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ROADWAYS AND INFRASTRUCTURE

Development of LCA benchmarks for Austrian torrent control structures

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Abstract

Purpose This study emerged from a research project that aimed to develop a Life Cycle Assessment (LCA) model for torrent control structures. This publication constitutes the last part of model development and shows the LCA results of the examined structure types considering the entire life cycle. These LCA results will be used in a further step to close the environmental knowledge gap within the area of sustainability assessment. The sustainability assessment of buildings is already widespread and standardised in Green Building Rating Systems (GBRSs), which use LCA benchmarks for the rating of environmental indicators. The development of GBRSs for infrastructure is somewhat younger than the developements in the building sector and the existing systems do not yet provide LCA benchmarks for the environmental rating of the structures. The study shows how to derive benchmarks from the LCA results and thus gives a quantitative basis for a future rating of environmental indicators of torrent control structures.

Methods The methodological basics for the LCA of torrent control structures were created by screening LCAs of several construction projects. From these construction projects, different structure types could be identified and classified. Functional units were developed, which can be assigned to the structure types. Uncertainties arise because these structure types are not always built in the same way. It can be distinguished between five uncertainties. Uncertainties of material dataset modeling, variable material use and machine use have been identified. Furthermore, the variable material use influences the emissions of transport. The transport in turn demonstrates uncertainties in the transport distances. Last but not least, there are variable service life times that dictate the replacement cycles of the structures. LCA benchmarks can be derived by the elevation of the various uncertainty distributions and its application in a Monte Carlo simulation.

Results and discussion By applying the method described above, it was possible to develop LCA benchmarks for different types of torrent control structures. These benchmarks show the range of LCA results for these structures. Furthermore, a sensitivity and uncertainty contribution analysis was carried out to investigate dependencies.

Conclusions By determining the range of LCA results, an estimate of environmental impacts in early planning stages becomes possible. Furthermore, this allows decision-making in early planning stages and throughout the entire life cycle of the structures, taking into account environmental impacts. A further development of the benchmarks requires the analysis of additional structures to increase the accuracy and to reduce parameter uncertainties.

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1 Introduction

Since industrialisation, humanity has contributed to 1 °C of global warming. The Intergovernmental Panel on Climate Change (IPCC) states in the fifth assessment report that global warming may increase to 4.5 °C if mankind does nothing against the climate change (Pachauri and Meyer 2014). Austria and its associated alpine regions are particularly exposed to global warming. In Austria, a warming of around 2 °C was registered (Anderl et al. 2018). Climate change manifests itself in a variety of effects in alpine regions. Special danger for humans and their belongings represents the fact that the runoffs are influenced by the decrease of the cryosphere. The annual runoffs are increasingly influenced by precipitation (Stocker et al. 2013). A higher frequency, an increase in the intensity of heavy rainfall and the decline of the cryosphere thus lead to the increase of extreme natural hazards by torrents (Gobiet et al. 2014).

Torrent control structures are designed to protect people, human habitat and infrastructure from alpine natural hazards (Suda 2012). In the 70s and 80s, a big amount was invested in this infrastructure and thus in hazard risk mitigation (Sinabell et al. 2016). This kind of infrastructure represents a considerable part of the construction industry. The average value of the annual investments in the field of torrent and avalanche control in Austria amounted to 145 million euros between 2012 and 2014. The construction of these structures does not only create monetary expenses but also greenhouse gas (GHG) emissions. A large proportion (~ 30%) of GHG emissions in Austria date back to the construction and industrial sector, which is so heavily involved in the climate change (UBA 2018).

In summary, building these structures increases the natural hazard risk, while actually reducing the risk of natural hazards. Due to the high settlement pressure, however, they are indispensable (Sinabell et al. 2016). In Schipper and Pelling (2017), a similar issue will be discussed. Although she considers the problem on a global level, the conclusion can be applied to the problem described above. It is possible to counteract this chain of events only by understanding the link between climate change, natural hazard risk and development. Only sustainable development can reduce climate change and natural hazard risk (Schipper and Pelling 2017).

On the one hand, the application of hazard zone planning can reduce settlement pressure, thereby reducing the risk to humans to natural hazards. On the other hand, climate change can be counteracted by a sustainable construction of protective infrastructure, which entails the reduction of natural hazards. This fact makes it logical to build special protective structures as much as possible with minimal use of resources and the lowest possible emissions without diminishing their protective function.

For the development of a sustainable infrastructure, there is the possibility of applying the approach of a sustainability assessment (Griffiths et al. 2018). Sustainability assessments have been used in the construction industry since the 1990s in the form of Green Building Rating Systems (GBRSs) (Doan et al. 2017; Marjaba and Chidiac 2016). There are currently more than 600 sustainability rating tools on the market (Liu et al. 2018). The most important rating systems in the building sector are Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM) and German Sustainable Building Council (DGNB) (Bocchini et al. 2014; Marjaba and Chidiac 2016).

The development of GBRSs for infrastructure is somewhat younger than the building sector. Over the past decade, attempts have been made to apply existing GBRSs to the infrastructure sector. As the infrastructure sector is not familiar with the use of sustainability tools and somewhat conservative, implementing these tools in the industry is a bit more difficult than the building sector (Chong et al. 2009; Griffiths et al. 2018).

Currently, no sustainability assessment is used in the planning of torrent control structures. The only assessment method of protective structures used is monetary. For larger construction projects, a cost–benefit analysis (CBA) must be performed (BMLFUW 2005) to demonstrate the necessity and effectiveness of the project.

Within sustainability assessments, Life Cycle Assessment (LCA) has been used to quantify and evaluate the environmental indicators of buildings (Zuo and Zhao 2014). Currently used sustainability tools for the infrastructure sector are also using LCA for their environmental indicators but only in qualitative criteria and there is still no quantification of this through benchmarking. Bocchini et al. (2014) highlight the lack of quantification of the environmental indicators to be evaluated in GBRSs for infrastructure.

In the field of quality management, Robert Camp defines the term benchmarking as "the search for those best practices that will lead to the superior performance of a unit or organization" (Camp 1989). In order to be able to rate the environmental criteria, first the best practice has to be quantified. Common GBRSs for buildings reflect the rating of environmental criteria through the results of the LCA. Benchmarks based either on the state of the art (reference building) or derived from already certified buildings serve as the basis for the assessment. Thereby, reference values for the best practice of projects can be derived (Ganassali et al. 2016).

This study is intended to close this gap of knowledge in the field of torrent control structures. So the question will be whether and how environmental reference values can be calculated for these types of structures.

By developing a methodology for the creation of LCA benchmarks, it should made possible to quantify the environmental indicators and the applicability of GBRSs for this field. The results of this study should give infrastructure planners the opportunity to make decisions about environmental aspects already in early planning stages. The aim is to give planners and decision makers the opportunity to apply easily the best practice in terms of environmental impacts, which will lead to a better performance and a more sustainable infrastructure.

2 Methodology

The development of LCA benchmarks for torrent control structures considers on one hand the requirements of the standards, which are dealing with the framework and the conduction of an LCA (EN ISO 14040, EN ISO 14044) (ISO 2006a; ISO 2006b). The methodological basics for the life cycle assessment of torrent control structures were created by screening the LCAs of several construction projects. Through the analysis of all relevant construction processes, it was possible to determine system boundaries, cutoff criteria, suitable data sources and hotspots of the processes (Paratscha et al. 2019).

On the other hand, by changing the consideration level, the specific standardisation has to be considered. At the product level, the specifications of EN 15804 (CEN 2013) must be observed. Studies at work level concerning the sustainability of civil engineering works have to consider EN 15643-5, which provides the requirements for the environmental assessment of this level.

The screening LCAs in the first study were performed for the product stage (A1–A3), the construction stage (A4–A5) and the end of life stage (C4). A second study was carried out to define the use stage (B4–B5) and thus to determine the service lifetime of the structures. Within the study, a probabilistic model based on condition rating was developed, which shows the degradation of the structures (Paratscha et al. 2018). Therefore, it was possible to represent the structure types in this study over their entire life cycle (see Fig. 1).

As the development of LCA benchmarks is intended to provide an assessment basis for the environmental indicators of the structures, first the handling of current assessment tools with this topic is presented, before the developed methodology is presented in detail.

