Dam removal as a management strategy for fisheries recovery: lessons from the Elwha River nearshore and implications for Formosa land-locked salmon

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Large dams have been a component of human engineering for over 5,000 years. Today? There are over 57,000 large dams world-wide (Lehner *et al*., 2011; Zarfl *et al*., 2015). China holds 19,000 large dams, the largest number in the world. The United States has the second highest number, at around 10,000 (Graf, 1999; Poff and Hart, 2002). As the large dams of the world age, large-scale dam removal is becoming a more frequent restoration action (Ho *et al*., 2017). Watersheds that hold large dams often have important connections to coastal systems. The relationships between large-scale dams, their removal, and the nearshore ecosystem function are critical to understand, but often not considered in ecosystem restoration planning for large scale dam removal. Through a decade's worth of collaborative field-work along the nearshore of the largest dam removal in the world, the Elwha River (Fig. 1), we define fish use response to large-scale dam removal.

The Elwha drift cell is approximately 20 km long and includes a number of land-forms including: lower river, estuary/delta, embayed shorelines, feeder bluffs, and spit (Shaffer *et al*., 2012; Fig. 2, Table 1). Over the course of dam removals, upwards of 20 million cubic meters of sediment was released, of which 60% was predicted to reach the coastal system within 5 years of dam removal. The Elwha dam removal began in September 2011 and concluded in September 2014. As of 2016, 95% of the sediment predicted to be delivered to coastal systems had arrived (Randle *et al*., 1996; Foley *et al*., 2017).

Four main shifts occurred in the nearshore as a direct result of dam removals: 1. Large volumes of sediment were delivered to the delta/estuary/shoreline in a short period (Fig. 3). However, sediment deposition along the sediment-starved shoreline continued to be disrupted due to remaining shoreline armoring, disrupting ecosystem restoration (Lee *et al*., 2018); 2. New delta and estuary habitats were formed very rapidly (Fig. 3). As of September 2015, approximately 2.6x106 m3 of sediment material has resulted in over 35 ha of new delta habitat, and increased the total area of the Elwha delta to over 150 ha (Shaffer *et al*., 2017a; Fig. 3); 3. Along the delta and lower river, there was an almost immediate shift in original habitats from tidally influenced to non-tidally influenced habitats, resulting in changes in resident fish communities (Shaffer *et al*., 2017b, Foley *et al*., 2017); 4. Despite being a sediment-starved system, restoration along most of the Elwha nearshore was only partially due to remaining impediments including lower river dikes and shoreline armoring (Parks *et al*., 2013; Parks, 2015; Shaffer *et al.,* 2009; Shaffer *et al*., 2017a).

Long-term study of fish in the estuary revealed varied fish community response to dam removal. While species richness and taxonomic diversity do not appear to have a significant response to dam removal, functional diversity in the nearshore does respond significantly, if briefly, to dam removal (Shaffer *et al*., 2018). Changes in functional diversity occur disproportionately in the new habitats, which have more unstable, and therefore less resilient, communities. Functional diversity in the original estuary sites appears to be more resilient than in the newly created sites due to the large-scale environmental disruption that, ironically, created the new sites. Further, functional diversity at the newly formed nearshore areas is predicted to stabilize as the habitats are vegetated and mature.

Despite large-scale changes to the delta of the Elwha, the community composition in the Elwha estuary continues to be defined by hatcheries that mask other community responses. Of particular concern is the interaction in the nearshore between hatchery and wild fish, including chum salmon (*Oncorhynchus keta*) critical to watershed recovery (Shaffer *et al*., 2017a; Fig. 4). The lesson? Hatchery and recovery goals should be analyzed critically to assure the most effective and timely watershed recovery intended with large-scale dam removals.

