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Review

Science to support conservation action in a large river system: The Willamette River, Oregon, USA

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ABSTRACT

Management and conservation efforts that support the recovery and protection of large rivers are daunting, reflecting the complexity of the challenge and extent of effort (in terms of policy, economic investment, and spatial extent) needed to afford measurable change. These large systems have generally experienced intensive development and regulation, compromising their capacity to respond to disturbances such as climate change or wildfire. Functionally, large river and basin management require insights gained from social, ecological, geophysical, and hydrological sciences. This multidisciplinary perspective can unveil the integrated relationship between a river network's biotic community and seasonally variable environmental conditions that are often influenced by human activities. Large rivers and their basins are constantly changing due to anthropogenic influences and as climate modifies patterns of temperature and precipitation. Because of these factors, the state of knowledge must advance to address changing conditions. The Willamette River, in western Oregon, USA, is a prime example of a basin that has experienced significant degradation and investment in rehabilitation in recent decades. Innovative science has facilitated development of fine-scale, spatially extensive datasets and models that can generate targeted conservation and rehabilitation actions that are prioritized across the entire river network. This prioritization allows investment decisions to be driven by site-specific conditions while simultaneously considering potentials for ecological improvement. Here, we review hydrologic, geomorphic, ecologic, and social conditions in the Willamette River basin through time—including pre-settlement, river development, and contemporary periods—and offer a future vision for consideration. Currently, detailed information about fish populations and habitat, hydrologic conditions, geomorphology, water quality, and land use can be leveraged to make informed decisions about protection, rehabilitation, and development. The time is ripe for strategic management and goal development for the entire Willamette River, and these efforts can be informed by comprehensive science realized through established institutions (e.g., public agencies, non-profit watershed groups, Tribes, and universities) focused on conservation and management. The approaches to science and social-network creation that were pioneered in the Willamette River basin offer insights into the development of comprehensive conservation-based planning that could be implemented in other large river systems globally.

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1. Introduction

Rivers and the tributaries that feed them are the lifeblood of functional socio-ecological systems. Large rivers are collection points for vast landscapes, delivering important ecosystem services to human communities including clean water, food, and recreational opportunities (Rinne et al., 2005; Yeakley et al., 2016). Worldwide, large rivers have been targeted for development and hydrologic modification for millennia (Macklin and Lewin, 2018). These anthropogenic actions reduce the geophysical resilience of free-flowing rivers, compromising ecosystem processes (Malmqvist and Rundle, 2002) and the services they provide, particularly in response to climate variability (Macklin and Lewin, 2018). Conservation efforts to rehabilitate large rivers are daunting, reflecting the vast scale of problems that include conflicting policy directions, significant data needs to support effective decision-making, and the differing views, goals, and values of the various stakeholders. However, once these complex problems have been identified and defined, innovation can lead to previously unrecognized opportunities for

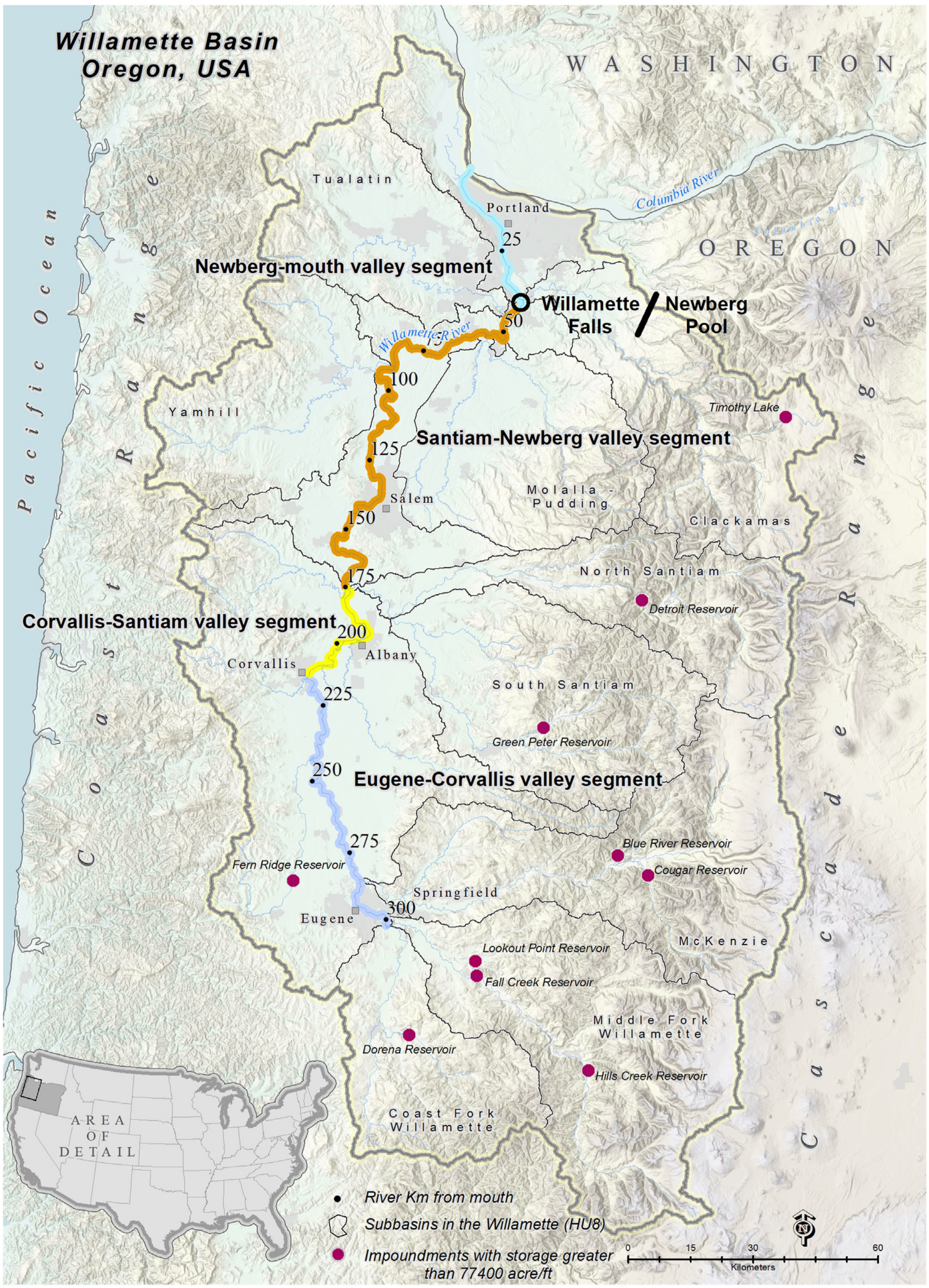

Fig. 1. The Willamette River basin and four valley segments, located in western Oregon between the Coast Range mountains to the west and the Cascade Range mountains to the east.

conservation, rehabilitation, and protection (e.g., Skidmore and Wheaton, 2022; Wiley et al., 2013; Wohl et al., 2015). Coupled with effective communication among researchers, conservation practitioners, and community members, applied problems can be addressed and mitigated (Cash et al., 2003; Ciotti et al., 2021; Scott et al., 2022).

Globally, historical patterns of human settlement have followed river corridors owing to ease of transportation and commerce, access to water and food, and the availability of nutrient-rich floodplain soils ideal for agriculture. For many rivers, high-density settlements have led to river pollution, compromising ecological functions and the services that lotic ecosystems provide (Malmqvist and Rundle, 2002). More recently, the construction of hydroelectric and flood-mitigation dams throughout large river systems have further modified the seasonal patterns of inundation that sustained productive lowland ecosystems and floodplains (Poff et al., 1997). Climate change threatens to further exacerbate existing degraded conditions in rivers via elevated temperature and modified flow regimes (Gido et al., 2023; Hamlet and Lettenmaier, 2007), providing further motivation to recover river and floodplain processes to forestall ecosystem collapse (Seavy et al., 2009).

Comprehensive management that protects rivers while allowing for multiple uses across the mosaic of landownerships is a substantial challenge. Further, effective management of large, regulated rivers requires participation from the different sectors that use the basin. In this case study, we focus on the Willamette River basin, Oregon (Fig. 1), where innovative developments in science are coupled with conservation-minded social networks leading to informed cross-boundary planning and decision-making. The Willamette River, the second largest tributary to the Columbia River by discharge, drains 28,800 km^2 of northwestern Oregon, joining the Columbia River near Portland, Oregon (Fig. 1). We review early human use of the Willamette River basin, including Indigenous land-use practices that were eventually replaced by methods implemented by European immigrants over a century ago. We also examine alterations to the river system from navigation engineering, flood mitigation, hydroelectric dam construction, and agricultural and urban development, and describe consequences to the native flora and fauna. Finally, we discuss some of the recent scientific contributions that have guided rehabilitation and conservation efforts in this basin. The integration of science into management actions in the Willamette River basin occurred through co-development from diverse groups that include Federal, State, Tribal, academic, and non-profit partners across a network of institutions and organizations. In practice, recovery and management of the Willamette River basin is a work in progress as rehabilitation practitioners, managers, and organizations learn from efforts to recover water quality, imperiled species, and other important ecosystem elements within this large, degraded river system. We intentionally use the term rehabilitation, rather than restoration, to refer to applied conservation actions throughout this paper to acknowledge the evolving nature of science and practice that contribute to effective conservation actions intended to result in improved ecological conditions.

