Master thesis

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Using life cycle assessment to predict site-specific biodiversity impacts from the construction phase of future hydropower dams

Trondheim, March 2021

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Abstract

Hydropower with reservoir storage can play a key role in mitigating climate change by providing renewable, low-carbon energy and energy storage capability to a world with a rapidly growing electricity demand. However, the deployment of remaining storage hydropower can potentially have large trade-offs with respect to biodiversity loss. This study assesses biodiversity impacts from construction materials of 743 potential future hydropower dams by applying the life cycle assessment methodology. Biodiversity impact contribution from land use, GHG-emissions, water use, acidification, freshwater eutrophication and photochemical ozone formation were estimated for two common dam types, namely concrete gravity and embankment dams. Results showed little difference in the biodiversity impacts from the two types. Land use (occupation and transformation) was the most important cause of biodiversity impact, before GHG-emissions in second place. This study was compared to the study of Dorber et al. (2020) which assessed the biodiversity impacts from the operation phase for the same hydropower projects. Aquatic biodiversity impact was substantially higher from the operation phase while median terrestrial impact was higher from the construction phase. The correlation between construction and operation impacts were weak which suggest that the operation impacts of hydropower projects are high when construction impacts are low and the other way around. The findings in this study suggest that it would be beneficial to include biodiversity impacts from the construction phase in decision-processes of future hydropower development.

Sammendrag

Vannkraft med reservoarlagring kan spille en nøkkelrolle i å redusere klimaendringene ved å tilby fornybar energi med lavt karbonavtrykk og energilagring til en verden med et raskt voksende strømbehov. Imidlertid kan utbyggingen av gjenværende magasinkraftverk potensielt ha store skadevirkninger med hensyn til tap av biologisk mangfold. Denne studien vurderer påvirkningen på biologisk mangfold fra byggematerialer til 743 potensielle fremtidige magasindemninger ved å anvende livssyklusanalyse. Bidraget til påvirkning på biologisk mangfold fra arealbruk, klimagassutslipp, vannbruk, forsuring, ferskvannseutrofiering og dannelse av fotokjemisk ozon ble estimert for to vanlige damtyper, nemlig gravitasjonsdemning og fyllingsdam. Resultatene viste liten forskjell i påvirkningene på biologisk mangfold fra de to damtypene. Arealbruk (okkupasjon og transformasjon) var den viktigste årsaken til påvirkning på biologisk mangfold, før klimagassutslipp på andreplass. Denne studien ble sammenlignet med studien av Dorber et al. (2020) som vurderte påvirkningene på biologisk mangfold fra driftsfasen for de samme vannkraftprosjektene. Påvirkningen på ferskvannsøkosystemer var vesentlig høyere fra driftsfasen, mens medianen av påvirkningen på landbasert biologisk mangfold var høyere fra konstruksjonsfasen. Korrelasjonen mellom konstruksjons- og driftspåvirkninger var svak, noe som tyder på at påvirkningen fra driftsfasen av vannkraftprosjekter er høye når konstruksjonspåvirkningen er lav og omvendt. Funnene i denne studien antyder at det vil være gunstig å inkludere påvirkninger på biologisk mangfold fra konstruksjonsfasen i beslutningsprosesser for fremtidig vannkraftutbygging.

Contents

Chapter 1

Introduction

Global temperatures are projected to increase 3.2 °C, relative to the pre-industrial period, by the end of 2100 (United Nations, 2020). A drastic and rapid shift from fossil to renewable energy is needed if the 1.5 °C or even the 2 °C target adopted in the Paris Agreement in 2015 are to be met (United Nations, 2015a). At the same, the 2020 version of WWF's Living Planet Report tragically affirms that populations of birds, mammals, reptiles, fish and amphibians have on average has declined with 68% since 1970 and that only about 25% of all ice-free land on Earth is still considered wilderness (Almond et al., 2020). As the pressure on the worlds ecosystems are greater than ever, it's important that the shift to clean energy is done with as little damage to nature as possible.

Hydropower has gained attention as the world demand for energy rises and efforts are made to replace fossil energy. In 2014 more than 3 700 hydropower dams with a capacity over 1 MW were planned or under construction (Zarfl et al., 2015). At that time, these hydropower plants were estimated to increase the global electricity production with 73 % (Zarfl et al., 2015). This commitment to hydropower is also reflected in financial investments. Hydropower accounted for 46 % of international investments in renewable energy in developing countries in 2017, which is more than investments in solar (19 %), wind (7 %) and geothermal energy (6 %) combined (United Nations, 2020). However, it should be noted that hydropower is quite expensive to build. In terms of global increased installed capacity from 2015 to 2016, ca. 35 000 MW of hydropower were added as opposed to ca. 51 000 MW of solar and ca. 71 000 MW of wind (Our World in Data, c).

Hydropower is responsible for approx. 60.1 % of energy generation from renewable energy sources (not including traditional biomass) and 6.4 % of worlds primary energy consumption (in 2019) (Our World in Data, a,d). Energy generation from hydropower has increased steadily in recent years, although not as rapidly as wind and solar (Our World in Data, a). It is likely that reservoir-based hydropower will become increasingly important in the future due to having relatively low life cycle emissions (24 g CO_2 eq./kWh incl. albedo effect (Schlömer et al., 2014)) and its ability to store energy and rapidly generate electricity when it is needed. This will allow for the development of emerging energy technologies like wind and solar power which are less flexible (Zarfl et al., 2019).

An expansion of hydropower, especially in developing countries, can help us achieve the United Nations' Sustainable Development Goal (SDG) number 7 (Affordable and clean energy) and 13 (Climate action), but it could also directly or indirectly benefit the other goals (United Nations, 2015b). For example, multiple use of hydropower reservoirs such as for drinking water supply, irrigation, flood control and navigation (Berga, 2016) can contribute to SDG 6 (Clean water and sanitation) and SDG 2 (Zero hunger). With climate change being an important driver of biodiversity loss (Almond et al., 2020), replacing carbon intensive energy sources with renewable sources can also be positive with respect to SDG 14 (Life bellow water) and SDG 15 (Life on land). However, precautions should be made so that the potential negative effects of hydropower on biodiversity do not outweigh the benefits.

Despite all its benefits, hydropower has several drawbacks with respect to both terrestrial and aquatic life. Dams create barriers which fragment river ecosystems and hinder migration of aquatic species along river systems (Bunn and Arthington, 2002). When reservoirs are created, terrestrial habitat is flooded which can negatively affect terrestrial species (Kitzes and Shirley, 2016). The transformation of the existing river ecosystem into lake ecosystem could benefit some species over others, and ultimately alter the species composition in the river and the lake (Gehrke et al., 2002). The operation of dams can modify the natural flow pattern of rivers by altering its magnitude, timing, frequency and rate of change (Poff et al., 1997). Flood peaks are often reduced, which in turn lower the frequency, duration and extent of floodplain inundation (Ward and Stanford, 1995). In addition, there are impacts on biodiversity from infrastructure, like roads and power lines, construction work and material use associated with dams.

The European Green Deal initiative by the European Commission aims to achieve net zero emissions of greenhouse gases (GHGs) for European countries by 2050 (European Commission, 2019). As a step to reach this goal the Commission published the Taxonomy Regulation which came into force in July 2020 (The European Parliament and the Council of the European Union, 2020). This is a classification system for what is allowed to be marketed as a sustainable activity and is intended to encourage investments in projects that contribute to climate change mitigation and adaptation without causing substantial damage to the environment (European Commission website).

The first draft of the technical screening criteria, called delegated acts (European Commission, 2020), was released in November 2020, and received critique from the Norwegian government for containing requirements for hydropower that were too strict (Royal Minitry of Finance, 2020). Norway and other countries that are heavily dependent on hydropower as their main energy supply are worried that hydropower would lose its status as a sustainable energy technology and thus receive less financial support. This study will add information to the debate about future development of hydropower by shedding light on which potential hydropower reservoir locations that have the least impact on biodiversity from dam construction in addition to the operation (Dorber et al., 2020).

In order to estimate the construction impacts on biodiversity the methodology of Life Cycle Assessment (LCA) were applied. LCA is a well-established framework for assessing a wide range of environmental impacts over the lifecycle of a product, process or activity, involving the creation (i.e. resource extraction, material production and product manufacturing), use/consumption and end-of-life phase (Rebitzer et al., 2004). It's main application is to provide support in decision-making for the industry, policy-makers and organizations, and to inform consumers (ISO 14040:2006; Hauschild and Huijbregts, 2015). A central part of the LCA methodology involves the use of characterization factors (CFs), which are multiplied with the quantity of emissions and resource use to obtain the impact contribution from different impact categories (Hauschild and Huijbregts, 2015). The three areas of protection referred to in LCA are human health, ecosystem quality and natural resources. Indicators that aims to measure the direct damage to one of these areas of protection are called endpoint indicators (Hauschild and Huijbregts, 2015).

A frequently used and recommended endpoint indicator to measure damage on ecosystem quality is potentially disappeared fraction of species (PDF) (Verones et al., 2017). PDF denotes the fraction of species that risk going extinct in a geographical area as a result of emissions or resource use from human activities. Attention should be given to which species groups and geographical scale an impact value in PDF refers to as this can have a substantial influence on the meaning and interpretation of the result (Verones et al., 2017).

1.1 Background and objective

Multiple studies have addressed the different environmental issues of hydropower production on both regional and global scale. Barros et al. (2011) and Hertwich (2013) focus on the methane emissions that is released from hydropower reservoirs due to degradation of organic matter without access to oxygen. A report from UNEP (2016) highlight that the site of hydropower plants, even for those that are geographically close to each other, can greatly influence the size of different types of environmental impacts. Zarfl et al. (2019) found that proposed hydropower dams to a large extent coincides with sub-catchments with high freshwater megafauna species richness. Barbarossa et al. (2020) addresses the issue of fragmentation due to existing and future hydropower dams, by quantifying the degree of connectivity for lotic (i.e. river) fish species worldwide. Wang et al. (2019) provide an assessment of water and carbon footprint of China's most important hydropower stations, contributing to over 80% of the country's total hydropower production.

However, these studies are either confined to a specific group of species, to a geographical region or a specific type of impact. Only one study was found that use life cycle assessment to quantify global damage to ecosystem quality (endpoint level) from hydropower (Gibon et al., 2017b). However, this study does not include any spatial differentiation.

In this study a global assessment of aquatic and terrestrial biodiversity impacts from the construction phase of potential future hydropower projects (HPs) with a country-specific resolution is performed.

The starting point of this study is a study by Gernaat et al. (2017) which investigated the remaining economic potential of hydropower left in the world. Here, "Remaining" refers to potential hydropower projects (HPs) that avoid conflict with existing dams, are located outside of nature protected areas and are not built downstream of the first existing dam on the main river of a drainage basin. "Economic" indicate potential hydropower that are able to produce electricity for less than 0.10 US$ per kWh. With these constraints, Gernaat et al. (2017) was able to identify 1 956 possible reservoir-based hydropower sites with potential to produce 3.9 PWh per year.

In a follow up study, Dorber et al. (2020) performed a spatially-explicit life cycle impact assessment, to identify where reservoirs with lowest aquatic and terrestrial biodiversity are located and to assess how much of the future hydropower potential could be utilized from a biodiversity perspective. Dorber et al. (2020) focused on biodiversity impacts from the reservoir operation. More specifically, biodiversity impacts from land occupation due to flooding of land, water consumption due to increased evaporation from the reservoir surface and increased methane emissions due to anaerobic decomposition of organic matter in the reservoir.

While, Dorber et al. (2020) focused on the operation phase of the reservoirs, this study will assess biodiversity impact related to material consumption from the construction of the dams. The basis for this thesis is also data provided by Gernaat et al. (2017), containing information about dam location, dam height and length. However, due to an update of the algorithm that was used to identify potential hydropower sites in Gernaat et al. (2017), the number of hydropower projects with location and expected annual production equal to Dorber et al. (2020) study was only 743. Because one of the goals for this study is to compare the biodiversity impacts from the construction with the impacts from operation, this study will focus on these 743 reservoirs with a total electricity production potential of 902 TWh per year, ranging from 82.7 GWh/yr to 36.2 TWh/yr. The location and annual production of these hydropower projects are shown in Figure 1.1.

