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ORIGINAL ARTICLE

Thirty years of river restoration in Switzerland: implemented measures and lessons learned

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Abstract In the age of climate change and ecosystem degradation, governments realise more and more that it is crucial to protect ecosystem health, to preserve water resources and to maintain flood protection. Therefore, several countries, among those Switzerland, have implemented laws to make the restoration of riverine ecosystems a legal obligation. In Switzerland, restoration projects were implemented as early as 1979, prior to these laws coming into force. For this article, 848 Swiss restoration projects, implemented between 1979 and 2012, were investigated, spanning a total of 307 river kilometres. No correlation was found between the geographical distribution of total restored lengths in a way that larger cantons performed more restorations. Neither was there a correlation between the total restored length and the canton's population density or financial status. Restoration activities increased steadily after 1992, with most restorations being reported for the years 2004, 2005 and 2009. The average restoration rate was 9.8 km per year, ranging between 0.5 km in 1979 and 23.9 km in 2004. Restoration measures were very diverse, ranging from measures that directly affected the wildlife, e.g. by providing habitats, to measures which indirectly enhanced conditions for the ecosystem, such as water quality ameliorations. Data regarding success evaluation was only available for 232 of the 848 projects, making it difficult to state whether the implemented restoration projects reached the intended objectives. Over the next 80 years, a further 4,000 km of Swiss rivers will be restored, requiring a restoration rate of 50 km per year, which, according to the data, is an achievable goal.

Keywords Ecosystem · Flood protection · Hydromorphology · River restoration · Success evaluation

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Introduction

Over the last 150 years, human activities, such as urbanisation, agriculture and hydropower generation, have led to a gradual degradation of riverine ecosystems (Mill. Ecosyst. Assess. 2005). In recent decades, it has become apparent that further degradation must be inhibited, as the damages to ecology, economy and society surmount the benefits gained from exploiting riverine ecosystems (Zeh Weissmann et al. 2009). Nowadays, river restoration is the globally accepted means to protect ecosystem health, to preserve water resources, and to maintain flood protection (Andrea et al. 2012; Palmer et al. 2005; Wortley et al. 2013). Hence, river restoration projects are being financed by governments and made a legal obligation in several countries (EU WFD 2000; Swiss Water Protection Act 814.20). As available funds for river restoration increased, the number of implemented restoration projects and literature published on this topic grew as well (Wortley et al. 2013). However, most scientific publications focus on the success evaluation of restoration projects rather than the restoration measures themselves (Palmer et al. 2005; Suding 2011). This gap is closed by showing, with the example of Switzerland, how river restoration was performed and how restoration practice changed over time.

Despite its small size, Switzerland offers a large spectrum of restoration experiences due to its topographical diversity. Over the course of the next 80 years, 40 million Swiss Francs or 44 million US Dollars are being allocated per year to restore 4,000 km of degraded rivers and their ecosystems (BAFU 2011). This article presents the geographical distribution of restoration projects in Switzerland and investigates spatial and temporal trends. Furthermore, information on implemented restoration measures, a comparison of Swiss and international restoration data, and project success is presented. The article concludes with recommendations for the international restoration practice and science.

Data acquisition and definition of terms

The term restoration, the expression most commonly utilised in literature (e.g. Amoros 2001; Bernhardt and Palmer 2011; Haase et al. 2013), is used to describe a variety of measures to enhance, improve or rehabilitate the structure and function of riparian and fluvial ecosystems (Roni et al. 2005; Roni and Beechie 2013). Thereby, each restoration project may involve several restoration measures, which either directly or indirectly rehabilitate the ecosystem. Thereby, *direct* measures specifically improve conditions for the ecosystem, e.g. by providing habitats, while *indirect* measures have a different objective, such as flood protection, which improves conditions for the ecosystem due to e.g. the reconnection of floodplains. Hence, measures, such as bioengineering or flood protection were included whenever they were implemented together with direct restoration measures.

In Switzerland, the cantonal authorities are responsible for the management of water bodies, and thus the planning of restoration projects. Hence, data sets were obtained from the cantonal offices or their web pages. In total, data from 848 restoration projects from 13 of the 26 cantons, recorded between 1979 and 2012 (Fig. 1), were investigated. Data sets contained information about the name of the river, the total restored length per river, the start and end time of the implementation of the restoration measures, the type and objective of the restoration measures, if and how success was evaluated and the results of this evaluation. Nonetheless, data sets were not exhaustive, as some cantonal offices only recorded projects of a specific size or after the year 2000; other projects did not contain information about the length or the date of the restoration, and some cantons only had data records until the year 2010. Hence, numbers represented are not absolute, but rather reflect the available data at this time.

In addition, data on the financial status and the level of urbanisation of the cantons was acquired to analyse spatio-temporal trends in river restoration (BFS 2009, 2012). Hereby, the financial status was represented by the gross domestic product of the year 2011 (GDP in Swiss Francs), the level of urbanisation by the population density of the year 2012 (inhabitants/km^2; BFS 2009–2013). The following two hypotheses were tested: (1) cantons with a higher GDP might have had more funds to finance river restoration projects, and (2) urbanised cantons might have more rivers in a degraded state than rural cantons and therefore a higher need for river restoration.

