Prepared in cooperation with the Eastern Shoshone Tribe of the Wind River Reservation, Wyoming, the Northern Arapaho Tribe of the Wind River Reservation, Wyoming, and Colorado State University

Cottonwoods, Water, and People—Integrating Analysis of Tree Rings with Observations of Elders from the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyoming

Open-File Report 2020–1072

U.S. Department of the Interior
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Cottonwoods, Water, and People—Integrating Analysis of Tree Rings with Observations of Elders from the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyoming

By Shannon M. McNeeley,[1] Jonathan M. Friedman,[2] Tyler A. Beeton,[1] and Richard D. Thaxton[1]

Abstract

We assessed the history of flow and riparian ecosystem change along the Wind River using cottonwood tree-ring data, streamgage records, historical temperature and precipitation data, drought indices, and local observations and Traditional Ecological Knowledge from elders of the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyoming. This assessment identified impacts that have occurred to riparian resources of concern to the Tribes, which will assist in prioritizing drought planning efforts. Impacts included reduced abundance, reduced regeneration, and increased mortality in cottonwoods (*Populus deltoides* and *P. angustifolia*); an increase in invasive species, especially Russian olive (*Elaeagnus angustifolia*), that are gradually replacing cottonwoods and other native woody plants; decreased abundance of native and culturally important plants; reduced abundance of culturally important fish; reduced volume and changes to the timing of flows; and changes in river course. This assessment documented the biophysical and social factors that have contributed to riparian ecosystem change and to reduced water availability and flows, including agricultural diversion, drought, and fire. Cottonwoods along the Wind River are as much as 300 years old. By relating tree-ring width to recorded streamflows, we were able to reconstruct streamflows confidently back to the 1850s and speculatively back to the mid-1700s. Extending the historical record of streamflows allows for a more-complete understanding of hydroclimatic variability and provides a foundation for developing preparedness and response strategies for drought management. Ring width of cottonwood trees at the Boysen Site was more strongly correlated to river flow than to local precipitation or temperature, indicating that growth of trees is controlled more by montane snowmelt than by local weather. Therefore, tree rings are a better indicator of water supply than of the local conditions controlling water demand. The extended flow record from tree rings revealed the occurrence of a major period of low flow from 1870 to 1910 that was not evident in the shorter instrumental records of flow and weather. Information from tree rings, streamflow measurements, drought indices, and elder observations all suggest that the early 2000s drought was the most severe, sustained drought in the last century. Our results illustrate how drought is experienced in different ways across locations and sectors, which underscores the importance of using multiple indicators for drought management. These results will contribute to ongoing assessment, monitoring, and planning efforts at the Wind River Reservation.

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Introduction

The Wind and Little Wind Rivers (fig. 1) are the principal streams of the Wind River Reservation, gathering montane snowmelt and sustaining the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyoming, and non-native farmers and ranchers on the reservation. Riparian forests, water resources, and Tribal well-being are interconnected. Flows support agriculture and riparian vegetation. The largest, oldest, and most-abundant trees along the Wind River are cottonwoods (genus *Populus*, fig. 2). Flow peak, volume, and seasonal timing are important for cottonwood recruitment and growth (Scott and others, 1997); cottonwoods promote bank stabilization and provide habitat for numerous riparian plants and animals (Rood and others, 2015; Brinson and others, 1981). Cottonwoods and the broader riparian environment are essential for the traditional, cultural, medicinal, spiritual, and subsistence practices of the Tribes. Cottonwoods are considered the tree of life in traditional stories, are used in the Sundance as the center pole, and are a central component of other religious and spiritual practices including sweat lodges. The broader riparian environment supports other plants important for traditional ceremonies and plant and animal resources that the Tribes rely on for subsistence.

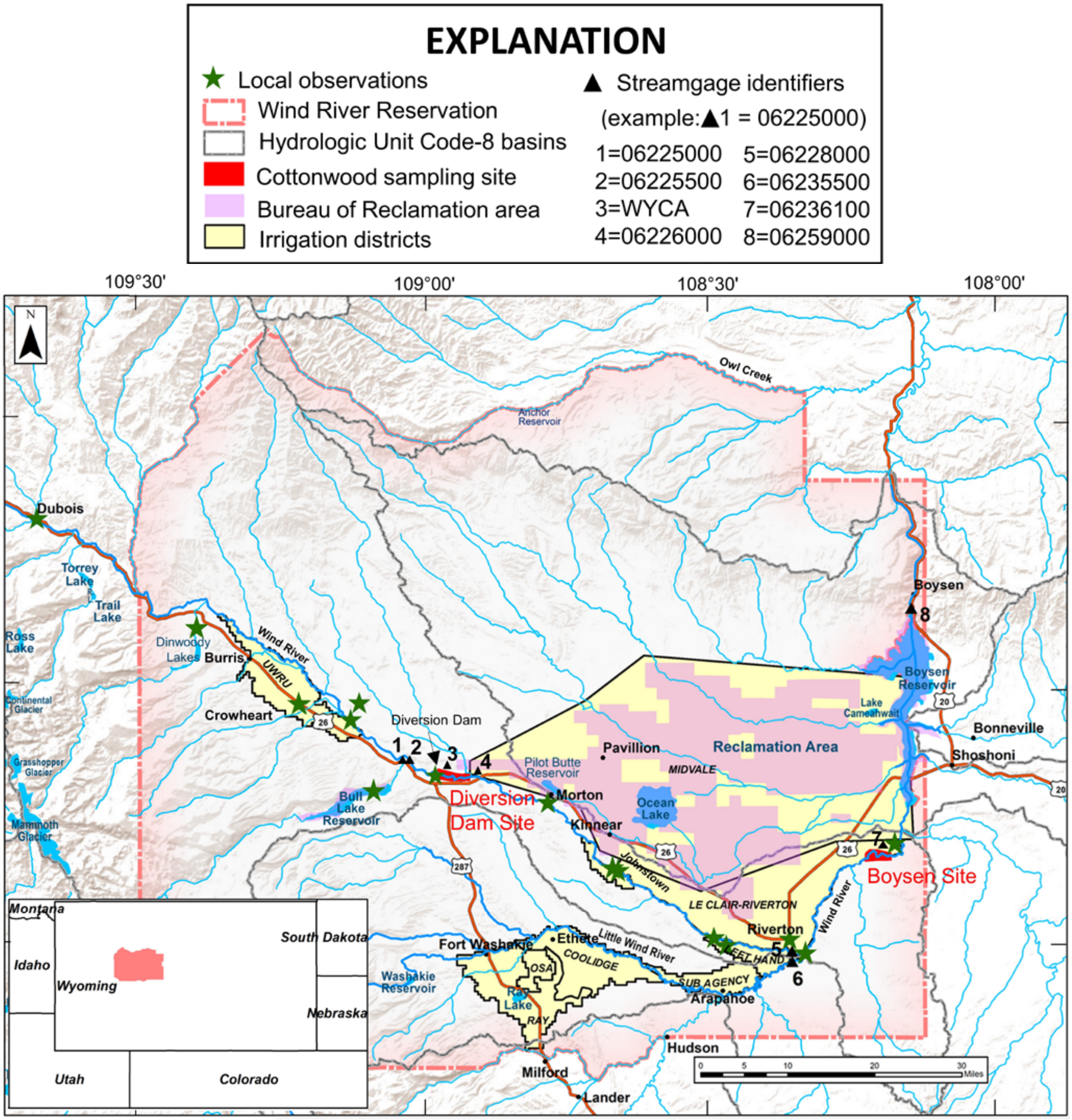


Figure 1. Cottonwood sampling sites, streamgages, and local observations of changes in riparian forest condition along the Wind and Little Wind Rivers on the Wind River Reservation, Wyoming.

Cottonwood establishment and growth are strongly influenced by water flows and precipitation (Scott and others, 1996; Schook and others, 2016). Tribal members have observed changes in cottonwood abundance over the last several decades due to severe and sustained drought conditions and water management. Projected increases in temperature and the frequency and persistence of drought conditions under future climate change could strongly affect riverine ecosystems, agriculture, and Tribal activities on the Wind River Reservation (Miller and Friedman, 2009; Conant and others, 2018; Ojima and others, 2015). Tree-ring analysis of cottonwood trees can tell us about past variation in climate and flow (Reily and Johnson, 1982; Schook and others, 2016). Tribal elders who have lived on that landscape for many

Figure 2. Cottonwood forest along the Wind River upstream from Boysen Reservoir at the Boysen Site, Wind River Reservation, Wyoming, May 2017. Cottonwoods become established on recently formed point bars, like the one on the far side of this channel. Over time, the forest thins until it reverts to grassland or shrubland. Photograph by Jonathan Friedman, U.S. Geological Survey.

decades and who rely on cottonwoods and other riparian species for many traditional cultural purposes, have deep, intimate knowledge of human-environmental relations and changes over time in these systems. Both of these sources of information are important for managing water resources and developing strategies and priorities for adaptation to drought and climate change at the reservation.

The Tribes at Wind River Reservation are developing a reservation-wide drought preparedness plan. Incorporating local knowledge and observation with tree-ring analysis will allow development of a holistic understanding of the connections between people, historic streamflow, and cottonwoods at the reservation. This will enhance the ability of water resource managers at the reservation to make more informed decisions about water, vegetation, riparian ecosystem health, agriculture, and fish and wildlife management.

The objectives of our research were the following:

1. Document how the river, cottonwoods, and the riparian ecosystem changed over time;

2. Identify the social, climatic, and environmental factors that contributed to this change;

3. Relate cottonwood ring width to recorded streamflows to reconstruct streamflows before the instrumental record;

4. Use multiple indicators to document past extreme events (for example, fires, droughts, and floods) and their impacts on flows and the riparian ecosystem.

In this assessment, we examined historical water flows in the Wind River by combining cottonwood tree-ring data with local observations and Traditional Ecological Knowledge of river and riparian ecosystem changes over time. Weather varies greatly across a watershed as large as the Wind River Basin, and effects on people depend upon their occupation and location within the watershed. For this reason, it is important to collect historic weather- and climate-related information from multiple sources. In this study, we reconstructed annual flow history and past droughts using interviews with Tribal elders in many different places, cottonwood tree rings from two locations, data from eight streamgages, and historic records of temperature and precipitation. This report presents the results of that study, including the cottonwood tree-ring analysis and the local observations and Traditional Ecological Knowledge of Tribal elders. These results will contribute to ongoing assessment, monitoring, and planning efforts at the Wind River Reservation.

We would like to thank the elders and tribal members of the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyoming, for participating and sharing their traditional, place-based knowledge and observations about the changing relations between the people, the cottonwoods, and the rivers at Wind River Reservation. Thanks also to our project co-lead, Mitch Cottenoir, and water technician, Al C’Bearing, who helped identify and recruit local elders for this study, and who provided logistical assistance during field research. Al C’Bearing, Jim Pogue, Crystal C’Bearing, and Yufna Soldierwolf coordinated contacts with tribal elders, Tribal Historic Preservation Officers, the Office of the Tribal Water Engineer, the Water Board, and landowners. Danielle Reimanis, Fisher Ankney, Al C’Bearing, Jim Pogue, Kenneth Ferris, Jennifer Wellman, and Crystal C’Bearing assisted with collection of cores. Al C’Bearing performed the chainsaw work collecting samples from dead cottonwoods at the Boysen Site. Anne MacKinnon shared information collected from project histories of the Midvale Irrigation District. This project was funded through a grant from the Bureau of Indian Affairs Tribal Resilience Program.

Research Methods

We used a mixed-methods approach to understand the relations between cottonwoods, the river, and the people of Wind River Reservation. Our methods included interviews with Tribal elders to document their knowledge and observations of the connection between cottonwoods and the Tribe, changes in the river and riparian forest, and extreme events and social factors that have impacted these forests. We also conducted a tree-ring analysis, where we related cottonwood tree-ring width to recorded flow history. This allowed us to reconstruct extreme drought and flood years back to the mid-1700s, which substantially extends the instrumental record of flows (1913–2017). Details on methods are provided in appendixes 1 and 2.

Interviews with Tribal Elders

In 2018, we conducted in-depth interviews with 17 Tribal elders who have rich local environmental knowledge of riparian systems (fig. 1). We asked the elders about their observations of (1) the relation of cottonwood trees and the riparian forest to the Tribes; (2) the relation between the rivers and cottonwoods; (3) observed changes in cottonwoods, river channels, and the abundance or balance of other riparian species; (4) extreme events that have impacted riparian forests; and (5) old stories that they have been told about drought, rivers, and cottonwoods (see appendix 1 for the full list of interview questions). Our results were also informed by participant observation of 12 individuals during a Wind River Water Resources Control Board meeting in Fort Washakie, Wyo. We mapped locations of these observations and compared and integrated our results with the tree-ring study, for example, by comparing the timing of drought events observed by elders and Tribal members to the dates recorded in tree rings. Also, our assessment adds context to information preserved in trees by documenting the varied social, climatic, and environmental factors that have contributed to local riparian change.

Sampling and Analysis of Cottonwood Tree Rings

We cored cottonwoods low in the Wind River Basin, where higher temperature and evaporation should make the trees more reliant on streamflow. We sought sites of interest to the Tribes where old trees were present. Most Tribal members and most of the elders we interviewed live in the Little Wind Basin, but most of the old trees are along the Wind River. Sampling of cottonwoods along the Little Wind River would have been ideal but was prevented by scarcity of trees old enough for tree-ring analysis. To maximize the relevance of the tree-ring data to the Tribes, we selected two sites on the Wind River upstream and downstream from the confluence with the Little Wind. One site was upstream from Boysen Reservoir (Boysen Site, fig. 1), and the other site was downstream from Diversion Dam (Diversion Dam Site, fig. 1). We cored 50 randomly selected cottonwoods at each site in July and August 2017 and used data from these trees to analyze the age distribution of the forest. Because many trees at the Boysen Site have recently died, we collected samples from an additional 36 dead trees by cutting a slab with a chainsaw in October 2018. We related tree-ring width to recorded water flows in each site by exploring correlations between annual ring width (adjusted for tree age) and monthly flow, precipitation, temperature, and the self-corrected Palmer Drought Severity Index (sc–PDSI; Wells and others, 2004). In addition, we calculated tree-ring width and annual flow in each water year (previous October through September). We used those results to reconstruct flow before the observed instrumental record. Finally, we overlaid recorded flows, reconstructed flows from tree rings, and sc–PDSI with elder observations of drought from the 1930s to 2013. (For more detailed methods, see appendix 2.) Tree-ring data are available in a data release (Friedman and Thaxton, 2020).