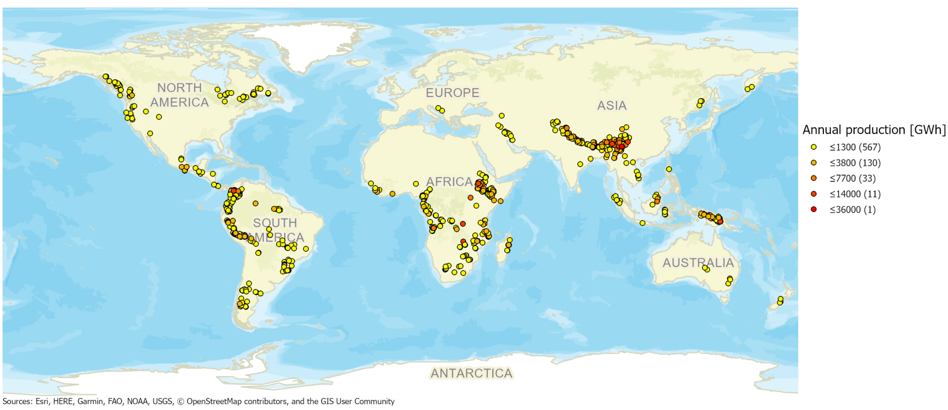

Figure 1.1: Map of 743 potential reservoir-based hydropower projects. The number of HPs are in parentheses

This thesis will complement the results of the study performed by Dorber et al. (2020) and aims to answer the following research questions: How will the results of Dorber et al. (2020) change if biodiversity impacts from dam-construction are included? Will the HPs with lowest biodiversity impact during the operation phase automatically have the lowest dam-construction impacts? If not, does this imply, that from a biodiversity perspective, we should use even less of the hydropower potential?

In order to answer these questions, the main goal is to perform a global life cycle assessment of the construction phase of 743 potential future hydropower projects to investigate the related biodiversity impact. The material production of two different dam types, namely embankment and concrete gravity dam, is assessed based on the material share found in existing dams inventories and dam volume calculations using the height and length provided by Gernaat et al. (2017). The Life Cycle Impact Assessment (LCIA) method used are LC-Impact and includes the impact pathways of climate change, land stress, water stress, terrestrial acidification, freshwater eutrophication and photochemical ozone formation. Impacts are analyzed in units of global Potential Disappeared Fraction of species times years [PDF*yr] per annual electricity production [kWh/yr] and per reservoir. Furthermore, this study will compare the terrestrial and freshwater biodiversity impacts from the construction and the operation phase with the individual impacts from each phase.

1.2 Theory

1.2.1 Dam types

Four common dam designs are embankment, gravity, buttress and arch dams (Song et al., 2018). The construction technologies and the type and quantity of materials used for the dam structure vary depending on the dam design and thus the environmental footprint of these dams differ (IEA, 2002; Zhang et al., 2015). Hence, the biodiversity impact of material production from future hydropower projects will depend on the distribution of different dam types that are built in the future.

Today, about 75% of all dams in the world are embankment dams (International Commission on Large Dams). They are generally less expensive than arch and gravity dams because they are mainly made of natural, excavated materials (IEA, 2002; Thomas, 1976). Embankment dam design and construction method are often dependent on the local conditions, like the rock and earth material available (Golze et al., 1977). For instance, about 90% of all Norwegian embankment dams use moraine in the core as sealing material because it's widely available in mountain areas where most dams are built (NGI, 1983). The design principle of gravity dams is using the weight of the concrete (or stone masonry) to withhold the water. In order to prevent the dam from overturning, sliding and foundation crushing the base width is adjusted according to the height. (Thomas, 1976). Arch dams are like gravity dams made of concrete but due to its curved shape arch dams are able to transmit the majority of load to the abutments instead of the bottom foundation and therefore generally uses less material than gravity dams (IEA, 2002; Thomas, 1976). However, they require a stable foundation and are often used in V-shaped valleys when the crest length-to-height ratio is less than 3 (Thomas, 1976).

Chapter 2

Methods

In short, this study performs an assessment of the biodiversity impacts from material production of the dam structure for 743 potential future reservoir-based hydropower dams applying the LC-Impact methodology. The amount of materials used in each of the dams were calculated by multiplying their volume with the average volume-wise share of materials that were found in existing life cycle inventories. In order to calculate the dam volume, assumptions about the shape and width had to be made because the data set of Gernaat et al. (2017) only provided dam height and length. Since construction materials, dam volume and thus the biodiversity impact varies with different dam types, calculations were done for two scenarios; 1. all future dams are of the concrete gravity type 2. all future dams are of embankment type. Realistically future dams will be a combination of different dam types, but these two scenarios aim to give an idea of the range of biodiversity impact that can be expected.

The stepwise approach for estimating the biodiversity impact is summarized in Figure 2.1. These individual steps will be further explained in this chapter.

2.1 Functional unit

This impact assessment uses two functional units (FU) defined as 1 kWh of annual electricity production from a hydropower plant (i.e. 1 kWh/yr) and 1 hydropower project (HP). Biodiversity impacts, in units of PDF*yr, from the construction phase are quantified per annual production and per hydropower project (sometimes also referred to as reservoir).

2.2 Finding the share of material in dams

In order to estimate the amount of materials required in the construction of potential future dams, the average volume share of the most common materials used in embankment and

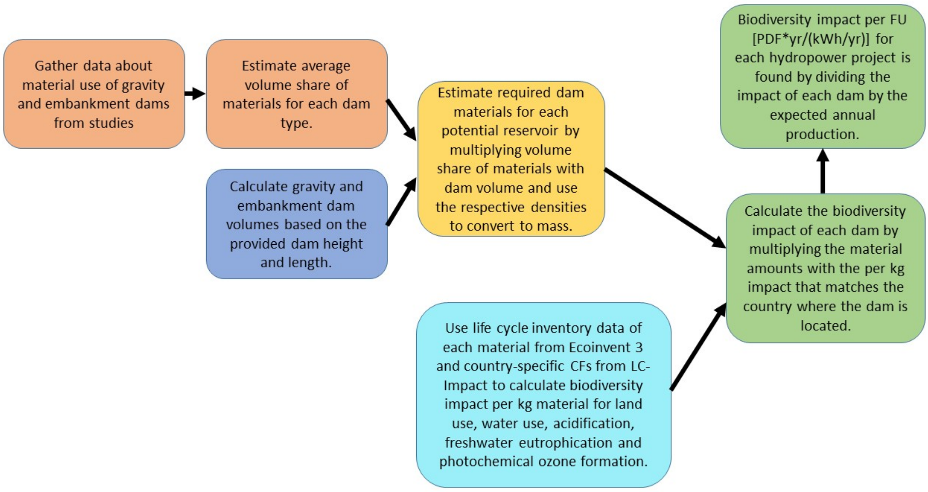

Figure 2.1: Approach for estimating biodiversity impact of material use in potential future dams

gravity dams were calculated. The volume share can then be multiplied with the volume of each dam to find the volume of different materials in each dam. Finally, the material volumes are converted into mass values by multiplying by their corresponding densities. When the mass of the materials for each dam is known the impact assessment can start.

The most common construction materials and their quantities are found by collecting inventory data from studies of hydropower projects. Only hydropower dams impounding a reservoir (i.e. storage or pumped storage facility type) were considered, which excludes run-of-river type of dams. Six studies with inventory data from gravity dams were found, while only three studies covered embankment dams. These are listed in Table 3.1 and Table 3.2 respectively. The level of detail in which inventory data were reported varied. Most studies report the material use in bulk without specifying which part of the dam it is used for (e.g. the powerhouse, spillway, generator and dam structure). It was therefore assumed that all materials were used in the dam structure when calculating the volumetric share.

A review revealed that steel and concrete/cement is the most listed materials for both gravity dams and embankment dams. In addition, one or more types of fill-material, such as rock, sand and earth, were commonly included in the inventory data for embankment dams. Various other resources, such as wood, aluminum, copper and explosives, were recorded infrequently and were therefore omitted. Based on this the dam structure were assumed to consist of concrete and steel for gravity dams and concrete, steel and gravel (fill-material) for embankment dams.

Most publications lists either concrete (e.g. Rule et al. (2009)) or cement (e.g. Pang et al. (2015)) in their inventories. Concrete used in dams is on average composed of 85% gravel, 10% cement and 5 % water (Flury and Frischknecht, 2012). As mentioned, concrete makes up most of the structure of gravity dams (Thomas, 1976) and in embankment dams concrete is sometimes used as sealing, either in the core or in front (NGI, 1983). Although cement itself also can be used in dams, for example in injections (Flury and Frischknecht, 2012), this use was considered negligible compared to the total used as a component of concrete. Therefore, in cases where a study only reports cement, it was assumed that cement was used solely as ingredient in concrete. The amount of concrete that the cement would produce was calculated based on the aforementioned ratio. In one study (Hidrovo et al., 2017) where both concrete and cement were reported, only the concrete was considered.

Different types of embankment dams get their name after the most significant fill-material that they are made of (NGI, 1983). Often a combination of fine grained masses, such as sand, clay and earth, and coarser masses, like gravel, rocks and boulders are used (Golze et al., 1977). Depending on the properties of these masses, they serve various purposes, such as sealing, filter, draining or protection against waves and ice (Thomas, 1976). For practical and economic reasons, the fill-material in embankment dams is often excavated near the dam site (Golze et al., 1977). Biodiversity impacts from fill-material are therefore likely to arise from the land occupation and emissions from the excavation site and machinery. Based on this, it was assumed that different types of fill-material have approximately the same footprint. Having medium coarseness, gravel was chosen as a proxy for all fill-materials.

Three studies that were included in the material share calculations require a short explanation. One study (Flury and Frischknecht, 2012) based their inventory data on an average of 52 dams, of which 34 of them were arch dams, 17 gravity dams and 1 buttress dam. However, this study was still included in the material share calculations for gravity dams because arch and buttress dams, like gravity dams, are by large composed of concrete (Golze et al., 1977). This is supported by the results in Table 3.1 which show that the average volume percentage of concrete and steel of the dams in this study are similar to studies that only assesses gravity dams.

Some dams combine sections with different dam design. This is the case for the Itaipu dam, located on the border between Brazil and Paraguay, which consists of embankment, buttress and gravity sections (Ribeiro et al., 2019). Since most of the dam lengthwise comprises of rockfill and earthfill sections (Barboza and Pastor, 1979) it was included in the material share calculations as an embankment dam. However, as shown in Table 3.2 the volume share of materials of Itaipu does differ significantly from the two other studies of embankment dams, by having a higher share of concrete and steel.

A third study by Zhang et al. (2015), assesses a concrete gravity dam scheme and an earth-core rockfill dam scheme for the same hydropower plant called Nuozhadu. That is why this dam is included in numerical foundation of both the gravity and embankment dam calculations.

The collected material quantities were mainly reported in units of kg or kg/kWh. First, the volume of each material (concrete and steel for gravity dams and concrete, steel and fill-material for embankment dams) were calculated by dividing the mass by the respective densities. Concrete density is 2357 kg/m^3 (Flury and Frischknecht, 2012), steel density is 7850 kg/m^3 (The Physics Factbook website) and gravel (wet) density is 2000 kg/m^3 (Geopixel website). Next, the volume percentage were calculated by dividing the volume of each material by the total volume of all materials. This is shown in Eq. 2.1, where *V* is the volume, *m* is the mass, ρ is the density and index *i* denotes the type of material.

$$\text{Volume \% of material } i = \frac{V_i}{V_{tot}} = \frac{\frac{m_i}{\rho_i}}{\sum_i \frac{m_i}{\rho_i}} \tag{2.1}$$

These calculations are provided in the supplementary information and shown in Table 3.1 and 3.2 in the results.

