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# The impact of dam removal and climate change on the abundance of the Formosan landlocked salmon

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A B S T R A C T

The Wuling basin in central Taiwan is the last refuge of the critically endangered Formosan landlocked salmon *Oncorhynchus masou formosanus*, but the habitat has been degraded by human interference, including agricultural practices and dam construction. Four check dams were removed in Kaoshan Stream between 1999 and 2001 to help restore the natural habitat, and we construct an age-structured stochastic simulation model to quantify the effect of this dam removal on salmon abundance. Typhoons are an important factor in the population dynamics, and the presence of dams may augment the mortality associated with typhoons. We define an annual typhoon score that measures the impact of typhoons on salmon survival. We found that habitat restoration resulting from dam removal is a more significant factor than the creation of upstream passage in increasing survival and that juveniles receive the largest benefit. The model predicts that the salmon in Kaoshan Stream would have disappeared by 2007 if the dams had not been removed, indicating that dam removal was effective in increasing abundance. To project the model forward 20 years, we use historical data to forecast future typhoon scores. The model projects that after dam removal, the salmon population will stabilize just below 400 by 2018, which indicates growth from the most recent observed value of 262 in 2014. We then modify the forecasted typhoon scores to include anticipated increases in typhoon intensity associated with climate change. All of these scenarios result in a downward rather than stable trend in abundance, with larger increases in the typhoon score associated with faster rates of decline in the population. However, the population remains above 100 over the next 20 years even in scenarios with high typhoon scores. The model suggests that dam removal reversed the salmon population decline, but the anticipated increase in rain intensity associated with climate change poses a future threat to the salmon.



## 1. Introduction

Dams are known to cause deterioration to river channels and often lead to decreased diversity of species (Hart and Poff, 2002). In recent decades, dam removal has become a more frequent strategy for restoring natural stream habitats. Taiwan has many short and steep rivers in the high mountains, where strong rainfall results in high water velocity, and there were over 3000 check dams constructed in Taiwan by 1999 (Chang et al., 1999), with the primary purpose of preventing the collapse of riverbanks and reducing sediment transport to lower elevations (Tsao, 1995).

Chichiawan Stream and its tributaries in the Wuling basin in central Taiwan are the last refuge of the critically endangered Formosan landlocked salmon *Oncorhynchus masou formosanus*. This habitat has been degraded by dam establishment and agricultural development, which are thought to be key factors in the decline in the abundance and range of the Formosan salmon after the 1960s (Tsao et al., 1998). The Formosan salmon population declined to about 200 individuals by 1984, at which time the Taiwanese government listed it as an endangered species (Lin et al., 1987). Abundance has increased since this time, ranging between 1000 and 5500 since 2005 in the entire Wuling basin, but there is continued concern for maintaining a stable population. There were 11 check dams in the Wuling basin in 2000, covering a length of less than 10 km (Tsao and Lin, 2000; Yan, 2000), and these dams did not

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allow upstream passage to the salmon. The salmon have adapted to an environment characterized by typhoons, but these dams have disturbed the salmon's habitat and have thus decreased its resilience. Dam removal is believed to increase salmon abundance (Chung et al., 2007), but the mechanism of this impact is uncertain. For instance, dams prevent salmon from returning upstream after being flushed downstream by typhoons, and dam removal has potential to increase survival by allowing salmon to return upstream. The presence of dams also affects the habitat quality, for example sediment buildup that reduces the availability of large boulders which offer shelter during typhoons (Lin et al., 2005; Chung et al., 2008). Segmentation is another example of habitat degradation created by dams, resulting in reproductive isolation.

Conservation of the Formosan salmon has received more attention since it received endangered status, and Shei-Pa National Park started monitoring the salmon population in 1994 (Yan, 2000). The park removed five check dams between 1995 and 2011 as a salmon conservation effort. A previous study (Chung et al., 2007) used matrix modeling to conclude that the salmon growth rate in Kaoshan Stream changed from negative to positive after dam removal, while remaining negative in Chichiawan Stream where dams remained intact at this time. We use simulation modeling to further quantify the effectiveness of dam removal in Kaoshan Stream, taking into account possible impacts from climate change. We compare predicted population trends between scenarios with and without dam removal, including the effect of anticipated changes in precipitation intensity. We also investigate whether the creation of upstream passage or habitat restoration is the primary mechanism by which dam removal increases salmon abundance. This type of modeling and analysis has potential application to other streams where dam removal is being considered for habitat restoration.