Human Modification of the River and Flow

One important influence on drought in the Wind River Basin is human modification of river flows. Flows in the Wind River are partly regulated by Pilot Butte Reservoir, completed in 1926, and Bull Lake Reservoir, completed in 1938 (fig. 1). Important flow diversions on the Wind River include the Wyoming Canal, completed in 1926 (Autobee, 1996), LeClair Canal, completed in 1915, and Riverton Valley Canal, completed in 1917. Diversions on the Little Wind River are smaller (fig. 1) and include Ray Canal, partially completed in 1894, Coolidge Canal, completed in 1905, and Sub-Agency Canal, completed in 1907 (Historic American Engineering Record, 1968). These dams and diversions enable irrigated agriculture in the basin and alleviate drought experienced by farmers and ranchers while aggravating effects of drought in the river and riparian corridor. Annual naturalized flows, the water-year flows that would have occurred without flow regulation and diversion, are calculated at the streamgage, Wind River below Boysen Reservoir (06259000; fig. 1; table 1; Martin and others, 2019). Comparison of these naturalized flows to the actual annual water-year flows measured at this streamgage from 1953 to 2013 indicates that 7 to 58 percent of annual flow is diverted upstream from this streamgage with an average diversion of 28 percent per year. Most flow diversions occur on the Wind River upstream from its confluence with the Little Wind River. The largest of these is Diversion Dam (fig. 1), which sends water into the Wyoming Canal to support primarily non-Tribal landowners in the Midvale Irrigation District. Increasing flow diversions over time are illustrated by the oldest streamgage in the basin, the Wind River at Riverton (06228000; fig. 3). Since around 1960 annual flow has decreased between Crowheart and Riverton by 50 percent or more in drought years (fig. 3). Since records began in 1941, however, flows in the Little Wind River have not decreased as much as those in the Wind River (fig. 3). The ability of Tribes to manage flows and the riverine ecosystems is complicated by The Bighorn General Stream Adjudication (1977–2014), which dictates how water is appropriated and administered in the Wind River Basin. This adjudication ruled that the tribes could use their Tribal-reserved water rights for agricultural purposes only (MacKinnon, 2019). It did not recognize other important uses of water named by the Tribes in the Wind River Water Code (including instream flows to protect fisheries and the riparian environment), and gave administrative control of water resources to the State of Wyoming (Flanagan, 2000; McNeeley, 2017; Robison, 2015).

In spite of water development, the timing and amount of annual flows in the Wind River are still dominated by snowmelt from the mountains, which typically occurs from May to July (fig. 4). Temperatures peak somewhat later in July and August. The lowest flows of the year occur in August and September, when the snowmelt peak is past, but irrigation demands are still high. Local precipitation is low overall, with an annual mean of 223.3 millimeters at Riverton from 1900 to 2017, peaking in May (fig. 4). Maintaining the historical magnitude and timing (for example, frequency, duration, and seasonality) of river flows is critical to support cottonwood reproduction and survival (Rood and others, 1995; Scott and others, 1997).

In addition to water storage and withdrawal, other activities have had important influences on the river and riparian forests. Beaver were abundant in the watershed and promoted water storage on the floodplain but were mostly removed by fur trappers by the mid-1830s (Hanson, 2000). The Wind River was used to transport more than 10 million railroad ties downstream to Riverton for construction of the Chicago and Northwestern Railroad from 1914 to 1946 (Pinkerton, 1981). Clearing and blasting of obstacles and blocking of side channels for these tie drives almost certainly reduced occurrence of woody debris and simplified the channel. Fire, sometimes human set, has removed forest from many reaches of the Wind and Little Wind Rivers. Livestock

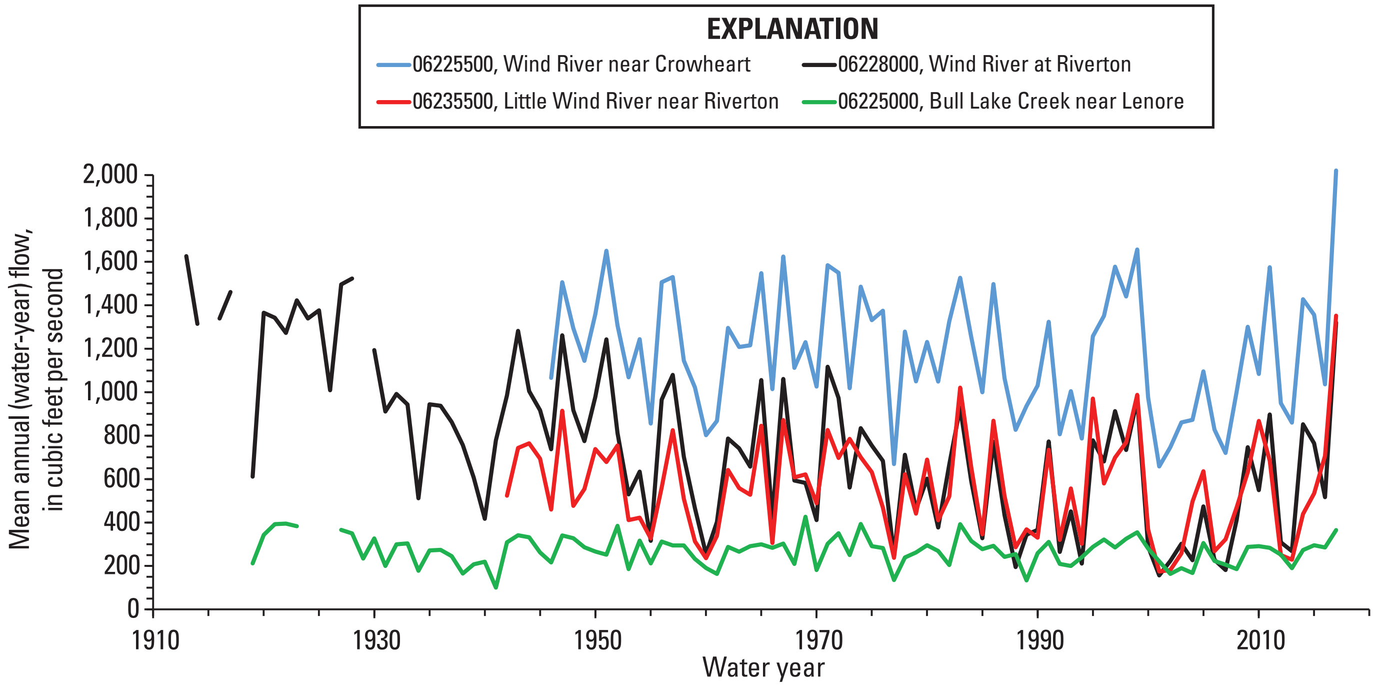


Figure 3. Mean annual (water-year) flow measured at U.S. Geological Survey streamgages (table 1) along the Wind River and its major tributaries in the Wind River Reservation, Wyoming, 1913–2017.

Table 1. Selected U.S. Geological Survey and Bureau of Reclamation streamgages on the Wind River and its major tributaries in the Wind River Reservation, Wyoming.

Streamgage identifier	Streamgage name	Managing agency
06225000	Bull Lake Creek near Lenore	U.S. Geological Survey
06225500	Wind River near Crowheart	U.S. Geological Survey
WYCA	Wyoming Canal ¼ mile below Diversion Dam	Bureau of Reclamation
06226000	Wyoming Canal near Lenore	U.S. Geological Survey
06228000	Wind River at Riverton	U.S. Geological Survey
06235500	Little Wind River near Riverton	U.S. Geological Survey
06236100	Wind River above Boysen Reservoir	U.S. Geological Survey
06259000	Wind River below Boysen Reservoir	U.S. Geological Survey

grazing has reduced abundance of traditionally important herbs (Flanagan, 2000; Cohn and others, 2016). Annual flushing of sediment accumulated behind Diversion Dam affects water quality, injuring fish and other aquatic animals (Bergstedt and Bergersen, 1997). Finally, human-induced climate change is increasing temperatures, causing glacial retreat and reduced snowpack, and increasing the frequency and severity of droughts and fires (Griffin and Friedman, 2017; McNeeley and others, 2018; Martin and others, 2020).

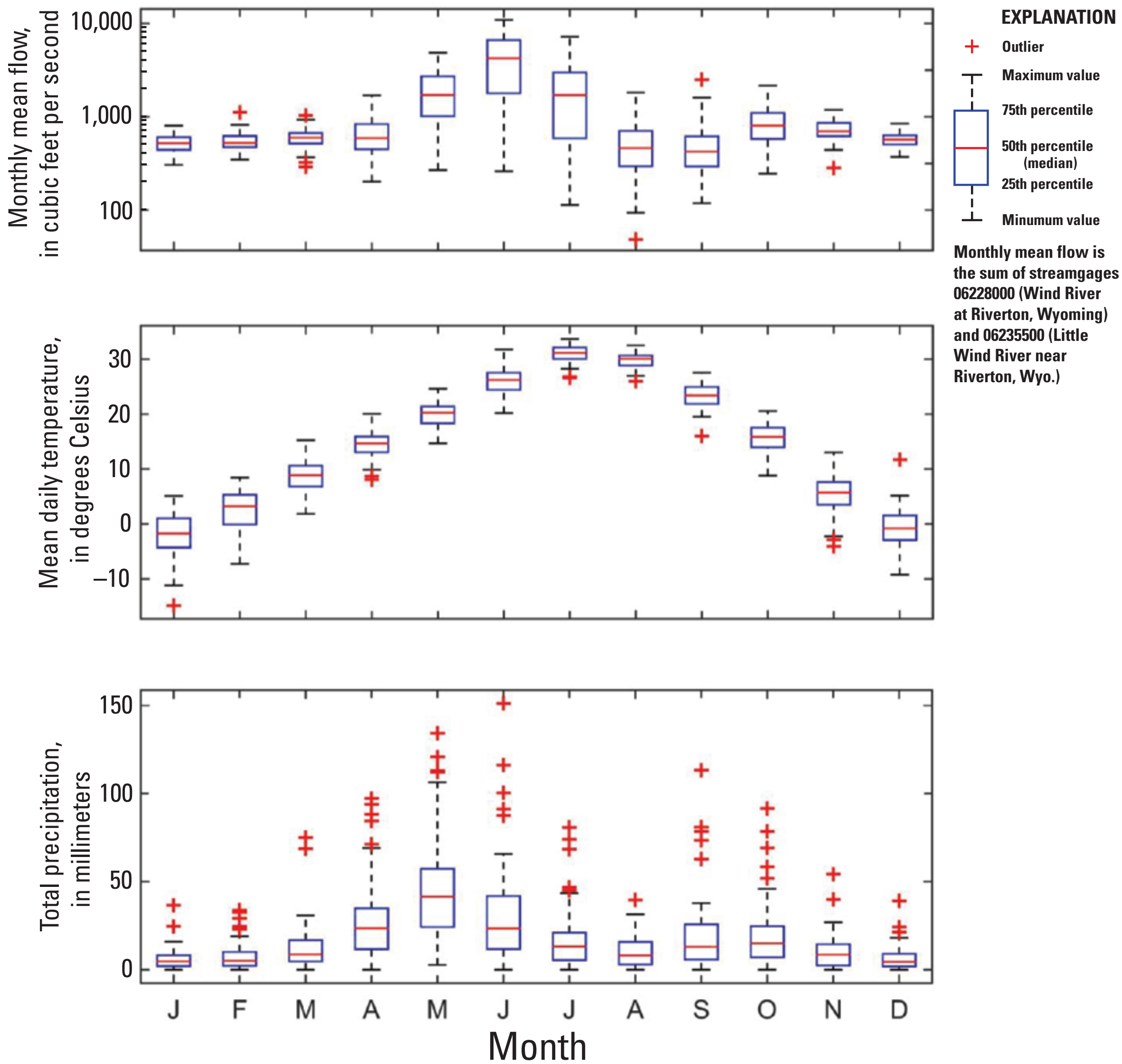


Figure 4. Monthly mean flow, mean daily maximum temperature, and total precipitation at the Boysen Site, Wind River Reservation, Wyoming, 1942–2016. Figure prepared using SEASCORR (Meko and others, 2011).

Cottonwood Species

Plains cottonwood (*Populus deltoides* subspecies *monilifera*), narrowleaf cottonwood (*Populus angustifolia*), and hybrids between them occur at both study sites. Narrowleaf cottonwood decreases downstream in abundance, whereas plains cottonwood increases. As a result, plains, narrowleaf, and hybrids constitute 3, 92, and 5 percent of cored cottonwoods at the Diversion Dam Site and 67, 28, and 5 percent at the Boysen Site (fig. 1). Because growth of the two species was similar within sites, we combined data from the two species and their hybrids at each site for tree-ring analysis.

Relation Between Riparian Forest and Tribes

Cottonwoods are deeply embedded in the cultural, ceremonial, spiritual, and religious practices of the Tribes. For instance, cottonwoods and birch (*Betula occidentalis*) are used in sweat lodges to heat rocks, and cottonwood and cedar (*Juniperus* sp.) are used in Native American Church. In the Arapaho language, cottonwood is referred to as “heenee3neebexo” (or “real wood;” interviewees 9 and 11, oral commun., 2018) because the trees burn slower and with less smoke when compared to others (for example, pine trees). For Sundance (or the “Offering Lodge”), cottonwoods are used as the center pole and for shade, leaves from plains cottonwoods are used to cool off dancers, and special ceremonies and prayers are practiced before cottonwoods are cut (interviewee 4, oral commun., 2017). Cottonwoods are also included in traditional stories. In one Arapaho story (interviewee 16, oral commun., 2018), the cottonwood is considered:

> The tree of life…And the elders always tell us that everything around us is living. And like the trees is the center…So the tree was like a foundation and it was protection of the life of the people. And we look to it to get a better life…The tip of the tree is where it’s fresher and greener. And that’s where we used to hang our offerings to the creator, for prayer. And it points skyward and it carries our prayers to the creator.

The white lining between the bark and the trunk (phloem) and the water that rushes out of cottonwoods when they are cut are said to hold medicinal properties. Cottonwoods and cedar were used in the house to remove sicknesses. Cottonwoods were used as food for horses—horses were fed the bark and leaves of cottonwoods when only essentials could be carried or when forage was not available. Cottonwoods were also used to build saddles and stirrups for horses.

The broader riparian environment is also important to the Tribes. Water is used in ceremonies, and the river supports a multitude of resources that the Tribes depend on. For instance, willows (*Salix* spp.) are used as fishing poles; birch, willow, and sage (*Artemisia* sp.) are used for traditional ceremonies; and red willow (*Cornus sericea*) is used for kinnikinic, a traditional mixture of plants and tobacco used for smoking. Riparian areas also provide important habitat for many wildlife species of importance, including elk, deer, moose, beaver, owls, and eagles. Riparian ecosystems support traditional plants used for food, such as chokecherry (*Prunus virginiana*), bullberry (*Shepherdia argentea*), and currant (*Ribes* spp.), along with peppermint (*Mentha arvensis*), and the river supports several important fish species, including ling (*Lota lota*), trout (*Salmo* spp., *Oncorhynchus* spp., and *Salvelinus* spp.), flathead chub (*Platygobio gracilis*), and sauger (*Sander canadensis*). These areas are also a place for families to gather together to learn about Tribal traditions, history, and culture, and to share time as a family.

Cottonwood Ages

Cottonwoods produced distinct annual rings (fig. 5), making it possible to count the years to the center ring. Age of cottonwood center rings ranged from 1818 to 2003 at the Boysen Site (fig. 6*A*) and from 1722 to 2004 at the Diversion Dam Site (fig. 6*B*). The ages of randomly selected trees (fig. 6) provide an estimate of the area occupied by forest patches of different ages (Friedman and Lee, 2002), indicating that large areas of forest along the Wind River date to 1864–74, 1925–33, and 1974–2004.

Cottonwood ages provide information about the timing of past flooding and associated channel change (Everitt, 1968). The tiny seeds of cottonwood are rapidly and widely dispersed but contain little stored energy and require abundant light and moisture for survival. Along meandering rivers seedling establishment tends to occur on recently deposited point bars along the inside of river bends (Scott and others, 1996; Schook and others, 2016). Rapid channel migration promoted by flooding leads to formation of large areas of point bars (Merigliano and others, 2013). In subsequent decades, the river migrates away from the point bars and gradual sediment deposition raises the local elevation, promoting long-term cottonwood survival (Everitt, 1968). In this region, the date of the center ring at coring height (fig. 6) lags behind formation of the underlying point-bar surface by a median of 7–9 years (Schook and others, 2017; Friedman and Griffin, 2017). The large number of randomly selected trees dating to the mid to late 1800s at both sites (fig. 6) suggests that extensive channel migration followed by lower flows at that time created the bars necessary for cottonwood establishment.