2.3 Dam dimensioning

Determining the dimensions of a dam is a comprehensive task that is customized to the conditions that apply to each hydropower project. Design choices are not limited to the physical load calculations but also includes economical aspects which may alter the design of the dam. Often there are more than one applicable dam types and design options. Due to the large number and the limited information about the dams included in this study the calculations and design choices are kept general and relatively simple compared to a real-life project. Dimensions are determined with the aim of representing a global average dam. The height and length of the potential dams are known, so in order to calculate the volume of the dams only their shape and width are needed.

2.3.1 Embankment dam dimensioning

Dam slope

Embankment dams generally have a triangular shape, however their dimensions are customized based on the topography and geology at the dam site (NGI, 1983). Dam stability increases with a gentler dam slope and reduces the chance for masses to slide out. Well drained masses, such as rock fillings, can lay stable in steeper slopes than poorly drained masses such as earth (Midttømme, 2006). For instance, fine-grained moraine used for sealing in earth dams should not have a steeper slope than 1:3 (i.e. height-to-width ratio). Coarser sealing masses that are better drained may have a slope of 1:2.5 or 1:2. Rock-fillings are usually stable with a slope of 1:1.5 without sliding out Midttømme (2006).

The 261.5 m tall earth core rockfill dam in China, Nuozhadu, has slopes of 1:1.9 upstream and 1:1.8 downstream Ma and Chi (2016). Another tall dam, the 240 m high Changheba earth core rockfill dam in China has a slope of 1:2 both upstream and downstream. Follsjødammen in Norway described as a typical Norwegian embankment dam has a slope of 1.5 both upstream and downstream NGI (1983). Other Norwegian dam slopes ranges between 1:1.3 and 1:3.0 NGI (1983).

As exemplified, the steepness of the dam slopes varies significantly. For the purpose of this study which aims to model an average embankment dam the upstream and downstream slopes were set to 1:1.7, which lies well within the maximum and minimum slopes that are used.

Dam crest width

The dam crest width is often determined based on practical considerations during construction, what kind of transport is planned on top of the dam when it is finished and general security measures (NGI, 1983). A width of minimum 5 m is common if the road is going to be a part of the national road network (NGI, 1983). However, Golze et al. (1977) recommend a crest width of at least 9.1 meter (30 ft.) in general. The height and length of the dam is also to some degree determining factors. Higher dams usually have wider dam crests to avoid cracking and shear deformation that can occur when different materials in the filter- and transition-zones are settling (Andersen et al., 2012).

In this study, the crest width, w_t, of embankment dams were calculated using the minimum requirement, suggested by the Norwegian Water Resources and Energy Directorate (NVE), given in Eq. 2.2 as a function of dam height h (Andersen et al., 2012).

$$w_t \geq 4 + h/30 \tag{2.2}$$

Dam volume

The parameters used to calculate the dam dimensions are shown in Figure 2.2.

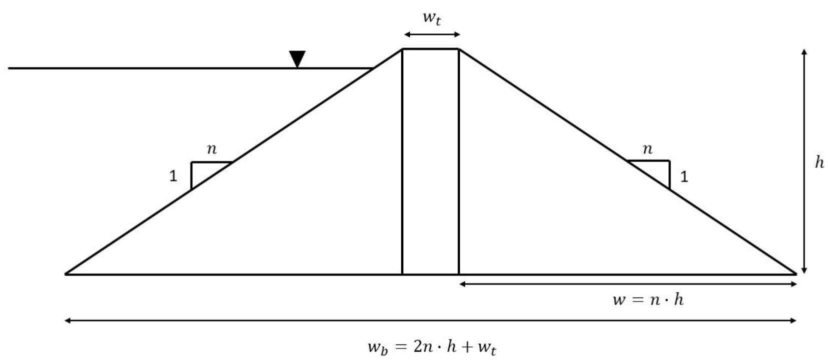

Figure 2.2: Vertical cross section of embankment dam with dimensions parameters.

After determining the crest width and the upstream and downstream slopes, the dam volume was calculated with Eq. (2.3),

$$V_{emb} = h \cdot (n \cdot h + w_t) \cdot l \tag{2.3}$$

where *h* is the dam height, *n* determines the slope by representing the width in the height-to-width ratio (1:n), w_t is the dam crest width and *l* is the length of the dam.

2.3.2 Concrete gravity dam dimensioning

As with embankment dams, calculations of dimensions were preformed based on a common gravity dam shape shown in Figure 2.3, which is similar to the one depicted in Golze et al. (1977). The dimension calculations preformed here assume the gravity dam to be a monolithic structure made of homogeneous concrete without cracks (U.S. Bureau of Reclamation, 1976).

Forces on a dam

Forces on a dam can be categorized into permanent loads, variable loads and accidental loads NVE (2003). Permanent loads include the hydrostatic pressure, pore pressure buoyancy, dead-weight of the dam and permanent sediment load. Variable loads are split into use-dependent loads (e.g. traffic on top of the dam, hydrodynamic load and variable sediment load), deformation loads (e.g. as a result of subsidence, tensions and pressure and temperature variations) and environmental loads (e.g. waves, ice and snow, volume expansion due to freezing and earthquake). Accidental loads are loads that occurs as a result of an accident, natural disaster and other abnormal conditions. This can be flood events, dam leakage, accidents during operation of hatches, earthquakes, landslide, terror and random accidents NVE (2003). Many of these loads are site and project dependent and most are difficult or impossible to estimate exact. In the following calculations for finding dimensions of a typical concrete gravity dam only permanent loads were included; hydrostatic pressure, pore pressure buoyancy and dead weight of dam and water. Dimensioning flood level were set to the same height as the dam. Tailwater was omitted from the calculations.

The basic dam design and the forces acting on the dam are shown in Figure 2.3.

It is common practice to check the stability of gravity dams with respect to overturning and gliding on critical planes NVE (2005). However, due to time constraints the dam dimensions were decided only based on safety requirements to prevent overturning.

First, the horizontal and vertical loading on the dam were calculated. Then, the torque around the axis of downstream edge, point *x* in Figure 2.3, were calculated in order to find out if the dam is stable for overturning (NVE, 2005). The general expression for torque, given in Eq. 2.4, are expressed as the magnitude of the force *F* times the arm *r* - the distance from where the torque is measured to the point where the force is applied.

$$\tau = F \cdot r \tag{2.4}$$

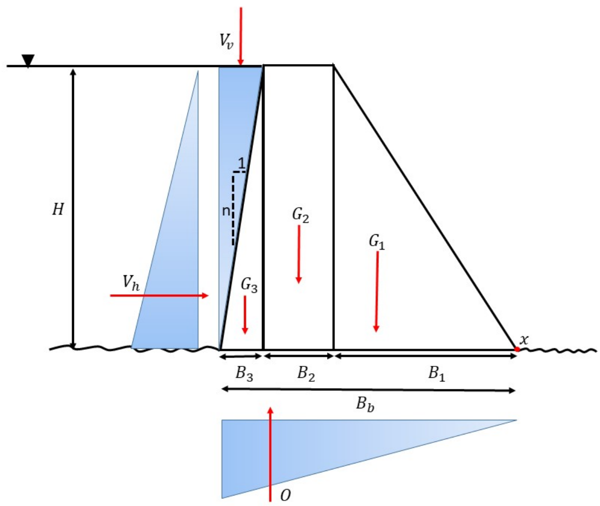

Figure 2.3: Vertical cross section of gravity dam, showing forces and dimension parameters.

Forces acting tangentially in clockwise direction around point x will push the dam to tip over, while forces acting in an anticlockwise direction will contribute to the stability of the dam.

Following forces were included in the dam stability calculations:

Horizontal loading

V_h - Horizontal force induced by the hydrostatic pressure from the reservoir water on the upstream surface of the dam - Eq. (2.5).

Vertical loading

V_v - Weight of water acting on inclined upstream surface - Eq. (2.8).

O - Buoyancy force from pore pressure acting on dam foundation - Eq. (2.11).

G_1 - Gravity acting on downstream section of dam - Eq. (2.14).

G_2 - Gravity acting on middle section of dam - Eq. (2.17).

G_3 - Gravity acting on upstream section of dam - Eq. (2.20).

The pore pressure is caused by the hydrostatic pressure that forces water into cracks and gaps in the dam and the foundation, thus giving rise to a buoyancy force (U.S. Bureau of Reclamation, 1976). To model this effect, it's assumed a thin gap between the dam and the foundation. The pressure drop upstream to downstream will cause water to flow in the gap and apply a buoyancy force vertically on the dam foundation (Thomas, 1976). In this model the dam itself is assumed impermeable. The buoyancy force is highest upstream and decreases linearly towards downstream of the dam as seen in Figure 2.3 (U.S. Bureau of Reclamation, 1976).

The equations for the dead weight of the three different dam sections G1, G2 and G3, shown in row 4 to 6 in Table 2.1, uses the density of concrete $\rho_c = 2357\ kg/m^3$ (Flury and Frischknecht, 2012). Water density is assumed equal $\rho_w = 1000\ kg/m3$ and the gravity acceleration $g = 9.81\ m/s^2$.

Nr.	Name	Load [N/m]	Arm [m]	Torque [Nm/m]
1	Horizontal water load	$V_h = \frac{1}{2}\rho_w g H^2$ (2.5)	$r_h = H/3$ (2.6)	$\tau_h = \frac{1}{6}\rho_w g H^3$ (2.7)
2	Vertical water load	$V_v = \frac{1}{2}\rho_w g \frac{H^2}{n}$ (2.8)	$r_v = B_b - \frac{H}{3n}$ (2.9)	$\tau_v = \frac{1}{2}\rho_w g \frac{H^2}{n}(B_b - \frac{H}{3n})$ (2.10)
3	Buoyancy	$O = \frac{1}{2}\rho_w g H B_b$ (2.11)	$r_o = \frac{2}{3}B_b$ (2.12)	$\tau_o = \frac{1}{3}\rho_w g H B_b^2$ (2.13)
4	Dead weight G1	$G_1 = \frac{1}{2}\rho_c g h B_1$ (2.14)	$r_{G1} = \frac{2}{3}B_1$ (2.15)	$\tau_{G1} = \frac{1}{3}\rho_c g h B_1^2$ (2.16)
5	Dead weight G2	$G_2 = \rho_c g h B_2$ (2.17)	$r_{G2} = B_1 + \frac{1}{2}B_2$(2.18)	$\tau_{G2} = \frac{1}{2}\rho_c g h B_2(B_1 + \frac{1}{2}B_2)$ (2.19)
6	Dead weight G3	$G_3 = \frac{1}{2}\rho_c g h B_3$ (2.20)	$r_{G3} = B_b - \frac{2}{3}B_3$(2.21)	$\tau_{G3} = \frac{1}{2}\rho_c g h B_3(B_b - \frac{2}{3}B_3)$ (2.22)

Table 2.1: Forces on gravity dam

Stability against overturning

According to the Norwegian safety requirement for overturning stability on gravity dams the point, *a*, where the resultant of all forces, *R*, is acting should be within the middle $\frac{1}{3}$-

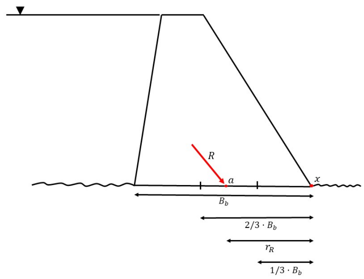

Figure 2.4: Resultant of all forces acting on dam

points of the cross section (NVE, 2005). This is expressed in Eq. 2.23 and shown Figure 2.4, where r_R is the arm of the resultant measured from the reference point *x*.

$$\frac{1}{3}B_b \leq r_R \leq \frac{2}{3}B_b \tag{2.23}$$

The safety factor against overturning, S, given in Eq. 2.24, is expressed as the relationship between stabilizing moment, M_S, and overturning moment, M_O. According to the Norwegian guidelines, it should generally be above 1.4 (NVE, 2005) and were set to $S = 1.5$ to have a small safety margin.

$$S = \frac{M_S}{M_O} = \frac{\tau_v + \tau_{G1} + \tau_{G2} + \tau_{G3}}{\tau_h + \tau_o} \tag{2.24}$$

Inserting the expressions for moments found in Table 2.1 into Eq. 2.24 gives us Eq. 2.25.

$$S = \frac{V_v(B_b - \frac{H}{3n}) + \frac{1}{3}\rho_c g h B_1^2 + G_2(B_1 + \frac{1}{2}B_2) + G_3(B_b - \frac{2}{3}B_3)}{\tau_h + \frac{1}{3}\rho_w g H B_b^2} \tag{2.25}$$

B_1 is then replaced in Eq. 2.25 using the relationship from Eq. 2.26.

$$B_1 = B_b - B_2 - B_3 \tag{2.26}$$

By rearranging Eq. 2.25 a quadratic equation, Eq. 2.27, on the form $aB_b^2 + bB_b + c = 0$ is obtained. Such a quadratic equation can be solved with the quadratic formula, provided by Eq. 2.28.

$$\left[\frac{1}{3}\rho_c gh - \frac{1}{3}\rho_w gHS\right] B_b^2 + \left[V_v - \frac{2}{3}\rho_c gh(B_2 + B_3) + G_2 + G_3\right] B_b$$
$$+ \left[\frac{1}{3}\rho_c gh(B_2 + B_3)^2 - M_h S - \frac{1}{3}\frac{H}{n}V_v - G_2(\frac{1}{2}B_2 + B_3) - \frac{2}{3}G_3 B_3\right] = 0 \quad (2.27)$$

$$B_b = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (2.28)$$

But before the total base width B_b can be calculated the upstream and middle base width, B_3 and B_2 respectively, needs to be determined.

