findings

Collectively, the results of the four study tasks provide emerging science to support adaptive management of environmental flows as well as highlight some outstanding questions.

Emerging Science to Support Adaptive Management of Environmental Flows on the Middle Fork Willamette River Basin

The streamflow analyses (Task 1) and channel change mapping (Task 2) provide information on the relation between environmental flows and geomorphic processes. From 2005 to 2012, the major changes in the alluvial section of this river included increases in bar area and changes in the location of bare gravel bars (figs. 13, 14, and 16). These geomorphic changes coincided with four flood events exceeding the Sustainable Rivers Project (SRP) recommendations for winter bankfull flows (19,000 cubic feet per second [ft^3/s]; Gregory and others, 2007b). Together, the results of the mapping and flow analyses show that bankfull flows, like those that occurred between 2006 and 2011, are capable of triggering considerable localized channel changes, even along a predominantly stable channel like the Middle Fork Willamette River in western Oregon. Thus, 19,000 ft^3/s seems to be a reasonable proxy for geomorphically effective flows in the alluvial section of the Middle Fork Willamette River.

Flow magnitude, however, is not the only component to consider when evaluating geomorphically effective flows for the SRP. Flow duration is another key component. As described for Task 2, we found that long duration, large-magnitude bankfull flows on the Middle Fork Willamette River are more geomorphically effective than shorter-duration floods of similar magnitude. This is because longer-duration flow events can scour bars, reset vegetation, and trigger substantial but localized channel changes, whereas shorter-duration flow events influence the size and location of gravel bars and propagate meander migration. As SRP implementation moves forward, it would be useful to evaluate the geomorphic effects caused by long-duration, low-magnitude events as well as short-duration, large-magnitude events. Such an investigation is warranted to better understand the balance of costs and benefits these two types of events have for flood risk, stored water resources, year-round dam operations, and other factors.

More detailed mapping for a smaller section of the Middle Fork Willamette River near floodplain kilometer (FPKM) 5 also shows the creation of bare gravel bars and subsequent succession of bare bars from herbaceous plants to shrubs and trees from 1994 to 2014 (figs. 18 and 19). These changes indicate some active geomorphic processes and vegetation succession despite the overall geomorphic stability of the river (Wallick and others, 2013). Nonetheless, the magnitude of modern active geomorphic and vegetation processes remains substantially less than historical processes, owing to revetments and diminished gravel supply (Wallick and others, 2013).

The evidence of geomorphically effective flows and vegetation succession on the Middle Fork Willamette River are two findings that are applicable to ongoing SRP flow implementation in this basin. They help set a realistic context for geomorphic and large-scale vegetation responses to a range of streamflows within the modern constraints of the river. As such, this information may help the USACE, TNC, and regulatory and management agencies in the basin to refine and adaptively manage environmental flow releases as new management priorities and scientific insights emerge.

Finally, drawdowns of Fall Creek Dam for fish passage will be continued in the future and likely will supply fine sediment to the Middle Fork Willamette River. Fine sediment deposits can form beneficial habitats for native species, such as rearing habitats for larval lamprey or germination sites for black cottonwood. Conversely, fine sediment also may block side channels and sloughs used by native Oregon chub as well as support the establishment of some invasive plants, such as reed canary grass, marshpepper knotweed, white sweet clover, and bird's-foot trefoil, which seem to thrive in sandy environments. Understanding the range of ecological effects of these drawdowns would be helpful for identifying combinations of drawdowns and streamflow regimes that may benefit native species. Findings from the Middle Fork Willamette River could potentially be used to inform planning for future drawdowns that may be implemented at other USACE dams in the Willamette River Basin.

Emerging Science Linking Streamflow, Geomorphic Processes, and Black Cottonwood in the McKenzie Oxbow Mapping Zone

The mapping zone of the McKenzie River near FPKMs 23–25 has active recruitment of black cottonwood, as indicated by the young black cottonwoods emerging from the willow canopy at the Oxbow site on the McKenzie River (fig. 34*B*). From the mapping, we can see that the gravel bar surface at this location formed primarily between 2005 and 2009, as the channel shifted westward following its avulsion between 2000 and 2005 and sediment was deposited on the north bank (fig. 20). Herbaceous vegetation colonizing bare gravel bars and transitioning to shrubs and trees also was observed over the last 5–15 years. The cohort of young black cottonwoods (and willows) is about 10 years old. These trees are evidence of active recruitment of black cottonwoods at this relatively geomorphically dynamic zone in the upper part of the alluvial McKenzie River. Here, streamflows are influenced by dam releases, canals, and flow from unregulated tributaries, but some banks are erodible (fig. 4). This active recruitment is related to the cascade of geomorphic change probably initiated by the large February 1996 flood, and reworked by subsequent peak flows. The successful recruitment of black cottonwood and willow in this mapping zone suggests that streamflows suitable for vegetation establishment are in place at least in some years.