Large area of forest dating to the late 1800s is consistent with observations along many other western rivers, including the Little Missouri River, North Dakota, the Yellowstone, Redwater and Powder Rivers, Montana, the Green River, Wyo., and the South Fork Snake River, Idaho (Merigliano and others, 2013; Schook and others, 2016, 2017), suggesting high flows and extensive channel migration occurred around that time across the region. Ongoing forest establishment since the 1980s (fig. 6) indicates that channel migration during high flows is still creating new surfaces for cottonwood establishment along the Wind River. In contrast, downstream along the Bighorn River, reduction of peak flows by Boysen Reservoir has reduced river migration rates and cottonwood establishment (Akashi, 1988), mirroring changes along many other large rivers in the northcentral United States, including the Missouri River (Johnson and others, 2012; Friedman and others, 2018).

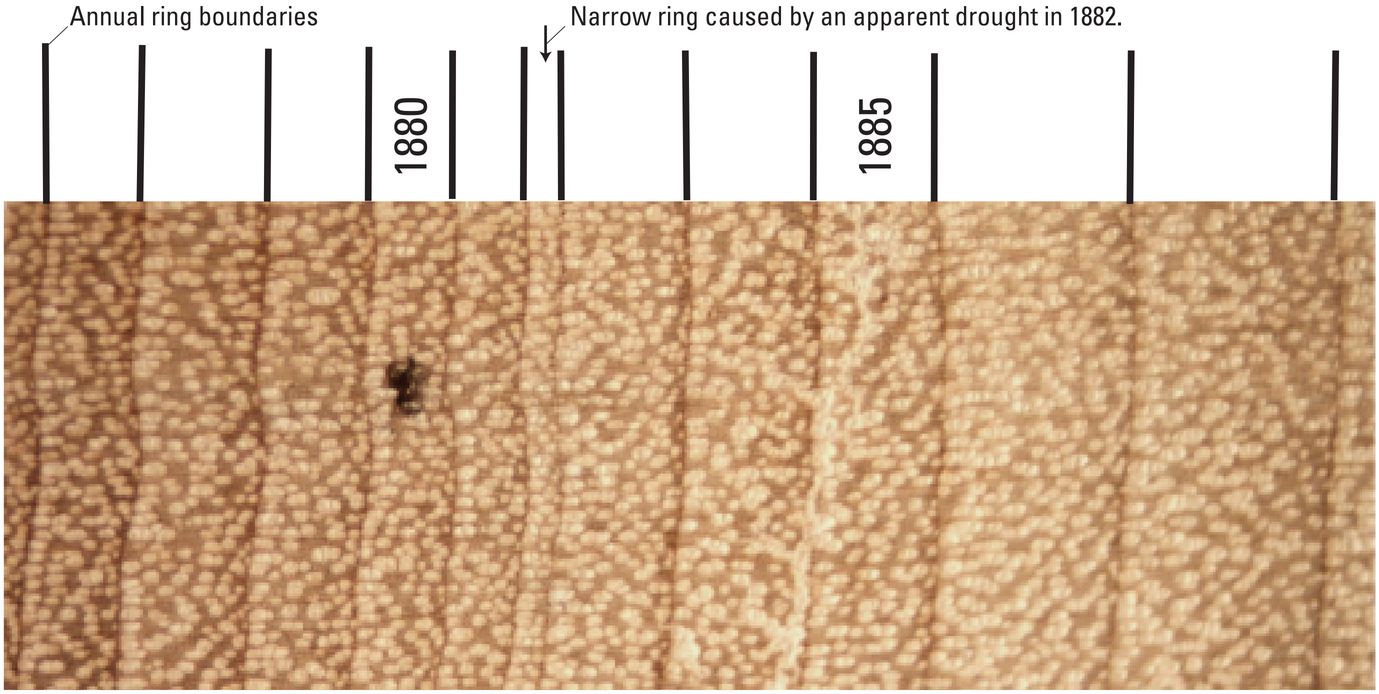


Figure 5. Photomicrograph of tree rings in core LDQ06B from the floodplain of the Wind River at the Diversion Dam Site, Wind River Reservation, Wyoming. Photograph by Richard Thaxton, Colorado State University.

Impacts of Social and Environmental Changes on Riparian Environments

Impacts to Cottonwoods

Elders observed several changes to cottonwood trees in the Wind and Little Wind River Basins over the last half century (fig. 7). They reported reduced abundance and tree mortality throughout the two river basins. For instance, an elder recalled that long ago the Little Wind River had much higher flows—in some cases flooding occurred up to the canopy of cottonwood trees. However, those high flows do not occur anymore due to dams that regulate the magnitude of floods and diversions, which has resulted in a less abundant cottonwood forest (Wind River Water Resources Control Board Member, oral commun., 2018). Elders suggested that some individuals may be overharvesting cottonwoods for ceremonial and personal use. People also observed changes in the relative abundance of the plains and narrowleaf cottonwood species—most indicated that the plains cottonwood was less abundant (interviewee 4, oral commun., 2017):

> The big trees [plains] are gone and it's a different type of a cottonwood now…now it's that little leaf [narrowleaf], you know, but the big leaves [plains] are the main big cottonwood trees that we used to have.

The reduced abundance of cottonwoods has resulted in community members and elders sometimes finding it difficult to find cottonwoods for traditional and cultural practices, and they must travel farther to find them. Elders observed changes in the age class, stand density, and composition of cottonwood forests. For instance, a lack of regeneration in the Little Wind and Wind River Basins was reported. Elders observed old, mature cottonwood forests, but they were not seeing the regeneration of younger trees in these stands. Elders also observed impacts from pests (that is, insects on cottonwoods), changes to the seasonal timing and amount of production during drought (that is, plants did not leaf out), and brittle trees that lacked moisture in the trunk. For instance, interviewee 10 (oral commun., 2018) said:

> When we went up to go get trees and stuff there was no water in them…So it [drought] took a toll on them…It was too dry…we would gather some of that, leaves for the sun dancers to cool off with and there wasn't any leaf growth.

Impacts to Other Riparian Plants and Animals

Two invasive trees, Russian olive, (*Elaeagnus angustifolia*) and saltcedar (or tamarisk, *Tamarix* spp.) were introduced to the western United States in the 1900s for bank stabilization and wildlife habitat (Friedman and others, 2005) and are increasing on the floodplain of the Wind River and its tributaries. For example, 10,000 Russian olives were planted for erosion control along Muddy Creek in 1965

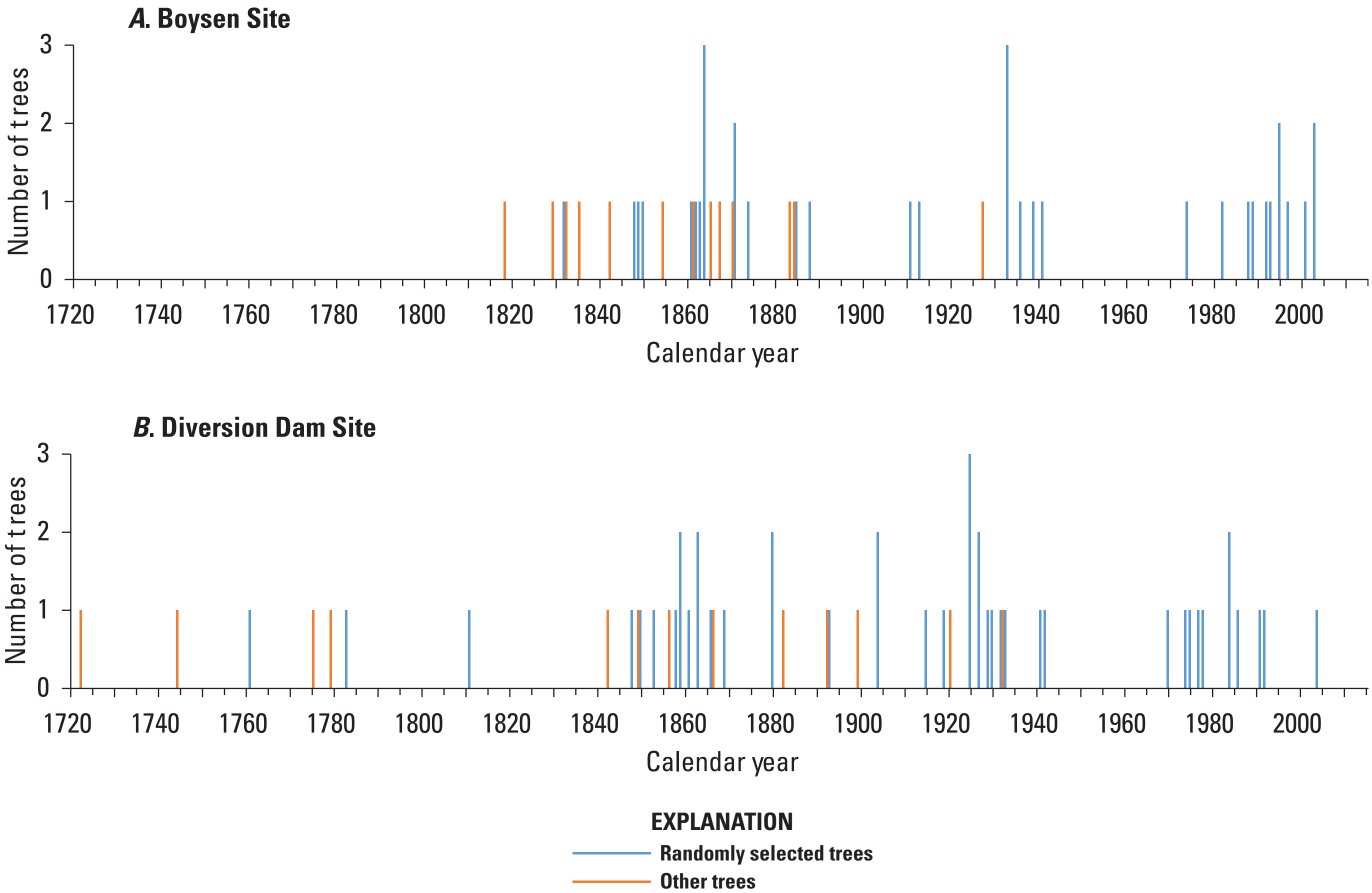


Figure 6. Establishment years for trees cored at the study sites, Wind River Reservation, Wyoming, 1722–2004. *A*, the Boysen Site (36 randomly selected trees and 13 other trees). *B*, the Diversion Dam Site (43 randomly selected trees and 13 other trees).

(Anne MacKinnon, written commun., March 22, 2019). Russian olive is gradually replacing cottonwood and other native plants, especially in downstream reaches including the Boysen Site (fig. 8; Cohn and others, 2016). Unlike cottonwood, Russian olive is able to reproduce in the absence of physical disturbance, allowing this invasive species to colonize undisturbed areas within existing cottonwood forest (Katz and others, 2005). Although it is replacing valued native species, Russian olive provides cover and nitrogen-rich fruit for wildlife (Katz and Shafroth, 2003), and some of the elders consider Russian olive important habitat. Saltcedar dominates the shoreline at the upstream end of Boysen Reservoir, but we found it only locally farther upstream. The elders also observed saltcedar around Ray Lake in the Little Wind River Basin. This species, like cottonwood, requires unvegetated moist sediment for establishment but, because of low temperatures, is less aggressive in Wyoming and Montana than farther south, except around reservoirs (Friedman and others, 2005). Unlike cottonwood, saltcedar releases seed throughout the summer, allowing it to colonize land exposed as the reservoir level is gradually lowered (Lesica and Miles, 2004).

Elders observed that increased competition with Russian-olive, along with the drying out of the floodplain (due to drought and diversions) and grazing impacts have resulted in the decline of other native and culturally important species, including currants, chokecherries, gooseberries *(Ribes* spp.), bullberries, plum trees (*Prunus* sp.), raspberries (*Rubus* spp.), peppermint, white sage (*Artemisia ludoviciana*), birch, and red willow (also discussed in Flanagan, 2000, and Cohn and others, 2016). These plants are now harder to find at the Wind River Reservation, which has resulted in the elders having to go off-reservation and even out of State to gather them. Changes to the seasonal production of these plants were attributed to moisture availability—in dry years, the elders observed reduced production in chokecherries, for example, whereas in wet years they observed increased production.

Elders also observed declines and changes in the distribution of fish and other aquatic life of importance to the Tribes. For instance, water shortages during 1999 and the early 2000s (due to drought and river channelization) in the Wind River affected flow so much that the elders reportedly could walk in the river near Left Hand Irrigation District, where only pools of water remained. This caused mortality in fish and freshwater crabs. Elders observed declines over time in

Figure 7. Image showing impacts reported in interviews. Graphic created using WordItOut.

ling, trout, sauger, and clams, whereas the flathead chub, which is an important minnow used to catch trout and ling, was reportedly nonexistent. Carp, suckers, and other "trash" fish have increased in abundance. Brown trout (*Salmo trutta*), which tolerate warm water, were historically only found in the lower reaches of the Wind River, but elders have recently observed them above Diversion Dam, apparently taking advantage of warmer temperatures.

Impacts to the Wind River

Human modifications and changes in weather and climate have diminished water availability, changed the timing of flows and flooding, caused soil erosion, and impacted water quality. The Wind River reportedly does not "sing" or "crack like thunder" anymore, which is a testament to the energy and high flows of the past (interviewee 10, oral commun., 2018):

> I don't hear the rushing of the water like it used to be. The water's starting to not sing…[In the past,] you could hear the water rushing…in good times the water is heavy duty and really roar the river, but then in dry times it's real silent.

The course of the Wind river has changed in places, which not only impacts riparian forests (for example, tree mortality), but also poses a potential risk to houses near the river. Elders also observed that rivers and streams were warmer, shallower, and wider than before. In addition, potential contamination from a former uranium mill near Riverton, trash dumping in streams, increased salinity, and contamination from agricultural and ranching runoff have all contributed to diminished water quality. Private, non-Tribal landowners have reportedly channelized the Wind River by throwing car bodies, refrigerators, and other trash into the river and by creating berms to divert the river for irrigation purposes.

Spatial Variability of Impacts

Although changes were observed throughout the Wind and Little Wind River Basins, the type and magnitude of change and the state of the riparian forest varied across the landscape. Specific locations in the riparian environment where the elders observed changes are highlighted in figure 1. Elders reported variation in the riparian environment above Diversion Dam and below the dam and toward Riverton. For instance, although some old, large trees were observed downriver by the Boysen Site, the elders observed older trees above Diversion Dam and near Bull Lake. Limited recruitment, or regrowth, was observed directly downstream from Diversion Dam (Diversion Site) and toward Riverton, for example, and reduced and (or) slower recruitment was observed after drought and fire on the North Fork of the Little Wind River and near Crowheart on the Wind River. It is important to note, however, that some of the elders observed areas that had good recruitment and growth; for example, Sheep Creek in the Lower Wind Basin, near the confluence of the Wind River and Bull Lake Creek in the Wind River Basin,

Figure 8. Dead cottonwoods and the Russian olives replacing them at the western group of dead trees within the Boysen Site, Wind River Reservation, Wyoming, October 12, 2018. Photograph by Richard Thaxton, Colorado State University.

and around Fort Washakie in the Little Wind Basin. Plains cottonwoods were generally described as declining, yet they could still be found in a few locations (for example, south of Pilot Butte Reservoir on the Wind River and Blue Sky Road in the Little Wind Basin).

