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Review Article

SWIMMING PERFORMANCE OF *Schizothorax sp.* AND PLANNING OF FISH PASSAGES IN NEPAL

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ABSTRACT
Swimming performance of migrating fish is crucial for the planning and design of effective fish passages. Commonly the fish swimming speeds are classified into five categories: 1) Optimum Swimming Speed, 2) Maximum Sustained Swimming Speed, 3) Critical Swimming Speed, 4) Maximum Domed Swimming Speed, and 5) Burst Swimming Speed. Swimming characteristics are related to the different species' adaptions to the environmental conditions. A variety of different factors affect the swimming capacity of fish which is directly related to fish size and species-specific morphology. A crucial abiotic factor is water temperature, which affects the fish physiology and thereby the swimming speed of the fish. This means that the fish's swimming speed can increase with increased water temperature. The swimming speed also increases with fish size. Fish often use burst speeds when passing a step in a fish ladder or entering a culvert. Burst speed is the highest speed attainable for fish, and it is the maximum energy output to be gained by using the white muscle (red muscle in salmonids). The burst speed can only be maintained for short periods of time (seconds). In the Himalayas, the main objective of many fisheries development plans is to secure future habitats and ensure up- and downstream migration of fish. *Schizothorax richardsonii* is often a targeted species in the area due to its importance as a food resource. If a fish passage is prepared for the upstream migration of fish, it is also crucial for the fish population development to ensure a safe downstream passage. Data on swimming performance for many of the native fish species in Nepal are scarce which complicates the design of suitable ecologically adapted fishways. In general, nature-like fish passes allow most of the species to migrate, followed by vertical slot fishways, meander fishways, and thereafter fish ladders of the pool-and-weir type. The key factor is to construct fish-passes that under all naturally required environmental circumstances can allow appropriate passage conditions of the targeted fish species.

Keywords: Fish passage, *Schizothorax*, swimming performance

INTRODUCTION
Along the Himalayas, there are many waterways that form the habitat of a species of fish commonly named snow trout, which is an important species for various fishing activities. The name may refer to various species with different local names within the native genus *Schizothorax* sp. In a literature review by Rufford (2015), the species *S. richardsonii* is described to be found both in Nepal and India, often inhabiting the cold mountain rivers at altitudes up to 2800 masl (meter above sea level) according to FAO (2002). Fish sizes of up to a maximum length of 60 cm have been reported from Nepal at this high altitude (Jha, 2006).

The species inhabits mountain streams and rivers of about 4–20 °C, where the adults generally prefer to live among rocks at stream depths of around 1–2 m (Rufford, 2015; Froese & Pauly, 2016). Adult fish have powerful muscular streamlined bodies and the spawning of mature fish (common sizes of 120–350 mm) might happen twice a year during spring an early monsoon, and during autumn or late monsoon (Shekhar *et al*., 1993). Koshi *et al.* (2016) say that spawning also may take place twice in a year from June-October and January-March. These documentations point to a species with high flexibility and good adaptability to local ecological conditions.

With reference to the Gandaki River system, the *S. richardsonii* zone is between 850 m to 2810 m above sea level, while the *S. progastus* zone is between 300 m and 850 m above sea level (Rufford, 2015). In the technical paper of FAO (2002), it is stated that in the lower S. *progastus* zone, the *S. richardsonii* will gradually be replaced by *S. progastus*. This difference in habitat selection seems to point at that *S. progastus* might be a species adapted to higher water temperatures than *S. richardsonii*. It is yet not known if the swimming characteristics of these species are different.

Although *S. richardsonii* is widely spread along the Himalayan, observations over the last 5-10 years indicate a severe decline of the populations in many areas, and the species is now categorized under the "vulnerable category" (IUCN, 2010). Aashna *et al.* (2020) point to global warming as an important factor in the decline of the populations and that this cold-water species will suffer habitat loss due to increased water temperatures. A factor that possibly might slow down the negative temperature effect is that the species might expand their range upwards into even more high-altitude streams.

