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Potential Effects of Dams on Migratory Fish in the Mekong River: Lessons from Salmon in the Fraser and Columbia Rivers

John W. Ferguson · Michael Healey · Patrick Dugan · Chris Barlow

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Abstract We compared the effects of water resource development on migratory fish in two North American rivers using a descriptive approach based on four high-level indicators: (1) trends in abundance of Pacific salmon, (2) reliance on artificial production to maintain fisheries, (3) proportion of adult salmon that are wild- versus hatchery-origin, and (4) number of salmon populations needing federal protection to avoid extinction. The two rivers had similar biological and physical features but radically different levels of water resource development: the Fraser River has few dams and all are located in tributaries, whereas the Columbia River has more than 130 large mainstem and tributary dams. Not surprisingly, we found substantial effects of development on salmon in the Columbia River. We related the results to potential effects on migratory fish in the Mekong River where nearly 200 mainstem and tributary dams are installed, under construction, or planned and could have profound effects on its 135 migratory fish species. Impacts will vary with dam location due to differential fish production within the basin, with overall effects likely being greatest from 11 proposed mainstem dams. Minimizing impacts will require decades to design specialized fish passage facilities, dam operations, and artificial production, and is complicated by the Mekong's high diversity and productivity. Prompt action is needed by governments and fisheries managers to plan Mekong water resource development wisely to prevent impacts to the world's most productive inland fisheries, and food security and employment opportunities for millions of people in the region.

Keywords Dams · Migratory fish · Fish passage · Mitigation · Fisheries

J. W. Ferguson (✉)
NOAA Fisheries, Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, Washington 98112, USA
e-mail: john.w.ferguson@noaa.gov

M. Healey
University of British Columbia, Vancouver, BC, Canada

P. Dugan
WorldFish Centre, Penang, Malaysia

C. Barlow
Australian Centre for International Agricultural Research, Canberra, Australia

Introduction

The Mekong River is the world's 10th longest river, extending 4,909 km from the Tibetan Plateau in China to its mouth in southern Vietnam (Liu and others 2009; Fig. 1). Its physical diversity, tropical location, and high productivity fostered the evolution of a diverse fish community comprised of about 850 freshwater species (Valbo-Jorgensen and others 2009), and as many as 1,100 indigenous species if coastal and marine species that use the Mekong River ecosystem are considered (Hortle 2009a). Species richness in the Mekong is second only to that in the Amazon River (Froese and Pauly 2010) and supports the world's largest inland fishery with approximately 2.6 million tonnes annual harvest (Hortle 2007).

A total of 135 fish species in the Mekong evolved potadromous life history strategies (Baran 2006). Perhaps the most famous is the Mekong giant catfish (*Pangasianodon gigas*), which grows to over 3 m in length and 300 kg in weight. This catfish undergoes extended migrations to spawning grounds in northern Thailand and Lao Peoples

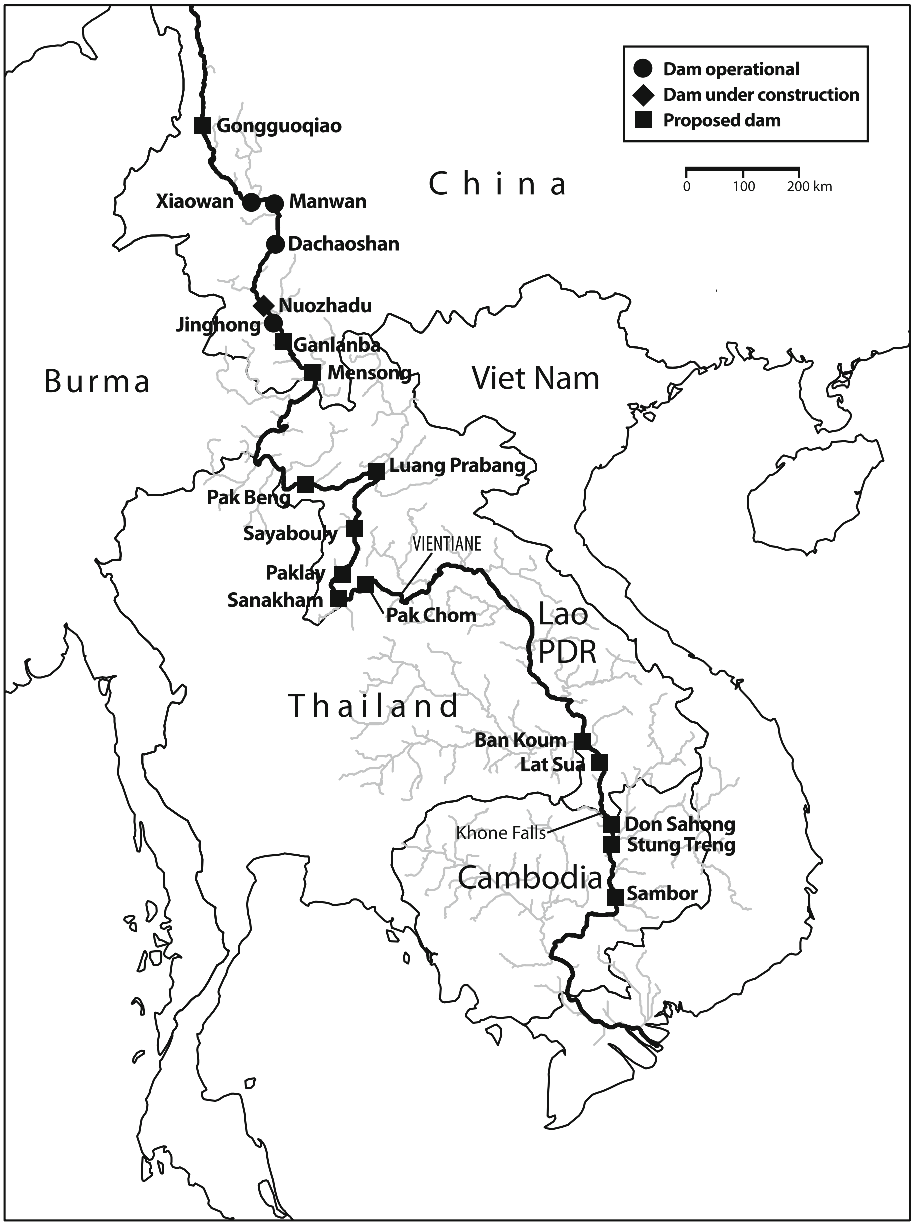

Fig. 1 Map of the Mekong River basin and locations of mainstem dams constructed, under construction, and proposed

Democratic Republic (PDR) where it was targeted (Starr 2006) and is now highly endangered (Hogan 2004).

The Mekong River lies in a region in desperate need of electricity for economic development and nearly 200 dams are completed, under construction, or planned in tributaries (Baran and others 2009; MRC 2010; Table 1). In China, four mainstem dams have been constructed, one is under construction, and three more are planned (MRC 2010). Outside of China in the Lower Mekong Basin (LMB), 11 mainstem dams are proposed that range in height from 6 to 40 m and would generate nearly 14,000 MW of power (Fig. 1).

Water resource development has significant effects on the structure and function of river ecosystems (Ward and Stanford 1979; Winston and others 1991; Reyes-Galván and others 1996; WCD 2001; FAO 2005). In large rivers, dams are obstacles to fishes that require movement to complete their life cycle (Larinier 2001; Winter and Van Densen 2001; Zigler and others 2004) and can cause decreasing population trends (NRC 1996; Parrish and others 1998; Jackson and Marmulla 2001). Dams can reduce species diversity and catch per unit effort of fisheries for short- and long-distance migratory species (Fernandes and others 2009). Providing passage for migratory species at dams is critical for maintaining the viability of potadromous and diadromous fish populations (Lucas and Baras 2001).

