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Costs of Ecological Mitigation at Hydropower Plants

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2.1 Introduction

The costs of fish-related mitigation measures can play an important role in determining which measures are adopted, yet there is relatively little publicly available information about this aspect. While the majority of the literature focuses on environmental impacts and mitigation strategies, there have only been a few studies about costs. For example, Nieminen et al. (2017) reviewed general economic and policy considerations for mitigation measures facilitating fish migration. They outlined several suggestions for simultaneously improving sustainable hydropower production and supporting migratory fish, including shifting the emphasis from technology to environmental standards and considering multiple values of migratory fish (e.g. consumption, recreation, tourism, aquatic

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food webs and ecosystem functioning). Further, Venus et al. (2020a) estimated cost tradeoffs between fish passage migration and hydropower in over 300 European case studies. They found that nature-like fish passages tend to incur fewer overall costs and power losses than technical designs. Finally, Oladosu et al. (2021) compiled costs of mitigating environmental impacts in the United States and showed that environmental costs vary significantly by type of hydropower project and mitigation measure. They also found that smaller plants tend to spend a higher relative share of total project costs on environmental mitigation. While these studies have focused on the costs of individual measures in specific case studies, they do not provide a robust overview of the magnitude of costs across different types of mitigation measures. This chapter presents an overview of the range of costs of different mitigation measures to compare available costs and their magnitudes. Further, as many mitigation measures are adopted in combinations, this chapter presents costs from two FIThydro case studies to understand cost considerations under different mitigation combinations. These case studies demonstrate how costs might be compared when multiple mitigation measures are adopted.

2.2 Cost Ranges of Mitigation Measures

As costs differ based on site-specific characteristics, it can be difficult to compare the costs from different hydropower plants. To provide an overview for policymakers of the magnitude of costs associated with different measures, this section summarizes costs from different sources and presents an overview of ranges of costs based on the following types of mitigation measures. Costs were collected directly from hydropower operators and energy producers (Vattenfall, France Hydro Electricité), researchers via a questionnaire, peer-reviewed literature and reports published by state authorities. To cover a wide range of regions, data from different regions (Europe, North America, Australia) were included. All costs were converted to Euros using the average 2010–2019 exchange rate (0.82 for USD/EUR and 1.46 for AUD/EUR) and rounded to defined increments to give a general impression of the cost dimensions rather than the specific costs of case studies.[1] The results are presented in Table 2.1.

2.2.1 Costs of Environmental Flow Measures

Environmental flow (henceforth e-flow) measures incur costs related to the flow release itself and structures used to release flow. The cost of release depends on several factors, specifically where, when and how much flow is released. E-flows can be released to the

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[1] Minimum costs were rounded down and maximum costs were rounded up to the following increments: 1, 5, 10, 20, 50, 100, 150, 200, 500, 1000, 2000, 5000, 10,000, 150,000, 100,000, 1,000,000. If only one value is provided, the cost estimate is based on a single case study.

Table 2.1 Cost ranges for sediment management measures

		Measure	Costs (Euros)		Unit	Source
			Minimum	Maximum		
Sediment	Routing	Drawdown reservoir flushing	1	50	Per cubic meter	Rovira and Ibàñez (2007), Espa et al. (2013)
		Sediment sluicing	NA			
	Removal	By-passing sediments	NA			
		Off-channel reservoir storage	NA			
		Mechanical removal of fine sediments (dredging)	5	10	Per cubic meter	Rovira and Ibàñez (2007)
		Minimising sediment arrival to reservoir	150,000		Per Vortex tube	Personal communication (Doessegger 2020)
	Restoration in rivers	Removal of bank protection	NA			
		Removal of debris	NA			

bypassed river reaches or through the turbine. If water is not released through the turbine, it can result in power losses. E-flows are also typically not released constantly throughout the year. Instead, the specific environmental targets and regulations dictate when and how much water should be released (World Meteorological Organization 2019) or more information about how dynamic instream flows can be used to ensure the functionality of river dynamics, see Auerswald and Geist (2018) and Casas-Mulet et al. (2017). For information about other habitat forming processes as well as biological requirements for life history needs, see Acreman and Ferguson (2010), Forseth and Harby (2014) and Pander et al. (2018).