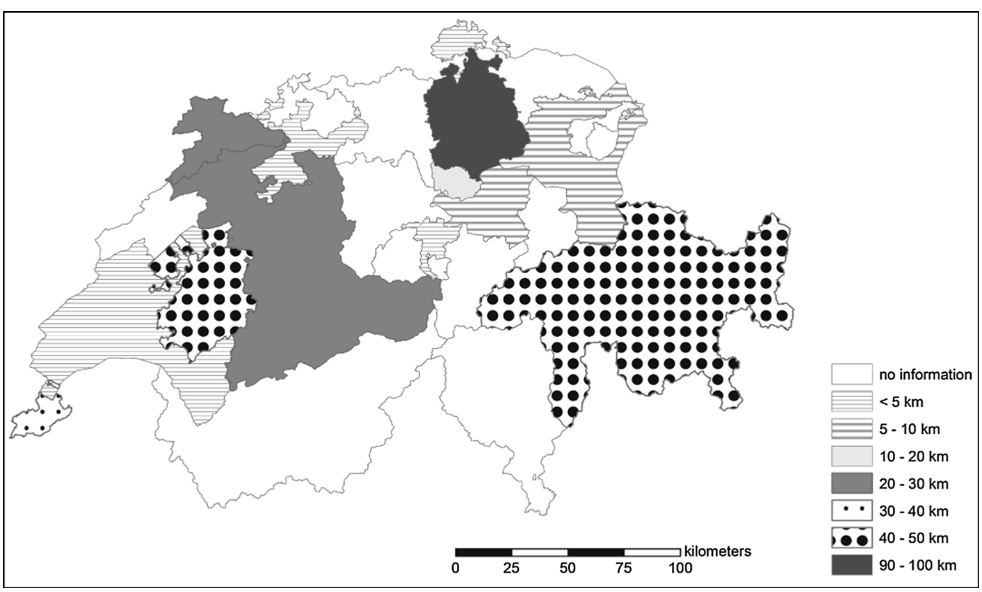

Fig. 1 Geographical distribution of total restored length per canton between 1979 and 2012. Data from 13 of the 26 Swiss cantons are included (Berne, Fribourg, Geneva, Grisons, Jura, Nidwalden, Schaffhausen, Schwyz, Solothurn, St. Gall, Vaud, Zug and Zurich)

Spatial trends in Swiss river restoration

To analyse spatial trends in river restoration, data on the total restored length per canton was combined with the geographical map of Switzerland (Fig. 1). Hereby, the investigated cantons span an area of 25,335 km^2 (61 % of the total area of Switzerland) and contain 37,699 km of rivers (62 % of the total Swiss river network). Of these, about 307 km were restored, ranging between total restored lengths of 1.5 km and 98 km per canton. However, due to gaps in data recording, these numbers might be significantly higher. As can be seen in Fig. 1, there is no clear spatial trend, such as a higher total restored length for e.g. larger cantons. Hence, the relationship between the total restored length and the financial status of the cantons (Fig. 2) and their level of urbanisation (Fig. 3) was investigated. However, as can be seen in the charts, there is no such trend. Further investigations in land use and the political situation, i.e. election results, in the cantons showed no clear trend either (BFS 2009–2013, data not shown).

Temporal trends in Swiss river restoration

Apart from the spatial trends in river restoration, the temporal trends were investigated, so as to determine whether the number or lengths of restoration projects increased over time. Figure 4 provides information about the time and length of implemented restoration projects for the cantons, the increase in total restored length for all of the 13 cantons, and the number of cantons performing restoration projects per year.

As can be seen in Fig. 4, the total restored length and the number of cantons implementing restoration projects increased steadily after 1992. The decrease in the total restored length in the year 2012 is due to several data sets ending in 2010. On a Swiss-wide basis, most restoration

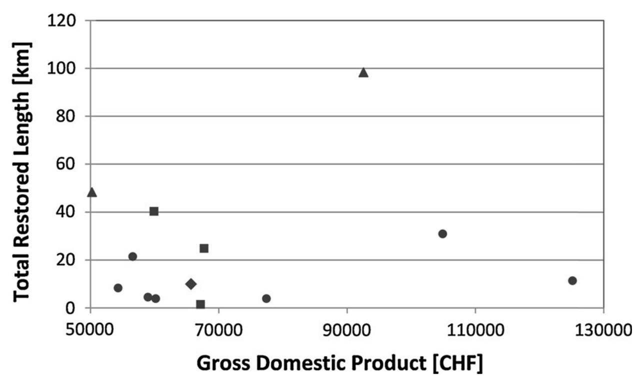

Fig. 2 Relationship between the total restored length and the canton's financial status (gross domestic product in Swiss francs). The symbols represent the sizes of the cantons involved: a *circle* symbolises cantons with a total area below 1,000 km^2, a *triangle* cantons with 1,000–2,000 km^2, a *diamond* stands for areas of 2,000–3,000 km^2, and a *square* represents a cantonal area of more than 3,000 km^2

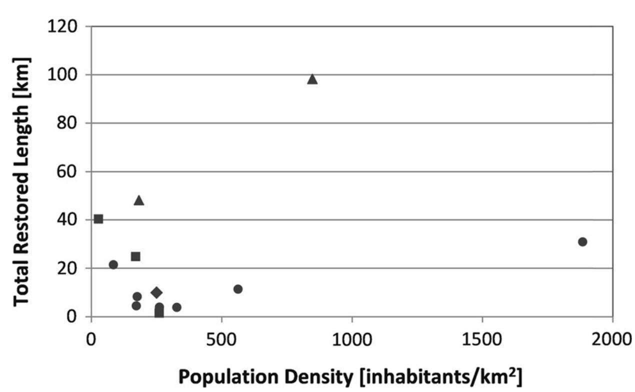

Fig. 3 Relationship between the level of urbanisation, as determined by the population density of the cantons, and the total restored length. The symbols represent the sizes of the cantons involved: a *circle* symbolises cantons with a total area below 1,000 km^2, a *triangle* cantons with 1,000–2,000 km^2, a *diamond* stands for areas of 2,000–3,000 km^2, and a *square* represents a cantonal area of more than 3,000 km^2