General considerations on fish swimming speeds

Commonly the fish swimming speeds are classified into five categories: 1) Optimum Swimming Speed, 2) Maximum Sustained Swimming Speed, 3) Critical Swimming Speed, 4) Maximum Domed Swimming Speed, and 5) Burst Swimming Speed (references in Gui *et al.* 2014). The maximum speed of fish (Burst), is an anaerobic process and can be sustained only for periods of around 15-20 seconds, related to fish size and water temperature. Fish often use burst speeds when passing a waterfall, a step in a fish ladder, or passing into a culvert. Burst speed is the highest speed attainable (Fig. 1), and it is the maximum energy output by using the white muscle (red muscle in salmonids). As stated by Gui *et al.* (2014) the Burst Swimming Speed (BSS) can be estimated to an upper limit of 10 body lengths per second (BL/s) for many fish species. Yet the BSS depends on the duration of the performed burst, which declines exponentially with time and increases with size in absolute units (cm/s) but decreases in relative units (BL/s). Temperature affects the fish physiology and thereby the swimming speed of the fish. Li *et al.* (2022) found that *Schizothorax prenanti*, a cold-water species, living in similar habitats as *Schizothorax richardsonii*, showed a maximum burst speed of 3.49 m/s.

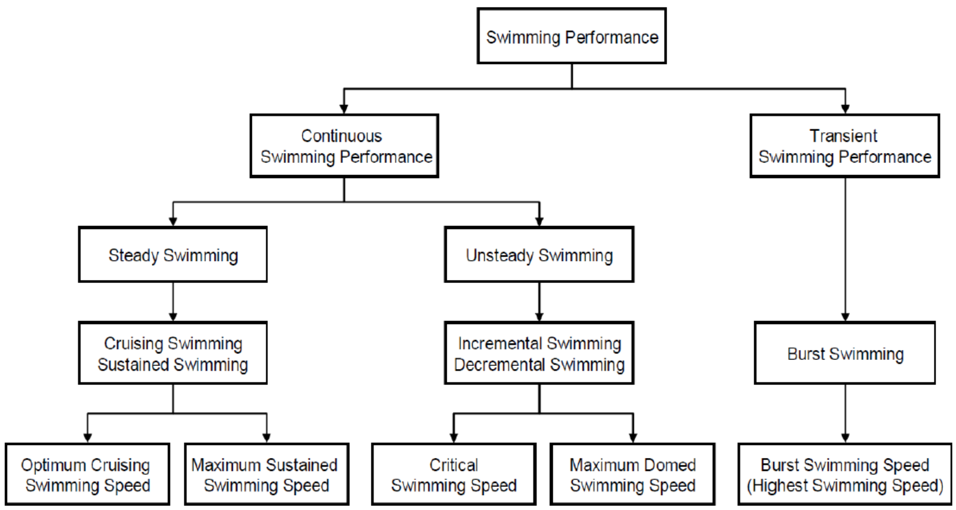

Figure 1. Various modes of fish swimming as presented by Gui *et al.* (2014).

The swimming speed of fish depends on: 1) the characteristics of the species, 2) the size of the fish, and 3) the ambient water temperature (Rodríguez *et al.*, 2006). Here various graphs have been developed and are widely used to support reliable fish-pass designs. As demonstrated for salmonids (Fig. 2), these describe the maximum swimming velocities of different sizes of fish at different water temperatures, all in relation to the maximum time that a fish can maintain the actual velocities (see Rodríguez *et al.*, 2006). Based on empirical data the estimated maximum distances (Dmax) swimmable against currents of different velocities for fish of various sizes have been estimated for salmon (*Salmo salar*) and brown trout (*Salmo trutta*) as follows:

$$D_{max} = \max\{(v - u)t, 0\}$$

where Dmax is the maximum distance swimmable (m), v the maximum swimming velocity (m/s), u the flow velocity (m/s), and t is the time over which v can be maintained (s). As demonstrated by Fig. 3 these graphs may be applied in fishway designs since fish in the passes generally only need to swim short distances against fast currents. Given the estimates of fish swimming capability (Fig. 3) the next step is to relate the curves to water velocities and energy profile in the fishway (for details see Rodríguez *et al.*, 2006).

