Journal of Environmental Management 264 (2020) 110417

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Over forty years of lowland stream restoration: Lessons learned?

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ARTICLE INFO

Keywords:
Freshwater restoration
Legislation
WFD
Clean water act
Catchment scale
Restoration techniques

ABSTRACT

Stream restoration efforts have increased, but the 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 over 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 the scale of application 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 the effectiveness of the measures was often lacking. Furthermore, a mismatch between restoration goals and restoration measures 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 tackling multiple stressors acting over large scales 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. Secondly, we advise to diagnose the dominant stressors and plan restoration measures at the appropriate scale of these stressors, generally the catchment scale.

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 egical, 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 selection of indicators for restoration success and the reference setting play a crucial role in the evaluation of river restoration projects (Angermeier, 1997; Morandi et al., 2014) and directly relate to the restoration objectives. Stream restoration objectives in are often either hydromorphological or biological, in which biological indicators can be structural, compositional, and functional (Weber and Peter, 2011). Furthermore, biophysical objectives need to include the scale in space and time of the recovery processes and expected states (Paller et al.,

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https://doi.org/10.1016/j.jenvman.2020.110417
Received 7 August 2019; Received in revised form 27 February 2020; Accepted 7 March 2020
Available online 21 March 2020
0301-4797/

2000). Thereby, it is crucial to set a reference that supports the expected direction of development. Ideally, the evaluation of restoration successes should examine if the restoration measures indeed met the restoration objectives, but until now the link between both is poor even virtually lacking (Kondolf and Micheli, 1995; Roni et al., 2008; Morandi et al., 2014). Moreover, comparisons of the effects of different measures are rare (Palmer et al., 2005; Mueller et al., 2014).

In stream restoration, either the pre-deterioration state or some reference state is considered as the starting point (Bernhardt and Palmer, 2011), whereby the first may provide information on the stressors to be tackled, a crucial step to select the most effective measures (Wohl et al., 2005). Yet, the identification of the most improtant combination of stressors affecting the ecological condition of a stream to select the appropriate restoration measures is still generally lacking (Merovich and Petty, 2007; Ormerod et al., 2010).

Despite the improvement of the hydromorphological and physico-chemical habitat quality, many stream restoration projects at the reach scale have not yet shown the expected outcomes (Roni et al., 2008; Palmer et al., 2010; Dolédec et al., 2015). Stream communities are largely shaped by regional-scale processes and structures (Poff et al., 1997; Lake et al., 2007), but the role of regional-versus local-scale variables in a restoration context has only scarcely been evaluated (Stoll et al., 2016).

Although monitoring appears to be taking place in quite a number of stream restoration projects (e.g. Bash and Ryan, 2002; Alexander and Allan, 2007), the design of the monitoring programs varies widely across projects and in most cases insufficient information is obtained. These deficits strongly hold back the process of 'learning-by-doing' in stream restoration.

Given the potential reasons for the lack of restoration successes discussed above the aim of the present study was to evaluate over 40 years of stream restoration (a synthesis of practical and theoretical knowledge gained so far) to fuel future perspectives (the development of concepts to bring new knowledge ino practice). 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 covering the period from the late sixties and seventies up to 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). The questionnaires covered different time periods: late sixties to 1993, 1993–1998, 1999–2003, 2004–2008 and 2009–2015, thus covering about 25, 5, 5, 5 and 7 years, respectively. The questions in each of the subsequent surveys were modified to include the most recent developments in stream restoration and were extended or shortened depending on the survey goals at that time. However, all questionnaires considered policy goals (mostly legislation and regulations), biophysical objectives, measures applied, the spatial scale of the measures and monitoring efforts (Table S1 and S2 in supplementary material). Based on progressive insights, additional questions on the effects of large-scale pressures from anthropogenic land use and on the 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, the first year a relevant publication was found from the late sixties onward, to 2019 (in supplementary material). In total, 315 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 the comparison between the questionnaires and the open literature the results obtained from the literature study were grouped in similar time-clusters as those of the Dutch restoration questionnaires: before 1993, 1994–1998, 1999–2003, 2004–2008 and 2009–2015, respectively. A complementary literature study for 2016–2020 was made to cover the most recent publications.

