The landscape drives the stream

Unraveling ecological mechanisms to improve restoration

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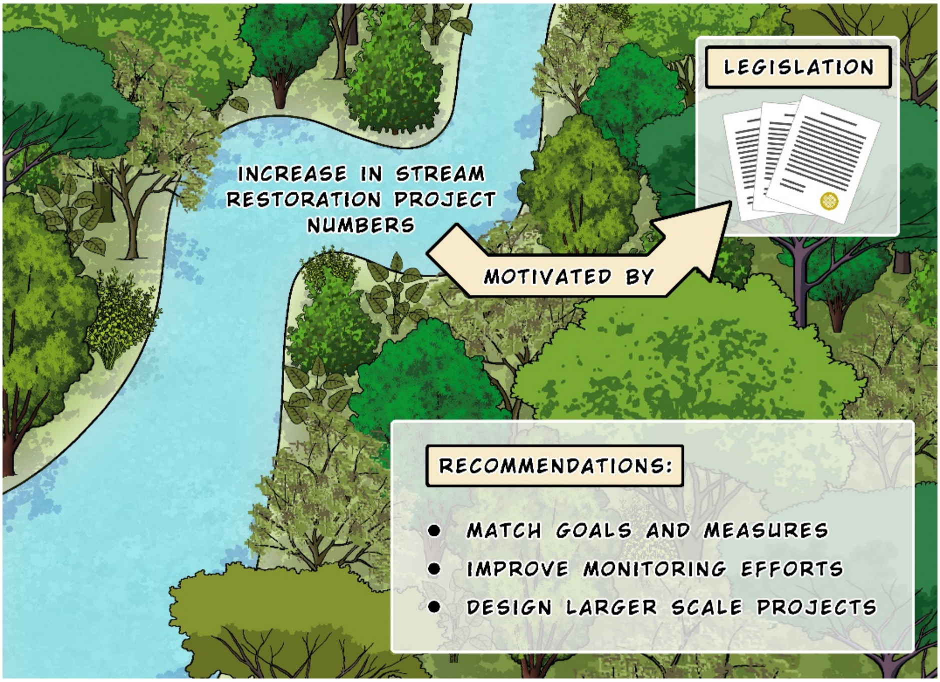
LEGISLATION
INCREASE IN STREAM RESTORATION PROJECT NUMBERS
MOTIVATED BY
RECOMMENDATIONS:
MATCH GOALS AND MEASURES
IMPROVE MONITORING EFFORTS
DESIGN LARGER SCALE PROJECTS

Chapter 2

40 years of stream restoration: lessons learned and future perspectives

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Highlights

- Legislation motivated the increase in stream restoration efforts.
- A mismatch between restoration goals and measures was observed.
- Proper stream restoration monitoring delays, acceleration is recommended.
- Large scale processes need much more attention in restoration.

Abstract

Stream restoration efforts have increased, but its success rate is still rather low. The underlying reasons for these unsuccessful restoration efforts remain inconclusive and need urgent clarification. Therefore, the aim of the present study was to evaluate 40 years of stream restoration to fuel future perspectives. To this purpose we evaluated the influence of policy goals on stream restoration efforts, biophysical restoration objectives, restoration measures applied including its scale and monitoring efforts. Information was obtained from five stream restoration surveys that were held among the regional water authorities in the Netherlands over the last 40 years, and from an analysis of the international scientific publications on stream restoration spanning the same time period. Our study showed that there was a considerable increase in stream restoration efforts, especially motivated by environmental legislation. However, proper monitoring of its effects was often lacking. Furthermore, a mismatch between the initial restoration goals and the actual restoration measures taken to achieve these goals was observed. Measures are still mainly focused on hydromorphological techniques, while biological goals remain underexposed and therefore need to be better targeted. Moreover, restoration practices occur mainly on small scales, despite the widely recognized relevance of large scale ecological processes for stream ecosystem recovery. In order to increase the success rate of restoration projects, it is recommended to improve the design of the accompanying monitoring programmes, allowing to evaluate, over longer time periods, if the measures taken led to the desired results, and secondly to scale up the spatial scale of stream restoration projects from local instream efforts to catchment wide measures to tackle the overriding effects of catchment wide stressors.

Key words: freshwater restoration, legislation, WFD, clean water act, catchment scale, restoration techniques.

1. Introduction

Degradation of stream ecosystems is widely recognized as the main cause of biodiversity impoverishment and the loss of ecosystem services (Malmqvist and Rundle, 2002; TEEB, 2010). To halt further degradation of the ecological, hydrological, morphological and physical-chemical status of water bodies, national and international regulatory organizations enforced legislations, such as the Water Framework Directive (WFD) in Europe (Carvalho et al., 2018) and the Clean Water Act in the USA (Doyle and Shields, 2012). These incentives boosted the number of planned and realized stream restoration projects (Bernhardt and Palmer, 2007; Violin et al., 2011; Wilcock et al., 2009). In parallel, the scientific community made efforts to enhance the knowledge on stream restoration ecology and to translate this knowledge into restoration practices (Palmer et al., 1997; Lake et al., 2007).

Despite the rapid increase in stream restoration funding, activities and research, success rates remained quite low (Palmer et al., 2010). Restoration practices still do not sufficiently take into account the appropriate scales, ranging from instream habitats to entire catchments, nor the complexity of stream ecosystems and should consider the key hydrological, morphological, chemical, and biological actors in concert (Nõges et al., 2016). Hence, the precise reasons for the unsuccessful restoration efforts remain still inconclusive (e.g. Miller and Kochel, 2009; Nõges et al., 2016) and need urgent clarification. The aim of the present study was therefore to evaluate 40 years of stream restoration to fuel future perspectives. To this purpose we evaluated: (1) the influence of policy goals on stream restoration efforts, (2) biophysical restoration objectives, (3) restoration measures, (4) the scale on which these measures were applied, and (5) monitoring efforts. To this end we integrated information obtained from five stream restoration surveys that were held among water authorities in the Netherlands over the last 40 years, and from an analysis of the international scientific publications on stream restoration spanning the same time period.