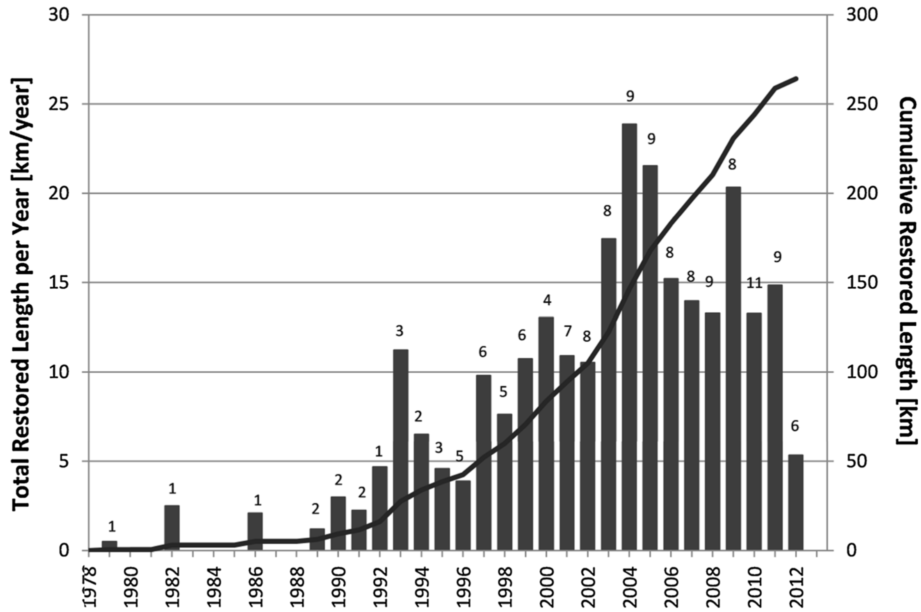

Fig. 4 Primary axis: overview over the total restored length in Swiss water courses between 1979 and 2012 in (km/year). The number of cantons involved is shown above each column. Secondary axis: increase of total restored length between 1979 and 2012 in (km). Please note the different scales of the axes

projects were being performed during the years 2004, 2005 and 2009. On a cantonal basis, however, most restoration projects were implemented after the year 1997, with maximum restoration activities varying for each canton: while some cantons, e.g. Grisons and Zurich, continuously performed and recorded river restoration projects since the 1990s, other cantons, such as St Gall and Solothurn only started recording them in recent years. According to Fig. 4, the total restored length for 13 of the 26 Swiss cantons accumulates to 270 km, as only projects where date and length of the restorations were known were included. The total cumulative restored length, i.e. the cumulative length including those projects in which the date of restoration was unknown, is close to 307 km, though, and would be even higher if data sets were conclusive. In 2011 it was decided to restore 4,000 km of the total 14,000 km of degraded streams (BAFU 2011) over the course of the next 80 years. This would require 50 km of river restoration per year in all of Switzerland. According to our data, restoration rates varied between 0.5 km in 1979 and 23.9 km in 2004, averaging to 9.8 km per year. Extrapolated to all of Switzerland, a restoration rate of 50 km per year therefore seems achievable if challenging.

Implemented measures

The investigated 848 projects included a total of 1,661 restoration measures implemented between 1979 and 2012. Related restoration measures were separated into eleven categories (Table 1). Hereby, each category comprised a multitude of restoration measures. Those either directly or indirectly rehabilitated the ecosystem, e.g. by providing habitats or by stabilising a river embankment by planting endemic trees. Some restoration measures were purely mechanical, such as the widening of the river bed, while others enabled the river to rehabilitate itself, e.g. by removing stabilising side walls.

Some restoration measures were implemented more frequently than others (Fig. 5). Habitat provision, channel bed remodelling, and deculverting make up 65 % of all implemented measures, thus being significantly more popular than the remaining 8 categories. To a certain extent this is an artefact, as e.g. the category channel bed remodelling is less clearly defined than e.g. deculverting and hence allows for more sub-categories, leading to a higher number of restoration measures in this group. Some measures, namely from the categories bioengineering, visitor management and water quality amelioration, were exclusively implemented in western Switzerland, while others, such as channel bed remodelling, deculverting, habitat provision and riparian zone construction works, were implemented in nearly all of the investigated 13 cantons.