However, observations from this more dynamic setting are not directly transferable to the entire alluvial McKenzie River. This is because downstream sections receive inputs of flow and sediment from unregulated tributaries and have revetments and bedrock outcrops that limit meander migration and avulsions at key locations (fig. 4; table 4). As such, future efforts will be needed to define geomorphically effective flows for the entire alluvial section of the McKenzie River. Extending the channel and vegetation mapping done for Task 3 to downstream reaches (as done in Task 2 for the Middle Fork) would allow us to examine geomorphic thresholds and realistic targets for future phases of the SRP for the entire alluvial section of the McKenzie River.

Evaluating Impacts and Benefits in Reach Scale Targets for the Sustainable Rivers Project

As described in Tasks 2 and 3, meander migration, avulsions, and other channel adjustments involve the concurrent erosion and scour of sediment from some landforms and the deposition of sediment on other landforms. For instance, channel migration liberates sediment, which is deposited downstream, forming bars, secondary channels, and other habitat features. Sediment freed by bank erosion is a particularly important source of sediment for habitat creation in the alluvial section of the Middle Fork Willamette River because upstream dams block nearly all bed material sediment that would otherwise be transported to its alluvial section (O'Connor and others, 2013). Other ecological benefits of coupled erosion and deposition include the creation of germination sites for black cottonwood, diverse riparian habitats for wildlife, increased channel complexity, enhanced hyporheic exchange, and potential buffering of stream temperatures.

Although coupled sediment erosion and deposition have many ecological benefits, bank erosion and scour can result in damage to local property and infrastructure (for example, Florsheim and others, 2008). For instance, if a hypothetical landowner on the south bank of the McKenzie River owned the floodplain surfaces with trees and shrubs in 1994 that were later dissected by the new channel in 2005 (fig. 20), then this landowner would have limited access to the property north of the new channel in subsequent years. Alternatively, channel movements may affect bridge, road, and water supply infrastructure, depending on the location and the magnitude of such movements. Understanding and anticipating these types of effects are critical to developing pragmatic and societally acceptable targets for future floodplain management and communicating SRP flow implementation to local communities. Combining the findings from this project and spatial datasets of land use, revetments, transportation and water infrastructure, and geology would be helpful for identifying locations where coupled sediment loss and deposition may substantial affect human uses along the alluvial sections. Repeat channel mapping also would help determine the sensitivity of these different types of locations to different magnitudes of streamflow events.

Next Steps for Environmental Flow Monitoring in the Willamette River Basin

Results of this reconnaissance study are helpful for identifying water years where the magnitude of peak flows exceeded the SRP flow recommendations on the Middle Fork Willamette and McKenzie Rivers, verifying the geomorphically effective flow threshold for the Middle Fork Willamette, examining channel and vegetation changes in response to streamflow, and observing how seedlings and clones of black cottonwood fared during the warm, dry summer of 2015. These results also provide a foundation for the development and implementation of the SRP environmental flow monitoring program in the Willamette River Basin. Key future monitoring considerations related to streamflow (table A-1), channel and vegetation mapping (table A-2), geomorphology and sediment (table A-3), and black cottonwood and other vegetation (table A-4) are outlined in appendix A. Of these tasks, the logical first steps would be to:

- **Complete additional analyses comparing observed streamflow with the SRP flow recommendations.** Analyses for Task 1 assessed whether streamflow magnitude exceeded SRP recommendations for WYs 2000–15. These analyses did not thoroughly address flow duration, number of events per year, rate of change, spring flow recession, and seasonal flow conditions. Quantitatively examining these types of flow metrics and making those analyses publically available would support flow implementation and adaptive management.

- **Determine geomorphically effective flow thresholds for the McKenzie River.** This study identified geomorphically effective flow thresholds for the Middle Fork Willamette River. We were unable to determine similar flow thresholds for the McKenzie River because repeat channel mapping was done for a small reach that is not representative of the streamflow, coarse sediment inputs, and channel stability conditions throughout the entire alluvial section of this river. Comprehensive repeat mapping and field observations of the alluvial section of the McKenzie River are needed to determine geomorphically effective flow thresholds for this river.
- **Delineate channel and floodplain features from future aerial photographs.** In the future, additional mapping from aerial photographs taken before and after different types of flood events in low-flow and high-flow years would be helpful to document the range of geomorphic and vegetation responses to individual and sequential flow events, to refine the geomorphic thresholds for channel change and habitat creation, and to relate these changes to SRP flow implementation and success toward program goals.
- **Inventory black cottonwoods and other plants in the alluvial sections of the Middle Fork Willamette and McKenzie Rivers.** An inventory of black cottonwoods would be helpful in identifying existing stand locations and age classes, relating stands to streamflow and channel conditions (past and present), and verifying whether vegetation mapped in Tasks 2 and 3 is primarily native or invasive plants. This inventory could be repeated over time to assess the persistence of younger black cottonwood stands and other plants in relation to SRP flow implementation.