2. Sources of information

Dutch stream restoration questionnaires were send to the regional water authorities and nature conservation agencies in the Netherlands in 1993 (Hermens and Wassink, 1992; Verdonschot et al., 1995), 1998 (Verdonschot, 1999; Verdonschot and Nijboer, 2002), 2003 (Nijboer et al., 2004), 2008 (Didderen et al., 2009), and 2015 (this study). All questionnaires considered policy goals (mostly legislation and regulations), biophysical objectives, measures applied, the spatial scale of the measures, and monitoring efforts (Table S1, in supplementary material). Based on progressive insights, additional questions on the effects of large-scale pressures from anthropogenic land use and on awareness regarding the dispersal capacity of aquatic organisms were included in the most recent survey.

A literature review was carried out covering the period from 1975 to 2015 (in supplementary material). In total, 260 scientific articles on restoration of low-gradient streams were examined on: geographic location, policy goals, biophysical objectives, restoration measures, spatial scale and the monitored groups of aquatic organisms. To aid comparisons, both the results of the Dutch restoration questionnaires and those obtained in the literature study were grouped in similar time-clusters: before 1993, 1994-1998, 1999-2003, 2004-2008 and 2009-2015.

3. The influence of policy goals on stream restoration efforts

Our analysis covered four decades of stream restoration practice. Since the first restoration projects documented in the early eighties of the previous century, a strong increase in the number of projects carried out by the Dutch water authorities is observed (Figure 1, top panel). While in the previous century only a few projects were carried out, in the most recent years about 30-35 new restoration projects were performed yearly. This increase in project numbers is corroborated by an increase in numbers of international scientific publications (Figure 1A). Most of the scientific publications referred to projects in the USA (49 %) and Europe (34 %). To gain insight into the underlying motivations, a timeline was constructed showing the most important legislations and regulations regarding freshwater ecosystem restoration (Figure 1B).

In addition, in the questionnaires the Dutch water managers were asked to what extent these policy goals motivated their restoration efforts. From the answers it became clear that new projects directly aimed to implement preceding legislations and regulations. In the Netherlands, especially the legislation from 1990 to establish a National Ecological Network (EHS; Minsterie van LNV, 1990) to protect and connect natural areas, the designation of Natura 2000 sites to protect threatened species and their habitats based on the provisions of the Birds and Habitats directives (EC, 1992) and the EU WFD from 2000 (EC, 2000) to protect and manage water resources were leading.

Similarly, in the USA various consecutive regulations motivated stream restoration. The United States (U.S) Clean Water Act (33 U.S.C. §1251 et seq., 1972), enacted in 1972 to regulate pollutant discharges and to define quality standards for surface waters, formed the umbrella for the Wetland Restoration Act (16 U.S.C. 3951 et seq.; 104 Stat. 4779, 1990), in which restoration of degraded stream ecosystems was first mentioned as part of the mitigation sequence. The 'principles for ecological restoration of aquatic resources' in 2000 was the next important milestone in stream restoration policy (USEPA, 2000), while in 2008 restoration was also clearly defined as compensatory mitigation in a regulation under the Clean Water Act (CWA, Section 404).

In the open literature, examples of the initiation of new restoration projects after new regulations came into practice can be found in consecutive publications, amongst others by McCuskey et al., (1994), Johnson et al. (2002), Shields et al. (2003), Frimpong et al., (2006), Stokstad (2008) and Shields (2009). These examples show the importance of environmental legislation as a regulatory tool to start stream restoration projects, despite the many obstacles to be taken, such as methodological issues and the design of monitoring programmes (Bernhardt and Palmer, 2011; Voulvoulis et al., 2017; Birk et al., 2012; Carvalho et al., 2018). As a positive feedback of the increased number of restoration projects, science further developed, which in turn allowed to refine the regulatory requirements (Hill et al., 2013).