In this case study, we focus on the history, status, and potential future of conservation and science in the Willamette River (Fig. 1). This paper is not meant to encompass all research and conservation efforts in the basin, but rather to consolidate emerging sciences to contextualize past practices that led to the current state of the river. We then look forward to describe how river conservation and science can contribute to the broader consideration of land use, land management, and human communities throughout the system. To accomplish this goal, we have divided this paper into three sections:

- Willamette River and floodplain—Underlying landscape and human footprint,
- Current river—Science supporting conservation,
- Conservation futures—Blending visions.

In each of these sections, we address the prevailing cultural, biological, and geophysical characteristics of the Willamette River. Our focus in this case study is on the function and processes of the gravel-bed main stem rather than its tributaries. Our aim is to present the underlying conditions, challenges, and accomplishments that have characterized rehabilitation and conservation of the Willamette River, as well as to describe current opportunities for ongoing conservation actions in a basin of increasing human population growth and economic development. Whereas this case study is intended to be a useful tool to enhance future work in the Willamette River basin, we hope that the experiences relayed here offer ideas to other groups challenged by rehabilitation in other large-river systems worldwide.

2. Willamette River and floodplain—Underlying landscape and human footprint

2.1. Prior to Euro-American arrival (before 1830)

2.1.1. Cultural elements

Historically, the Willamette River basin was occupied by Indigenous communities whose hunting and gathering practices were tailored to available resources. Willamette Falls (rkm 42; Fig. 1) may have been a barrier to upstream migration by migratory fishes except during high spring flows (Toepel, 1985) and this river feature concentrated migratory fish species providing enhanced harvest opportunities for Indigenous people for thousands of years. Myers et al. (2006) estimated that the Indigenous (pre-1900) fishery at Willamette Falls may have yielded 138–909 metric tons of spring-run Chinook Salmon (*Oncorhynchus tshawytscha*) annually. Intertribal fishing at Willamette Falls also targeted Pacific Lamprey (*Entosphenus tridentatus*, Close et al., 2002), a critical First Food (e.g., core foods used by Indigenous Communities prior to Euro-American arrival). Other First Food sources found in the Willamette Valley included deer *(Odocoileus hemionus)*, elk *(Cervus canadensis)*, camas bulbs *(Camassia quamash)*, Wapato tubers (*Sagittaria latifolia*), and various species of fish, berries, nuts, and roots (Engum, 2020). The multiple bands of Indigenous communities throughout the Willamette Valley collectively used fire for clearing the savanna of brush and tall grasses to facilitate hunting and enhance the growth and subsequent collection of desirable plants (USFWS, 2017; Zenk, 2008).

2.1.2. Biological complexity

Indigenous fire management supported extensive savanna and wet prairie regions throughout the Willamette Valley (Johannessen et al., 1971; Scott, 1923; USFWS, 2017; Zenk, 2008). Large populations of American Beavers (*Castor canadensis*) enhanced the complexity of streams, ponds, and wetlands (Naiman et al., 1988; Scott, 1923), which supported diverse biological communities of plants and animals, including migratory birds (Taft and Haig, 2003).

In addition to migratory spring-run Chinook Salmon (Schroeder et al., 2016), steelhead trout (*O. mykiss*), and Pacific Lamprey that were able to migrate past the Willamette Falls during high flows (Myers et al., 2006), resident species such as Coastal Cutthroat Trout (*O. clarkii*) and Bull Trout (*Salvelinus confluentus*) primarily resided in tributaries above the Corvallis-Santiam valley segment (Fig. 1), but also in the main stem with varied fluvial life histories (Seals and Reis, 2003; Zymonas, 2011).

The main stem Willamette River is comprised of water from three major types of tributaries: those with headwaters in the Cascade Range, the Coast Range, or the valley floor. Cascade Range tributaries are fed by springs and meltwater originating from high-elevation glaciers and snow fields and they carry coarse bedload substrates and cold water to the mainstem river (Hughes and Gammon, 1987). Major Cascade Range tributaries include the Clackamas, North and South Santiam, Calapooia, McKenzie, Middle Fork Willamette, and Coast Fork Willamette rivers. These tributaries support salmon and steelhead runs and some continue to support Bull Trout (Bull Trout are now found in portions of the McKenzie and Middle Fork Willamette rivers, but were historically more widely distributed; ODFW, 2005). Coast Range tributaries are fed by groundwater accumulated mostly as winter rains; they carry finer substrates and cool water to the mainstem river. Major Coast Range tributaries include the Tualatin, Yamhill, Luckiamute, Willamina, Marys, and Long Tom Rivers, which support native cold-water fish species such as Cutthroat Trout (ODFW, 2005). Valley floor tributaries are much smaller, warmer, and lower gradient than Cascade Range or Coast Range tributaries, with bed substrates composed mostly of sand and fine materials (Wallick et al., 2022). Typical fish species in valley floor tributaries include Reticulate Sculpin *(Cottus perplexus),* Western Brook Lamprey *(Lampetra richardsoni),* and Redside Shiner *(Richardsonius balteatus)* (Hughes et al. 1998). As Willamette River tributaries traverse the valley floor they transition from cold, to cool, to warm-water systems, influenced by distance from cold-water discharges and changing amounts of solar inputs; fish assemblages' transition accordingly in valley-floor tributaries although they are dominated by warm-water fishes (Hughes et al., 1990, 1998; McGarvey and Hughes, 2008).

2.1.3. Underlying geology and geomorphology

The Willamette River basin is bordered by the volcanic Cascade Range to the east and uplifted basalts and marine sandstones of the Coast Range to the west (Omernik, 1987; Tague and Grant, 2004). The basin has cool, wet winters, with precipitation falling predominantly as snow in the Cascade Range and as rain in the Coast Range and Willamette Valley. Precipitation is the greatest along the crest of the Cascade Range, where rainfall and snowmelt infiltrate through the geologically young, porous volcanic rocks of the high-elevation, High Cascades lithologic province (on the far-eastern side of the Willamette Valley), supporting steady year-round river flow at large spring complexes in the region (Stearns, 1928; Tague and Grant, 2004). In contrast, the less-permeable and lower-elevation, Western Cascades and Coast Range are steep and highly dissected, primarily resulting in surface water run-off in response to precipitation. Historically, large winter floods often resulted from basin-wide rain-on-snow events (Harr, 1981). These large floods transported water, nutrients, wood, and sediment, shaping the landforms, aquatic habitats, and vegetation patterns historically found in complex floodplains along the Willamette River (Oetter et al., 2004). In summer, streamflow historically receded to baseflows generated from groundwater throughout the basin.

The Willamette River can be divided into four valley segments that are useful for describing its general hydro-geomorphic characteristics both historically and today (Fig. 1; Hughes and Gammon, 1987). The first valley segment from Eugene to Corvallis historically had a laterally dynamic, high-gradient, and multi-threaded channel, with wooded islands, side channels, large gravel bars, cobble/gravel bed substrate, and erodible banks; the channel in this valley segment meandered across a wide, forested floodplain (Benner and Sedell, 1997; Hulse et al., 2002; Sedell and Froggatt, 1984; Wallick et al., 2013). The historical multi-threaded channel was created by interactions between large floods, large wood, bank erosion, and channel avulsion (Wallick et al., 2013). The second valley segment from Corvallis to the Santiam River was (and remains) stable owing to its geology and physiography. Here, the Willamette River main stem is predominantly a single-thread, low-gradient channel that is relatively straight, bordered by either Holocene alluvium or resistant Pleistocene gravels with sparse gravel bars and gravel bed substrate. The Corvallis-Santiam valley segment has relatively low rates of meander migration and avulsions compared to the Eugene-Corvallis valley segment (Wallick et al., 2007). The third valley segment, from the Santiam River to Newberg and the Newberg Pool (a naturally formed channel-spanning pool above Willamette Falls), is generally low gradient, with a single-thread channel that alternates against paired terraces underlain by resistant Pleistocene gravels. The fourth river segment runs from Newberg to the Willamette River's confluence with the Columbia River. The channel in this valley segment was, and is, single thread and laterally stable owing to bedrock, and is tidally influenced downriver of Willamette Falls. The bed substrate in the Newberg Pool is dominated by bedrock, claypan, and sand, whereas that in the lower Willamette River is sand, cobble, claypan, and bedrock (Hughes and Gammon, 1987).

2.2. Euro-American arrival and river development (1830–1970s)

2.2.1. Changes in culture and biology

The Willamette River was substantially altered from its original state during the 19th and 20th centuries by Euro-American arrival, economic development, and river management (Gregory et al., 2019, Fig. 2). This alteration was set in motion when the basin was visited by the Lewis and Clark expedition in 1806 and Euro-American immigrants began arriving in earnest during the 1820s and 1830s (Robbins, 1999; Scott, 1923). Willamette River basin Indigenous communities agreed to confederate as part of the Willamette Valley Treaty of 1855 and were then forcibly removed to either the Confederated Tribes of the Grande Ronde Community of Oregon in the headwaters of the South Yamhill River, or to become part of the Confederated Tribes of Siletz Indians on Oregon's mid-coast (Spores, 1993). Before widespread Euro-American settlement, most beavers had already been eliminated by trappers (Hughes et al., 2005, 2019; Robbins, 1999). Settlement resulted in a reduction of the controlled burns traditionally implemented by Indigenous communities, causing reduction in prairie and savanna vegetation types, and expansion of coniferous forest (Christy and Alverson, 2011).