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Appendix A. Environmental Flow Monitoring Considerations for the Sustainable Rivers Project in the Willamette River Basin.

Table A-1. Future monitoring considerations related to streamflow.

[SRP, Sustainable Rivers Project; USGS. U.S. Geological Survey]

Streamflow monitoring considerations	Rationale
Compare observed streamflows with SRP flow recommendations	Analyses for Task 1 assessed whether streamflow magnitude exceeded SRP recommendations for WYs 2000–15. These analyses did not directly address flow duration, number of events per year, rate of change, spring flow recession, and seasonal flow conditions, all of which are important metrics for evaluating success toward meeting the SRP geomorphic and ecological goals. Quantitatively examining these types of flow metrics and making those analyses publically available would support flow implementation and adaptive management.
Determine geomorphically effective flow thresholds for the McKenzie River	This study identified geomorphically effective flow thresholds for the Middle Fork Willamette River. We were unable to determine similar flow thresholds for the McKenzie River because repeat channel mapping was done for a small reach that is not representative of the streamflow, coarse sediment inputs, and channel stability conditions throughout the entire alluvial section of this river. Comprehensive repeat mapping and field observations of the alluvial section of the McKenzie River are needed to determine geomorphically effective flow thresholds for this river.
Develop an approach for ranking flow events that do not meet SRP flow recommendations	Flow events can be geomorphically effective even if they do not exceed SRP flow recommendations in magnitude or timing. A methodology for characterizing these types of flows would inform SRP implementation, and provide the data needed for adaptive management and flow recommendation refinements.
Identify flow thresholds for synergy between flow events	Channel changes from the repeat mapping indicate that there may be cumulative and synergistic geomorphic effects resulting from sequential bankfull events. This is because the first event can scour vegetation and initiate new channels, essentially "priming" the floodplain for easier scour and notable reworking by sequential high-flow events. If periodic, sequential flow events maintain geomorphic complexity and dynamism, then SRP flow recommendations may not need to be met every year to provide the intended geomorphic and ecological benefits.
Collect stage and discharge data throughout the alluvial reaches in other years and seasons	SRP flow recommendations for inundation are based on discharge at USGS streamgages. If we could relate discharge and stage throughout the alluvial sections, then we could identify the channel and floodplain features that are inundated at specific discharges, assess the associated inundation effects on the recruitment of black cottonwood, and determine surface water connections between the mainstem, secondary, and floodplain channels. This study collected stage data at two sites from June to August 2015 on these rivers. More stage data collected over a range of flows and more locations are needed to develop robust stage-discharge relations.

Table A-2. Future monitoring considerations related to channel and vegetation mapping.

[SRP, Sustainable Rivers Project]

Mapping monitoring considerations	Rationale
Complete mapping of the alluvial section of the McKenzie River	This study mapped a short section of the McKenzie River that is not representative of the streamflow and sediment conditions throughout the alluvial section of the McKenzie River. Thus, mapping of the entire alluvial section is needed to determine thresholds for geomorphically effective flows. A logical starting point would be to map the alluvial section of the McKenzie River using the 2005, 2011, and 2012 aerial photographs and adding more photographs as needed.
Improve vegetation data in the mapping datasets	Mapping datasets produced by this study can be improved with field verification to classify vegetation types and age classes. These datasets would provide baseline datasets for future monitoring, assessments of vegetation, and tracking vegetation growing on bars in relation to SRP flow implementation.
Refine mapping of floodplain channels	Floodplain channels, such as sloughs and old secondary channels, are key habitats for Oregon chub, juvenile spring Chinook salmon, red-legged frogs, and other native species. However, channel stability limits the creation of new floodplain sloughs. There is no accurate inventory of current features, their dimensions, and their changes over time. Mapping for Task 2 showed that aerial photographs are not the best dataset for mapping these channels where the forest canopy is dense. Lidar would be a logical dataset for mapping the location and area of these landforms, whereas water-penetrating bathymetric lidar would be even better because it also provides the water depth (down to about1.5 meters).
Delineate channel and floodplain features from future aerial photographs	Additional mapping from aerial photographs taken before and after different types of flood events in low-flow and high-flow years would be helpful to document the range of geomorphic and vegetation responses to individual and sequential flow events, to refine the geomorphic thresholds for channel change and habitat creation, and to relate these changes to SRP flow implementation and success toward program goals.