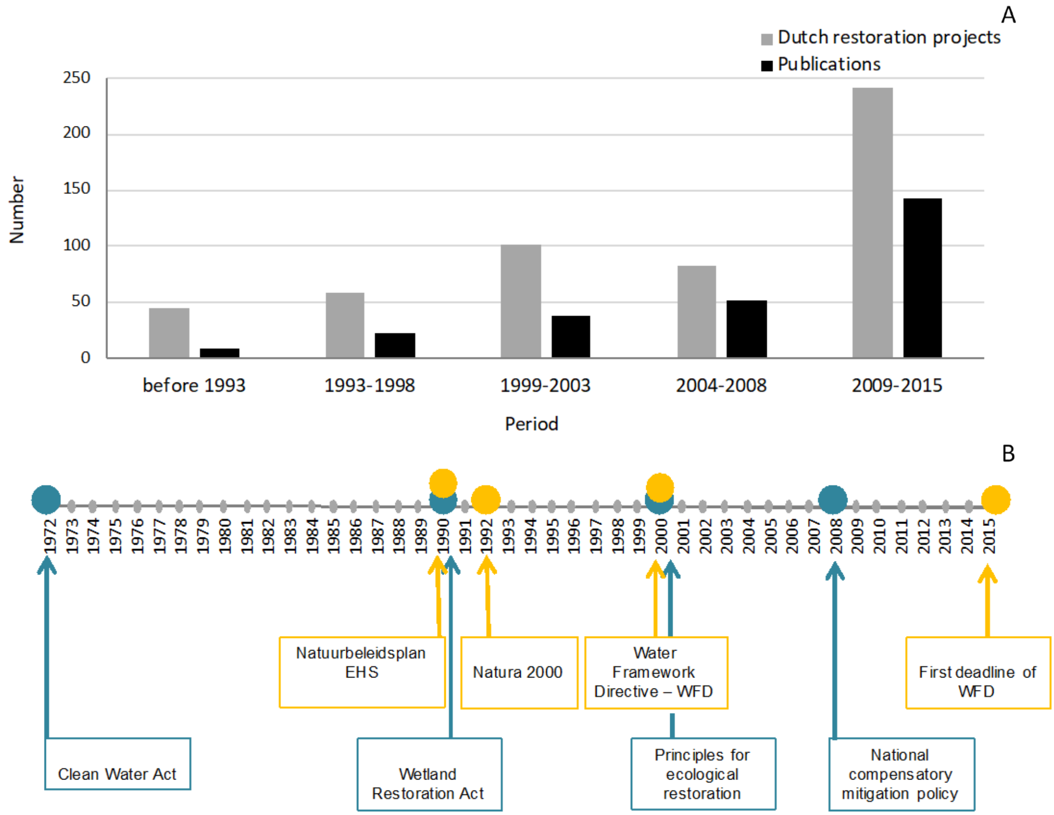


Figure 1: Timeline of the number of Dutch stream restoration projects and scientific publications per time period (before 1993, 1993-1998, 1999-2003, 2004-2008, and 2009-2015)(A), and the introduction of freshwater restoration legislations and regulations in the Netherlands, Europe (yellow) and the USA (blue) (B).

4. Biophysical restoration objectives

Morphological objectives were the most frequently referred ones during all studied periods in both Dutch restoration projects and scientific publications (Figure 2, first panel). The measures involved were re-profiling of the stream bed and banks and re-meandering of the stream channel, in the Netherlands as well as abroad (e.g., Rinaldi and Johnson, 1997; Kondolf et al., 2001; Kasahara and Hill, 2006; Krapesch et al., 2009; Schiff et al., 2011; Kristensena et al., 2014).

In Dutch restoration projects hydrological objectives were frequently referred to by the water authorities, but these appeared to a lesser extent in the scientific publications (Figure 2, second panel). In contrast, until 2004 biological objectives were more frequently mentioned in the scientific literature than in the Dutch questionnaires. In the most recent questionnaire, however, the biological objectives became the most important ones in the Dutch projects, driven by the WFD that requires specific biological goals to be achieved (Figure 2, third panel). Yet, to achieve these goals, in the Dutch projects as well as in the scientific publications, almost no direct biological measures (e.g., species reintroduction and invasive species control) were taken, but only indirect ones, mainly hydromorphological measures to improve habitat quality and connectivity (e.g. constructing fish ladders and bypasses alongside dammed streams).

Chemical water quality objectives were less frequently mentioned by the Dutch water authorities and in the scientific literature, except for the period 2004-2008 (72%; Figure 2, fourth panel). Given that in the period before 1993 many wastewater treatment plants (WWTP) were built and improved, it is surprising that chemical objectives were not more prominent in this period. However, because WWPT’s are more associated with human health and sanitation rather than with freshwater ecosystem restoration, most probably these measures were not identified as stream restoration measures in our literature review (Figure 2 fourth panel). Societal objectives were least considered in Dutch stream restoration projects and in scientific publications (Figure 2 bottom panel).

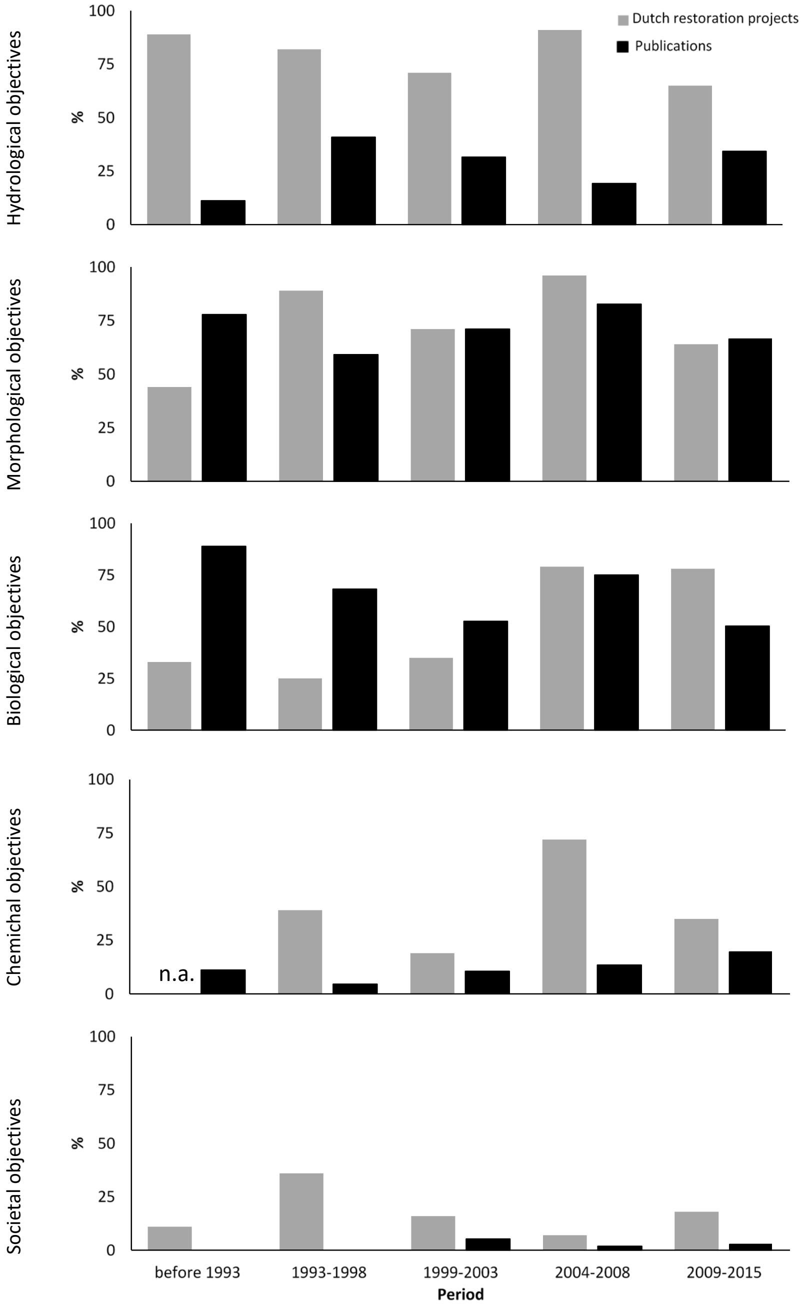


Figure 2: Percentage of objectives named in the surveys related to hydrology, morphology, chemistry, biology and society in Dutch stream restoration projects (D) and in scientific publications (S) per time period (before 1993: D n=45; S n=9, 1993-1998: D n=59; S n=22, 1999-2003: D n= 101; S n=38, 2004-2008: D n= 82; S n=52, 2009-2015 : D n= 246; S n=143).

