Evaluation of the Habitat for Downstream Migration of Chum Salmon in the Wusuli River Using a Suitability Index

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An animal's habitat is its dwelling place and contains a combination of biotic and abiotic environmental factors and resources that an animal depends on to maintain normal life (Chen and Gao 1992; Yan and Chen 1998). Water reductions and deterioration of ecological functions in aquatic habitats lead to discontinuity of spatial distribution within the ecosystem. This exerts direct impact on species' behavior, population size, and survival (Young et al. 1991). Developed from theories on animal habitat selection, ecological niche differentiation, and restriction factors, the Habitat Suitability Index (HSI) is a tool used to evaluate habitat by constructing functional relationships. The HSI model and the Instream Flow Incremental Methodology (IFIM) when used together can help scientists determine the condition of salmon habitat (Duker 1977; Kaeriyama et al. 1978).

Chum salmon *(Oncorhychus keta)* is a unique species in the North Pacific, and they can migrate over 3,000 km in their river migrations as juveniles and adults (Liu et al. 2010a). Chum salmon is an important ecological environmental indicator, and it is of high scientific and economic value (Bakkala 1970). The migrations of salmon connect the fresh water, estuary, and ocean ecosystems of the North Pacific, which integrates the food chain of water, land, and air (Helle 1979).

The Heilongjiang and Wusuli rivers are major tributaries of the Amur River. The Heilongjiang River and the Wusuli River and its tributaries contain important spawning sites for chum salmon (Liu et al. 2010b; Tang et al. 2010). The Wusuli River is located (43°06′-48°17′N, 129°10′-137°53E) between China and Russia: China is westward of the main channel centerline and Russia is eastwards of it (Fig. 1). The Wusuli River is 905 km long with a main stem of 492 km. The main tributaries include the Muling, Abuqin, and Naoli Rivers located in China, and the Yiman, Bijin, Heluo (Huoer) Rivers located in Russia. The Wusuli River watershed size is 187,000 km^2, of which 61,500 km^2 is located in China. The Wusuli River basin encompasses more than 170 small and large tributaries, most of which are supplied mainly by rain and snow. The upper river and midstream areas pass through the longitudinal valley between China's Wanda Mountain and Russia's Sichote-Alin Mountain and it flows onto a flood-plain mire and wetland. Normal water depth is 2-5 m. There is an average of 148 days of freeze-up in most years and maximum ice thickness is 1.15 m. Date of ice break-up on the river was April 20 in 2010 and April 15 in 2011. There is adequate water in spring with the supplement of abundant snow melt, and water temperature is relatively low. China has established the National Nature Reserve of Heilongjiang Treasure Island, the Naoli River, the Sanjiang Wetland, and the Provincial Nature Reserve of Wusuli. These reserves have completely enclosed the original wetland ecosystem on the Sanjiang plain. These natural reserves have been placed on the "List of International Important Wetlands".

China began successful artificial propagation of chum salmon in the Haiqing section of Wusuli River in the 1950s and established a chum salmon breeding station in Raohe County. Chum salmon habitat now faces deterioration from a variety of both natural and artificial impacts, including climate warming, pollution, vegetation and wetland reduction, decreasing water supply, shrinkage of chum distribution, blockage of fish migration, deterioration of spawning sites, and overfishing. These factors have endangered the species in this area. Because microsatellite analysis of chum salmon genetic diversity in the Heilongjiang River indicates stock declines are not caused by genetic factors, there is a possibility of rebuilding the stock (Chen et al. 2004). However, it is uncertain whether the ecological environment in the river is recoverable to the point of producing chum salmon.

We evaluated the Wusuli River for its suitability as a downstream migration corridor for chum salmon. We used the HSI and IFIM in our study to help us find feasible suggestions for ecological protection and to provide a scientific basis of achieving chum salmon population recovery. Our study area included the Hutou, Raohe, and Haiqing sections of the Wusuli River (Fig. 1). These sites were selected because of their historical importance as chum salmon spawning and migration sites.

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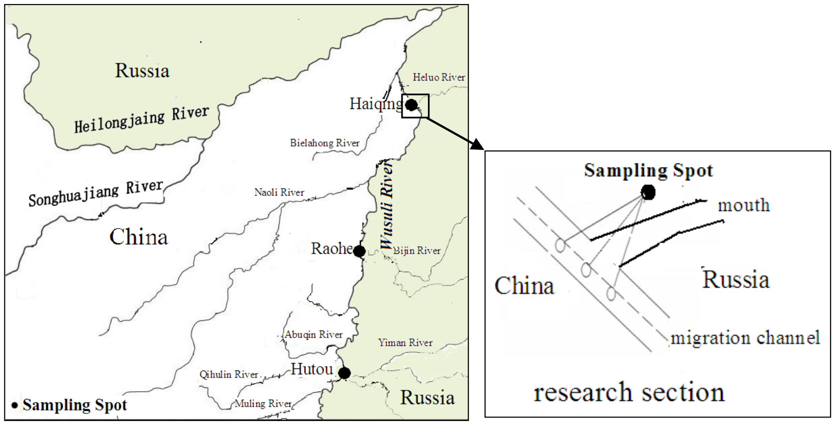

Fig. 1. Map of the region of the Wusuli River with inset showing sampling locations.