The costs associated with power losses depend on the amount and timing of water released. However, water losses (m^3s^{-1}) cannot be directly converted into monetary losses. Water losses must first be converted to power losses (kWh). Then, power losses can be converted into monetary values using electricity prices. However, these prices can vary significantly based on the region, the time of year/day, inflow-conditions and the type of power market (e.g. balancing, day-ahead, reserve markets, etc.) (Pérez-Díaz and Wilhelmi 2010; Pereira et al. 2019; Ak et al. 2019). For this reason, there was limited information on the costs of e-flow measures. Especially at peak flows, it is also possible to use water for e-flow after the turbines have reached their utilization capacity (Pander and Geist 2013; Stammel et al. 2012). In such cases, the water used for e-flow does not decrease turbine productivity nor incur costs.

The cost of structures (e.g. gates) for flow release depends on the following factors: (i) retrofitting or new structure, (ii) use of the structure, (iii) location relative to the plant, and (iv) material/labour costs. If an existing structure is retrofitted for flow release, it will likely cost more than building a new structure. Further, the structure may be exclusively used for flow release or also used to preventing hydropeaking. If the structure is used for multiple purposes, it may also incur higher costs overall. Structures used to mitigate hydropeaking such as an attenuation reservoir can also be used. Costs increase relative to the size of the dam in the attenuation reservoir (Charmasson and Zinke 2011). The location of the structure relative to the plant is also important. Usually, such structures are built at the outlet of the plant (e.g., retention reservoirs, tunnels or bypasses). Finally, local conditions such as the cost of materials and labour will also affect the magnitude of costs. Once the structure is built, there may be some recurring costs in the form of maintenance (Venus et al. 2020b).

2.2.2 Costs of Sediment Management Measures

To understand the drivers of costs of sediment management measures, it is important to note that there are three main mechanisms for managing sediment: (i) flow release, (ii) temporary creation and maintenance of habitat (e.g., dredging), and (iii) permanent structures that facilitate sediment transport (e.g., vortex tube). Following the categories in Table 2.1 sediment routing mainly relies on flow release while removal and restoration in rivers require both temporary and permanent measures.

For the costs of flow release, refer to Sect. 2.2.1. When using flow for sediment management, there are a few specific considerations. Similar to other e-flow measures, costs are usually recurring and dependent on the lost volume of water. Although sediment management is primarily done to prevent damage to the turbines, it is also possible that damages occur and incur costs. Further, the timing of e-flow is important, as e-flow and dredging could be competing events.

Due to dynamic river processes, sediment can settle close to the hydropower station. Thus, the mechanical removal/placement of sediment is a temporary action, representing a recurring cost. The magnitude of the costs depends on several factors including structural requirements (i.e., size of the river, size of the facility, amount of gravel), site accessibility as well as machinery rental and labour costs. Mechanical removal (dredging) of fine sediments cost approximately 5€–10€ per m^3 in a Spanish case study (Rovira and Ibàñez 2007). In addition, sediment erosion downstream of hydropower dams can result in breakthrough events and also result in substantial cost. For both reasons, ensuring sediment transport through the dam is typically the target.

The costs of structures (e.g. sediment bypasses such as pressurised pipelines, tunnels, canals) tend to be non-recurring and depend on the site topography, obstacle size and shape and hydraulics of the river (Healy et al. 1989). A Vortex tube used to minimize sediment arrival to the reservoir was estimated to cost approximately 150,000€ per tube (Personal communication A. Doessegger 2020). Some recurring costs may be incurred in the form of maintenance.

2.2.3 Costs of Fish Migration Measures

Fish migration measures include both upstream and downstream measures and incur costs related to the cost of the structure itself, power loss and ongoing maintenance. In general, fish migration measures are constructed either when the hydropower plant is built (new) or added when new licenses are needed (retrofitted). When newly built with the power plant, the costs are generally much lower as all the engineering elements required are already available (Table 2.2).

