



Review Paper

The role of stream restoration in enhancing ecosystem services

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Abstract Striving for an integrated semi-natural stream-floodplain system as restoration target would optimally serve biodiversity and the provisioning of ecosystem services. This pursuit is currently limited by multiple pressures and constraints that come with, amongst others, a high human population density and intensive land-use. To be able to weigh the ecological and societal needs in lowland-stream watersheds, we analysed the developments in lowland-stream restoration in relation to the actual and potential state of ecosystems services these systems provide. To reach an ecological-societal balance in stream restoration, we pose five steps: (i) Choose a clear and realistic restoration target, (ii) Map and quantify environmental stressors at local to watershed scale, (iii) Map and

quantify biological indicators at local to regional scale, (iv) List potential restoration measures to remove or mitigate stressors, and (v) Build scenarios, composed of combinations of measures fitting the societal context of the watershed. The most promising scenarios make use of watershed processes and involve establishing a transverse landscape zonation, from the streams' riparian zone to the uplands. Such landscape transition poses a challenge for policy makers and implies a strong societal change. Therefore, a framework is provided with building blocks that help to find a suitable balance in practice.

Keywords Lowland stream · Stressor · Measure · Biological indicator · Zonation

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Introduction

Streams and their adjacent wetlands are highly valued ecosystems and are of major importance for local, regional, and global biodiversity as well as the provisioning of ecosystem services (Costanza et al., 1997). Ecosystem services were defined by the Millennium Ecosystem Assessment as benefits that people obtain from ecosystems (Reid et al., 2005). Streams are a renewable resource, providing services that have always been an attractor for human settlement and activity (Vörösmarty et al., 2005). Pressures by human activities upon these ecosystems increased,

especially the last centuries, which strongly degraded stream biodiversity and ecosystem services.

Recently, the answer to losses of ecosystem services and stream ecosystem degradation was the implementation of stream restoration measures. In the Netherlands, lowland stream restoration dates from the late sixties of the last century and accelerated after several important legislations and regulations were put in place in the Netherlands and Europe. The establishment of a National Ecological Network (Dutch Ministry of Agriculture, Nature and Fisheries, 1990) to protect and connect natural areas, the European (EU) designation of Natura 2000 sites to protect threatened species and their habitats based on the provisions of the Birds and Habitats directives (European Commission, 1992), and the European Water Framework Directive (WFD) established in the year 2000 (European Commission, 2000) to protect and manage water resources were leading. Recently, over 40 years of stream restoration in the Netherlands was evaluated on (i) the influence of policy goals on stream restoration efforts, (ii) the developments in biophysical restoration objectives and measures, (iii) the scale on which these measures were applied, and (iv) the monitoring efforts (Dos Reis Oliveira et al., 2020).

Ecological restoration can be defined as “the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed” (Balensiefer et al., 2004). To this definition, Aronson et al. (2006) added that ecological restoration is a process that recovers and improves the functionality of ecosystems within landscapes, consisting of both agricultural land, urbanized areas, and set-aside nature reserves. When implemented in densely populated areas, like in the Netherlands and other lowland areas in the western European plains, restoration recovers, and improves the functionality of lowland stream ecosystems within intensively used agricultural and urbanised landscapes. Such lowland stream ecosystem recovery augments biodiversity and ecosystem services at the landscape scale and includes humans as integral members of the system. Thus, stream ecosystem restoration is concerned with the full gradient of protected natural areas towards environments where people live, grow food, and extract natural resources and everything in between.

Faced with the rapidly growing pressures on the stream environment, sustainable stream ecosystem restoration clearly plays a key role in biodiversity

protection and services recovery as well as improving human well-being (van Anandel & Aronson, 2012). But in a human-inclusive restoration approach the natural, original, or reference approach must be brought in balance with the anthropogenic socio-economic system. The question is how to combine biodiversity, ecosystem services, and users' functions into one sustainable framework and methodology. Therefore, the aim of this paper is to provide an overview of the key ecosystem services provided by lowland streams, and to discuss challenges and opportunities for sustainable ecosystem recovery by integrated stream, stream valley, and stream watershed restoration aiming at both biodiversity and ecosystem services.

Degradation

Lowland streams occur, amongst others, in the lowland areas of the Western European plain. They are characterised by a low gradient (slope 0–5‰), a current velocity of 5–30 cm/s in summer and early autumn and 30–60 cm/s in late autumn to spring. The streams width and depth ranges on average between 0.5–20 m and 0–1.5 m, respectively and the substrate mainly consists out of sand and fine and coarse particulate organic material. They are mainly fed by rain- and groundwater, and often lack a well-defined source, though sometimes they are fed by a more or less diffuse source area and then show a more constant discharge pattern (Verdonschot, 1990). Their discharge shows a smoothed relation with the amount and frequency of precipitation in the various seasons. The streams are accompanied by trees that provide shade which reduces daily maximum water temperatures, input of organic material, and physical structure in the form of roots and dead woody debris. In the Netherlands, lowland streams occur in both the eastern and southern part of the country (Verdonschot & Nijboer, 2002).

Until the Middle Ages, impact of human activities on the streams and their valleys was limited and consisted of timber harvesting, fishing, and hunting. The lowland streams were often difficult to reach because they were fringed by wet, peaty valleys or extensive peat bogs. Most streams ran through such swamps and marshes, creating a mosaic landscape with permanent and temporary pools, secondary stream channels, and cut-off meanders. Streams that

cut into relatively drier areas, often elevated aeolian sand depositions, developed a meandering course due to trees temporarily fixing and, when falling over, changing the course of the stream (Higler, 1993; Eekhout, 2014). During floods, fine sand and silt were deposited in the floodplains, which initiated a highly diverse vegetation mosaic and a high faunal diversity in the stream valleys.

Since the Middle Ages, lowland streams were diverted, new channelized waterways were dug to power watermills (e.g., which were used for sawing, grain grinding, drainage for mining sites, and production of brass, textile, needle, oil) (Esser et al., 2020), to provide water for washeries and streams were diverted to higher parts of the valley for irrigation and natural fertilisation of the lower valley meadows. There are estimations that about two-third of the streams currently present have been dug (Baaijens et al., 2011). Stream valley swamps were drained and reclaimed, and riparian forest was logged. In watersheds, where extensive bogs and bog complexes were drained, its associated streams disappeared. The hydrology of the watersheds and the morphology of the streams gradually changed, leading to ecosystem degradation (Baaijens et al., 2011). Still, the landscape of around 1900 is considered appealing for many biologists, mainly because of its species richness and patchy landscape with small-scale heterogeneity. Therefore, until recently this landscape was used as reference in policy documents (Hertog & Turnhout, 2018).

One of the main causes for the subsequent large-scale changes to the Dutch stream valley landscape was the introduction of fertilizers during the twentieth century. From that moment on, agricultural practices intensified and expanded. Together with an accelerating population growth, hydromorphological degradation, eutrophication, and pollution of the Dutch streams strongly increased. Up to the nineties of the last century streams were modified by channelisation of the longitudinal profile and normalization of the stream channel, and regulation of the water level by weirs. This strongly reduced the length of the streams, homogenised the streambed and shape, and increased flow dynamics, with more and longer periods of drought and extreme floods (Eekhout, 2014). The first channelization took place in the nineteenth-thirties in the lower courses, in the sixties the middle courses were altered and in the seventies to nineties

the (small) upper courses were impacted. In the nineties of the last century, only about 4% of the Dutch lowland streams was still in a near natural state (Driessen et al., 1998).

