ECOHYDRAULIC RESEARCH TO PROTECT DOWNSTREAM MIGRATING FISH AT HYDROPOWER AND OTHER RIVER INFRASTRUCTURE: SOLVING A GLOBAL PROBLEM THROUGH INTERNATIONAL COLLABORATION

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Freshwater fishes are among the most threatened vertebrates and population declines have huge implications, not only from a biodiversity perspective but also in terms of protein resources in developing countries. A major cause of fish population decline is water resource development, including the construction of dams, weirs, and hydropower facilities. Although fishways, which support upstream migrations, have historically been the primary consideration when mitigating the impact of hydropower and irrigation infrastructure, there is now a growing appreciation that many species require safe downstream passage at different life stages (including as egg, larvae, juveniles or adults). Fish passing downstream through these structures can be exposed to harmful hydraulic conditions, including rapid decompression, mechanical strike and elevated shear and turbulence. In recent decades, significant progress has been made in understanding these impacts on migrating salmonids in North America, with the goal of optimising the design and operation of hydropower to improve fish survival. However, the problem is global and many of the world's largest and most diverse freshwater fisheries (e.g. Mekong and Amazon Basins) currently threatened by the expansion of hydropower, remain unstudied. In other areas (e.g. Murray-Darling Basin) small-scale hydropower operations are being explored on existing irrigation networks, with limited understanding of the potential impact. In this presentation we outline the state of the science in ecohydraulic research which is being used to meet this global challenge through international collaboration. Techniques include the use of autonomous sensor technology to quantify hydraulic conditions,

migration studies to determine likelihood of exposure, and laboratory studies into hydraulic stress to determine operational ranges required to minimise injury and mortality.

1 GLOBAL WATER RESOURCE DEVELOPMENT AND FISHERIES SUSTAINABILITY

River infrastructure, including dams, weirs, and hydropower facilities, alter river flows, degrade habitat, and disrupt both upstream and downstream fish migrations [1]. Infrastructure can create a complete barrier to fish migration, or selectively injure or kill fish as they pass downstream [2]. One of the greatest threats to fish in many parts of the world is the rapid expansion of hydropower development [3]. About 20% of the world's electricity is generated by hydropower [4] and it is becoming the fastest growing renewable energy source, especially in areas such as South East Asia, Brazil, and Africa [5]. In Brazil, hydropower generation is projected to increase by 38%, and to achieve this, 48 hydropower dams are proposed for construction by 2020 [6]. The total estimated hydropower potential of the Lower Mekong River basin is 30 GW, and currently 14 mainstem dams are planned for the Mekong River and hundreds (if not thousands) of smaller facilities are being considered for tributary streams and floodplain wetlands on low head (<6 m) structures. In countries like Australia, where new large-dam hydropower projects are less likely to be constructed, opportunities are frequently being explored to install small-scale (typically less than 10 MW) hydropower facilities at existing irrigation weirs [7, 8].

Although water resource and hydropower developments have economic and livelihood benefits, they can have damaging social and environmental impacts. Mitigating these impacts can be costly if they are not considered early in the development process. For instance, in the Columbia River in the USA, more than US$7B has been spent retrospectively on efforts to save large migrations of iconic salmonids. Whilst this has helped save salmonids from extinction, there is still a reliance on hatchery production through much of its natural range. Dams in Brazil are likely to threaten fish diversity within the Amazon Basin (which has the most biodiverse fisheries resources in the world, with 20% of the world's freshwater fishes, representing about 1,400 species). The Mekong River basin has the second most biodiverse fish fauna in the world and the Lower Mekong (encompassing, Cambodia, Laos, Thailand and Vietnam) supports the world's largest inland fishery; worth between US$4.3 and $7.8 billion annually [9]. In this region, fish and other aquatic organisms account for 47%–80% of total animal protein consumed [10]. There is clearly an environmental, social and economic imperative to ensure that current and future water resource development (including hydropower) does not further compromise the global sustainability of fish populations.

2 INTERNATIONAL ECOHYDRAULIC RESEARCH TO PROTECT DOWNSTREAM MIGRATING FISH

Fish protection at river infrastructure is a global problem and therefore requires a global solution. Major investment in ecohydraulic research will be needed to promote innovations in the design and operation of weirs, dams and hydropower technology if current fisheries losses throughout the world are to be abated. Researchers across North and South America, Europe, South East Asia and Australia, have begun an international collaborative effort to expand our understanding beyond juvenile salmonids to other species, life stages, and river systems. This international cooperative effort is being driven by a desire to reduce global replication and redundancy in ecohydraulic research and is underpinned by the use of state-of-the-art technologies.