2.1 Green building rating systems for infrastructure

The rating systems originating from building construction have nowadays extended to the infrastructure sector and have been adapted for it. There are currently many different rating systems for infrastructure (Liu et al. 2018). The following selection of the existing infrastructure rating systems includes Nachhaltigkeitsindikatoren für Strasseninfrastrukturprojekte (NISTRA), Greenroads, BREEAM New Construction: Infrastructure (pilot), Civil Engineering Environmental Quality Assessment and Awards Scheme (CEEQUAL) and Envision (Bocchini et al. 2014). It should be mentioned that BREEAM Infrastructure and CEEQUAL were merged in 2018.

In Switzerland, a sustainability assessment system of road infrastructure projects called NISTRA has been in use since 2003. Although the system includes environmental criteria, it largely excludes the construction stage of the projects and monetises the environmental impacts (ASTRA 2003).

An additional sustainability assessment tool related to road construction is Greenroads. Greenroads is a voluntary, publicly available third-party rating system. The free Greenroads tool was launched in 2011 by the University of Washington. The proposed LCA methodology (Stripple 2001) is very extensive but not mandatory, and there is also the possibility to perform a streamlined LCA (Weitz et al. 1999) for a successful rating. Nonetheless, the LCA specifications are scientifically based (Anderson and Muench 2013). It is suggested that the LCA be performed by a professional LCA practitioner. It is proposed to have the LCA performed by a professional and not to simplify it, as in other rating systems. The evaluation of the LCA results is based on published LCA case studies and relates to the conditions of the various emission sources. Otherwise, the application of an LCA is only qualitatively assessed and not quantitative (Muench et al. 2011).

BREEAM is the world's first sustainability rating scheme for the built environment. The BREEAM New Construction: Infrastructure (pilot) scheme is a performance-based assessment method and certification scheme for new infrastructure assets. The pilot infrastructure scheme operates in a similar way to other BREEAM schemes. BREEAM New Construction: Infrastructure (pilot) was developed by BRE Global Limited (BRE 2015). Considering the environmental criteria, LCA is first used for screening taking into account EN 15978 and the Eeb Guidance document, in the planning phase to identify hotspots. Later in the project, a holistic LCA will be created according to common standards. By implementing the potential for improvement resulting from the LCA, a good evaluation of the project can be achieved. However, as the system is still in the pilot phase, there are still no minimum requirements for these criteria and therefore no benchmarks are available (BRE 2015).

CEEQUAL was first offered to the public in 2003 with version 2. CEEQUAL was developed by a team led by the Institution of Civil Engineers, supported by the Institution's Research & Development Enabling Fund and the UK Government. Meanwhile, the system has been further developed to version 5 and is part of the BRE Group since 2015 (CEEQUAL 2015). There are no benchmarks in this GBRS. This scheme assesses issues such as the consideration and minimization of environmental impacts. However, the scheme

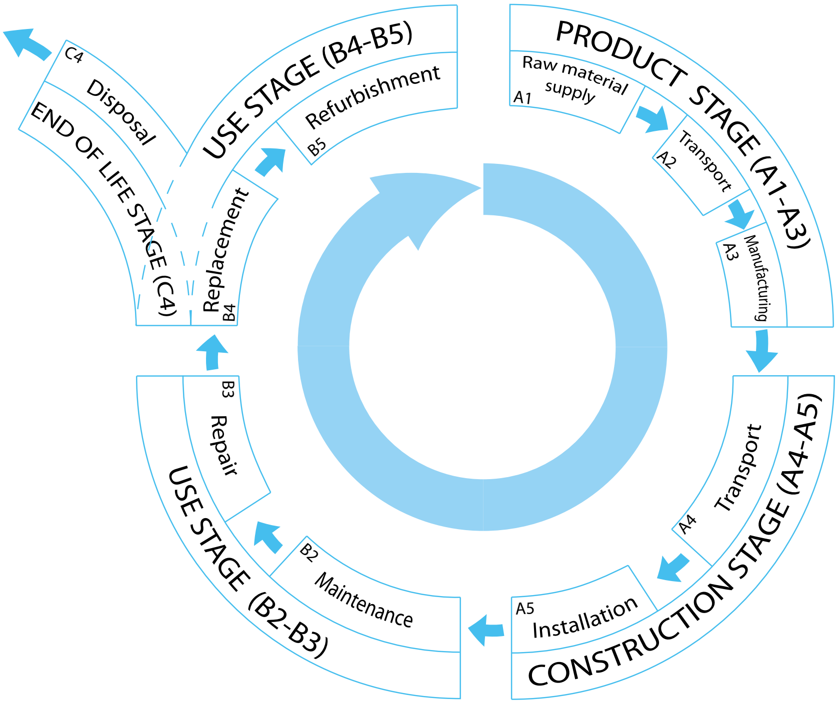


Fig. 1 Life cycle stages of torrent control structures

does not indicate how environmental impacts have to be assessed. Nonetheless, the performance of a LCA and the analysis of the life cycle for optimization purposes are included as a qualitative criterion (CEEQUAL 2015).

Another tool that is gaining more and more importance in the USA is Envision^{TM}. It was developed by the American Public Works Association (APWA), the American Society of Civil Engineers (ASCE) and the American Council of Engineering Companies (ACEC). The tool is similar to CEEQUAL and was released in 2012 by the Institute for Sustainable Infrastructure (ISI) (ISI 2019). In contrast to CEEQUAL, Envision pays more attention to the constraints of an infrastructure project and can deliver a more balanced assessment of the three pillars of sustainability. As Envision deals more intensively with the planning and design of the projects, the execution phase is somewhat neglected. However, the other tools have a weaker performance in the planning phase of the rated projects (Bocchini et al. 2014; Griffiths et al. 2017). Within the rating system, however, LCA approaches are required, e.g. to show the reduction of net embodied energy of building materials, but a holistic LCA is not required (ISI 2015).

In summary, it can be emphasised that a quantifiable evaluation method for the environmental impacts of projects is missing within the rating systems described. Within the rating systems, it is often pointed out that for the quantification of the criteria, there are still some basics missing. For example, these basics can consist, e.g. in a certain number of rated projects or basic research data. This study aims to provide these basic research data for an environmental assessment of torrent control structures through the development of LCA benchmarks.

2.2 Differentiation of torrent control structure types

The analysed protective structures are torrent control structures that were built in Austria. A division of the different structure types according to their function, arrangement, height, type of construction, main building material and static system is defined in ONR 24800 (ON 2009).

Torrent control structures can be divided into longitudinal and transverse. The transverse structures covered in this study are ground sills, groynes, submerged sills, check dams and ground ramps. Check dam structures can additionally be distinguished by their function and type of construction. In this study, however, only check dams with consolidating and stabilising effects occur.

Consolidation check dams and submerged sills have the function of preventing debris flows and depth erosion of the torrent bed. Consolidation is achieved by causing a vertical downfall, which reduces sediment transport, depth erosion and the flow velocity of the torrent. Check dams and submerged sills differ by their downfall height. Check dams are characterised by a downfall height of over 2 m. Ground sills are flush aligned with the torrent bed and thus cause no downfall but stabilise the torrent bed. Groynes are built from the embankment into the torrent but do not cover the entire torrent width and provide stabilisation. Ground ramps produce an oblique downfall and have a high surface roughness. Longitudinal structures are bank protection structures and thus stabilise the embankments against erosion by the torrent. Bank protection structures are principally bank protection walls (ON 2009). Table 1 shows which construction types were analysed in this study.

2.3 Definition of the functional units

The basic definition of the functional unit (FU) in life cycle assessment is contained in EN ISO 14040 and EN ISO 14044 but does not deal with specific products or systems. In EN ISO 14040, the functional unit is defined as follows:

> “The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of the functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis.” (ISO 2006a)

Depending on the product system considered, the FU may vary. Each torrent has different characteristics and processes. Accordingly, individual protection measures are required for each project. These protective measures are ensured by different structures made of different materials. This makes it necessary to consider the entire protection system when planning torrent control structures. Taking into account the entire protection system, which has the function of protection against extreme events such as debris flows, it is recommended to use the entire protection system as a FU.

Due to the individuality and complexity of each protection system, it cannot be compared with others. However, the comparison between project variants of the protection system, which have identical performance characteristic, is possible because the same protection function can be achieved with different combinations of structures (Paratscha et al. 2019).