Three replicate sampling stations were located in the junction of the Wusuli River and three other rivers: Heluo River, Bijin River, and Yiman River (Fig. 1). Stations were situated about 30-50 m above or below the river mouth along the main stem for a total of nine sampling stations. We collected samples continuously for 10 days from the last third of April to the beginning of May 2010, which is during the time period of downstream chum salmon migration. Temperature, dissolved oxygen (DO), pH value, transparency (SD), substrate, depth, and flow velocity data were collected at 30-50 cm water depth. Alkalinity (Alk), hardness (TH), NH_4^+, NO_2^-, COD (chemical oxygen demand), and plankton samples were collected and brought to the laboratory for determination by national standard methodologies. The comprehensive pollution index method using pH, COD, DO, NH_4^+, TN (total nitrogenous-compounds), and TP (total phospho-compounds) were measured according to surface water and environmental quality grading standards. Plankton diversity was based on the evaluation standard for aquatic organism in rivers and reservoirs using the Shannon-Wiener index. Values presented for each section are averages of the three stations.

The HSI for chum salmon downstream migration in relation to water temperature and DO are shown in Fig. 2-1 and 2-2 and results from model conditions for water temperature, flow velocity, depth and substrate for chum salmon during downstream migration are shown in Figs. 2-3 through 2-6. The minimum HSI value by factor was determined to be the final HSI value at each sampling site. The critical values used to evaluate the HSI and IFIM habitat were the same. The habitat was suitable for downstream migration of chum salmon if 0.8 ≤ HSI or IFIM ≤ 1; habitat was less suitable if 0.6 ≤ HSI or IFIM < 0.8; habitat was marginally suitable if 0.4 ≤ HSI or IFIM <0.6; and habitat was not suitable for chum salmon migration if HSI or IFIM <0.4.

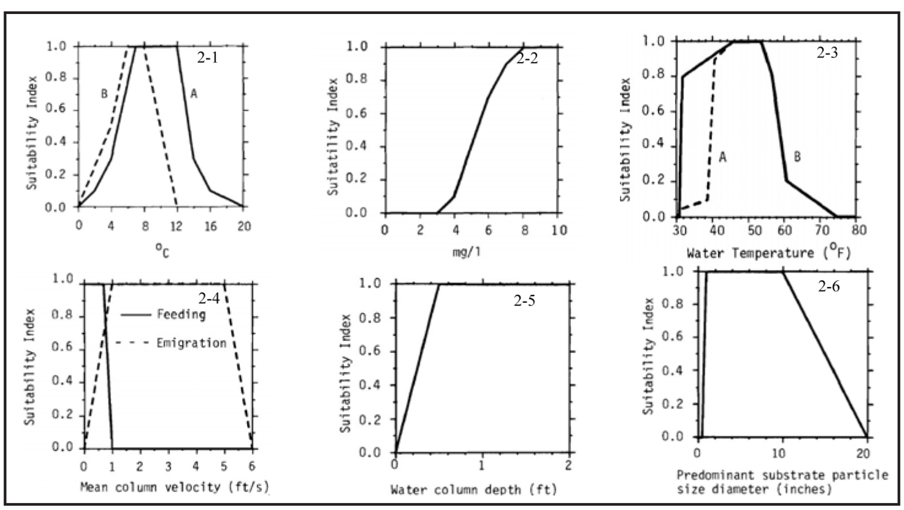

Fig. 2. Temperature, DO, substrate particle size, velocity, and water column depth in relation to the HSI. Fig. 2-1: solid line A is the highest temperature during the day and dotted line B is the lowest temperature. Fig. 2-3: solid line is the downstream migration model, and dotted line is the feeding model. Fig. 2-4: solid line is feeding period, and dotted line is condition in the downstream migration channel.

Table 1. Summary of the HSI values with respect to temperature and DO for evaluation of downstream migration habitat of chum salmon in the Wusuli River.

Survey section	Temperature		HSI of T°	DO (mg/l)	HSI of DO	HSI
	high	low				
Hutou	7.5	6.4	1.0	8.9	1	1.0
Raohe	6.5	5.6	0.9	9.0	1	0.9
Haiqing	6.2	5.4	0.85	9.1	1	0.85

According to our results, water temperature HSI values were 0.85-1.0 and dissolved oxygen HSI values were 1.0 (Table 1). Water temperature at the survey sections ranged from 6.2 to 7.5°C. Water temperature and DO in the Hutou, Raohe, and Haiqing sections declined one by one. These three sections are distributed from upstream to downstream and from south to north, which follows the geographical law of hydrology, weather, and climate. Based on the minimum HSI value of temperature and DO, we concluded the HSI of the three Wusuli River sections (Haiqing, Raohe and Hutou, values 0.85, 0.9 and 1.0, respectively) demonstrated the Wusuli River main stem was suitable habitat for chum salmon downstream migration.