The costs for restoring upstream fish migration are dependent on the size of the fishpass (height of obstacle, length of fishpass, discharge of the fishpass), design (technical vs. nature like construction design), and material (concrete, rip-rap structures, cost of required land, etc.). Barrier removal restores the natural river flow and does not incur recurring costs. As the costs are per project, per unit costs can be calculated. Between types of fishpasses, there is a wider range of costs for pool-type and baffle passes compared to nature-like passes. This may be linked to site-specific issues. If the site is difficult to access, construction of passes with concrete may incur relatively higher costs. Nature-like passes may incur comparatively lower costs as they use natural materials (e.g. stones, vegetation, etc.) rather than concrete. However, pool-type and baffle passes may require less space and can often be designed according to standard formulas. Depending on the location, the costs of acquiring additional land may prohibit the construction of natural passes. Fish lifts, screws and locks tend to incur higher costs per project as these technologies are more complex and only preferred at hydropower plants with limited space or very high heads.

As nature-like passes may necessitate more space to overcome a higher obstacle (i.e., land acquisition costs) and cannot be standardised like technical passes (i.e. planning and construction costs), they are often thought to incur greater costs. However, in a review of European fish passage facilities, nature-like measures were found to cost less than technical measures even when controlling for the height of the obstacle and length of the pass. As nature-like fishpasses can also serve habitat functions including spawning

Table 2.2 Cost ranges for fish migration measures

		Measure	Costs (Euros)		Unit	Source
			Minimum	Maximum		
Fish Migration	Downstream	Operational measures (turbine operations, spillway passage)	NA			
		Sensory, behavioural barriers (electricity, light, sound, air–water curtains)	800	4000	Per m^3/s	Turnpenny et al. (1998)
		Fishfriendly turbines	500,000		Per turbine	Dewitte et al. (2020)
		Skimming walls (fixed or floating)	3,000		Per m^3/s	Venus et al. (2020c)
		Bypass combined with other solutions	10,000	25,000	Per m^3/s	Ebel et al. (2018)
		Fish guidance structures with narrow bar spacing	2,000	40,000	Per m^3/s	Venus et al. (2020b)
		Fish guidance structures with wide bar spacing	2,000	40,000	Per m^3/s	Venus et al. (2020b)
		Bottom-type intakes (Coanda screen)	17,000		Per m^3/s	Turnpenny et al. (1998)

(continued)

Table 2.2 (continued)

		Measure	Costs (Euros)		Unit	Source
			Minimum	Maximum		
	Upstream	Complete or partial migration barrier removal	2,000	1,000,000	Per project	California Department of Fish and Game (CDFG) (2004)
		Nature-like fishways	5,000	20,000	Per vertical meter	Rutherfurd et al. (2000)
		Pool-type fishways	10,000	100,000	Per vertical meter	California Department of Fish and Game (CDFG) (2004), Porcher and Larinier (2002), Venus et al. (2020b)
		Baffle fishways	5,000	100,000	Per vertical meter	California Department of Fish and Game (CDFG) (2004), Venus et al. (2020b)
		Fishways for eels and lampreys	600		Per meter length	Pulg et al. (2020)
		Fish lifts, screws, locks, and others	10,000	500,000	Per project	Venus et al. (2020b)
		Trap and truck	NA			

or feeding habitats, investing in nature-like solutions may be the preferable conservation action (Pander et al. 2013). For an analysis of how different factors affect costs related to fish migration measures, see Venus et al. (2020b).

Downstream migration measures tend to be less technically advanced (Porcher and Larinier 2002). As many downstream migration measures are adaptations of existing facilities at hydropower plants (screens/racks) or operational changes, there is less information about their costs. Downstream migration can be facilitated through either passive (flow release) or active (screens, sensory/behavioural barriers, other guidance structures) measures. No information on the costs of operational measures (i.e., turbine operation, spillway passage) was found in the review. This may be because they are site- and operation-specific. Sensory and behavioural barriers ranged in costs from 800 to 4,000€ per m^3/s (Turnpenny et al. 1998). An example of a fishfriendly turbine (Very-Low-Head) costs 500,000€ per turbine (Dewitte et al. 2020). Skimming walls cost approximately 3,000€ per m^3/s (Venus et al. 2020b). Bypasses combined with other solutions range from 10,000€ to 25,000€ per m^3/s (Ebel et al. 2018). Fish guidance structures either with narrow or wide bar spacing ranged from 2,000€ to 40,000€ per m^3/s (Venus et al. 2020b). A Coanda screen cost approximately 17,000€ per project (Turnpenny et al. 1998).