Based on experiences in other systems, there is no doubt that impacts to Mekong fish and fisheries from water resource development could be substantial. For example,

Table 1 Summary characteristics of the three river systems evaluated

Characteristic	Fraser	Columbia	Mekong
Catchment (km^2)	234,000	567,000	795,500
Length (km)	1,400	2,000	4,900
Mean annual discharge ($m^3\ s^{-1}$)	3,600	7,800	14,500
Maximum discharge ($m^3\ s^{-1}$)	8,000	24,500	40,000
Minimum discharge ($m^3\ s^{-1}$)	800	1,800	2,000
Number fish species[a]	36	27	774
Number of existing or planned mainstem dams[b]	0	15	19
Approximate number of existing or planned tributary dams[c]	7	>100	200
Adult fish passage facility criteria developed?	Yes	Yes	No
Juvenile fish passage facility criteria developed?	Yes	Yes	No
Fish swimming performance data available?	Yes	Yes	No
Use of hatcheries to support fisheries	Limited	Extensive	Very limited

[a] Number of fish species as reported in Froese and Pauly (2010) to use one common database

[b] Columbia River dam total includes 13 mainstem Snake and Columbia River dams that currently pass fish, two mainstem Columbia River dams that are impassable to fish, and three mainstem Snake River dams that are impassable

[c] Fraser River dam total includes dams on the Stave, Bridge, Seton, Nechako, Coquitlam, and Alouette Rivers and at the outlet of Mable Lake; Columbia River data from NRC (1996); Mekong River data from Baran and others (2009)

the combined fishery from natural harvest and aquaculture has an estimated value of US$3.6–6.5 billion at the point of first sale (Hortle 2009b), and considerably more when multiplier effects are included (Yim and McKenney 2003; Rab and others 2004). These values do not consider the food security and employment benefits the fisheries provide for millions of people with limited livelihood alternatives, nor do they recognize that Mekong fish are the main source of animal protein, vitamins, and calcium for 60 million people in the LMB (Baran and others 2007; Hortle 2007).

The potentially large impact on Mekong fisheries from water resource development led us to review development of two fisheries-rich rivers in North America to identify strategies that might be useful in balancing environmental, economic, and social aspects of development in the Mekong. Specifically, we focused on differential impacts to migratory species because fisheries on this subset of species comprise a large proportion of Mekong harvest (Barlow and others 2008).

We chose the Fraser and Columbia rivers for this comparison for several reasons. First, the review was aided by the two rivers having a common hydrology and settlement history by Europeans, similar ecoregion locations, and similar levels of biodiversity (Froese and Pauly 2010). In terms of informing Mekong water resource development, however, an important distinction existed: the mainstem Fraser River is free flowing and the watershed contains few large dams, whereas the Columbia River basin has 13 mainstem dams that fish must pass to complete their life cycle and more than 130 large dams in total (NRC 1996). This stark contrast provided a unique opportunity to explore key issues facing Mekong River planners and resource managers, including the overall impact of dams and the relative impact of mainstem versus tributary dams on fish abundance.

Second, although the Fraser and Columbia rivers have low species diversity (Table 1) they both contain a rich diversity of salmon populations (*Oncorhynchus* spp.) with complex life history traits that evolved because of the region's geologic history and complex river structure. For example, Gustafson and others (2007) estimated that nearly 1,400 populations of Pacific salmon inhabited the Pacific Northwest and California historically. This complexity at the population level is analogous to the level of speciation in the Mekong, and aided a prospective assessment of potential impacts to Mekong fish resources.

Third, Pacific salmon are highly migratory within river systems and any differential effects on salmon noted in this review would be instructive for our main area of focus: how dams might affect migratory species in the Mekong. Fourth, the science surrounding how anthropogenic structures modify large river systems in the Pacific Northwest and affect salmon populations is well developed and is being synthesized (e.g., NRC 1996, 2004; Williams 2008), allowing for an unambiguous review. Finally, salmon in the Pacific Northwest have high cultural and economic value and impacts on these species have far reaching socio-economic implications for the region. Salmon represent a logical template for understanding issues to be considered when planning development of the Mekong, given the socio-economic concerns over the potential impact on Mekong fisheries.

Also, migratory fish in both regions have a common adaptation in their adjustment to pulses in freshwater flow. In the Columbia and Fraser, salmon evolved to time juvenile (Zabel and others 2008) and adult (Keefer and others 2008) migrations to the hydrological cycle (i.e., the spring freshet). Similarly, seasonal variations in flow levels in Neotropical rivers enlarge the available rearing habitat, decrease fragmentation between habitats, increase food resource availability, and have a role in regulating fish reproduction and recruitment (Fernandes and others 2009). Any dependence on flow levels is more evident for long-distance migratory species (Fernandes and others 2009), as these species use the seasonally flooded habitats as nursery areas (Agostinho and others 2004). These attributes appear especially true in the Mekong where seasonal large changes in flow pulses come with the monsoon season, many species move onto floodplains to spawn during the wet season and retreat to river channels in the dry season (Poulsen and others 2002). Thus, in addition to any passage effects, dams that alter wet season flows will also impact this adaptation to pulse floods, as Fernandes and others (2009) observed in the Paraná River in Brazil. Some species, such as the Mekong giant catfish, are already endangered for reasons unrelated to dams and water resource development will exacerbate an already high risk of extinction for these species, and put others at risk.

However, many aspects of the Fraser and Columbia are not directly comparable to the Mekong. For example, the three rivers reside in distinctly different biogeographic provinces, contain entirely different ichthyofauna, and have very different fisheries. Also, salmon in North America evolved to synchronize juvenile entry into marine ecosystems and adult entry into freshwater to maximize survival and population productivity (Muir and others 2006; Scheuerell and others 2009). Since migratory fish in the Mekong are potadromous, there is no obvious counterpart to the possible effects of dams on the timing of marine and freshwater entry in the Mekong.

These limitations notwithstanding, the contrasting approach taken to water resource development in the Fraser and Columbia rivers offered an opportunity to explore key questions facing Mekong decision makers. Because of the differences noted above and a general lack of long-term harvest data in the Mekong, we used a descriptive approach based on high-level indicators rather than a quantitative evaluation of effects on specific parameters, such as abundance or harvest.

Our assessment followed five steps. First, we estimated trends in general fish abundance based on adults counted passing a dam (Columbia) or estimated river escapement (Fraser). Second, we evaluated the extent to which salmon production in the Columbia and Fraser rivers currently relies on artificial production to mitigate for dam-passage mortality and maintain fisheries. Third, we estimated the proportion of wild fish in adult salmon returns. Fourth, we compared the number of salmon species or populations needing protecting under federal legislation to avoid extinction (the U.S. Endangered Species Act [ESA] of 1973) or are regarded as endangered by the Committee On the Status of Endangered Wildlife In Canada (COSEWIC; a committee of scientific experts who review the data on each species and recommend listing to the government). Finally, we discussed how results of the Fraser-Columbia comparison might apply to fish populations in the Mekong River.

Fraser River

The Fraser River drains an area of 234,000 km^2 or about 25% of the province of British Columbia. It is the largest river in Canada that discharges into the Pacific Ocean, originating in the Rocky Mountains and flowing 1,400 km to the Pacific Ocean at the city of Vancouver. The Thompson and Nechako are major tributaries, although many rivers join the Fraser before it enters the Strait of Georgia, including the McGregor, Quesnel, Chilcotin, Coquihalla, Harrison and Chilliwack (Fig. 2). Mean annual discharge is 3,600 m^3 s^{-1} but the hydrograph is dominated by snowmelt, and discharge ranges from approximately 8,000–800 m^3 s^{-1} between spring and winter, respectively.

According to Northcote and Larkin (1989), the Fraser River is the greatest salmonid producing system in the world. Seven species live in the basin and five of these are commercially valuable and harvested mainly in the ocean: sockeye (*Oncorhynchus nerka*), pink (*O. gorbuscha*), chum (*O. keta*), coho (*O. kisutch*), and Chinook salmon (*O. tshawytscha*). The two remaining species, steelhead (*O. mykiss*) and cutthroat trout (*O. clarkii*) are harvested mainly in freshwater recreational fisheries. The economic value of Fraser River salmon harvest is estimated at C$41.7 M annually (McRae and Pearse 2004). Additionally, salmon fisheries conducted by aboriginal societies in the basin are critically important for non-economic purposes such as religious and cultural ceremonies and subsistence.