Restoration

Early developments in stream restoration in the Netherlands, over the period of 1960–1998, were evaluated in 2002 (Verdonschot & Nijboer, 2002) and the later periods were summarized by Dos Reis Oliveira et al. (2020). Several surveys were held amongst regional water authorities, provincial governments and nature conservation organisations. Between 1960 and 1990 about 70 projects were counted, from 1990 and 1993 170 projects and this number increased until 1998 to 206 projects (Table 1). Most of the early stream restoration projects focused on water quality improvements and reforestation of the stream banks. The first mainly dealt with installing and improving wastewater treatment plants (WWTPs) and the second on planting riparian trees (Landesamt für Wasser und Abfall, 1989). None of the projects directly stated to improve ecosystem services, despite that pollution reduction can be considered a measure to enhance human wellbeing and bank revegetation no doubt contributes to the improvement of several services, such as bank erosion control, improved aesthetic values, and climate regulation (for a full overview see Riis et al., 2020). WWTP operation had a huge effect on the ecological quality of many streams, decreasing the organic pollution. Replanting the stream banks, later accompanied by the re-profiling of the streambed, concerned measures that were mostly carried out at a local scale, limited to at most a stream length of several hundreds of meters, concentrated in the middle courses and often located in nature reserves (Verdonschot, 1995). From the early 1990s on, restoring the morphological features of the streams' length profile became more and more important. Most projects included some form of re-meandering, by digging bends which followed the path of the historic stream, and creating asymmetric transversal profiles representing the typical asymmetric erosion-sedimentation profile in a bend. In the nineties, local residents more and more became involved in restoration projects and those morphological changes added to the improvement of cultural services, like aesthetic values

Table 1 Percentage of streams in which a measure was undertaken in the time periods of before 1993, 1993–1998, 1999–2003, 2004–2008, and 2009–2015. Per measure the major

parameter group, the spatial component and the parameter group upon a measure sort effects are indicated

Major parameter	Spatial component	Parameter group	Measure	to 1993	1993–1998	1999–2003	2004–2008	2009–2015
Hydrology	Stream channel pattern		Reconnect sub-catchments				30	
			Restore original stream channel pattern		25	5	5	39
	Catchment	Groundwater	Promote rain water infiltration	0	32	4	7	10
			Raise ground water level				44	30
			Retain water in drainage ditches by weirs				2	3
			Raise drainage base				51	31
			Remove drainage structures	21	32	4	23	18
	Floodplain	Water retention	Reduce water extraction	3	7	6		3
			Re-use purified wastewater effluent		4			
			Improve water buffer zones		21	8	13	16
			Rehabilitate floodplain flooding	17	36	23	40	45
			Increase water retention capacity	14	54	33	39	17
	Stream channel	Water level	Natural water level management				14	25
			Remove weirs and barriers (free flow)	14	29	10	31	54
	Morphology	Floodplain	Floodplain structure	Develop forest	14	36	12	
Riparian zone		Floodplain structure	Allow riparian vegetation development					7
			Riparian structure/Water retention	Lower stream banks to enlarge wet banks			8	80
			Create small floodplain wetlands				33	53

Table 1 (continued)

Major parameter	Spatial component	Parameter group	Measure	to 1993	1993–1998	1999–2003	2004–2008	2009–2015
			Lower level adjacent mowing field	3	32	15	32	67
			Create nature-near banks			7	27	32
			Create wetland banks				22	14
			Create a two-stage profile	38	21	17	8	40
			Develop woody riparian vegetation	45	43	30	48	80
		Habitat	Dig isolated pools		46	22	30	60
			Dig one-side connected backwater				2	20
			Create fish winter refuges				16	33
	Stream channel	Longitudinal profile	Allow to remainder		21	5	5	35
			Dig new meanders	38	57	37	80	54
			Restore the former streambed			7		35
			Create a (semi) natural stream bed				25	46
			Install bypasses	3	21	10	3	32
			Reconnect backwaters	4	25	8		36
			Initiate micromeanders		14	4	16	32
		Transversal profile	Channel re-profile (shallowing, narrowing, widening)	7	46	13	80	55
			Create a (semi) natural stream bed		36	10	70	50
			Create steep and overhanging banks	3	18	3	16	38
			Remove bank fixation	17	25	12	14	54

Table 1 (continued)

Major parameter	Spatial component	Parameter group	Measure	to 1993	1993–1998	1999–2003	2004–2008	2009–2015	
Chemistry (water quality)	In-stream	Stream bottom	Enhance in-stream wood debris and gravel beds					6	
			Install pool sequences or pool-riffle units	4		1	16	9	
			Enhance in-stream structures (objects)	17	4	3	3	45	
			Install species specific structures		4	2		12	
	Stream channel pattern	Pollutants flow	Separate wastewater flows	7	18	4			
			Separate agricultural and natural flows				3	15	
		Floodplain	Filter function	Construct buffer zones	7	21	10	18	25
		Riparian zone	Filter function	Construct helophyte filters/horse-shoe wetlands	7	4	2	2	
				Create horse-shoe wetlands		4	1		
				Reduce fertilizer runoff input	10	21	6	7	17
				Reduce toxic load (runoff)				16	4
				Change land uses				33	24
		Stream channel (point sources)	Pollutants	Reduce sewage storm overflows	7	18	3	2	4
				Reduce inlet of non-local water				2	10
Reduce sewage storm overflows	14			18	10	3	4		
Improve wastewater treatment				4	2	3	13		
In-stream	Pollutants	Dredge the stream bottom			2		18		
		Reduce the load of micropollutants	7	19	1				

Table 1 (continued)

Major parameter	Spatial component	Parameter group	Measure	to 1993	1993–1998	1999–2003	2004–2008	2009–2015
Maintenance	Riparian zone	Vegetation	Introduce grazers (mammals on stream banks)				24	6
			Nature-near bank vegetation maintenance				40	21
			Bank vegetation management				17	
	In-stream	Vegetation	Extensive maintenance (macrophytes)				91	9
			Nature-near aquatic vegetation maintenance				25	21
			Phase dredging					
Biology	In-stream	Substrate	Specific measures to conserve or initiate recovery of species populations				9	23
		General	Re-introduce species	10	7	1	1	6
Biology	In-stream	Fish	Fish friendly management near weirs, sluices and barriers				3	1
			Facilitate fish migration (bypass, ladder)	31	50	18	80	58
		Fish/Algae	Active biological control				1	

and recreation and education. The latter became especially recognised when interpretive signs were placed to inform the public about the values and biodiversity of streams.

Over time, and especially after the legislation of the Water Framework Directive became in place in 2000 (European Commission, 2000), the number of restoration measures increased (<1993 n=27, 1993–1998 n=6, 1999–2003 n=40, 2004–2008 n=53, 2009–2015 n=57). In the last period, the measures that were taken in >50% of the projects

were the removal of weirs and other barriers (free-flowing streams), creating small floodplain wetlands, sod removal for bank and valley restoration, woody riparian vegetation development, excavation of isolated pools (as reproduction habitat for amphibians), digging new meanders, re-profiling of the stream channel (shallowing, narrowing, widening), create a (semi) natural stream bed by adding substrates such as dead woody debris and gravel beds, and facilitating of fish migration (bypasses, fish ladders). Most of these measures not only focused on the in-stream

characteristics, but also included the streams' floodplain. Fish connectivity was the far most important focal point. In combination these measures were likely to be successful in improving—at least in theory—the ecological quality, meaning the quality of an ecological system, in terms of biological, physical, and chemical conditions and of environmental integrity. In practice, due to the local scale of the measures realized and because individual measures were taken instead of combinations of measures which tackled the major stressors, ecological improvement was hampered.