2.2.4 Costs of Habitat Measures

There are a variety of measures, which can be used to improve aquatic habitats in hydropower affected environments. They range from small-scale measures that address single life stages of species to the holistic restoration of ecosystem functioning (Table 2.3). In general, the more complex the restoration target, the higher the costs of mitigation (Pander and Geist 2013). Habitat mitigation measures incur costs related to (i) temporary adjustments of physical habitat and (ii) permanent construction measures. Adjustments to the flow conditions through the release of water can also improve ecosystem functioning. The magnitude of costs depends on the several site-specific factors: ecological targets, desired habitat type, degree of habitat connectivity, size of the area to be restored, materials and site accessibility (Pander and Geist 2018).

The temporary creation of physical habitat entails instream habitat adjustments such as the placement of spawning gravel, stones and deadwood as well as the cleaning of substrate. The costs of such measures are usually recurring. This is because many habitat improvements are not self-sustaining as obstacles (e.g. hydropower plants) in the river have altered natural river dynamics. Hence, these measures have to be repeated or improved over time. For example, the introduction of gravel for spawning grounds is usually needed on a yearly basis in catchments with high erosion rates (Pander et al. 2015). The restoration of habitat (e.g., construction of off-channel habitats) and shoreline habitat (e.g. restoration of the riparian zone vegetation) tends to be non-recurring.

Table 2.3 Cost ranges for habitat measures

		Measure	Costs (Euros)		Unit	Source
			Minimum	Maximum		
Habitat	Instream habitat adjustments	Placement of spawning gravel in the river	10	100	per cubic meter	Personal communication Loy (2020), Personal communication Zehender (2020)
		Placement of stones in the river	50	150	per cubic meter	Cramer (2012)
		Cleaning of substrate—ripping, ploughing and flushing	1	50	per square meter	Cramer (2012)
		Placement of dead wood and debris	10	150	per meter	Cederholm et al. (1997)
	Restoring habitat	Construction of a 'river-in-the-river'	50	5,000	per meter	Saldi-Caromile et al. (2004)
		Construction of off-channel habitats	1	100	per square meter	Evergreen Funding Consultants (2003)
	Shore-line habitat	Environmental design of embankments and erosion protection	10	150	per meter	Cramer (2012)
		Restoration of the riparian zone vegetation	1	50	per square meter	(Evergreen Funding Consultants 2003)

The costs of habitat measures are more accessible compared to other hydropower mitigation measures as they are often applied in non-hydropower contexts. However, it is important to note that in hydropower-affected environments, functional reliability of the energy system must be guaranteed and this can in turn cause higher costs for habitat measures. For example, drifting deadwood in a hydropower-affected environment is likely to be more expensive since it needs additional structures such as anchor bodies to secure it on site for safety reasons (Pander and Geist 2010, 2016).

2.3 Cost Comparisons from FIThydro Testcases

The FIThydro project studied several Testcases with different environmental targets to assess their cost-effectiveness. In this section, the costs of two Testcases are presented: Las Rives in France and Guma in Spain. While different mitigation strategies may incur costs related to energy losses and construction costs, they may also enable increased energy production.

The Las Rives hydropower plant is situated on the River Ariège in southern France in a reach home to cyprinids and salmonids. The river ecosystem is affected by hydropower as well as agricultural runoff (e.g. nutrients, pesticides). There are mitigation targets related to downstream and upstream migration as well as e-flows. Although French authorities require a specific amount of e-flow, the operator released less by agreeing with the authorities to improve downstream fish migration conditions at the plant. Specifically, the trash rack in front of the hydropower was re-designed and a new DIVE turbine was installed to increase e-flow and power production. Additionally, the plant has an alternate vertical slot pass that was integrated with a DIVE turbine to increase the attraction flow for upstream migrating fishes. As a result of mitigation, the operator increased power production and decreased fish mortality.