5. Restoration measures

The five most frequently applied Dutch stream restoration measures all concerned hydromorphological improvements: re-meandering, channel re-profiling, providing space for inundation, bypassing dams and stimulating the development of riparian vegetation (Table 1). In the literature, a very similar pattern was observed, since the majority of publications referred to hydromorphological measures, especially enhancing instream structure (e.g., rocks), adding large wood, riparian vegetation development, re-meandering and creating space for inundation (Table 1). Yet, a more diverse set of measures was applied in the Dutch restoration projects.

Improving chemical water quality and applying biological management measures became more apparent only after 2009. In Dutch restoration projects, measures to improve the chemical water quality often referred to the reduction of runoff of fertilizers, the construction of (riparian) buffer zones and, more recently, changing the land use of the stream valley. Internationally, the main measures to improve water quality were dredging the stream bottom and improving wastewater treatment efficiency. Biological measures applied in stream restoration projects were recorded mostly after 2004. Dutch measures were generally related to changes in instream vegetation mowing practices, while the exclusion of herbivores by fencing riparian zones was internationally the most commonly mentioned measure, followed by the re-introduction of species (Table 1).

Table 1: Percentage of Dutch water authorities and scientific publications applying stream restoration measures (morphological, hydrological, chemical, biological and societal) per time period (before 1993, 1993-1998, 1999-2003, 2004-2008, 2009-2015).

		Dutchwater authorities (%)					Publication (%)				
		before 1993	1993-1998	1999-2003	2004-2008	2009-2015	before 1993	1993-1998	1999-2003	2004-2008	2009-2015
Hydrology	Restore the histrorical stream network	n.a.	39	22	39	45	0	0	0	0	6
	Provide space for inundation / restore wetlands or floodplains	n.a.	69	65	69	82	11	27	17	13	17
	Restore the (semi-)natural stream bed	n.a.	0	0	62	73	0	0	6	0	1
	Channel re-profiling (shallowing, narrowing, widening)	n.a.	77	30	85	100	0	0	0	4	15
	Remove drainage structures in the stream valley	n.a.	54	44	31	36	0	0	0	0	1
	Develop hydrological buffer zones	n.a.	39	22	54	45	0	5	0	2	0
	Raise the ground water level	n.a.	0	44	69	72	0	0	3	0	1
	Reconnect backwaters	n.a.	8	35	23	55	0	0	0	0	0
	Re-meander the stream channel	n.a.	77	61	77	100	0	9	14	15	16
	Promote rain water infiltration in the uplands	n.a.	54	26	39	36	0	0	3	0	0
	Reduce water extraction	n.a.	15	30	0	18	0	0	3	0	1
	Remove barriers and wiers/restore connectivity	n.a.	62	39	69	91	0	0	0	4	6
	Disconnect or redirect agricultural side-streams	n.a.	0	0	15	45	0	0	0	0	1
	Install bank protection	n.a.	0	4	0	0	11	9	6	8	7
Morphology	Remove bank fixation	n.a.	39	9	46	91	0	0	3	2	6
	Re-profile stream banks	n.a.	62	35	85	82	0	0	3	0	2
	Dig isolated pools in the stream valley (habitat amphibians)	n.a.	77	52	69	73	0	0	0	0	2
	Develop a near-natuiral riparian zone (forest, wooded bank)	n.a.	0	4	62	64	0	0	0	0	1
	Dig one-side connected backwaters	n.a.	0	0	31	27	0	0	0	0	0
	Lower stream banks gradually to create inundation zones/wetlands	n.a.	0	30	46	82	0	0	0	0	0
	Construct a two-stage profile	n.a.	31	22	46	55	0	5	0	0	1
	Construct bypasses (fish ladders), e.g. around dams, wiers	n.a.	77	44	85	100	0	0	0	0	0
	Enhance in-stream wood debris retention or add large wood	n.a.	0	0	4	100	33	9	17	27	15
	Install in-stream structures, like sand banks and stones	n.a.	8	30	23	64	22	14	14	27	18
	Restore pool sequences or pool-riffle units	n.a.	0	17	23	18	22	5	3	10	14
	Initiate micromeanders (add deflectors)	n.a.	31	30	15	64	11	0	3	2	6
	Stimulate vegetation development on sand bars	n.a.	0	0	0	0	0	0	0	0	1
	Stimulate riparian vegetation development	n.a.	54	52	69	91	11	18	11	15	13