Table A-3. Future monitoring considerations related to geomorphology and sediment

[SRP, Sustainable Rivers Project]

Geomorphology and sediment monitoring considerations	Rationale
Develop a coupled framework linking a bed-material budget with estimates of transport capacity	SRP flow recommendations focus on discharge magnitude and timing, which influence the supply and movement of bed material and values of transport capacity. Changes in bed-material transport and transport capacity can cause aggradation, incision, bed armoring, and changes in channel width. We do not have a framework for evaluating streamflow effects on these two variables in the Willamette River Basin. An efficient approach would be multi-faceted: (1) sediment volumes from Fall Creek Lake and reach aggregated bank erosion are computed using lidar differencing, (2) sediment transport rates are inversely computed using a "morphological approach," and (3) transport capacity is computed from equations of bed-material transport using a hydraulic model (Wallick and others, 2010).
Make repeat bed elevation surveys of channel and floodplain features to document patterns of aggradation and incision	Substantial increases or decreases in bed elevations can affect habitat restoration and infrastructure. Incision is a distinct possibility for bed-material limited rivers, such as the Middle Fork Willamette, and may lessen channel complexity. In contrast, fine sediment aggradation is the primary concern for floodplain sloughs where gradual filling will decrease flood storage and habitat for Oregon chub, red-legged frogs, and juvenile salmon. Incision and aggradation can be documented using repeat longitudinal profiles or water-penetrating lidar. Such data would be helpful for documenting reach-wide patterns of aggradation and incision, verification of the sediment budget and transport capacity framework, and tracking channel elevation changes over time.
Determine extent and integrity of natural and anthropogenic features controlling meander migration and channel avulsion	Meander migration and channel avulsion are an important geomorphic process for creating new gravel bars and secondary channel features, such as alcoves. Natural, non-erodible features, such as bedrock and Pleistocene gravel outcrops, as well as revetments and levees limit meander migration along the alluvial sections of the Middle Fork Willamette and McKenzie Rivers. Effort is needed to determine the extent and integrity of privately owned revetments and naturally resistant banks along these rivers and their associated effects on geomorphic and habitat responses to streamflows.

Table A-4. Future monitoring considerations related to black cottonwood and other vegetation.

[SRP, Sustainable Rivers Project]

Black cottonwood and invasive plant monitoring considerations	Rationale
Collect vigor data for black cottonwood and other plants early and later in the growing season and after high flows	We observed 190 seedlings and clones from vegetative sprouts from June to August 2015. We do not know if these black cottonwoods will survive the growing season and scouring in winter 2015–16. Repeat monitoring in 2016 would provide data on the survival of these plants. Also, it would help us evaluate whether or not clones are a more viable recruitment pathway than seedlings. We hypothesize that cottonwood clones may have a temporal and height advantage over seedlings because (1) clones can grow before seed release; (2) can draw on stored energy and moisture to survive drought, pest, and browsing stress; and (3) can grow rapidly and outpace shading by invasive plants. Future monitoring would benefit from revisiting the transects of this study and adding more transects on various bar types in geomorphically dynamic and stable zones along the alluvial sections of these rivers.
Continue to assess interactions between black cottonwood and invasive plants	We observed large coverages of marshpepper knotweed, white sweet clover, and bird's-foot trefoil that often were collocated with black cottonwood seedlings and clones in the monitoring transects. These invasive plants did not appear to suppress entirely the growth of black cottonwood. Conditions of when invasive plants do and do not suppress black cottonwood warrant further investigation.
Create an inventory of black cottonwoods and other plants in the alluvial sections of the Middle Fork Willamette and McKenzie Rivers	An inventory of black cottonwoods would help us identify existing stand locations and age classes, relate stands to streamflow and channel conditions (past and present), and verify whether vegetation mapped in Tasks 2 and 3 is composed primarily of native or invasive plants. This inventory could be repeated over time to assess the persistence of younger black cottonwood stands and other plants in relation to SRP flow implementation.
Track fine sediment releases from Fall Creek and relations with black cottonwood and invasive plants	Future drawdowns of Fall Creek Dam for fish passage will contribute fine sediment to the Middle Fork Willamette River. These inputs have ecological benefits, such as creating burrowing habitats for larval lamprey. They also may support black cottonwood and invasive plants when deposited on high elevation surfaces that are dry in the summer. Understanding the linkages between fine sediment releases, black cottonwood, and invasive plants would be helpful in identifying combinations of drawdowns and streamflow regimes that may benefit native plants instead of invasive plants.

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Director, Oregon Water Science Center
U.S. Geological Survey
2130 SW 5th Avenue
Portland, Oregon 97201
http://or.water.usgs.gov

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