The Guma hydropower plant is situated on the River Duero in north-western Spain, which is home to cyprinids including some endemic ones of high conservation importance (e.g., Iberian barbell, northern straight-mouth nase, Northern Iberian chub and Pyrenean gudgeon). Dams and hydropower as well as agricultural use (e.g. irrigation) affect the ecosystem. At the plant, the operator addressed challenges related to upstream migration, spawning habitat and e-flow. For upstream mitigation, the operator installed a pool and weir fishway with a submerged notch, bottom orifice and attraction flow. Although Spanish authorities do not require e-flow, the operator ensured sufficient flow for functionality of the fishpass. Within the FIThydro project, researchers used scenario modelling to compare changes in the attraction flow at the fishway and morphological alterations between the power station tailrace and the fishpass branch. The simulated results showed that the morphological alterations and the increase of attraction flow could potentially improve upstream migration and facilitate access to the spawning areas upstream of the hydropower plant.

2.3.1 Calculating Costs of Operational Changes

Costs included operational changes (e.g. shutting down the turbines), morphological modifications (e.g. digging terrain to increase the depth) and structural solutions (e.g. trash racks). For the operational changes, annual and daily power production was calculated using the hydraulic head and turbine efficiency. This was combined with the power price to calculate the costs of increasing the e-flow and reducing the water passing through the turbines for energy production. In another case, the Short-term Hydro Optimization Program (SHOP)2 was used to calculate the loss of energy and costs of shutting down the turbines during the migration period, and from increasing the e-flow.

Energy losses were calculated by comparing the monetary values of energy production with the actual situation and production at the different hydropower plants. In both cases, the morphological and construction costs were annualized with an amortization period of 14 years and a discount rate of 5%. In Las Rives, the construction costs were in most cases higher than the power losses, considering also that the new turbine increases the production and the e-flow included in the attraction flow reduces the losses. In Guma, the morphological costs were lower, but all measures included a loss of income. However, it is important to consider that construction and morphological costs will be recovered after 14 years, but not the energy production losses.

2.3.2 Cost Comparison of Fishfriendly Measures

In Las Rives, costs of several actions related to downstream passage mitigation were compared (Fig. 2.1). These included variations of installing a new bar rack, shutting down the turbine and adding a new turbine (Fig. 2.1). Mitigation measures costs included the construction of new devices as well as income gain and losses, which consists of increasing the e-flow that is or is not used for energy production and shutting down the turbines.

(Note: Costs are ordered from lowest total cost to highest total cost. Negative costs (−) show that the measure created additional benefits, which reduced total costs of the measure.)

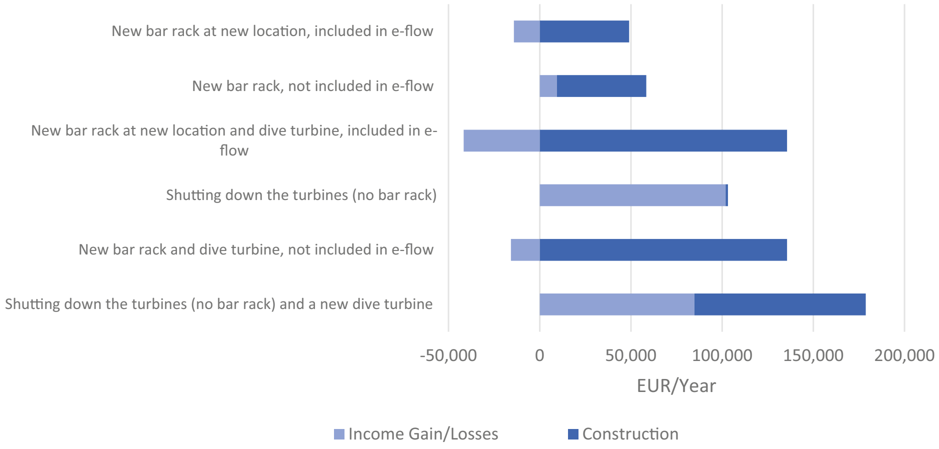

Fig. 2.1 Total costs of downstream mitigation measures at Las Rives (2.7 MW)