In the case of considerations at structure level, the definition of an individual FU per structure type is quite reasonable. In the tender procedure and in the service description, structures are divided into groups, according to ÖNORM A 2063 (ON 2015). This division is similar to the ONR classification and specifies FUs at the economic level. It seemed reasonable to use a cross-section of ONR classification and tender procedure for the definition of the FUs. Due to various functions of structure types, this is also mandatory according to the definition of the FU in EN ISO 14040.

The definition of the FU for bank protection structures is relatively easy to determine. Bank protection structures protect an area of the embankment from erosion. So, it is obvious that the surface area of the structure [m^2] is used as a FU for bank protection structures. For ground ramps, the surface area is also suitable because it reflects the protected ground area by the structure.

The FU of groynes is a bit more difficult to set. Their function is to reduce the flow velocity of the stream and thereby prevent side erosion of the embankment. The effect of the structure increases depending on how far it extends into the torrent. As a result, the FU running meter [m] can be derived.

As ground sills do not cause a downfall, their effect is related to the torrent width and thus length [m] can be used as a FU for these structures.

Consolidation check dams and submerged sills have similar functions and thus the same FU. Submerged sills and consolidation check dams can be designed as a gravity wall, a slab wall or as a cantilever retaining wall.

For gravity walls, horizontal forces are counteracted by the weight of the structure. In order to achieve a high weight, these structures are quite massy. Gravity check dams can be made of concrete, masonry, log cribs and gabions. Since the

Table 1 Analysed structure types and proposed FUs

Static system	Construction material	Linear structures					
		Transverse structures					Longitudinal structures
		Ground sill	Ground ramp	Groyne	Submerged sill	Check dam	Bank protection wall
Slab wall or as cantilever retaining wall	Reinforced concrete	m		m	m^2	m^2	m^2
Slab wall or as cantilever retaining wall	Stone faced concrete				m^2	m^2	
Gravity wall	Stone masonry	m	m^2	m	m^3	m^3	m^2
Gravity wall	Dry stone masonry				m^3		m^2
Gravity wall	Stone gabion			m	m^3	m^3	m^2
Gravity wall	Stone riprap	m	m^2	m			m^2
Gravity wall	Wood lo crib wall	m			m^3	m^3	m^2

weight and the height of the downfall are decisive for the function of these structures, the volume [m^3] is used as FU since this represents both. Because each type of construction has a different specific weight, direct comparisons between the types are not allowed.

Reinforced concrete slab check dams divert horizontal forces to the lateral flanks and to the structural sole. In the case of cantilever retaining structures, a horizontal foundation plate is added, whereby the forces are mainly diverted via the sole. For these types of structures, the surface area of the components [m^2] is proposed as FU. For existing foundations, the horizontal surface of the foundation must be added. The proposals for the FUs of all construction types are summarised in Table 1.

With the above FUs, the various components of a protection system can be defined such that a comparable LCA on structure level can be created. These FUs and the associated environmental impacts serve as the basis for a variant calculation in the planning stage. On this basis, the environmental impacts of protection system variants can be quickly represented and compared. The planner thus has the possibility to design a protective system on the basis of environmental criteria.

2.4 System boundary and life cycle inventories

The system boundary of the life cycle benchmarks consists of a holistic cradle-to-grave approach that represents all relevant life cycle stages. These stages are the product stage (A1–A3), the construction stage (A4–A5), the use stage (B2–B5) and the end of life stage (C4) (see Fig. 1). Since the calculations refer to Austrian buildings, the geographical system boundary is limited to Austria.

The definition of the inventory-related data was developed on the basis of cost calculation. When calculating the costs of construction, it is customary to distinguish one-off costs from the remaining costs (ON 1999). One-off costs are costs incurred for site setup and site clearance. In this study, this approach was translated to the calculation model. Construction site setup such as site development was excluded because this is different for each site and allows no comparison.

2.4.1 Product stage

The product stage includes the extraction and processing of raw materials, transportation to the manufacturer and manufacture including the provision of all substances, products and energy (CEN 2011). The product manufacturing information comes from the database ecoinvent 2.2 (Frischknecht et al. Frischknecht 2007). This database provides all the material records needed for this analysis. During the screening, data sets that specifically relate to the Austrian production of local construction materials were developed. In addition, it was necessary to treat material inherent properties in module A1 as inputs to the system and to treat them as outputs in the end of life stage C4 again. This concerns the uptake of CO_2 or energy intake of wood during the growth (Paratscha et al. 2019).

2.4.2 Construction stage

The construction stage includes all construction processes. This includes the delivery of all construction materials and machinery necessary for the construction of the structure as well as all the processes for the completion of the structure (CEN 2011). The data for the construction processes were determined from the construction reports. Construction reports are cost calculations and they are based on calculation rules, which are regulated in the Austrian standard ÖNORM B 2061 (ON 1999). The construction reports contain no information about the transport processes of construction materials. Therefore, the transport distances of the different construction materials and machines were derived from data of the statistical office of the European Union (Eurostat 2018). The data for the construction machinery was generated from the online non-road database (FOEN) for the reference year 2015 (FOEN 2017). The online non-road database tool is calculating air pollution emissions and the fuel consumption of the non-road sector in Switzerland. Since the same machines are used in Austria, the Swiss database forms a good basis for an LCA with Austria as geographical system boundary.

2.4.3 Use stage

The use stage describes the period between completion and demolition or replacement of the structure. The first section of the use stage (B2–B3) considers the maintenance of the structures (CEN 2011). For the maintenance of torrent control structures, annual monetary maintenance rates are applied in the cost–benefit analysis created by the Austrian Service for Torrent and Avalanche Control (BMLFUW 2005). These maintenance rates were applied to the LCA results of the production and construction stage. There is a distinction between three maintenance rates. For concrete or masonry structures, annual maintenance rates of 0.2% of the construction phase can be assumed. One percent of the construction phase is calculated annually to maintain riprap structures. Wood structures are valued at 0.5%.

In the second part of the use stage (B4–B5), the replacement of the structures is taken into account if their service life is shorter than the consideration period of the life cycle. The service lifetime of the structures was calculated using a specially developed stochastic predictive model by using a homogeneous Markov chain approach (Paratscha et al. 2019).

2.4.4 End of life stage

According to EN 15978 (CEN 2011), the end of life of structures is reached when all components and materials that have to be removed from the site are finally removed. The difference between conventional buildings and torrent control structures is that the structures have reached their end of life after loss of functionality and then go directly into nature as a landfill (Paratscha et al. 2019). Thus, the stored CO_2 is returned to the natural cycle and the energy contained in the material is not used any further. The CO_2 and the energy stored during growth (A1) of wood, leaves the system again in module C4 so module D can be neglected.

2.5 Uncertainty and variation in LCA

Uncertainties arise due to knowledge gaps which can occur during the entire creation process of an LCA. Uncertainties may arise during goal and scope analysis, inventory analysis and impact assessments. These knowledge gaps can be found in input and output parameters.

The handling of uncertainties in LCA has been discussed since the 1990s. A classification of the occurring types of uncertainties is essential. There are different approaches how to classify uncertainties (Björklund 2002; Heijungs and Huijbregts 2004; Walker et al. 2003). Huijbregts (1998) distinguishes between parameter uncertainty, model uncertainty, uncertainty due to choices, spatial variability, temporal variability and variability between object/source and also suggests tools for examining them.

A simplified classification offers the division into parameter, model and scenario uncertainties. This study refers to the variation of input parameters within the life cycle stages. The variability of input parameters is one of the most addressed sources for the resulting uncertainties into LCA (Reap et al. 2008). Input parameters are quantifiable and measurable. The uncertainty arising from the variance of input parameters can be assigned to the parameter uncertainties. Parameter uncertainties are arising from incomplete knowledge about the true value of a parameter. These knowledge gaps can arise when creating the life cycle inventory due to imprecise, incomplete or even the absence of measurement data (Igos et al. 2018).

Already in Huijbregts (1998), it was demanded to specify uncertainties in the databases so that the consistency of the data records could be reproduced. These claims were followed up and thus databases can now indicate these uncertainties. However, the unrestricted handling of probability distributions of the parameters is not possible with every software. The use of openLCA (v.1.7) provides a good basis for dealing with uncertainties (Igos et al. 2018). This study was performed with this software and the ecoinvent v .2.2 database.