3. Results

3.1. *The influence of policy goals on stream restoration efforts*

Our analysis covered over 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 was observed (Fig. 1 A). While in the previous century only a few projects were carried out, in the most recent years (2009–2015) yearly about 30–35 new restoration projects were performed in the Netherlands. This increase in project numbers is corroborated by an increase in numbers of international scientific publications (Fig. 1A) reaching about 20 publications per year in the period of 2009–2015 and 14 recently (2016–2019). Most of the scientific publications referred to projects in the USA (42%) and Europe (39%). To gain insight into the underlying motivations, a timeline was constructed showing the most important legislations and regulations regarding freshwater ecosystem restoration (Fig. 1B).

In the questionnaires the Dutch water managers were asked to what extent 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 EU 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. The introduction of the WFD coincided with the highest number of stream restoration projects performed in the Netherlands, as well as in other European countries, since the ambition of obtaining good ecological status in all surface European water bodies by 2027 was then established (Hering et al., 2010).

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 were explicitly 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).

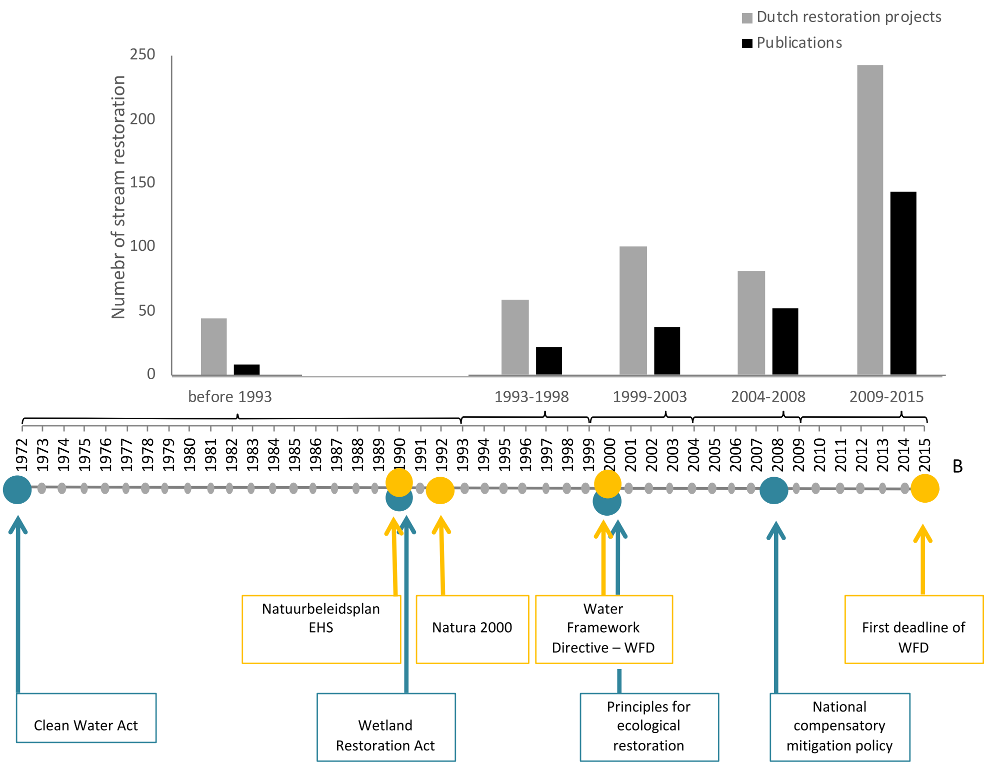

Fig. 1. Timeline of the number of Dutch stream restoration projects and scientific publications per time period (before 1993, 1993–1998, 1999–2003, 2004–2008, and 2009–2015)(A), and the introduction of freshwater restoration legislations and regulations in the Netherlands and Europe (yellow boxes) and the USA (blue boxes) (B). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In conclusion, the science – policy interaction and the development of improved legislation has shown to be an important driver for taking restoration measures. To further improve stream restoration success the ecological knowledge on the importance of stream functioning at the landscape scale can support legislators to widen their goals from a specific water body towards the full stream valley and even the whole catchment area. This way, stream restoration could become a part of landscape spatial planning.