To determine whether specific combinations of restoration measures were particularly popular, the prevalence of all category combinations was analysed. This included the frequency of single categories as well, as most restoration projects implemented a large variety of restoration measures, but from only one category. The most common

Table 1 Restoration measures implemented in Switzerland between 1979 and 2012

Category	Objectives	Measures
Bioengineering	Stabilisation of riparian structures (e.g. fascines); re-vegetation; enclosing of wildlife areas; diversification of the local flora; suppression of neophyte growth; creation of habitats; provision of shade	Sowing/planting of endemic and site-specific plants (e.g. pioneer plants, reeds, sedges, shrubs, fruit and riparian trees (e.g. willow)) systematic clearing of trees; pruning of trees; pollarding of willows, poplars, etc.; sawing trees off above the root collar to stimulate stool sprouting; construction of fascines; installation of seeding mats on embankments
Channel bed remodelling	Bedload management: reduce or encourage channel bed erosion	Recreate water course specific flow dynamics; removal or rebuilding of sediment traps and bedload collectors; deposition of eroded material; creation of areas for sedimentation; installation of nets over the sediment; installation of wood/stone weirs and spur dykes; construction of boulder ramps to reduce the flow energy of the water
	Channel bed deepening: create a higher water column as habitat and thermal refuge for aquatic organisms	Excavation of accumulated sediments; narrowing of the channel bed and increasing of channel slope to induce erosion
	Removal of artificial barriers: re-establishment of longitudinal connectivity; recreate water course specific dynamics and structures; bedload management	Removal of stone/concrete weirs and dams; re-establishment of fish migration (construction of block/ground/concrete ramps, vertical-slot passages, pool passes and bypass channels); installation of opening in weirs; installation of pools in front of barriers; adjusting the water level of incised channels
	Removal of stabilising elements from the river bed: recreate a water course specific dynamic and structure; create habitats for flora and fauna; enable groundwater-surface water interactions	Removal of stone blocks and concrete tiles from the channel bed
	Structuring of the channel bed: recreate a water course specific dynamic and structure; create habitats for flora and fauna	Placement of material (e.g. wooden pegs, deadwood, tree spurs, root stools, gravel, boulders); installation of spur dykes, wood/stone weirs; demolition of anthropogenic structures (e.g. walls, bridges, pumping stations); construction of coves, shore protuberances, gravel banks, stream islands, meanders, or fords; recreation of the original channel bed; reduction of the curvature of meanders
Channel diversion	Redirection of water courses away from roads; improvement of appearance; amelioration of recreational value	Mechanical excavation of a new channel bed
Deculverting	Establishment of lateral, longitudinal and vertical connectivity; creation of habitats for flora and fauna	Uncovering piped streams, combined with channel bed remodelling
Floodplain rehabilitation	Construction of new side channels: flood protection; creation of habitats for flora and fauna	Construction of new channels, drainage trenches, canals and ditches
	Reconnection of alluvial forests: flood protection; creation of habitats for flora and fauna	(Re-)connecting of unconnected alluvial forests to the main river; opening and lowering of side dams; redirection of rivers into their former channel beds; re-establishment of water course specific dynamics
	Rehabilitation of oxbow lakes and side channels: flood protection; creation of habitats for flora and fauna	Reconnection of oxbow lakes to the main river; removal of accumulated sediments
Flood protection	Protecting anthropogenic structures from flood damage	Removal or construction of concrete walls, dams or bank reinforcements; relocation of garden sheds, houses and foot paths too close to the water course; construction of retention and temporary storage reservoirs with or without permanent ponds; reconnection of flood plains;increasing the height of existing dams, walls, or weirs, foot paths, village squares, and arable land; construction of weirs to redirect storm water into wetlands and swamps; installation of overflow channels for storm water; construction of separate sewers for storm water and sewage

Table 1 continued

Category	Objectives	Measures
Habitat provision	Creation and re-establishment of habitats for flora and fauna	Fish: placement of dead wood, root stools, boulders, wooden barriers with hideouts and recesses, fascines and overhanging shores as shelters; varying of water depths; installation of recess zones for flood events; creation of spawning grounds and areas for juvenile fish, with still waters and lose gravel or sand
		Crayfish: excavation of deep water zones and hideouts
		Amphibians and reptiles: construction of pools, permanent and temporary ponds, water-filled ditches or biotopes
		Reptiles: installation of sun terraces, screes, stone walls and dead wood stacks
		Heliophytes: construction of sun terraces
		Birds: installation of nesting sites and perches
		Beavers: installation of hedge screens
		General: planting of trees, bushes, reeds and hydrophytes; installation and re-establishment of ponds and wetlands; construction of small bays, and of shores with varied inclination; re-establishment of grasslands
Reintroduction	Encourage and accelerate recolonisation of aquatic fauna	Reintroduction of fish and other aquatic organisms
Riparian zone construction works	Structuring of stream banks: addition or removal of structures and plants as flood protection measure; increase lateral connectivity; creation of habitats for flora and fauna	Stabilisation of shores and embankments: placement of boulders, dead wood and root stools; installation of rock-filled log cribwalls, fascines, and rock or wooden groynes; repair or construction of dams and concrete or stone walls; bioengineering methods (see above)
		Removal of stabilising elements: removal of concrete blocks, stone or concrete walls and dams; reduction of size of dams
		Modelling of terrain: lowering or elevation of embankments or reducing/increasing slope; introduction of sand or gravel; refilling of sediments
	Local widening of channel bed: increase in flow capacity; flood protection; support development of natural channel structures and dynamics; reduce channel bed erosion; creation of habitats	Removal of bank reinforcements, mechanical excavation of sediments
Visitor management	Encouraging or prohibiting public access: protecting nature; improving recreational value	Repair, construction or relocation of foot paths or pedestrian bridges; planting of hedges or tree hedges; installation of fences, playgrounds and observation points, leisure and fishing areas, nature trails and benches
Water quality amelioration	Enhancement of surface water quality: reduction of harmful substances; improvement of overall health of ecosystem	Prohibition of feeding water fowl; relocation of sewage ponds; treatment of agricultural wastewater; construction of washing bays for agricultural vehicles