Frequently impassable terrestrial transportation routes made the Willamette River the focus for commercial navigation (Portland General Electric, 2018; Orr and Orr, 2019). In the 1820s, Oregon City was founded near Willamette Falls, and steamboats began transiting the river in the 1850s. Passage past Willamette Falls to the Columbia River was not possible until a lock was completed in 1873, and by 1889 hydropower facilities were added to the site (Sinclair, 2017; Portland General Electric, 2018; Orr and Orr, 2019). The river was extensively channelized and de-snagged to produce a wet-season navigable river from the Columbia River to the City of Eugene (Benner and Sedell, 1997; Hulse et al., 2002; Sedell and Froggatt, 1984) (Fig. 2).

The basin's rich soils and abundant water encouraged large-scale agricultural development throughout the Willamette Valley (Sinclair, 2017; Orr and Orr, 2019). The City of Portland was incorporated in 1851, quickly becoming the largest city in the state. Development resulted in further changes to the river's geomorphology and hydrology, as well as loss of extensive floodplain forests (Gregory et al., 2019). Further, rapid development throughout the Willamette Valley resulted in a need to develop flood-mitigation measures which substantially altered the hydrograph from its natural state (Fig. 2).

The construction and operation of dams and reservoirs on Willamette River tributaries profoundly affected the river. High-head dams and downstream re-regulating dams were primarily constructed during the 1940s–1960s, and a total of 150 dams currently function on Willamette River tributaries (Kuby et al., 2005), including 13 federally managed flood-mitigation dams (Willamette Valley Project dams owned and operated by the United States Army Corps of Engineers https://www.nwp.usace.army.mil/Locations/Willamette-Valley/). Some of the dams also are operated to produce hydropower. Large high-head dams (exceeding 15 m in height; International Commission on Large Dams, 2013) in the Willamette River basin create large storage reservoirs that collect water during winter and spring to protect downstream areas from flooding and release water during summer and autumn. Operations at high-head dams often produce unnatural streamflow and temperature patterns in downstream reaches and water passed over spillways can elevate total dissolved gases that harm fish (Politano et al., 2007; Orlins and Gulliver, 2000). Re-regulating dams are commonly built a short distance downstream of high-head dams to create a small reservoir that collects outflows from the high-head dam and allows for operations that normalize riverine flows to downstream reaches. Although these multipurpose structures provide hydropower and recreational opportunities, their most important benefit is providing flood-mitigation to downstream population centers along the main stem Willamette River. Although this benefit is critical for human safety, these dams alter the connectivity, sediment transport, and hydrograph of the system, adversely affecting aquatic species and the entire river ecosystem (Angilletta et al., 2008; Hamilton

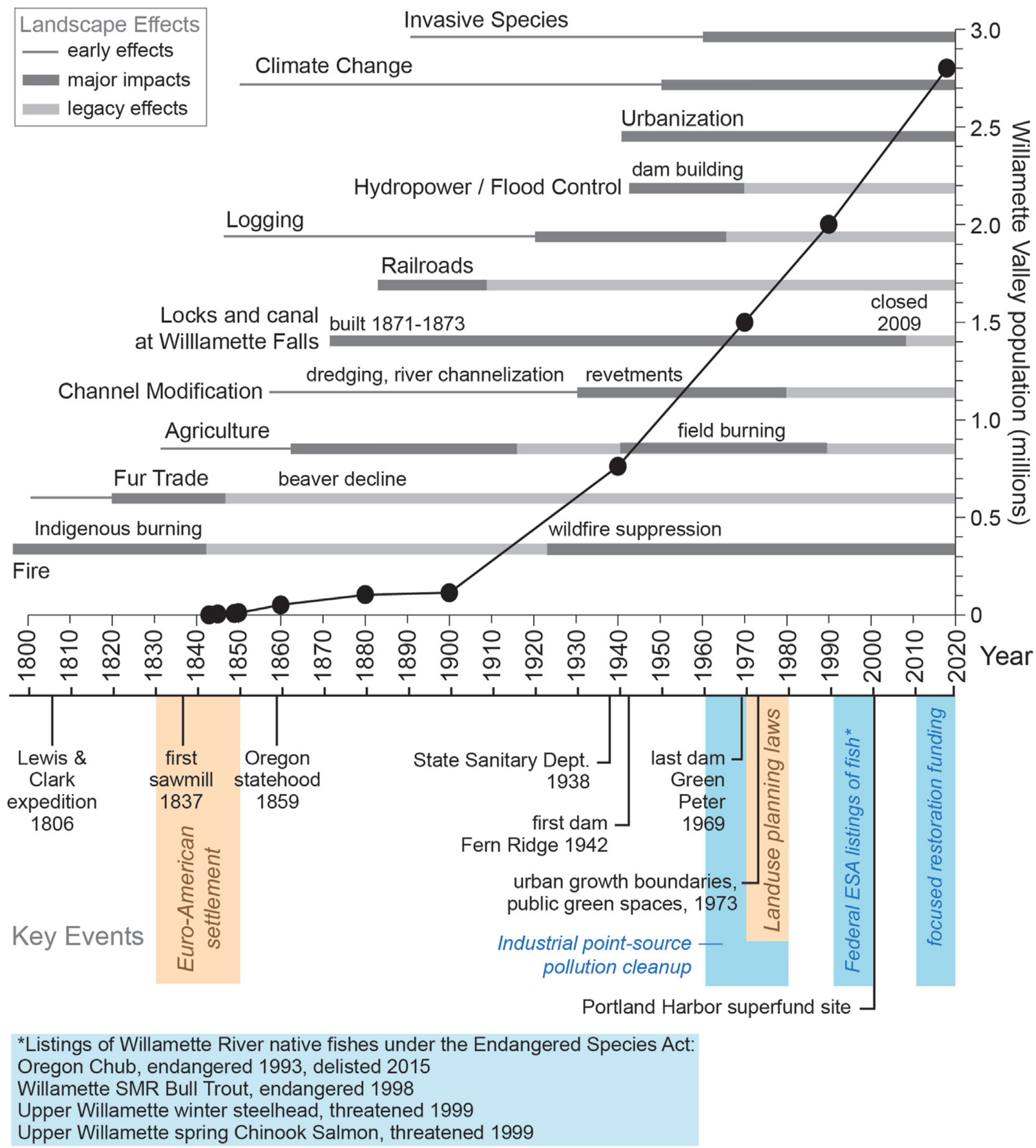

Fig. 2. The Willamette River basin has been a focus for agriculture, hydropower development, and urbanization, among other human uses since colonists began to alter the region in the 19th century. Early effects tended to be diffuse and less intense, however, as development and population increased, major impacts affecting river geomorphology, water flow, land use, vegetation composition, and water quality occurred.

et al., 2022; Hulse et al., 2002; Keefer et al., 2013; Wallick et al., 2007).

Operations of high-head dams in Willamette River tributaries have resulted in substantial changes in the hydrograph of the mainstem river through reduced peak discharge, decreased water temperatures and increased discharge during summer, and increased water temperatures during winter (Angilletta et al., 2008; Hummel, 2018). Native migratory fish species such as steelhead, Chinook Salmon, and Bull Trout encounter passage challenges in large storage reservoirs and at dams in the system, resulting in substantial migration delays and increased mortality (Hansen et al., 2017; Hamilton et al., 2022; Keefer et al., 2013). Downstream fish passage structures have not been developed at these dams, so passage occurs through existing structures (spillways, turbines, regulating outlets) where survival has been low (<60%; Hansen et al., 2017). In-reservoir predation by stocked non-native fish and parasitism are also substantial (Murphy et al., 2021; Neal et al., 2021), and winter steelhead, spring-run Chinook Salmon, Bull Trout, and Coho Salmon (below Willamette Falls) are listed as threatened or endangered under the U.S. Endangered Species Act (e.g., Crozier et al., 2019).

The transformation of the Willamette Valley into an urbanized and agricultural landscape with urban, agricultural, and industrial effluents has significantly compromised water quality throughout the basin (Hughes et al., 1998, 2005, 2019; Hughes and Dunham, 2014). A 1945 survey found that native fish habitat and populations were degraded by compromised water quality (Dimick and Merryfield, 1945). Hindcast predictive models developed from 82 wadable Willamette Valley lowland streams (sampled along an anthropogenic-disturbance gradient) estimated species loss across taxonomic groups (Van Sickle et al., 2004): valley streams were estimated to have experienced losses of 1.8 native fish species (median), 5 Ephemeroptera/Plecoptera/Trichoptera (EPT) taxa, and 19 previously common macroinvertebrate taxa. Additionally, the Willamette Valley was estimated to have 21% reductions in fish assemblage index of biological integrity scores (Hughes et al., 1998) because of agricultural and urban development (Van Sickle et al., 2004).

2.2.2. Modifications to river geomorphology and flow

Since 1850, flood mitigation, bank stabilization, large-wood removal, conversion of riparian forests to agriculture, and other large-scale alterations have substantially changed the basin's flow, sediment, and large-wood regimes. These changes are reflected in a narrower floodplain corridor and a less-complex assemblage of landforms in the present-day floodplain between Eugene and Corvallis (Fig. 3). Construction and operation of flood mitigation/hydropower dams have largely confined peak flows to the bankfull channel, decreasing the magnitude of large floods and the magnitude and frequency of small floods (Fig. 4; Wallick et al., 2013). Today, many areas of the historical floodplain no longer experience occasional inundation or sedimentation, and geomorphic processes like meander migration and avulsion occur within a narrower active channel owing to the lack of flooding. In unaltered systems, sediment supply contributes to habitat diversity by providing inputs of material to be worked by the river into complex habitat. However, the flood-control dams trap more than 80% of bed sediments that historically entered the lower, alluvial reaches of the Middle and Coast Fork Willamette Rivers and the South Santiam River (O'Connor et al., 2001). Additionally, revetments (bank stabilization structures made of materials including rock, wood, and concrete) were constructed between the late 1930s and 1970s by the U.S. Army Corps of Engineers to prevent erosion and to stabilize channels. Revetments are most extensive along the Willamette River from the Santiam River to Eugene, and on the South Santiam and McKenzie Rivers (Hughes et al., 2005). Between Eugene and Portland, 26 percent of the banks along the Willamette River have revetments, with most located on the outside of meander bends (Gregory, 2008; Hulse et al., 2002). Much of the lower 40 km of the river banks in and near Portland is bulkhead (Hughes and Gammon, 1987).