The upstream base width, B_3, is calculated with Eq. 2.29 when the height, *h*, and upstream face slope, expressed as the dam width-to-height ratio, 1:n, is known.

$$B_3 = \frac{1}{n} \cdot h \quad (2.29)$$

In order to focus the weight of the concrete upstream and thus better withstand the water load from the reservoir, the upstream face of gravity dams is usually made vertical (Golze et al., 1977). However, a slope or a batter is sometimes used, especially on dams with wide dam crest (Golze et al., 1977) but also to reduce the risk of sliding (U.S. Army Corps of Engineers, 1995).

From an environmental and economic perspective minimizing the dam volume would be beneficial. Therefore, by applying the quadratic formula, Eq. 2.27 was solved for different values of B_2 and *n* and plotted against the dam volume as shown in Figure 2.5. The dam volume was calculated with Eq. 2.30.

$$V = \left(\frac{1}{2}B_1 + B_2 + \frac{1}{2}B_3\right) hl \quad (2.30)$$

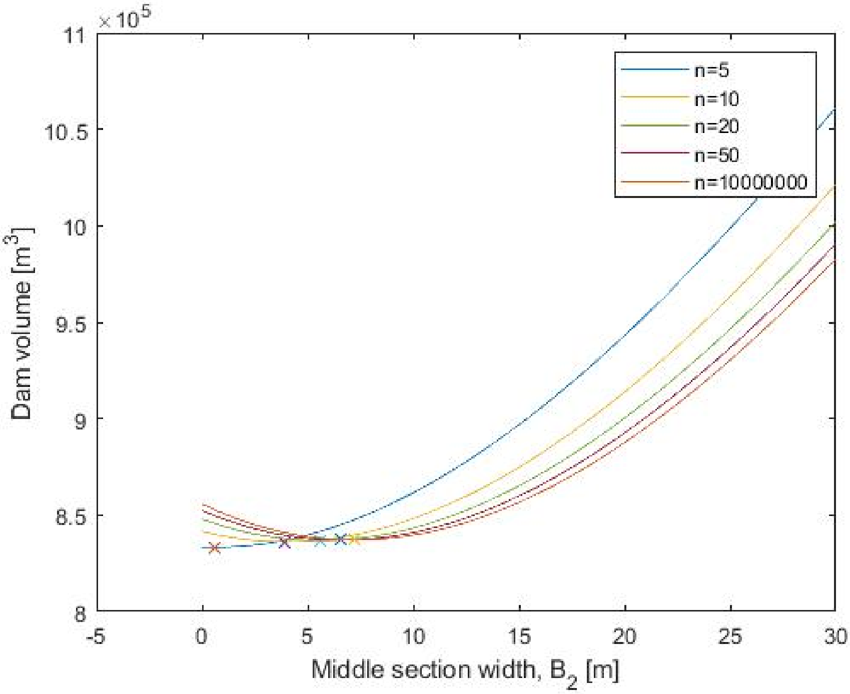

Figure 2.5: Dam volume plotted as a function of the middle section base width, B_2, for different upstream face slopes (n-values). The point where the dam volume reaches its lowest value is marked with a "x" on each graph. The figure is produced based on an example dam with height of 66m and length of 420m which is the average height and length of the 743 dams.

Increasing the *n*-value correspond to making the upstream face slope steeper, meaning the n = 100000000 graph practically represents a vertical face.

Figure 2.5 show that dam volume decreases marginally with a less steep upstream slope. However, the resultant arm is drawn closer to the lower overturning stability requirement as the upstream slope gets less steep, which negatively affects the overturning safety. On the other hand, the sliding safety is improved with a slope because of the reservoir water is pushing down on the dam. A slope of 1:10 was therefore chosen as a compromise between minimizing the dam volume and improved sliding safety versus better overturning safety.

The middle section width, B_2, was for each dam set to the value that generate the lowest dam volume, marked with a 'x' in Figure 2.5. It was also checked that the resultant arm, r_R, is within the middle $\frac{1}{3}$-points of the cross section as is expressed in Eq. 2.23.

2.4 LCIA

The LC-Impact methodology (Verones et al., 2020) was adopted to quantify the global potential disappeared fraction of species (PDF) from land use, water consumption, GHG-emissions, acidification, freshwater eutrophication and photochemical ozone formation. Country-specific characterization factors (CFs) provided in units of $PDF \cdot yr$ per unit of substance emitted (e.g. per kg CH_4) or per unit of resource used (e.g. per m^2 land area) were used to estimate the damage on ecosystem quality. LC-Impact also include characterization factors (CFs) for biodiversity impact from toxicity. However, toxicity impact was not included because the endpoint unit $[PDF \cdot m^3 \cdot day]$ is not directly comparable to the unit of the other impact categories $[PDF \cdot yr]$.

Marginal CFs were applied for all impact categories except for freshwater eutrophication and photochemical ozone formation where only linear CFs are available (Verones et al., 2020). The marginal modelling approach is the standard modelling method used in LCIA (Hauschild and Huijbregts, 2015). In this approach, CFs are derived by evaluating the effect on the impact indicator of increasing the background concentration/pressure by a small amount (i.e. taking the derivative of the cause-effect curve) (Hauschild and Huijbregts, 2015). The linear modelling approach is applied when the background concentration/pressure is unknown (Hauschild and Huijbregts, 2015).

For water stress and climate change both core and extended CFs are available. As opposed to core CFs, extended CFs for water stress includes effects from ground water consumption in addition to surface water consumption (Pfister et al.). For climate change, the extended CFs have a time frame of 1000 years, compared to 100 years for core CFs. The extended CFs were chosen because this study aims to assess the biodiversity impacts in a way that is as complete as possible, including the long-term effects.

When estimating the impacts from each reservoir an important assumption was made: all impacts take place in the country where the material is consumed, meaning where the potential future reservoir is located. This is a simplification because materials are often produced outside of the country where they are used. However, predicting where a future hydropower project would acquire its materials is not an easy task. One alternative method for predicting the origin of dam materials would be considering trade between countries by using so-called input-output tables. Another method is to assume the materials are obtained from the material production facilities closest to the reservoir location. However, these alternatives would likely be very time consuming and may not improve the accuracy of the results substantially.

Life cycle inventory data (i.e. emissions and resource use) per kg concrete block GLO, steel, low-alloyed GLO and gravel, round GLO were gathered from the Ecoinvent 3 database. The cut-off system model was chosen, which allocate the primary production of materials to the primary user (Ecoinvent website). As a result, the primary producer is not rewarded for providing material that is recyclable, thus the recycling processes receive recyclable material free of burden. Only impacts from the recycling process itself are allocated to recycled materials. Any usable by-products from waste treatment (e.g. heat) are free of burden because the burden is allocated to the waste producer (Ecoinvent website).

Land occupation and transformation

Land occupation and transformation impacts per kg of concrete, steel and gravel were first calculated individually before they were combined into one single impact score for land use.

The Ecoinvent database contains more land use type categories than LC-Impact. While LC-Impact distinguish between six land type categories, namely ”annual crops”, ”permanent crops”, ”pasture”, ”urban”, ”extensive forestry” and ”intensive forestry”, Ecoinvent 3 uses several more refined categories (e.g. ”construction site”, ”annual crop, non irrigated, extensive”, and ”shrub land”) (Koellner et al., 2013; Chaudhary et al.). In order to include the impact from Ecoinvent land use types which does not unambiguously fit into one of the LC-Impact categories, a conversion was made between the two. For instance, ”inland waterbody” and ”water bodies, artificial” were interpreted as the LC-Impact land type ”urban land” because these land use types were assumed to have little value as habitat for terrestrial species. Ecoinvents ”unknown” category were translated as ”pasture” because it has CFs that are in in the middle of the range with respect to impact (Chaudhary et al.). Marine land use types such as ”seabed drilling and mining” were omitted. A full list of the land use type conversions is provided in the supplementary information. Based on this translation, land occupation and transformation area inventory were summed to the LC-Impact categories before they were multiplied with the respective CFs for all countries.

2.4.1 Impact calculations

Emissions and resource use gathered from Ecoinvent 3 were multiplied with the associated CFs from LC-Impact for each impact category in order to calculate the country-specific biodiversity impact per kg of each material. Then, the biodiversity impacts of each dam were calculated by multiplying the amount of material required with the impact per kg material that correspond to the country where a potential dam is located.

Mathematically the impact score $is_{m,i,e,l,c}$ per kg of material *m* belonging to impact category *i* for elementary flow *e* (emitted substance or resource used) at location (country) *l* in compartment *c* (e.g. air, soil or water) can be expressed with Eq. 2.31

$$is_{m,i,e,l,c} = q_{m,e,c} \cdot CF_{i,e,l,c} \tag{2.31}$$

where *q* is the quantity of elementary flow *e* in compartment *c* per kg of material *m*.
CF is the characterization factor belonging to impact category *i* for elementary flow *e* at location *l* in compartment *c*.

The impact score per kg material *m* from impact category *i* is found by summing the contributions, shown in Eq. 2.32.

$$IS_{m,i} = \sum_{e} \sum_{l} \sum_{c} is_{m,i,e,l,c} \tag{2.32}$$

Finally, the impact score for reservoir *r* from impact category *i* is calculated with Eq. 2.33

$$IS_{r,i} = \sum_{m} [m_{r,m} \cdot IS_{m,i}] \tag{2.33}$$

This calculation procedure is similar to the one described in Hauschild and Huijbregts (2015) Eq. (1.2) and (1.3). The difference is that, in this study, the amount of material is first included in the calculations at the end with Eq. 2.33.

Finally, terrestrial or aquatic ecosystem damage were calculated by aggregating the impacts from the different impact categories. Terrestrial damage comprises of $PDF \cdot yr$ from land use, water use, terrestrial GHG, acidification and photochemical ozone formation, while aquatic GHG and freshwater eutrophication make up the aquatic damage. It's important to note that the different impact categories in LC-Impact have different taxonomic coverage (Verones et al., 2020). The implications of this are that impacts on some species are given more weight than others.