Nearshore habitats are critical for many forage fish species, and they are an important ecosystem component for large-scale dam removals. Along the Elwha drift cell, surf smelt (*Hypomesus pretiosus*) and Pacific sand lance (*Ammodytes personatus*) are two species of forage fish that spawn along intertidal reaches of very specific grain size beaches. This function is disrupted due to sediment starvation associated with a combination of large-scale dams and armoring of feeder bluffs (Parks *et al*., 2013; Parks, 2015; Wefferling, 2015). Forage fish spawning response to dam removal appears to be complex and may be related to multiple factors including high inter-annual variability in physical habitat conditions, geographic factors and complex life histories of forage fish (Shaffer *et al*. in prep). Habitat suitability for forage fish spawning appears to be increasing with ecosystem process restoration and habitat creation, maturation and stabilisation, indicating that time may be an important factor in nearshore restoration for forage fish spawning (Shaffer *et al*. in prep).

Over a decade of work has revealed that coastal restoration associated with large-scale dam removals occurs at a drift cell scale, and so must be considered at this scale (Shaffer *et al*., 2012). Given the size and diversity of landforms within the Elwha drift cell, response to sediment delivery to each of these differs in space and time, and is defined by distance from the river mouth, hydrodynamics of the shoreline, and remaining alterations that disrupt sediment and hydrologic processes.

In a watershed, ecosystem restoration associated with large-scale dam removals can take decades (Anderson and Hoffman, 2017). While some elements of nearshore restoration can occur immediately, others take longer, or do not occur at all due to remaining ecosystem impediments. It is therefore important, as part of the restoration process, to plan for decades long monitoring and to ensure that nearshore ecosystem function for multiple life history stages of nearshore species, including forage fish, are incorporated as critical ecosystem habitat components.

Finally, large-scale dam removals are expensive. Elwha dam removals (just the dam removal) cost over US$300 million. This does not include monitoring costs. For the nearshore, this partial funding has left much of the high priority nearshore ecosystem restoration and monitoring undone. Based on this result, it is therefore far better fiscally and ecologically to conserve intact ecosystems, and when possible, to restore at an ecosystem scale.

Implications of dam removal for Formosa landlocked salmon

Formosa landlocked salmon (*Oncorhynchus formosanus*, "FLS") have relatives in Japan but became landlocked in Taiwan as sea level rose (Behnke *et al.,* 1962). Erosion control dams have been built in the last remaining habitat of FLS that have restricted movement among populations and potentially inhibited the founding of new populations (Makiguchi *et al*., 2009). Because of their declining population size and narrow distribution, the species is listed as critically endangered in the IUCN Red Book (Koteelat, 1996). More recently some of these dams have been breached. This management tool has had diverse consequences for the FLS population. Dam destruction has also promoted the upstream movement of another native fish species, the shovelmouth minnow, *Onychostoma* (=*Varicorhinus*) *barbalatum*, which compete with FLS for space but not diet (Tsao *et al*., 1996; Liao *et al*., 2012).

Four dams were demolished on Kaoshan Stream, a southern tributary of the Chichiawan Stream, in 2001. Modeling results suggest that population growth rates increased (and became positive) in Kaoshan Stream after 2001; census observations corroborated this result showing increased numbers of juveniles, subadaults and adults after dam destruction (Chung *et al*., 2007). However, riverbanks were steeper and river velocity increased compared to before dam removal, leading to elevated erosion (Chung *et al*., 2008). Such erosion is exacerbated during typhoons, that are common in Taiwan, and cause widespread flooding. Salmon are thought to be forced downstream during flood events where they experience higher water temperatures, faster current velocities, reduced insect densities, higher turbidities, and smaller-grained less preferred sediment, all leading to inferior habitat (Chang *et al*., 2017). Poor FLS breeding years appear to be related to flooding during these typhoons, and explain why models suggest density-independent control and importance of substrate variance to FLS abundance (Chung *et al*., 2007, 2008; Hsu *et al*., 2010). In 2004 another dam (#2) on the mainstem Chichiawan Stream was destroyed by a typhoon and in 2011, dam #1 downstream from dam #2 was removed before the flood season. Results of a BACI experiment started before removal of dam #1 and finalized in 2013 showed that the insect community was resilient to the flow fluctuations, recovering within a year after dam removal, that *O. barbalatum* increased in abundance and moved upstream where they had not been reported before the dam removal, and that salmon numbers were unchanged (Chang *et al.,* 2017) but displaced individuals were able to migrate back to their home range after the flood (Chen, 2012). Further dam removals are planned. It is recommended that before that happens, detailed work should be performed on the interaction between salmon and minnows and, if necessary, upstream dams be breached next to reduce further movement of *O. barbalatum* (Hasegawa, this issue).

