Case study of a water bioengineering construction site in Austria. Ecological aspects and application of an environmental life cycle assessment model

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Abstract

Recently, applications of soil and water bioengineering constructions using living plants and supplementary materials have become increasingly popular. Besides technical effects, soil and water bioengineering has the advantage of additionally taking into consideration ecological values and the values of landscape aesthetics. When implementing soil and water bioengineering structures, suitable plants must be selected, and the structures must be given a dimension taking into account potential impact loads. A consideration of energy flows and the potential negative impact of construction in terms of energy and greenhouse gas balance has been neglected until now. The current study closes this gap of knowledge by introducing a method for detecting the possible negative effects of installing soil and water bioengineering measures. For this purpose, an environmental life cycle assessment model has been applied. The impact categories global warming potential and cumulative energy demand are used in this paper to describe the type of impacts which a bioengineering construction site causes. Additionally, the water bioengineering measure is contrasted with a conventional civil engineering structure. The results determine that the bioengineering alternative performs slightly better, in terms of energy demand and global warming potential, than the conventional measure. The most relevant factor is shown to be the impact of the running machines at the water bioengineering construction site. Finally, an integral ecological assessment model for applications of soil and water bioengineering structures should point out the potential negative effects caused during installation and, furthermore, integrate the assessment of potential positive effects due to the development of living plants in the use stage of the structures.

Keywords Water bioengineering · Case study · Ecological assessment · Life cycle assessment · Global warming potential · Cumulative energy demand

Introduction

The relationship between soil/water bioengineering and ecology

There has recently been a trend towards more sustainable construction techniques. This concerns not only the building construction sector, but also the field of hydraulic and

civil engineering. An ecological alternative, which pursues the same objectives as conventional civil engineering structures, is soil and water bioengineering (SWBE). The important fact is that SWBE uses natural components for soil and water related engineering projects, which take into account not only the technical perspective, but also ecological and socio-economic values [1–5]. As its name indicates, SWBE deals with both soil and water related engineering. Consequently, the fields of application are wide-ranging, including shallow landslide and gully stabilisation, protection against superficial erosion and other earth constructions in soil bioengineering, along with protecting and stabilising river banks, and river restoration in water related bioengineering. This paper presents a case study which was undertaken at the river Thaya, and therefore, the term “water bioengineering” is subsequently used throughout. The natural materials used in SWBE

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projects are first and foremost, living materials such as seeds, plants, or parts of plants. It may be necessary to use additional auxiliary materials, such as stones, wooden logs, and many other supporting materials, to complement and support the structure [6–8].

In the relevant literature, different authors describe the construction procedure and dimensioning of SWBE structures [6, 8–13]. Additionally, there is a proposal by Giupponi et al. for assessing the ecological success of SWBE structures, which applies the index of ecological success (IES). This index is based on a phytosociological analysis of vegetation [14]. Another approach for a sustainability assessment of eco-engineering measures is presented by Mickovski and Thomson [15]. They establish some key performance indicators reflective of both engineering and sustainability requirements for eco-engineering in the context of stability, active use of vegetation, and long-term sustainability. The development of this eco-engineering framework should help the stakeholders to shape the goals and objectives of their projects, guide their design, monitor them during construction, and also to assess the contribution of the project in terms of the degree of sustainability over the post-construction lifetime [15]. However, a method for assessing SWBE structures in terms of their potential environmental impacts (life cycle assessment, LCA), taking into consideration the carbon balance or energy demand, is still not applied by any other authors at present.

It appears to be a fact that SWBE per se is environmental friendly or of ecological value. But what does “ecological” actually mean? The historical evolution of the term ecology started in 1866, when Ernst Haeckel defined ecology as “the comprehensive science of the relationship of the organism to the environment” [16]. Since its definition, the term ecology has undergone a lot of changes, including the separation of animal and plant ecology in the early twentieth century [17, 18]. Later on, the integration of both animal and plant ecology was again integrated into the definition of ecology, and nowadays, the interactions between organisms and the physical environment are an inherent part of it [19]. Furthermore, the need to integrate the interaction between organisms, and the effects of material flows in nature (for example, carbon dioxide emissions), seems to make sense. Nowadays, a broader definition of the term ecology has developed: “the scientific study of the distribution and abundance of organisms and the interactions that determine distribution and abundance” [16, 20]. The development of the term ecology indicated that not only flora, fauna and the ecological operability of the ecosystem are part of its definition, but also the physical environment, with its material flows (for example, the carbon cycle). This takes us back to the need for an ecological assessment of SWBE structures, where potential negative impacts on flora, fauna and the entire ecosystem which can be caused by anthropogenic material flows

(emissions, resource consumption, etc.) as well as anthropogenic interventions are analysed.