Elders observed that fisheries above Diversion Dam were more abundant and healthier than fisheries below the dam. They also observed more wildlife, increased water availability, and enhanced water quality upstream from the dam. Invasive plant species were observed throughout riparian areas on the Wind River Reservation, yet Russian olive was especially problematic in irrigation districts and the infestation was the worst in the area between Riverton and Boysen Reservoir. Saltcedar was not as widespread as Russian olive, though it was observed in the Riverton to Boysen Reservoir area and around Ray Lake.

Mechanism of Observed Impacts on Riparian Forest

The pattern of an overall decline in cottonwood with strong local variation is consistent with known demographic patterns for plains cottonwood. Because they require moist open sand bars for survival, cottonwood seedlings do not become established beneath their parents (Scott and others, 1996). Existing stands dry out over time as the river migrates away and flood deposition raises the local elevation. These stands (fig. 9*A*) age and are eventually replaced by grassland and shrubland (fig. 9*B*; Friedman and Lee, 2002). New stands arise elsewhere next to the channel, where the tiny, mobile wind- and water-dispersed cottonwood seeds are able to quickly occupy new point bars created by the migrating river (Merigliano and others, 2013). Large-fruited, culturally important understory shrubs (like bullberry, chokecherry, and currant) are gradually brought by birds and other animals into moist-shady, middle-aged cottonwood stands but then gradually decline over the decades as these stands dry out and the cottonwood overstory dies off. As a result, even if cottonwoods were not declining overall, the best gathering locations for trees and fruits would always be changing. Damming and diversion have decreased the volume (fig. 3) and peak of the annual snowmelt flood on the Wind River, resulting in reduced cottonwood reproduction. Cohn and others (2016) found that the decline of traditional gathering areas is now accelerated by increasing drought, fire, and livestock grazing, which is supported by our interviews. Decline of cottonwood stands over time can be slower for narrowleaf cottonwood because this species more readily produces new trees from root sprouts after fire or other disturbance (Rood and others, 2007), allowing stands of trees to persist for a longer time. This could explain the more rapid decline of plains cottonwood compared to narrowleaf cottonwood observed by some elders in this study and in Cohn and others (2016).

Cottonwood Growth

Ring width decreased with increasing age (across rows in fig. 10), and years of low growth tended to be consistent between trees (down columns in fig. 10), indicating that cottonwood rings consistently record droughts. Because of the strong effect of tree age on growth, we followed the standard practice of detrending ring width for tree age (see appendix 2). This makes it possible to examine changes in age-adjusted tree growth for each site.

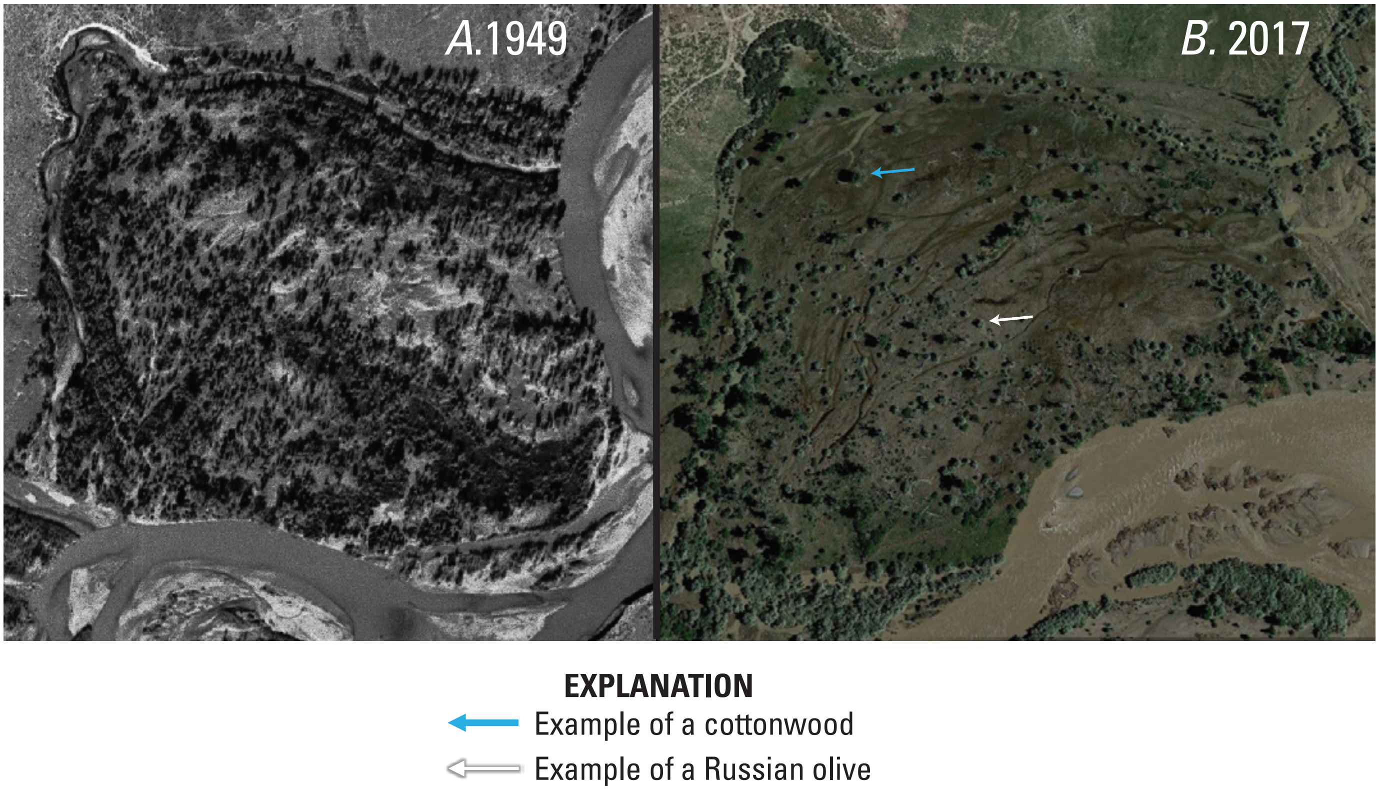


Figure 9. Decrease in forest extent over time in the floodplain area occupied by the western group of dead trees within the Boysen Site, Wind River Reservation, Wyoming. *A*, forest dominated by cottonwood, July 29, 1949. Photograph from the U.S. Geological Survey. *B*, same forest showing cottonwoods (bright green trees with big shadows) have mostly died and invasive Russian olive (small olive-green trees) are now colonizing the area, June 24, 2017. Base-map image from Google, Landsat/Copernicus.

Boysen Site

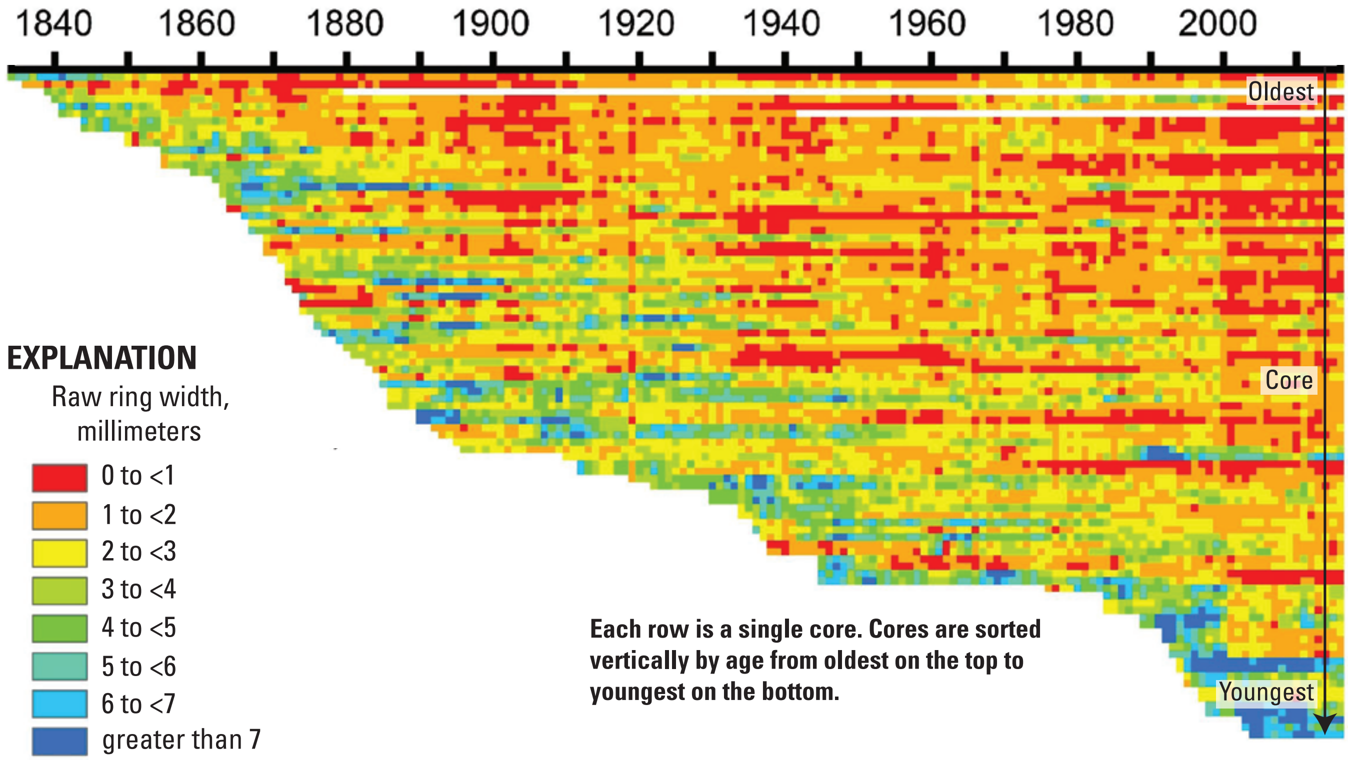
The climate of the lower Wind River is so dry that growth of cottonwood trees at the Boysen Site is limited by water availability even though it is a floodplain. Cottonwood ring width is strongly and positively correlated with flow, especially in May–August during and immediately after the season of high flows from montane snowmelt (fig. 11). Ring width at Boysen is also negatively correlated with temperature but only significantly so in May (fig. 11, Edmondson and others, 2014; Meko and others, 2015). In other words, higher flows increase growth, whereas lower flows and higher spring temperatures decrease growth. Such water limitation has been found for cottonwood growth along many low-elevation rivers in dry locations in the western United States. In wetter locations (for example, in the mountains), water is more abundant and tree growth may be limited by other factors. Water limitation of growth is the basis of reconstructions of drought and flow in dryland rivers from cottonwood tree rings (Edmondson and others, 2014; Meko and others, 2015; Schook and others, 2016) and indicates that water withdrawals are likely to decrease cottonwood growth. The highest correlation between monthly flow and ring width occurred in July (Pearson correlation coefficient (r) was 0.62; r values range from −1 to 1, and values closer to −1 or 1 indicate higher correlation), but 12-month means of flow produced even higher correlations (r=0.72) for the 12-month periods ending in July, August, and September. In subsequent analyses, we used flows for the 12 months ending in September, also known as water-year flows, because they were strongly correlated with tree growth and are commonly used to inform water-management decisions. Local precipitation is low, and poorly correlated with ring width (fig. 11), indicating that river flow, not local precipitation, provides most of the moisture necessary for cottonwood growth along the lower Wind River.

Ring width at the Boysen Site is strongly and positively related to flow (fig. 12; eq. 1); the coefficient of determination (R^2) was 0.52. R^2 indicates the proportion of variance in the dependent variable (that is, water-year annual flow [Q]) that can be explained by the independent variable (that is, mean adjusted ring width [W]):

$$Q = 1{,}179W^{1.920} \quad (1)$$

Regression equations were used to reconstruct flow before the observed instrumental record. The relation between river flow and cottonwood growth is non-linear, meaning that the effect

A, Boysen Site



B. Diversion Dam Site

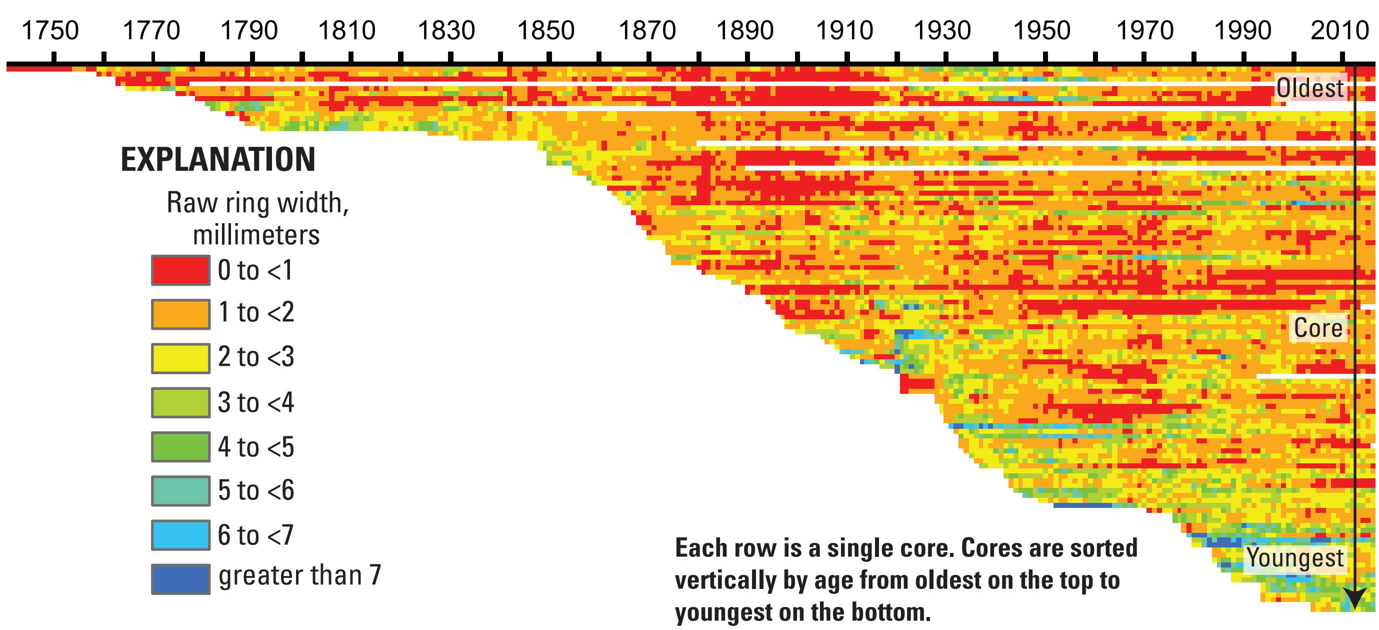


Figure 10. Raw ring widths for all cores sampled at the study sites, Wind River Reservation, Wyoming. *A*, Boysen Site, 1834–2016. *B*, Diversion Dam Site, 1733–2016.

on growth of a given decline in flow becomes stronger with decreasing flow (fig. 12; Meko and others, 2015). This means that low-flow events have a disproportionately large effect on tree growth, and that ring widths record droughts more precisely than floods.