2.4.2 Impact comparison on a per reservoir basis

A deeper comparison between terrestrial construction and operation impact was conducted. Four scenarios were made in order to find out if the amount hydropower potential that can be utilized from a biodiversity perspective changes by adding the construction impact to the operation impact. It was investigated which hydropower projects (HPs) that would be built if terrestrial biodiversity impact is limited to:

less than 75% - i.e. 3.93×10^{-2} PDF*yr for combined (construction + operation) impact, and 2.46×10^{-2} for operation impact

less than 50% - i.e. 2.62×10^{-2} PDF*yr for combined impact, and 1.64×10^{-2} for operation impact

less than 25% - i.e. 1.31×10^{-2} PDF*yr for combined impact, and 8.22×10^{-3} for operation impact

less than 10% - i.e. 5.24×10^{-3} PDF*yr for combined impact, and 3.29×10^{-3} for operation impact

of the cumulative impact (i.e. 5.24×10^{-2} PDF*yr for combined impact, and 3.29×10^{-2} for operation impact).

For each scenario, each of the 743 HPs were placed into one of four groups. These groups reveal how many HPs that are going to be built depending on whether combined impact or operation impact is the basis for the decision. The groups are defined as follows;

Group 0: # of HPs that are not built regardless of considering operation or total terrestrial impact.

Group 1: # of HPs that are only built when considering operation terrestrial impact

Group 2: # of HPs that are only built when considering combined (construction + operation) terrestrial impact

Group 3: # of HPs that are built both when considering combined and when considering operation terrestrial impact

With this grouping, the total number of HPs built when considering combined terrestrial impact is the sum of Group 3 and Group 2 HPs. Likewise, the total number of HPs built when considering operation terrestrial impacts is the sum of Group 3 and Group 2 HPs.

For each scenario, the location of HPs in Group 1 to 3 were plotted on a world map using ArcGIS Pro version 2.5.0 (Esri). This was done in order to identify which regions of the world HPs can be realized if the goal is to avoid a large proportion of the terrestrial biodiversity impact. MATLAB R2020b was used both in dam dimension calculations and in the LCIA.

2.4.3 Impact categories

This section gives a brief overview of the impact categories from LC-Impact Version 1.0 that were adopted in this study. More detailed information can be found in the LC-Impact report (Verones et al.).

Land stress

The country CFs that were used in this study is created by taking the share of ecoregions within each country (Chaudhary et al.). Ecoregions are areas of ”distinct assemblage of natural communities and species” (Olson et al., 2001). The land use characterization factors are specific for mammals, birds reptiles amphibians and vascular plants (Verones et al., 2020). Marginal CFs were chosen, but also average CFs exists.

Water stress

Water stress (also called water use/consumption) impacts were regarded as terrestrial because they relate to mammals, birds, reptiles, amphibians and vascular plants (Pfister et al.). CFs provided in LC-Impact uses a marginal modelling approach.

Climate change

There are no country-specific CFs for climate change because GHGs are assumed to distribute equally across the atmosphere. Aquatic CFs are based on impacts on fish, while terrestrial impacts are based on mammals, birds, frogs, reptiles, butterflies and plants (Steinmann and Huijbregts). Climate change CFs uses a mix of marginal and average modelling.

Terrestrial acidification

Terrestrial acidification cover damages to vascular plants from air-emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3) (Azevedo et al., a). The damages arise from a fall in soil PH following deposition of acidifying nitrogen and sulfur compounds (Azevedo et al., a).

Freshwater eutrophication

The origin of freshwater eutrophication is the emission of nitrogen and phosphorus into water bodies. Of the two, phosphorus is the most important reason for eutrophication in freshwater while nitrogen is most important for marine eutrophication. LC-Impact provide country CFs for emission of phosphorous into water and soil taking into account impacts on fish species (Azevedo et al., b). CFs are based on a linear modelling approach (Azevedo et al., b).

Photochemical ozone formation

The first step on the impact pathway for photochemical ozone formation is the emission of nitrogen oxides (NO_x) and Non Methane Volatile Organic Compounds (NMVOCs) into the air (van Zelm et al.). When these compounds transform into ozone(O_3) in the lower part of the atmosphere (troposphere) they can be absorbed by plants and reduce the growth and seed production (Ashmore, 2005). The country CFs used in LC-Impact is based on effects on forests and natural grassland and uses linear modelling.

Chapter 3

Results and discussion

This chapter starts by going through the average share of materials used in gravity and embankment dams based on the performed literature search. Then, the results of the biodiversity impact calculations for different impact categories are presented. Finally, the biodiversity impacts from material use in the construction phase found in this study were compared with the operation impacts from Dorber et al. (2020).

3.1 Material share

As shown in Table 3.1, the percentage share of concrete and steel that are used in the 6 gravity dams considered are fairly consistent. The volumetric share of concrete and steel varies only from 99.61% to 99.78% (99.72 % on average) and 0.22% to 0.39% (0.28% on average) respectively. From Table 3.1 it is evident that concrete is the dominant material in terms of both mass and volume. The small variation in the concrete-steel volume ratio puts greater certainty in the biodiversity impact results from gravity dams despite the relatively small collection of studies.

Besides being the main material used in the dam structure, concrete has a wide range of applications in a hydropower facility, such as buildings, tunnels, powerhouse and spillways (Flury and Frischknecht, 2012). Likewise, steel has more uses than just as reinforcement in the dam, for example in the turbine, generator, buildings and pipelines (Flury and Frischknecht, 2012). Even though this study only assesses the biodiversity impacts from material use of the dam structure, the inventory data that was gathered might well include materials used for other applications. As a result, the volumetric share used in the calculations may be shifted towards a higher share of steel or concrete. This is a small limitation that could be improved in future assessments if more detailed inventory data become available.

Table 3.1: Gravity dam inventory and share of construction materials.

Reference		(Li et al., 2017)	(Zhang et al., 2015)	(Pang et al., 2015)	(Rule et al., 2009)	(Flury and Frischknecht, 2012)		(IEA, 2002; Uchiyama, 1995)	
Power plant		Xiangjiaba (XJB)	Nuozhadu	Guanyinyan small hydropower plant	Clyde dam	Average based on 52 dams			
Country		China	China	China	New Zealand	Switzerland		Japan	
Facility type		Sorage	Storage	Storage	Storage	Storage			
Dam type		Gravity	Gravity	Gravity - dam-toe	Gravity	35 arch, 17 gravity and 1 buttress		Concrete dam	
Dam construction materials	**Unit**						**Unit**		**Average**
Concrete	kg	6.49E+10	4.00E+06	5.12E+07	2.32E+09	1.05E+09	kg/kWh	6.87E-02	
Steel	kg	4.83E+08	4.80E+04	4.27E+05	1.86E+07	7.63E+06	kg/kWh	9.06E-04	
Dam weight (concrete and steel)	kg	6.53E+10	4.05E+06	5.17E+07	2.34E+09	1.05E+09	kg/kWh	6.96E-02	
Weight % concrete		99.26%	98.81%	99.17%	99.21%	99.28%		98.70%	99.07%
Weight % steel		0.74%	1.19%	0.83%	0.79%	0.72%		1.30%	0.93%
Concrete	m3	2.75E+07	1.70E+03	2.17E+04	9.84E+05	4.43E+05	m3/kWh	2.91E-05	
Steel	m3	6.16E+04	6.11E+00	5.45E+01	2.37E+03	9.72E+02	m3/kWh	1.15E-07	
Dam volume (concrete and steel)	m3	2.76E+07	1.70E+03	2.18E+04	9.87E+05	4.44E+05	m3/kWh	2.92E-05	
Volume % concrete		99.78%	99.64%	99.75%	99.76%	99.78%		99.61%	99.72%
Volume % steel		0.22%	0.36%	0.25%	0.24%	0.22%		0.39%	0.28%

Table 3.2 show that the volumetric material share of fill-material in embankment dams ranges from 84.07% to almost 100 % (94.21% on average). On average, 5.74% of the volume of embankment dams is concrete and 0.05% is steel. The volumetric share of materials used in embankment dams varies more than for gravity dams, much due to the Itaipu dam, which as mentioned also has gravity and buttress sections. Other types of embankment dams, not represented here, may also affect the uncertainty of these results. For example, rockfill dams with either frontal sealing or impervious core made of concrete, may require a higher amount of concrete than the Nuozhadu and Baba dam. With this taken into account, the higher concrete consumption of the Itaipu dam may actually compensate for the lack of data from these other types of embankment dams.

The number of studies that were found reporting inventory data were relatively few. Other studies has also expressed the lack of available inventory data from the construction phase of hydropower plants (Moreau et al., 2012; Gibon et al., 2017a; Flury and Frischknecht, 2012). What may help to explain this is high dam age and many different contractors and subcontractors involved in the construction process (Flury and Frischknecht, 2012). Confidentiality issues can also make it difficult to gain access to inventory data (Wernet et al., 2009).

In this study, only the most commonly reported materials used in HPs was included. With several and more detailed inventory data sets available, studies like this could also include other materials and products like explosives, diesel, copper, oil and electricity which was found reported (Ribeiro and Silva, 2010) and are most likely used in many HPs. This could improve the accuracy of the impact estimations.

Table 3.2: Embankment dam inventory and share of construction materials.

Reference		(Zhang et al., 2015)	(Hidrovo et al., 2017)	(Ribeiro and Silva, 2010)	
Power plant		Nuozhadu	Baba	Itaipu	
Country		China	Ecuador	Brazil and Paraguay	
Facility type		Storage	Storage	Storage	
Dam type		Embankment - earth core rock-fill dam	Embankment	Embankment with gravity and buttress sections	
Dam construction materials	**Unit**				**Average**
Fill material	kg	4.61E+10	3.06E+10	1.13E+11	
Concrete	kg	1.00E+06	5.26E+08	2.54E+10	
Steel	kg	3.45E+05	1.11E+07	7.97E+08	
Dam weight (fill material, concrete and steel)	kg	4.61E+10	3.11E+10	1.39E+11	
Weight % fill material		100.00 %	98.28 %	81.17 %	93.15 %
Weight % concrete		0.00 %	1.69 %	18.26 %	6.65 %
Weight % steel		0.00 %	0.04 %	0.57 %	0.20 %
Fill material	m3	2.30E+07	1.53E+07	5.74E+07	
Concrete	m3	4.24E+02	2.23E+05	1.08E+07	
Steel	m3	4.39E+01	1.42E+03	1.02E+05	
Dam volume (fill material, concrete and steel)	m3	2.30E+07	1.55E+07	6.83E+07	
Volume % fill material		100.00 %	98.55 %	84.07 %	94.21 %
Volume % concrete		0.00 %	1.44 %	15.78 %	5.74 %
Volume % steel		0.00 %	0.01 %	0.15 %	0.05 %

3.2 Biodiversity impacts from dam construction phase

Size and spread of impacts

Biodiversity impacts per kWh yr^{-1} for the different impact categories are shown in Figure 3.1 and Table 3.3. Looking at the impact from each category, the size varies by several orders of magnitude. The impact category with largest impact, for both dam types, is land use (average between 2.83×10^{-14} and 3.27×10^{-14} PDF*yr/(kWh/yr)). The land use impact is about one order of magnitude higher than the terrestrial GHG impact (average between 1.97×10^{-15} and 3.01×10^{-15} PDF*yr/(kWh/yr)), which is the second most significant impact category. Freshwater eutrophication and photochemical ozone formation have the smallest impacts, which on average are more than 100 000 times lower than from land use.

The range of impact from dams varies between the impact categories. The variation in impacts caused by GHG-emissions are small with few outliers compared to the other categories. The difference between the dam with highest and the dam with lowest impact is only about two orders of magnitude. In contrast, impacts from acidification span over six orders of magnitude. The dams with largest acidification impacts are on the same level as impacts from aquatic and terrestrial GHG-emissions, although the median value lies between three and four orders of magnitude bellow the value of GHG-emissions.