All five Pacific salmon species are anadromous, spawning in freshwater but migrating to sea as juveniles where they grow rapidly and attain sexual maturity. Spawning migrations range from short distances to lower mainstem and tributaries sites for chum salmon, to spawning areas as much as 1,300 km inland for sockeye and Chinook salmon. While steelhead/rainbow trout and cutthroat trout do have anadromous populations, most complete their life cycle in freshwater.

Variability in salmon recruitment to adult stages in the ocean drives adult return patterns (Hare and others 1999), but access to freshwater spawning and rearing habitat in the

Fig. 2 Map of the Fraser River basin

Fraser River has been considerably altered by anthropogenic factors in three main ways and affected population abundance. First, extensive mining and dewatering followed the discovery of gold beginning in 1858. For example, a mining dam built below Quesnel Lake (Fig. 2) decimated a run of sockeye salmon estimated to have averaged 10 million fish (Roos 1991). Second, in the late 19th and early 20th centuries, many temporary dams were built to store logs for later processing at mills downstream. These dams blocked salmon migrations, scoured spawning gravels, and destroyed eggs when the logs were flushed downstream. A sockeye run in the upper Adams River was permanently lost from such a dam, although today the area below the dam produces the largest sockeye run in the basin. Third, perhaps the most serious effect of development on salmon was a large rockslide in the Fraser River Canyon in 1914 in an area known as Hell's Gate (Fig. 2). Rock debris from blasting a railway path increased water velocities at an already constricted area and blocked passage for most sockeye salmon (Roos 1991), and likely for many Chinook and coho salmon as well.

The migration blockage at Hell's Gate, coupled with continued heavy fishing by both the US and Canada, caused sockeye populations to collapse from an average annual catch of more than 8.5 million fish prior to 1916 to less than 1.7 million fish from 1917 to 1932 (Ricker 1987), and pink salmon abundance declined by 75%. This led to the formation of the International Pacific Salmon Fisheries Commission (IPSFC) in 1937 to manage the rebuilding of sockeye and pink salmon runs through the construction of fish passage facilities at Hell's Gate and managing fisheries to ensure that escapement was adequate for stock productivity. Gradually, sockeye salmon abundance increased (Fig. 3). The Hell's Gate slide had relatively little impact on pink salmon, since they spawn mainly downstream from Hope (Fig. 2).

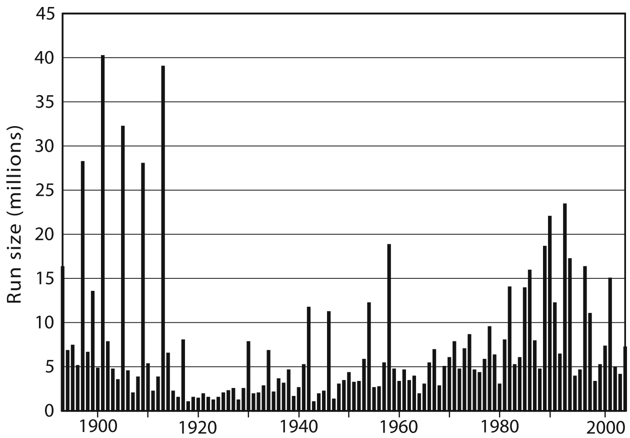

Fig. 3 Estimated annual abundance (millions) of adult sockeye salmon returning to the Fraser River, 1893–2005; adapted from PSC (2009). A large rockslide at Hell's Gate in the Fraser River Canyon in 1914 blocked passage for most sockeye salmon

Starting in the early 20th century, hydroelectric dams installed in tributaries such as the Coquitlam, Alouette, and Bridge rivers blocked access and altered downstream flows for all five salmon species. In some cases, such as the Bridge River where a dam diverted water into Seton Lake (Fig. 2), important runs of sockeye, pink and Chinook salmon were affected. Here the developer worked with experts to reduce impacts by installing adult fishways and spawning channels and operating the dam to manage flow regimes (Roos 1991). In contrast, water diversion from damming of the Nechako River decimated a major Chinook salmon population and impacted a major sockeye run.

Despite a rush to develop hydropower sites in British Columbia during the middle 20th century, no mainstem dams were constructed on the Fraser River. This restraint was not for lack of proposals, with the most ambitious being a 216-m high dam at Moran canyon near Lillooet (Fig. 2) that would have generated as much power as Grand Coulee Dam (Washington, US) and 2 Hoover dams (Nevada, US) combined from water stored in a 260-km long reservoir. If constructed, the dam would likely have been the first of many mainstem and major tributary dams. However, public opinion over the Moran project was deeply divided along familiar lines: opponents argued the dam would destroy salmon runs and proponents argued the power was necessary for economic development. A decision not to dam the Fraser was made (Evenden 2004), but why this occurred during an era of dam building is not entirely clear, as dam proposals had many influential supporters including the provincial government. Several factors likely contributed to this outcome. First, salmon runs in the river were economically important to both Canada and the US and were administered under an international agreement, making it difficult for British Columbia to unilaterally initiate a project that would impact US interests. Second, a careful review and analysis by the IPSFC (Andrew and Geen 1960) had demonstrated the impact of a mainstem dam on salmon runs, and led dam proponents to recognize that mitigation efforts (fish ladders and artificial propagation) could not negate all impacts. This same analysis was later used to support a lasting prohibition on Fraser River dams (Anonymous 1971). Third, numerous other large power development projects in the province could be pursued that were less contentious. Finally, fishery management in Canada is the responsibility of the federal government, which also has a fiduciary responsibility to British Columbia's aboriginal peoples, whose cultures are intimately linked with salmon. The federal government opposed Moran Dam because of its likely impact on both salmon and native Canadians.

Throughout its history of development, the Fraser River has remained a highly productive salmon river. The most complete data are for sockeye (Fig. 3). Runs peaked at 38 million fish prior to the Hells Gate blockage, collapsed after 1914, slowly recovered until 1975, and then increased rapidly to near historic abundance in the 1990s. Northcote and Atagi (1997) describe an increase in the abundance of pink and Chinook salmon in the Fraser from the 1950s through the 1990s, and after most dams in the basin were in place. Chum salmon abundance increased through the 1980s but declined in the 1990s, and coho salmon numbers also declined throughout this timeframe for unknown reasons. Recent declines in sockeye salmon abundance and the continuing decline in coho salmon notwithstanding, the Fraser River remains one of the most productive fishery systems in the world. Most observers agree that salmon production could not have been maintained had the Fraser mainstem been dammed in the mid 20th century (Evenden 2004).

Columbia River

The Columbia River is 2,000 km long and drains an area of 567,000 km^2 from seven western states in the US and one province of Canada. The river rises in the Rocky Mountains of British Columbia, flows northwest and then south into Washington and turns west to form a border between much of Washington and Oregon before emptying into the Pacific Ocean near Astoria, Oregon. Its largest tributary is the Snake River, although numerous other tributaries provide extensive spawning and rearing habitat for salmon including the Yakima, John Day, Deschutes, and Willamette rivers (Fig. 4).