Aim and scientific research question

The aim of this paper is to present the problem which was addressed, and the water bioengineering solution which was found, during our case study at the river Thaya. Additionally, the application of an environmental life cycle assessment model for water bioengineering constructions will be presented. In this case, the impact categories cumulative energy demand (CED) and global warming potential (GWP) have been analysed. The application of the LCA model, which was already applied and presented in von der Thannen et al. [21], has been applied in this case study to a typical water bioengineering construction site at the River Thaya in Bernhardsthal, Lower Austria. The objective of the paper is to present the water bioengineering solution, its ecological benefits and the environmental impacts caused by a water bioengineering construction site during the construction process. Furthermore, the results of the water bioengineering system have been compared to the results of a potential conventional alternative.

The following scientific research questions were devised: (1) Which method (water bioengineering or conventional) is the best—from an environmental point of view—for solving the problem of river bank erosion at the river Thaya? (2) How much of an environmental impact, in terms of energy demand and emissions, will be caused during the construction period? (3) Which processes have the most negative impacts and, therefore, should be optimised in order to reduce potential emissions and energy demand?

Methodology

Case study site at the river Thaya

The study site is located at the river Thaya in Bernhardsthal, Lower Austria (Fig. 1). The river still strongly meanders and forms part of the border between Austria and the Czech Republic.

Water bioengineering measures were already put in place in 1995 in order to stop the erosion process at the cut bank. At the time, wooden pilots (pine wood) were placed in the riverbed two metres away from the eroding riverbank. Coniferous trees were installed between the pilots and the riverbank, and some stones were placed underneath the low water level. Living plant material was used sparingly. Thus, the soil was not additionally protected by roots of living plants and the erosion process continued.

The river bank eroded again progressively at the cut bank over the last years (Fig. 2a, b) and this jeopardised the forest

Fig. 1 Map of the river system (Thaya, Morava, Danube) showing the location of the study site at the river Thaya, marked with the red circle

Fig. 2 **a**: Initial situation: erosion at the cut bank of the river Thaya; **b**: Progressive erosion behind the previous constructions from 1995

road which passes above the river bank. The main problem is a consequence of the loss of land and the forest road, which is the result of the erosion process. From an ecological perspective no interventions would be necessary, because river bank erosion is a natural process. However, from a legal and technical point of view, erosion control measures must be implemented.

The local conditions and the ecological benefits of bioengineering works indicated the implementation of water bioengineering structures. The water bioengineering project was organised in 2018 by the viadonau—Österreichische Wasserstraßen-Gesellschaft mbH and supported by the Institute of Soil Bioengineering and Landscape Construction, University of Natural Resources and Life Sciences Vienna

(BOKU). Two different water bioengineering measures were planned in 2017 and implemented in March 2018.

The construction site is approximately 150 m long in total and located at the cut bank of the river Thaya. The implemented water bioengineering constructions consist of a brush mattress with willows (55 m long) and a pile wall (95 m long). The construction stages for the pile wall are described in the following figures (Fig. 3a–d).

As a first step, the wooden pilots were implemented at two metres apart. Secondly, dead wood was placed between the pilots, reaching into the waterfront to shape a rough riverbank. Furthermore, the wooden pilots and the dead wood were connected by wooden crossbars and wooden pincers (see Fig. 3c). Additionally, some dead wood was placed in

Fig. 3 **a:** Initially, wooden pilots were installed; **b:** Secondly, dead wood was placed between the pilots to shape a rough waterfront; **c:** Side view of the completed construction; **d:** Top view of the completed construction

the upper section of the construction to provide continuous structural diversity because it was locally available.