There are many different methods to perform an uncertainty analysis. However, the method most often used is stochastic modeling through Monte Carlo simulation. The disadvantage of this method is that the calculations are time consuming when many input parameters are to be considered. In many cases, up to 10,000 simulations are needed to get reliable results (Larsson Ivanov et al. 2018). Since the same problem arose in this study, the simulations had to be reduced to 1000 iterations. The implication of this reduction in simulation runs is discussed in more detail in the “Results and discussion” section.

2.5.1 Parameter uncertainties within the life cycle inventory

This section discusses various parameter uncertainties identified during data collection. As noted above, this study exclusively deals with parameter uncertainties related to the life cycle inventory. A graphic description of the calculation model is shown in Fig. 2.

Within the product stage, two different variables can be found. These variables consist in the uncertainty of material dataset modeling by the data creator ecoinvent (U_1) and the variable quantities of materials used for the construction of the structure types (U_2).

Since the modeling of data sets is difficult due to missing information or different production processes, ecoinvent provides uncertainty distributions of the various data sets. Considering U_1, lognormal distribution has been used for nearly all unit processes of ecoinvent data v 2.0 (Frischknecht 2007). There are also ecoinvent datasets for which only one record was available and therefore a simplified standard procedure consisting in a qualitative assessment of data quality indicators based on a pedigree Matrix was applied to quantify the uncertainty for these datasets (Weidema et al. 2013; Weidema and Wesnæs 1996). The uncertainties applied in the ecoinvent database may differ from reality (Lasvaux et al. 2015). Ecoinvent, however, provides a good basis for background information if no other sources of information such as environmental product declarations (EPDs) are available (Igos et al. 2018).

The amount of materials used for the construction of the structures (U_2) was determined by data from the standard service description (SSD) and from the projects analysed in the screening LCAs. From this data, the probability distribution of the materials used for the construction of the different structure types could be derived (see Appendix A in the Electronic Supplementary Material). For the representation of these uncertainty distributions, a lognormal distribution was assumed. Weidema et al. (2013) and (Limpert et al. 2001) are listing some advantages of using a lognormal distribution.

An important thing in setting uncertainties is to note the fact that parameters can correlate with each other. Lloyd and

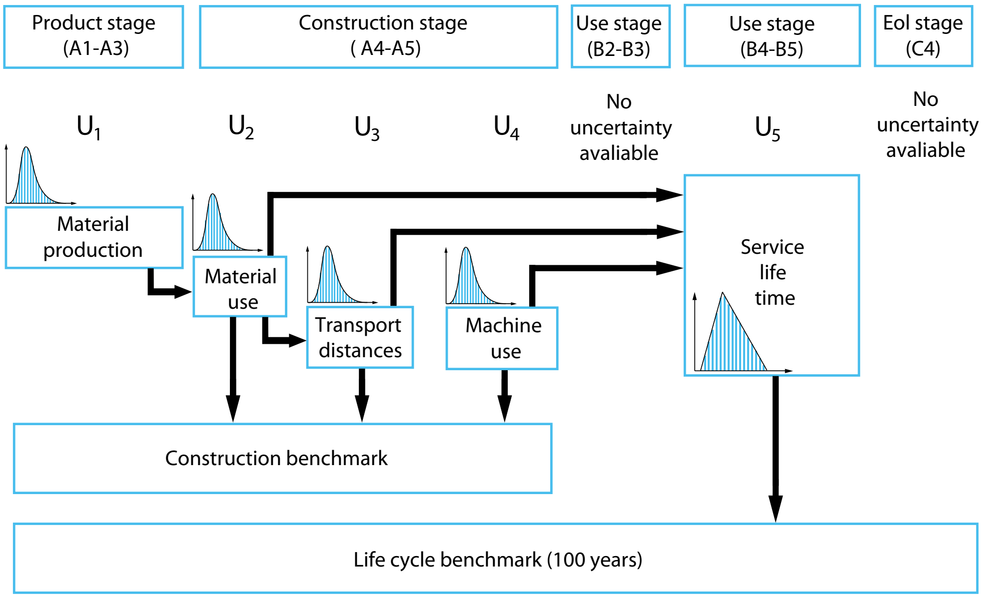


Fig. 2 Framework for the creation of LCA benchmarks for torrent control structures

Ries (2008) have observed in their study that only 29% of the examined studies are recognising this fact. The correct way to handle the correlation of uncertainties is to use multivariate random sampling. Bojarski et al. (2008) show how to use this method in combination with the application of a Monte Carlo simulation on parameter level. In order to apply this correctly in the study, dependencies between the uncertainties were incorporated into the model.

Considering the construction stage, there are two additional variables to be added. Since the structures are not always built in the same way, a variance of the transport distance (U_3) in correlation to the differing construction material quantities (U_2) and a variance of machine use (U_4) is observed. This brings two uncertainties in this stage to bear.

The probability distribution of the transport distances for the different building materials and the construction machines to the construction site was retrieved from the statistical data of the statistics about the annual road freight transport, by type of goods and type of transport (Eurostat 2018; Paratscha et al. 2019). Also for these distributions, a lognormal distribution was assumed.

The machine use (U_4) was determined in the same way as the use of building materials. Accordingly, a lognormal distribution was assumed. Unfortunately, the FOEN non-road database (FOEN) does not provide any information regarding the uncertainties of the specified fuel consumption and emissions of the considered construction machinery. Accordingly, this background information is not available for the construction machines.

In the use stage, maintenance and replacement of the structures are considered. In the case of the maintenance rates, no uncertainties were applied because these were not available. With regard to the service lifetime of the structures, uncertainty distributions (U_5) could be determined, which were applied to the previous results of the production and the construction stage. In contrast to all other uncertainties, a triangular distribution was assumed for the probability distribution of the service lifetime. Additional information about the specially developed prediction model can be found in Paratscha et al. (2018).

The resulting distributions were used to perform a Monte Carlo simulation including 1000 calculation steps. The modeling of the structure type inventories and the Monte Carlo simulation were carried out in Open LCA 1.7.0. Additional information on the life cycle impact assessment and inventory can be found in Paratscha et al. (2019).

2.6 Benchmark development

The aim of this study is to develop LCA benchmarks for a quantifiable evaluation method of environmental impacts caused by infrastructure projects, which can be applied in GBRSs. Therefore, the development of the LCA benchmarks for torrent control structures was based on existing methodology of GBRSs in the field of building construction.

There are two types of LCA benchmarks in the three main GBRSs (building construction). Internal and external benchmarks can be distinguished. Internal benchmarks are created by modeling a reference building based on the current normative specifications, which is the benchmark that should be undercut. This system is used in LEED certifications (Ganassali et al. 2016). By contrast, BREEAM and DGNB evaluate buildings based on external benchmarks. The DGNB system defines its benchmarks through the buildings they have already certified and the statistical data of a

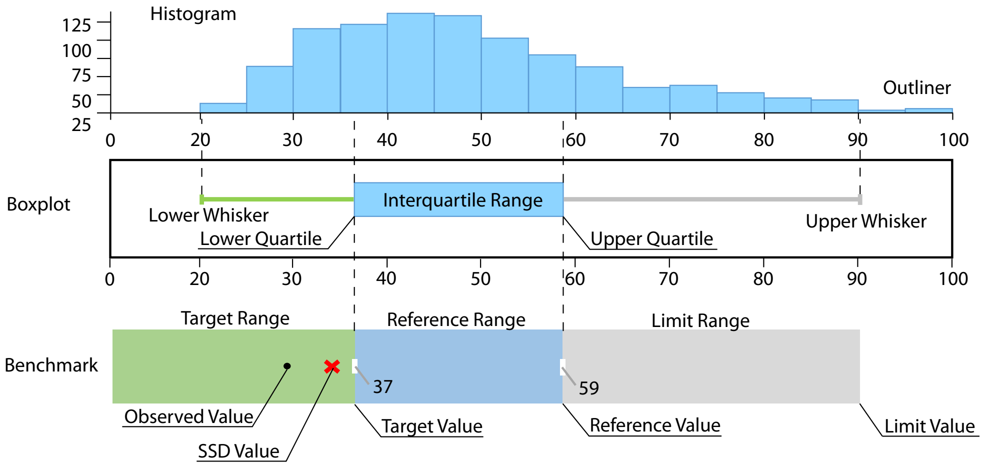


Fig. 3 Conversion framework of the LCA result distributions to the LCA benchmarks

representative building stock. The building stock is derived from a research promoted by the Federal Ministry of Transport, Building and Urban Development (Köning 2010). The GBRS BREEAM uses external data referring to different construction typologies, which are specified for different countries. In this case, the LCA analysis is applied only within construction technology evaluation (Ganassali et al. 2016).