The reason for this is likely because GHG CFs are global as opposed to CFs for the other categories which are country-specific. Dams located in countries with high species richness, vulnerable ecosystems and many endemic species that risk global extinction will have a higher impact score than dams located in countries with common land types and

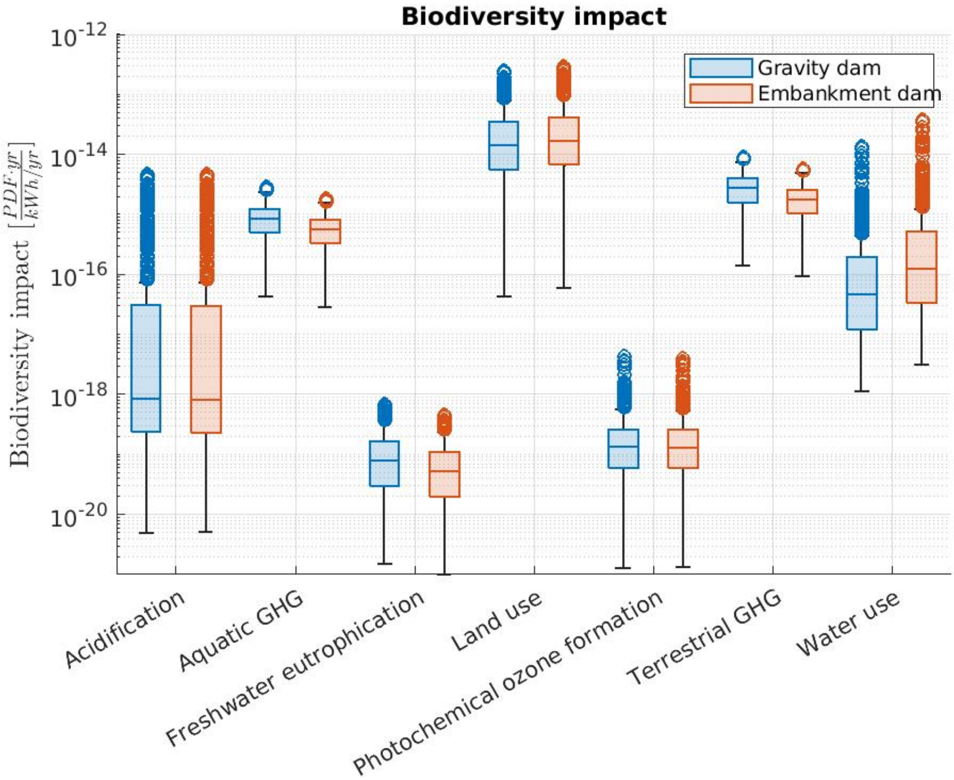

Figure 3.1: Biodiversity impacts per kWh annual electricity production from material use in potential future reservoir-based dams given they are either gravity or embankment dams. Note that the scale is logarithmic because of the large variation in impacts from different impact categories. The whiskers represent $1.5 \cdot IQR$ above and below the box. *IQR* stands for interquartile range and is the distance between the first and the third quartile ($IQR = Q_3 - Q_1$, i.e. the length of the box)

globally widespread species. Consequently, there will be greater spread in impacts than from GHG-emissions which act globally and rely only on the amount of material consumption.

As seen in Figure 3.1, the span of impacts from water use is also large. The top 4 dams with highest water use impacts are located in Australia. In addition to reside many species that are not found anywhere else on Earth. Australia is also a country that is extremely dry which can explain this results (Pollino and Couch, 2014).

The top three countries with the highest average land use impacts are Costa Rica, the Philippines and Madagascar, all of which are known for their rich and unique nature. Island states often have a unique wildlife because the water barrier limits the competition with species from the mainland and allows life to evolve in new directions. However, these species are often confined to a one or few islands, which makes them vulnerable to intervention. The land use CFs takes this into account as they are based on the geographical extent of species, and the threat level obtained from IUCN red list of threatened species (Chaudhary et al., 2015).

The importance of land occupation and transformation damage on ecosystem quality from hydropower was also evident in a study by Gibon et al. (2017b). They found that about half of the damage to ecosystem quality was caused by land occupation and transformation, while the other half was induced by climate change. Similar to results from this study, impacts from freshwater eutrophication and acidification were marginal in comparison.

Gravity vs embankment dams

Figure 3.2 show the contribution of different materials to four of the most important impact categories. The main construction materials (i.e. concrete for gravity dams and gravel for embankment dams) is also the main contributors to biodiversity impacts from land use. However, looking at GHG-emissions impacts for embankment dams, concrete and steel is responsible for a relatively large proportion of the impacts (29.3% and 15.5% respectively) considering they only make up 5.74 % and 0.05% of the dam volume.

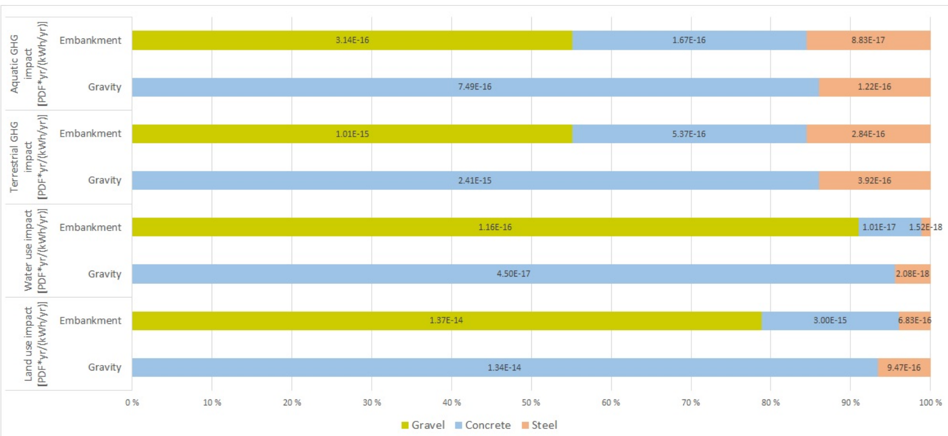

Figure 3.2: Biodiversity impact contribution of gravel, concrete and steel to land use, water use, terrestrial GHG and Aquatic GHG based on median values.

Terrestrial and aquatic GHG biodiversity impact are on average 34.7 % lower for gravity dams compared to embankment dams. These results match the results of Zhang et al. (2015) (also included among the studies reporting dam inventory) which found that an earth-rockfill embankment dam had 24.7% less CO_2-emissions than concrete gravity dams because of the carbon intensive concrete production.

Overall, the biodiversity impact from gravity dams versus embankment dams are relatively equal as seen in both Figure 3.1 and Figure 3.3. However, the mean terrestrial impact is 12.4 % higher for embankment dams, mostly due to greater land use impact. Also water use impact (considered terrestrial) is larger compared to gravity dams. On the other hand, gravity dams have on average 53.1 % greater aquatic impact than embankment dams, mainly because of the concrete consumption which results in higher aquatic GHG impact.

Table 3.3: Minimum (ignoring numbers that are zero), maximum, mean and median of biodiversity impacts per reservoir and per kWh/yr.

		Biodiversity impact per reservoir [PDF*yr/reservoir]				**Biodiversity impact per FU [PDF*yr/(kWh/yr)]**			
Impact category		Min	Max	Mean	Median	Min	Max	Mean	Median
Land use	Gravity	5.87E-08	4.00E-04	2.36E-05	9.69E-06	4.33E-17	2.41E-13	2.83E-14	1.43E-14
	Embankment	8.41E-08	4.24E-04	2.69E-05	1.16E-05	5.96E-17	2.83E-13	3.27E-14	1.74E-14
Water use	Gravity	1.15E-09	1.14E-05	1.56E-07	3.47E-08	1.16E-18	1.35E-14	3.36E-16	4.70E-17
	Embankment	3.34E-09	3.12E-05	4.22E-07	9.46E-08	3.17E-18	3.78E-14	9.17E-16	1.28E-16
Terrestrial GHG	Gravity	8.85E-08	2.39E-05	2.42E-06	1.50E-06	1.44E-16	8.99E-15	3.01E-15	2.80E-15
	Embankment	6.06E-08	1.51E-05	1.56E-06	9.72E-07	9.44E-17	5.73E-15	1.97E-15	1.83E-15
Aquatic GHG	Gravity	2.75E-08	7.43E-06	7.52E-07	4.66E-07	4.46E-17	2.80E-15	9.37E-16	8.71E-16
	Embankment	1.88E-08	4.68E-06	4.86E-07	3.02E-07	2.93E-17	1.78E-15	6.12E-16	5.69E-16
Acidification	Gravity	6.91E-12	3.74E-06	1.17E-07	5.75E-10	5.10E-21	4.59E-15	2.16E-16	6.51E-19
	Embankment	7.45E-12	3.70E-06	1.17E-07	5.73E-10	5.28E-21	4.59E-15	2.18E-16	6.47E-19
Freshwater eutrophication	Gravity	4.23E-13	1.71E-09	8.93E-11	4.99E-11	1.52E-21	6.67E-19	1.19E-19	7.99E-20
	Embankment	2.77E-13	1.12E-09	5.88E-11	3.33E-11	9.98E-22	4.54E-19	7.85E-20	5.37E-20
Photochemical ozone formation	Gravity	3.64E-13	2.88E-09	1.59E-10	7.82E-11	1.31E-21	4.29E-18	2.37E-19	1.38E-19
	Embankment	3.74E-13	2.69E-09	1.51E-10	7.66E-11	1.35E-21	3.95E-18	2.27E-19	1.34E-19
Terrestrial	Gravity	4.27E-07	4.20E-04	2.63E-05	1.15E-05	4.41E-16	2.50E-13	3.18E-14	1.79E-14
	Embankment	3.25E-07	4.38E-04	2.90E-05	1.29E-05	3.29E-16	2.90E-13	3.58E-14	2.11E-14
	Operation	1.84E-08	8.72E-03	4.42E-05	4.61E-06	2.89E-17	4.44E-12	3.89E-14	7.78E-15
Aquatic	Gravity	2.75E-08	7.43E-06	7.52E-07	4.66E-07	4.46E-17	2.80E-15	9.37E-16	8.72E-16
	Embankment	1.88E-08	4.68E-06	4.86E-07	3.02E-07	2.93E-17	1.78E-15	6.12E-16	5.69E-16
	Operation	1.51E-09	3.26E-04	4.85E-06	9.28E-07	2.00E-18	4.21E-13	8.24E-15	1.37E-15

3.3 Comparison of biodiversity impacts from construction with operation phase

In the following sections, construction impacts calculated in this study are compared with operation impacts quantified by Dorber et al. (2020) on a per kWh/yr and per reservoir basis. The impacts from gravity dam construction are based on more studies, giving a more consistent data foundation compared to the impacts from the embankment dam construction. Therefore, only the impacts from gravity dam construction are used in the comparison with impacts from the operation phase. Moreover, impacts from the two dam types turned out to be approximately the same sizes, and hence, it is assumed that the differences are small.

3.3.1 Impact comparison on a per kWh/yr basis

As shown in Figure 3.3, the terrestrial biodiversity impact is higher (131%) from construction than from operation if looking at the median value. However, the mean terrestrial impact is higher (22%) for operation, as seen in Table 3.3. This is explained by the most harmful HPs with respect to operation which pull up the average value. The terrestrial biodiversity impacts from construction varies over a narrower range (between 4.41×10^{-16} and 2.50×10^{-13} PDF*yr/(kWh/yr)) compared to the operation impacts (between 2.89×10^{-17} and 4.44×10^{-12} PDF*yr/(kWh/yr)).