2.2.3. Conservation approaches

Recognition that water quality had declined to the detriment of native aquatic species and human communities led to the development of wastewater treatment beginning in the 1940s by the Oregon Sanitary Authority (Fig. 2). The initial focus of the wastewater treatment effort was to develop primary and secondary treatment facilities for cities and industries. Summer low-flow conditions were augmented with released water from reservoirs throughout the system, and collectively, these efforts markedly improved water quality throughout the mainstem Willamette River (Hughes and Gammon, 1987; Hughes et al., 2019). In the late 1960s and 1970s, the Willamette River Greenway was developed, which improved and expanded protection of riparian areas along the mainstem river to encourage recreation and river use (Gifford, 2014). Land use planning laws were implemented in 1973 to protect agricultural lands from development, causing cities to be constrained into urban growth boundaries, thus limiting urban sprawl (Abbott, 1993).

3. Current RIVER—SCIENCE supporting conservation

3.1. Conservation Culture

A community of conservation-oriented interest groups has developed over time in the Willamette River basin. This was facilitated by the development of the Oregon Plan for Salmon and Watersheds (a.k.a., the Oregon Plan), beginning in 1997 (OCSRI, 1997) and habitat conservation planning pursuant to federal endangered and threatened species listings (Spence et al., 1996). Even before the Oregon Plan, local communities and individuals had been instrumental in efforts to clean the river, primarily focused on water quality (see preceding section) rather than physical habitat rehabilitation. However, the funding and broad implementation of the Oregon Plan in the 1990s created a network of active grass-roots organizations that focused on tributaries of the Willamette River, galvanizing rehabilitation work on private streams and uplands throughout the basin. Coincident with Oregon Plan was a 1998 voter initiative measure brought by The Nature Conservancy and passed by voters to dedicate 15% of the Oregon Lottery receipts for "parks and salmon". This initiative led to the development of the Oregon Watershed Enhancement Board (OWEB) which has been an integral leader and partner organization, providing substantial funding for conservation initiatives over recent decades.

Although watershed councils proliferated in the tributaries of the Willamette River, no centralized rehabilitation group was developed for the mainstem Willamette River. To fill this gap, OWEB, Meyer Memorial Trust (MMT), and the Bonneville Power Administration (BPA) formed a funding partnership to meet large-scale rehabilitation demands. The Willamette Anchor Habitat Working Group (WAHWG) coalesced around this funding partnership. Early in the funding partnership, MMT committed to building the capacity of core implementers, and OWEB and the Willamette Wildlife Mitigation Program (led by BPA and the Oregon Department of Fish and Wildlife) worked with several Indigenous communities and the land trust community to secure key parcels from willing sellers; all funders worked to fill information gaps. Funders supported an

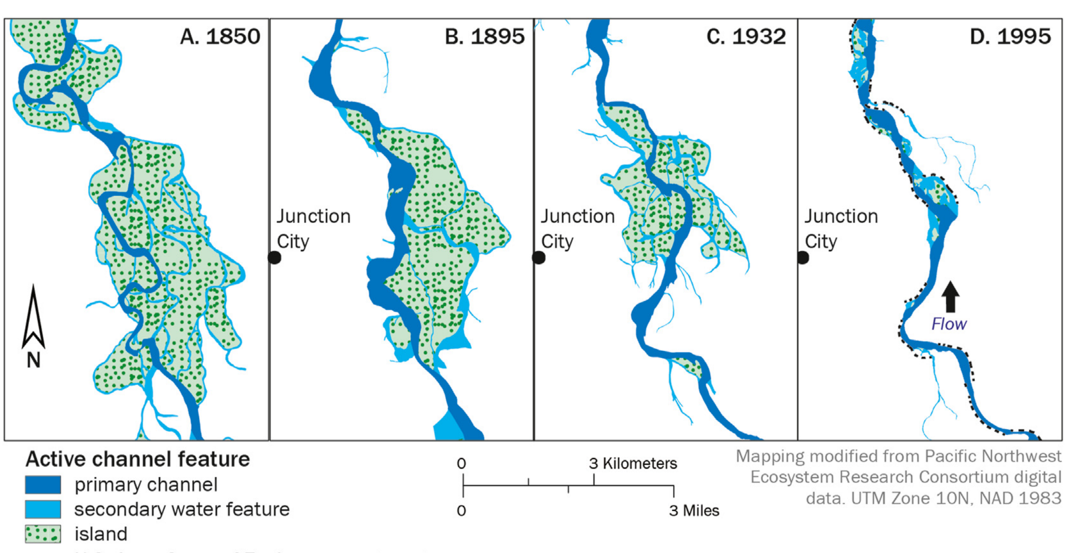

Fig. 3. Revetments, channel simplification, wetland drainage, and other forms of river hardening have significantly reduced the interaction between the main channel of the Willamette River and its floodplain, as well as the dynamism of secondary water features such as side channels, alcoves, and oxbows. This figure illustrates that pattern of development between 1850 and 1995 in a short river reach located near Junction City, Oregon.

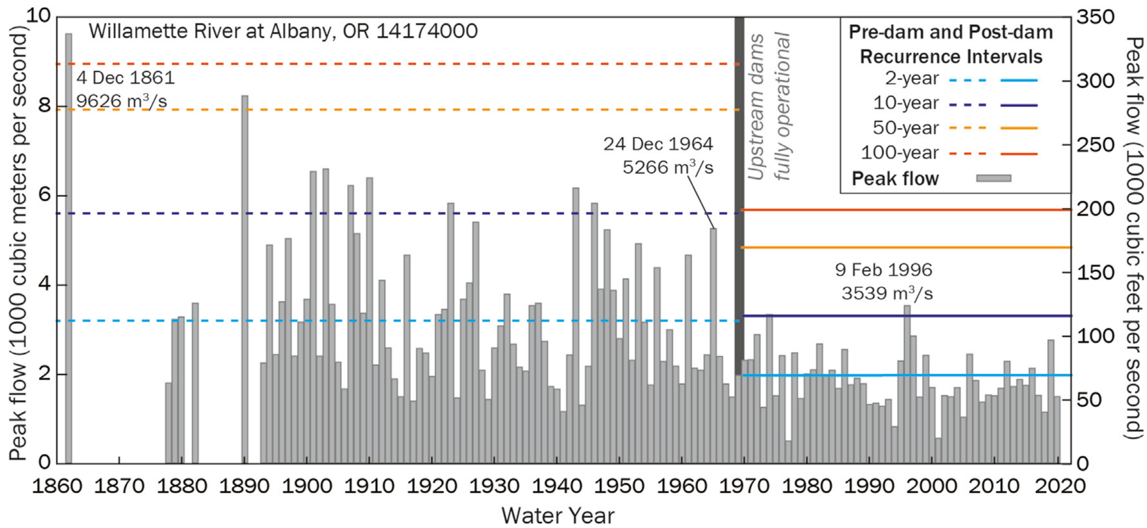

Fig. 4. Flow regulation in the mainstem Willamette River has been implemented through the construction and integrated management of dams in its tributaries, that also serve as sources of hydropower. The last large flood of record occurred in the Willamette River system in 1964, as completion of upstream dams to regulate flow in the late 1960s effectively reduced high-flow events in the following decades. River flow modification alters habitat for in-stream species, and for floodplain species that depend on periodic inundation.

effort by the Nature Conservancy to synthesize existing Willamette River conservation studies and assessments, which produced a map illustrating areas of high ecological significance which were termed “anchor habitats”. Anchor habitats are characterized by relatively intact in-channel and floodplain habitats (primarily for fish and birds) that contain high conservation value. Implementation of the concept of anchor habitats is based on the concept that protection and rehabilitation occur in a sequential fashion along the river corridor (Fig. 5). The funding partnership has since supported the WAHWG practitioners in pursuing strategic rehabilitation opportunities in anchor habitat locations, based on three primary objectives:

- Re-establishing side-channel complexity and length,
- Re-connecting the river with its floodplain,
- Expanding the geographic extent and improving the health of floodplain forests.

The anchor habitat framework resulted in a significant increase in the number of rehabilitation projects and associated efforts to monitor ecological effects and native fish assemblages along the mainstem Willamette River (Hughes et al., 2019, section 3.4 below).

The WAHWG tracks and monitors conservation actions using two key sources of information: the “slices” framework and the Willamette River Basin Planning Atlas (Hulse et al., 2002). Slices is a spatial database first described in the Willamette River Basin Planning Atlas that documents key indicators of river and floodplain health as a status-and-trends monitoring tool. The tool divides the mainstem river into 1-km segments (“Slices”) at right angles to the floodplain's center axis. These Slices span both banks of the river and provide a fixed frame of reference for tracking temporal and spatial changes in site-specific river characteristics. The Slices database continues to be updated, typically at 3–5 year intervals depending on the indicator, and the database is publicly accessible online (https://oregonexplorer.info/places/basins/willamette?qt-basin_quicktab=1). The Willamette River Basin Planning Atlas links to ongoing use of Slices. The atlas includes a variety of different spatial datasets and information describing landforms, water resources, biotic systems, human population, land use and land cover, and trajectories of change. Descriptions, datasets, and spatial data are available online (https://www.fsl.orst.edu/pnwerc/wrb/Atlas_web_compressed/PDFtoc.html).