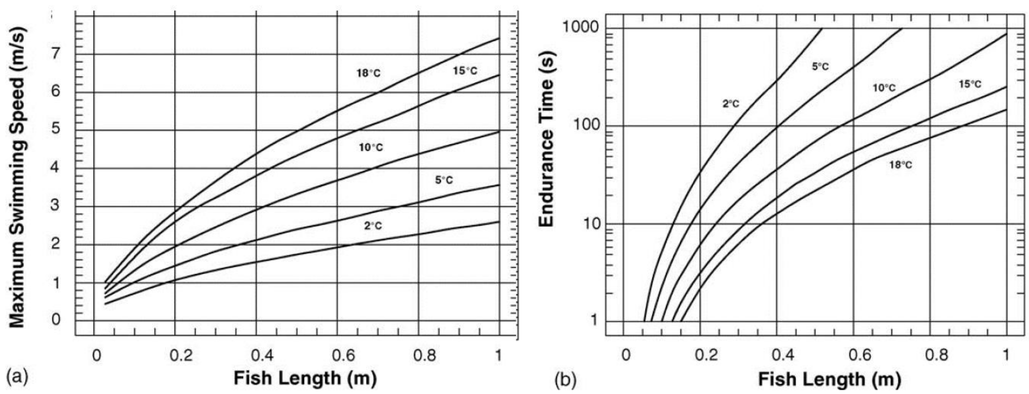

Figure 2. Graphs for salmonids a) maximum swimming velocity v compared to fish length and b) maximum endurance time for which v can be maintained (also compared to fish length), in both cases at different temperatures (modified from Rodríguez *et al.* 2006).

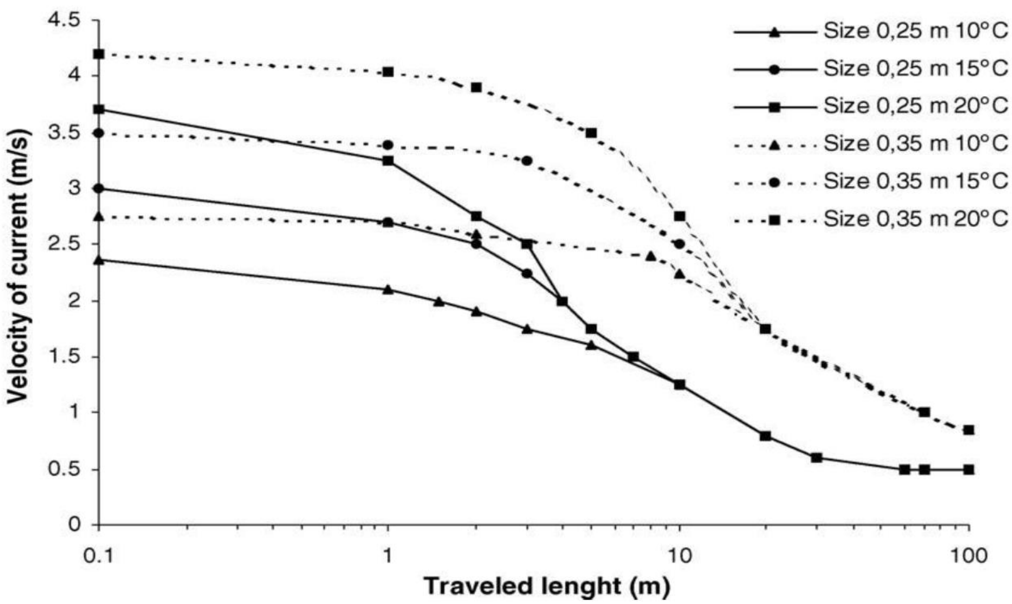

Figure 3. Illustration of maximum swimmable distance (Dmax, m) compared to different water velocities, for 25- and 35-cm fish, at a water temperature of 10, 15 or 20 °C (from Rodríguez *et al.* 2006).

Swimming performance of *Schizothorax sp.* and resembling species

The adult *Schizothorax sp.* in the Himalayas have powerful muscular streamlined bodies and generally dwell in rapid and high volumes of water. Studies have demonstrated that Cyprinids living in these types of rapid-flow habitats generally have adapted to a higher swimming speed than fish originating from lentic areas: In total, there are currently 64 recognized species in the *Schizothorax sp.* genus (Rufford, 2015) of which the swimming capability of most of the species has not been studied. The detailed data that was found in various reports are listed below.