Many of the Boysen trees are dead or dying. Occurrence of dying trees varies strongly across the floodplain. Older stands of trees farther from, and higher above, the channel seem to be experiencing higher mortality. We collected slabs from west and east groups of standing, dead trees within the Boysen Site (see appendix 2, fig. 2.1) to determine when these trees died and how their growth compared to living trees through time. Most of these trees died after 2008 (fig. 13). Trees that died earlier than 2008 have already fallen and are generally too rotten to date. Through the 1950s, ring widths of dead and living trees at the Boysen Site were similar (growth ratio close to 1 in fig. 14). The east group began to decline relative to living trees in the late 1950s, and the west group began to decline in the late 1970s. This gradual decline indicates that the recent mortality is not a result of recent droughts alone. The floodplain area occupied by the west group was densely forested in 1949 (fig. 9). Other historic imagery indicates that most flow in the main channel migrated south away from this area between 1954 and 1972 and that a meander bend east of this area was cut off, apparently from natural causes, between 1975 and 1981. By 2017, almost all cottonwoods in this area had died. The surface is now being colonized by Russian olive, the small light-green trees now dominating the image in figure 9*B*. As older cottonwoods die on surfaces far from the channel, new cottonwood forest is being established elsewhere on recently deposited surfaces. Because cottonwoods rely on river water for survival, declines in flows may be accelerating the mortality of the older trees.

Diversion Dam Site

Ring widths at the Diversion Dam Site are not as strongly correlated with flows as those at the Boysen Site. Changes in operation of Diversion Dam apart from the reduction in annual flows appear to have strongly affected growth. Ring width showed strongly declining growth from the 1950s to 1973 followed by a sudden and sustained increase in growth beginning in 1974 (fig. 15). Annual flows show neither the gradual decline nor the sudden increase and the year-to-year variations in flow during this period do not match those of ring width (fig. 15). Annual variation in temperature and precipitation also do not correspond to this sequence of changes in ring width (data not shown). In contrast, average flows in winter (November–March) are consistent with growth patterns (fig. 16). Flows diverted at Diversion Dam were used to generate power in winter at Pilot Butte Dam until 1973. The period of declining growth in the 1950s and 1960s coincided with reduced winter flows. The sudden and sustained increase in growth in 1974 began after the power plant at Pilot Butte Dam was shut down on June 15, 1973, partly because of costs related to ice formation in winter (Autobee, 1996). Although

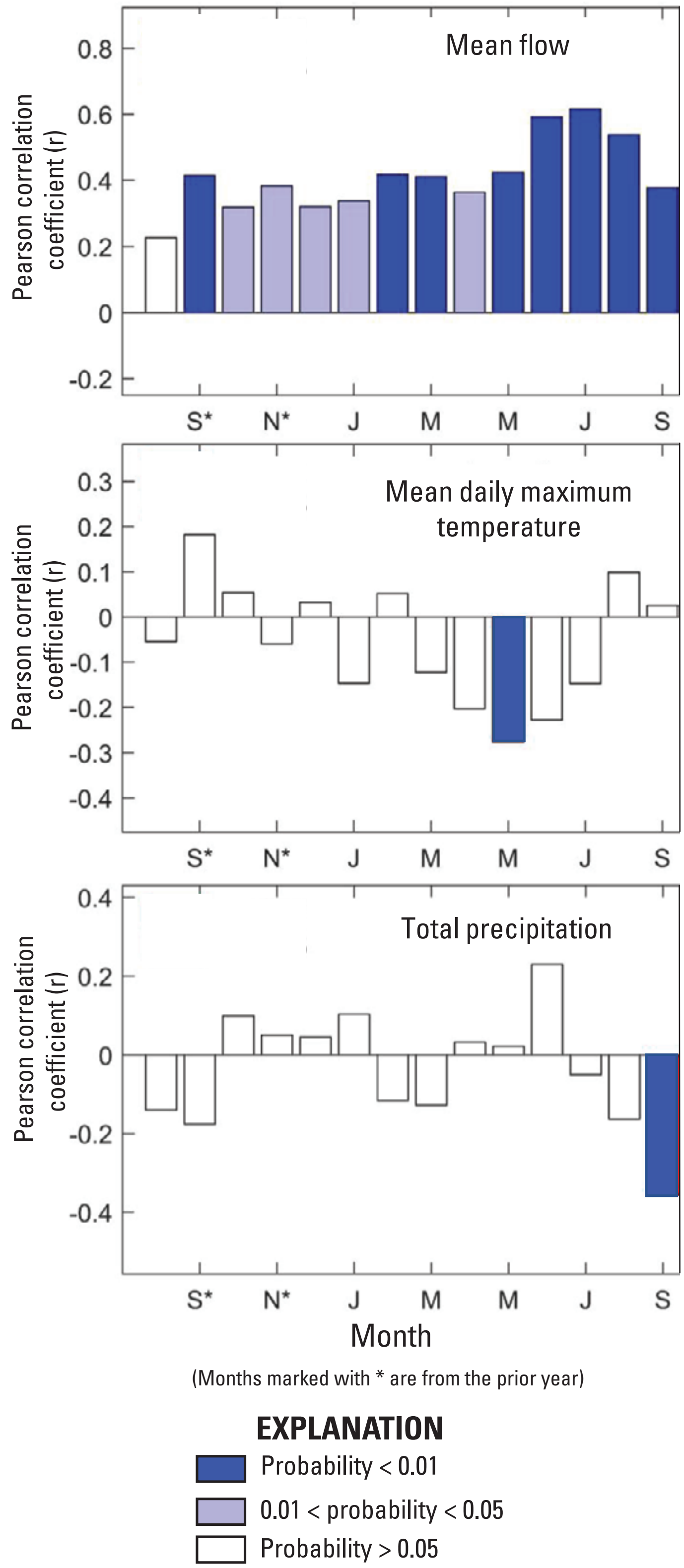


Figure 11. Pearson correlation coefficients between mean adjusted annual ring width and mean monthly flow, mean daily maximum temperature, and total precipitation for the Boysen Site, Wind River Reservation, Wyoming. Bar color indicates significance determined by Monte Carlo simulation (Meko and others, 2011).

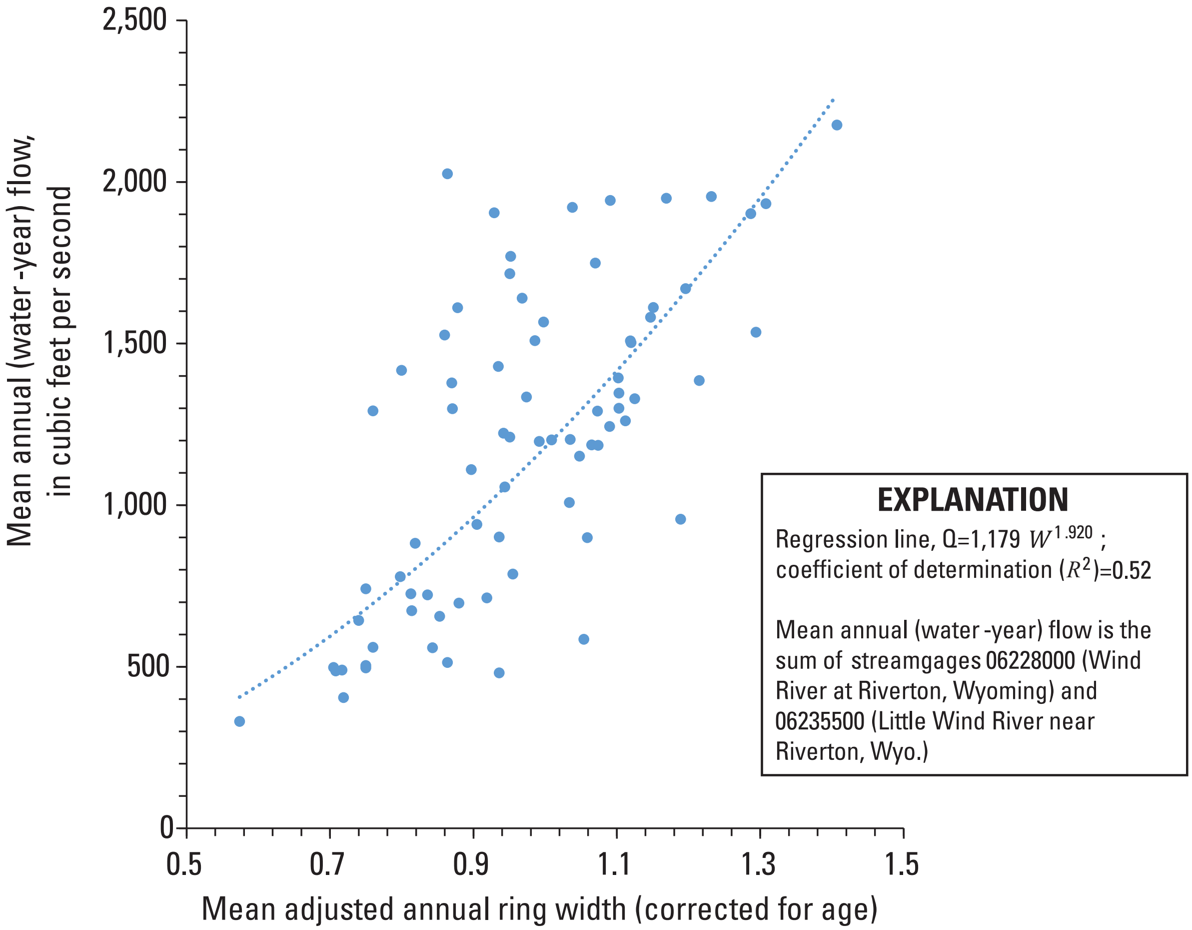


Figure 12. Mean annual (water-year) flow versus mean adjusted annual ring width at the Boysen Site, Wind River Reservation, Wyoming, 1942–2016.

the power plant was operated again from 1990 to 2007 flow records indicate that winter diversions never resumed (Bureau of Reclamation, 2019).

Altered winter flows have not previously been reported to affect cottonwood growth. Cottonwoods might be expected to be unaffected by changes in winter flows because they have no leaves, and stems are not growing in the winter. On the other hand, the xylem vessels necessary to transport water up a cottonwood stem are generally embolized (blocked by air bubbles) by freeze-thaw events in the winter. The bubbles can be removed by wetter conditions in late winter, but in cottonwoods the completeness of this refilling varies from year to year (Sperry and others, 1994; Hacke and Sauter, 1996). Greatly reduced flows in late winter could reduce the efficiency of this refilling process, reducing growth. Restoring those flows could allow more complete refilling of embolized vessels allowing more rapid growth to resume. It should be noted that multiple renovations occurred at Diversion Dam and Wyoming Canal in the 1970s (Autobee, 1996); it is, therefore, possible that the change in cottonwood growth was related to some factor other than winter flows.

A second reason for a weaker relation between flow and ring width at Diversion Dam compared to Boysen is that the higher elevation at Diversion Dam corresponds to lower temperatures and evaporation rates, leading to weaker water limitation of growth. For example, even after the sudden increase in growth in 1974, ring width and flow were only weakly related (R^2=0.10). On the other hand, before Diversion Dam began operating in 1926 (Autobee, 1996), ring width at Diversion Dam and Boysen were strongly related (R^2=0.61 for 1866–1925), and drought years in the two chronologies were similar (fig. 17), suggesting that the Diversion Dam chronology can be used tentatively to extend the drought record developed at Boysen where trees are not as old.

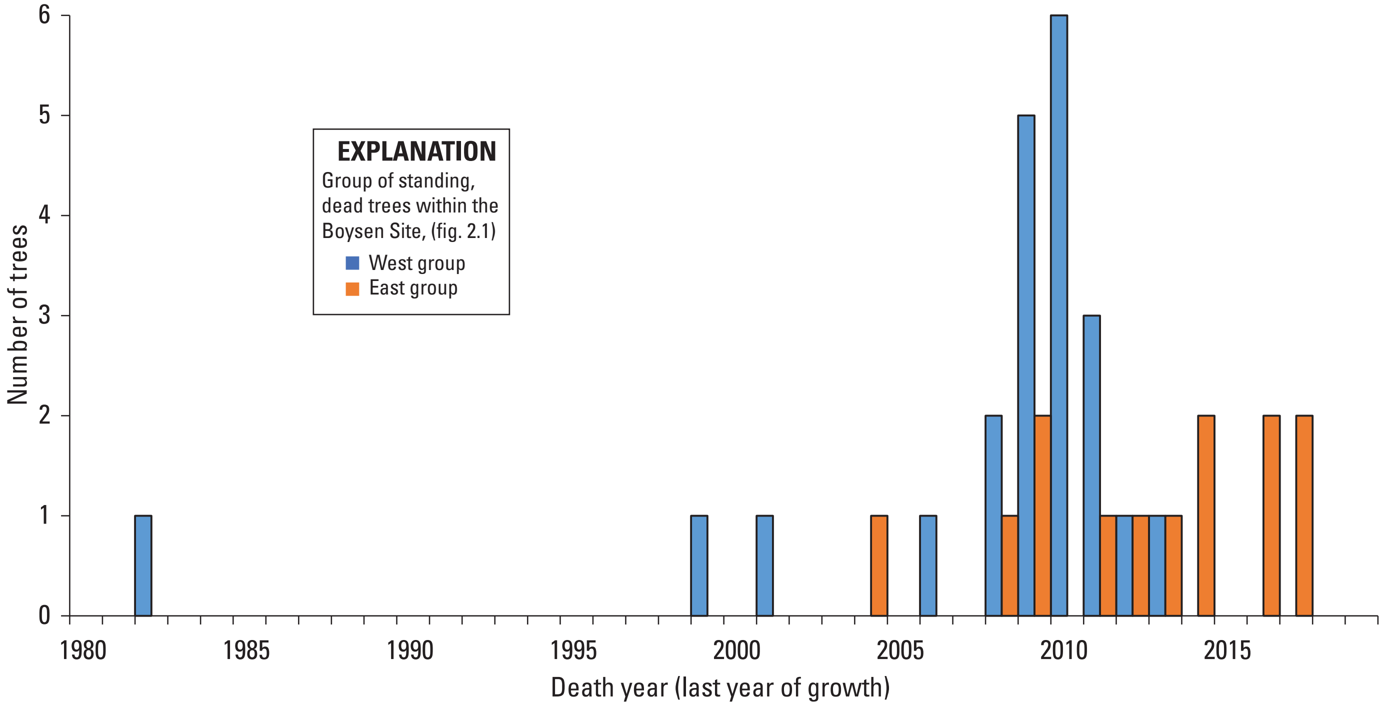


Figure 13. Death year (last year of growth) for 36 dead trees sampled at the Boysen Site, Wind River Reservation, Wyoming.