A more detailed description of some of the restoration measures may be found in publications by Woolsey et al. (2005) and Zeh (2007)

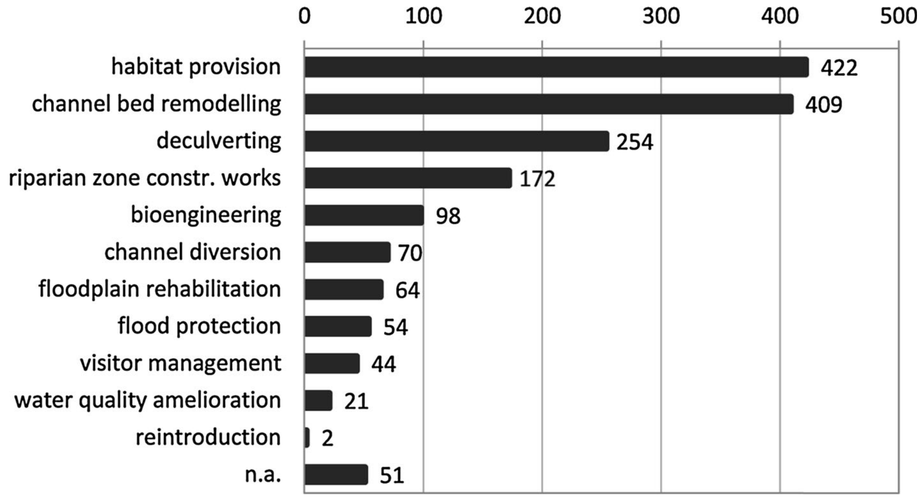

Fig. 5 Categories of restoration measures implemented in Switzerland between 1979 and 2012. The labels indicate the number of restoration measures in the respective category

single categories were habitat provision, deculverting and channel bed remodelling. This was followed by the combination of the two categories of channel diversion and deculverting; the prevalent combination of three categories was channel bed remodelling, habitat provision and riparian zone construction works. The four categories of channel bed remodelling, flood protection, habitat provision and riparian zone construction works occurred only few times, as did the five-categories-combination bioengineering, channel bed remodelling, habitat provision, riparian zone construction works and visitor management. Combinations of six and more categories rarely occurred, usually combining measures to sustainably recreate a natural terrain while implementing flood protection measures. One- or two-category combinations of interventions with a higher degree of mechanical interference, such as deculverting and mechanical recreation of the channel bed, were favoured over more sustainable combinations of three or more categories in which these high-interference measures were combined with measures to recreate a more natural setting and then protect the latter from human intervention. Generally, cantons in western Switzerland favoured the more sustainable combinations of restoration measures, while cantons in central and eastern Switzerland favoured single measures with a higher degree of mechanical interference, such as deculverting.

Brief description of selected restoration projects in Switzerland

Three water courses were selected to provide an overview over the bandwidth of restoration projects implemented in Switzerland: the Perrentengraben, a small brook in western Switzerland; the Rombach, a stream in south-eastern Switzerland; and the River Thur in north-eastern Switzerland. They were selected from three different categories of stream orders to illustrate the range of restoration projects from small brooks to large rivers in rural areas of perialpine and alpine Switzerland. Restoration projects in urban areas were omitted, in spite of their high number of occurrence, as they mainly focussed on the re-establishment of longitudinal connectivity by removing migration obstacles and the deculverting of previously covered brooks, which were already illustrated by the examples of the Rombach and the Perrentengraben. Further case studies of Swiss restoration projects may be found in Woolsey et al. (2005).

Perrentengraben, Canton Fribourg

The Perrentengraben is a small brook with a discharge ranging between 1 and 10 m^3/s, situated in a rural area in western Switzerland. In 2001, 0.8 km of the brook were restored to create a more natural environment and support its biodiversity.[1] This river restoration was selected from the 848 projects, as it combined a large variety of restoration measures often found in Switzerland. After deculverting the brook, which improved longitudinal, lateral and vertical connectivity, the channel bed was restructured to enable a more natural flow dynamics and provide habitats and recesses for the local fauna. The banks were remodelled and stabilised with stones and an indigenous flora. Apart from facilitating habitats for terrestrial animals, these measures also improved lateral connectivity and provided

[1] http://www.maisondelariviere.org/index.php/fr/activites/recherche/projets-termines/projet-renaturadata/330-la-maison-de-la-riviere-activites-recherche-renatura-data-boiron-de-morges-passe-a-poissons-sous-la-route-suisse.

Fig. 6 Rombach at Pizzöl **a** before and **b** after restoration (© AJF Graubünden)

Fig. 7 Rombach at Fuldera **a** before restoration and **b** an animation of the planned outcome after restoration of the Rombach (© Pio Pitsch)

shade, an important factor in water temperature regulation. Furthermore, a retention basin was installed, providing further habitats and flood protection. A more challenging restoration measure was the amendment of the water quality, which was achieved by treating agricultural waste water prior to its discharge into the brook.

The restoration of the Perrentengraben combined various restoration measures from the categories bioengineering, channel bed remodelling, deculverting, flood protection, habitat provision, riparian zone construction works and water quality amelioration to a sustainable river restoration, which encouraged self-regulation of the brook. This river restoration was one of the few projects which acknowledged the importance of "outside" factors, such as water quality, to the successful restoration of an ecosystem.

