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Critical review

Environmental and social aspects of underwater logging

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A B S T R A C T

Underwater logging is a relatively new concept in forestry that has significant economic benefits but also consequences for the environment and local communities. Underwater logging has traditionally been undertaken by divers. However, safety concerns mean that conventional harvesting methods using divers need to be replaced by more sophisticated mechanized harvesting techniques. This paper outlines the environmental and social aspects of underwater logging, highlighting issues that must be considered before any underwater harvesting operations are executed. While the economic reasons for harvesting underwater logs seem compelling, as do the associated social benefits, such as employment generation, there are significant environmental impacts of removing trees from reservoirs, as submerged trees serve as important ecological habitat for aquatic life. Due to the absence of any regulatory regimes encompassing underwater logging, we propose best-practice guidelines for underwater logging operations and suggest the need for a comprehensive sustainability framework based on internationally recognized criteria and indicators to ensure underwater logging operations are environmentally safe, socially beneficial and economically viable.

1. Introduction

Over the last 100 years, many countries have invested in hydroelectric power to meet their ever-increasing energy demands and, as a result, large tracts of forested land have been flooded by the creation of large dams developed for hydroelectric power (Tenenbaum, 2004). In many cases, trees were not removed prior to flooding. Lucas (2007) has argued that the time required to plan and build a dam, which is usually between two to five years, is shorter than the time required to harvest the large amounts of timber available in some of these forests, which explains why timber with considerable economic value is often flooded. In some countries, appropriate harvesting technology was unavailable at the time of dam construction, and in many cases, the tree species were considered undesirable and the loss was deemed acceptable. For example, in Tasmania, Australia, the site of Pieman Lake was opened up to forestry to avoid wasting the timber. However, the region's dense forest and inaccessible nature made logging difficult and by the time the area was ready to be flooded, only a small portion of the lake's footprint had been logged, resulting in the remaining forest being flooded. In Brazil, it is estimated that only 1% of the above-ground biomass was removed prior to the flooding of Tucuruí Lake (Fearnside, 1997), drowning a major timber resource.

The World Commission on Dams (2000) estimated that more than 45,000 large reservoirs were in place by the end of 20th century, many of which contained submerged forests. An example of a large reservoir containing a drowned forest is provided by the Nechako reservoir in northern British Columbia, constructed in 1952. After displacing First Nations people from their land, a private company reversed the flow of a river, creating a new lake estimated to contain 15 million trees (Randalls and Petrokofsky, 2014). Crockford (2008) has estimated the value of submerged forests globally to be approximately $50 billion, with new areas continuing to be flooded.

Underwater wood recovery is not a new phenomenon, and salvage loggers have for many decades recovered lost logs from lakes, rivers and major waterways. Salvage logging enterprises were particularly focused on the recovery of logs lost while being floated down rivers. These were mostly located in areas where there had been significant use of water-transportation by logging companies. Drowned logs, sunken trees, and wood from building demolition are all considered "rediscovered wood" and some argue that rediscovered wood could contribute to meeting international wood demand (Tenenbaum, 2004).

A more recent innovation is to harvest trees that have been flooded during dam construction, a process known as underwater logging. This generally takes place in still water. In some cases, the crowns of the trees remain above water whereas in others the entire tree is underwater. In all cases, the trees die but decay underwater can be slowed dramatically by the anaerobic environment. The interest in underwater harvesting comes from eliminating hazards to shipping and the untapped supply of high-valued species, such as old growth red cedar and tropical hardwoods (Milne et al., 2013). The potential of underwater

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Table 1
Important underwater logging operations in reservoirs around the world.

Country	Reservoir	Reservoir area	Year of logging operations	Reference
Canada	Lake Ootsa	890 km^2	1970	Klotz (1975)
USA	Lake Cushman	16.23 km^2	1991	McLean (1991)
Surinam	Lake Brokopondo	12,200 km^2	2004	BWWI (2017)
Brazil	Lake Tucurui	2247 km^2	1987	Fearnside (1997)
Panama	Lake Bayano	350 km^2	2010	Randalls and Petrokofsky (2014)
Ghana	Lake Volta	8502 km^2	2008	Fitzgerald (2008)
Australia	Lake Pieman	2653 km^2	2015	HydroWood (2017)
Malaysia	Lake Kenyir	260 km^2	1991	Loke et al. (1998)

logging has been recognized by a number of states across the world, and countries, such as Canada, the United States, Panama, Brazil, Australia, Ghana and Malaysia, have begun to exploit this resource (Table 1).

Proponents of underwater logging argue that the negative effects associated with deforestation could be reduced significantly through the harvesting of flooded timber resources (Lucas, 2007). However, in some cases, the human population displaced by the construction of the reservoir would have continued to clear forests in the inundated area had the reservoir not been created, and some logging activities may have been displaced to forests outside the submergence area (Fearnside, 1997).

