SEVENTH FRAMEWORK PROGRAMME

THEME 6: Environment (including Climate Change)

REFRESH

Adaptive strategies to Mitigate the Impacts of Climate Change on European Freshwater Ecosystems

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Deliverable 1.5: Overview of practical climate adaptation strategies in European freshwaters at sub-catchment and local scales

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract

Climate change has been linked to changes in flows, water levels, nutrient cycles, availability of toxic substances, oxygen regimes and a number of biological features like, physiology, phenology, species distributions, and interspecific interactions. Projected future climate change will undoubtedly result in even more dramatic shifts in the states of many aquatic ecosystems. Managing water resources and aquatic ecosystems in the face of uncertain climate requires new approaches. The focus of management and restoration will need to shift from (historic) references to potential future ecosystem services, and from reactive measures towards pro-active ones. Strategic adaptive management based on potential future climate impact scenarios will need to become a part of any action.

The objective of Deliverable 1.5 is to produce a practical guide to the most effective management strategies, applicable at sub-catchment and local scales, for use throughout Europe.

Firstly, in the REFRESH Deliverable 1.4 a list of sub-catchment and local scales adaptation measures was compiled for stream and rivers, and for lakes. The list was specified per climate region Atlantic, boreal, alpine, continental, and Mediterranean. The list comprises measures that are normally being taken by local authorities/managers in different ecoregions and water types (for all kinds of purposes). To design a practical guide for water managers the scores were translated into a climate adaptation label per adaptation measure.

Secondly, strategic adaptation measures aim to either improve resistance and resilience thus to enable persistence of aquatic ecosystems or to accept change and accommodate this. Therefore, three building blocks of a best practice framework for managing resilience in aquatic ecosystems were put into practice:

1. the principles from resilience thinking (nine basic principles)
2. the ecosystem approach (including the 5-S-Model and the DPSIRR chain),
3. strategic adaptive management.

The three together compose a practical guide for strategic adaptive management for aquatic ecosystems.

Content

1. Introduction

1.1 Background

Recent rapid changes in the global climate have altered aquatic ecosystems around the world. Climate change has been linked to changes in flows, water levels, nutrient cycles, availability of toxic substances, oxygen regimes and a number of biological features like, physiology, phenology, species distributions, and interspecific interactions. Projected future climate change will undoubtedly result in even more dramatic shifts in the states of many aquatic ecosystems. These shifts will provide one of the largest challenges to water resource managers. Managing water resources and aquatic ecosystems in the face of uncertain climate requires new approaches. Many adaptation strategies have been proposed for managing aquatic systems in a changing climate. Most of the adaptation strategies and measures:

(i) are based on general ecological principles and

(ii) are measures that managers are already using.

To address climate change, managers will need to act over different spatial and temporal scales. The focus of management and restoration will need to:
(i) shift from (historic) references to potential future ecosystem services, and
(ii) from reactive measures towards pro-active ones.

Strategic adaptive management based on potential future climate impact scenarios will need to become a part of any action.

1.2 Objective

The objective of Deliverable 1.5 is to produce a practical guide to the most effective management strategies, applicable at sub-catchment and local scales, for use throughout Europe.

2. Methods

2.1 Sub-catchment and local scales measures

In the REFRESH Deliverable 1.4 a list of sub-catchment and local scales adaptation measures was compiled for:

1. stream and rivers
2. small shallow and large deep lakes

The list was specified per climate region:

- Atlantic
- boreal
- alpine
- continental
- Mediterranean

The list comprises measures that are normally being taken by local authorities/managers in different ecoregions and water types (for all kinds of purposes). Furthermore, it includes only measures that mitigate direct and indirect effects of climate change. The measures are scored with the number(s) that corresponds to the one or more major climate change effects (Table 1).

Table 1. Score that relates each measure to a specific climate pressure.

score	climate change induced pressure	example
0	no climate change related pressure	
1	temperature rise	direct, like warming, stratification
2	increase winter precipitation	direct effects, like run off, water level fluctuation, spates, inundation
3	summer extremes	direct effects, like droughts, spates
4	water quality	indirect effects, like nutrient cycling, eutrophication, oxygen regime changes, salt seepage
5	others	indirect effects, like exotic species, terrestrialisation

To design a practical guide for water managers the scores were translated into a climate adaptation label. For this label the scores 1 to 5 were taken into account. If an adaptation measures scores for all 5 climate change induced pressures then this measures highly contributes to climate adaptation. The fewer scores a measures has the lower its contribution. This approach resulted in the definition of climate adaptation labels (Table 2).