The WFD aims to harmonize the legal framework of water policy in the EU and to strengthen the orientation of the water policy towards a sustainable and environment-friendly use and environmental protection of surface waters. These aims imply several benefits that reflect a number of ecosystem services. For lowland streams, these services concern improvement of drinking-water quality for cattle, drought and flood prevention, recreation and amenity value, enhancement of biodiversity, and bringing more balance between interests among different social groups, like citizens and rural residents. Vermaat et al. (2016) used indicators of ecosystem services to assess the success of river restoration, including the Dutch river Regge. The authors quantified provisioning (agricultural products, wood, reed for thatching, infiltrated drinking water), regulating (flooding and drainage, nutrient retention, carbon sequestration) and cultural (recreational hunting and fishing, kayaking, biodiversity conservation, appreciation of scenic landscapes) services for separate habitats within each stream reach, and summed these to annual economic value normalized per reach area. Vermaat et al. (2016) concluded that the total ecosystem service value was significantly increased in the restored reaches.

Ecosystem services of (near-natural or restored) lowland streams,

lowland stream networks and their catchments provide numerous services that are essential to sustain ecosystems and human populations (Peterson et al., 2001; Yeakley et al., 2016; Colvin et al., 2019) (Table 2). The Millennium Ecosystem Assessment identified four broad categories of ecosystem services, including provisioning, regulating, supporting, and cultural services (Millennium Ecosystem Assessment, 2005; Costanza et al., 2011; Milcu et al., 2013) (Fig. 1).

Provisioning services refer to material or energetic outputs from ecosystems, such as food, water, timber, and other resources. Food or crop services include the production of agricultural products, such as grains, vegetables, fruits, and grass to support livestock. Increasing agricultural production on intensively managed farmland caused a decline in, amongst others, water and air quality, erosion regulation, nutrient cycling, biodiversity, and landscape quality and as such negatively impact biodiversity (Maréchal et al., 2008; Pilgrim et al., 2010). On the other hand, traditional, extensive, low-input agricultural production was and is mostly valued for its cultural and landscape quality and can be rich in biodiversity. In-stream provisioning services in lowland streams refer to fisheries (e.g., salmonids), which over the last century changed dramatically from providing food (provisioning service) to having an important recreational value (cultural service; Welcomme, 1998). Besides fishing, which was and still is important, until the end of nineteenth century crayfish *Astacus astacus* (L.) trade and consumption was also common in Europe (Pöckl, 1999). In the twentieth century, distribution and population density decreased significantly because of the crayfish plague (*Aphanomyces astaci* (Schikora 1903)), habitat deterioration and fishing (van Kuijk et al., 2021). Floodplain and riparian rehabilitation, including the restoration of natural flood regimes, dam removal, reduction of sediment loads through erosion protection, instream habitat improvements, and reconnection of isolated habitats have proven effective for improving habitat and increasing local fish abundance (Roni et al., 2008).

Peat formation was widespread in lowland stream valleys, ranging from wetlands with sedges and reeds to alder swamps. Peat excavation for fuel and draining of wetlands to reclaim land resulted simultaneously in a loss of other ecosystem services, like flood prevention and water storage, nutrient and contaminant retention, carbon fixation and storage, feeding grounds for fish, hotspots for biodiversity, and decreasing the diverse gene pool (de Groot et al., 2002).

Another important group of provisional services comprises the domestic, industrial, and agricultural use of water. Increasing human water demands, in the form of water abstractions and intensive drainage, resulted in lowered groundwater levels and decreased recharge levels. This has resulted in periodic droughts

Table 2 Classification of ecosystem services with examples from lowland streams including degradation by human activities, opportunities and needs for restoration of services, and their services indicators

Service	Activity	Degradation	Opportunity	Needs	Service indicator
Provisioning services					
Food / crop	Fisheries (e.g., fish, crustaceans)	Loss of the indigenous crayfish <i>Astacus astacus</i> . Manipulation of natural fish communities by stocking	Regaining natural fish communities and potential niches for crayfish	Natural stream function and connectivity with the floodplain	Yearly yield of commercial beneficial key species or their abundances
Fiber (timber)	Wood production (coppice)	Water level regulation and vegetation management	Restoring wetland forest in the floodplain	Large floodplain area	Surface area of forest under sustainable management and timber yields
Peat formation	Peat extraction as energy source	Most peat is excavated and peat growth has stopped	Floodplain wetlands store carbon and initiate peat formation	Large area with intact floodplain functioning	Surface area of wetland with C-storage potential
Effluent purifier	Purifier of enriched waste water	Reduction of purification capacity	Last purifying step of treated waste water	Floodplain and riparian zone (helophyte filtering)	Ecological water quality
Domestic water use	Drinking water withdrawal	Groundwater lowering and stream intermittency	Clean water implies drinking water extraction from streams in downstream areas	Healthy* stream valley ecosystem	Ground water quality and sustainable available quantity
Industrial water use	Process water withdrawal	Groundwater lowering and stream intermittency. Pollution by laundries, extraction by breweries	Circularity within industrial facilities	Legislation	Chemical surface water quality
Agricultural water use	Irrigation water withdrawal	Groundwater lowering and stream intermittency. Nutrients and toxic substances load	Provision of sufficient clean water	Large area with intact floodplain functioning	Chemical surface water quality and sustainable available quantity
Regulating services					
Self-purification	Maintaining of water quality by natural filtration and nutrient retention, detoxification	Reduction of land-water zones, shallow banks and wet profiles by channelization and intensive land use in flood plains	Improving self-purification capacity by intact community functioning	Large riparian and floodplain zones with (partly) managed zonation to improve filter functioning	Healthy ecological functioning
Flood control (buffering)	Retention capacities of riparian zones, wetlands, and buffering of flash floods	Buffering capacities harmed by disconnection of stream and floodplain and water level regulation	Preventing floods and droughts	Large floodplain area	Number, frequency and magnitude of floods and droughts

Table 2 (continued)

Service	Activity	Degradation	Opportunity	Needs	Service indicator
Land–water-interactions	Groundwater recharge, transition zones between terrestrial and aquatic ecosystems	Loss of wet riparian and floodplain zones and land–water transitions	Restoring land–water interactions functioning with high biodiversity. Contributing to ground water recharge, infiltration rate and retention capacity	Intact floodplain functioning	Degree of connectivity with the floodplain
Erosion-sedimentation regulation	Floodplain and bank protection, reduction of siltation	Increased erosion led to incision of the streambed	Restoring the erosion-sedimentation balance by watershed measures	Watershed scale hydrological balance and moderate dynamics	Floodplain area protected against soil erosion and peak flows (see flood control)
Climate regulation	Cooling in summer, warming in winter and reducing temperature, humidity and runoff variations	Loss of wooded riparian and forested floodplains	Restoring physical land–water interaction functioning	Large floodplain and swamp areas area	Area of wooded riparian and forested floodplain
Diseases and pest regulation	High biodiversity resists occurrence of diseases and pest species	Loss of biodiversity resulted in occurrence of diseases and pest species,,	Reduction of coliforms and other pathogens, and invasive species	Improvement of water and habitat quality at floodplain scale	Yearly infection rates
Cultural services					
Recreation and tourism	Recreational areas, canoeing, fishing	Loss of natural landscape is loss of tourism. Risk further degradation by physical pressure and overfishing, fish population mismanagement	Regional economic value by monetary return, aesthetic value and healthy fish	Large mosaic-like restored landscapes	Recreational and tourism economic benefits
Aesthetic values	Aesthetic landscape elements	Full loss of values of beauty and appreciation of landscapes and heritages	Appreciation and valuation by the public	Large mosaic-like restored landscapes	Survey under residents on perception and use
Spiritual and religious values	Sacred springs, environmental stewardship	Full loss of values	Appreciation and valuation by the part of the public	Natural functioning of specific elements, like spring areas	Survey under residents on perception and belief
Cultural heritage and identity	Cultural heritage, identity and place attachment	Change of appreciation and loss of values	Appreciation and valuation by public and especially local residents	Restored landscape elements and visual objects	Qualitative interviews and photo elicitation