3.2. *Biological science*

Researchers, conservation scientists, agency biologists, and others have inventoried aquatic species, their distribution in the Willamette River, habitat preferences, and environmental needs. This information facilitates conservation planning and rehabilitation in the basin (see Slices in section 3.1) and continues to evolve. Research conducted in recent decades has contributed to system-wide insights related to native and non-native fish species. That research has linked fish to their habitats, effects of dams and flow augmentation on survival and habitat availability for ESA-listed fish, and documented use of cold-water habitats by native Bull Trout, Rainbow Trout, and Coastal Cutthroat Trout (Barrett and Armstrong, 2022; Hansen et al., 2017; Hughes et al., 2019; Peterson et al., 2022; White et al., 2022).

The diverse assemblage of fish species that exist in the contemporary Willamette River basin, comprising a mixture of native and non-native species (Williams, 2014), provides a foundation for a Willamette River fish assemblage decadal assessment (2011–2013 unpublished data from Gregory, Fig. 6). A cooperative study by farmers, agencies, and Oregon State University revealed that many mainstem native fish species occupy winter-wet agricultural ditches (and that some reproduce there), likely reflecting their historical connections to such intermittent habitats (Colvin et al., 2009). Native species include suckers (*Catostomus* spp.), sculpin (*Cottus* spp.), minnows (several genera), Pacific salmon and trout (*Oncorhynchus* spp.), and Western Brook Lamprey (*Lampetra richardsoni*). Common non-native species include basses (*Micropterus* spp.), sunfishes (*Lepomis* spp.), and bullheads (*Ameiurus* spp.), among others (Williams, 2014). Oregon Chub (*Oregonichthys crameri*), a floodplain-obligate cyprinid endemic to the Willamette River basin, was imperiled and ESA-listed (endangered) in 1993. Efforts to conserve the species and recover its habitat were successful and conservation measures by a variety of public and private landowners in the basin resulted in its de-listing in 2015 (Hughes et al., 2019; USFWS and Wildlife Service, 2015).

Spring Chinook Salmon and winter steelhead have struggled to persist in the current Willamette River due to flood mitigation and landscape-scale modifications to the Willamette River floodplain and its tributaries. Fish habitat and water quality continue to be compromised, particularly from the Santiam to Columbia River (Hughes et al., 2005, 2019; Hughes and Gammon, 1987). Native migratory species exist throughout the basin, which is conceptually managed as a “split-basin”

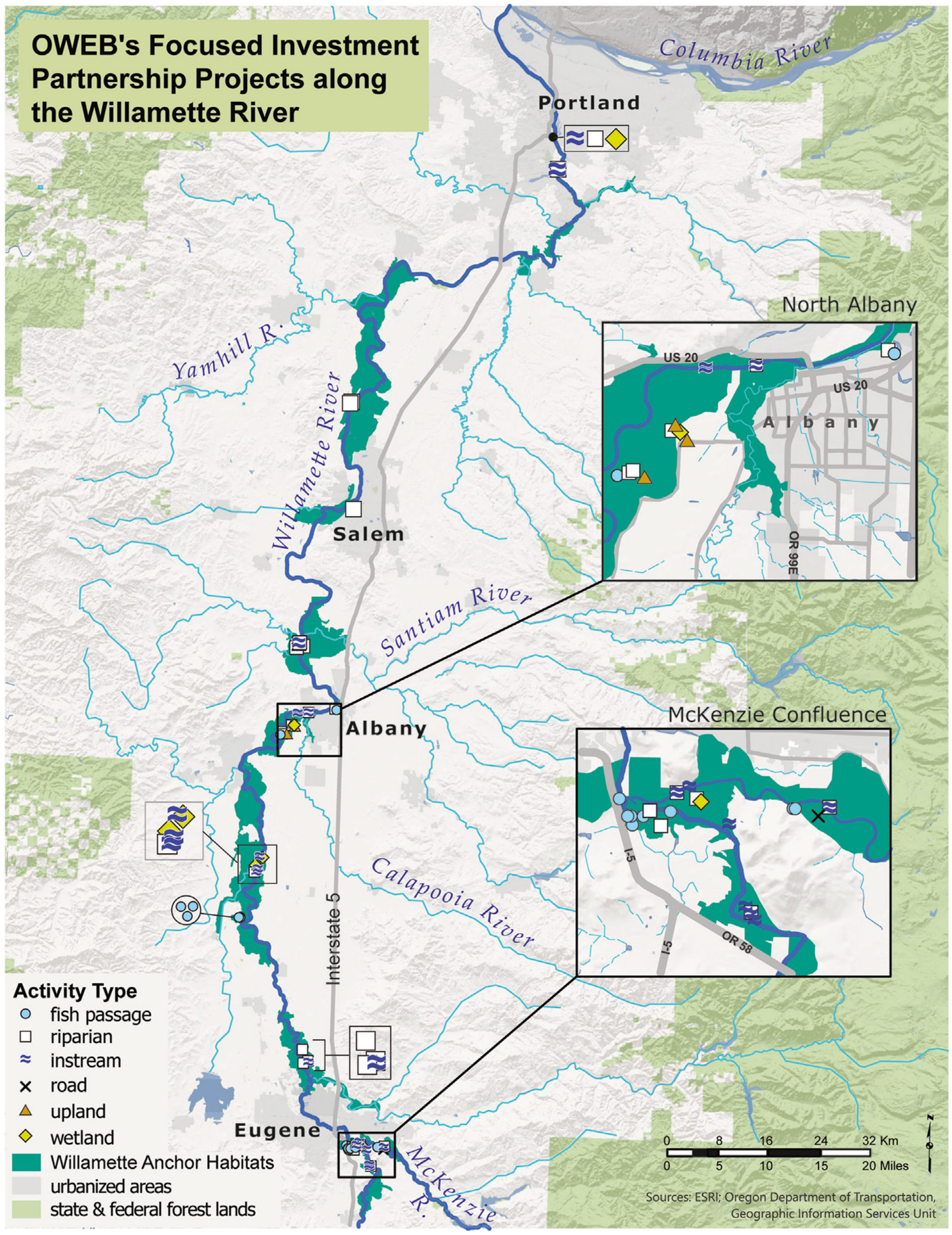

Fig. 5. The Oregon Watershed Enhancement Board (OWEB) facilitates innovative and diverse focused partnerships among large funding organizations over time, leading to the implementation of 61 projects on the mainstem Willamette River, representing $US24,000,000 in investments to date.

with fish populations located upstream and downstream of high-head dams receiving different consideration (personal communication, Rich Piaskowski, U.S. Army Corps of Engineers). Anadromous species are maintained above high-head dams that lack fish passage structures through trap-and-haul programs that collect returning adults and transport them upstream of dams and storage reservoirs where they are released to spawn naturally in the system (Kock et al., 2021). Progeny of these transported adults move downstream and rear for months in storage reservoirs where downstream passage options are limited at the dams (Ohms et al., 2022). Juveniles produced by adults that spawn downstream of dams in the system typically rear in the tributaries and mainstem river for several months prior to initiating ocean migration, but multiple life-history strategies exist (Schroeder et al., 2016).

Rehabilitation of juvenile salmonid rearing habitat has been emphasized because of its importance in supporting populations of these key species. Research has shown that juvenile salmonid habitat availability (e.g., floodplain, off-channel, side-channel areas) responds to changes in stream flows (that inundate areas and allow access) based on local channel and floodplain morphology (White et al., 2022). In the Willamette River from Eugene to Corvallis, habitat quantity for a diversity of life-stages is positively related to flow level, where the smallest quantity of habitat occurs at low flows and the largest quantity occurs at high flows when the river connects to floodplain, alcove, and side-channel areas. From Corvallis to the Newberg Pool, habitat quantity decreases as flows increase from low to moderate levels, making the channel deeper and faster, with little commensurate gain in wetted area (White and Wallick, 2022; White et al., 2022). However, as river flow increases to higher levels in this valley segment, habitat quantity increases as water overflows into off-channel features and low-lying floodplains, eventually resulting in large gains in habitat area at high flows. Off-channel features are defined as bodies of water that are adjacent to the main channel and are connected during summer low-flow discharge levels (Landers et al., 2002). On the Willamette River, these include side channels, beaver ponds, and alcoves, with the latter being connected to the main stem only