3.2. Biophysical restoration objectives

In Dutch restoration projects hydrological objectives were frequently referred to by the water authorities, since hydrological issues, such as flood control, are a constant concern in the Netherlands, but these appeared to a lesser extent in the scientific publications (Fig. 2, first panel, Table S1).

Morphological objectives were the most frequently referred ones during all studied periods in both Dutch restoration projects and scientific publications (Fig. 2, second panel, Table S1). 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; Kristensen et al., 2014).

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%; Fig. 2, fourth panel, Table S1). 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 (Fig. 2 fourth panel).

Societal objectives were least considered in Dutch stream restoration projects and in scientific publications (Fig. 2 bottom 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 (Fig. 2, third panel, Table S1). 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).

In conclusion, both hydrological and morphological objectives were far most important for the initiation of stream restoration in the first four periods. In the Netherlands, however both groups of objectives became less important in favour of biological objectives. Internationally though, morphological and biological objectives prevailed without clear tendencies over time. The latter may be due to the prevailing nature of the scientific publications. In the Netherlands, as elsewhere in Europe, The Water Framework Directive proved its value to set biological objectives and stimulated more focus on combined key environmental conditions over different scales in space and time.

3.3. Restoration measures

In general, higher percentages for the measures taken by Dutch authorities are given as each water authority was responsible for multiple restoration projects. Each scientific publication mostly referred to only one or a few restoration measures that were in fact applied and from which only data for the manuscript were extracted.