Rombach, Canton Grisons

The Rombach is an alpine stream in south-eastern Switzerland. Its discharge ranges between 1 and 23 m^3/s, with an annual mean of 3 m^3/s.[2] Between 1995 and 2010 various sections of the river were restored to improve conditions for fish and maintain flood protection.[3] Two restorations at Pizzöl (Fig. 6a, b) and Fuldera (Fig. 7a, b) were selected: the installation of a block pass to ease the migration of fish and the restoration of a 2 km long stretch of a channelized section. The block pass was built in a section of the river where erosion had formed a migration

[2] http://www.hydrodaten.admin.ch/de/2617.html.

[3] http://map.geo.gr.ch/oberflaechengewaesser/oberflaechengewaesser.phtml.

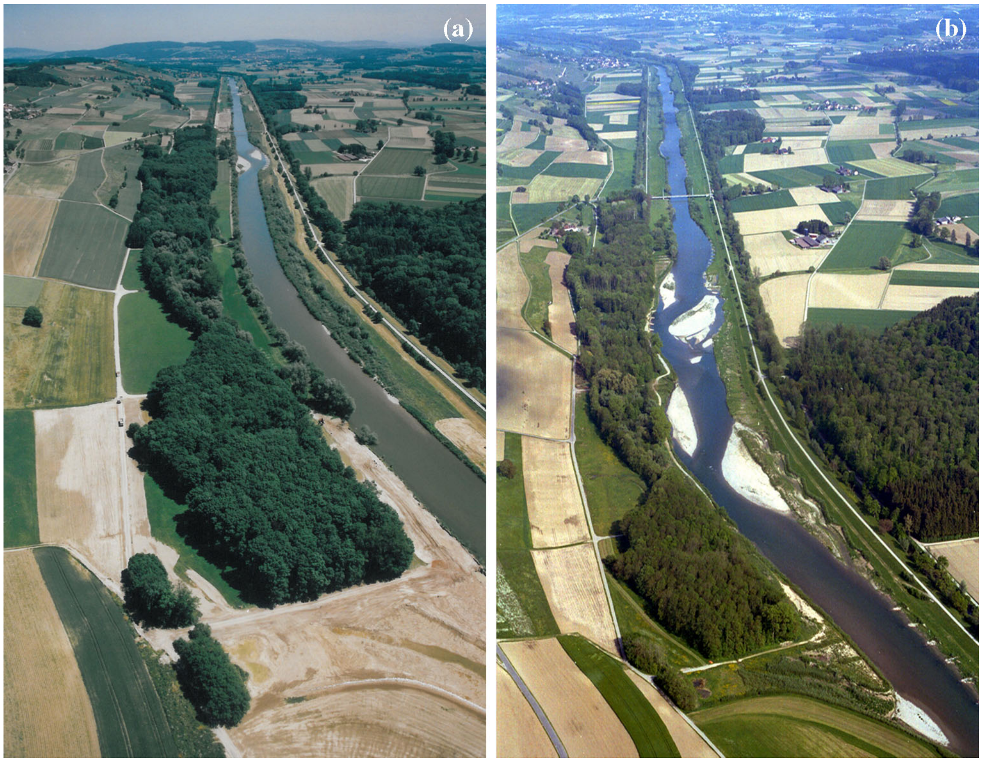

Fig. 8 River Thur **a** before and **b** after restoration (© BHAteam Frauenfeld)

obstacle impassable for juvenile fish. The migration obstacle was overcome by the insertion of large blocks in the stream bed, which were installed in various depths to encourage the formation of pools along the block pass. By spreading the difference in height over a distance of 50 m even juvenile fish may swim upstream. Positive side effects of the block pass were the reduction of flow energy in the water, which reduced erosion and acted as an additional flood protection measure. Furthermore, appearance was improved. This restoration project combined measures from the categories channel bed remodelling, flood protection, habitat provision and visitor management. It was selected, as this kind of restoration is very common in Switzerland.

The second project at the Rombach restored a 2-km section of the stream. After draining the swampy area and channelizing the stream in 1945, biodiversity decreased dramatically. Hence, it was decided to reverse the negative effect of the drainage and channelization. Therefore, land was repurchased to enable a widening of the stream. Stabilising elements were removed from the stream banks and the surrounding floodplains lowered to encourage a self-regulated development of natural stream dynamics and in-stream structures. The insertion of dead wood further encouraged the development of natural stream dynamics and provided aquatic habitats. Eroded sediment was reintroduced and a downstream sediment trap removed to enable a more natural bedload management. In place of the previous sediment trap habitats for amphibians were created. The reconnection of side arms created further habitats for fish and amphibians and provided crucial spawning grounds for both. Bioengineering methods, such as the installation of willow fascines or the planting of indigenous plants, were selected to stabilise the stream banks, thereby providing terrestrial habitats and shade for water temperature control. As these measures greatly improved the ecological potential of the Rombach, it is planned to reintroduce the stone loach, a fish previously extinct in this stream.

This restoration project combined measures from the categories bioengineering, channel bed remodelling, floodplain rehabilitation, flood protection, habitat provision, reintroduction, riparian zone construction works and visitor management to recreate a natural, self-regulated ecosystem. The Rombach restoration was selected as it is a good example for a very effective restoration in a rural, alpine region, in which the ecological conditions and appearance could be greatly improved.