Table 2 (continued)

Service	Activity	Degradation	Opportunity	Needs	Service indicator
Educational values	Education activities by schools, universities and information exchanges for stakeholders (farmers, NGOs, water managers and so on)	Loss of educational examples of well-functioning stream valley ecosystems and landscapes and biodiversity experiences	Knowledge on, appreciation of and valuation by the public, stakeholders and students	Large mosaic-like restored and natural functioning landscapes	Number of educational programmes
Cultural heritage	Water mills, historic water works, flow fields	Loss of historical values	Knowledge on, appreciation of and valuation, and fitting in future functioning	Local adaptations in the landscape or constructions	Inventory of historical 'objects'
Supporting services					
Water cycling	Water storage in ground-water, retention structures like wetlands and retarding discharge	Loss of storage and retention capacity by increased downward flow	Re-installing storage and retention capacity of the watershed, floodplain and stream	Intact watershed, floodplain and stream functioning	Retention time in the catchment (water balance)
Soil formation	Soil formation and fertilization by sedimentation in riparian zones and managed floodplain flooding	Loss of natural flooding with sedimentation-erosion processes, exchange of materials (loss of spiraling functioning)	Connecting stream and floodplain	Intact flood plain functioning	Soil condition
Nutrient retention and cycling (spiraling)	Nutrient (temporary) storage in rivers and riparian and floodplain zones, nutrient spiraling in rivers	Disconnection of stream and riparian and floodplain zones. Loss of physico-chemical processes in the land–water interface	Connecting stream and floodplain and re-installing nutrient spiraling and sedimentation-erosion processes	Intact and interacting stream, riparian and floodplain communities over large areas	Nutrient balance
Provision of habitat	High habitat variability in a mosaic of structural gradients	Great habitat loss by altered land and water uses	Restoration of habitat variation by restoring multiple gradients in the landscape resulting in high biodiversity	Intact watershed and or floodplain functioning	Structural heterogeneity
Biodiversity and food web dynamics	High niche diversity and species richness, ecosystem resilience and resistance	Loss of niche variation by hydrological, morphological and chemical homogenization	Restoration of niche variation by restoring multiple gradients in the landscape resulting in high biodiversity	Intact stream, riparian zone and flood plain functioning	Indices of biodiversity and food web structure

'Ecosystem health' is defined as the state of an ecosystem relative to a desired management target or reference condition

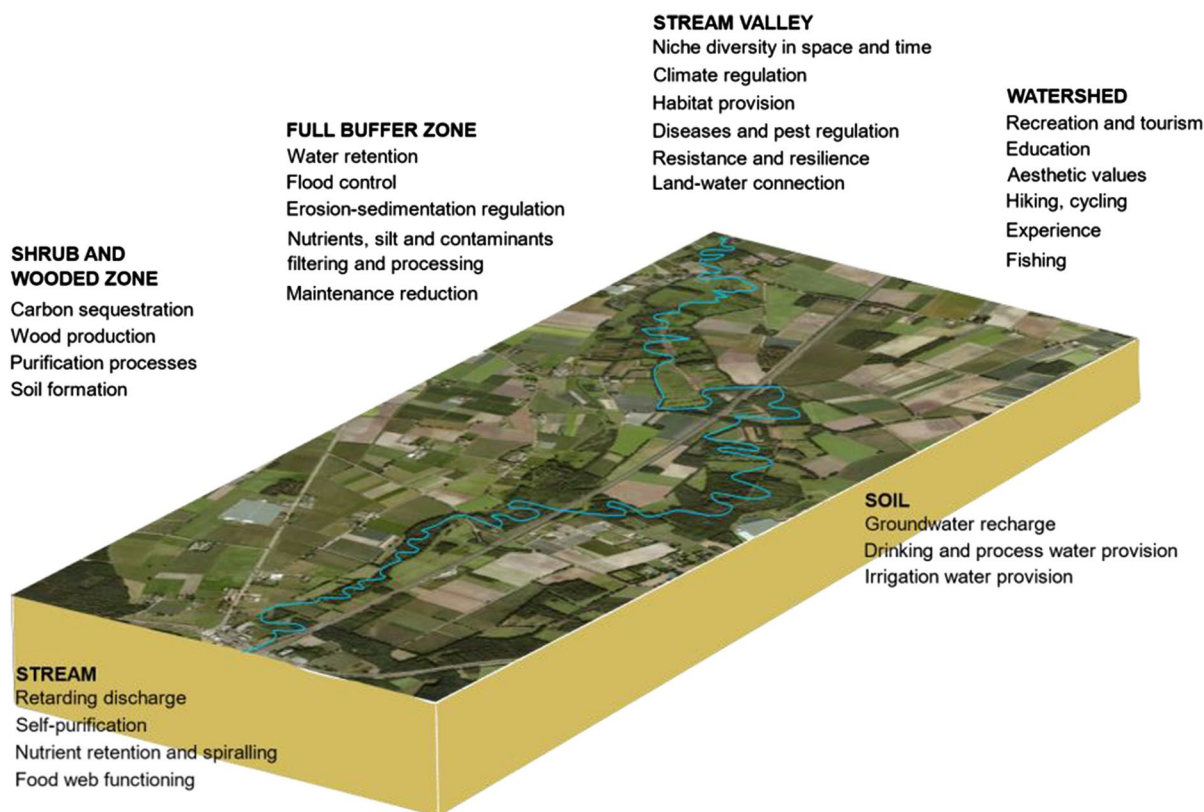


Fig. 1 Ecosystem services in a lowland stream watershed

(van Lanen & Peters, 2000) and flow intermittency (García and Pardo, 2016; van Huijgevoort et al., 2020). To restore lowland groundwater systems and the services they provide, measures must be implemented to increase the storage in the elevated parts of the watersheds to improve infiltration rates, which often involves changes in land use (Querner et al., 1997; Gehrels, 1999).

In summary, agricultural services contributed to degradation and will decrease by floodplain restoration. On the other hand, some services, like fisheries, (ground) water safety, availability and use, water purification, and peat development will benefit from restoration.

Regulating services refer to factors that the ambient environment provides, such as flood control, erosion-sedimentation regulation, climate regulation, land–water-interactions, self-purification, and diseases and pest regulation. In the Netherlands, lowland stream channel modifications and stream valley wetland drainage had severe negative

consequences for the stream and stream valley ecosystem functioning, of which the loss of land–water interactions had a major impact (Verdonschot & Nijboer, 2002). Hydrological services, such as flood control, erosion-sedimentation regulation, and climate regulation diminished. Weirs were installed to mitigate the effects of drainage during periods of low flows. They were closed to increase groundwater levels but resulted in low-flow velocities or even stagnant conditions in the streams. Consequently, fine sediment (e.g., silt) was deposited on the streambed, resulting in coverage of mineral sediments and a deteriorating water quality (Eekhout et al., 2015). During high flows, weirs were lowered, and flow velocities increased dramatically in the channelized stream channels causing channel incision and the disappearance of heterogeneous in-stream habitat mosaics (Eekhout & Hoitink, 2010). To restore these regulating services, hydrological measures are necessary to rehabilitate the moderate

discharge dynamics, which were historically present in undisturbed lowland streams.