By volume, the Columbia is the fourth-largest river in the US and has the greatest flow of any North American river draining into the Pacific Ocean. Mean annual discharge is

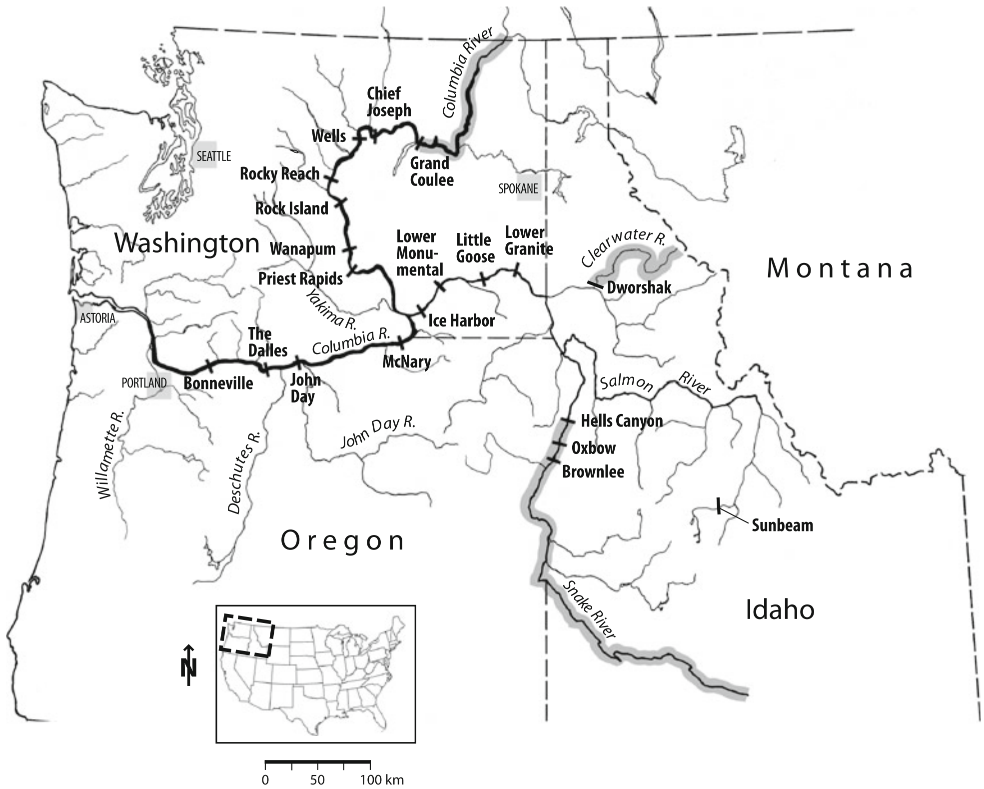

Fig. 4 Map of the Columbia River basin and major hydroelectric, irrigation, and flood control dams. *Shaded areas* depict river reaches where access by salmon is blocked by major dams

approximately twice that of the Fraser at 7,800 $m^3\ s^{-1}$ and its hydrograph is similarly dominated by snowmelt. The Columbia's highest recorded flow was 35,000 $m^3\ s^{-1}$ in June 1894 before the river was dammed. Under contemporary conditions, a maximum flow of 24,500 $m^3\ s^{-1}$ was recorded in 1996 and a minimum discharge of 1,800 $m^3\ s^{-1}$ was experienced during a drought in 2001.

The fish community is comprised of the seven species of salmon and trout as described for the Fraser River, above, which are made up of numerous populations that resulted from repeated glacial expansions and retreats in the basin (Waples and others 2008). Pacific lamprey (*Lampetra tridentata*), green sturgeon (*Acipenser medirostris*), and eulachon (*Thaleichthys pacificus*) are also anadromous species present in the Columbia (and Fraser). American shad (*Alosa sapidissima*) are anadromous but are not native, having migrated to the Columbia River after being introduced to the Sacramento River from the eastern US in 1871. The potadromous white sturgeon (*A. transmontanus*) also inhabits the mainstem Columbia and Snake rivers (and Fraser).

Prior to European contact, an estimated 7.5–10 million adult salmon returned to the river annually (Chapman 1986; NRC 1996). Salmon have been an important source of food for Native Americans for at least 10,000 years (Butler and O'Connor 2004) because they were abundant, seasonally predictable, and could be dried for storage. Native Americans caught 19,000 tonnes (42 million pounds) of salmon annually in the early 19th century (Schalk 1986).

Extensive harvest by Euro-Americans in the mainstem Columbia River began after the first salmon cannery was built in 1866 (Fig. 5). Harvest declined starting in the early 1900s from overfishing, tributary habitat degradation, blocked access to spawning habitats from dams, and mortality during passage at mainstem dams (NRC 1996; Lichatowich 1999), but has increased somewhat recently (Fig. 5). Salmon harvest in the Columbia River basin contributed US$142 M annually to local communities in 2005 (IEAB 2005).

By 1900, hundreds of small dams had been built in the Columbia basin to transport lumber (Sedell and Luchessa 1982), provide water for municipal and industrial purposes, irrigate crops, and sustain livestock. Gold was also discovered and mining likely had negative effects on salmon habitat. Sunbeam Dam on the Salmon River supplied power to a mine but lacked fish passage facilities, and sockeye salmon runs declined precipitously after its construction (Waples and Johnson 1991; Selbie and others 2007).

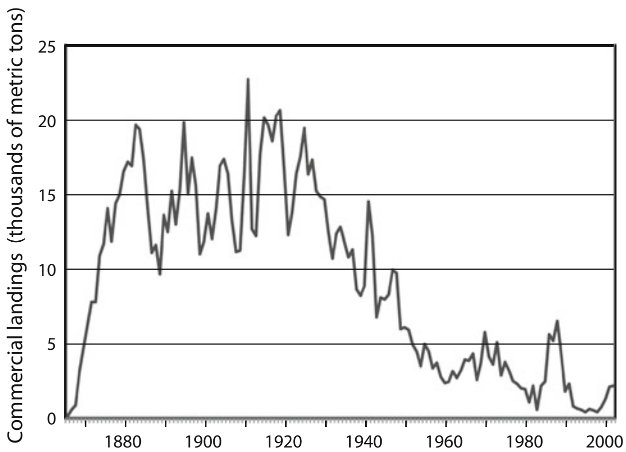

Fig. 5 Estimated annual commercial harvest of salmon in the Columbia River, 1863–1993; adapted from NRC (1996) and updated using data provided by Washington Department of Fish and Wildlife

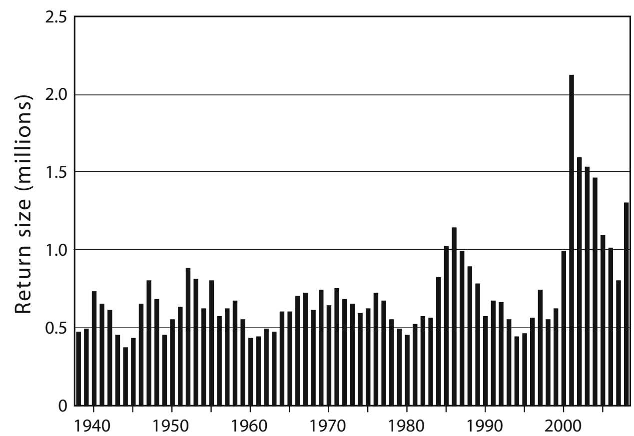

Fig. 6 Total number of adult salmon counted at Bonneville Dam annually, 1938–2009; adapted from Federal Columbia River Power System 2008 Progress Report; accessed online February 2010 http://www.salmonrecovery.gov/BiologicalOpinions/FCRPS/

In the late 1920s, political forces in the US generally favored private development of hydroelectric dams in the Columbia River basin. Rock Island Dam, installed in 1930, was the first mainstem dam to be constructed and adult salmon ladders were a component of its design. However, with the onset of the Great Depression, construction of federal hydropower projects of unprecedented size was begun for economic development. Bonneville and Grand Coulee dams were completed in 1938 and 1941, respectively. Today, ten mainstem dams span the Columbia River below Grand Coulee, four additional federal dams span the lower Snake River, and more than 130 large private and federal dams in the basin are used for hydropower production, flood control, transportation of commerce, and irrigation (NRC 1996; Fig. 4).