River Thur, Cantons Zurich and Thurgau

The River Thur (Fig. 8a, b) is a perialpine river in north-eastern Switzerland. It is the longest Swiss river without a retention basin, leading to a very dynamic discharge regime (Woolsey et al. 2007; Peter et al. 2012). Discharge ranges between 2.2 and 1130 m^3/s, with a mean discharge of 47 m^3/s (Pasquale et al. 2011). Due to frequent flooding by the then meandering river, long sections of the River Thur were straightened and channelized in the 1890s. However, flood protection was inadequate and several kilometres of the river were thus restored until 2002 (Schneider et al. 2011). This restoration project was selected, as it illustrates the constraints in restoration practice: conditions for the local ecosystem had to be improved without diminishing flood protection or endangering the water quality in river-side pumping stations. To nevertheless achieve good ecological status, side dams were removed and the river widened in applicable areas, i.e. river sections without pumping stations or settlements nearby (Schneider et al. 2011).

These measures reconnected alluvial forests and increased the flow capacity of the river, both supporting sustainable flood protection, while at the same time stimulating a more natural flow dynamics and meandering structure, and providing habitats for the local flora and fauna. Further habitats were created by placing dead wood and root stools into the stream and by structuring of the channel bed, partially by the reintroduction of eroded materials, which created gravel bars and in-stream islands. The latter were valuable habitats for pioneer plants and ground-breeding birds, such as the little ringed plover (Pasquale et al. 2011). The lowering and structuring of the river banks provided additional habitats and improved lateral connectivity. These measures were supported by thorough information of the public, mainly with information boards or public events, to encourage a respectful interaction with the newly restored ecosystem, e.g. by respecting certain areas being out of bounds during breeding season.

The restoration of the River Thur combined measures from the categories channel bed remodelling, floodplain rehabilitation, flood protection, habitat provision, riparian zone construction works and visitor management. This restoration project indicates that even with major constraints river restoration can have positive effects on the environment.

Comparison of Swiss and international restoration practice

To draw comparisons between Swiss and international restoration practice, a thorough literature search was performed. Results for Asia, the Americas and Europe can be found in Table 2.

As can be seen, the restoration measures reported most often in international literature were channel bed remodelling, habitat provision, floodplain rehabilitation and bioengineering. However, these results do not necessarily represent the full spectrum of restoration measures implemented all over the world, as only a small proportion of restoration projects is being published in international literature. Nevertheless, it is interesting to see that Chinese literature mainly reported bioengineering as their favoured river restoration measure (Wang et al. 2014; Wu et al. 2013; Zhang et al. 2013a, b), while in the Americas and Europe channel bed remodelling and habitat provision were reported most often (Amoros 2001; Buijse et al. 2002; Doll 2003; Filoso and Palmer 2011; Gilvear et al. 2012; Haase et al. 2013; Habersack and Piégay 2008; Henry et al. 2002; KCI Associates 2003; Kondolf et al. 2013; Lorenz and Feld 2013; Louhi et al. 2011; Mendiondo 2008; Miller and Kochel 2013; Muhar et al. 2008; North Carolina Department of Transportation 1999; Richardson and Pahl 2005). Furthermore, all investigated European countries except one reported floodplain rehabilitation as implemented restoration measure (Amoros 2001; Buijse et al. 2002; Gilvear et al. 2012; Haase et al. 2013; Habersack and Piégay 2008; Henry et al. 2002; Lorenz and Feld 2013; Muhar et al. 2008; Pataki et al. 2013), while only one and two projects reported these restoration measures for China (Wang et al. 2014) and the Americas (Filoso and Palmer 2011; Richardson and Pahl 2005), respectively. In Switzerland, only a minor proportion of restoration projects implemented floodplain rehabilitation as restoration measure. However, in Switzerland the majority of restoration projects were small-scale projects, while international literature may only report large-scale river restorations. Therefore, if merely restoration projects of similar dimensions were compared, the restoration measures preferred in Switzerland might actually be very similar to those reported in international literature. Unfortunately, project dimensions were rarely reported in the investigated articles and therefore it is difficult to compare Swiss and international restoration practice.

Success evaluation

Data regarding success evaluations were available for 232 of the 848 restoration projects. Of these, 77 projects evaluated the success of their project, of which 76 were regarded successful; 37 projects were planning to evaluate success at some point in the future; for 15 projects a success evaluation was regarded unnecessary, while 103 projects did not perform or plan success evaluations.

Those projects performing success evaluations employed a multitude of methods: from the more comprehensive characterisation of ecological and ecomorphological conditions, to the monitoring of discharge, vegetation and population growth of amphibians, crayfish,