There are various lessons concerning dam removal that apply to both the Elwha River and Chichiawan Stream. First, as illustrated in both situations, dam removals are essentially sediment projects. In the Elwha, sediment transport and deposition has led to many changes in the ecosystem including formation of new nearshore habitat. In the Chichiawan Stream, erosion has led to declining habitat quality for FLS. Second, responses to dam removal can be rapid as illustrated by changes in habitat and the biotic community in 1–3 years post-removal. Finally, it is important to follow a BACI approach so that such changes can be documented, and to ensure that adaptive management plans can be developed and implemented early in the planning process.

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Figure 1 Elwha watershed and two large-scale dams removed 2011-2014.

Figure 2 Elwha drift cell with landforms

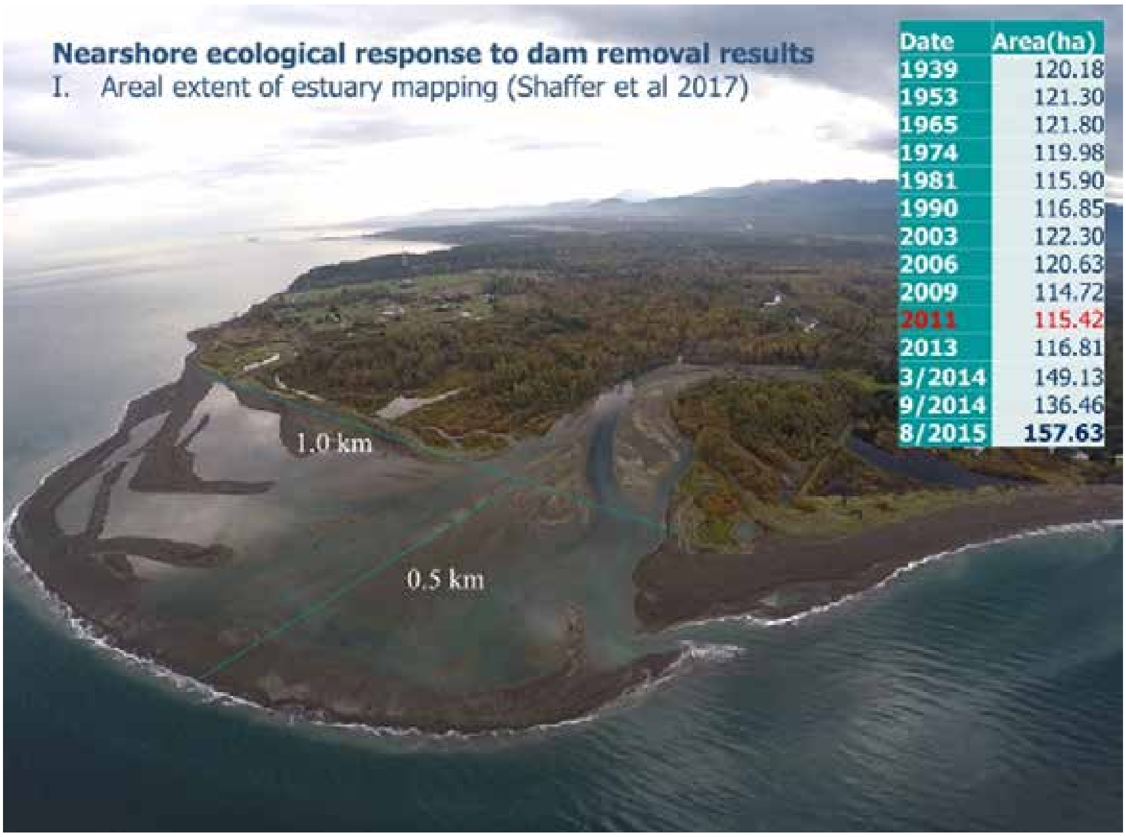

Figure 3 Elwha delta growth (reprinted with permission Shaffer et al. 2017b)