The five most frequently applied Dutch stream restoration measures

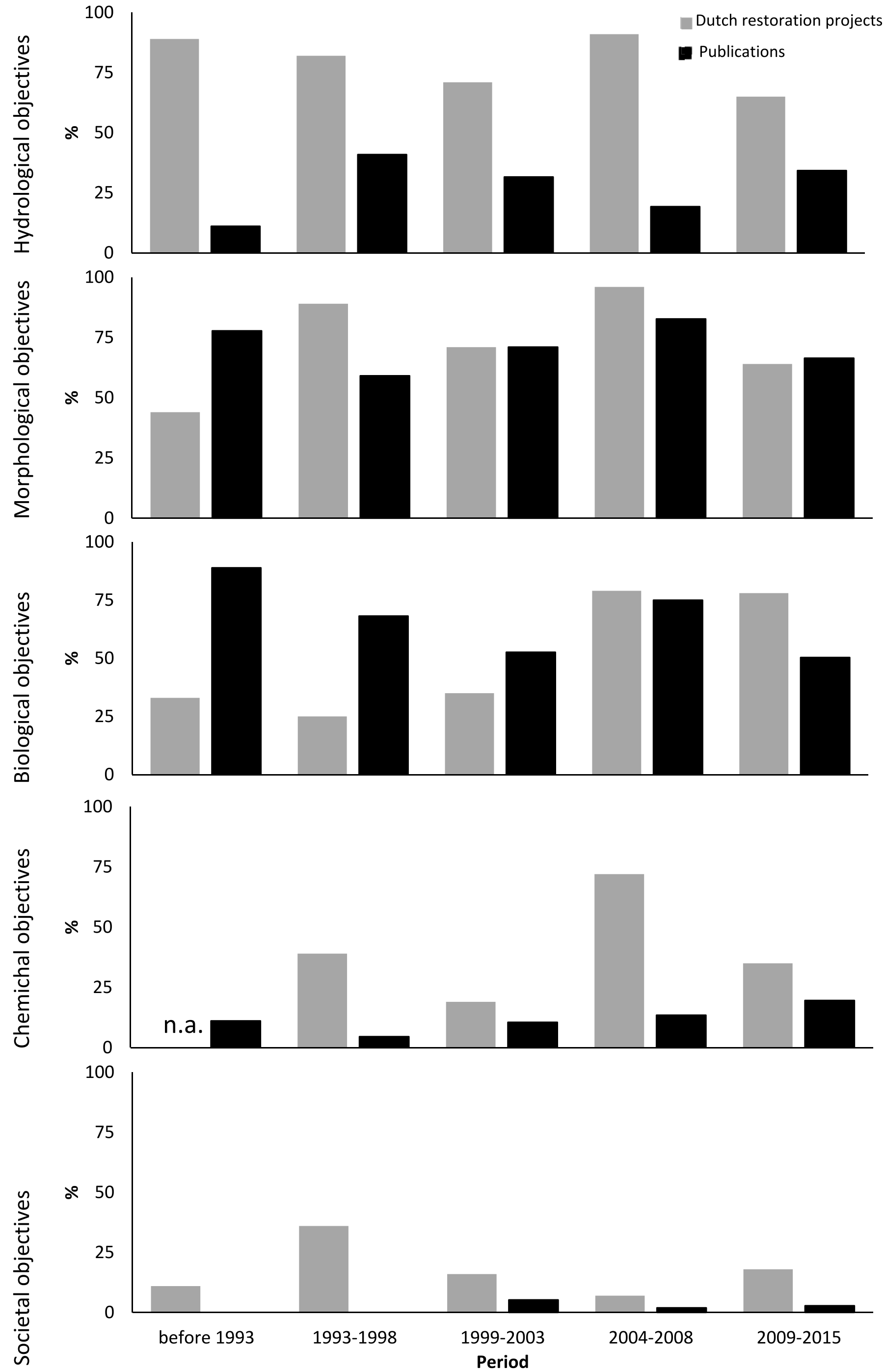

Fig. 2. Percentage of objectives named in the surveys related to hydrology, morphology, chemistry, biology and society in Dutch stream restoration projects (D) and in scientific publications (S) per time period (before 1993: D n = 45; S n = 9, 1993–1998: D n = 59; S n = 22, 1999–2003: D n = 101; S n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

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-natural 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
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

In conclusion, despite the key role of hydrology in stream ecosystem functioning, morphology still is the most important environmental feature improved in restoration. Over the latter years in the Netherlands taking hydrological measures in the stream valley and even in the whole catchment is emerging. Internationally this development is not yet visible. The tendency to formulate objectives in terms of species did not yet result in changes in measures. In the Netherlands, there is a transition from attention for point sources of pollution towards diffuse sources and a development to tackle such stressors by introducing buffer zones. Stream restoration can benefit strongly from improved land use legislation in combination with wide buffer zones to reduce runoff of both water and substances (nutrients and toxicants). A second important development is the reduction of maintenance to provide freedom for natural stream and stream-valley processes.

3.4. The scale on which restoration measures were applied

The majority of stream restoration projects in the Netherlands (Fig. 3A) and in the scientific publications (Fig. 3B) only considered small scales. Recentely however (2016–2019), the percentage of large scale projects (38%) in scientific publications increased. Yet, 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; Gabriele et al., 2013).

The limited availability of space for restoration projects, often only available in nature conservation areas, co-directed the selection of sites in the Netherlands. Therefore, most of the restored stream trajectories