Another regulating service of streams and their floodplains is self-purification. The biological activity of fungi, bacteria, plants, and animals, as well as the dilution and mixing processes provide a high self-purification capacity (Heidenwag et al., 2001). Self-purification is defined as the summary of all physical, chemical, and biological processes by which the quantity of the load, in terms of dissolved nutrients or substances such as organic matter, a stream receives is decreased. The biodegradation of organic substances up to mineralisation, nitrification, and denitrification leads to self-purification in streams. The assimilation of the dissolved organic substances and nutrients in the water is more effective in natural stream stretches than in regulated stretches (Šaulys et al., 2020). Furthermore, physical habitat features enhance self-purification capacity, like the extend of the contact zone between water and sediment. Permanent nutrient sinks and temporary nutrient storage in stream valley systems represent an important component of watershed nutrient budgets (Kronvang et al., 1999). Therefore, the latter authors advised that watershed management measures, such as nature restoration at the watershed scale, can help to combat diffuse nutrient pollution.

Finally, large water level fluctuations, droughts, and eutrophication associated with disturbed stream ecosystems are linked to the occurrence of nuisance and vector-borne disease transmission by mosquitoes (Hubálek & Halouzka, 1999; Patz et al., 2004; Schäfer et al., 2008). Undisturbed stream valleys with stable hydrodynamics, resulting in large permanently wet areas hosting a diverse community of predators that prey on the immature stages of mosquitoes, often produce few to no mosquitoes and are the most source-oriented strategy to combat mosquito-borne diseases (Barik, 2015).

In summary, in the past water management mainly focused on water quantity, like flood and drought control and erosion-sedimentation regulation, which contributed to strong degradation. But those former highly prioritized regulating services will together with climate regulation, land–water-interactions, self-purification, and diseases and pest regulation, all benefit from stream restoration.

Cultural services refer to the non-material uses of stream valley landscapes, such as aesthetic, spiritual,

religious, identity, recreation and tourism benefits, educational values, and cultural heritage (Garcia et al., 2017). The human perception of the stream landscape engages people and decides on their valuation and support (Gobster et al., 2007; Do, 2019). Local residents can have a strong psychological, symbolic, and emotional association with a landscape and identify themselves with their environment. Furthermore, the aspect functional attachment is directly related to social placement. Including these human-nature relationships in restoration helps to address the need for nature and biodiversity recovery amongst stakeholders (Toivonen et al., 2019).

Recreation enhances the health and quality of human life and generates value for both stream valleys and its tourism (Yeakley et al., 2016). Often not the natural but the park-like landscapes are seen as areas that can simultaneously provide numerous recreational opportunities, like hiking, jogging, biking, and wildlife viewing, and still conserve biological diversity (Miller & Hobbs, 2000).

A stream and its valley can function as an important educational element within a region. Through outdoor visits and observations these landscapes can create awareness of water quantity, water quality and biodiversity issues. Education raises the awareness of those issues and contributes to a future sustainable human attitude.

Landscapes providing a high variety in cultural services were best developed before the introduction of artificial fertilizers and agricultural intensification. In the second half of the twentieth century, agricultural intensification more or less fully homogenized the stream valley landscapes, resulting in a major loss of cultural services (Tanentzap et al., 2015).

In summary, channel straightening, removal of riparian vegetation, and landscape transformation to agricultural land and urban settlements, diminished most cultural services. Restoration of the floodplain landscape brought most cultural services back and restored the public awareness that nature is not a cattle-grazed meadow but a highly diverse and structured lowland floodplain landscape where trees dominate.

Supporting services refer to the maintenance of life-supporting conditions, such as water cycling, soil formation, nutrient retention and cycling, provisioning of habitats and biodiversity, and food web dynamics. In low-gradient floodplains, deeper groundwater

flows control the streams' baseflow, resulting in more or less stable flow conditions during dry periods. Surface and subsurface flows create discharge peaks in response to heavy precipitation events. The variability in intensity, timing, and duration of precipitation in combination with the terrain-slope, soil texture, and evapotranspiration define the streams' hydrograph. In undisturbed situations in areas dominated by sandy soils, this hydrograph is flattened, and responses to storm events are slow due to the water storage and retention in the soil and floodplain swamps and marshes, respectively (Poff et al., 1997; Dosskey et al., 2010; Gericke et al., 2020).

Disturbance of the natural floodplain vegetation, lowering of the groundwater table and increasing the surface and subsurface runoff by, amongst others, drainage results in a more dynamic hydrograph and causes disruptions in the natural water cycle. Agricultural land use increases surface and subsurface flow, which is even further accelerated by the installation of drainage structures such as tile drainage and drainage ditches. Organic matter rich soils do increase the water retention in sandy soils and slow down runoff (Rawls et al., 2003). Lowering the subsurface and surface runoff by removing drainage structures and promoting vegetation development, e.g., by the application of buffer strips, strongly increases the nutrient retention capacity of a stream valley (Vought et al., 1994) and vegetation extends the nutrient spirals due to absorption and transformation, but also because of lower water temperatures resulting from shading effects.

The downstream transport of nutrients is described as spiralling and describes the ability of a stream to utilize nutrients during the cycle of uptake, transformation, and release. Spiralling length, then, is an index of the utilization of nutrients originating from the surrounding watershed. This concept incorporates both reuse and retention and provides an approach for relating downstream fluxes to instream metabolic activity (Newbold et al., 1981). Restoring the retention capacity of the stream floodplain will 'tighten' the spirals and increase its nutrient retention capacity.

From all supporting services touched upon above, it becomes clear that they are all connected to the presence of a relatively large-scaled natural or near-natural landscape, especially the presence of floodplains and stream stretches with a high variety of habitats. These systems do not only host a wide variety

of ecosystem services, but also hold high biodiversity and complex food web dynamics. On the landscape-scale, natural streams and their valleys exhibit a distinct transversal hydrodynamic gradient, spanning from the main stream channel, via wetlands with different types of inundation regimes to the high and permanently dry higher areas on the slopes of the stream valley. On the local scale, micro-topographical and -geomorphological variation result in a mosaic of hydromorphological and chemical gradients, which guarantees a wide variety of habitats, in space and time, created by the dynamic interaction of water, sediment, and biota, ultimately leading to high biodiversity (Runhaar et al., 1997; Silvertown et al., 1999; Ward et al., 2002).

In summary, loss of the natural floodplain vegetation and lowering of the groundwater table for agricultural and urban development resulted in a degraded hydrograph and disturbed water cycle. Especially, restoration of wide floodplains with long lateral gradients will enhance supporting services, such as a more balanced water and nutrient cycling and retention, improvement of floodplain soil formation, and last but not least provisioning of habitat and biodiversity, and improved food web dynamics.

Lessons learned

After the turn of the century, the demand for stream restoration increased rapidly due to legislation, such as the European Water Framework Directive, especially in densely populated areas with intensive agriculture, like the western European lowlands. Despite the multitude of lowland stream restoration projects success rate turned out to be low (Louhi et al., 2011; Pander & Geist, 2013; Nilsson et al., 2015; Dos Reis Oliveira et al., 2020). The main causes for this setback were:

- (i) The lack of specific objectives considering the demands of society (Palmer et al., 2014).

For a long time, the ultimate restoration goal or point at the horizon for any stream restoration project was a near-natural, pristine, or original state, or a 'wildland' (Palmer et al., 2005). In densely populated areas with intensive agriculture, such as the Netherlands, this goal looked more like striving for the historical

range of variability (cf. Morgan and Collicutt, 1994) or to maximise biodiversity or valued species (Feld et al., 2011). More recently, functioning and process thinking become more on the foreground (dos Reis Oliveira et al., 2020) and supports both the need for and potential achievement of multiple ecosystem services. A balance between restoring the structure and functioning of lowland streams and creating conditions which meet the societal needs, in terms of ecosystem services, is needed (Dufour & Piegay, 2009; Suding, 2011; Palmer et al., 2014).