For the benchmark development of torrent control structures, a hybrid method of internal and external benchmarks was applied. The predetermined structure types from the SSD are considered as reference structures that represent the internal benchmarks. The calculated structure types from the analysed construction reports are used to reproduce the structure stock and thus represent the external benchmark. By combining these two methods, a hybrid benchmark was developed.

Environmental benchmarks have been developed for the construction phase, which include the stages A1–A5. In order to cover the entire life cycle, the use stage (B1–B3) and the end of life stage (C4) are added to the life cycle benchmarks (see Fig. 2).

By determining the different uncertainty distributions (U_1-U_5) of the input parameters and the application of Monte Carlo simulation, it is possible to represent the range of the LCA results. Basically, this application determines the range between the worst case scenario and the best case scenario. The distributions of the LCA results, calculated by the Monte Carlo simulation, are representing the benchmarks. Benchmarks are intended to represent the best practice. An indication of best practice information regarding torrent control structures can be found in the SSD. Since the benchmarks were generated from a hybrid method, the results of the reference structures are added to the SSD data.

In the area of GBRSs (building construction), benchmarks consist of a target value, a reference value and a limit value. The assessment of the buildings is based on these values. In this study, these values are modeled on the characteristics of a box plot (see Fig. 3).

The limit value defines the minimum achievable requirements in GBRSs. If these are not achieved, no points can be awarded for the assessment. The present benchmarks define the limit value as the upper whisker of the box plot. The upper whisker represents the highest observation value, which is less

Table 2 List of developed benchmarks depending on the structure type (*X* original dataset, *X** translated dataset)

Static system	Construction material	Linear structures		
		Transverse structures		Longitudinal structures
		Submerged sill	Check dam	Bank protection
Cantilever/slab retaining wall	Reinforce concrete	X*	X	
Gravity wall	Stone masonry	X*	X*	X
Gravity wall	Stone riprap in concrete			X
Gravity wall	Stone riprap			X
Gravity wall	Double lo crib wall	X*	X	X*
Gravity wall	Single log crib wall			X

than or equal to the value of the upper quartile plus 1.5 times the interquartile range (IQR).

The IQR is the range between the upper and lower quartile where 50% of the observation values are situated. The upper quartile marks the 75% limit of the observation values and the lower quartile the 25% limit. The IQR represents the so-called reference range. The upper quartile represents the reference value, which describes in GBRSs a reference building built according to the state of the art. The lower quartile represents the target value used in GBRSs. The target value represents the requirement level for buildings with a high contribution to sustainable development. The target range is not bounded at the bottom by the lower whisker because otherwise sustainability would be limited.

Table 2 indicates for which construction types benchmarks could be developed in the course of this study. In the case of reinforced concrete structures and double log crib structures, data was available for the construction of check dams. This input data was also applied to submerged sills. This assumption is possible because the structures differ only in their fall height. For the creation of the benchmark for double log crib structures as a bank protection structure, the input data of the check dams were translated with the ratio 1:3. This is due to the different FUs. The assumption is that 1-m^2 bank protection wall consists of 3-m^3 double log crib wall. In the case of stone masonry walls, the inventory data of the construction as bank protection structures were translated with the ratio 1:1 to check dams and submerged sills. Structures made of riprap or single log crib wall are only indicated for bank protection structures because this construction is not common for check dams and submerged sills.

3 Results and discussion

Two types of benchmarks were calculated. On the one hand, attention was paid to the construction of the structures, and on the other hand, the results were presented for the entire life cycle.

Figures 4, 5, 6, 7, 8, 9, 10 and 11 present the results for the impact category of global warming potential (GWP_{100}). The results shown in Figs. 4, 5, 6, 7, 8, 9, 10 and 11 refer to the construction of the structures and include the production and the construction stage (GWPc). The resulting benchmarks for other impact categories can be found in Appendix B (Electronic Supplementary Material).

As explained in the "Benchmark development" section, the probability distribution of the input parameters of the production and construction stage was created from the inputs of the SSD and the available reference structures. The LCA results of the SSD and the reference structures are shown in the graphs of the benchmarks, if available. Since there are not clear SSDs for all construction types, these are missing for the reinforced concrete structures and stone masonry structures (see Figs. 4, 8 and 9).

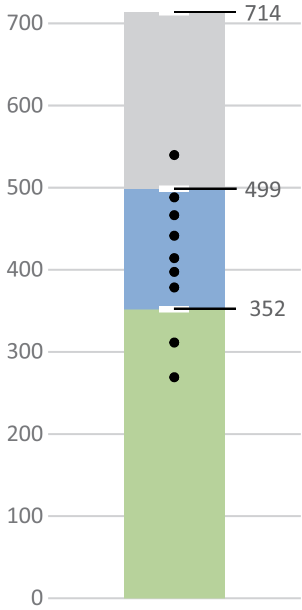


Fig. 4 GWPc benchmark for check dams constructed in reinforced concrete [kg CO_2 eq./m^2]

The results of the life cycle benchmarks shown in Figs. 12, 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22 refer to the construction of the structures and the use stage including the whole life cycle (GWP_{LC}). The resulting life cycle benchmarks for other impact categories can be found in Appendix B (Electronic Supplementary Material).

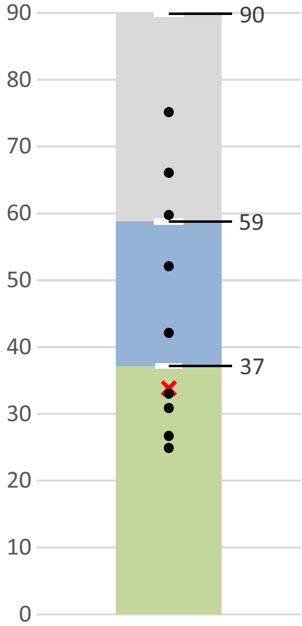


Fig. 5 GWPc benchmark for check dams constructed as a double log crib wall [kg CO_2 eq./m^3]

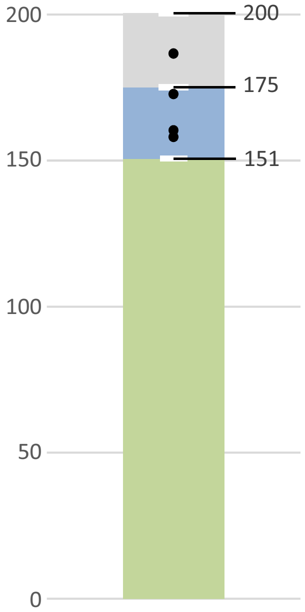


Fig. 6 GWPc benchmark for check dams constructed as a stone masonry wall [kg CO_2 eq./m^3]

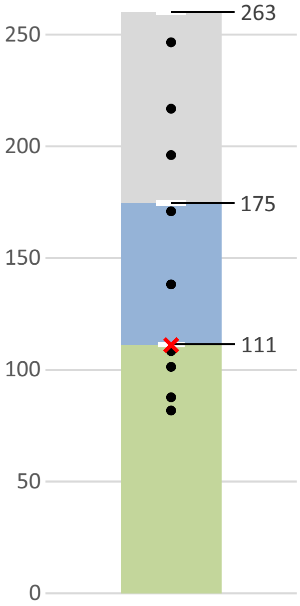


Fig. 8 GWPc benchmark for bank protection structures constructed as a double log crib wall [kg CO_2 eq./m^2]

For the calculation of the life cycle benchmarks, the structure-specific maintenance rates and service life times were applied as described in the "Use stage" section. Thus, the entire life cycle of the structures can be represented. The annual maintenance rates differ according to the construction material used for the construction of the structures (BMLFUW 2005). As the maintenance rates refer to the results of the construction phase, the annual emissions resulting from maintenance vary accordingly (see Fig. 23). The assumed service life time represents the lower limit of the time to failure and describes the moment in which already 10% of the structures can be destroyed (Paratscha et al. 2018). As shown in Fig. 23, the moment of the replacement of the structure is also associated with uncertainties and may vary accordingly as shown in Appendix A (Electronic Supplementary Material).