Life Cycle Assessment (LCA)

The methodology of life cycle assessment provides the possibility of achieving a better understanding of the potential environmental impact of products or services. The objective of an LCA model is the compilation, as well as the evaluation, of inputs and outputs, and the assessment of the potential environmental impacts of a product system throughout its lifecycle [22]. In the field of building construction, the methodology for an environmental LCA has been developed [23, 24]. In contrast to the building sector, there is a lack of knowledge in the application of life cycle assessment in the field of SWBE. In the field of natural hazard protection, only few and limited case studies, such as those undertaken by Gebauer et al., Noda et al., Storesund et al. and Paratscha et al. [25–28], are available.

It is necessary to define the system boundary within the definition of goal and scope. In the standard CEN 2011 for the field of construction, the system boundary is defined as cradle-to-grave (referring to the whole life

cycle), cradle-to-gate (including raw material acquisition up to finalised building materials), or gate-to-gate (taking into consideration the construction process only) [23].

System boundary and functional unit

In order to assess the water bioengineering construction site in terms of its environmental impact, the system boundary is defined as being cradle-to-gate (material acquisition and construction stage). Within this method, different impact categories can be chosen to assess the potential environmental burden. In the present paper, the relevant impact categories are stated as being: GWP with the reference unit [$\text{kg CO}_2\text{-eq.}$] and the CED considering non-renewable resources with the reference unit [MJ]. The main focus of the paper is to show the processes which cause the most environmental impacts by implementing the water bioengineering system. This information can be of value in highlighting the opportunities to reduce these impacts. The functional unit in this case study is defined as “150 m of embankment protection of the river Thaya”.

Inventory analysis

The inventory analysis of the present case study is presented in Table 1. Site visits, with detailed documentation and the analysis of construction reports, were necessary in order to detect all relevant inputs. Table 1 contains a summary of all relevant transports (on- and off-site), machine use on the construction site, and materials used. The summarised transport distances for the trucks include the empty transport back to production site.

Regarding the system boundary in greater detail: it excludes manpower (as is typical for the LCA method) and all smaller tools (without power consumption). The transport of workers (to and from the construction site), and the power consumption of the building container and mobile sanitary system have all been excluded, mainly due to lack of data.

Software and database

For the purpose of the application of the LCA method, the software OpenLCA version 1.7.0 was used as a means of analysing this case study. Additionally, the Swiss Ecoinvent database version 2.2, released in 2007, was used. A large amount of important data for civil engineering has been collected in the Ecoinvent database, which is adaptable for SWBE materials and processes.

Life cycle impact assessment

This case study uses the impact assessment methods CML 2001 (V.4.4, based on IPCC 2007) and CED (V.1.0.1). The impact indicator GWP₁₀₀ was selected from CML 2001 to

show the environmental impact of emitted greenhouse gases. The impact indicator CED focussing on non-renewable primary energy demand was selected from the impact assessment method CED.

Results

Ecological aspects of installation and further development of the water bioengineering structures

The process of construction was conducted under high ecological standards. The majority of the wooden piles from previous constructions were still in a very good condition, and therefore, we were able to reuse them in the new constructions. Furthermore, the constructions were installed solely from the landside, in order to avoid any disruption to the habitats in the riverbed. Several guidelines and directives were taken into consideration in order for us to comply with ecological standards [8, 29, 30]. However, on the landside, some trees had to be cut down, and the river bank had to be adapted to set up the construction site and implement the water bioengineering structures. Unfortunately, it was necessary to accept these impacts on the environment. From a hydrological perspective, the implementation of the structures has not affected the current situation, but meets the requirements of embankment protection.

The water bioengineering system is able to achieve ecological effects, such as creating new habitats, structural diversity, shading, soil drainage and stabilisation. However, environmental burden occurred during the construction process. As conventional alternative a riprap was considered, because it is a hard and heavy construction technique but still considered as a soil bioengineering measure [6, 8]. Additionally, a riprap would not fit aesthetically to the regional landscape and it provides less ecological benefits.

After three months, the water bioengineering system can be seen to be developing well, and the willows and other plants implemented during the constructions have already grown (Fig. 4c, d).