Unlike construction impacts, that were calculated using country averaged CFs, operation impacts were based on CFs specific for terrestrial and aquatic ecoregions (Olson et al., 2001; Abell et al., 2008). For land use the country CFs are modelled using the share

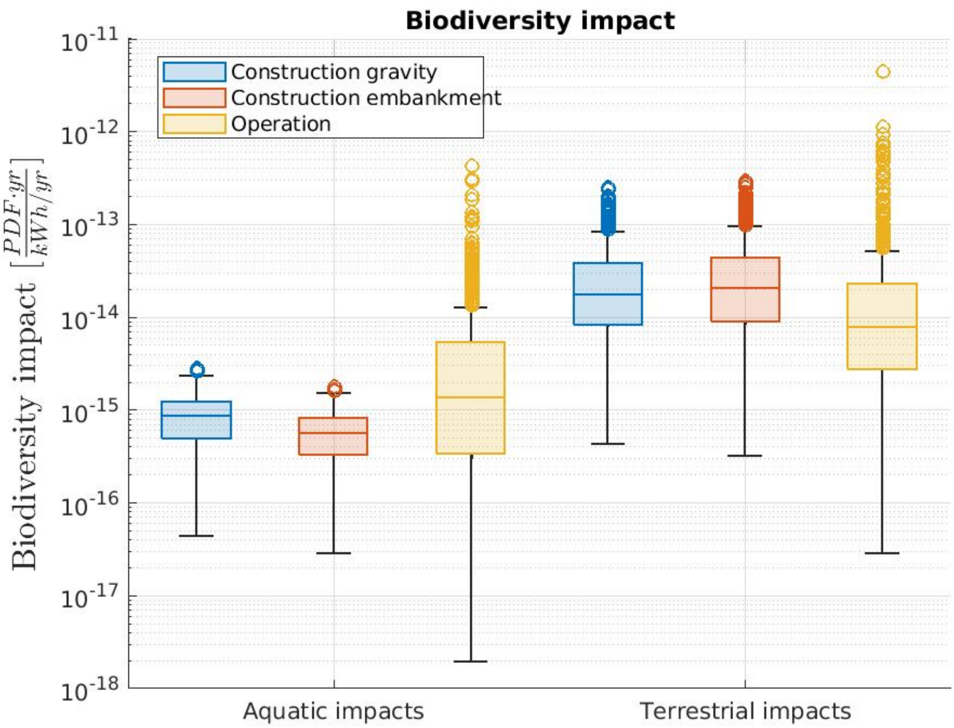

Figure 3.3: Terrestrial and aquatic biodiversity impacts from construction (given they are either gravity or embankment dams) and operation phase of potential future reservoir-based dams. Note that the scale is logarithmic because of the large variation in impacts.

of different ecoregions within each country (Chaudhary et al.). As a consequence, a HPs located in an ecoregion with high damage potential, can be estimated to have an unrealistic low impact value if the ecoregion only make up a small part of the country area. This effect is more prominent in large countries, for example USA, Canada, Russia and China, which have a great range of ecosystem types within the country, but only have one CF each. In other words, operation impacts have higher spatial resolution than the construction impacts. This methodological difference may explain why a greater variation is seen in the operation impacts compared to the construction impacts.

Aquatic biodiversity impact from the operation phase is 57% higher compared to the construction phase regarding the median value and 779% (almost 9 times) higher with respect to the mean value. Like for terrestrial impact, the large spread in aquatic operation impacts, with a few high-impact reservoirs, is responsible for this large difference between the mean and median value. The reservoir with greatest aquatic impact from operation is over 150 times higher than that of construction. On the other hand, the minimum impact reservoir of construction is only 22 times the size of the minimum operation.

One explanatory factor for the greater aquatic operation impact is that aquatic impact of water consumption is not addressed for the construction phase. As mentioned previously, the water use CFs in LC-Impact only cover terrestrial taxonomic groups (Pfister et al.).

Correlations

The Pearson product-moment correlation coefficient, r, was used to investigate the correlation between different data parameters. In addition, possible correlations between construction and operation impacts, construction and combined impacts and operation and combined impacts are visualized in Figure 3.5 (terrestrial) and Figure 3.6 (aquatic) in the Appendix. These figures were made by ranking HPs from 1 to 743 based on the size of different types of impact and then plotting the ranks against each other.

No strong correlation was found for terrestrial biodiversity impacts between the construction and the operation phase ($r = 0.05$ for impact values and $r = 0.09$ for ranks). This is also apparent from Figure 3.5a in Appendix. The aquatic impact correlation was also fairly weak between the two phases ($r = 0.06$ for impact values and $r = 0.21$ for ranks) as shown in Figure 3.6a in Appendix.

One possible way of explaining this finding is that the operation impacts due to land use ultimately rely on the area occupied by the reservoir. This is also true for water consumption due to evaporation. However, the impacts found in this study depend on the dam volume which in turn rely on the height, length of the dam. Now, there does not need to be any connection between reservoir area and dam volume. For instance, a small dam placed in the bottleneck of a valley can create a large reservoir. Conversely, a large dam built in a narrow valley may impound a relatively little area, even if the reservoir volume is large. Also, reservoirs created at sites were a lake already exists may occupy little new land area. The relatively weak correlation between reservoir surface area and dam volume ($r = 0.12$) supports this reasoning. Local variations in topography, as was also highlighted by UNEP (2016) as an important determinant of dam size and building material requirements and consequently the impacts of the hydroelectric plant.

Another important factor which can help explain the weak relationship between operation phase and construction phase biodiversity impact is the difference in spatial resolution which was mentioned earlier. Dorber et al. (2020) points out that the local environmental variations, such as the flooded land cover type, species richness, ecoregion and global extinction probability, is the main reasons for variations seen in operational land use impacts. Similarly, river size and location, species richness and global extinction probability was the main factors responsible for aquatic impacts. As explained earlier, these spatial variations are to some degree hidden in the construction impacts, because of the use of country CFs as opposed to ecoregion CFs.

By looking at the correlation between construction vs combined (construction + operation) and operation vs combined impacts we can say something about the importance of the contribution from the two hydropower life cycle phases. The correlation between ranked terrestrial impact from construction vs combined is quite strong ($r = 0.74$), as is also seen in Figure 3.5b. However, correlation between the actual impacts is weaker ($r = 0.25$). This indicates that the terrestrial construction impact is more important for the prioritization of HPs than for the size of the actual impact.

The correlation between terrestrial impact from operation vs combined is strong for both impact values and ranked values ($r = 0.98$ for impact values and $r = 0.61$ for ranks). It can be seen from Figure 3.5c that the top combined-impact reservoirs are especially strongly related to operation phase impacts. However, ranked correlation with combined impacts are overall a little higher for construction phase than for operation phase, as is also seen by comparing Figure 3.5b and Figure 3.6c. This indicates that it is important to account for both construction and operation impact when assessing the damage to terrestrial biodiversity from hydropower projects.

The picture is a little different when looking at aquatic biodiversity impact. No strong relationship was found between construction and combined aquatic impact values ($r = 0.08$). Once again, the construction impacts have a stronger influence when ranking the reservoirs ($r = 0.45$ for ranks) as shown in Figure 3.6b. Still the influence is not as large as for terrestrial impacts.

Aquatic impacts are to a great extent dominated by impacts from the operation phase ($r = 1.00$ for impact values and $r = 0.94$ for ranks). This is also apparent from Figure 3.6c. The operation phase is responsible for almost all impact in the top range which is displayed by the linearity in Figure 3.6c.

These results imply that if the goal is to minimize the aquatic biodiversity impact, the operation phase should be focused on. However, this result should be interpreted with reservation because, as mentioned before, freshwater biodiversity impact of water consumption from construction was not assessed. Other negative effects of hydropower production such as river fragmentation (Barbarossa et al., 2020), alteration of the natural flow regime (Poff et al., 1997) and the river-to-lake habitat transformation (Gehrke et al., 2002) which were not considered in this study, can also change the perception of which life cycle phase should be weighted most in a decision-situation. Preferably, as many impacts as possible should be considered.

3.3.2 Impact comparison on a per reservoir basis

This section will only focus on the comparison of terrestrial impact per reservoir. Dorber et al. (2020) found that 96% of the total hydropower potential can be utilized and at the same time avoid half of the terrestrial biodiversity impact from operation. This is still true for the smaller selection of 743 HPs that were investigated in this study. But will this result change if the construction impacts are added to the operation impacts? Can still a high hydropower potential be utilized while avoiding most of the terrestrial biodiversity impact?

In order to answer these questions, it was investigated which hydropower projects (HPs) that would be built in four scenarios where terrestrial biodiversity impact is limited to less than 75%, less than 50%, less than 25% and less than 10% of the cumulative potential. How this was done is explained in detail in the Methods chapter. The results of this investigation are shown in Figure 3.4.

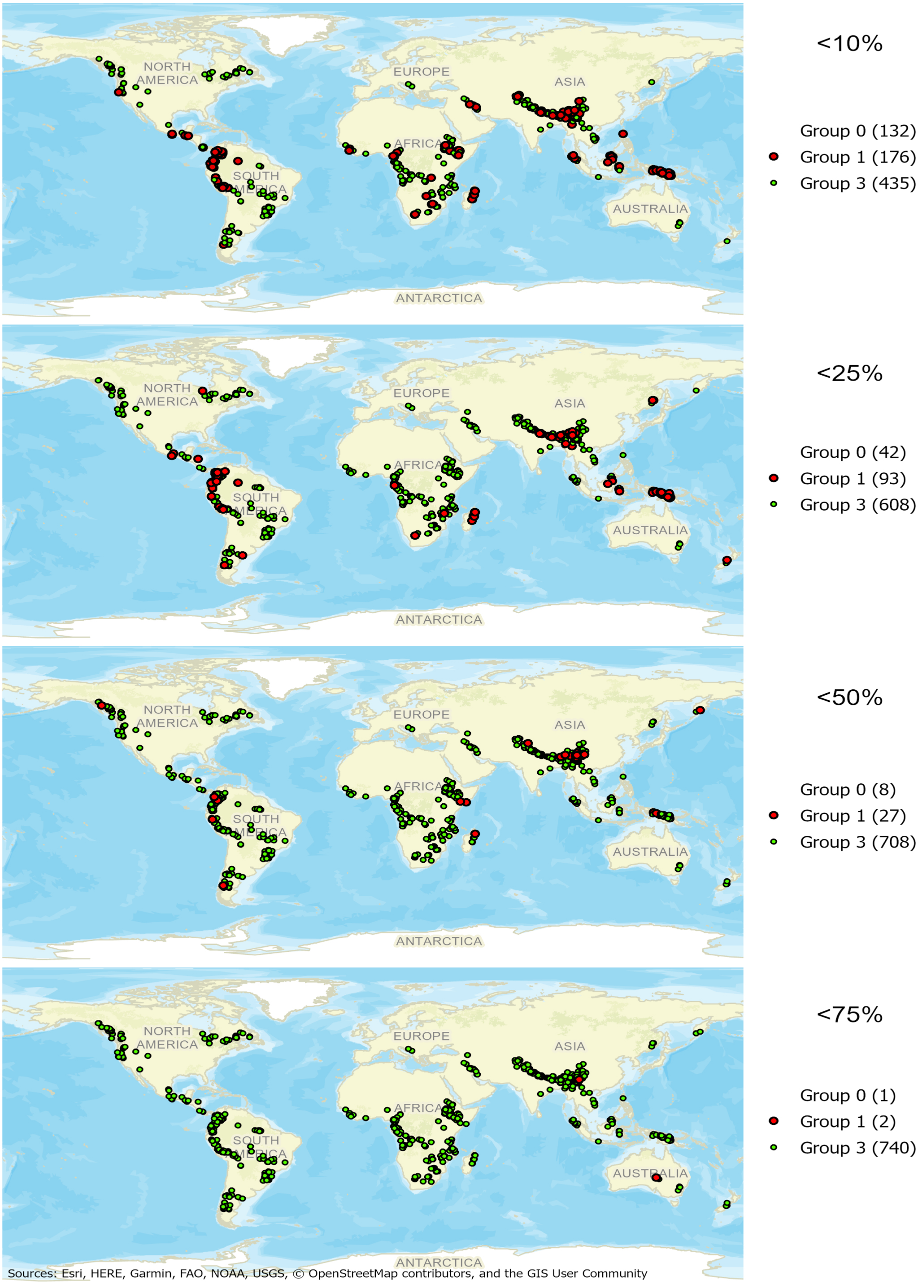

Figure 3.4: HPs that is realized in scenarios where terrestrial biodiversity impact is limited to $<10\%$, $<25\%$, $<50\%$ and $<75\%$. HPs in Group 3 would be realized regardless of considering combined (construction + operation) or just operation impact. HPs in Group 2 would be realized only in the case combined impact is considered. HPs in Group 1 would be realized only in the case operation impacts is considered. HPs in Group 0 will not be realized in either case. The number of HPs are in given in parentheses and sum up to 743 in each scenario.