Table 2. Results of the IFIM model for quality of the habitat for downstream migration of chum salmon. Vel is water velocity; Depth is water depth; Sub is substrate particle size diameter; T is water temperature.

Survey section	Vel ($m \cdot s^{-1}$)	IFIM of Vel	Depth (m)	IFIM of Depth	Sub (cm)	IFIM of Sub	T (°C)	IFIM of T	IFIM
Hutou	0.6	1	7	1	2	0.8	7.5	1	0.8
Raohe	0.7	1	8	1	3	1	6.5	0.95	0.95
Haiqing	0.7	1	8	1	2.5	0.99	6.2	0.93	0.93

The IFIM values ranged from 0.93 to 1.0; flow velocity ranged from 0.6- to 0.7 $m \cdot s^{-1}$ and all IFIM of velocity values were 1.0 (Table 2). Water depths ranged from 7 to 8 m, and all IFIM of depth values were 1.0. Substrate particle diameters ranged from 2.5 to 3 cm and IFIM of substrate values ranged from 0.8 to 1.0. Results reveal the minimum IFIM of the Hutou section was 0.8, the Raohe section was 0.95, and the Haiqing section was 0.93. These results showed all sections studied were suitable habitat for downstream migration of chum salmon.

Table. 3. Results of water quality analysis to evaluate the habitat for downstream migration of chum salmon. SD is transparency; Alk is alkalinity; TH is water hardness, COD is chemical oxygen demand, TN is total nitrogenous compounds, and TP is total phospho-compounds.

Survey station	SD （m）	Alk mg/L	TH $CaCO_3$mg/L	pH	COD mg/L	NH_4^+ mg/L	NO_2^- mg/L	TN mg/L	TP mg/L
Hutou	0.8	0.32	8.9	7.5	7.9	0.0089	0.0003	0.24	0.053
Raohe	0.8	0.26	0.51	7.8	7.8	0.0075	0.0003	0.22	0.013
Haiqing	1.2	0.44	0.84	7.8	8.3	0.1	0.0002	0.25	0.041

Analysis of water quality variables, NH_4^+, NO_2^-, TN (total nitrogenous compounds), and TP (total phospho-compounds), indicated values were within the normal range for downstream migration of chum salmon (Table 3). Input of these parameters into the comprehensive pollution index indicated that the Hutou, Raohe, and Haiqing sections were all lightly polluted, but could satisfy water quality standards for migrating salmon. Water hardness (TH) values varied widely from 0.51 to 8.9 mg/L. The Hutou section had the highest relative hardness, which may be caused by the large amount of calcium carbonate brought into Wusuli River during snow melt. The COD was high and ranged from 7.8 to 8.3. These high values were related to the unique regional environment in Northeast China.

The average density of plankton in each sampling section varied widely. Results showed the average diatom density was 78.01% of total phytoplankton. The Shannon-Wiener index for phytoplankton was 1.033. The water quality was determined to be moderately polluted according to the evaluation standard of aquatic organisms in rivers. Zooplankton was dense in the spring, averaging about 89.9% of total plankton. There were 23 zooplankton species observed at each section including four types of protozoa, 14 rotifers, three cladocerans, two copepods, and some larval forms. Rotifers were the most abundant zooplankton species. The Shannon-Wiener index for zooplankton was 1.51. The water quality was determined to be as slightly polluted according to the evaluation standard of aquatic organisms in reservoirs. The high density of zooplankton in spring could provide prey for juvenile chum salmon during their downstream migration.

Strong chum salmon runs are beneficial to human society because healthy chum salmon stocks facilitate social and economic development. Our results showed the Wusuli River and its tributaries have suitable habitat for chum salmon downstream migration. Therefore, it is necessary to insist on prioritizing protection of their habitat.

Forest and wetlands can maintain supply of water to rivers in the dry season and maintain water quantity and depth, a necessity for normal downstream migration. Increasing protection of surrounding forest and wetlands and returning land located along the river into these habitat types will reduce sedimentation in rivers and improve environmental quality. Flushing of sediment from farms and bare land into the river can cause deterioration of salmon habitat. Projects, such as dredging, dam construction, sand excavation, and stone removal, cause serious damage to water quality and substrate by making the river turbid and causing sludge to accumulate on the river bottom. Sludge in key sections of the Wusuli River should be removed to reveal the gravel substrate and give chum salmon a suitable environment for spawning. It is also necessary to supervise and manage the pollution along the river so domestic sewage and plant effluent enter the river only after treatment.

Basic habitat conditions need to be restored in order to reconstruct it for the salmon community. It is necessary to increase efforts to protect and manage the ecological environment of the Wusuli River basin by focusing on prevention and supervision. Such efforts should include strict control of key regions along the river, management planning, and developing scientific approaches to utilize water and forest resources that protect the ecological balance. Furthermore, relevant departments should increase technical investments to protect vegetation and wetland areas along the Wusuli River and its tributaries in order to return natural harmony to the river.

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