		Dutchwater authorities (%)					Publication (%)				
		before 1993	1993-1998	1999-2003	2004-2008	2009-2015	before 1993	1993-1998	1999-2003	2004-2008	2009-2015
Chemical water quality	Construct horse-shoe wetlands	n.a.	16	4	0	0	0	0	0	0	0
	Dredge the stream bottom	n.a.	0	26	0	36	11	5	3	2	3
	Construct helophyte filters	n.a.	16	35	23	0	0	0	0	0	0
	Construct buffer zones	n.a.	39	35	23	64	0	0	3	0	2
	Separate wastewater flows	n.a.	46	26	0	0	0	0	0	0	1
	Reduce fertilizer runoff input	n.a.	54	52	39	18	0	0	0	2	1
	Reduce the inlet of non-local water	n.a.	0	17	15	18	0	0	0	0	0
	Reduce sewage storm overflows	n.a.	39	44	15	9	0	0	0	0	3
	Reduce toxic load	n.a.	39	30	15	9	11	0	0	0	1
	Reduce the load of pollutants	n.a.	0	39	8	9	0	0	0	0	3
	Improve wastewater treatment	n.a.	15	13	15	9	11	5	0	2	3
	Change stream valley land use	n.a.	0	4	54	64	0	0	0	2	1
Biological management	Introduce large herbivores (grazing of stream banks)	n.a.	0	9	54	36	0	0	0	0	0
	Exclude herbivores (fencing)	n.a.	0	0	0	0	0	0	6	4	2
	Active biological control (eliminate exotic species)	n.a.	0	30	8	9	0	0	0	0	1
	Extensify instream macrophyte maintenance	n.a.	0	44	85	100	0	0	0	0	0
	Adjust water management to benefit fish	n.a.	0	0	8	27	0	0	0	0	0
	Promote natural water level management	n.a.	0	35	39	64	0	0	0	0	0
	Extensify bank vegetation maintenance	n.a.	0	52	77	73	0	0	3	2	1
	Re-introduce species	n.a.	8	17	8	9	0	0	6	2	2
	Species specific measures to conserve or initiate recovery of populations	n.a.	0	35	46	55	0	0	0	0	0
Social and Others	Recreational and aesthetic measures	n.a.	0	0	0	0	0	0	0	0	1
	Best management practices in the catchment	n.a.	0	22	0	0	0	0	3	2	2
	Acidification control	n.a.	0	0	0	0	0	0	0	4	0
	Use of models or simulations	n.a.	0	0	0	0	0	0	0	4	11
	Eliminate thermal pollution	n.a.	0	0	0	0	0	0	3	0	0

6. The scale on which restoration measures were applied

The majority of stream restoration projects in the Netherlands (Figure 3A) and in the scientific publications (Figure 3B) considered small scales only. Ecological processes at the catchment scale, such as aquatic organism dispersal and colonization ability and land use effects were rarely mentioned, despite their acknowledged importance for ecological recovery (Schiff et al., 2011; Verdonschot et al. 2012; Kail and Hering, 2009; Stranko et al., 2012; Weigelhofer et al, 2013).

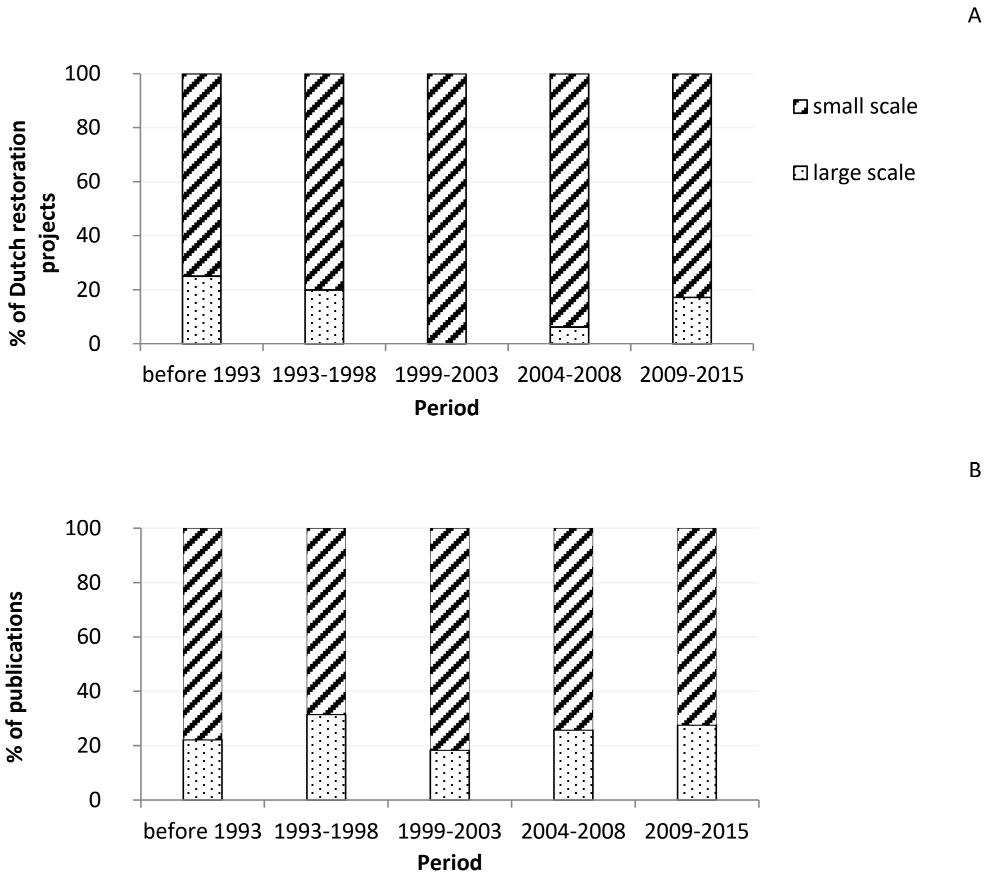


Figure 3: The spatial scale considered in stream restoration projects in the Netherlands (A) and in scientific publications (B) per time period (before 1993, 1993-1998, 1999-2003, 2004-2008, 2009-2015).