- (ii) Proper monitoring of the effectiveness of the measures was often lacking (Kondolf & Micheli, 1995; Suding, 2011; Dos Reis Oliveira et al., 2020).

Effective lowland stream monitoring should include: (i) clear and specific objectives that are mutually compatible; (ii) an on forehand defined monitoring and evaluation design, preferably a Before-After-Control-Impact (BACI) design that supports scientifically sound impact evaluation and excludes autonomous developments; (iii) post-project measurements to account for time-lags in biological processes, e.g., at least a decade; (iv) and an adaptive attitude, including willingness to acknowledge failures, that facilitates post-project adjustments to keep developments on track (Kondolf, 1995). Only then lessons can be learned and generalised to the benefit of future projects, which does not mean that all projects should be monitored according to this design, but sufficient case studies to build a reliable knowledge base on restoration effectiveness. The observation by Palmer et al. (2005) that ecological success rates were markedly below the success rates self-reported by the project contacts are worrisome in this context (Alexander & Allan, 2007). For both monitoring of biodiversity and ecosystem services, respectively target species and desired services indicators—that are preferably directly linked to the objectives of the project—need to be included in such monitoring programs.

- (iii) A mismatch between ecological restoration goals and restoration measures, as the latter are still mainly focused on (hydro) morphol-

ogy, without considering the often-occurring impacts of multiple stress.

The ghost of the ‘Field of dreams’ hypothesis (Palmer et al., 1997) still haunts. Small-scale measures aiming at improving habitat structure, e.g., installing large dead wood patches, create gravel bars, or reprofile banks are relatively easy to apply without interfering too much with other societal and economic interests, like water quantity management for water safety and availability, and agricultural production. Both major groups of human activities pose hydrological and chemical stress upon streams and prevent ecosystem recovery despite the local morphological interventions (Kail et al., 2007). Thus, without tackling these other stressors the ecological impact of measures on the habitat scale is relatively small (Pedersen et al., 2006). Furthermore, despite the advantages for water safety, water availability and agricultural production in the larger, non-restored parts of the catchment, the disbalance between these advantages and the relatively minor contribution of small scale (hydro) morphology measures to a number of other services remains. Tackling all components of the ecosystem would regain opportunities for other services.

- (iv) Measures are mainly taken on small scales despite the knowledge that most stressors act over large scales.

Although small-scale benefits of stream restoration seem obvious, effects on species populations and ecosystem functioning hamper (Bernhardt & Palmer, 2011). Lowland stream environments are ecologically complex with multiple confounding factors and our knowledge of how rheophilic species populations interact with their habitat more often remains unknown. Processes in lowland stream ecosystems act over multiple spatial and temporal scales with ‘top down’ and ‘bottom up’ controls often termed dominance and feedback (Allan & Starr, 1982; Frisell et al., 1986). They depend on the hydrology, morphology, chemistry, and biology of the stream and its surroundings embedded in the geophysical and geochemical characteristics and the climate of the watershed (Ward, 1989; Verdonschot, 2000).

Including the watershed in stream restoration implies taking account for the hierarchical order of processes. It is of no use to start at a small scale, e.g., a certain habitat or short trajectory in a stream, if there are stressors acting over a larger scale, such as high nutrient input or fast runoff from the infiltration area of the watershed. In a watershed-oriented approach, processes at different scales varying from habitat to watershed are considered. Thus, considering the spatial and temporal scale of stream restoration projects strongly depends on the scale of the stressors (Lake et al., 2007). Success is more likely when the scale of the stressor meets the scale of the measures, more often it means large-scale interventions (Bernhardt & Palmer, 2011; Bond & Lake, 2003; Kondolf et al., 2008). Even though large-scale interventions are thought to be infeasible due to available resources and conflicts of interest. Furthermore, large-scale improvements are also needed to reach most of the goals related to optimize ecosystem services. Provisioning, cultural, regulating, and supporting services all depend on large-scale processes to be restored.

A second question concerning large scale restoration is about “How much needs to be restored to meet a good ecological status and an optimal gain of ecosystem services?”. In German this question refers to the so-called “Strahlwirkungskonzept”, the cumulative spatial effect of restoration efforts (see also Lake et al., 2007; Kondolf et al., 2008; Ogston et al., 2015; Copeland et al., 2021). Roni et al. (2010) for example noted that at least 20% of a watershed needed to be restored in order to see a 25% increase in salmon smolt production. For services optimization, such data are lacking but tackling the larger-scale and multiple stress situation would improve many more ecosystem services without losing the currently prevailing water quantity and agricultural services.

The way forward

On the one hand, striving for semi-natural streams with floodplains would optimally serve biodiversity and the provisioning of several ecosystem services, but would also limit other services that come with a high human population density and intensive land use. On the other hand, the current multiple-stress-cocktail in most western European lowland streams hampers biodiversity and many ecosystem services

to a large extent. Therefore, a search for a better balance between the ecological and societal needs in lowland stream watersheds is urgently needed. This implies navigating between the different interests as often conditions resulting in high biodiversity can limit other ecosystem services, especially provisioning services. A strong demand for the latter, especially agricultural products, has caused much of the stream degradation in the past. Keeping agricultural production in coherence with biodiversity implies the development of nature-inclusive agricultural production (Runhaar, 2017). Here we present a framework, constructed out of building blocks that help to find a suitable balance in practice. Of course, any weighing of interests depends strongly on the context in space and time. To select promising restoration measures, a realistic restoration target needs to be chosen, there should be insight into the role of stressors and biology at the local, regional and watershed level, knowledge is needed about the effectiveness of restoration measures, alone and in combination, and attention should be paid to biotics when formulating goals.

- (i) Choose clear and realistic restoration targets for biodiversity and ecosystem services

To select both indicators for ecosystem services (Table 2) and target species for biodiversity one can use reference conditions for Dutch lowland stream types using existing knowledge on economic and societal services valuation, and historical data and predictions based on data from other geographical regions, respectively (Nijboer et al., 2004). Alternatives for ecosystem services values can be obtained by using restored and control catchments in ecosystems services surveys and analyses. Alternative options for target species or communities are paleo-reconstruction, the use of ecological and biogeographical information on individual species, or modeling using stress trajectories or establishing dose–response gradients from which reference conditions can be predicted (Higler & Verdonshot, 1992; Johnson et al., 1993; Reynoldson & Wright, 2000).

To make the biodiversity restoration target realizable, one should examine the source populations of species present within the watershed itself and in the surrounding watersheds. This information could be used to construct a realistic target species list. Next, the societal, geohydrological,

-morphological and -chemical processes at watershed scale should be analysed, whereby irreversible environmental changes in the area must be taken into account. Since also major societal activities will play a role, these will be accounted for (see item iv). Taking the natural watershed processes into account will enhance the major ecosystem functioning as well as the potential of ecosystem services at the lowest costs (European Commission, 2015; Chen et al., 2021).

(ii) Map and quantify stressors and services valuation at local to watershed scale

To be able to tackle all relevant stressors that pose chronic or pulse problems and contribute to longer-term declines in the structure and function of a watershed, it is essential to detect them (Kenney, 1997; Verdonschot, 2000). This means examining where the sources of stressors are located, how they are distributed spatiotemporally, and what their stress intensities are within the watershed (Allan et al., 2004). Furthermore, all current ecosystem services must be mapped and quantified. Some indicators that support identification and quantification are listed in Table 2. Next, the positive or negative effect of each occurring service on biodiversity should be indicated.