Bonneville Dam is located 235 km upstream from the river mouth and has played a prominent role in salmon management since its completion, when 471,000 salmon were counted passing its fish ladders. Annual counts have ranged from 362,000 (1944) to 2,116,000 (2001) and averaged 1,360,000 fish during the most recent decade. Annual lamprey counts from 1939 to 1969 ranged from 33,000 (1950) to 380,000 (1969) fish. Lamprey counting was stopped in 1969, but resumed in 1997, and annual counts have since ranged from 19,000 (2000) to 117,000 (2003) fish. A total of 5,273 American shad were counted in 1938, whereas on average, 3,092,000 fish passed the dam each year during the most recent 10-year period (USACE 2009a). The number of salmon counted at Bonneville Dam was relatively stable until a peak in 1986, followed by a decline in the mid-1990s and subsequent increase with a record abundance in 2001 (Fig. 6).

However, the recent upward pattern in dam counts masks an increased reliance on production from 178 hatchery programs associated with 351 salmon and steelhead populations in the basin (HSRG 2009). For example, 19% (geometric mean; 95% CI 14.3 to 23.9%) of the adult spring Chinook salmon returning to the upper Columbia River since 1980 was of wild origin (based on data reported in WDFW and ODFW 2010).

Use of hatcheries was based on the simple assumption that salmon abundance was limited by mortality in freshwater and would increase in direct proportion to the number of eggs that survived a controlled environment (NRC 1996). However, we now know that this was a simplistic and erroneous view of salmon ecology. Hatchery fish have a lower fitness in natural environments than do wild fish, with the loss of fitness occuring in as little as one or two generations (Risenbichler and Rubin 1999; Berejikian and Ford 2004; Araki and others 2008). Wild-born descendents of captive-bred parents also have reduced reproductive fitness. For example, Araki and others (2009) estimated that overall relative reproductive fitness was only 37% in wild-born fish from two captive-bred parents. Furthermore, for anadromous species, hatchery production can negatively affect wild stock production through density-dependent effects in marine ecosystems (Levin and others 2001; Buehle and others 2009).

Adult fish ladders at the 13 mainstem dams on the Snake and Columbia rivers were designed as integral components of each dam's configuration and have performed quite well overall. In contrast, only the mainstem dams constructed most recently contained facilities designed to route juvenile salmon past turbines during downstream migrations, and these systems initially performed poorly (Williams and Matthews 1995; Ferguson and others 2007). Cumulative impacts to juvenile salmon during passage through multiple dams became especially apparent during the extreme low flow years of 1973 and 1977, when survival through the hydropower system was estimated at less than 3% (Williams and Matthews 1995).

This poor survival demonstrated that salmon stocks could not be maintained without additional protection measures, and the region began to seriously address juvenile salmon passage at dams. Major programs implemented since 1977 have focused on (1) collecting juvenile fish at upper dams and transporting them in trucks or barges to release sites below Bonneville Dam (initiated in 1980), (2) identifying a volume of water stored in flood control reservoirs that can be used to augment river flow during salmon migrations (1982), (3) spilling water to pass fish through non-turbine routes (the amount varies but ranges up to 60% of instantaneous project flow; 1982), (4) installing specialized systems that guide juvenile fish away from turbines and around dams (1975), (5) maintaining gas supersaturation levels below 115% in forebays and 120% in tailraces (1996), (6) developing surface-oriented passage routes for juvenile salmon at dams (1990s), and (7) developing new turbine designs that pass juvenile salmon more safely (1990s). The survival of juvenile salmon through the hydropower system has generally improved as these actions have been implemented. Williams and others (2001) estimated that juvenile salmon survival from 1993 to 1999 with eight dams in place was similar to survival during 1966 and 1967, when only four mainstem dams were in place. Also, Williams and others (2005) reported that survival of juvenile Chinook salmon through the 8-dam complex in the drought year of 2001 was approximately an order of magnitude larger than was observed during a similar low-flow event in 1977.

The Northwest Power and Conservation Council (NPCC) was formed in 1980 by the US Congress to balance electrical power production and fish and wildlife resources in the region (http://www.nwcouncil.org/). The NPCC approves US$ 230 M annually for projects to mitigate impacts from hydropower and storage dams. In addition, operations to improve fish passage conditions at federal dams reduce power generation by approximately 1,000 MW annually (http://www.bpa.gov/power/pg/hydrspl.shtml), and the US Congress also allocates US$ 90 M to the U.S. Army Corps of Engineers each year to make structural modifications to federal dams to improve salmon survival. Mighetto and Ebel (1994) chronicle efforts to save salmon in the Columbia River.

Annual water management plans guide water use regimes in the basin (TMT 2009), and mainstem dams are operated to achieve juvenile salmon survival rates of 96 and 93% during spring and summer, respectively (USACE 2009b). Power production can supersede fish protection only if needed for system stability and public safety, and even then additional mitigation measures may be implemented to offset impacts to salmon (NPCC 2001).

Finally, strategies to mitigate the effects of dams have focused almost exclusively on low-head dams (e.g., Muir and others 2001; Ferguson and others 2007), although dams in salmon rivers are often greater than 100 m in height and block access to spawning and rearing habitat. For example, the construction of Grand Coulee (122 m high), Brownlee (128 m), and Dworshak (219 m) dams significantly decreased the amount of spawning and rearing habitat available to salmon (Fig. 4). The NRC (1996) estimated that as of 1975, water resource development had decreased the number of stream miles available to salmon in the basin from 17 to 100%, depending on the various salmon stocks and river reaches being considered.

Strategies for collecting juvenile salmon migrating through reservoirs behind high-head dams are starting to be developed and tested. For example, a US$ 40 M floating collector captured up to 87% of marked sockeye and coho salmon migrating through the 95-m high Upper Baker Dam reservoir (Washington). This capture rate required that 20% of powerhouse generation capacity (28 $m^3 s^{-1}$) be pumped through the collector to attract fish (Personal Communication, Nick Verretto, Puget Sound Energy, Bellevue, Washington).

Today, an estimated 30% of the historic Columbia River salmon populations have been extirpated (Gustafson and others 2007) and many remaining stocks have undergone a significant reduction in abundance since the 1970s. Currently, 12 of the 16 evolutionarily significant units (ESU; population groupings considered to have evolutionary significance; Waples 1991) are listed as threatened or endangered under the federal Endangered Species Act (1973) and receive additional protections to rebuild their status.

Mekong River

The Mekong River originates at approximately 5,000 m elevation and is confined to narrow valleys bordered by mountains through its 2,000-km course in China. In northern Lao PDR it drops to an elevation of 350 m, and flood plains border the river in many portions of the country. In northern Cambodia, its elevation is effectively at sea level even though the river continues some 500 km before reaching the South China Sea. In Cambodia and Vietnam, the river forms one of the world's mega deltas covering approximately 55,000 km^2, most of it less than 5 m above sea level. The Mekong's catchment covers 795,000 km^2, making it one of the biggest rivers in Asia (MRC 2005).

The major tributaries of the Mekong are located south of the China border. On the eastern bank in Lao PDR, the river is fed by a series of large tributaries (Nam Ou, Nam Ngum, Nam Theun, Nam Hinboun, Se Bang Fai, Se Bang Hieng and Se Done rivers) arising in the Annamite Ranges. On the western side in Thailand the Nam Songkhram is the main tributary in the north, while downstream the larger the Nam Mun and Nam Chi rivers join before entering the mainstem at the town of Pakse. Further south, three major tributaries (the Se Kong, Se San and Sre Pok rivers) arise in the Vietnamese and Lao PDR sections of the Annamite Ranges, and collectively provide about 25% of the mean annual flow volume in the mainstem at Kratie in northern Cambodia (MRC 2005). The remaining major tributary is the Tonle Sap-Great Lake system, connected to the Mekong at Phnom Penh in Cambodia.

Mean annual flow is 475 km^3, but the flow pattern is highly seasonal with an annual flood driven by the Southwest Monsoon. While mean annual discharge is 14,500 $m^3 s^{-1}$, mean monthly discharges reach a maximum of 40,000 $m^3 s^{-1}$ in September and a minimum of 2,000 $m^3 s^{-1}$ in April (MRC 2005). The flood inundates vast areas of wetlands in the lower Mekong basin every year (in major floods, approximately 60,000 km^2; MRC 2010). One of the Mekong's major tributaries, the Tonle Sap, has the unique feature of flowing upriver during the annual flood to seasonally inundate the Great Lake in Cambodia (Campbell and others 2009).