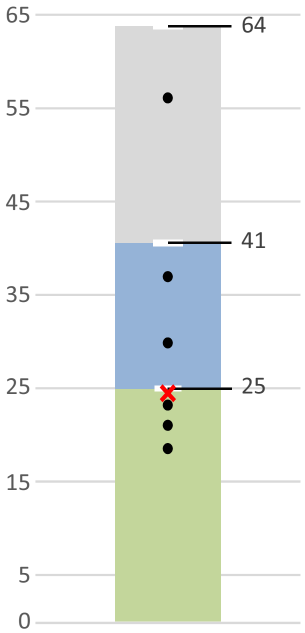


Fig. 7 GWPc benchmark for bank protection structures constructed as a single log crib wall [kg CO_2 eq./m^2]

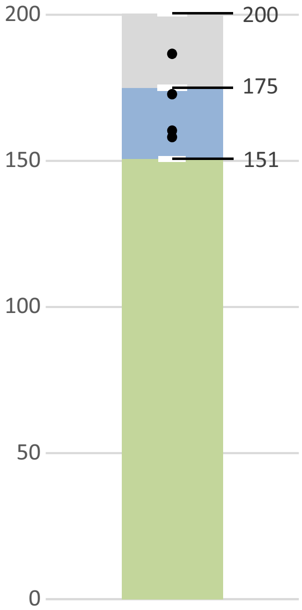


Fig. 9 GWPc benchmark for bank protection structures constructed as a stone masonry wall [kg CO_2 eq./m^3]

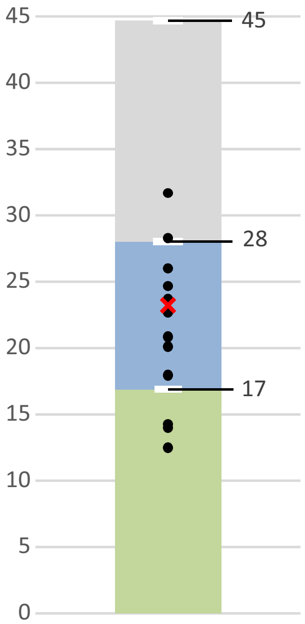


Fig. 10 GWPc benchmark for bank protection structures constructed as a riprap wall [kg CO_2 eq./m^2]

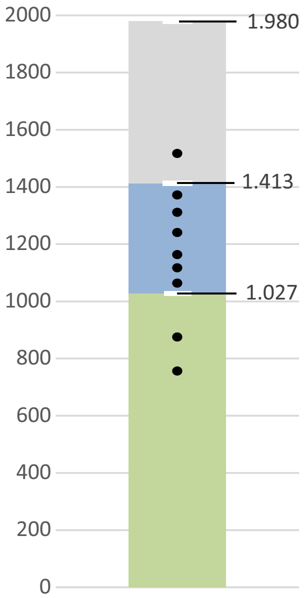


Fig. 12 GWP_{LC} benchmark for check dams constructed in reinforced concrete [kg CO_2 eq./m^2]

3.1 Sensitivity analysis and uncertainty contribution analysis

In the course of this study, it was examined how the life cycle modules (A1–B5) contribute to the result and how the parameter uncertainties contribute to the uncertainty of the final results. This has been applied to all types of material that can be used to construct check dams.

In a first step, the processes were calculated without specifying uncertainties and, accordingly, without Monte Carlo simulations. The median of the probability distributions in this case describes the input parameters for the calculations. These input parameters of the processes can be found in Appendix A (Electronic Supplementary Material).

Appendix C (Electronic Supplementary Material) shows the GWP_{100} results for check dams made of reinforced

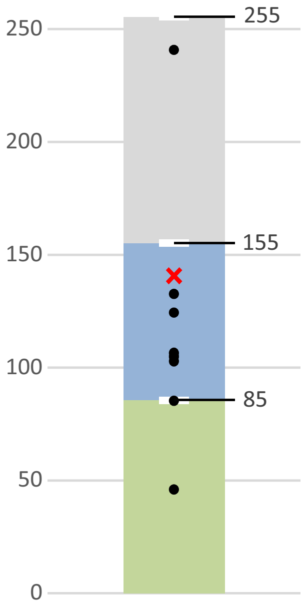


Fig. 11 GWPc benchmark for bank protection structures constructed as a riprap wall in concrete [kg CO_2 eq./m^2]

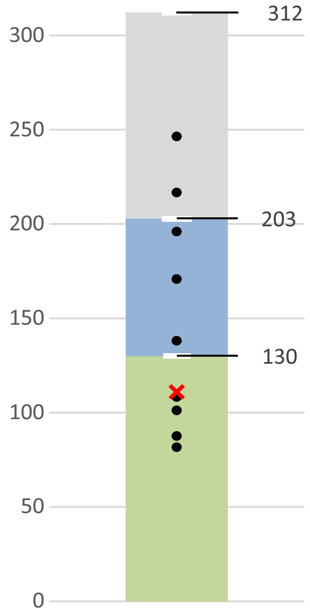


Fig. 13 GWP_{LC} benchmark for check dams constructed as a double log crib wall [kg CO_2 eq./m^3]

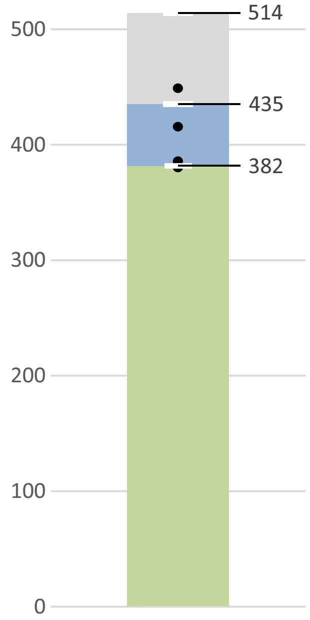


Fig. 14 GWP$_{LC}$ benchmark for check dams constructed as a stone masonry wall [kg CO$_2$ eq./m^3]

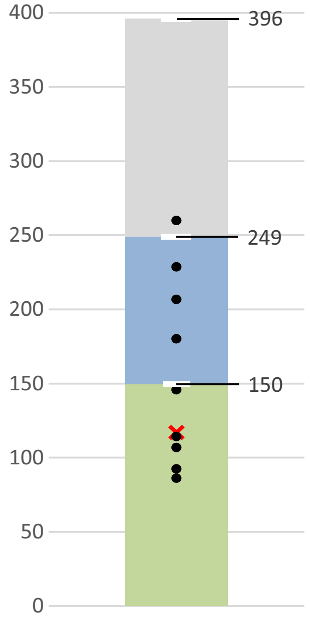


Fig. 16 GWP$_{LC}$ benchmark for submerged sills constructed as a double log crib wall [kg CO$_2$ eq./m^3]

concrete, double log cribs and stone masonry. Looking at the results, calculated without uncertainty, it can be seen how the contribution of the modules to the final impacts shifts from the construction material to the construction and transport processes, when using a timber construction (see Fig. 24).

In the construction variants that are using emission-intensive materials such as cement, mortar or steel, the contribution of modules A1–A3 (material production) to the construction phase emissions is around 90%. Considering the double log crib structure, the contribution of the material production to the construction emissions is only around 8%.