In Guma, costs of several actions related to different levels of e-flow and morphological changes (Fig. 2.2). Mitigation measures costs included morphological changes such as the addition of blocks from different sizes, morphological alternation of a river bed channel (by widening and shaping) and the income losses such as the increase of the e-flow from 1 to 3 respectively.

These examples from the FIThydro Testcases demonstrate how the losses associated with operational changes can be incorporated into cost comparisons for potential mitigation strategies. To improve future cost assessments of mitigation measures, it is important to make cost data publicly available as much as possible. In turn, this will improve transparency of mitigation and aid decision makers in supporting effective ecological mitigation at hydropower plants.

2.4 Conclusion

The costs of fish-related mitigation measures play an important role in their adoption. There is a wide range of costs depending on the type of measure adopted and site-specific factors. As evident from the empirical data and the experiences from the case studies, there are trade-offs between power production and mitigation, particularly when combinations of measures are adopted. However, it is also important to remember that these costs should be weighed against their ecological benefits. Specifically, they can contribute to achieving

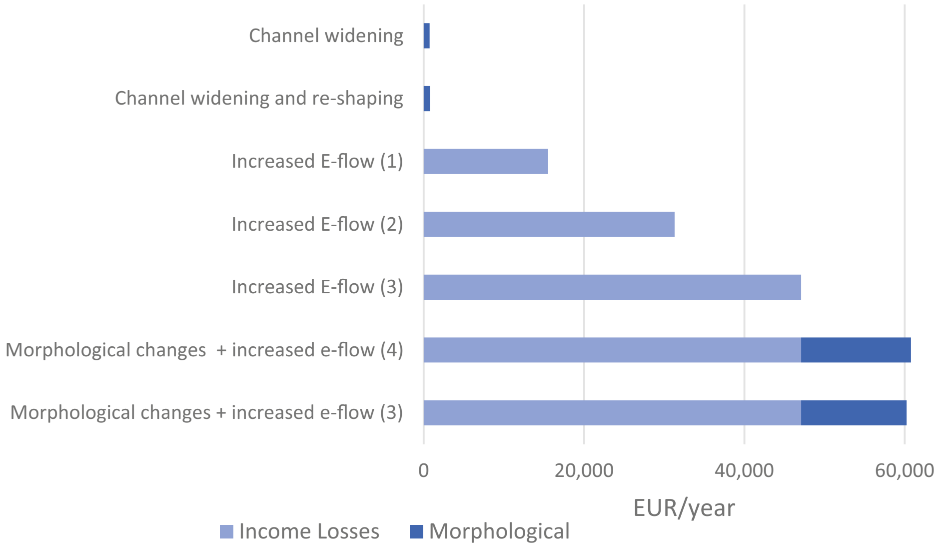

Fig. 2.2 Total costs of e-flow and morphological changes at Guma (2.25 MW)

"good ecological potential" and "good ecological status" in water bodies, a key target formulated in the European Water Framework Directive.

In light of ecological targets, managers should also consider that mitigation measures are often not self-sustaining. In such cases, managers might consider adaptive river management, which is an iterative process that responds to the dynamic river environment and improves management decisions as information is attained (Geist and Hawkins 2016). From a cost perspective, this means that costs are recurring rather than non-recurring. Similarly, monitoring is also an important part of adaptive river management. Further, environmental monitoring for hydropower has been found to be positively valued by the public and should be included in cost-benefit analyses (Venus and Sauer 2022). Thus, it is important that planners not only consider costs of the measures but also ongoing monitoring. While some critics cite monitoring costs as a disadvantage of adaptive management, investments in well-designed monitoring programs may be cost-effective compared to the costs of designing entirely new mitigation programs.

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