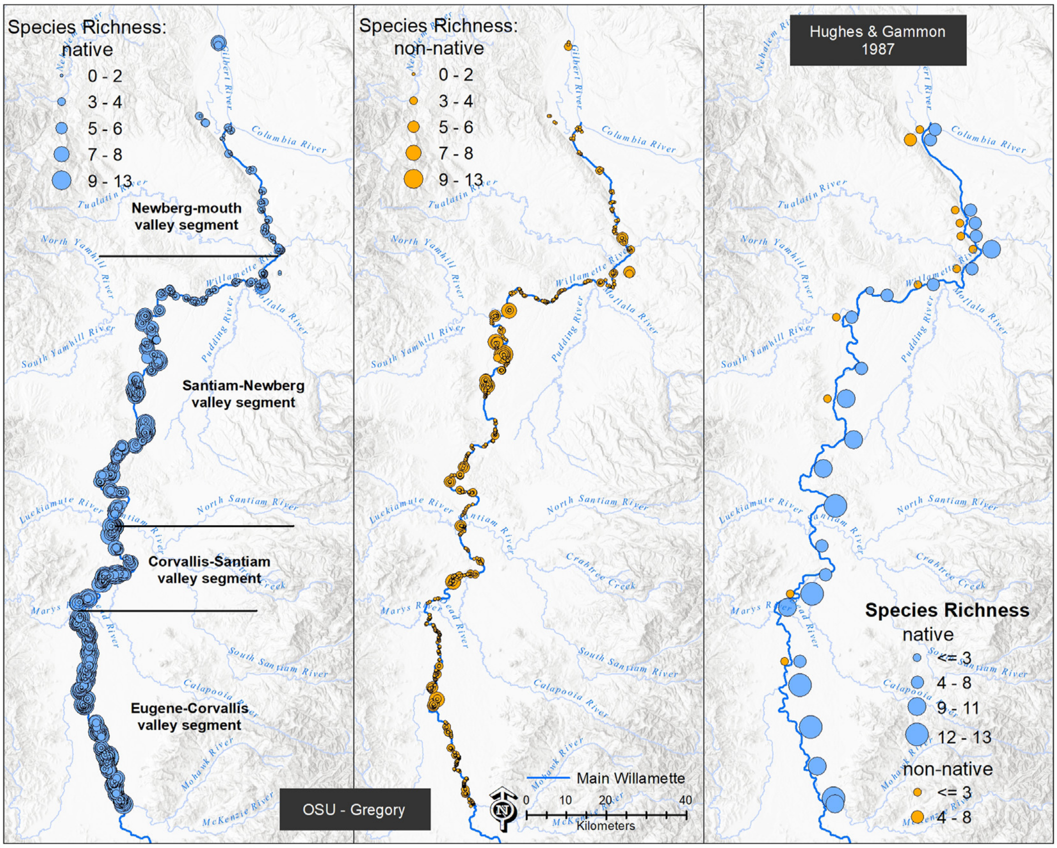

Fig. 6. Patterns in the distribution of native and non-native fish species are important for investment decision-making throughout the mainstem habitats of the Willamette River, both in terms of targeting native habitats, and for monitoring river health over time by understanding patterns of use by native fishes. For interpretability, the densely collected OSU-Gregory dataset is split into native and non-native fish species richness, while both native and non-native species are displayed in the Hughes and Gammon (1987) data.

at one end (typically the downstream end) during most stream flows (Smith et al., 2020). Additional site-specific characteristics that play a role in the availability, condition, and accessibility of these features include upstream connection, water depth, hyporheic connection, and presence or absence of aquatic or riparian vegetation (Smith et al., 2020).

Research has pointed to a nuanced use of cold off-channel microhabitats by native fish (Barrett and Armstrong, 2022). Cold floodplain habitats can exhibit complex and dynamic heterogeneity in both temperature and dissolved oxygen. For example, several cold-water alcoves frequently used by Coastal Cutthroat Trout during summer show distinct vertical gradients in dissolved oxygen in such a manner that the coolest temperatures are also hypoxic (Gombert et al., 2020; Smith et al., 2020). Vertical heterogeneity in dissolved oxygen and thermal gradients in off-channel features of the Willamette River are likely affected by the presence of vegetation that can shade the feature, and add or consume dissolved oxygen, depending on the type of vegetation present (e.g., submerged and emergent vegetation; Smith et al., 2020) or time of day. Further, hyporheic flow, which can be found in cold-water alcoves, tends to have low concentrations of dissolved oxygen (Zarnetske et al., 2011). These shifting oxygen gradients affect how cold-water fish use microhabitats, and understanding of this may help to adjust the management and rehabilitation of mainstem and off-channel habitats to better support habitat use by native species versus non-native species.

3.3. Insights from fluvial geomorphology

Geophysical investigations have provided insights into differences in geomorphic change, hydraulics, and water-quality patterns along the Willamette River. Work describing changes from historical conditions (Gregory et al., 2019) provide context for an assessment of current river condition. This information has helped to broaden the understanding of longitudinal differences in the Willamette River system and provides a basis for conservation of native species.

Several studies have found that the Willamette River valley segment between Eugene and Corvallis has changed the most dramatically since the 1830s (Fig. 3) and remains the most laterally dynamic valley segment, with side channels, gravel bars, and alcoves (Hulse et al., 2002; Wallick et al., 2013, 2022). In contrast, the Willamette River valley segment from Corvallis to the Columbia confluence is largely a single-thread channel confined by revetments, resistant Pleistocene gravels, or bedrock, and has remained relatively stable over time (Hulse et al., 2002; Wallick et al., 2013, 2022). These fundamental characteristics of the underlying geomorphology can be linked to rehabilitation actions and goals that will vary depending on where they are implemented along the river.

Channel form (e.g., meandering, braided, single-thread) creates a template upon which hydrology and hydraulics interact to create aquatic habitats for a variety of species and life stages. Channel hydraulics of the current river vary longitudinally with distance downstream, in turn shaping the type and abundance of aquatic organisms observed. Differences in the geomorphic and hydraulic templates of the river affect the distribution of cold-water fish species (for Chinook Salmon and steelhead, see White et al., 2022). Transition from higher spring-season flows to lower summer-season flows reduces Willamette River habitat availability between Eugene and Corvallis for cold-water fishes while increasing availability lower in the system. Despite the documented effect of channel hydraulics on distributions and populations of aquatic organisms throughout the river, the effects of streamflow on habitat quantity may be secondary to the effects of water temperature, with the latter likely to be more limiting for many organisms than the availability of physical habitat.

Water temperatures and dissolved oxygen patterns vary substantially in space and time in the main channel and off-channel features of the Willamette River (Smith et al., 2020). The main channel regularly exceeds water-quality criteria for water temperature, adopted for cold-water fishes in the basin (ODEQ, 2007, 2022). The duration and magnitude of these temperature criteria exceedances differ by season, species, water year, and location along the main channel (Stratton Garvin and Rounds, 2022; White et al., 2022). Upstream of the Newberg Pool, the water temperature of the main channel tends to be warm and well-mixed (Fig. 7). Dissolved oxygen concentrations in this portion of the river are suitable for most aquatic organisms. Streamflow and water temperature relationships can be complex downstream of dams because reservoirs tend to thermally stratify during the warm season, allowing water of different temperatures to be withdrawn from different elevations in the reservoir. As a result, downstream water temperatures in

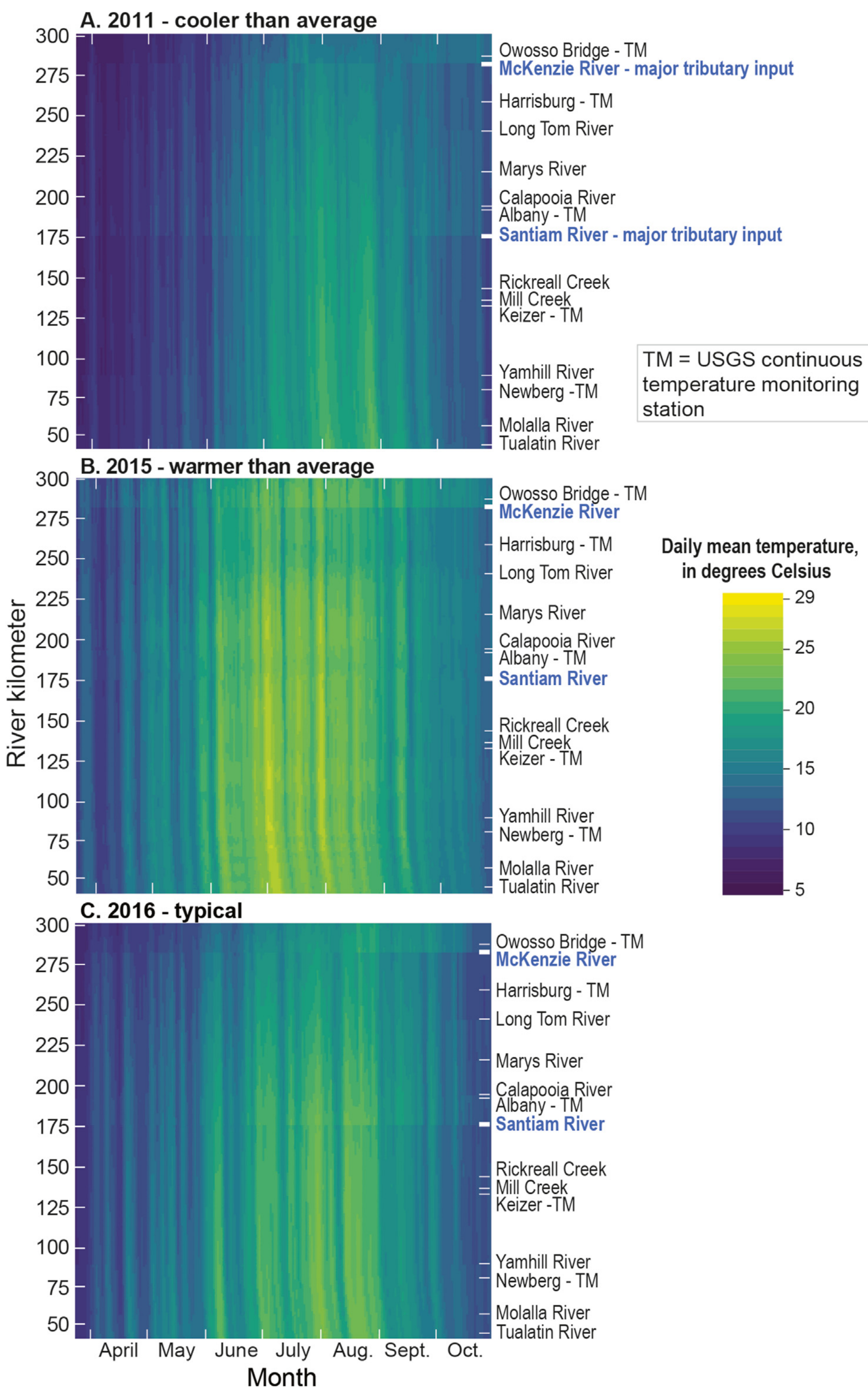

Fig. 7. Modeled baseline daily mean temperatures in the mainstem Willamette River from its head at the confluence of the Coast Fork Willamette and Middle Fork Willamette Rivers to Willamette Falls. Inputs from tributaries alter Willamette River temperatures across all year types, from cool and wet to warm and dry. Temperature data from specific years is presented: (**A**) modeled temperatures from 24 March–30 October 2011, representing a cooler and wetter than average year; (**B**) modeled temperatures mod from 24 March–30 October 2015, representing a warmer and dryer than average year; (**C**) temperatures collected from 23 March–30 October 2016, representing a typical year. Source images and data for this figure are from Stratton Garvin and Rounds (2022).