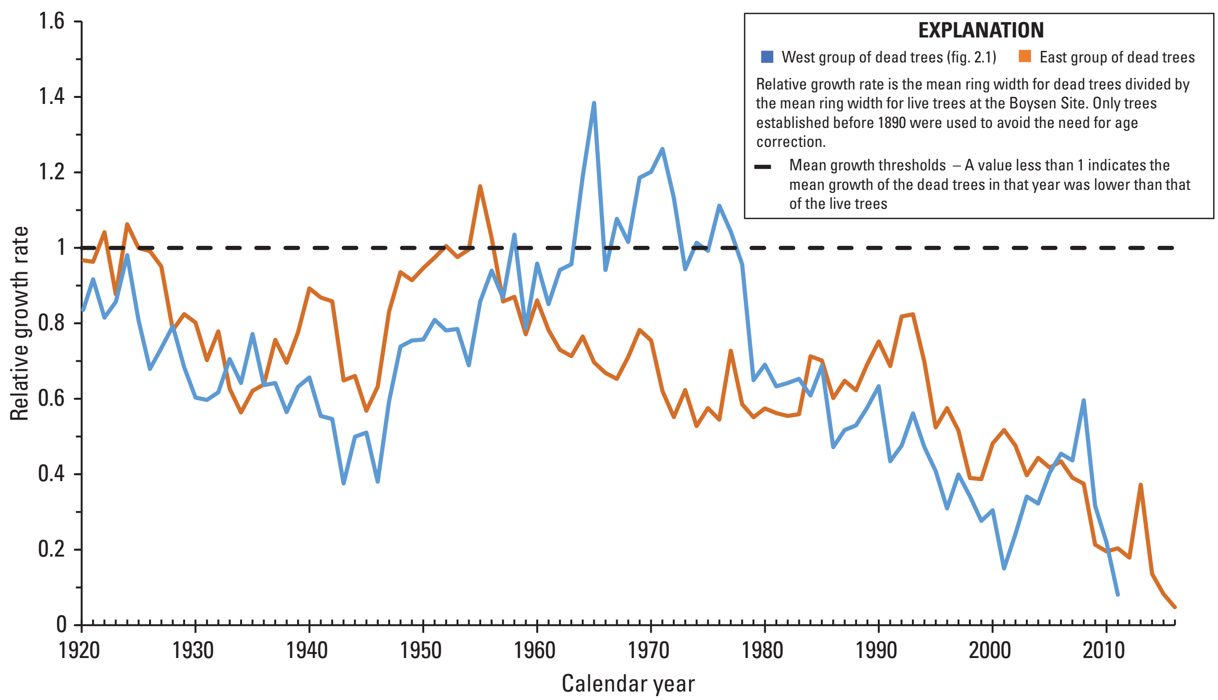


Figure 14. Relative growth rates for dead trees from two areas within the west and east groups within the Boysen Site, Wind River Reservation, Wyoming.

Flow Reconstruction from Multiple Sources

We reconstructed the history of droughts and floods using interviews of Tribal elders, cottonwood tree rings, streamgages, and historic records of temperature and precipitation. Elders observed several severe drought years and multiple-year droughts that have created significant water shortages and soil moisture deficits in the Wind River Basin (fig. 18). Drought years recalled by elders included the multiple-year drought that started in the late 1990s and lasted into the early 2000s. Elders also recalled a significant drought in 1988, a multiple-year drought in the 1930s, and a severe drought during 2012–13, for example (fig. 18). Elders observed several fires in the Little Wind and Wind rivers, which often coincided with severe drought events (for example, 2012; fig. 18), and which have removed forest from many reaches of the Wind and Little Wind Rivers. Several flood events were also reported (fig. 18). The elders also observed changes to runoff timing, a reduction in runoff volume, and changes to flood frequency and intensity.

Cottonwood ring widths at the Boysen Site record droughts and floods that also appear in the flow record (1942–2016; fig. 19; corroborated years in table 2) and flows and growth have declined together since the 1940s. The match between flow and growth is not perfect, however. For example, the tree rings missed high flows in 1943, 1951, 1957, and 1986, and overestimated low flows in 1988, 1992, and 1994 (fig. 19). The elders' observations of droughts aligned well with droughts recorded in tree-rings and flow records, particularly more recent or exceptional drought events (fig. 20). This is a common issue with individual recall bias (Bell and others, 2019) and is why the elders were more uncertain about the exact drought year, or years, when they occurred 30 or more years ago (fig. 20).

From 1913 to 1941 the contribution of flow from the Little Wind River was not measured, but flow data collected from the Wind River above the confluence with the Little Wind River (streamgage 06228000, fig. 1) confirms the timing of droughts and high flows as indicated by the tree rings during that period (corroborated years in table 2). The correlation between flows and ring width allows use of the ring widths to reconstruct flows from before the streamgage record (fig. 19), which indicates multiple droughts and high flows back to 1834 (reconstructed years in table 2). Ring widths in the early part of the record from the Diversion Dam Site (fig. 17) suggest years of droughts and high flows back to 1743 (suggested years in table 2). The long record provided by the tree rings places recent trends in a longer-term context. For example, the tree rings at both sites show an extended drought from 1870 to 1911 before the wet conditions of the 1920s (fig. 17). This drought is confirmed by reconstructions using montane conifers for flow in the Little Popo Agie River and Bull Lake Creek (Watson and others, 2009) and for precipitation in the Bighorn Basin in north-central Wyoming (Gray and others, 2004).

Flow data, interviews with elders, tree rings from the Boysen Site, and sc–PDSI combine to suggest that the drought of 2000–4 was the most severe drought in the last century or more (fig. 20). The year 2001 had the lowest annual flow recorded at both the Wind and Little Wind Rivers at Riverton, and low flows persisted from 2000 to 2003 (fig. 3). This period was reported as a severe, sustained drought in multiple interviews with major impacts to agriculture and fisheries (figs. 18 and 20). Adjusted ring widths at the Boysen Site were lower than in any other year except 1902, and low growth extended from 2000 to 2003 (fig. 19). The year 2001 had the lowest value on record for the sc–PDSI (fig. 20). Further, the elders noted a trend toward more persistently dry conditions since the early 2000s drought (figs. 18 and 20). McNeeley and others (2018) found reduced snow-water equivalent and precipitation for 2000–15 compared to 1984–2000 across the Wind River Reservation. Finally, considering flows throughout the Missouri River Basin, Martin and others (2020) found that the drought of 2000–10 may have been the most severe in the last thousand years. Projected increases in temperature will increase the likelihood of such severe, sustained droughts in the future (Conant and others, 2018).

Differences among drought reconstructions illustrate the spatial variation in drought severity across the Wind River Basin. For 1942–2016, annual ring width at the Boysen Site is strongly correlated with streamflow (r=0.69) but only moderately correlated with the sc–PDSI (r=0.40). The sc–PDSI is a function of local temperature and precipitation. Flow in the Wind River is dominated by snowpack high in the Wind River Range. The differing correlations suggest growth of cottonwoods at the Boysen Site is controlled by montane snowmelt more than by local weather. From the perspective of a rancher along the river, the demand for irrigation water in a drought is determined largely by local temperature and precipitation (that is, sc–PDSI), but the supply of irrigation water is set by river flow, which is controlled by montane snowpack and water management (McNeeley and Beeton, 2017).

The experience of drought on the ground is a combination of biophysical and social factors, which may vary within and among subbasins, irrigation districts, and individual allotments (McNeeley and others, 2018). Further, differences in the seasonal timing of drought exposure and water needs among different sectors affect who, or what, is impacted, when, and why, which therefore requires using multiple drought indices and indicators at scales aligned with management decision timelines. McNeeley and others (2018) conducted a joint hydroclimate and social analysis of the 2015 microdrought (that is, a drought that is short in duration, highly local, and due to the unique social-ecological context) at the Wind River Reservation. Warmer temperatures during the winter, reduced snowpack, and an earlier transition of snow to rain in high elevations resulted in earlier, accelerated, and reduced runoff, which, when coupled with limited storage capacity to capture early flows and a rapid drying in late summer, led to the irrigation season being closed over 1 month earlier than

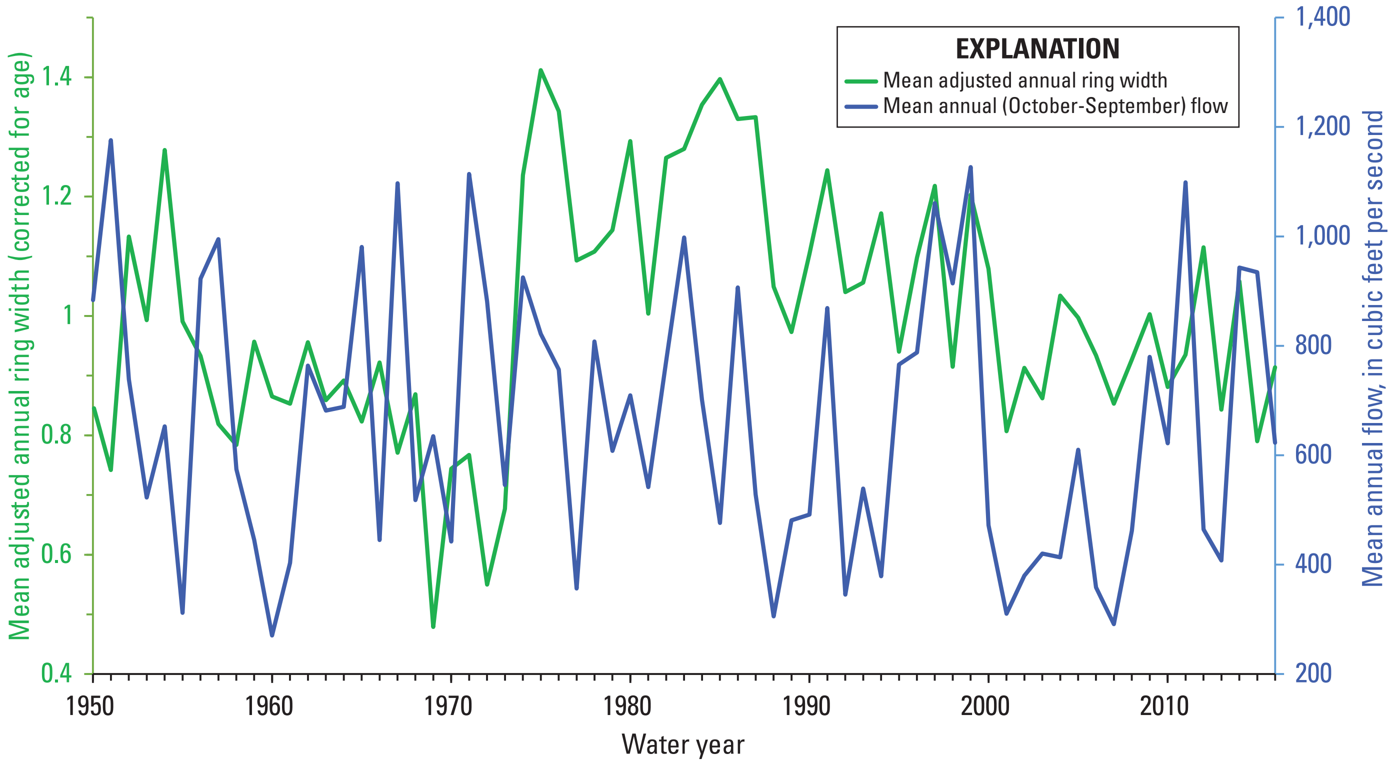


Figure 15. Mean adjusted annual ring width and water-year (October through September) flow at the Diversion Dam Site, Wind River Reservation, Wyoming.

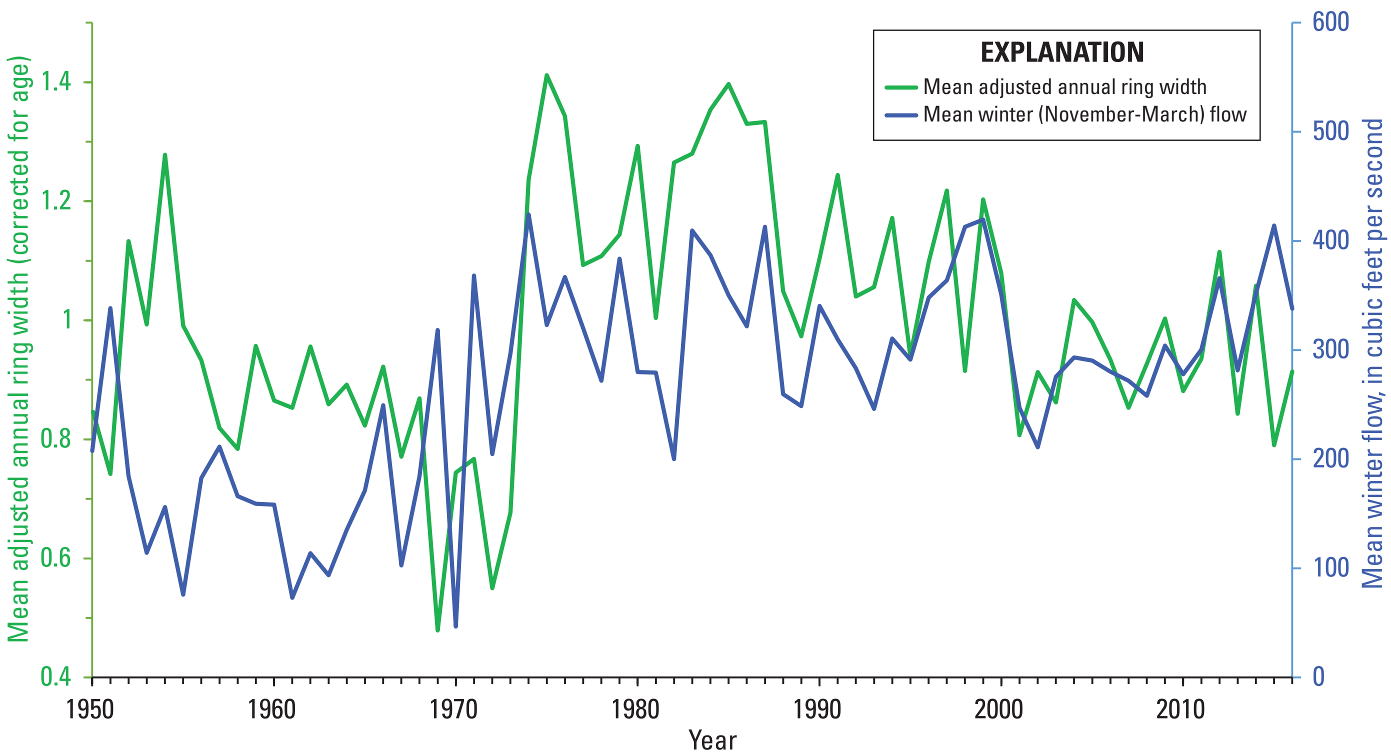


Figure 16. Mean adjusted annual ring width and winter (November through March) flow at the Diversion Dam Site, Wind River Reservation, Wyoming.