2.1 Sensing what fish 'feel'

Fish need only a fraction of a second to pass downstream through a weir, dam or hydropower turbine. But, even this short time can be dangerous, and is sometimes fatal. Until recently, it has been difficult to determine what was responsible for this injury, making it difficult to find a solution. 'Sensor Fish' technology [11], developed in North America, has been giving scientists insight into the conditions fish experience during downstream passage through river infrastructure [12, 13]. Sensor Fish are electronic devices that can be sent downstream through a dam, weir or hydropower turbine or other passage routes to collect data about the stresses that real fish experience. The sensors contained within the 'fish' measure the speed and rotation that a fish undertakes in all directions, as well as changes in temperature and water pressure.

The collected data can reveal whether fish are exposed to extreme stress when passing river infrastructure and whether better designs could be employed. Damage to fish when passing hydro facilities can occur due to:

rapid drops in water pressure, also known as decompression; high shear stress, which occurs when water masses travelling at differing speeds and in different directions intersect, and collision with hard surfaces such as turbine blades, weir gates and concrete pylons. Scientists are using Sensor Fish data to better understand the conditions faced by downstream migrating fish at structures and to guide laboratory experiments aimed at determining safe conditions for migrating fish.

2.2 Laboratory studies to determine critical ecohydraulic thresholds

Rapid and extreme drop in water pressure (decompression) is one factor that can cause injury or death as fish pass downstream through infrastructure. For example, pressure drops through hydropower turbines have been observed equivalent to a fish being shot from sea level to above Mount Everest in less than one second [14]. Injury resulting from rapid decompression is called barotrauma and has the potential to eventually kill fish. Injuries can include: rupture of the swim bladder; eyes becoming dislodged from their sockets; bleeding from internal organs and blood vessels; and gas bubbles becoming trapped internally and in vital organs such as the eye, heart, gills and fins - referred to as emphysema. Barotrauma can result from over-expansion of the swim bladder. This occurs because as the surrounding pressure falls, the volume of gas in the swim bladder rises. Another suspected cause is when dissolved gas comes out of blood and body fluids. This can happen because blood and other fluids cannot hold as much dissolved gas at lower pressures.

To help guard against barotrauma at river infrastructure, researchers need to determine what levels of decompression should not be exceeded in order to ensure fish safety. In a recent global review of barotrauma research [15], a systematic approach to achieving this was outlined. A review of the biology (e.g. swim bladder physiology), life history traits, and migratory needs of species in a region will help identify key species for investigation. Computational fluid dynamics modelling or direct field measurements using Sensor Fish are necessary to understand the degree of decompression that a fish may be exposed to [14, 13]. Direct observation of fish migratory behavior (e.g. using telemetry tags with depth/pressure sensors) are useful in establishing what depth fish are migrating prior to exposure (as this will affect the ratio of pressure change, and ultimately the level of injury sustained). With all this information at hand it is possible to expose fish (whether it be eggs, larvae, juveniles or adults) over a range of pressure changes that they may be exposed to in the field using specially-designed pressure chambers [16, 17]. Injury or mortality models can be generated from the data collected, allowing predictions of critical thresholds of decompression to be made.

A very similar systematic approach is relevant to understanding and mitigating the effects of fluid shear stress. After determining likely exposure levels of shear with the use of CFD modelling or sensor fish, fish can be exposed in the laboratory to different shear stress generated by a submerged jet of water in a flume [18, 17]. As with barotrauma, critical thresholds of shear can by determined by constructing injury and mortality models.

Fish entrained into turbines may experience blade strike injuries which can often be fatal. Similarly, a fish moving downstream through an irrigation regulator could strike the downstream apron, gate or dissipation sills when travelling at a high velocity. The likelihood for fish to experience strike is dependent on several factors, including water velocity, gate design, blade rotation speed, blade spacing, and fish length. The potential for exposure to strike at a structure can be determined in the field by interpreting acceleration, rotation and pressure data collected using sensor fish [19]. Mathematical modelling can also be used to predict the probability of strike, and a technique known as bio-indexing has proven successful in identifying operational ranges that can minimize blade strikes and maximize fish survival [20].

2.3 Field based verification

The laboratory methods explained above use a reductionist approach, where particular stressors are observed in isolation of each other. While this allows the mechanism for injury and specific thresholds of concern to be more accurately determined, it is clear that fish are never exposed to these hydraulic stresses in isolation (as evidenced by sensor fish recordings). There may therefore be merit in validating lab-based injury and mortality models in the field, at hydropower turbines or weirs to improve confidence in design and operational recommendations. Such studies can involve passing live fish through a structure at the same time as Sensor Fish. But caution must be exercised to ensure that fish are appropriately acclimated prior to passage, which can be difficult to achieve, and has been a flaw in previous field-based trials.

By identifying thresholds of different damage types separately, field based models can more easily be cross-referenced with predictions made in the laboratory.

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