Results of the LCA calculation

The impact categories CED and GWP were investigated in the water bioengineering case study at the river Thaya. The diagrams show the results for the GWP. The results of CED are presented in the text numerically, as the distribution can be seen to be similar to what is shown in the diagrams. The machines operating on the construction site were the cause of most emissions (8065 kg CO_{2-eq.}), followed by the transport (4674 kg CO_{2-eq.}). The materials were responsible for the least emissions (2667 kg CO_{2-eq.}). Taking into

Table 1 Inventory data of the water bioengineering case study at the river Thaya

Category	Position	Amount	Unit
Transports	Truck	4017	km
	Passenger car	400	km
Machinery on construction site	Truck	137	h
	Digger	102	h
	Tractor	98	h
	Power saw	72	h
Materials	Round wood	73.96	m ³
	Soil	75	m ³
	Gravel	46.06	t
	Rootstock	30	pcs
	Steel	53.61	kg
	Lime stone boulders	87.5	t
	Reinforcing steel	46.52	kg
	Wire	27.5	kg
	Willow branches	25	m ³

Fig. 4 a, b: Situation after construction; c, d: Situation following the implementation of water bioengineering measures after three months

consideration the CED, it is clear that the machinery used the most energy (118008 MJ), followed by the transport (71490 MJ) and the materials (40592 MJ).

Figure 5 shows the contribution to emissions which every single transport vehicle makes, as well as the degree

of emission created by the machinery and material used on the construction site. As can be seen, the trucks used for transportations on- and off-site are the culprits for most of the emissions. Additionally, Fig. 5 shows the cumulative percentage of the emissions, which can be broken down into

Fig. 5 Total emissions caused by each process, and the cumulative percentage

the following: approximately 30% caused by transports, 50% caused by the machines on the construction site and 20% a result of the materials used.

Comparison to a conventional alternative—riprap

If a riprap was to be built on the same site, as a conventional alternative, the impact analysis would show different results. First and foremost, a riprap would not fit into the landscape, because boulders are not typical for this region. Secondly, a conventional structure could not provide as many ecological benefits as the water bioengineering system. However, the volume of the construction type constitutes a large difference. A riprap is more or less a 2D construction, whereby the top layer of the soil has to be prepared, after which stones are placed. It is almost the same procedure for the brush mattress. However, for the pile wall, which consists of a 3D construction, a lot of volume of soil has to be removed in order to build the basic structure. Once the basic structure is finished, stones and soil can be used as backfill. This shows that a higher use of machinery is necessary for the pile wall, which, in turn, affects greenhouse gas emission and energy balance.

Table 2 The hypothetical inventory data of the conventional alternative riprap

Category	Position	Amount	Unit
Transports	Truck	8862	km
Machinery on construction site	Truck	93	h
	Digger	93	h
	Power saw	56	h
Materials	Lime stone boulders	750	t
	Gravel	50	t

Table 2 below shows the inventory data for the fictive construction riprap. The construction site equipment and preparatory work were adapted from the water bioengineering construction site, except for the machines that were not necessary for the conventional alternative.

The results show that the conventional alternative riprap produced 16399 kg CO_{2-eq.} (energy consumption: 238155 MJ) in total, whereas the water bioengineering alternative (brush mattress and pile wall) produced 15407 kg CO_{2-eq.} (energy consumption: 230090 MJ) in total. This shows that the water bioengineering alternative is only slightly better than the conventional measure with regards to GWP and CED. When running the machines on the construction site, the water bioengineering measure produces worse results with 8065 kg CO_{2-eq.}, whereas the riprap caused 4984 kg CO_{2-eq.} emissions (see Fig. 6). This means a rate of emissions one and a half time higher caused by the machines used at the water bioengineering construction site. With regards to transport, the results are different, showing that the emissions caused by the conventional measure (9386 kg CO_{2-eq.}) are at least twice the level of emissions caused by the water bioengineering measures (4674 kg CO_{2-eq.}). The difference in terms of the materials is smaller. The materials used for the construction of the conventional measure caused 2030 kg CO_{2-eq.} of emissions, and the water bioengineering measure caused 2667 kg CO_{2-eq.} (see Fig. 6).