Stressors are ranges of variable values that impact the watershed integrity and also some of its ecosystem services, but also services can act as stressors. Hereby integrity is defined as the capacity of a watershed to support and maintain the full range of ecological processes and functions essential to the sustainability of biodiversity, the watershed resources and the ecosystem services provided to society (Flotemersch et al., 2016; Thornbrugh et al., 2018). Therefore, de Vries et al. (2019) developed a method to quantify the cumulative stress acting on macroinvertebrate assemblages in lowland streams. The authors identified all stressors acting on multiple scales in lowland stream watersheds, quantified the adverse effects of these stressors, and calculated the cumulative stress. Such an Ecological Watershed Analysis visualizes the ecological bottlenecks at a relevant spatial scale. Based on this outcome, combinations of measures are then determined that address the multiple stress-

ors, considering the operating scale and position within the hydrological system. The latter is crucial in any watershed approach but needs to be further extended by adding the indicators of ecosystems services and their potential to act as stressor or being supportive. Such extension would provide the possibility to not only assess ecological developments but also to include societal advantages.

(iii) Map and quantify biological indicators and ecosystem services at local to regional scale

Even under the current conditions, the organisms provide information about the environmental abiotic and biotic conditions. Species occurrences reflect their adaptive response to the prevailing environment (Stearns, 1976; Southwood, 1977; Verberk et al., 2013). This not only involves their ecological preferences and the outcomes of biotic interactions, but also includes dispersal capacity, colonisation potential, and successful establishment. Successful restoration measures for biodiversity create the preferred abiotic preconditions for the desired biotic community, but this does not guarantee the actual return of the target species.

With the progressive loss of biodiversity, it is becoming increasingly difficult for target species to colonize suitable sites. Therefore, it is necessary to generate more knowledge about the dispersal capacity of target species and to determine the size of source populations, the distance to these source populations, the presence of dispersal barriers. Furthermore, the mutual interactions between species should be studied in more detail. By mapping the distribution of indicative or target organisms (e.g., macrophytes, macroinvertebrates, or fish) in the watershed under study as well as the surrounding watersheds, not only the current population distributions of target species but also the presence of nearby source populations becomes visible (see also item i). By comparing the species lists and their ecological preferences between watersheds ecological bottlenecks might be identified.

Ecosystem services can be defined as the contributions of ecosystem structure and function to human well-being. Thus, well-functioning stream ecosystems that carry high biodiversity or natu-

ral capital are the basis for a constant contribution from nature to society. More often biological indicators representing structure and functioning are used to assess the biodiversity status. But also nature's contributions to society or ecosystem services should directly be assessed and mapped with well-chosen indicators that deliver a major tool for policy and decision making on different scales (Burkhard & Maes 2017). Amongst other Palomo et al. (2017) provide a list of useful tools to apply and map ecosystem services. These maps can efficiently communicate complex information, are useful for raising awareness about areas of ecosystem services supply and demand, can contribute to environmental education and support landscape planning, environmental resource management and (spatial) land-use optimisation (Burkhard & Maes, 2017).

(iv) List potential measures

As not every restoration measure could be applied everywhere, scenarios are used to determine which restoration target range is feasible, currently and under future conditions (e.g., climate change scenarios), with a focus on sustainable conditions within the watershed comprising a high biodiversity and providing many ecosystem services.

Knowledge on the ecological bottlenecks provides the starting point for the selection of potential measures. As source-oriented restoration measures are always much more effective than effect-oriented measures, one should always include and examine the first group, as targeting causes of degradation is much more effective than targeting its symptoms (Wiering et al., 2020). Furthermore, by tuning measures that alleviate the negative effects of degraded hydrological cycles, morphological homogenised streams and valleys, and chemically loaded watersheds, will be most effective if they fit the geohydrological, -morphological and -chemical capacity of the watershed. Such nature-based approach would profit services the most. Hereby, the potential of measures needs to be confronted with the societal needs. Such watershed-scale approaches can be composed of different combinations of measures (Morris et al., 2016; Jakubínský et al., 2021):

- To obtain ecosystem services that relate to the hydrology of the watershed, such as water provisioning, flood protection, drought prevention, and water availability, a set of potential measures to improve water retention through management of infiltration is available. Examples are: optimization of rain water watershed infiltration to achieve improved upland water storage, increased water retention capacity of the landscape, more space for periodic flooding of the lower parts of the stream valleys, reduction of overland flow by land-use changes and buffer strips, removal or reduction of drainage and water extraction operations, winter cropping, tillage removal, field drainage to increase infiltration, removal of weirs to re-establish the longitudinal continuum, extensification of stream vegetation management schemes to retard downstream flow, development of urban green infrastructure, and stormwater drainage management.
- To obtain ecosystem services that relate to the landscape structure potential measures such as afforestation of the watershed, wooded riparian buffer strips development, and creating wetlands in the stream valley could be applied. Also, space could be created to allow flooding of the lower parts of the stream valley to alleviate flood risks further downstream. Reconnecting the land–water stream ecosystems allows the exchange of water, sediment, nutrients, and organisms (Amoros & Bornette, 2002). To establish in-stream morphology improvements and lateral valley connectivity measures that initiate self-development of the stream-floodplain system (passive restoration) are preferred. To recover morphological characteristics similar to those found in natural lowland stream beds, comprising meandering longitudinal channels, stable asymmetrical cross-sections, a sequence of fast and slow flowing sections, and a heterogenous stream bed substrate composition with both mineral and organic substrate types providing a high habitat diversity (Brookes, 1987), also reprofiling measures are possible. This means active restoration of the longitudinal and transversal stream profile.
- To obtain ecosystem services that relate to the water quality of the stream and valley potential measures are the reduction of the use of fertilizers and biocides and reduction of biological contami-

nation of the surface water through legislation, construction of buffer zones and wetlands, transition to paludiculture, application of catch crops after harvesting, cattle manure management, and farm water retention by the construction of retention ponds and ditches (Bergström et al., 2015; Bol et al., 2018; Rinke et al., 2019)

- Potential biodiversity measures to improve habitat quality in space and time, in-stream and in the stream valley could be achieved by restoring undisrupted landscape gradients and connections, for example, reconnecting stream and its floodplain, the restoration of floodplain wetlands (swamps, marshes) and ponds that replace old cut-off meanders and longitudinal connectivity, the construction of buffer zones, or through weir removal or construction of fish bypasses and modifications in migration barriers. Furthermore, reducing or abandoning maintenance (vegetation mowing, dredging) will strongly contribute to biodiversity improvement (Zedler and Kercher, 2005). Reinforcement of populations can be achieved by increasing the size of existing source populations. This can be done either through increasing the size of current habitats and by improving its quality, or by improving the species' distribution itself by creating dispersal corridors or steppingstones of suitable habitat between water systems. Reintroduction at potentially suitable locations offers an alternative solution (Jourdan et al., 2019).
- Build scenarios