The Mekong contains a diverse fish fauna representing an exceptionally large number of taxonomic families: the Mekong fish database lists a total of 87 families (Valbo-Jorgensen and others 2009), with 65 being documented in Cambodia (Rainboth 1996) and 50 in Lao PDR (Kottelat 2001). In terms of species diversity, cyprinids are the dominant family, along with catfishes of the families Bagridae, Siluridae, Pangasiidae, Sisoridae and Claridae.

Mekong fishes are often grouped according to their ecology and migration patterns. "White fishes" undertake long-distance migrations between floodplains and along major rivers and often move hundreds of kilometres upstream for spawning. This group includes many cyprinids and pangasiid catfishes. "Black fishes" live in lakes and swamps on the floodplains; they are generally classed as non-migratory, although in the dry season they move to refuge pools in lakes and nearby rivers. Examples include snakeheads (Channidae), clarius catfishes (Clariidae) and climbing perch (Anabantidae) (Poulsen and others 2002). "Grey fish" are an intermediate group, living in lakes and swamps in the wet season and undertaking lateral migrations to tributaries and nearby river systems in the dry season. Examples include some catfishes of the family Bagridae (MRC 2010).

The general migration patterns for white fishes in the Mekong have been separated into three distinct but interconnected migration systems. These are the lower system from the coast in Vietnam to the Khone Falls in southern Lao PDR; the middle system from Khone Falls upstream to Vientiane, Lao PDR; and the upper system in northern Lao PDR (Fig. 1; Poulsen and others 2002). There is considerable movement of fish between the lower and middle migration systems, although it appears that there may be relatively little exchange of fish between the upper system and those downstream (Poulsen and others 2002)

Fisheries in the Mekong are extremely diverse, varying seasonally and geographically. Different nets, traps, lines and trawls are used to target all groups of fishes occupying a wide diversity of habitats (Deap and others 2003). While more than 200 species are caught and utilized (MRC 2010), 50–100 species make up the bulk of the commercial trade. Migratory species have been estimated to comprise between 40 and 70% of the overall yield of fish in the basin, equivalent to 700,000–1,600,000 tonnes per year (Barlow and others 2008).

Hydropower development in the Mekong was relatively constrained in the decades after World War II as a consequence of political instability in the region. Many plans were developed in the 1960s, but enacting them was not possible until regional peace was attained in the late 1970s. In the 1980s and 1990s, dams were built on tributary systems in Vietnam (Se San), Lao PDR (nine in total, with the three largest being on the Nam Theun, Nam Ngum and Se Kong rivers (www.poweringprogress.org)), and Thailand (Nam Mun). Currently, there are 20 operational dams and more than 40 dams under construction or being planned in the tributary systems of the four lower Mekong countries (www.poweringprogress.org; MRC 2010; Baran and Myschowoda 2009). An additional 150 potential dam sites have been identified (Baran and others 2009). From a fisheries perspective, perhaps of greatest concern are nine mainstem dams being planned in Lao PDR and two in Cambodia (Fig. 1; MRC 2010). These dams could have a large impact on biodiversity and fisheries production, because as barriers to migration they will interrupt the life cycle and restrict access to spawning and feeding habitats for many species (Barlow 2008).

The Mekong's fishery yield is based on estimated per capita consumption of fish in 2000 (Hortle 2007). The great majority of the catch is harvested in the portion of the watershed below China. In Lao PDR, 50–80% of people fish, and fishing provides 20% of household income. In Cambodia, 80% of the 1.2 million people living around Tonle Sap use the lake and its rivers for fishing, and fishing is the primary income source for 39% of these people (Ahmed and others 1998). In Vietnam's Mekong Delta, capture fisheries are crucial to livelihoods. For example, in the An Giang province 60% of the people are part-time fishers (Sjorslev 2001). In Tay Ninh province, 88% of households classified as 'very poor' depend on fisheries, and 44% of those classified as 'high income' are fisheries dependent (Nho and Guttman 1999).

There is a common perception that the fisheries of the Mekong are in decline (Friend and others 2009), but an examination of the few long-term fisheries databases available do not indicate any such trends. Halls and Paxton (in press) analysed 12 years of data from the Tonle Sap stationary trawl fishery, the most intensively monitored inland fishery in south-east Asia, and found no obvious decline in biomass indices, mean weight, or species composition through time. Analyses of trap fisheries (7 years of data) and gill net fisheries (10 years of data) in southern Lao PDR, and three years of data on gill net catches on the mainstem in Vietnam, Cambodia, Thailand and Lao PDR also indicated no trend in catch per unit effort (MRC 2010). Nevertheless, in some parts of the basin there are declining numbers of large species, such as the Mekong giant catfish (Hogan and others 2004) and *Probarbus* spp. (Baird 2006). The perception of declining yields may result from confusion about observable declining catches per individual fisher (e.g., Navy and Bhattarai 2009) and an overall yield throughout the basin that is variable, but not declining (Halls and Paxton in press; MRC 2010).

Impacts of current dams on downstream fisheries in the Mekong have been much debated, but unfortunately, little quantitative information is available. The impacts from the Pak Mun Dam in Thailand are the most extensively documented (e.g., Roberts 1993, 2001; Schouten and others 2000; Foran and Manorom 2009: Jutagate and others in press). The dam prevented fish from migrating into the Mun River from the Mekong and the fish ladder installed was ineffective (Schouten and others 2000). Representation from affected fishers led the Thai government to open sluice gates at the dam in 2003 and each year thereafter, which resulted in species in reaches upstream of the dam increasing from 75 to 139 (Jutagate and others in press). The Yali Dam located on the Sesan River in Vietnam was estimated to have caused a 57% loss of income for villagers downstream in Cambodia, with reduced fish catches accounting for more than half of the loss (McKenney 2001). Villagers downstream of the Theun-Hinboun Dam reported the blocking of fish migrating upstream and reduced catches of fish after the dam was operational, although this could not be quantified because pre-construction surveys were not undertaken (Warren 2000). Despite these examples and the considerable public discussion on impacts of dams on fisheries, fisheries considerations are still effectively ignored when it comes to planning hydropower developments in the Mekong region (Baran and Myschowoda 2009).

Results from the Fraser-Columbia Comparison

When we compared patterns in abundance between the Fraser and Columbia rivers, we found no substantial differences, and thus no obvious effects of water resource development on salmon in the Columbia River. Sockeye salmon abundance in the Fraser River peaked in early part of the 20th century, declined significantly starting in approximately 1915 due the velocity barrier at Hell's Gate, and gradually increased thereafter (Fig. 3). Since the late 1930s, the number of salmon counted at Bonneville Dam has been relatively stable until the most recent decade, when it increased along with in river harvest (Figs. 5, 6). The measures of abundance were different between the two rivers and were based on estimated adult salmon escapements into the entire Fraser basin versus actual counts of salmon entering the interior portion of the Columbia River basin at Bonneville Dam. However, since counts at Bonneville Dam comprise the majority of salmon entering the river, the two indicators were judged sufficient for comparing gross trends.

In contrast, we found substantial differences in the extent to which salmon production in the two rivers relies on artificial production to support fisheries and mitigate for dam-passage and other sources of mortality. In the Fraser River, the Canadian federal government's Salmonid Enhancement Program is comprised of only 12 hatcheries (http://www.pac.dfo-mpo.gc.ca/sep-pmvs/index-eng.htm). The Pacific Salmon Commission report on sockeye and pink salmon (PSC 2009) makes no mention of hatchery production in its annual assessment because there are no hatcheries for these two species. However, there are three artificial sockeye salmon spawning channels and two channels originally constructed for pink salmon on the Seton River.