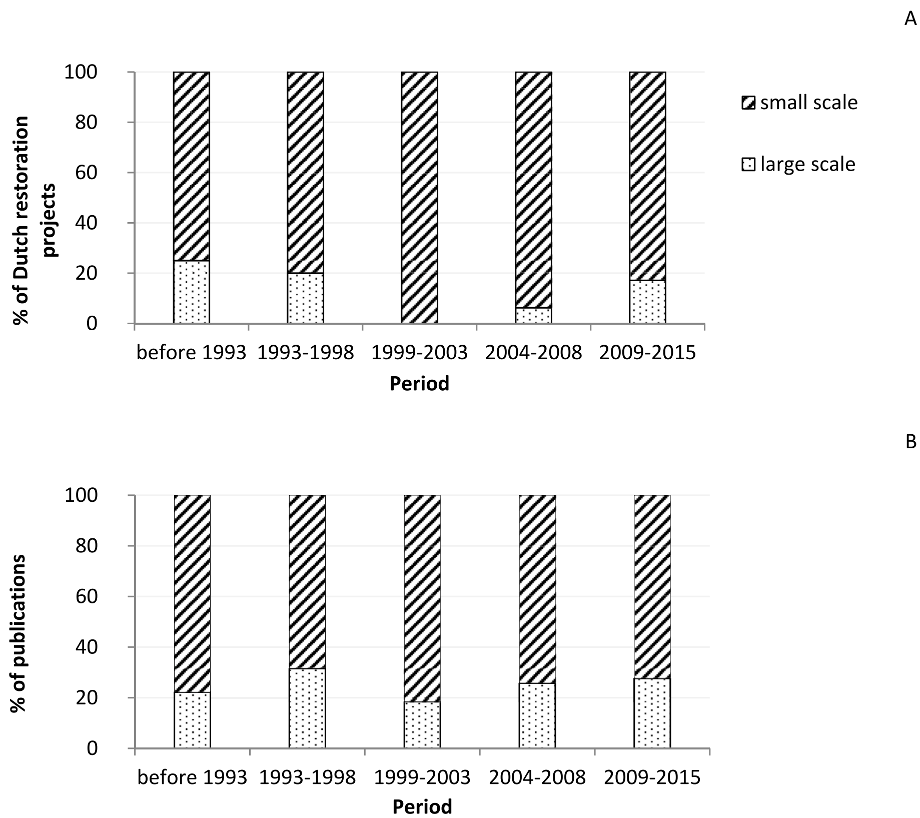

Fig. 3. The spatial scale considered in stream restoration projects in the Netherlands (A) and in scientific publications (B) per time period (before 1993, 1993–1998, 1999–2003, 2004–2008, 2009–2015).

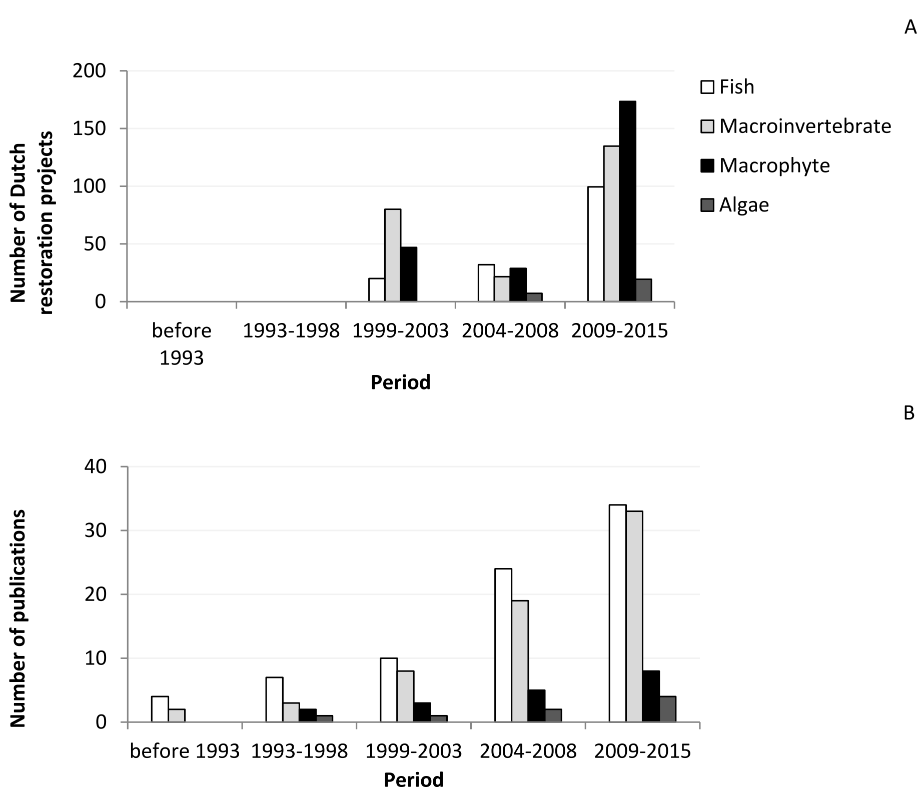

Fig. 4. Number of restoration projects in the Netherlands (A) and international scientific publications (B) in which monitoring of macrophytes, fish, macroinvertebrates and benthic algae has been carried out per time period (before 1993, 1993–1998, 1999–2003, 2004–2008, 2009–2015).

were located in areas designated as natural area instead of in agricultural or urban areas. Generally, 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; Gabriele et al., 2013).