Interspecific variation in hypoxia tolerance, swimming performance, and plasticity in cyprinids that prefer different habitats

Fu *et al.* (2014) quantified and compared hypoxia tolerance and swimming performance among cyprinid fish species from rapid-, slow- and intermediate-flow habitats (four species per habitat) in China. The data demonstrated that Cyprinids living in rapid-flow habitats generally have higher swimming performance than fish originating from lentic areas. This was expressed as maximum velocities where fish can maintain their position and are not swept downstream, abbreviation U crit-values. Critical swimming speed (U crit) for juvenile *S. prenanti* (85 mm in length) was found to be around 6-7 body lengths (BL)/s. Li *et al.* 2022 found that *S. prenati* showed a burst speed of 3.49m/s. *S. prenanti* is a cold water species with a streamlined body living in rapid flow habitats similar to *S. richardsonii* and it seems reasonable that the swimming performance also might be closely related, but there are so far no available comparative studies done.

Effect of temperature on swimming performance of juvenile *Schizothorax prenanti*

Cai *et al.* (2014) estimated the swimming performance of *S. prenanti* at four temperatures (15, 19, 23, and 27 °C), and numerical models were used to characterize the effect of temperature on swimming performance. As temperature increases, critical swimming speed (U crit) increases from 15 to 23 °C and then decreases significantly. The highest U crit (around 7.7 BL/s) was at 24 °C. Swimming efficiency was similar from 19 to 23 °C but decreased significantly at 27 °C. The results of the investigation advance the knowledge of fish metabolism while swimming and provide data critical for fishway design.

Aerobic swimming performance of juvenile *Schizothorax chongi* (Pisces, Cyprinidae) in the Yalong River, southwestern China

Tu *et al.* (2010) studied *Schizothorax chongi* which is found in the rapid stream of southwestern China and relies on energy reserves to carry out its upriver spawning migration. Energy-saving behavior may thus be crucial for upriver migrants at difficult passages and be valuable for designing effective fishways. Their bioenergetic model (fish of body length c. 10-13 cm and body mass from 14 to 36 g) demonstrated an optimal swimming speed (U opt) of 5.5 BL/s, whereas, at the highest velocities usually > 9-10 BL/s, the swimming became less steady and darting bursts were used to maintain position, causing rapid movement forward in the flume before resuming continuous swimming. The authors conclude that fishway design must take into account the kinematics of fish swimming ability in terms of swim pattern including tail beat frequency (TBF) and tail beat amplitude (TBA). This means that the minimal slot width (in the vertical slot fishway), should be calculated for the largest individuals of *S. chongi* (60 cm) and thus not be less than 60 cm x TBAmax. Since the authors found TBAmax to be around 0.27 BL/s this means that a fishway for the species should have slot widths of a minimum of 16 cm, yet the authors mention the need for further research to support the design of effective and comprehensive fishways.

Evaluation of the swimming ability of wild-caught *Onychostoma barbatula* (Cyprinidae) and applications to fishway design for rapid streams in Taiwan.

Lin *et al.* (2008) evaluated the swimming of *Onychostoma barbatula*, a migratory Cyprinid found in mountain rivers of Taiwan, to obtain data that may be applied to the design fishways. They found that swimming speed increased progressively to 13 BL/s at 16 °C for the studied fish of total body length from 5 to 21 cm. They stated that for these small fish, a suitable fishway should have a minimal slot width of 9 cm (for individual fish) and a maximal water velocity of c. 1.27 m/s.

Swimming capability of *Schizothorax oconnori*

Ye *et al.* (2013) tested the swimming of the endemic species *Schizothorax oconnori* in the Yarlung Zangbo River. The results showed that the absolute critical swimming speed increased with the body length and the relationship was Y1=-39.369+13.23X-0.371X2+0.004X3(Y1 was cruising swimming speed, X was body length), while the relative critical swimming speed declined with the increase of body length. Absolute burst swimming speed increased with the increase of body length and the relation was approximately linearity, but the relative burst swimming speed declined with the increase of body length. Under three tested velocities the sustained swimming speed of the fish was 60 cm/s, while the endurance swimming speeds were 80 cm/s and 100 cm/s. The authors claim that the information can be useful for fishway designs.