As pointed out above, salmon abundance and fisheries in the Columbia basin are dependent upon 178 hatchery programs, many of which were implemented explicitly to mitigate impacts from private and federal dams installed in the basin. In 2008, an estimated 147,000,000 juvenile salmon arrived at the Columbia River estuary prior to entering the Pacific Ocean. While the hatchery component varies with species and river location, it was 75% of the yearling juvenile Chinook salmon arriving at McNary Dam (Fig. 4) that year (Ferguson 2008). Similar measures of the proportion of migrating juvenile salmon that are wild- versus hatchery-origin do not exist in the Fraser.

Next, we compared the proportion of wild- and hatchery-origin adults returning to each river and again found substantial evidence of differential effects from water resource development on salmon. Under contemporary conditions, the majority of adults returning to the Fraser and Columbia rivers are of wild- and hatchery-origin, respectively. In the Fraser, many highly productive and valuable salmon populations of all species continue to thrive. While several artificial channels are used to enhance salmon spawning for some species, in general, the amount of artificial propagation is insignificant compared to wild production. In fact, data on the proportion of adult salmon returning to the basin that are wild- versus hatchery-origin does not exist.

In the Columbia River, most adult fish that enter the river now were produced in hatcheries. As discussed above, 19% of the adult spring Chinook salmon that have returned to the upper Columbia River since 1980 were of wild origin. The wild proportion of Snake River spring/summer Chinook salmon was 77% in 1980, but declined to only 12% in 1997 and had a geometric mean of 39% (95% CI: 32–45%) from 1980 through 2009. For the index of summer steelhead destined for upriver spawning sites from 1984 to 2009, 22% (95% CI: 19–26%) were of wild origin (WDFW and ODFW 2010). For fall Chinook salmon entering the Columbia River, the geometric mean of the wild proportion was 52% (95% CI: 49–54%) from 1985 to 2008 (WDFW and ODFW 2009). This group is comprised of a very productive wild population that spawns in the last remaining free-flowing reach of the Columbia River.

When we compared the number of salmon species or populations needing protection under the US Endangered Species Act (ESA) of 1973 or are regarded as endangered by COSEWIC, we again found substantial differences between the two rivers. In the Fraser River, Cultus Lake sockeye and interior coho populations have been designated as endangered. Studies of the genetic structure of interior coho indicate that there are five populations, but due to the vast areas of the Fraser River basin, additional demographically independent groups (sub-populations) also likely exist (DFO 2005). In sharp contrast, 12 of 18 salmon and steelhead ESUs in the Columbia River are listed as threatened or endangered under the ESA (http://www.nwfsc.noaa.gov/trt/index.cfm). Each ESU is comprised of numerous individual populations, such as the 23 extant populations in the Snake River spring/summer Chinook salmon ESU. In total, 71 salmon populations in the Columbia River are federally listed as threatened or in danger of extinction, which greatly exceeds the comparable number in the Fraser River.

Discussion and Lessons for the Mekong

Our review of the Fraser and Columbia rivers and its lessons for the Mekong can be summarized as follows:

Overall Impacts from Hydropower Development are Large

The evaluation of the four high-level indicators leads us to an overall conclusion that the impact of large-scale hydroelectric development on migratory fish was substantially different between the Fraser and Columbia rivers, and much larger in the more developed Columbia. Low-head mainstem dams (<30 m) installed in salmon rivers can increase adult migration rates through a series of dams due to their ability to migrate rapidly through slack-water reservoirs (English and others 2006). However, lowered escapement can occur from losses between dams and mortality to adults that pass downstream through dams while searching for their natal river (Keefer and others 2005), and dams can reduce the productivity of interparous species when adults migrating downstream experience mortality during dam passage (Ferguson and others 2008). Dams can also affect spawning habitat downstream of dams by altering flow discharge patterns (Dauble and others 1999). Dams can cause direct mortality to juveniles migrating downstream through dam passage routes (Muir and others 2001), and mortality that is manifested indirectly and in reaches below a dam (Ferguson and others 2006) or downstream from a hydropower system (Williams and others 2005). Dams can also affect the survival of juvenile fish migrating through a series of dams by slowing migrations and altering ocean-entry timing (Muir and others 2006). Low-head dams can also modify juvenile rearing patterns once rivers are impounded (Connor and others 2005).

White sturgeon in the Columbia River are potadromous, and any information on the effects of dams on fish dependent on this life history strategy would be highly insightful to the Mekong situation. Prior to development, white sturgeon in the Columbia River ranged freely in mainstem reaches and took advantage of scattered and seasonally available food resources (Bajkov 1951). Today, their habitat is partitioned into reservoirs and river sections between dams and where the remaining spawning habitat is further reduced by hydropower system operations (Parsley and Beckman 1994). Beamesderfer and others (1995) evaluated the population dynamics of white sturgeon in lower river impoundments and concluded that potential yield from impounded populations was reduced by the installation of mainstem dams.

The lesson for Mekong development planners and resource managers is that we can expect these types of impacts from low-head dams to also occur in the Mekong, along with possible changes in productivity patterns when tropical rivers are impounded (Jackson and Marmulla 2001). Dams can have substantial effects on fish populations and fisheries, and understanding their potential impacts is an important aspect of seeking a balance among opposing demands and the best environmental, economic, and social outcomes for the Mekong region. Baseline studies and monitoring programs will have to be implemented in the Mekong to assess impacts to fish from river development over time, and disentangle any hydropower impacts from other impacts such as climate change and pressures from human population growth and urban development.

Greater Impacts on Migratory Fish from Mainstem Versus Tributary Development

The decision to not dam the mainstem Fraser River likely allowed natural production to largely sustain the viability and productivity of most salmon populations.

Thus, our broad-scale review led us to conclude that in general, impacts are greater from mainstem dams compared to tributary dams.

However, there are many qualifiers and caveats to such a broad conclusion. First, tributary dams in the Columbia largely blocked access to spawning grounds and extirpated many populations dependent on these habitats, and our assessment was conducted long after these dams were built. Second, the impacts of tributary dams are more local in nature compared to those of mainstem dams and can be significant. As described above, the Sunbeam Dam constructed in 1910 in Idaho likely had a significant and negative effect on sockeye returning to natal lakes above the dam, from which wild stocks never recovered and where only one adult passed Lower Granite Dam (Fig. 4) in 1990 (WDFW and ODFW 2010).

However, the overriding lesson from the Fraser-Columbia comparison for Mekong River development planners is that effects from mainstem dams are likely to be greater than from tributary dams because of how migratory fish differentially use various habitats available to them in large river systems. This is especially likely to be the case in the Mekong River because effective upstream and downstream passage systems at dams for the large and taxonomically varied number of species have not been developed. Based on first principles, and given the relatively low exchange of fish between the upper Mekong system and those downstream, we concluded that dams located higher in a basin would result in fewer impacts to the total assemblage of migratory fish species compared to those lower in the system. This suggests that dams located in the middle and lower LMB (central Lao PDR, Cambodia and Vietnam) will have a comparatively larger impact on fish production and fisheries than dams in the upper LMB (northern Lao PDR) due to species being more diverse and abundant in flood plain areas located on the lower LMB (MRC 2010). However, we recognize that localized impacts will occur from dams located in the numerous Mekong tributaries and in the Chinese section of the river.

A strategic environmental assessment taking into account all economic, environmental, and social considerations to indicate the point along the mainstem where dams should be built is being conducted by the Mekong River Commission (http://www.mrcmekong.org). Such as assessment should also consider the need for some tributaries to remain undammed to retain connectivity among key river components, allow successful spawning and recruitment of keystone migratory species, and conserve fish diversity.

Multiple, Adaptive Approaches are Needed to Manage Migratory Fish Resources Impacted by Mainstem Dams

Mitigation of the effects of mainstem dams on Columbia River fish resources has relied on multiple engineering solutions. These include structures to safely pass fish migrating upstream and downstream at dams, water stored in flood-control reservoirs that is used to increase river flow and simulate freshets to aid fish migrations and manage mainstem water temperatures, and artificial propagation to mitigate for lost habitat and dam passage mortality. The Columbia River experience indicates that it can take 40 years to develop solutions to impacts from mainstem dams, even when the research infrastructure, funding, and political support are present to do so.