The limited availability of space for restoration projects, often only available in nature conservation areas, co-directed the selection of sites in the Netherlands, as most of the restored stream trajectories were located in areas designated as nature instead of in agricultural or urban areas. Restoration of stream trajectories in a landscape in a relatively good environmental state, such as forests, have a higher chance of success and may cost less. This connection between conservation and restoration shows that both are still seen as complementary (Ormerod, 2003). The restoration of highly impacted streams in urbanized and agricultural areas is thus often neglected, most probably due to the global model of “economic development”, that does not prioritize natural ecosystem processes nor biodiversity in heavily exploited areas (Marques et al., 2019). According to Kail et al. (2009), the problems to restore degraded urban and agricultural streams also arise from a lack of knowledge on how to enhance the quality of systems in such a low ecological state. Examples refer to, amongst others, the technical difficulties to improve wastewater treatment plant effluents and to limit runoff from anthropogenic land uses (Bernhardt and Palmer, 2007; Rhodes et al., 2007; Weigelhofer et al., 2013).

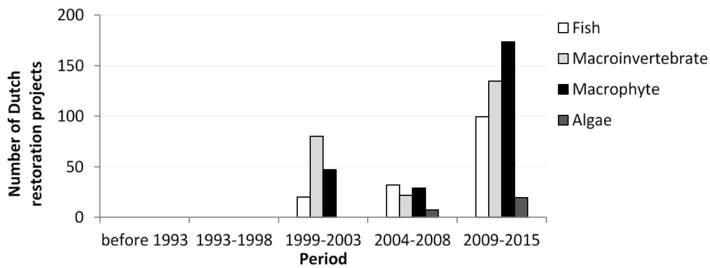
7. Monitoring efforts

Over the last 40 years, substantial biological monitoring took place in the majority of Dutch stream restoration projects (98% in 1999-2003, 80% in 2004-2008 and 83% in 2009-2015). Macroinvertebrates and macrophytes were monitored most frequently (Figure 4A). Over the studied 40 years' time period, 99% of the scientific publications mentioned the monitoring of one or multiple organism groups, mainly fish and macroinvertebrates (Figure 4B).

Although a high percentage of restoration projects were monitored, in both Dutch restoration projects and in the scientific publications little information was available about the monitoring design (e.g. Before-After or Control-Impact) and duration (e.g. number of years pre- and post-restoration). In Dutch restoration projects information about the application of a before-after monitoring design was available for the period of 2004-2008. For macrophytes, a before-after monitoring design was used in 69 % of the total number of projects. For fish this percentage was 65 %, for macroinvertebrates 50 % and for algae only 20%. Even if a before-after design was used, monitoring was in most cases not specifically designed for the restoration project of concern. It is common practice to simply use the standard monitoring sites already present in the streams without taking the potential effects of the measures on the biota into account. Indeed, the majority of Dutch respondents pointed at the lack of proper monitoring (questionnaire of 2009-2015). Also worldwide this has been repeatedly underlined as a key problem in evaluating the effects of stream restoration (e.g. Kondolf and Michlei, 1995; Wissmar and Beschta, 1998; Downs and Kondolf, 2002; Bash and Ryan, 2002; Palmer et al., 2005; Woolsey et al., 2007; Klein et al., 2007; O'Donnell and Galat, 2008; Densmore and Karle, 2009; Jahnig et al., 2011; Bennett et al., 2016). Often, pre- and post-monitoring is not included at all in the restoration plans, and in those few cases where monitoring took place, a proper design, such as a before-after and impact-control set-up, in combination with a rationale on the choice of biological metrics was rarely considered.

The lack of meaningful monitoring data hampers a proper evaluation of stream restoration projects (Jansson et al., 2005) and, consequently, the actual reason for the observed low success rates remain unknown. In order to improve the design of the monitoring programs accompanying restoration projects, theoretical (Palmer et al. 2005; Lake et al.,2007) and practical (e.g. Voulvoulis et al., 2017; Birk et al, 2012; Verdonschot and Nijboer, 2002) guidelines should be applied, and more funding to undertake meaningful monitoring must be allocated (Gillilan et al., 2005; Jansson et al., 2005).

A



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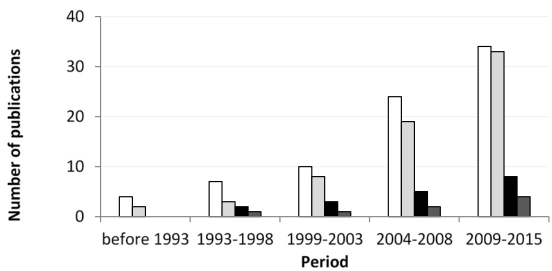


Figure 4: Number of restoration projects in the Netherlands (A) and international scientific publications (B) in which monitoring of macrophytes, fish, macroinvertebrates and benthic algae has been carried out per time period (before 1993, 1993-1998, 1999-2003, 2004-2008, 2009-2015).

8. Future perspectives

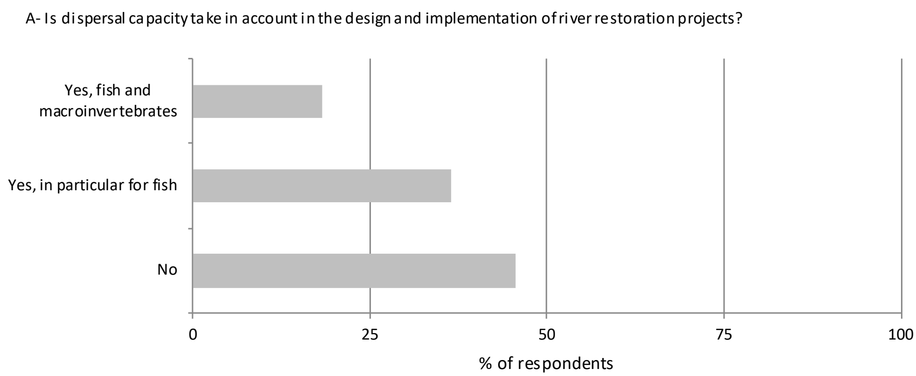
Over the last 40 years, stream restoration techniques improved and new techniques were introduced, such as the addition of large wood, that has been used to enhance instream habitat quality in many projects around the world (Bernhardt et al., 2005; Feld et al., 2011; Roni et al., 2014). More recently, “rewilding” approaches, such as rehabilitation stream side marshes by reconnecting the stream and its valley and reintroducing beavers have been increasingly used to restore degraded stream ecosystems and to increase biodiversity (Baker and Eckerberg, 2016; Hood and Larson, 2015; Roni and Beechie, 2013, dos Reis Oliveira et al., 2019).