With regards to the lines of cumulative percentage, the transport necessary for the water bioengineering construction caused 30% of total emissions, whereas the transport necessary for the conventional construction caused nearly 60%. Adding the percentage of emissions caused by the machines on the construction site to this, the water bioengineering measure reaches about 80% (around 50% due to the machines) of total emissions caused, and the conventional

Fig. 6 Comparison of the water bioengineering site and the conventional construction site, in terms of the emissions caused by transports, machines and materials

structure nearly 90%. Therefore, the materials used in the water bioengineering construction caused nearly 20% of the total emissions, whereas the materials used in the conventional measure caused around 10% (see Fig. 6).

Considering the service life time of the conventional and the water bioengineering structures will have a noticeable effect on the results. In this case study, we have two ways of taking the service life time into account: on the one hand, a conventional calculation can be done based on a literature review; on the other hand, a realistic scenario could be considered. In literature, we found an average service life time for structures mainly built of stone (in our case study the conventional alternative) of 70 years [31, 32]. For structures mainly built of wood (in our case study representing the water bioengineering structure), we found values for the service life time varying from 15 up to 60 years [26, 31–35]. This wide range of service life time for wooden structures can be explained by the various external effects (climate, water contact, radiation, etc.) affecting the condition of wood. In the case study, a service life time of 35 years was chosen for the wooden construction material of the water bioengineering structure. Consequently, it would mean that the water bioengineering structure has to be build two times to reach the same service life time as the conventional structure built of stones. However, the developing plants from the bioengineering structure also have to be considered for the service life time. These plants provide stabilisation effects at the time when the wooden constructional material has reached the end of life phase. An assessment of the service life time of dynamic and living measures like characteristic water bioengineering structures is dependent on various natural factors and, therefore, extremely challenging. As shown in Fig. 7, the water bioengineering structures have to develop their function with the growth of the living plants, whereas the conventional structure provides full function

after completion. During the use stage, conventional structures are slowly degrading, and at some point, conservation measures will be necessary. Water bioengineering measures have got huge potential to develop naturally and sustain themselves, but maintenance work is important to reach full functionality. The end of life scenarios considered in Fig. 7 are demolition, decay and exclusively for water bioengineering measures reaching the natural state. This approach of considering the service life time is more realistic, but needs to be incorporated for every single structure taking into account external effects.

Discussion

The case study which has been presented in this paper represents a typical water bioengineering project and is helpful to show the benefits of applying the LCA method. The well-documented construction site, and the possibility to follow the status of progress, facilitated the undertaking of presenting a post calculation of the implemented structures. Therefore, the paper presents the results of LCA which has been applied to a real water bioengineering case study, whereas the first case study presented in von der Thannen et al. was based on several hypotheses [21]. Unfortunately, there is no other case study or literature known in the field of SWBE—dealing with LCA methodology and potential negative impacts of ecological construction methods—to compare with or cite previous studies.

The results of the study confirmed first expectations, on the one hand, such as the following major impacts for the two construction types: the transport emissions of the conventional alternative, which were twice as high compared to the water bioengineering measures; the emissions from machines running on the construction site, which were one

Fig. 7 Function development of water bioengineering and conventional structures over time considering different maintenance and end of life scenarios

and a half time higher at the water bioengineering construction site. One reason, therefore, can be seen as the use of additional machines such as a tractor and a power saw which was necessary. On the other hand, the results concerning the materials used at the sites were unexpected, because the materials used to implement the water bioengineering construction were shown to cause 637 kg CO₂-eq., which were more emissions than the conventional alternative. The reason can be simply explained, in the water bioengineering measures many different materials are used (wood, stones, steel) and the main building material, wood, is not calculated as CO₂ neutral, because there are many energy consuming and emission producing processes in the supply chain. Consequently, the idea that water and soil bioengineering projects are not ecological alternatives per se has to be taken into consideration. There are many different factors to bear in mind. Furthermore, the LCA model for SWBE structures will provide transparency for the responsible planners, by pointing out the truth of costs—involving natural resources—of all construction stages and components.