Fish passage systems designed for salmon cannot simply be pulled off the shelf and expected to work in a multitude of other situations because each system has to be designed for a specific site and hydraulic conditions, fish species, and life stages present. For example, Moser and others (2005) reported passage rates of 50% for Pacific lamprey attempting to migrate past dams using ladders designed for salmon, compared to rates of >90% for the salmon. Furthermore, simply installing fish passage facilities does not guarantee that fish passage impacts will be reversed. This is because facilities must be evaluated to ensure they meet performance criteria, modified after construction if needed, and maintained properly (Porcher and Travade 2002).

These findings have important implications for the Mekong, where little information exists on fish behaviour and the biological performance criteria needed to design fish passage facilities at barriers have yet to be developed. This will require years of laboratory studies, field research, the engineering of potential designs, and likely a trial-and-error approach to testing their effectiveness. The fact that the Mekong has nearly 30 times the number of species (Table 1) and approximately 100 times the biomass of rivers in North America (Dugan 2008) only compounds the challenge of designing successful systems. Since design guidelines may differ greatly among species (Oldani and Baigun 2002; Haro and others 2004), a variety of facilities that operate simultaneously may be needed to address fish passage in river systems with high biodiversity. Facilities will also need to accommodate the scale of fish migrations in the Mekong where tens of different species are migrating simultaneously and in numbers often exceeding millions of fish per day (Baran and others 2005; Halls and Paxton in press).

In the Mekong, significant amounts of flow at dams should be dedicated to fish passage facilities to ensure their effectiveness, based on a need to increase flow volume to overcome design uncertainty (many species are poor swimmers and successful design criteria for many does not exist). However, use of large flow volumes for fish passage facilities may be difficult during the dry season when shortages may lead to conflicting demands for water. In the absence of detailed information, Thorncraft and Harris (2000) identified a general guideline whereby 10% of dry season flow should be allocated to fish passage facilities. We note, however, that in the Columbia River basin, from 25 to 35% spill at dams is typically required to attain good passage conditions for fish migrating downstream.

The Columbia River experience also suggests that mainstem dams must be operated for fish passage during fish migration periods to achieve high levels of fish protection. In other words, once dams are installed, they become integral components of fish migration corridors, and power operations need to be integrated with fish requirements to maintain fisheries. However, as pointed out by Williams (2008), technological fixes in the Columbia River have not fully restored migratory conditions to levels under which salmon evolved, and while they may keep salmon stocks from going extinct, they are not likely to provide complete mitigation for freshwater ecosystems altered by water resource development.

The Ability of Salmon to Negotiate Upstream Fish Passage Facilities is Comparatively Greater Than That of Tropical Species

The swimming capabilities of fishes vary greatly among species with differing body form, size, and muscle structure (Wardle 1975; Videler 1993). Within the same species, swimming ability varies according to life stage (juvenile or adult) and with environmental conditions such as water temperature and dissolved oxygen (Videler 1993).

Adult salmon are extremely strong swimmers, capable of leaping falls and weirs and swimming at burst speeds of 8 m s^{-1} (Bell 1991). When encountering migration obstacles, salmon repeatedly search for openings to pass the obstruction, adult fish ladders at mainstem Columbia River dams were designed based on this knowledge and required few modifications. This allowed adults to pass dams, complete their spawning migrations, and populations to be maintained. Had the adult systems not been installed during dam construction or had they performed poorly, the decline in stocks would have been rapid and many additional populations would have been lost.

In general, most freshwater fishes do not have the burst, sustained, or cruising capabilities of salmon nor their ability to leap over small falls and obstructions. Consequently, fish passage facilities that work well for salmonids will not necessarily be suitable for fish with lesser swimming capabilities and cannot be assumed to work for all the species in tropical rivers. Indeed, Oldani and others (1998) observed that fish passage efficiency past dams was quite low (<2% for all species) in South America's Paraná River and inadequate to maintain fish populations.

To be successful, effective fish passage systems used at Mekong dams will need to be considered integral design components and operated from the time the reservoir behind the dam is first filled. Given the diversity of Mekong fish species and a lack of information on migration behaviours, we speculate that developing fish passage requirements for representative (umbrella) species will aid the conservation of other co-occurring species (Fleishman and others 2000).

Use of Artificial Production

Hatchery-produced fish play a major role in sustaining overall abundance and in-river fisheries in the Columbia River. Techniques to artificially rear juvenile salmon had been in use for 60 years when the first federal mainstem dam became operational in 1938, and research on these techniques continues today. However, reliance on these measures comes with a cost. Today, US$130 M is spent each year to operate the 178 hatchery programs in the Columbia basin (pers. Commun., Rob Walton, NOAA Fisheries). Perhaps more importantly, the effects of hatchery practices on maintaining genetic diversity, fitness, population structure, and the ecology of wild salmon are still generally unknown (Fraser 2008). This leads us to assume that it could take decades to develop successful artificial production techniques for the numerous Mekong species. Even if technically feasible, it is difficult to envisage that the long-term funding and political support needed for stocking programs would be made available in developing countries on the scale necessary to compensate for the potential loss of wild fisheries resources.

High-Head Versus Low-Head Dams

At this time we cannot inform the question of whether low-head or high-head dams might present a better option for reducing impacts to Mekong fish, given the information available. As discussed above, most salmon passage facilities have been designed to pass fish around low-head dams. An expert panel assessment, utilising experience from Europe, Asia, Australia and North and South America, reviewed the information available in the Mekong. The panel concluded it was unlikely that fish passage technologies would successfully provide safe routes for the many migratory species and the large biomasses attempting to pass the low-head dams planned for the Mekong's mainstem (Dugan and others 2010). However, it is equally questionable whether mitigation strategies currently being designed and tested for salmon at high-head dams would perform in a tropical system such as the Mekong.

Colonization After a Passage Barrier is Removed

One issue facing resource managers is the rate of recolonization once a barrier to fish migrations has been removed, and whether barrier removal is a viable restoration alternative if other mitigation alternatives fail. Dam removal is becoming increasingly common in North America to restore ecological process and reopen access to spawning and rearing habitat for migratory fish (Gregory and others 2002), but little is known about actual colonization rates. Pess (2009) developed a model to determine when populations of pink salmon became self-sustaining after new passage facilities open a long-term migration blockage at Hell's Gate in the Fraser River. This analysis was based on spawning data from 1947 to 1987 from 66 streams. He concluded that decades were required to develop self-sustaining populations of this species, even with the generally favorable conditions that existed in the Fraser where pink salmon had a large source population below Hell's Gate to colonize from. Other advantages favoring this recolonization were high intrinsic growth rates linked to favorable climate-driven conditions (i.e., ocean productivity), a constant supply of dispersers, and large amounts of newly available habitat. It is hard to say whether similar time frames would be required for colonization to occur if passage facilities were retrofitted to Mekong dams that blocked migrations, or dams were removed due to their impacts to fish abundance and fisheries. However, we suggest it may make take at least as long as Pess (2009) estimated for pink salmon in the Fraser, given the generally favorable conditions under which their recolonization took place.

Conclusions

Our review of four high-level indicators of trends in Fraser and Columbia salmon abundance and composition indicated that impacts to fish productivity and fisheries from large-scale water resource development can be substantial. In river basins such as the Mekong where fisheries play a prominent role in national economies and rural livelihoods, considering alternative options before proceeding with development of mainstem dams is critical. Because the knowledge needed to design, install, and operate fish mitigation facilities at dams in the Mekong region does not exist, additional monitoring and research on the biological requirements of key migratory species is needed. Hopefully, such efforts will be undertaken soon to help retain the long-term ecological integrity of one of the world's most important rivers, and reduce impacts to the world's largest inland fishery and a critical source of food and income to millions of people in the region.

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