reaches close to dams are directly affected by withdrawal depth from the reservoir (Rounds and Stratton Garvin, 2022). The relationship between tributary thermal conditions and mainstem temperatures of the Willamette River are particularly evident from the Santiam River, and McKenzie River, even in years that are cooler or warmer than average (Fig. 7). Both tributaries contain multiple dams whose management affects temperature and discharge throughout the year.

In contrast to the relatively uniform and well-mixed water temperature and dissolved oxygen concentrations in the main channel of the Willamette River, recent research has found that off-channel features may vary longitudinally or laterally in these physiochemical characteristics. In general, off-channel features with cold water have stratified water columns. At these sites, the near-bed layer of cold water may be maintained by sufficiently long hyporheic flow paths (Gombert et al., 2020). Stratification in alcoves is influenced by the stage of the main river channel. A rise in stage can quickly affect a feature's upstream surface-water connection. A feature that is disconnected and stratified at a low stage can become connected and de-stratified, or well-mixed, at higher stages (Gombert et al., 2020; Smith et al., 2020).

Clarification of the processes that affect thermal and oxygen patterns in the Willamette River, its tributaries, and off-channel floodplain environments is critical to moving forward in conservation prioritization and planning of rehabilitation efforts. The mosaic of thermal patches responds to seasons and streamflow, as well as the gradient of the Willamette River, contributing to observed patterns in the distribution of native fishes. Ongoing science such as this contributes to a better understanding of the linkages between biological processes and drivers of physical conditions, contributing to conservation policies and funding decisions.

3.4. Conservation and rehabilitation in action

Reliance on science to inform prioritization of rehabilitation actions has been a cornerstone of planning in the Willamette River. To date, rehabilitation of aquatic habitats on the mainstem Willamette River floodplain has incorporated participation by a diverse group of interested parties with long-term overlapping goals (see Conservation Culture section 3.1). Innovative funding opportunities have facilitated rehabilitation across the Willamette River floodplain through creative partnerships among non-profit partners, state and federal agencies, Indigenous communities, and local watershed councils. Funding partners with the WAHWG (see Conservation Culture section 3.1) have provided more than $US24,000,000 to fund 61 projects on the mainstem Willamette River floodplain. Projects have included increasing side-channel complexity, eradication of aquatic and terrestrial invasive species, floodplain and channel reconnection, rehabilitation of side channels, and enhancement of habitats in alcoves, side channels, and ponds created from relic gravel pits.

The above collaborations among interest groups have led to promising results. The successful recovery of Oregon Chub was made possible through the efforts of a small but active working group made up of state and federal agencies, Indigenous communities, universities, land trusts, other non-governmental organizations, and the voluntary support of private landowners (Scheerer, 2007; Hughes, 2015; Hughes et al., 2019). Private landowners were critical to Oregon Chub recovery efforts, as more than 50% of these fish occur in aquatic habitat located on private property. Recovery of Oregon Chub populations resulted from a combination of better monitoring and understanding of the distribution of the fish, work with landowners to develop new habitats, improved floodplain management, and transplanting fish into different habitat locations (Scheerer, 2007; Hughes, 2015; Hughes et al., 2019).

Collaboration among diverse organizations targeting physical habitat rehabilitation efforts intersects with long-term work to improve water quality in the mainstem Willamette River. As described previously, efforts to improve water quality became a priority for state agencies working on the Willamette River in the 1970s (Hughes et al., 2019). This included the development and implementation of state laws regulating discharges into the river. High-profile efforts, such as the Big Pipe Project in Portland completed in 2011 (an engineering effort that has reduced combined sewer overflows from Portland to the Willamette River by 94%), along with nearly 2500 low-profile projects in Portland (such as the installation of projects that increase stormwater infiltration into the ground or divert stormwater to a river or stream rather than the combined sewer to the river), have been implemented (BES and City of Portland, 2023). As a result of these efforts, and others, the Willamette River is cleaner today than it has been in many decades (Figs. 8 and 9), contributing to better water quality for all species living in or near the water, including humans.

Water-quality improvements in the mainstem Willamette River have been tracked by the Oregon Department of Environmental Quality (ODEQ) through their water-quality index (Fig. 8). To calculate this index, individual water-quality variables are converted into sub-index values using parameter-specific equations that account for variability in the data. These values are then aggregated using a formula that allows the most-impaired parameter to impart the greatest influence on the water-quality index and ensures that small individual changes are detectable in the aggregated index score (Cude, 2001). The variables included in the index are water temperature, dissolved oxygen (percent saturation and concentration), biochemical oxygen demand (BOD), pH, total solids, ammonia and nitrate nitrogen, total phosphorus, and bacteria. Comparing water-quality index scores from 1990 (includes water years 1981–1990) with scores from 2020 (includes water years 2011–2020) at nine locations along the mainstem Willamette River revealed that the 2020 water-quality index scores were consistently higher (Fig. 9). The notable dip in the 1990 score resulted from lower BOD and increased total solids and total phosphorus values, potentially from increased agricultural runoff and storm sewer overflows.

4. Conservation future: Blending VISIONS

As conservation planners look to the future of the Willamette River system, goals can be grounded in a foundation of past ecologically driven investment decisions and strong community involvement, founded on comprehensive scientific studies. After recognition in the 1950s of the poor water quality in the Willamette River, conservation actions have resulted in improved water quality and improved fish habitat condition throughout the river main stem. Additionally, current science products inform planning and actions by providing the ecological context for fish

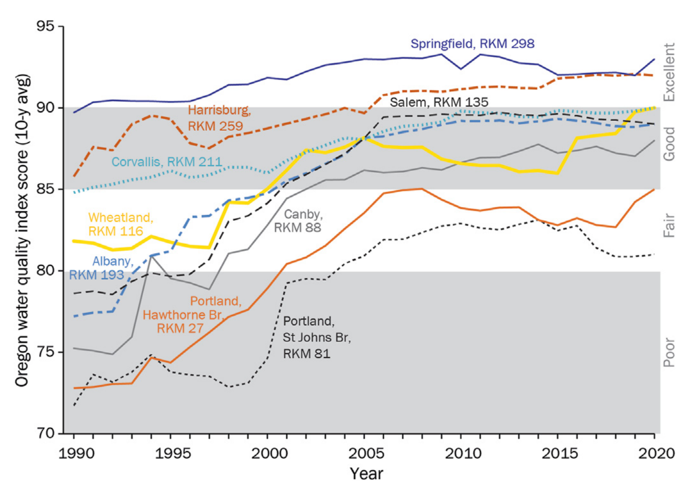

Fig. 8. Oregon water quality index scores over time at multiple sites from the Willamette River in Portland, Oregon (Hawthorne Bridge, river kilometer 27) to Springfield (river kilometer 298). Water-quality index scores are based on empirical water-quality data collected by the Oregon Department of Environmental Quality.

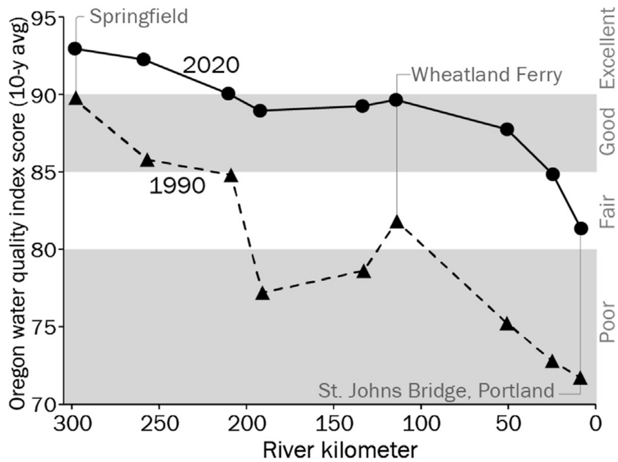

Fig. 9. Oregon water-quality index scores averaged over 10-year increments by river kilometer. Across sites, water quality has improved between 1990 and 2020. Water-quality index scores are based on empirical water-quality data collected by the Oregon Department of Environmental Quality.

distributions, fish-habitat use, and linkages between native fish (e.g., habitat use, survival, growth, and behavior) and thermal regimes. Geophysical and environmental data, including models of river hydrology, temperature throughout the year, and geomorphology, provide a foundation on which to further understand the river ecosystem.