Analysing the ecological value of SWBE measures, two aspects must be considered. On the one hand, the ecological benefits involved in a soil or water bioengineering measure are relevant (habitats, biodiversity, biomass production, protective function, etc.), and on the other hand, the possible negative impacts on ecosystems caused by soil or water bioengineering measures, during the period of construction (e.g. emissions, energy consumption, intervention in ecosystems and nature) should be taken into consideration. The latter have not as yet been considered in any scientific study until the present time, but this should be a recommendation in the future research and practice. In the present case study, we consciously did not consider other impact categories focussing on biodiversity (e.g. land use), because these impact assessment methods still “suffer from a number of gaps and faces enduring challenges such as the inclusion of a spatial dimension” [38, p.89]. Furthermore, using biodiversity indicators mostly requires the collection of primary data because average secondary data (from any location around the world, which are actually available in databases) reduces the accuracy of results [36]. Additionally, the construction process was conducted solely from the landside, in order to avoid any disruption to the habitats in the riverbed and we did not change the use of land in the presented case study.

Conclusion

The results of LCA case studies in SWBE show that the potential negative impacts can be well estimated for the construction phase. However, a general assessment is only possible to a limited extend because many different factors like regional conditions, dimensions of the structure (depending

on length and height of the embankment), type of construction and materials play a key role. Additionally, there is a clear demand to create uniform standards and raise awareness about ecological costs and benefits of SWBE structures over the entire life cycle. This would be an important step to bring back the origin of the discipline of SWBE. In the early days of SWBE, the use of local materials and manual work was the only way to build these structures, limiting the impact on the environment [37]. Today, this origin got lost in some way and we use the opportunity of cheap transports and materials, coming from other regions, and heavy machinery to facilitate the construction process.

The potential positive effects of ecological construction techniques (e.g. biodiversity, ecological corridors, soil drainage, structural diversity, water and temperature regulation) are often described and praised in literature [6, 8, 12, 29, 38, 39]. An assessment of the potential positive effects is often missing but would be very important to quantify the benefits of these techniques.

The current study is a contribution to scientific as well as practical progress in the field of SWBE to better understand the potential negative impacts emerging during the construction stage of ecological construction methods. The implementation of the assessment of potential positive effects and ecosystem services emerging during the use stage of ecological construction techniques will be an essential step in the future studies.

This leads us to an integral holistic assessment of SWBE projects in the future, assessing the entire life cycle (including the use stage and end of life stage) and considering impact categories, other than GWP and CED, focussing, for example, on biodiversity.

In order to apply holistic LCA models the use stage and the end of life stage have to be considered by using the cradle-to-grave system boundary. Furthermore, with the application of the cradle-to-grave system boundary, the positive material inherent properties of wood, in terms of CO₂ and energy, will be included. Additionally, this indicates the need for intense research regarding the development of biomass, capturing CO₂ and energy, in SWBE structures, the options of usage considering the biomass which is produced, and finally the duration of the wooden components (storing CO₂ and energy). Therefore, modelling the use stage of SWBE systems, including biomass development and the durability of materials (e.g. wood), should be the future goal. Taking into account the individual service life time of the structures will have noticeable effects on the LCA results.

Furthermore, it could be of international interest to develop a database containing monitoring data regarding plant development, and the durability of wood or other materials, implemented in SWBE structures. Finally, the question arises as to whether SWBE systems can achieve ecologically positive effects through feedback effects

(capturing the CO₂ by the plants, development of ecosystems and habitats, etc.) which are a result of the development of plants; and how these effects can be assessed and integrated in the LCA model.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability The datasets generated during and/or analysed during the current study are included in this published article or are available from the corresponding author on reasonable request.