However, such a shift cannot be observed when considering the entire life cycle. The relationship between construction phase (A1–A5) and use phase (B1–B5) is very similar by the consideration of the different building materials. Thirty-five percent of the emissions could be attributed to the construction

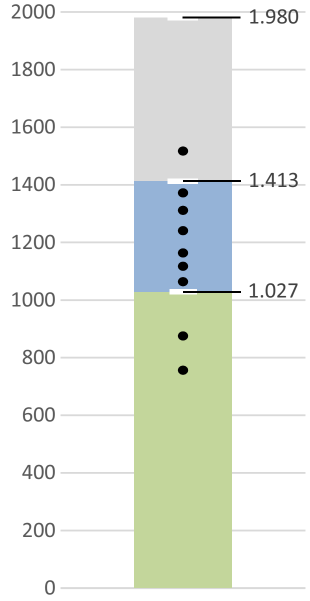


Fig. 15 GWP$_{LC}$ benchmark for submerged sills constructed in reinforced concrete [kg CO$_2$ eq./m^2]

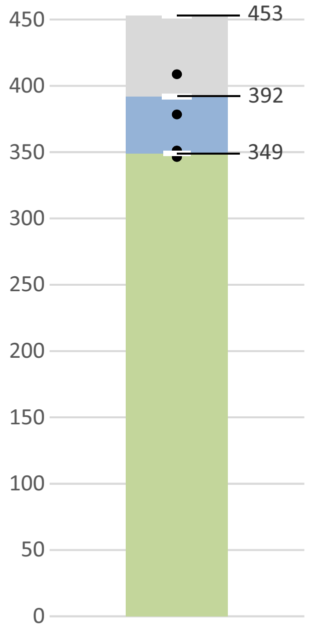


Fig. 17 GWP$_{LC}$ benchmark for submerged sills constructed as a stone masonry wall [kg CO$_2$ eq./m^3]

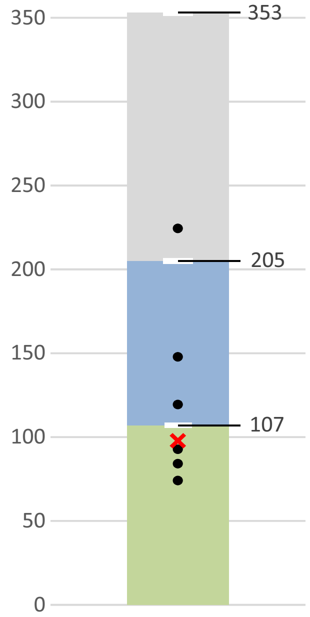


Fig. 18 GWP$_{LC}$ benchmark for bank protection structures constructed as a single log crib wall [kg CO2 eq./m^2]

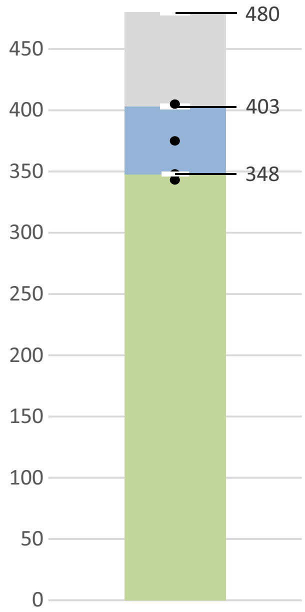


Fig. 20 GWP$_{LC}$ benchmark for bank protection structures constructed as a stone masonry wall [kg CO2 eq./m^2]

of the structures and 65% of the emissions to the maintenance and replacement of the structures. In the case of the stone masonry check dam, the emissions shifts to the construction phase because the service lifetime of the structure is a bit longer and accordingly the structure does not have to be replaced so often (see Appendix C in the Electronic Supplementary Material).

In a second step, the contributions of the various parameter uncertainties to the final uncertainty distribution were observed (see Fig. 25). To find out this contribution, all processes belonging to a certain uncertainty were calculated separately. By applying the Monte Carlo simulation to these process groups, it was possible to calculate the IQR of the emissions caused by these processes and thus the contribution of the uncertainties of these process groups to the final result.

Within the construction phase, the same behaviour can be observed as with the median values. The production of

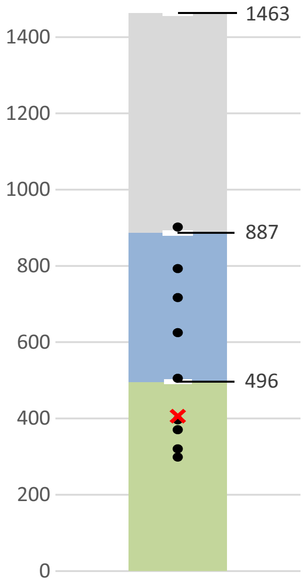


Fig. 19 GWP$_{LC}$ benchmark for bank protection structures constructed as a double log crib wall [kg CO2 eq./m^2]

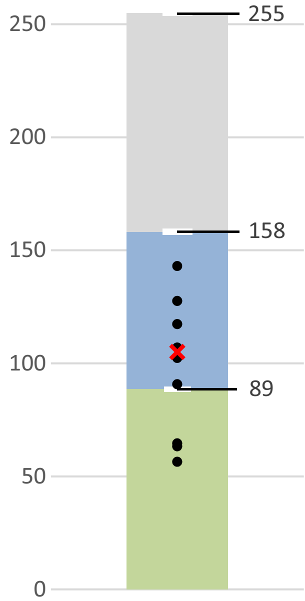


Fig. 21 GWP$_{LC}$ benchmark for bank protection structures constructed as a riprap wall [kg CO2 eq./m^2]

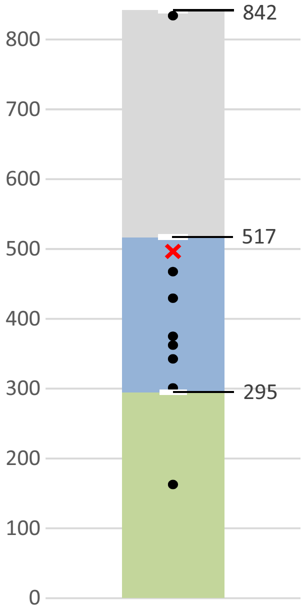


Fig. 22 GWP$_{LC}$ benchmark for bank protection structures constructed as concrete riprap wall [kg CO2 eq./m^2]

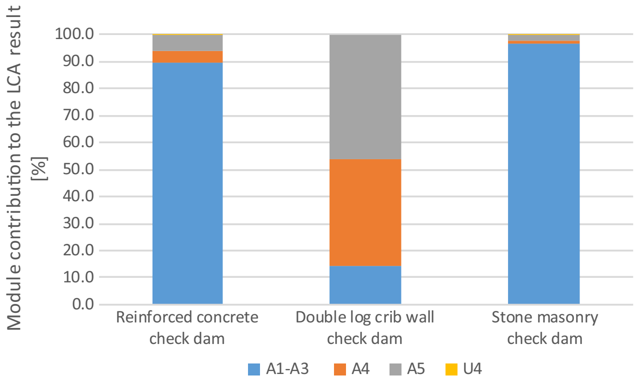


Fig. 24 Sensitivity analysis of LCA results concerning check dams

materials dominates when using emission-intensive building materials (around 90%) and the use of wood shifts the emphasis of emissions to construction processes and transport. By a higher median of the process emissions, it comes to a higher contribution to the final uncertainty.

Within the production of building materials (A1–A3), two uncertainty factors can be observed. On the one hand, the uncertainties for the production of building materials (U1) and, on the other hand, the variation of its quantity (U2) have to be considered. In this study, it can be observed that, irrespective of the choice of material, the ratio between the IQRs of U_1 and U_2 is always 1.5:3. This means that around 33% of the uncertainty in material production can be attributed to the generic data of ecoinvent and about 67% to the variation in the amount of material used for construction. Appendix C (Electronic Supplementary Material) provides additional information on the sensitivity analysis.