In conclusion, all over the past forty years the scale at which restoration took place remained mostly small, often without mentioning water safety, while the surrounding land uses restrict large scale approaches. Water quality legislation sets appropriate objectives but does not include spatial planning. The latter is needed to obtain large scale changes in the landscape.

3.5. Monitoring efforts

Over the last >40 years, some kind of 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 (Fig. 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 (Fig. 4B). In the most recent period (2016–2019), the scientific publications on stream restoration showed a small increase in monitoring data on ecosystem processes (13%), such as food and trophic resources (Cashman et al., 2016), metabolism (Graeber et al., 2018), decomposition (Frainer et al., 2018) and the cycling of nutrients (Lavelle et al., 2019).

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 applying or not applying a before-after monitoring design was available for the period of 2004–2008. For macrophytes, from 2004 to 2008 a before-after monitoring design was used in 69% of the total number of projects, for fish this percentage was 65%, for macroinvertebrates 50%, but for algae only 20%. Even if a before-after design was applied, 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 that already make part of the regular monitoring program in the streams without taking the potential effects of specific restoration 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 Micheli, 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). Nilsson et al. (2015) indicated that the lack of clear biotic responses in restoration projects could partially be attributed to a poor monitoring method. 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. Moreover, the monitoring duration should also be considered for a proper evaluation of the restoration outcome (Hasselquist et al., 2015), since the time scale required for recovery may take over a decade (Jones and Schmitz, 2009).

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. Nilsson et al. (2016) pointed out the importance of collecting appropriate monitoring data to be able to evaluate all phases of a restoration project, as well as for future projects. In order to improve the design of the monitoring programmes 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; Nilsson et al., 2016) guidelines should be applied, and more funding to undertake meaningful monitoring must be allocated (Gillilan et al., 2005; Jansson et al., 2005).

In conclusion, even though parameters are measured after restoration the usability of the results for future projects seems low. The reason for the lack of 'learning by doing' is mainly embedded in the too simple and too limited monitoring approaches, e.g. the lack of using CI or BACI designs and low frequent measurements. Investment in directed monitoring would make future projects much more successful and cost-effective. Moreover, the slowly but steady increasing number of monitoring data provides growing opportunities for meaningful syntheses of study outcomes and the establishment of efficient feedback of new findings from scientists to practitioners. Such outcomes could further strengthen monitoring efforts.

4. Discussion: trends in >40 years of lowland stream restoration and next steps

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 (Fig. 2, Table 1), they in fact solely focused on specific morphological (habitat improvement) or hydrological (flow) conditions, as was already observed two decades ago (Verdonschot and Nijboer, 2002; Palmer et al., 2010, 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 become 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 et al., 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;

Kuglerová et al., 2014; Tonkin et al., 2018). 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; Gabriele et al., 2013). On the other hand, it is not the small scale of a restoration project per se that limits restoration success, but rather the spatial mismatch between stressors and restoration, in combination with a lack of specific beforehand diagnosis of the actual limiting stressor.

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 (Fig. 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 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 (Fig. 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.

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 (Fig. 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 (Fig. 6B). Yet, these problems can only be tackled at a large scale (Violin et al., 2011; Kail and Wolter, 2011; Gabriele 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