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References

1. Rey, F., Bifulco, C., Bischetti, G.B., Bourrier, F., de Cesare, G., Florineth, F., Graf, F., Marden, M., Mickovski, S.B., Phillips, C., Peklo, K., Poesen, J., Polster, D., Preti, F., Rauch, H.P., Raymond, P., Sangalli, P., Tardio, G., Stokes, A.: Soil and water bioengineering: practice and research needs for reconciling natural hazard control and ecological restoration. *Sci. Total Environ.* **648**, 1210–1218 (2018). <https://doi.org/10.1016/j.scitotenv.2018.08.217>
2. Rauch, H.P., Sutli, F., Hoerbinger, S.: Installation of a riparian forest by means of soil bio engineering techniques—Monitoring results from a river restoration work in Southern Brazil. *Open J. For.* **4**, 161–169 (2014)
3. Howell, J.: Roadside bio-engineering. His Majesty's Government of Nepal, Kathmandu (1999)
4. Lammeranner, W., Laaha, G., Rauch, H.P.: Implementation and monitoring of soil bioengineering measures at a landslide in the middle mountains of Nepal. *Plant Soil* **278**, 159–170 (2005)
5. Petrone, A., Preti, F.: Suitability of soil bioengineering techniques in Central America: a case study in Nicaragua. *Hydrol. Earth Syst. Sci.* **12**, 1241–1248 (2008)
6. Florineth, F.: Pflanzen statt Beton. Sichern und Gestalten mit Pflanzen Patzer Verlag, Berlin-Hannover (2012)
7. Gerstgraser, C.: Ingenieurblogische Bauweisen an Fließgewässern. Grundlagen zu Bau, Belastbarkeiten und Wirkungsweisen. Wien, Österr. Kunst- u. Kulturverlag (2000)
8. Zeh, H.: Ingenieurblogie: Handbuch Bautypen. Zürich: vdf Hochschulverl (2007)
9. Begemann, W. & Schiechl, H. M.: Ingenieurblogie: Handbuch zum ökologischen Wasser- und Erdbau. Bauverlag GmbH, Wiesbaden und Berlin (1994)
10. Gray, D.H., Sotir, R.B.: Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control. Wiley, New York (1996)
11. Schiechl, H. M. & Stern, R.: Handbuch für naturnahen Erdbau. Eine Anleitung für ingenieurblogische Bauweisen. Österreichischer Agrarverlag, Wien (1992)
12. Schiechl, H. M. & Stern, R.: Handbuch für naturnahen Wasserbau. Eine Anleitung für ingenieurblogische Bauweisen. Österreichischer Agrarverlag, Wien (1994)
13. Zeh, H.: Ingenieurblogische Bauweisen im naturnahen Wasserbau. Praxishilfe. Umwelt-Wissen Nr. 1004. Bundesamt für Umwelt (BAFU), Bern (2010)
14. Giupponi, L., Bischetti, G.B., Giorgi, A.: A proposal for assessing the success of soil bioengineering work by analysing vegetation: results of two case studies in the Italian Alps. *Landsc. Ecol. Eng.* **13**, 305–318 (2017)
15. Mickovski, S.B., Thomson, C.S.: Developing a framework for the sustainability assessment of eco-engineering measures. *Ecol. Eng.* **109**, 145–160 (2017)
16. Begon, M., Howarth, R.W., Townsend, C.R.: Ökologie. Springer, Berlin Heidelberg (2017)
17. Tansley, A.G.: The problems of ecology. *N. Phytol* **3**(8), 191–200 (1904)
18. Elton, C.S.: Animal Ecology. Sidgwick & Jackson Ltd., London (1927)
19. Ricklefs, R. E.: Ecology. Thomas Nelson & Sons Ltd, London (1973)
20. Townsend, C. R., Begon, M. & Harper, J. L.: Essentials of ecology. Oxford: Blackwell Publishing. 530 pp, paperback. ISBN 1-40510-328-0 (2003)
21. von der Thannen, M., Hoerbinger, S., Paratscha, R., Smutny, R., Lampalzer, T., Strauss, A., Rauch, H.P.: Development of an environmental life cycle assessment model for soil bioengineering constructions. *Eur. J. Environ. Civ. Eng.* (2017). <https://doi.org/10.1080/19648189.2017.1369460>
22. ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework. ISO 14040:2006 07 01 (Vol. ISO 14040:2006). Geneva: International Organization for Standardization (ISO) (2006)
23. CEN 2011. EN 15978: 2011 11 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method Planning & implementation of construction projects, Buildings, Other buildings. *DIN EN 15978*. Brussels: European Committee for Standardisation (CEN) (2011)
24. CEN 2013. EN 15804:2012+A1:2013-11 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products planning & implementation of construction projects, Building construction, Other aspects. Brussels: European Committee for Standardisation (CEN) (2013)
25. GEBAUER, S., GRUNDER, H. T., IDEL, M., KHORASANI, R., LÜHR, H. P. & RIETH, U.: Eisensilikat-Gestein und Natursteine im Wasserbau. Fachzeitschrift: Binnenschiffahrt **55**(3), 82–88 (2001)