Organizations that have successfully implemented the anchor habitat concept continue to expand the inventory of connected habitat throughout the basin. Increasing lateral and longitudinal connectivity among mainstem, tributary, side channel, alcove, and beaver-pond habitats along the river system targeted cold-water fish habitat, enabling greater success from existing rehabilitation projects (OWEB FIP, 2021). The currently modified flow regime (resulting from hydroelectric/flood-mitigation dams in tributaries) affects survival and distribution of cold-water fishes through factors such as water temperature. Currently, water temperature conditions are found to be a greater limiting factor than flow in a variety of habitats (Stratton Garvin, 2022; White and Wallick, 2022; White et al., 2022). Thus, rehabilitation projects are needed that focus on simultaneously increasing side-channel complexity, reconnecting the floodplain, improving the health of floodplain forests, and limiting the abundance of non-native predaceous fish species, all of which are instrumental for recovery of native fish species (Hughes and Herlihy, 2012; Keith et al., 2022). Such complicated and multi-dimensional conservation actions for mainstem rehabilitation require an overarching organization like the WAHWG, with active participation from member organizations to continue prioritization, coordination, and implementation of projects.

There are several challenges to the continued recovery of the mainstem Willamette River. Channel-restructuring flood flows have become rarer because of management for flood mitigation/hydropower production by dams. When possible, controlled flood releases could be periodically implemented during the winter high-flow season. Refining dam and hatchery operations to minimize flow-alteration effects in the basin could reduce survival risks for wild Chinook Salmon, winter steelhead, and Pacific Lamprey populations (NMFS, 2008; Poirier et al., 2021; Schroeder et al., 2016). Unsafe levels of personal-care products, pesticides, pharmaceuticals, and other contaminants have been documented in water release by municipalities along the Willamette River and elsewhere in the Pacific Northwest (Maas-Hebner et al., 2014; Segerstrom et al., 2017; Yeakley et al., 2014). Strengthening municipal discharge permits could reduce contamination risks to fish, birds, mammals, aquatic macroinvertebrate assemblages, and other biota as well as human health. Portland Harbor remains a toxic Superfund Site affecting its aquatic biota (Farr and Ward, 1993; Hughes and Gammon, 1987). Although point sources of pollution may be the easiest to control, the Willamette River main stem also suffers from diffuse pollution (of nutrients, sediment, and heat), particularly from agricultural land uses (Mulvey et al., 2009; Thornbrugh et al., 2018; Van Sickle et al., 2004), and insufficient large wood. Establishing riparian buffer strips (wetlands, woodlands) along Willamette Valley stream networks could mitigate diffuse pollution risk factors (Hughes and Vadas, 2021; Kaufmann et al., 2022; Mulvey et al., 2009; Van Sickle et al., 2004). An emerging problem for the river ecosystem is invasive, non-native predators, such as Smallmouth Bass (*Micropterus dolomieu*) and Walleye (*Sander vitreus*), which are likely to further disperse with climate warming and reduced flood flows (Adams et al., 2003; Hughes and Herlihy, 2012; Lavigne et al., 2008; Sanderson et al., 2009; Sharma et al., 2009; Rubenson and Olden, 2020).

In the future, natural habitats and environments will experience increasing pressure from a changing climate, human population growth, and over consumption (Gido et al., 2023; Limburg et al., 2011; Santelmann et al., 2012). Population growth and intensive land use will intersect with environmental changes associated with climate warming, compounding stressors for native biota and ecosystems. Ongoing diligence in the application of existing land-use planning laws as well as targeted enhancement of ecologically relevant habitats and environments could eventually lead to a Willamette River that more closely resembles the pre-settlement river of the past, even allowing for the needs of an expanding human population (Fig. 10).

In pursuit of this vision, we recognize an imminent need to improve communication and sharing of knowledge among practitioners, resource managers, and the public throughout the Willamette River basin. Ideally, scientists, managers, and interested community members from different perspectives could work together to co-create a shared knowledge foundation that would help everyone involved in river management decisions to better understand the perspectives, technical insights, and values represented among groups. These types of trans-disciplinary discussions are challenging. Quintas-Soriano et al. (2022) offered a framework for assessing the coupling or de-coupling of river social-ecological systems as a means of informing potential outreach actions and management implications. Collaborative efforts that incorporate organizations or trained mediators to create a bridge among participating groups to achieve shared and accepted goals were supported by Cash et al. (2003), who also identified the difficulties and time commitment necessary in such undertakings. Between 2008 and 2023, a variety of actions were highlighted for the Willamette River basin that, if implemented, could yield a meaningful, commonly shared knowledge foundation to support river management decisions. Each of these actions deserves greater investment in the development of communication strategies and could serve as a starting point to inform future priorities and conservation actions in this large river system. These actions could involve:

- Annual knowledge-sharing workshops where Indigenous community members, managers, and researchers, all share updates from their respective fields.
- "State of river" science syntheses on websites to provide easy, commonly accessible information on river conditions, status, trends of hydrological conditions, fish assemblages and other attributes of the river system.
- Revising and review of the Slices framework for compatibility with emerging management needs.
- Establishment of community listening sessions among scientists, managers, and community members to discuss local needs, concerns, and goals to build shared understanding.
- Scientists could travel to communities around the basin for annual presentations to the public (for example, watershed councils already host "pub talks" in many basins).
- Rehabilitation practitioners could travel to science and management agencies to share "on the ground" perspectives about the challenges,

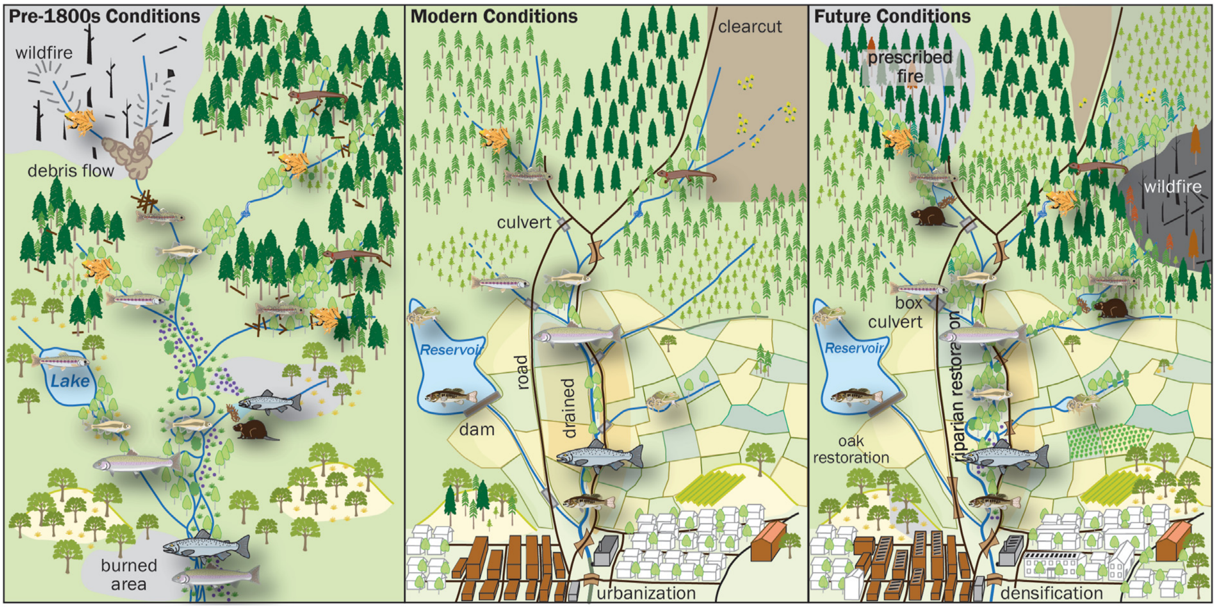

Fig. 10. Envisioning the future of land use, conservation, ecosystems, and dynamic disturbances for the Willamette Valley is aided by conceptualizing what the valley once contained, as well as modern and future conditions. In this figure, native fish species, amphibians and floodplain habitat-engineering beavers are represented among a suite of different simplifications of forest and vegetation composition, land use, urbanization, and road connectivity. Now is the time for envisioning the future of the valley in light of past rehabilitation and conservation actions, as well as comprehensive and informative science.

opportunities, and realities of conducting river rehabilitation, and how scientists and managers could better support their work.

- Scientists could be encouraged to publish research and monitoring findings on a timely basis, and to ensure that science efforts prioritize river-management decisions.
- Scientists and rehabilitation professionals could publish and publicly share findings regarding the effectiveness of river, in-stream habitat, and riparian monitoring efforts.
- Agencies and organizations over-seeing basin-wide rehabilitation could publish programmatic reports summarizing rehabilitation projects that were implemented across the basin, including the locations, goals and actions implemented.
- Scientists could improve website presence and share high-level findings of research studies, links to reports and other easy-to-understand summaries of new and emerging research topics and findings.
- Scientists could publish fact sheets and other plain-language, short summaries, that are useful for decision-makers.

Recognizing that science, management issues, and ecological conditions rapidly evolve, this knowledge foundation will require constant cultivation and maintenance to ensure that the information is timely, relevant, and reflects emerging issues, and that annual communication activities remain useful to all parties. Furthermore, collaborative learning opportunities would further strengthen the understanding of all who live in the Willamette River basin regarding innovative science, as well as the justification for, and reasoning behind, different types of rehabilitation projects, initiatives, and other land use actions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. As co-Editor-in-Chief of *Water Biology and Security*, Robert M. Hughes was not involved in the editorial review or the decision to publish this article.

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