Other advantages of underwater logging include the direct and indirect social and economic benefits, including improvement in lake transportation safety, recovery of the fibre value of an otherwise lost resource, and creation of jobs and training opportunities for local communities (Asare and Helmus, 2012). With continuing dam construction, especially in South-East Asia and Brazil, the amount of flooded forest is growing, increasing the number of potential underwater logging sites (Randalls and Petrokofsky, 2014).

The greatest potential downside to underwater logging is facing customers' concerns about how the wood is harvested in underwater logging projects (Greenemeier, 2005). While with terrestrial logging such concerns can be assuaged through third-party certification systems, increased social and environmental expectations point to a growing need for reservoir managers and owners to understand and address the challenges and opportunities posed by submerged forests. Underwater logging is not addressed in current forest management certification schemes. Despite underwater logging being an innovative industry with considerable social and environmental implications, it has received very little attention in the academic literature. Here, we summarize what is known about the environmental and social aspects of underwater logging. We examine the harvesting techniques that have been adopted, and use examples of various underwater logging projects in the world to shed light on its environmental and social aspects. Finally, we propose best-practice guidelines for underwater logging operations that could serve as a reference for operators in mitigating risks associated with underwater logging operations.

2. Harvesting methods

2.1. Commercial divers

The conventional way to extract submerged underwater logs has been to hire divers to operate chainsaws underwater. However, the method of using divers is both dangerous and expensive (Tenenbaum, 2004). Previous studies have reported Pulmonary Overinflation Syndrome in underwater loggers, which is a group of barotrauma-related diseases caused by the expansion of gas trapped in the lungs, or over pressurization of the lungs with subsequent overexpansion and rupture of the alveolar air sacs due to unsafe diving practices (Rozali et al., 2006). Although divers' certification is required for underwater loggers in North America and other Western countries, in many developing countries, including Panama and Malaysia, many industrial diving activities are unregulated and underwater loggers may have no prior diving training. Added to this, the use of faulty breathing equipment is not uncommon (Halim, 2004).

Underwater divers are also exposed to the risk of developing decompression illnesses (DCI), a condition that is developed from formation of bubbles in the tissues or circulation system as a result of inadequate elimination of inert gas (nitrogen) after a dive (Zin and Sulaiman, 2008). Although accurate figures are not available for the incidence of such problems with divers performing underwater logging; Loke et al. (1998) reported six cases of DCI in underwater loggers in Malaysia from March 1994 to August 1996, including two fatalities.

2.2. Mechanized underwater logging

One of the earliest attempts to salvage underwater logs from a reservoir took place in British Columbia in 1970 in Lake Ootsa, utilizing a self-propelled barge equipped with a grapple (Klotz, 1975). More recently, in an attempt to reduce the safety hazards to divers and related unsafe diving practices, Triton Logging, a Canadian entity, developed specialized machinery called the Sawfish to harvest underwater trees (Milne et al., 2013). The Sawfish harvester is designed to work entirely underwater. The Sawfish system uses air bags that are attached to submerged logs so that the log is brought to the surface after being cut. The sawfish uses biodegradable vegetable-oil-based hydraulic fluids to minimize water pollution during salvage operations (Tenenbaum, 2004).

3. Enviornmental and social aspects of underwater logging

3.1. Environmental aspects

Concerns have been raised about the environmental and social impacts of underwater logging projects. Although only a few studies have examined the habitat value of snags, the ecological importance of submerged logs and large woody debris (LWD) has been well-documented (Linohss et al., 2012; Shields et al., 2004). In natural environments, submerged logs are particularly important as habitat that forms the basis of aquatic food webs, especially where invertebrate diversity, abundance, biomass, and productivity are important (Linohss et al., 2012). LWD has been shown to enhance habitat and hydraulic complexity (Kaeser and Litts, 2008), to regulate fungal communities (Tsui et al., 2000), and to trap and retain organic matter (Raikow et al., 1995). In addition, it provides cover and refuges that reduce predation risks (Crook and Robertson, 1999), and in river channels, it mediates channel-forming processes, such as sediment transport and deposition (Montgomery and Piégay, 2003). Although most research literature shows that the routine clearance of wood from water courses is not consistent with maintenance of healthy aquatic ecosystems, within Europe LWD accumulations are generally seen as a river management problem and are routinely cleared from river channels (Piégay and Gurnell, 1997).

While the value of LWD in streams has been well-documented, the value in still water is less certain, particular at depth. Even less information is available for artificial situations, such as reservoirs that have not had much time to develop mature aquatic ecosystems. As a result, it is difficult to determine whether the information obtained from fluvial systems can be applied to the lacustrine environment, and some aspects are clearly different. Due to their value and the impacts associated with harvesting submerged trees, a permit is required in most countries before the recovery of submerged timber can proceed. However, once an underwater logging operator has secured the appropriate authorization from the government or resource owner, there