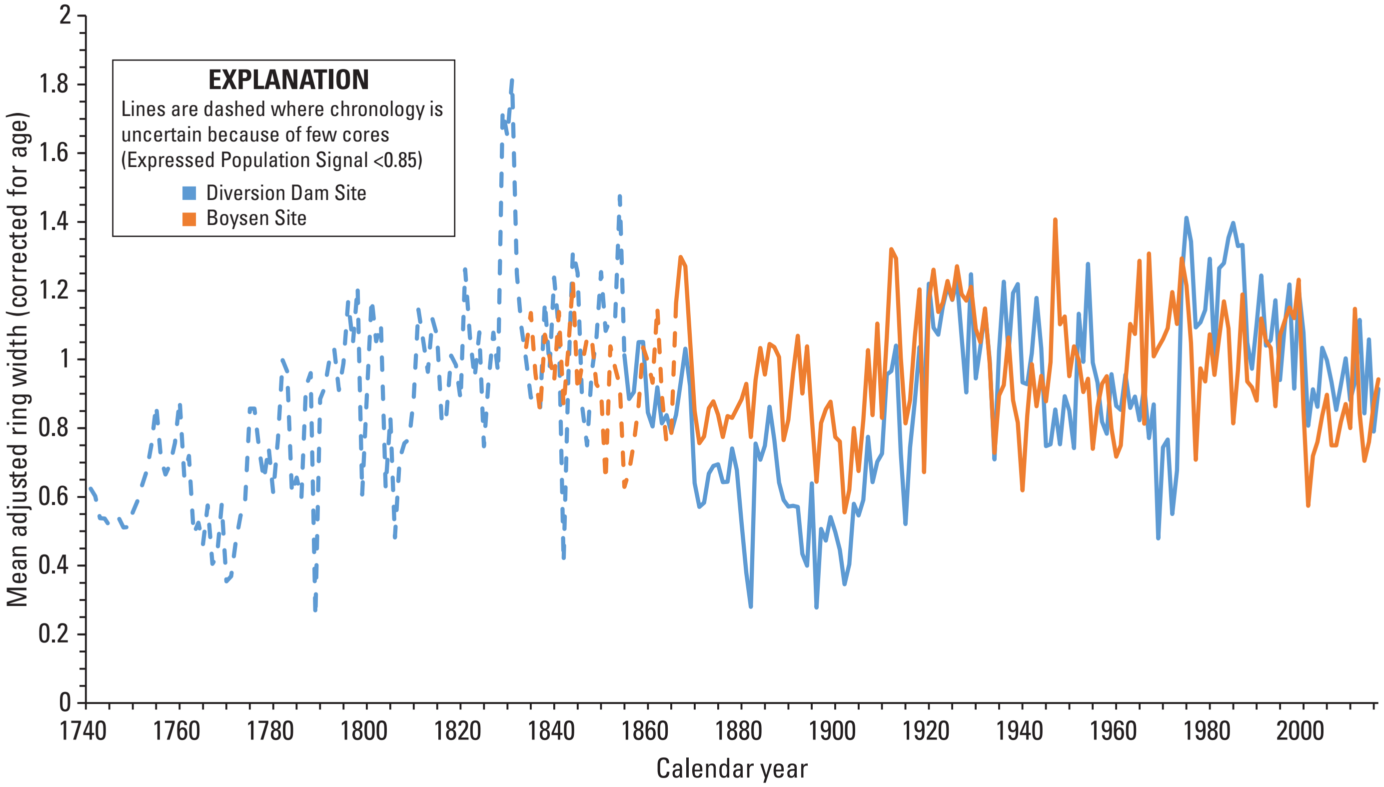


Figure 17. Mean adjusted ring width for trees at the Boysen and Diversion Dam Sites, Wind River Reservation, Wyoming.

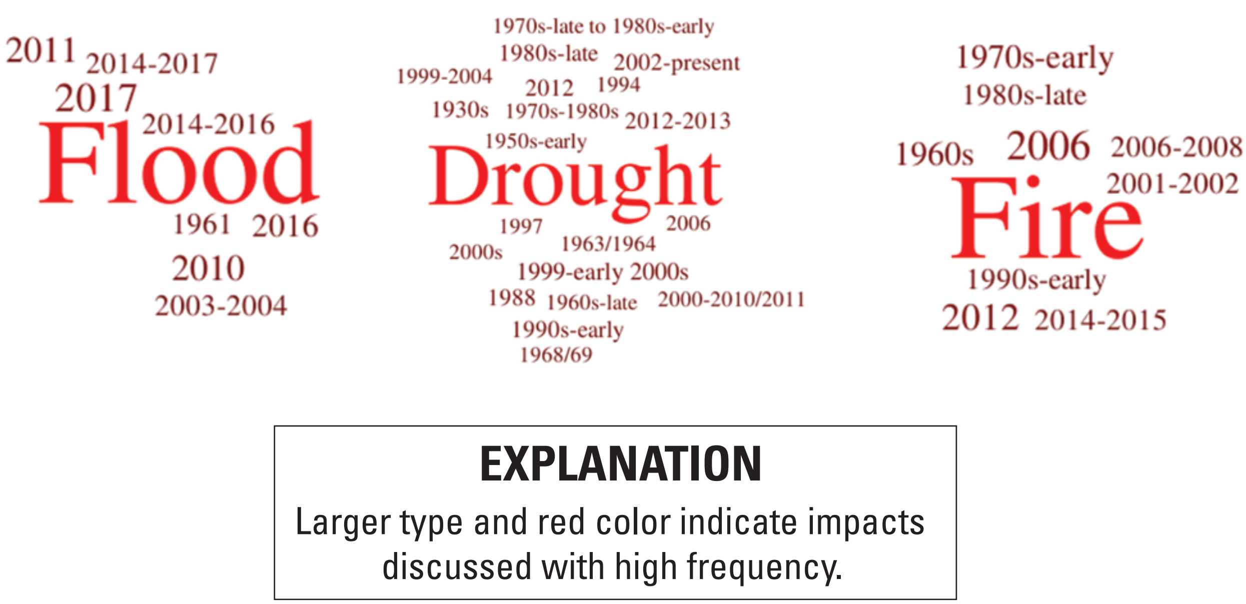


Figure 18. Drought, fire, and flood years reported by Tribal members, Wind River Reservation, Wyoming.

Table 2. Years of low and high flow indicated by tree-ring width at the Boysen Site, Wind River Reservation, Wyoming, 1743–2013.

Confidence level	Years
Low flow	
Suggested[1]	1743–49
	1756–58
	1761
	1784
	1789
	1806
Reconstructed[2]	1837
	1842
	1851
	1855–56
	1864–65
	1871–72
	1889–90
	1896
	1902–3
	1905
Corroborated[3]	1919
	1934
	1940
	1955
	1959–61
	1966
	1977
	1985
	1988–90
	1994
	2000–2
	2006–7
	2012–13
High flow	
Suggested[1]	1772–73
	1801
	1829–31
Reconstructed[2]	1844
	1867–68
	1912–13
Corroborated[3]	1947
	1965
	1967
	1983
	1999
	2011

[1]Early low- or high-growth years at the Diversion Dam Site suggesting low or high flows at the Boysen site with low confidence on the basis of the moderately strong correlation between growth at the Boysen Site and growth at the Diversion Dam Site.

[2]Low- or high-growth years at the Boysen Site from before the streamgage record indicating low or high flows at the Boysen Site with moderately high confidence because of the strong correlation between growth at the Boysen Site and streamgage data.

[3]Low- or high-growth years at the Boysen Site indicating low or high flows at the Boysen Site with high confidence because of corroboration by streamgage data.

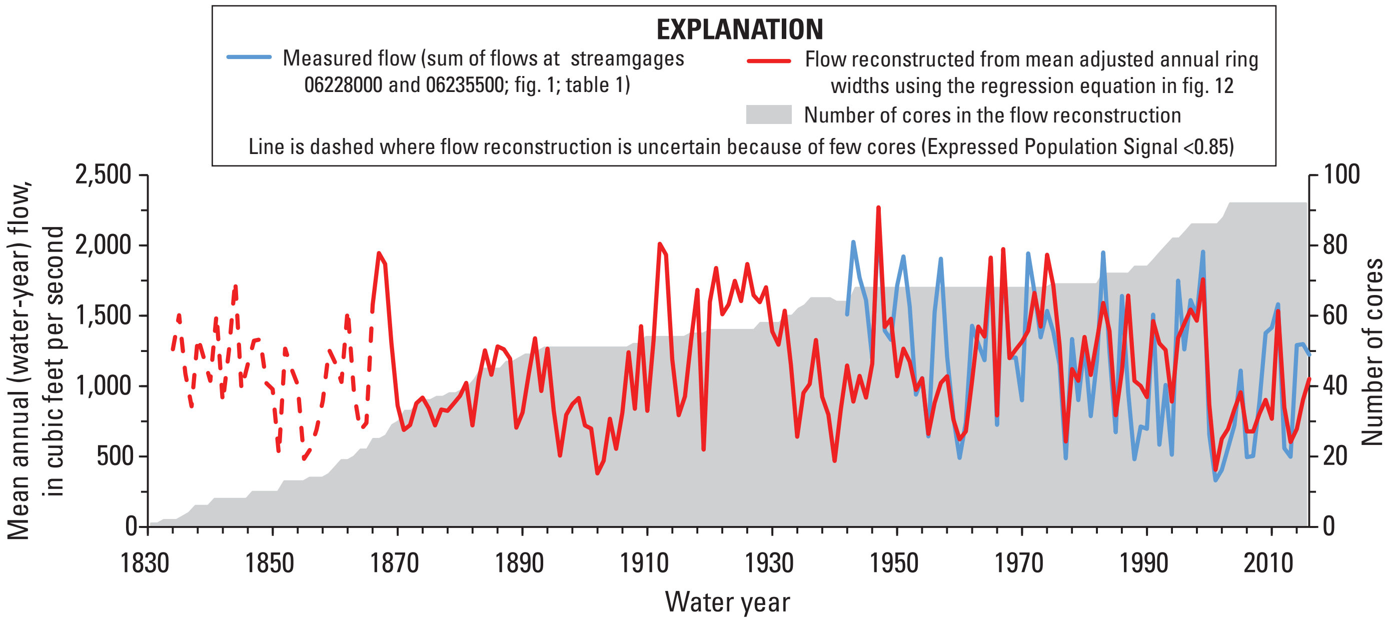


Figure 19. Mean annual (water-year) flows reconstructed from ring widths and measured for the Wind River above Boysen Reservoir (Boysen Site), Wind River Reservation, Wyoming.

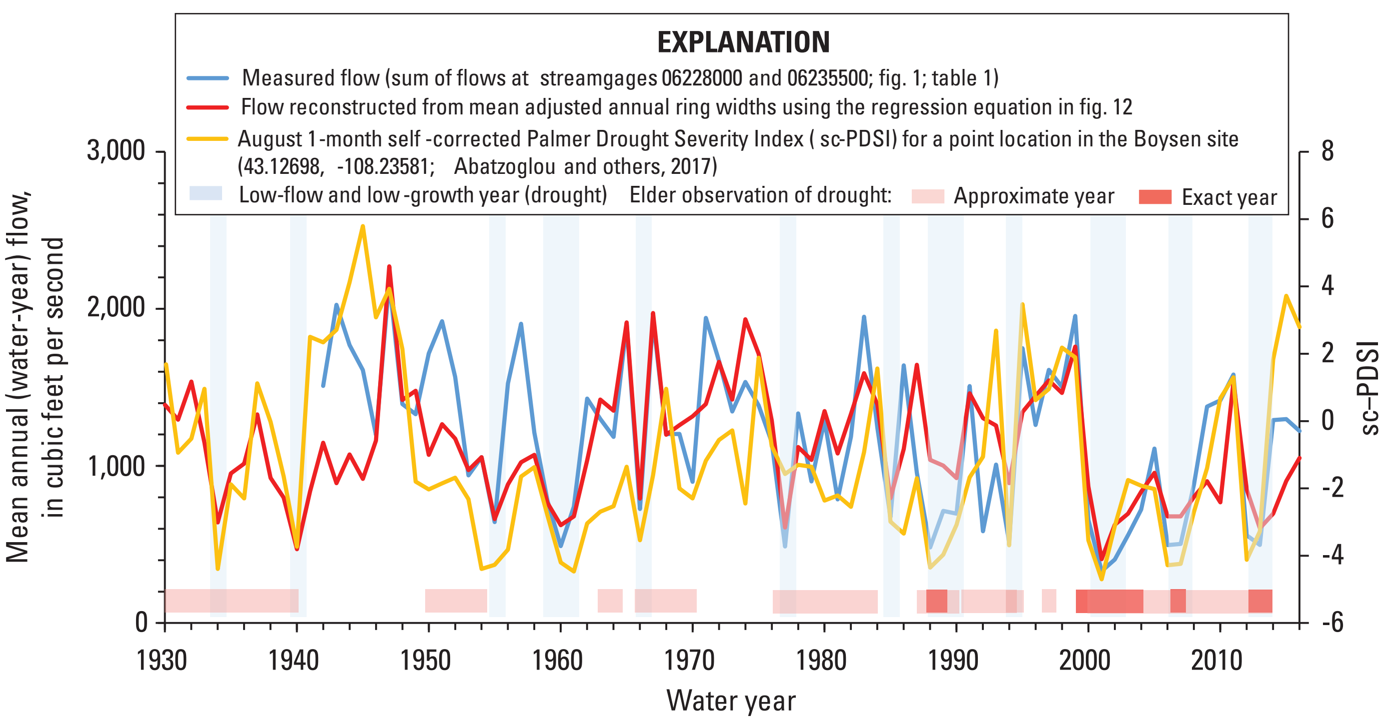


Figure 20. August 1-month self-corrected Palmer Drought Severity Index for a point location in the Boysen Site, Wind River recorded annual flows, reconstruction of flows from ring-widths, low-flow and low growth years (that is, drought), and elder observations of drought, Wind River Reservation, Wyoming, 1930–2014.

typical with significant impacts to agricultural producers. The Evaporative Drought Demand Index was able to capture this rapidly evolving drought in the summer, yet other conventional indices, such as the U.S. Drought Monitor, did not capture the evolving drought conditions until the fall when the irrigation season was already closed (McNeeley and others, 2018). Annual flows, ring width, and the sc–PDSI also did not capture this microdrought (figs. 19 and 20), in part because they sense drought at a longer time scale. This underscores the importance of using multiple lines of evidence to fully understand drought exposure and impacts to local livelihoods and the environmental resources on which they depend.

Summary

We assessed the history of drought and riparian ecosystem change along the Wind River using cottonwood tree-ring data, stream-gage records, historical temperature and precipitation data, drought indices, and local observations and Traditional Ecological Knowledge from elders of the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyoming. Using this multifaceted dataset, we documented drought years over the last two centuries that have impacted local riparian areas and people who depend on riparian resources. Elder observations of drought aligned with recent and (or) extreme droughts recorded in flow history, self-corrected Palmer Drought Severity Index (sc–PDSI), and tree-ring data. Ring width of trees at the Boysen Site was strongly correlated to streamflow, which allowed reconstruction of flows confidently back to the mid-1860s and speculatively back to the 1740s. This extended flow record revealed the occurrence of a major period of low flow from 1870 to 1910 that was not evident in the shorter instrumental records of flow and weather. Ring-width, streamflows, sc–PDSI, and local observations all suggest that the early 2000s drought was the most severe drought in a century or more.

Flow diversions, recent extreme droughts and fires, and invasion of Russian olive are decreasing the vigor, area, and reproduction of cottonwood forests along the Wind and Little Wind Rivers. This has made it more difficult for elders to collect plains cottonwood products necessary for traditional activities. Culturally important shrub species found with cottonwood, like bullberry, chokecherry, and red willow are also in decline. In spite of these challenges, cottonwoods more than 200 years old are still present along the Wind River. Furthermore, flow in the Wind and Little Wind Rivers is still dominated by snowmelt floods that drive channel migration, promoting reproduction of cottonwood on recently deposited sandbars. In summary the riparian forest is in gradual decline but not collapsing like the forest along the Bighorn River downstream from Boysen Reservoir and the Missouri River in Montana, North Dakota, and South Dakota.

Water availability varies over time and across the Wind River Reservation in response to variability in precipitation, temperature, river flow, and water management. Drought on a ranch may result from (1) an increased water demand caused by high local temperature or low local precipitation; or (2) from a decreased supply of irrigation water caused by reduced montane snowmelt or upstream diversions. Ring width of cottonwood trees at the Boysen Site was more strongly correlated to river flow than to local precipitation, temperature, or sc–PDSI, indicating that growth of trees is controlled by montane snowmelt more than by local weather. Therefore, tree rings are a better indicator of water supply than of the local conditions controlling water demand. Drought indicators vary in their rate of response to changing conditions. For example, the Evaporative Drought Demand Index captures intense, brief drought more effectively than annual flows, ring width, or sc–PDSI. This complexity underscores the importance of using multiple indicators for drought and documenting local observations alongside collection of data from river flow, weather, and tree rings.