Table 2 Restoration measures reported in international literature

River	Location	Country	Restoration measure											Other	References
			Bioeng.	Channel bed remodelling	Channel diversion	Decul-verting	Floodplain rehab.	Flood protection	Habitat provision	Reintroduction	Riparian zone constr.	Visitor manag.	Water quality amelioration		
Asia															
Liaohe River		China	X				X				X		X		Wang et al. (2014)
Liaohe River	Yinzhou district	China	X												Zhang et al. (2013a, b)
Nanfeihe River	Anhui province	China	X												Wu et al. (2013)
Tarim River	Xinjiang Uyghur autonomous region	China												Discharge management	Zhang et al. (2013a, b)
Americas															
Tijuco Preto	São Carlos	Brazil	X	X					X		X			Stakeholder engagement	Mendiondo (2008)
Howard's Branch	Anne Arundel County/ Maryland	USA	X				X								Filoso and Palmer (2011)
Rocky Branch	North Carolina	USA	X	X					X			X	X		Doll (2003). In: Sudduth et al. (2011)
Sandy Creek	North Carolina	USA		X			X								Richardson and Pahl (2005). In: Sudduth et al. (2011)
Spa Creek	Anne Arundel County/ Maryland	USA	X	X					X		X				Filoso and Palmer (2011)
Selby Creek	California	USA		X											Kondolf et al. (2013)
Third Fork Creek	North Carolina	USA	X	X					X		X				KCI Associates (2003). In: Sudduth et al. (2011)
Various	North Carolina	USA		X											Miller and Kochel (2013)
Tributary to Walnut Creek	North Carolina	USA		X											North Carolina Department of Transportation (1999). In: Sudduth et al. (2011)
Weems Creek/ Bristol	Anne Arundel County/ Maryland	USA		X					X						Filoso and Palmer (2011)

Table 2 continued

River	Location	Country	Restoration measure											Other	References
			Bioeng.	Channel bed remodelling	Channel diversion	Decul-verting	Floodplain rehab.	Flood protection	Habitat provision	Reintroduction	Riparian zone constr.	Visitor manag.	Water quality amelioration		
Weems Creek/ Moreland	Anne Arundel County/ Maryland	USA		X					X						Filoso and Palmer (2011)
Weems Creek/ Mall	Anne Arundel County/ Maryland	USA		X					X						Filoso and Palmer (2011)
Wilelinor Stream Valley	Anne Arundel County/ Maryland	USA	X				X								Filoso and Palmer (2011)
Europe															
Upper Drau River	Carinthia	Austria		X			X		X		X				Muhar et al. (2008)
Various	Alpine regions	Europe	X	X			X		X		X			Increase minimum flow; raise groundwater level	Habersack and Piégay (2008)
Various		Finland		X					X		X				Louhi et al. (2011)
Upper Rhône	Brégnier-Cordon plain	France		X			X		X						Amoros (2001); Henry et al. (2002)
Various		Germany		X	X		X	X	X		X		X	Extensification of landuse	Haase et al. (2013)
Various		Germany		X			X		X		X				Lorenz and Feld (2013)
Danube	Báta oxbow	Hungary					X								Pataki et al. (2013)
Lower Rhine	Beneden Leeuwen	Netherlands					X		X						Buijse et al. (2002)
Lower Rhine	Gameren	Netherlands					X		X						Buijse et al. (2002)
Lower Rhine	Opijnen	Netherlands					X		X						Buijse et al. (2002)
Various	Scotland	UK	X	X			X	X	X	X	X	X	X	Stakeholder engagement; non-native animal species removal and monitoring	Gilvear et al. (2012)

The full description of restoration measures may be found in Table 1 fish and macrozoobenthos, to the investigation of public acceptance and cost control. The majority of success evaluations, though, investigated the effects on fish, particularly salmonids, by counting the number of fish swimming through a fish pass, or by monitoring their spawning and the development of their juveniles. Each project had its specific aim and hence evaluated their success in a different way, which makes it difficult to compare their results with each other and with the international literature. In Switzerland, river restoration would be successful if the natural functioning of the river was re-established (Swiss Water Protection Act 814.20). Most of the investigated projects, however, only improved specific aspects of the rivers' natural functioning. This leads to a major issue in success evaluations, which is reflected in the international literature as well: the outcome of the success evaluation of a project largely depends on how success was defined in the first place (Higgs 1997; Wortley et al. 2013). As all of the 232 investigated projects had different definitions of success, it is difficult to state whether these restorations were indeed successful or not.

Conclusions

In Switzerland more than 307 km of degraded rivers have been restored since 1979, with the number of restoration projects increasing steadily over the course of time. While there was no clear correlation between the total restored lengths and the size of the cantons, their population density or financial status, there was a geographical trend in the types of restoration measures being implemented. It is difficult to come to a definite conclusion regarding the success of the restoration projects, as there was not enough data available, and completed success evaluations only tested specific aspects, such as the migration of fish, rather than improvements for the whole ecosystem. However, this did indicate that project planning might not have had a three-dimensional approach to restoration, as only aspects, such as the migration of fish, were considered rather than the rehabilitation of lateral, longitudinal and vertical connectivity. Furthermore, water quality ameliorations, which would have a profound effect on the ecosystem, were rarely considered. Based on our findings, it is therefore recommendable to making success evaluations a legal obligation, thereby clearly defining how to evaluate success and what would be considered a successful restoration, with respect to the environment, but also society and economy. This would include the performance of detailed predefined investigations of a river prior to its restoration to clearly define the issues and identify potential causes for these issues, to define restoration goals based on these findings, and to re-investigate the water course after restoration following a regulated predefined code of practice. These actions are crucial to allow learning from past experiences so that future projects will have maximum benefit with minimum expenses. Restoration efforts clearly are a step in the right direction, but further efforts are required to identify the issues leading to ecosystem degradation and establish best practices for the restoration of these degraded ecosystems. To achieve these goals, it is crucial to perform comparable success evaluations in all restoration projects and to publish these results in freely accessible online data banks. In general, the results of our investigation were encouraging, demonstrating that over the last 30 years river restoration has evolved from a disputed rarity to an implicitness, leading to a further 4,000 km of degraded rivers being restored over the course of the next 80 years.

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