General concerns in fisheries management projects at regulated river sites

In general, both large and small scale, run of the river, hydropower schemes have a resembling impact on the local river environment (Rivinoja *et al.*, 2010). It is well known that most studies in regulated rivers have focused on how the longitudinal connectivity affects the migrations of fish which involves up- and downstream movements along river corridors. To maintain river connectivity fishways can be constructed. Nevertheless, relatively few studies have evaluated their efficiencies and only a handful have looked at the overall effect of re-establishing or maintaining the connectivity. Furthermore, just facilitating longitudinal connectivity will not have any long-term effects, unless essential requirements for affected species and life stages are considered. For fish, this should include appropriate habitats for spawning, rearing, and foraging (Jha, 2006). The flow alterations occurring in regulated rivers may stress the aquatic fauna and cause limited amounts of appropriate habitats. The effects of hydropower on the biota are likely to vary depending on construction type and specific river environment. Still, knowledge of the ecodynamic situation in regulated rivers seems rather scarce.

At present a variety of fishways exist. Common bypasses for upstream migrating fish consist of technical ladders, which are normally: 1) Pool and weir, 2) Denil slot, 3) Vertical slot, and 4) Meander fishways (Helbig *et al.*, 2021), and the type of design that are the nature-like bypasses. In river ecosystems with many fish species, it is favorable that the fish-pass designs are adapted to the weakest swimmers in the run, or if one target species is selected, the hydraulic conditions in the fish passage shall be adapted to the ecological situation that statistically requires the lowest burst speed of the target species. The effectivity of the fish passage should aim to pass more than 95% of the adult upstream migrants safely and rapidly (see Rivinoja *et al.*, 2010).

Mature upstream migrating adult fish generally search for the highest flows, and as a result passage problems can arise due to low attraction flows in bypasses which might hinder fish if they are attracted towards impassable routes from turbine outlets or dams rather than to bypasses. Delays at power stations may be considerable in terms of increased energy costs, which may lead to lowered reproductive fitness during spawning. For fishways to function properly not only must the fish be able to find the fishway (attraction efficiency), but they must also be able to successfully ascend it (passage efficiency). To guide fish towards fishways is often complicated, especially when fish must leave the main stem of the river. In many cases, and particularly in larger rivers, channels and dewatered sections are associated with low residual flow conditions and may have partial obstacles, that may cause the fish to move slowly or even stop and return downstream (see Rivinoja, 2005). When the fishway is situated in the main stem, close to a power station, the design of the fishway entrance and its position in relation to the tail-race is crucial for the effect of the fish path.

In the Himalayas, the main objective of many fishery development plans is to retain the habitat availability of migrating fish and to ensure the up- and downstream migrations of the targeted species, especially *S. richardsonii* that is an important food resource.

An important prerequisite for a fish ladder to work is that the water velocities in the fish ladder steps are lower than the burst speed for the targeted species in question and that between the steps there are areas with low speeds that give the fish a possibility to rest. It is also important that fish ladders are designed with a view to functioning in the entire temperature range when fish migrate within the river. The design of a fish ladder for *S. richardsonii* in Trisuli in Nepal has assumed maximum water speeds in the fish ladder steps of about 1m/s (Kaasa 2018), which is about 1/3 of the estimated burst speed for *S. prenati* (a maximum of 3.49 m/s), that live in similar river habitats as *S. richardsonii.*

CONCLUSIONS

Data on swimming performance for many of the native fish species in Nepal are scarce which complicates the design of suitable ecologically adapted (eco-adapted) fishways. In general, nature-like fish passes allow most of the naturally occurring species to migrate, followed by vertical slot fishways, meander-type fishways, and thereafter fish ladders of pool-and-weir types. The key is to construct fish ladders that give hydraulic conditions in the fish ladder that are adapted to the available energy output that the target species can perform under the actual ecological conditions. A good starting point is to look at the burst speed for the migratory species in question, for instance, *S. richardsonii*, and that the requirement to pass the fish ladder steps is less than the burst speed. In the fish ladder, there must also be resting opportunities for fish between the more demanding steps. The design assessments of a fish ladder for *S. richardsonii* should also include function during the entire temperature interval during the migration period.

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AUTHOR CONTRIBUTIONS

The authors have collaborated on the conceptualization, sought a knowledge base, and carried out validation of relevant literature, contributed with experiential knowledge from many years of work with the species in question, carried out writing and review of the text, as well as obtained funds to carry out the preparation of the article. The authors have read and consented to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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