While in the past many projects intended to improve the entire stream ecosystem, they in fact solely focused on specific morphological (habitat improvement) or hydrological (flow conditions) conditions, as was already observed two decades ago (Verdonschot and Nijboer, 2002; Palmer et al., 2010; Palmer et al., 2014). This was and can still be explained by a firm trust in the statement that 'if habitat heterogeneity increases, so does biological diversity' (Field of Dreams Hypothesis; Palmer et al., 1997). Nevertheless, a fully integrative approach, tackling all stressors, but also taking important biological aspects into account, such as colonization (Westveer et al., 2018), dispersal (Engström et al., 2009), distance to source populations (Brederveld et al., 2011; Stoll et al., 2013), re-introduction of species (Jourdan et al., 2018) and control of invasive species (Scott and Helfman, 2001), are still rare. Moreover, stream restoration practice should also be aware of the ecological risks that can occur after restoration, such as ecological traps when species get more threatened by the novel habitat conditions post restoration in comparison to the initial conditions (Robertson et al., 2013; Hale et al., 2015), providing opportunities for invasive species (Matsuzaki et al., 2012; Franssen et al., 2015; Merritt and Poff, 2010), introducing non-natural hydrological conditions (Vehanen et al., 2010; Jeffres and Moyle, 2012) and enhancing sediment toxicity to amphibians (Snodgrass and Stoll, 2008).

Furthermore, many stream restoration projects still consider small scale measures and solutions, and neglect that stream ecosystems are strongly governed by catchment scale processes (Allan, 2004; Palmer, 2010; Ward, 1998; Wiens, 2002; Sundermann and Stoll, 2011). Several authors have already shown that large scale restoration is crucial for ecological recovery (Schiff et al., 2011; Verdonschot et al., 2012; Kail and Hering, 2009; Stranko et al., 2012; Weigelhofer et al, 2013).

To improve the success rate of stream restoration projects, goals and measures have to match, science-based monitoring should be performed, and the catchment scale has to be considered. In the Netherlands, even 15 years after Verdonschot and Nijboer (2002) proposed to include large scale effects in the guidelines for stream restoration, thus to consider ecological processes that occur at the catchment scale or larger, such as land use impacts and dispersal capacity of aquatic organisms (in line with Palmer et al., 2014), to date this still remains a challenge.

To better understand the reasons why landscape ecology is poorly considered, in the latest questionnaire we asked the Dutch water authorities about the inclusion of dispersal capacity and land use effects in the design of stream restoration projects. From their answers it appeared that only half of the water managers took faunal dispersal capacity and colonization processes into account in stream restoration projects, and if they did, it mainly concerned fish (Figure 5A). Macroinvertebrate dispersal capacity was rarely included in the design and implementation of restoration projects, although this group is one of the key indicators of ecological quality, an essential food source for a number of fish species, and are essential for stream ecosystem recovery through their role in many ecosystem processes. The most commonly used measure to improve dispersal capacity was to connect restored trajectories to the adjacent up- and downstream sections, while the reintroduction of species was the least frequently applied measure (Figure 5B). While dispersal capacity relates to connectivity, colonization and survival depends on, amongst others, habitat quality and food availability (van Puijenbroek et al., 2019). Furthermore, colonization potential depends on the distance to source populations and their densities, both driving the success of colonization (Westveer et al., 2018), which is generally limited to a distance of about 5 km (Stoll et al., 2013; Tonkin et al., 2014; Winking et al., 2014). Hence, it is concluded that dispersal capacity must be incorporated into the design of restoration projects.



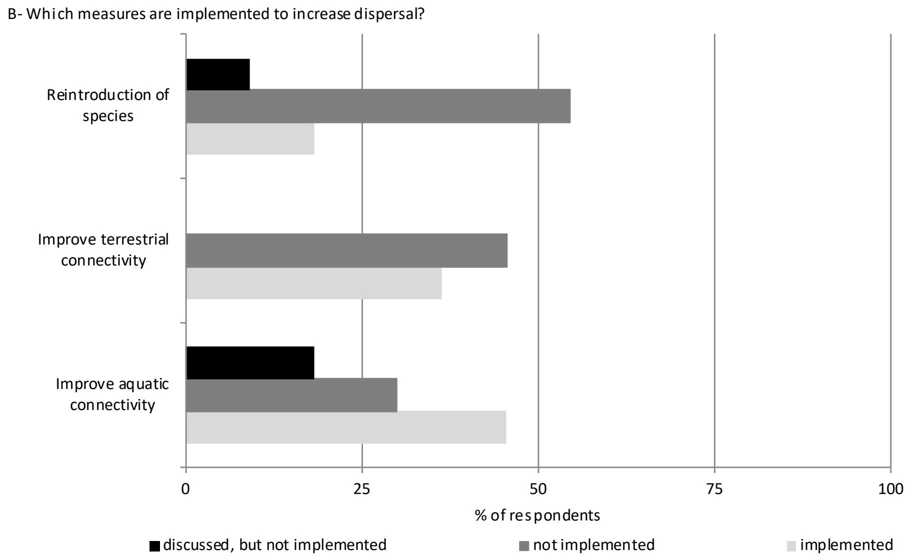


Figure 5: Percentage of water authorities (n = 11) that took the dispersal capacity of aquatic organisms (macroinvertebrates and fish) into account (A). Percentage of water authorities that took measures to increase dispersal potential (B).