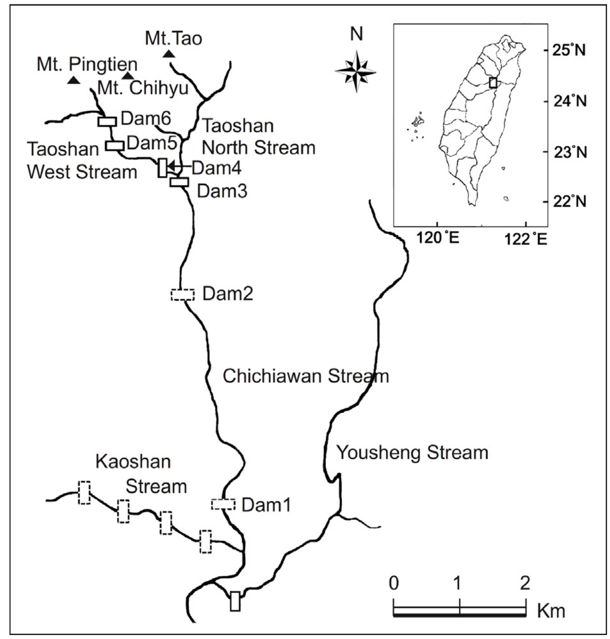


**Fig. 1.** Wuling basin in Shei-Pa National Park. Dams that have been removed are sketched in dashed lines. Dam 1 was removed in 2011, and dam 2 was destroyed by a typhoon in 2004. The four check dams in Kaoshan Stream were partially removed between 1999 and 2001.

## 2. Methods

### 2.1. Study area

Kaoshan Stream (24°21′ ~ 24°31′N, 121°20′ ~ 121°35′E) is a third-order stream in the Wuling basin in Shei-Pa National Park in central Taiwan and is a tributary of Chichiawan Stream on an upstream reach of the Dajia River (Fig. 1). At an elevation of about 1700–1800 m, it is considered to have a high mountain subtropical climate, with stream temperatures normally below 15 °C. The mean gradient is 0.028–0.087 and the stream width ranges from 2.5–19 m (Chung et al., 2008). Typhoons affect this region annually between June and October, causing stream discharges to increase during summer and fall. Four check dams were constructed in this stream in the 1970s, and all four dams were partially removed between 1999 and 2001 to allow passage to salmon (Lin et al., 2004). The catchment area consists of natural forests and is less affected by agriculture than the neighboring streams (Yu and Lin, 2009), making this stream a good candidate for analyzing the effect of dams on salmon abundance in isolation from other types of human interference. The total number of salmon was counted by snorkeling two times each year (summer and early winter) from 1995 to 2014 (Tzeng, 2005), and we used only the early winter data for an annual count taken during the same season each year. However, data were unable to be collected during the early winter in 2007 and 2008 due to flood conditions. The early winter population ranged between 24 and 310 before dam removal (1995–2001), and it has ranged between 100 and 1032 after dam removal (2002–2014) (Fig. 2). The data reported the abundance in three groups, classified by length: juveniles (0–15 cm), subadults (15–25 cm), and adults (>25 cm).

We devised an age-structured model by sex, with demographic and environmental stochasticity, to investigate the effect of the presence and the partial removal of dams on the abundance of

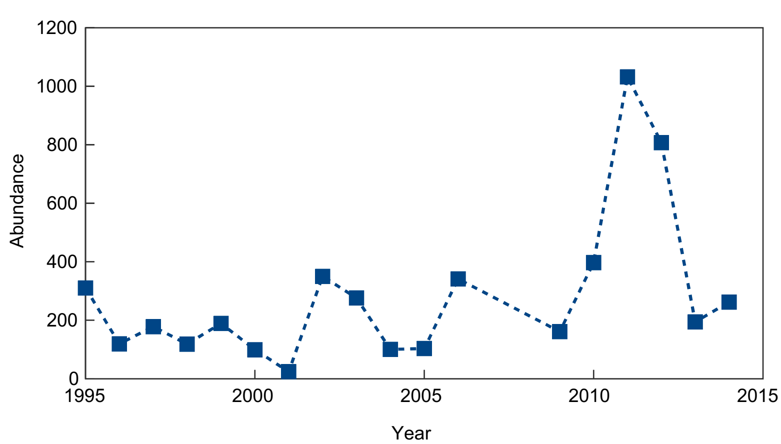


**Fig. 2.** Observed total salmon abundance in Kaoshan Stream. The population was declining before the dam removal (2001) and has exhibited some growth afterwards.