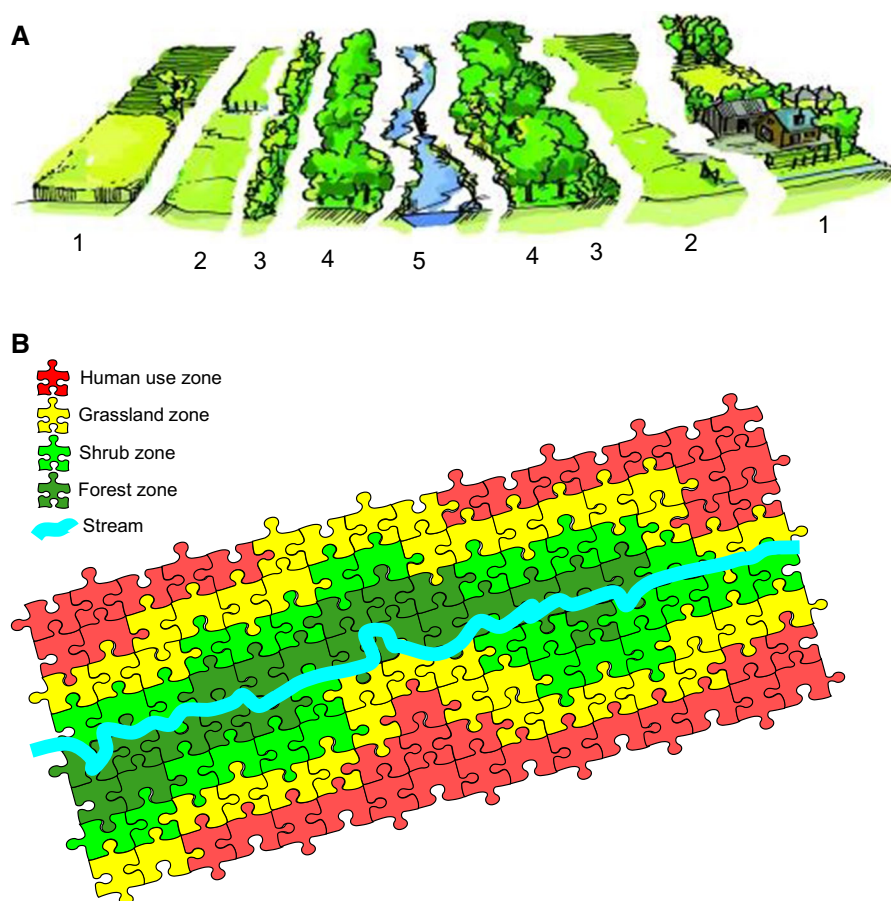
When going from potential combinations of measures in lowland stream watersheds to optimization of ecosystem services the context of historical, societal, economic and ecological interests is very important. This context is almost always watershed to stream stretch specific. Thus, stakeholder involvement is needed whereby the advantages and disadvantages of combinations of measures and their positive and negative effects on interests needs to be made clear. Hereby, spatial planning is crucial. For example, forested lowland floodplains have a positive impact on discharge dynamics, reducing flood intensities (keeping urban areas save) and preventing long periods of droughts (increasing agriculture production), but ask for space which is in commonly in agricultural use. The requirements to optimize ecosystem services (Table 2) can be summarised as: restoration measures

cover a large spatial scale, the hydrological situation in the watershed should result in a moderate dynamic discharge regime, measures focus on creating patchy or mosaic-like wet floodplain and riparian zones and is supported by legislation, like WFD and spatial planning. To accomplish this, hydrological measures should be taken in the infiltration areas of the watershed (higher grounds/uplands) and a lateral zonation of the floodplain should be created containing different types of land use or vegetation. The zonation concept considers five building blocks or components (Fig. 2A) (Verdonschot, 2010):

- (1) A human use zone, covering the upland parts of the watershed, in use for agriculture, urbanisation, forestry, and nature. Water infiltration, groundwater recharge, and water retention are crucial goals in this zone.
- (2) A grassland zone in extensive use is bordering the highest part of the streams' inundation zone (extreme peak flow zone). Here grassland is in extensive use. Fertilizers and biocides are not used. This area filters (subsurface) runoff and reduces inflow of nutrients, sediments, and contaminants in the lower parts of the valley.
- (3) A wet shrub zone borders the grassland zone and provides space for inundation, contributes to water storage and retention, increases the filtering capacity to further reduce nutrient, sediment, and contaminant loads.
- (4) A wet forest zone comprises the riparian zone of the stream banks. It optimises the water and substances storage and filtering, respectively. Furthermore, the trees shade the stream, leading to cooling of the stream water and provide coarse and fine organic material promoting in-stream functioning.
- (5) The stream is free-flowing, with a moderately stable discharge regime and erosion-sedimentation processes. These conditions form the basis of a good ecological status of the aquatic ecosystem.

In many cases, this zonation cannot be realised across the entire floodplain and must be balanced with other human activities and societal needs. For example, in a UK watershed already a zonation of 20–40% of the total watershed area could reduce peak magnitude of up to 19%, by de-synchronization of the timings of sub-watershed flood waves

Fig. 2 The zonation of a lowland stream floodplain: **1** zone of human use, **2** extensive grassland, **3** wet shrub, **4** wet forest zone, and **5** the stream channel (A). The ecosystem services-biodiversity puzzle in lowland stream valleys (B)



(Dixon et al., 2016). Therefore, each zone can either or not be present or its extent can be wider or smaller, resulting in a mosaic-like floodplain landscape. This asks for an accurate and detailed spatial planning that is context dependent. It is like a puzzle that constitutes a major challenge to reach a sustainable use of the watershed that provides a whole array of ecosystem services (Fig. 2B). To solve this puzzle evidence-based evaluations and cross-disciplinary knowledge exchange will strengthen the approach and help to prioritize areas and measures (Suding, 2011).

Nonetheless, from a target species or biodiversity perspective recovery can be incomplete due to shifts in species distributions, legacies of past land use, strong species feedbacks, regional shifts in species pools or losses of source populations, colonisation barriers, dispersal distances, and time-lags. Further measures in the watershed can be taken to improve connectivity, but also assisted recolonisation could be

considered when natural colonisation is not likely to occur on short-term (Jourdan et al., 2019).

Stream valley landscapes which maximize ecosystem services and sustain high biodiversity consequently require a drastic "conversion" of the current landscape. This landscape transition will pose a challenge for policy makers and implies a strong societal change. Currently, climate change resulting in more extreme floods and droughts, transitions in agricultural production needed to reduce the amount of nutrient runoff, atmospheric nitrogen deposition and pesticide loads, and biodiversity losses urge for this transition. At the same time this transition is supported by a greater public awareness of the need to change. The majority of the land required will likely be obtained by transforming agricultural fields, which comes with economic costs. So, what is needed are financial incentives and farmers action perspectives, along with a long-term vision on regional land-use objectives, and knowledge on land use, ecosystem

services, and biodiversity needs and interactions (Runhaar, 2017; Vermunt et al., 2022). Last, but not least, the transition must be underpinned by long-term legislation and regulation.

Conclusions

Lowland streams and their valleys could harbor a disproportionately high biodiversity (e.g., 75% of the total biodiversity in the Netherlands) and deliver important ecosystem services. Despite the high urbanisation rate and the intense agricultural practices in the lowland stream valleys nowadays, chances to reconnect streams and their valleys and to regain biodiversity and ecosystem services increased due to societal pressure. This is fuelled by the recognition of problems associated with the loss of biodiversity, especially insects, and the effects of climate change. Scientifically, the recognition of the relevance of tackling multiple stressors acting over large scales for stream ecosystem recovery is clear. The most promising restoration scenarios for flood and drought risk management, restoration of morphological features, reduction of eutrophication and toxic contamination, improving connectivity and biodiversity recovery involve a zonation of the riparian zone and stream valley floodplain on the watershed scale which makes use of watershed processes. Furthermore, restoration projects should first rehabilitate hydrological watershed processes, reduce flows of nutrients and contaminants, and restore connectivity before implementing local instream habitat improvement projects. Monitoring at the appropriate spatial and temporal scales would be of support. In practice, the puzzle between societal and ecological needs can be laid in the context of specific spatial planning and willingness.

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Author contributions PFMV designed the study, co-conducted the surveys and performed the literature review. PFMV and RCMV co-wrote the manuscript.

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Code availability Not applicable.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval No approval of research ethics committees was required as it concerned literature.

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