The results of this study support drought planning and riparian vegetation management on the Wind River Reservation. We used tree rings to extend the flow record and documented the effects of varying river flow and local weather on agriculture, riparian forests, and culturally important resources for the Eastern Shoshone and Northern Arapaho tribes. This documentation of the biophysical and social factors that contribute to water availability at the Wind River Reservation will benefit ongoing drought planning and adaptation. Our assessment documented the relationship between the Eastern Shoshone and Northern Arapaho Tribes of the Wind River Reservation, Wyo., and riparian forests, and particularly highlighted the resources of traditional and cultural importance to both tribes that need to be addressed in drought planning activities. Relatedly, the assessment documented where resources were most impacted, which helps to prioritize areas for riparian restoration and identify target indicator species for drought monitoring and ecological restoration.

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Appendix 1. Interview Questions

The following are the elder interview questions:

1. What can you tell me about the relationship between the Tribe and the cottonwood trees?
2. Have you seen changes in the trees during your lifetime?
3. What can you tell me about the relationship between the cottonwood trees and the river?
4. How has the river changed in your lifetime – esp. areas around Diversion Dam and between Boysen Reservoir and Riverton? [show map of sampling areas]
5. Are there other old stories or long time ago stories you know about the trees that you can share with us?
6. Are there other old/long time ago stories about the river that you can share?

History of the floodplain/cottonwood forests (may have addressed above, only ask if they haven't yet or if can provide more details):

7. Past events they remember: droughts, fires, big floods, cottonwood dieback or disease outbreaks
8. Changes in abundance and/or balance of riparian forest species narrowleaf versus plains, bullberry bushes, chokecherries, currants, invasive Russian olives, tamarisks
9. Remember any die offs of riparian forests during drought?
10. Any major changes to the river channels in those regions Jonathan sampled? (show map)
11. Any oral history about droughts in the 1800s? or written?

Appendix 2. Details of Cottonwood Sampling and Analysis

In July and August 2017 and October 2018, we cored cottonwood trees at two sites along the Wind River (fig. 1): upstream from Boysen Reservoir (Boysen Site, fig. 2.1), and downstream from Diversion Dam (Diversion Dam Site, fig. 2.2). At each site, we randomly selected 50 points and cored the closest tree to each point to minimize bias in tree selection (fig. 2.3; Briffa and Melvin, 2011). We discarded 15 points from the Boysen Site and 5 points from the Diversion Dam Site because these points were within the river or an unforested part of the floodplain or because the cores were not readable. The randomly selected trees were used to analyze the age distribution of the forest. For the purpose of flow reconstruction, we added 12 more trees at the Boysen Site (fig. 2.1) and 19 more trees at the Diversion Dam Site (fig. 2.2) to increase representation of older trees. From each tree, we used a Haglöf increment borer to collect two cores 1.2 meters above the ground. Coring only living trees ignores the larger number of trees that have already died. Because many trees at the Boysen Site have recently died, we collected samples from an additional 36 dead trees by cutting a slab with a chainsaw in October 2018. We mounted and sanded cores using progressively finer grades of sandpaper between 120 and 1,200 grit. Cross-dating was performed visually under a dissecting microscope using skeleton plots (Stokes and Smiley, 1996) and was quality controlled using the program COFECHA (Holmes, 1983; Grissino-Mayer, 2001). Where cores missed the tree center, we calculated the number of missing rings by dividing the radius of curvature of the innermost ring boundary by the average width of the four innermost complete rings (Meko and others, 2015).

We applied Signal-Free Regional Curve Standardization to correct ring width for the effect of tree age while preserving low-frequency (century-scale) variation (Briffa and others, 1992). We used the program CRUST to perform this detrending (Melvin and Briffa, 2014), applying two growth curves at each site to minimize the effect of Modern Sample Bias, the tendency to select mostly slow-growing old trees because fast-growing old trees have already died (Schook and others, 2016). We applied an age-dependent smoothing spline to the growth curve and calculated growth indices using the ratio of measured and expected ring width. We averaged all the indices in each year using the robust biweight mean. This yielded a single chronology for each site showing mean annual ring width adjusted for tree age. In plots of these chronologies, we dashed the line in early years when small sample size increased uncertainty as indicated by an Expressed Population Signal less than 0.85 (Wigley and others, 1984). We used the program SEASCORR (Meko and others, 2011) to explore correlations between mean adjusted annual ring width and monthly flow. We calculated regressions between mean adjusted annual ring width at a site and annual flow in each water year (previous October through September), and used the resulting regression equations to reconstruct flow before streamgage installation.

To characterize flows at the Boysen Site we combined flows from the streamgages Wind River at Riverton, Wyoming (06228000), and Little Wind River near Riverton, Wyo. (06235500; fig. 1). These two streamgages are just above the confluence of the Wind and Little Wind Rivers. This combination of streamgages provided flow data back to 1942 and closely matched flows measured from 1991 to 2012 at the downstream end of the Boysen Site at the short-lived streamgage Wind River above Boysen Reservoir near Shoshoni, Wyo. (06236100). For the 22-year period of overlap of these three streamgages, mean annual flow at streamgage 06236100 averaged 107 percent of the sum of streamgages 06228000 and 06235500, respectively, and the correlation of annual flows over the same period was strong (correlation coefficient [r] was 0.999). Because our Boysen Site was downstream from the confluence with the Little Wind River, flows experienced by the trees at this site have not decreased as strongly as those along the Wind River upstream from the confluence. To characterize flows at the Diversion Dam Site, we used data from the streamgage Wind River near Crowheart, Wyo. (06225500), and subtracted diversions into the streamgage Wyoming Canal near Lenore, Wyo. (06226000), for years 1950–73 and from station WYCA on the Bureau of Reclamation Hydromet site (https://www.usbr.gov/gp/hydromet/res070.html) for years 1974–2017 (fig. 1).

We obtained monthly mean maximum temperature and total monthly precipitation from the U.S. Historical Climatology Network (National Climate Data Center, 2018). These temperature data have been corrected for biases caused by changes in streamgage operation and instrumentation over time (Menne and others, 2009). For Riverton (station USH00487760), precipitation data spanned 1900–2017 and temperature data spanned 1923–2017. For Diversion Dam (station USH00482595), precipitation data spanned 1904–2017, and temperature data spanned 1923–2017. We downloaded data for the self-corrected Palmer Drought Severity Index (sc–PDSI) for 1930–2017 from the West-Wide Drought Tracker (Abatzoglou and others, 2017; Western Regional Climate Center, 2019) for a point near the Boysen Site (43.12698N, 108.23581W). We used Pearson correlation to relate August sc–PDSI to mean adjusted annual ring width at the Boysen Site. Wind River recorded flows, reconstructed flows, and sc–PDSI were also overlaid with local observations of drought from the 1930s to 2013. Tree-ring data are available in a data release (Friedman and Thaxton, 2020).

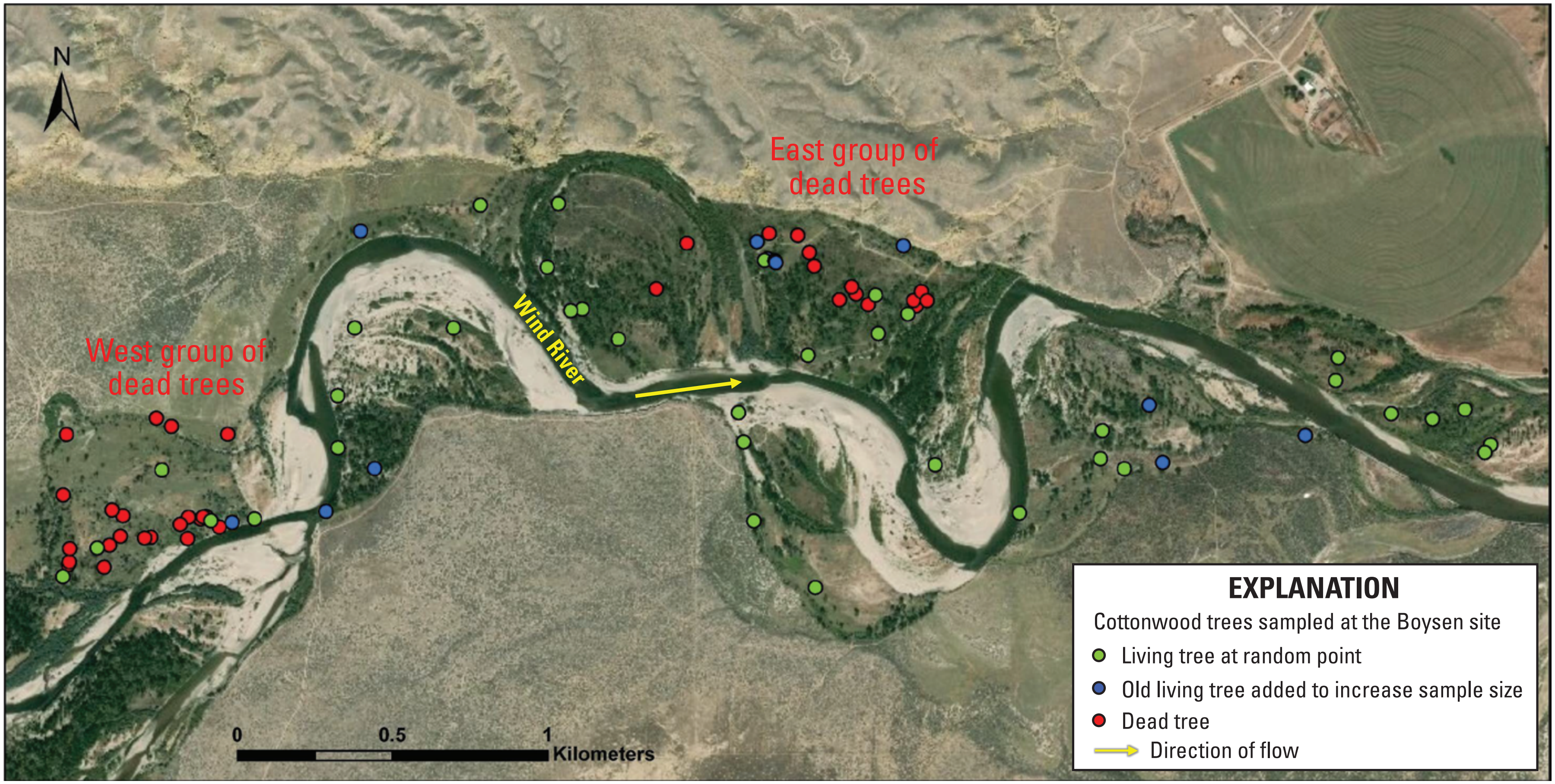

Figure 2.1. Cottonwood trees sampled, including living trees at random points, old trees added to increase sample size for early years, and dead trees, at the Boysen Site, Wind River Reservation, Wyoming.

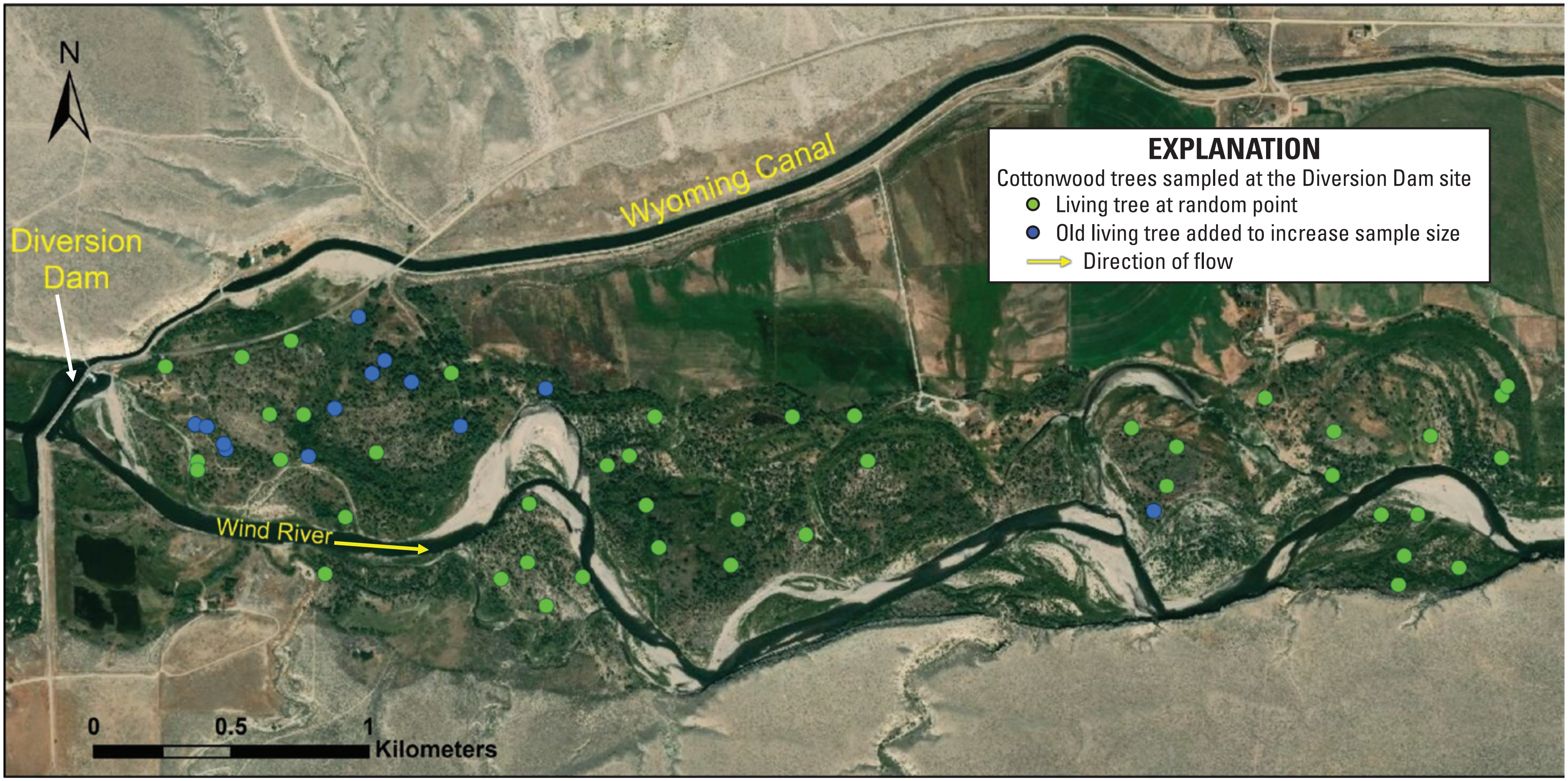

Figure 2.2. Cottonwood trees sampled, including trees sampled at random points and old trees added to increase sample size for early years, at the Diversion Dam Site, Wind River Reservation, Wyoming. No dead trees were sampled at this site.

Figure 2.3. Al C'Bearing, Office of the Tribal Water Engineer, collecting a core from a narrowleaf cottonwood at Arapaho Ranch along Owl Creek, Wind River Reservation, Wyoming, October 15, 2018. Photograph by Jonathan Friedman, U.S. Geological Survey.

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