All water managers indicated that they took the effects of the land use in the stream valley into account when designing restoration projects, yet the scale considered differed (Figure 6A). The majority of stream restoration projects in the Netherland only considered small scales, despite that the water authorities were well aware of the major environmental problems, such as increased sedimentation, nutrient and toxic loads, extreme peak floods and droughts, and losses of riparian woody vegetation (Figure 6B). Yet, these problems can only be tackled at a large scale (Violin et al., 2011; Kail and Wolter, 2011; Weigelhofer et al., 2013). Furthermore, there is no single solution to reduce all land use impacts. Stream restoration measures should therefore identify and tackle catchment specific stressors, relevant for the site of interest (Palmer et al., 2010). Yet, still little knowledge is available on how the mechanisms behind land use impacts act on the stream ecosystem (dos Reis Oliveira et al., 2018). Therefore, to further improve the number of successful stream restoration projects, catchment specific land use impacts should receive much more attention.

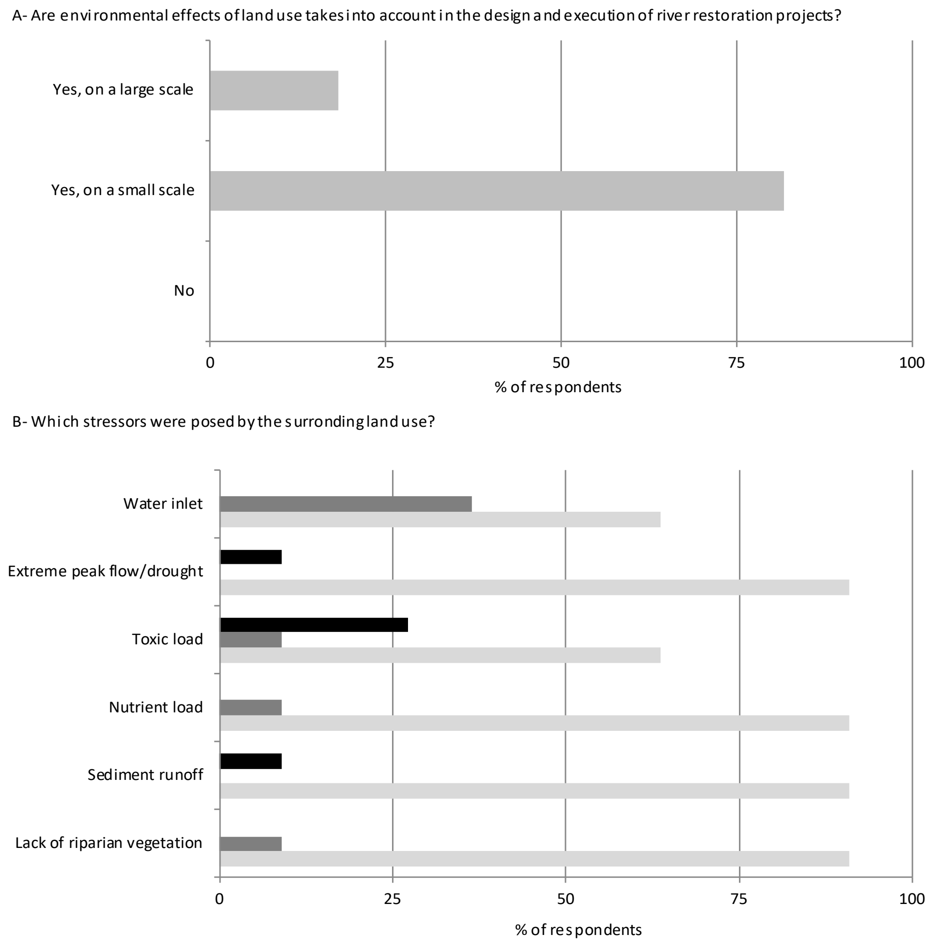


Figure 6: Percentage of water authorities (n = 11) that took land use into account in restoration projects (A). Effects of surrounding land-use observed in restored stream trajectories (B).

In conclusion, over the last 40 years there was a considerable increase in stream restoration efforts motivated by environmental policy, legislation and regulations. Yet, a mismatch between biophysical objectives and restoration measures, a monitoring deficiency, and restoration plans neglecting large scale catchment wide effects hampered the success of ecological stream restoration. It is therefore recommended to improve the monitoring programs accompanying restoration projects by applying the proper design, matching the relevant spatiotemporal dimensions for the ecosystem under study. This allows to evaluate, over longer time periods, if the measures taken led to the desired results, and secondly to scale up the spatial scale of stream restoration projects from local instream efforts to catchment wide measures.

Supplementary material

Table 1: Categories and respective definitions (parameters or key word) from stream restoration biophysical objectives, scale and monitoring.

	Category	Parameter/ key-words
Biophysical objectives	Hydrological	flow, hydraulics, velocity, discharge, flood, drought, retention, turbulence and transport
	Morphological	channel configuration, substrate cover, digging, adding structures, habitat, shelter
	Chemichal	nutrients load, toxic compounds (metals, pesticides), pH, conductivity, redox, oxygen, water and sediment quality
	Biological	Species, population or community recovery, stocking, re-introduction, invasive species control
	Societal	ethnology, heritage, aesthetic, recreation
Scale	Large	entire stream, stream stretch or lateral channel longer than 1500 m, catchment, surrounding land use (> only riparian zone), aquifer and effluents
	Small	stream stretch shorter than 1500 m
Monitoring	Fish	Community, population or specific species
	Macroinvertebrate	Community, population or specific species
	Macrophyte	Instream aquatic taxonomic groups
	Algae	Algae, phytobenthos and periphyton

Literature review

Scientific articles from 1975 until 2015 were selected at the search engines Web of Science, Scopus and Google scholar by using the following key-word:

"lowland reach"* OR "lowland channel"* OR "lowland stream"* OR "lowland river"* OR "lowland creek"* OR "lowland ditch"* OR "low gradient reach"* OR "low gradient channel"* OR "low gradient stream"* OR "low gradient river"* OR "low gradient creek"* OR "low gradient ditch"* AND restor* OR recov* OR rehabilit* OR revitali* OR renat* OR enhance* OR mitigate*

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