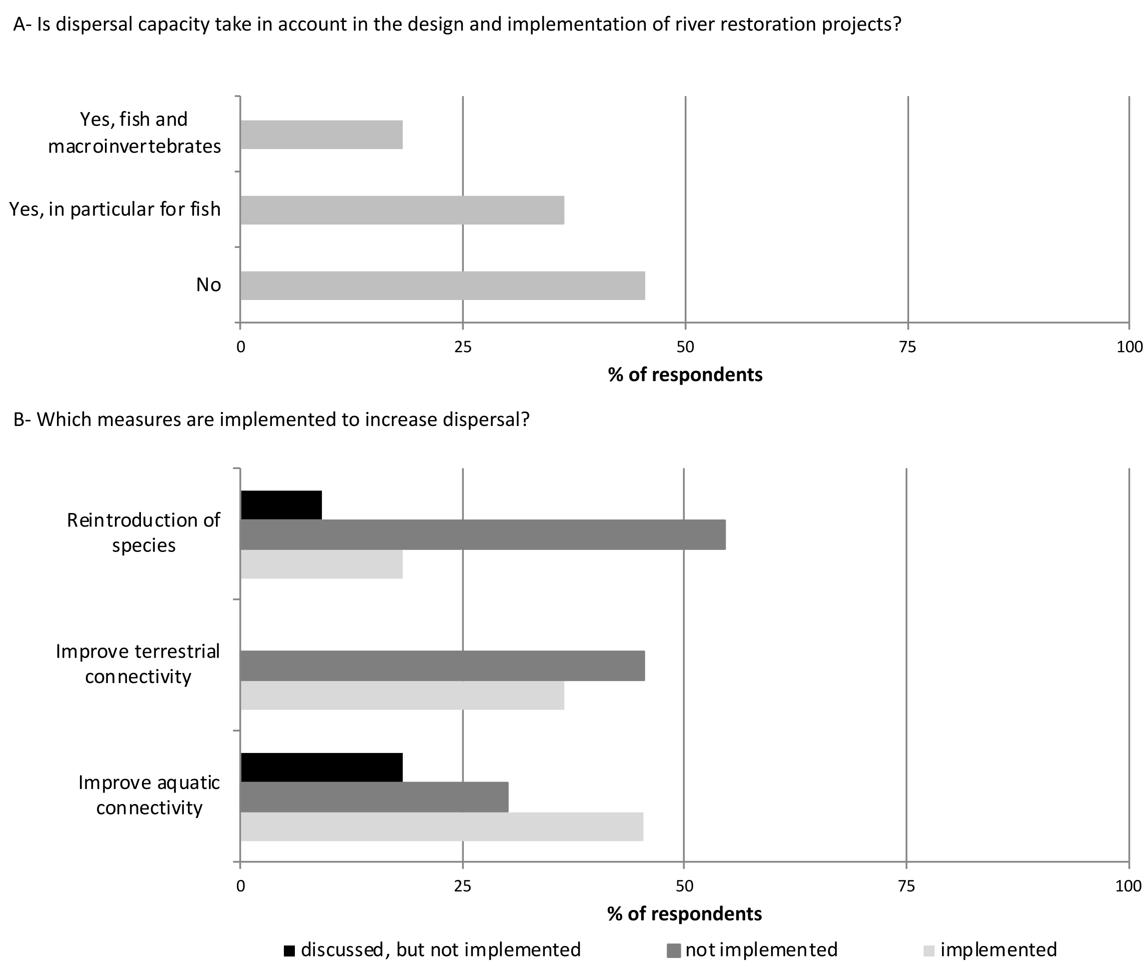

Fig. 5. Percentage of water authorities (n = 11) that took the dispersal capacity of aquatic organisms (macroinvertebrates and fish) into account (A). Percentage of water authorities that took measures to increase dispersal potential (B).