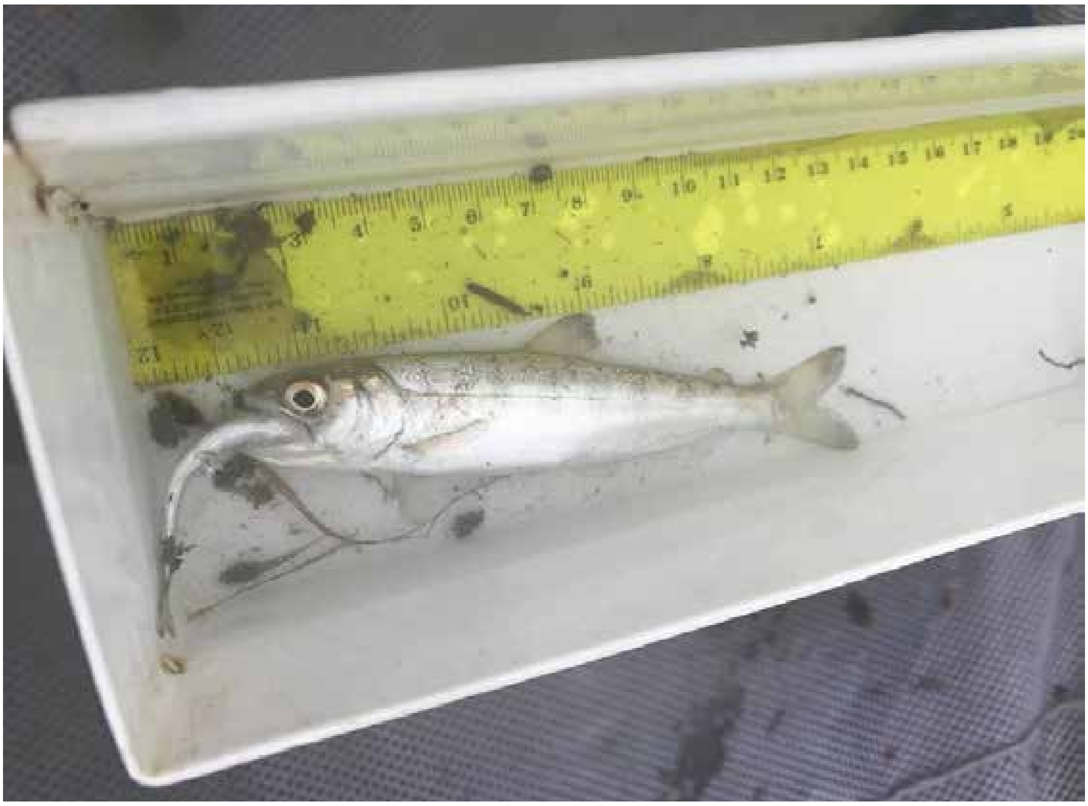

Figure 4 Hatchery coho salmon eating wild outmigrating chum salmon, Elwha estuary May 2017 (photo by Breyanna Waldsmith, Coastal Watershed Institute)

Table 1 Elwha drift cell by landform post dam removal.

Landform	Length (km)	Area (ha)
Lower river	0.8	
Estuary (post dam removal)	1.2	158
Embayed Shoreline	7	
Feeder bluffs	6	
Spit	5	
Total	**20**	

Table 2 Hatchery role in defining the percent composition of salmonid species in the Elwha system (Shaffer *et al*. 2017a)

	Prior to dam installation (Ward et al. 2008)	2008-2015 (Shaffer *et al*. 2017a)	
	River	Released from hatcheries	Estuary
Chinook (O. *tshawytscha*)	5%	78%	78%
Coho (*O. kisutch*)	8%	13%	13%
Chum (*O. keta*)	13%	1%	1%
Pink (*O. gorbuscha*)	66%	0%	0%
Sockeye (*O. nerka*)	4%	0%	0%
Steelhead (*O. mykiss*)	4%	5%	5%
Bull trout (*Salvelinus confluentus*)	1%	0%	0%

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