26. Noda, R., Kayo, C., Sasaki, T., Takaoku, S.: Evaluation of CO₂ emissions reductions by timber check dams and their economic effectiveness. *J. Wood Sci.* **60**, 461–472 (2014)
27. Storesund, R., Massey, J. & Kim, Y.: Life cycle impacts for concrete retaining walls vs. bioengineered slopes. In: Reddy, K.R., Khire, M.V., Alshawabkeh, A.N. (eds.) *GeoCongress 2008: Geosustainability and Geohazard Mitigation*, pp. 875–882. New Orleans, LA, 2008. ISBN (print): 9780784409718 (2008)
28. PARATSCHA, R., VON DER THANNEN, M., SMUTNY, R., LAMPALZER, T., STRAUSS, A. & RAUCH, H. P.: Screening LCA of torrent control structures in Austria. *The International Journal of Life Cycle Assessment* (2018). <https://doi.org/10.1007/s11367-018-1501-5>
29. EFIB - Europäische Richtlinie für Ingenieurbiologie/European Guidelines for Soil and Water bioengineering/Directrices Europeas de Bioingeniería del Paisaje/Directrices Europeas de Engenharia Natural/Directives Européennes pour le Génie Biologique/Direttiva Europea per l'Ingegneria Naturalistica. In: INGENIEUR-BIOLOGIE, E. F. F. (ed.). Aachen : Gesellschaft für Ingenieurbiologie e.V. (2015)
30. BMLFUW (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft): Technische Richtlinien für die Bundeswasserbauverwaltung RIWA-T. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien (2015)
31. Bergmeister, K., Suda, J., Hübl, J. & Rudolf-Miklau, F.: Beton Kalender. Schutzbauwerke gegen Wildbachgefahren. Ernst W. & Sohn Verlag, Berlin, ISBN: 978-3-433-03301-2 (2008)
32. Suda, J., Rudolf-Miklau, F. (2009) Rund um den Lebenszyklus von Schutzbauwerken: Schadenshäufigkeit, Zustandsbewertung und Dauerhaftigkeit. Wildbach- und Lawinenverbau, 73. Jg., S. 163. Verein der Diplomingenieure der wildbach und lawinenverbauung Österreichs, Villach.
33. Böll, A., Greber, W., Graf, F. & Rickli, C. (1999) Holzkonstruktionen im Wildbach-, Hang- und Rensenverbau. Berichte der Eidgenössischen Forschungsanstalt für Wald, Schnee und Landschaft. Birmersdorf
34. BMLFUW: Richtlinien - für die Wirtschaftlichkeitsuntersuchung und Priorisierung von Maßnahmen der Wildbach- und Lawinenverbauung gemäß § 3 Abs. 2 Z 3 Wasserbautenförderungsgesetz 1985. Teil I: Kosten-Nutzen-Untersuchung (KNU) und standardisierte Nutzenuntersuchung: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Sektion Forstwesen, Marxergasse 2, 1030 Wien (2006)
35. BAFU. EconoMe 3.0 - Richtwerte zur Bestimmung der jährlichen Kosten. In: BUNDESAMT FÜR UMWELT BAFU, A. G. & SBB, S. B. (Eds.). 3003 Bern (2015)
36. Winter, L., Lehmann, A., Finogenova, N., Finkbeiner, M.: Including biodiversity in life cycle assessment—State of the art, gaps and research needs. *Environ. Impact Assess. Rev.* **67**, 88–100 (2017). <https://doi.org/10.1016/j.eiar.2017.08.006>
37. Bischetti, G.B., Di Fi Dio, M., Florineth, F.: On the origin of soil bioengineering. *Landsc. Res.* **39**, 583–595 (2014). <https://doi.org/10.1080/01426397.2012.730139>
38. Hacker, E., Johannsen, R. (2012) Ingenieurbiologie. Ulmer Verlag, Stuttgart
39. Patt, H., Jürging, P., Kraus, W. (2011) Naturnaher Wasserbau. Entwicklung und Gestaltung von Fließgewässern. Springer, Heidelberg

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