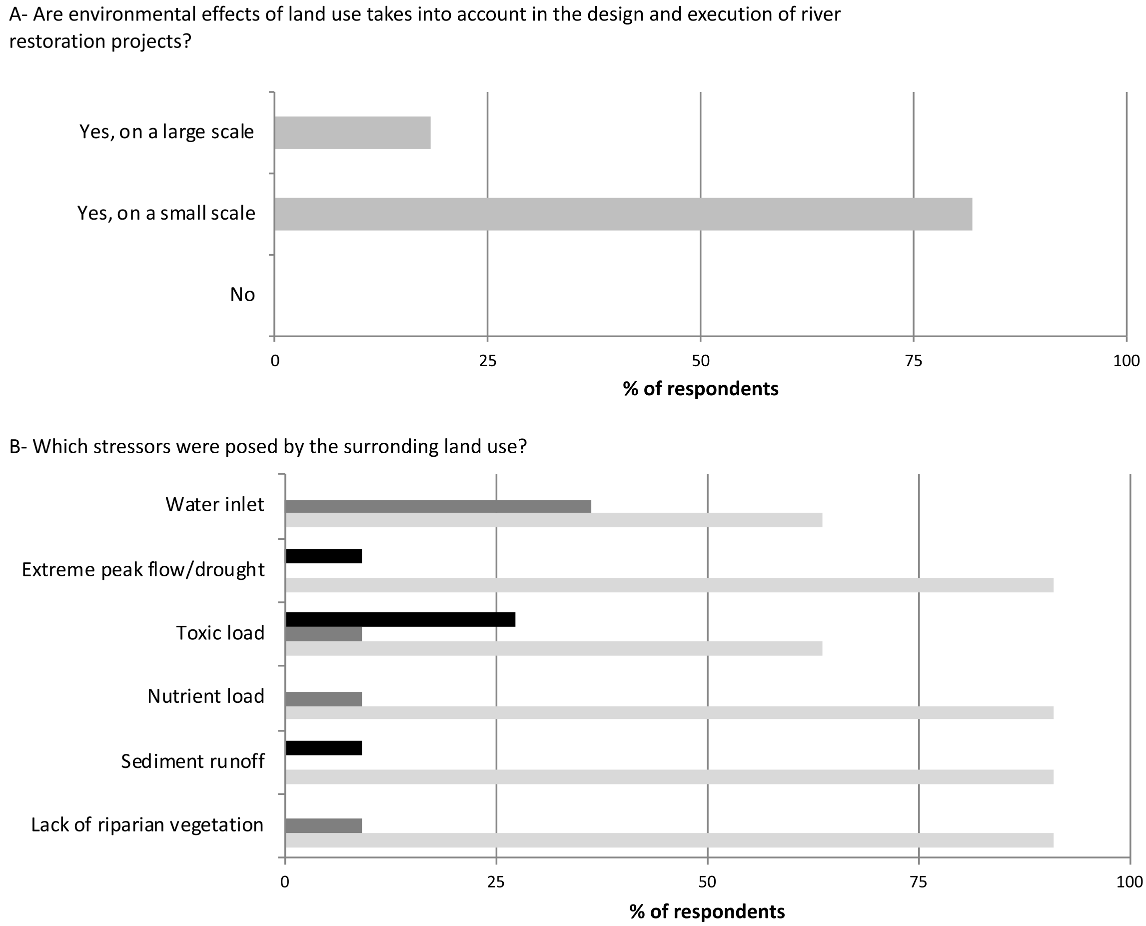

Fig. 6. Percentage of water authorities (n = 11) that took land use into account in restoration projects (A). Effects of surrounding land-use observed in restored stream trajectories (B).

impacts should receive much more attention.

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 programmes accompanying restoration projects by applying a 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. Secondly, we recommend to scale up the spatial scale of stream restoration projects from local instream efforts to catchment wide measures. Combined efforts of legislators, water managers and scientists can and will improve both legislation and implementation as soon as data-based knowledge on successes of stream restoration measures advances.

Author contributions

PCRO, JJW and PFMV designed the study. PCRO and JJW conducted the survey. PCRO performed the literature review. PCRO, JJW, PFMV, MK, HG and RCMV wrote most of the manuscript.

Declaration of competing interest

None.

Acknowledgements

We would like to thank the Dutch water authorities Waterschap Vallei en Veluwe, Waterschap De Dommel, Waterschap Peel en Maasvallei, Waterschap Vechtstromen, Waterschap Brabantse Delta, Waterschap Aa en Maas, Waterschap Rijn en IJssel, Waterschap Rivierenland, Waterschap Roer en Overmaas, Waterschap Hunze en Aa's and Waterschap Drents Overijsselse Delta for participating in the survey. PCRO received funding from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil (grant number 200879/2014-6, 2014) and JJW was funded by the Dutch foundation for applied water research (STOWA).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110417.

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