First of all, none of the scenarios had HPs that would be built when only accounting for the combined terrestrial impact (Group 2). One way of interpreting this is that the low-impact reservoirs are in most cases built regardless of whether construction impacts are included or not while the high-impact reservoirs, which are largely governed by operation impacts, will not be built also when considering construction impacts. This is also a sign of the strong correlation between operation and combined impacts with respect to per reservoir ($r = 0.99$), just as it was per kWh/yr ($r = 0.98$).

The $<75\%$ scenario and the $<50\%$ scenario are similar, with the vast majority of HPs being built, both when regarding combined impacts and when regarding operation impacts (Group 3). The reason for this is that a few HPs with very high operation impact add a lot to the combined impact. So much that even halving impact would still mean that most HPs can be realized. As many as 708 of the HPs, accounting for 86% of annual electricity production, can be realized if half of the terrestrial biodiversity impact is avoided. The fact that few HPs (2 HPs for the $<75\%$ scenario and 27 HPs for the $<50\%$ scenario) are built solely by considering operation impacts (Group 1) supports this explanation. In other words, construction impact has less significance if we look at the HPs with the highest impact, as was also true when comparing on a per kWh/yr basis.

If less than 25% of terrestrial impact is allowed, 608 HPs (accounting for 61% of annual production) can be built with respect to combined and operation impact (Group 3). Similarly, if less than 10% of terrestrial impact is allowed, 435 HPs (accounting for 31% of annual production) can be built. Although this is a considerable reduction from the other scenarios, it still corresponds to a production size of 554 TWh/yr and 277 TWh/yr respectively. This equals 86% and 44% respectively of the annual hydropower production in Europe (632 TWh in 2019) (Our World in Data, b).

Note that the number of HPs that is only built when considering operation impacts (Group 1) is increasing as less terrestrial biodiversity impact is allowed (42 HPs for $<25\%$ and 132 HPs $<50\%$). This indicates that construction impact become important if we rule out the HPs with the highest impact. This characteristic is also shown in Figure 3.7 in Appendix where terrestrial biodiversity impact from operation is sorted in ascending order and plotted cumulatively together with construction and combined impacts. In this figure the construction + operation -curve follows the construction-curve in the beginning (until ca 400 TWh/yr) before it flattens out and the two curves separate. This suggest that HPs with high terrestrial construction impacts have relatively low operation impacts. Conversely, HPs with high terrestrial operation impacts have low construction impacts, as the flat profile at the end of the construction-curve and the exponential profile of the operation-curve indicates.

Several locations stand out as beneficial if the aim is to prevent most of the potential terrestrial impacts. For instance, seven of the ten HPs with lowest combined terrestrial impacts are located in Canada. Hotspots for hydropower development in the $<10\%$ scenario include, in Africa, the Congo basin and several of the basins located in Ethiopia (the Juba-Shibeli basin, the Lake Turkana basin, Latagiti swamp basin and the Nile basin). In South America La Plata basin south in Brazil and the western parts of Amazon basin in Peru is especially interesting. In Asia upper reaches of the basins of Brahmaputra, Ganges, Yangtze and Mekong have large potential. Many of the same basins have also been highlighted in other studies as having a large remaining hydropower potential (Zarfl et al., 2019; Moran et al., 2018).

So, should we exploit less of the remaining hydropower potential if we include construction impacts? Based on the decision-approach used in the scenario-analysis in this study, it will not make a big difference unless we want to avoid more than 75% to 90% of total potential terrestrial impact. This is because the HPs with highest operation impacts contribute so much to the total combined impacts that most reservoirs will be built unless we aim to avoid a high share of the total terrestrial impact. However, construction impacts become much more important if we rule out the relatively few HPs with highest impact and then look at which HPs we should prioritize. HPs with high construction impacts have low operation impacts and vice-versa which the weak correlation between construction and operation impacts also indicates. This implies that both life-cycle phases should be included. In terms of aquatic biodiversity impacts, they are to a large extent dominated by the operation phase. However, this may be because aquatic impact from water consumption from the construction phase was not addressed.

3.4 Research outlook

While this study shows the importance of the contribution of construction materials to biodiversity impacts from potential future hydropower projects, several impact pathways, materials, products and other refinements can be examined to obtain a more a complete assessment. Especially aquatic impact from water consumption should be investigated, but also impacts from toxicity remain unaddressed. Adding materials, such as explosives, diesel, copper, oil and electricity, would benefit the impact estimations, but will require several and more detailed inventory data from existing hydropower plants. Assessing biodiversity impacts on an ecoregion scale for the construction phase would be interesting and could increase the variations in the impacts and improve spatial accuracy of the results. Today, LC-Impact only provide this option for land stress.

Future work also include assessing the impact of infrastructure (e.g. roads, power lines) which is likely to have increasing influence because many of the most accessible hydropower sites are already exploited. Transport emissions could also be looked at in future assessments. A LCA of two planned hydropower plants in Chile revealed that transportation accounted for a large proportion of the different impact categories from one of the plants due to the remote location (Gibon et al., 2017a). The remotely located hydropower plant had substantially higher GHG-emissions compared to the other hydropower plant which was located in proximity to existing infrastructure.

This assessment expands the understanding of biodiversity impacts from future hydropower production. This information can be important in a world that strive to mitigate climate change by replacing fossil fuel with renewable energy sources and at the same time protect its last remaining wildlife.

Acknowledgements

Thanks to Martin Dorber and Francesca Verones for helpful discussions and guidance. Special thanks to Martin Dorber and David E. H. J. Gernaat for sharing their data.

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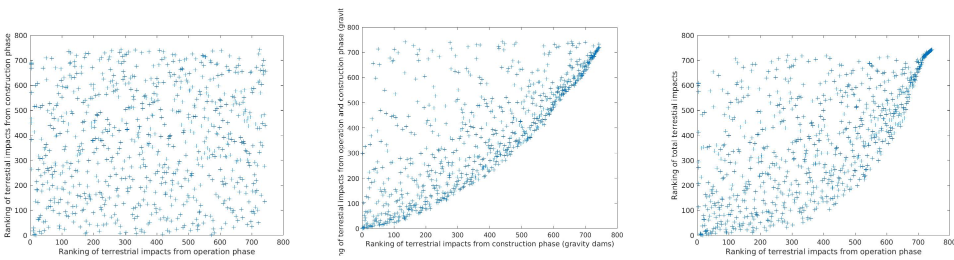
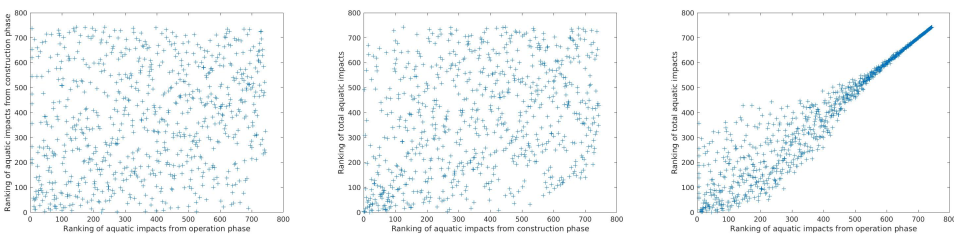
Appendix

Each reservoir was given ranks from smallest to largest based on the size of terrestrial construction impact, terrestrial operation impact and total terrestrial (construction + operation) impact. A low rank correspond to a low impact and a high rank correspond to a high impact. Ranks are adjusted for ties by computing the average. The ranks were plotted against each other in Figure 3.5 to detect any correlation between construction, operation and the combined impacts. The same was done for aquatic impacts in Figure 3.6.



(a) Operation vs construction **(b)** Construction vs total **(c)** Operation vs total

Figure 3.5: Correlation between ranking based on terrestrial impact



(a) Operation vs construction **(b)** Construction vs total **(c)** Operation vs total

Figure 3.6: Correlation between ranking based on aquatic impact

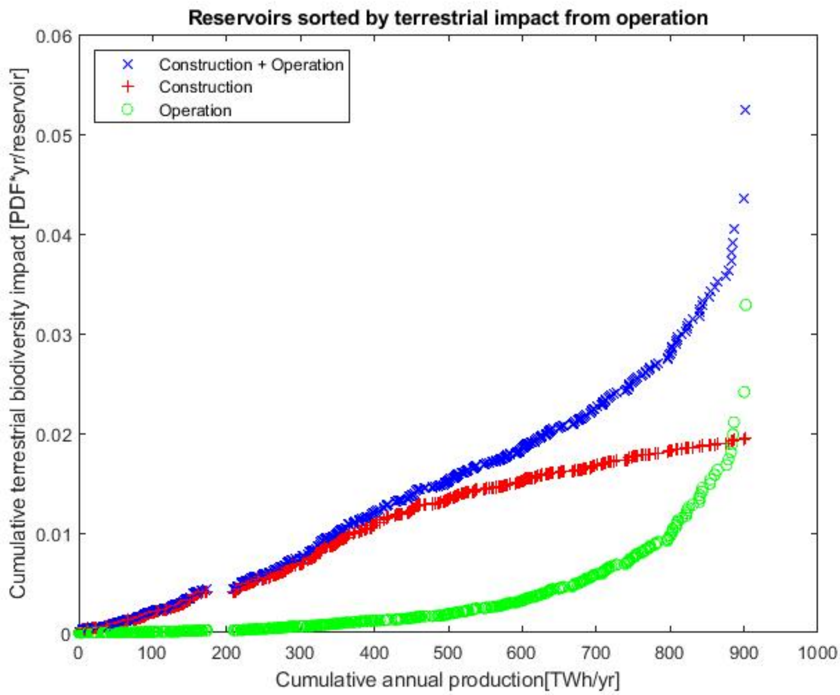


Figure 3.7: Cumulative potential terrestrial biodiversity impact per reservoir [PDF*yr/reservoir] compared to the cumulative annual electricity production [TWh/yr]. Reservoirs were first sorted by terrestrial biodiversity impact from operation before they were plotted cumulatively.

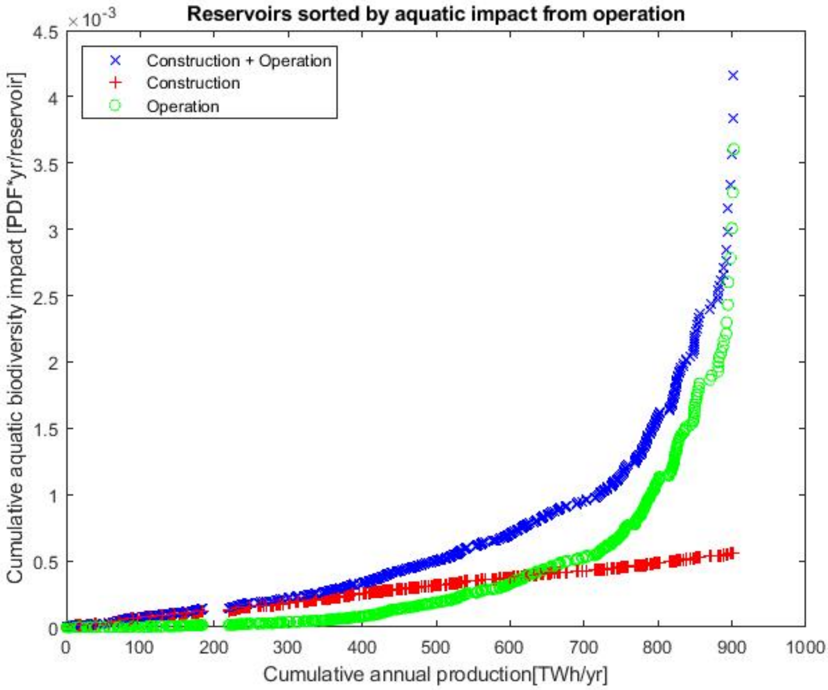


Figure 3.8: Cumulative potential aquatic biodiversity impact per reservoir [PDF*yr/reservoir] compared to the cumulative annual electricity production [TWh/yr]. Reservoirs were first sorted by aquatic biodiversity impact from operation before they were plotted cumulatively.

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