3.2 Comparison of the standard service description results and the benchmarks

The input data used for the construction of the structures come in this case from the standard service description. The SSD indicates average material quantities and prices for the construction of these structures. These values are used to create offers and are default values. The calculated outputs of the SSD structures are very close to the target values of the benchmarks when considering the global warming impact category (see Table 3). Only in the case of bank protection structures constructed as concrete riprap wall, the SSD value is clearly above the target value. However, the fact that the IQRs are higher than the SSD values means that the SSD design could not be complied in most cases. The agreement of the SSD values with the

Fig. 23 Consideration of the GWP100 over a period of 100 years for double log crib wall check dams with a maintenance rate of 0.5%

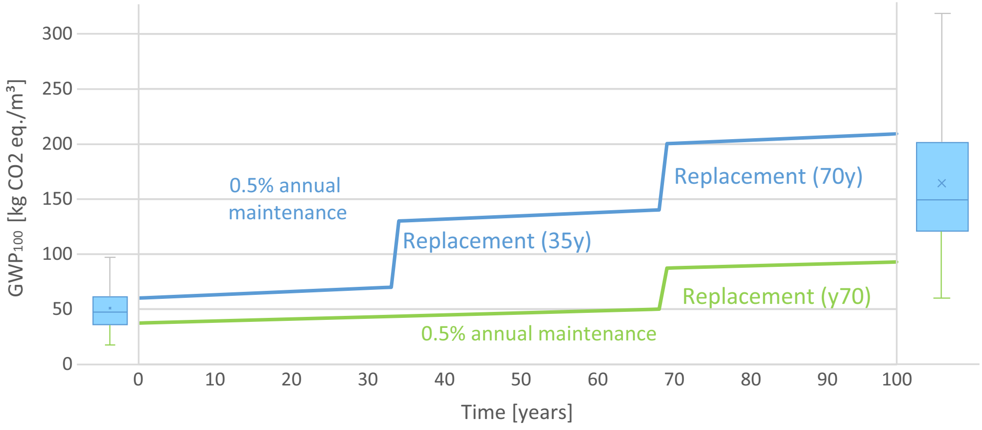


Table 3 Comparison of reference and target values with the SSD results

Structure type	Check dam	Submerged sill	Bank protection wall	Bank protection wall	Bank protection wall	Bank protection wall
Material type	Double log crib wall	Double log crib wall	Single log crib wall	Double log crib wall	Riprap wall	Riprap wall in concrete
Construction values [kg CO_2 eq.]						
Reference value	59	–	41	175	28	155
Target value	37	–	25	111	17	85
SSD value	33	–	24	111	23	141
Life cycle values [kg CO_2 eq.]						
Reference value	203	149	205	887	158	517
Target value	130	150	107	496	89	295
SSD value	108	114	98	396	105	496

target values shows that, even when considering environmental impacts, the proposed design can be understood as a target value.

3.3 Effect of the number of Monte Carlo simulations on the results

In Larsson Ivanov et al. (2018), it is noted that in most cases more than 10,000 Monte Carlo iterations are necessary for reliable LCA results. In the "Uncertainty and variation in LCA" section, it was already mentioned that it was necessary to limit the simulation runs of this study to 1000 in order to guarantee feasibility.

In order to check the consistency of the calculated results, the benchmarks of two structure types were carried out with 10,000 iterations, so that the deviations that result from the increase in simulation runs can be represented. In order to present a differentiable result, two structure types with different building materials were chosen. On the one hand, the calculation was carried out for the life cycle of the reinforced concrete check dam and, on the other hand, for the life cycle of the double log crib check dam.

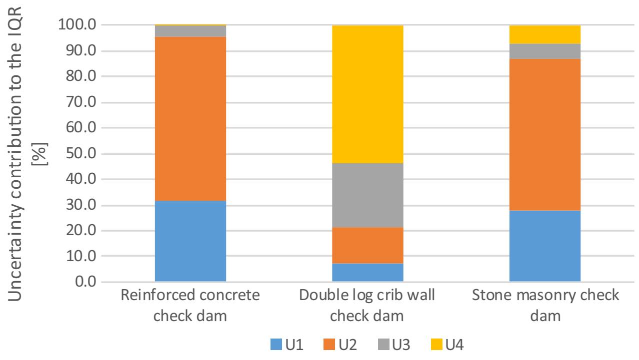


Fig. 25 Contribution analysis of uncertainties concerning check dams

Figures 26 and 27 show the deviation of the median and the IQR caused by the increase in simulation runs for the selected structure types. These deviations were calculated for 11 impact categories.

In the case of the reinforced concrete check dam, the median shifts on average by 0.77% and the IQR by 2.75%. The maximum deviation of the IQR is 5% (acidification potential) and the maximum deviation of the median is 2% in the case of the ozone layer depletion.

When the double log crib check dam is observed, the average median shift is 1.16% and the IQR shift is 3.75%. The maximum deviation of the IQR is observed in freshwater aquatic ecotoxicity with 10% and the maximum deviation of the median is 3% for terrestrial ecotoxicity.

4 Conclusions

The present study was the first to establish LCA benchmarks for torrent control structures. The methodological approach provides a framework for the future development of such benchmarks. Furthermore, this allows decision-making in early planning stages and throughout the entire life cycle of the structures, taking into account environmental impacts.

SSD processes represent the state of the art in construction and thus reflect best practice. It has been shown that the SSD processes also represent the best practice in terms of environmental impacts. The LCA results of the SSD processes are in the range of the developed target values and thus represent an environmental way of construction which should serve as a target.

Within the uncertainty analysis, it could be shown that the contributions of the various uncertainties within the construction phase vary depending on the choice of material. The contribution of uncertainties to the overall result (IQR) correlates with the average output of the processes. When using cementitious building materials, the focus is on emissions

Fig. 26 Deviation of the median and the IQR caused by the increase of Monte Carlo simulations runs for reinforced concrete check dam

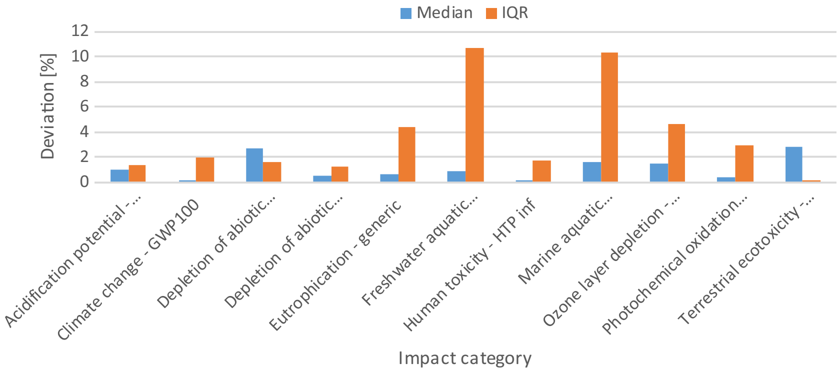
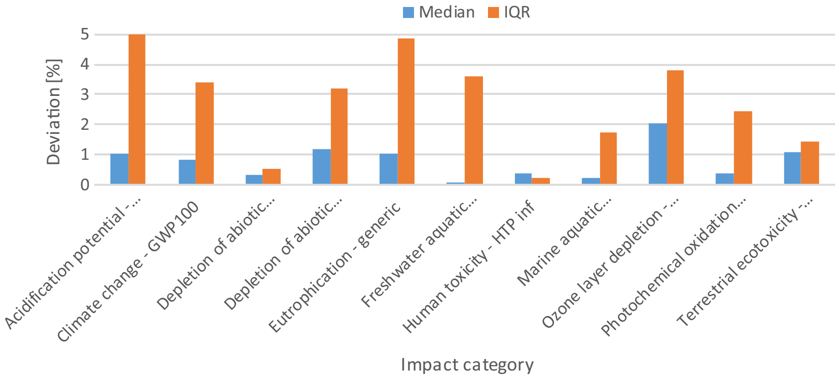


Fig. 27 Deviation of the median and the IQR caused by the increase of Monte Carlo simulations runs for a double log crib check dam



and also on the uncertainties of these materials. For buildings that consist of low-emission building materials, the contribution of emissions from the material area shifts to the construction process. In contrast to Bojarski et al. (2008), most uncertainty does not originate from background information, such as from ecoinvent data sets, but from the foreground information of the processes.

The contributions from the construction phase compared to the use stage are quite similar and independent of the choice of material. The ratio between the emissions caused by the construction and the emissions caused by the maintenance and replacement of the structures shows a ratio of 1:2.

It could be shown that the reduction of the Monte Carlo simulations to 1000 runs changes the LCA result and the IQR only marginally, considering different impact categories. Overall, it can be summarised that, on average, the results can vary by 1–3% due to the lower number of simulation runs.

The development of these LCA benchmarks represents the first step towards environmental assessment of torrent control structures and closes the knowledge gap that was pointed out by Bocchini et al. (2014).

A further development of the benchmarks requires the analysis of additional structures. The more structures are included in benchmarking, the more accurate the variability of the LCA results can be. A good documentation of the maintenance actions could define additional uncertainty factors and thus provide further input for the creation of benchmarks. Further research on the service lifetime of the structures will continue to change the life cycle benchmarks, as this area of research is still in its early stages.

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