Table 2. Climate change adaptation labels.

colour code	colour	number of climate induced pressures	explanation
🟩	dark green	4-5 (+++)	win-win measure
🟩	light green	2-3 (++)	win-win measure
🟩	pale green	1 (+)	no regret measure
🟨	yellow	0	
🟥	red	-	regret measure

2.2 Development of a framework for adaptive management

Adaptation measures aim to either improve resistance and resilience thus to enable persistence of aquatic ecosystems or to accept change and accommodate this (Verdonschot & Besse 2012). Resistance and resilience are strongly enhanced by:

- Large scale heterogeneity
- Large habitat sizes with high quality
- Connectivity
- Resilient Management

Adaptive or resilient management that focusses on resilience of aquatic ecosystems uses the appropriate adaptation strategies when:

- Using local skills and knowledge
- Using specialist expertise
- Being flexible to respond to events
- Willing to consider (accept) change
- Having resources
- Integrating with other objectives

But what is adaptive management and how can it be brought into practice? Therefore, an approach for managing resilience in aquatic ecosystems is needed: a practical adaptive management framework. Frameworks are neither a models nor theories but help to consider, organise and understand systems, to link cause and effect, and to guide decisions about management. The strength of frameworks are the recognition of 'why', 'what' and 'how' components. An important role of frameworks is to identify robust, qualitative arguments. Frameworks are to sharpen intuition and stimulate imagination rather than to provide precise quantitative information (Walters & Korman 1999).

The components of a best practice framework for managing resilience in aquatic ecosystems developed for rivers by Parsons et al. (2009).

They use three building blocks:

4. the principles from resilience thinking (Table 3),

Resilience is the amount of change a system can undergo (its capacity to absorb disturbance) and remain within the same regime that essentially retains the same function, structure and feedbacks (Walker & Salt 2006). Resilience thinking seeks to determine how societies, economies and ecosystems can be managed to confer resilience: that is, how to maintain the capacity of a system to absorb disturbance without changing to a different state.

Table 3. Nine fundamental principles of resilience thinking.

1. Recognition of the potential for alternate stable states to exist within aquatic systems
2. Recognition that aquatic system properties can vary significantly within a stable state
3. Aquatic system properties can display significant spatial and temporal variability at different scales within a stable state.
4. Thresholds exist within aquatic systems and act as tipping points between alternate stable states.

5. Thresholds exist at multiple scales, but not all result in a shift to an alternate state.
6. 'Slow' variables are important in driving regime shifts.
7. Aquatic systems cycle through adaptive loops and their position within the loop sets their form and function.
8. Aquatic are essentially social-ecological systems that integrate ecosystems and human society.
9. Managing water bodies for resilience requires adaptability or the capacity to adapt to and influence change.

5. the ecosystem approach (Table 4),

The ecosystem approach focuses on the interactions among ecological entities and their environments, and thus takes an encompassing and synthetic view of nature rather than a fragmented view (Likens 1992). The ecosystem approach recognises the influences of disturbance, scale, spatial heterogeneity, and spatial variability on the relationships between ecological entities and their environments. Contemporary views of ecosystems also view humans as a keystone species within the ecosystem.

Table 4. Six fundamental principles of the ecosystem approach.

1. Variability and heterogeneity are fundamental drivers of pattern and process in aquatic ecosystems.
2. Fluxes and cycling (spirals) of materials and energy are important drivers of aquatic ecosystem dynamics.
3. Water bodies are hierarchically organised whereby patterns and processes must be viewed at different scales.
4. Understanding aquatic ecosystems requires a focus on interactions between different disciplinary elements (for example: biological, chemical geomorphological, hydrological, social and economic).
5. Aquatic ecosystems can be understood through causal or correlative approaches: the choice of method depends on prior knowledge and the scale of focus.
6. Humans are keystone elements of aquatic ecosystems: they are drivers of change and users of ecosystem goods and services.

3. strategic adaptive management (Table 5).

Strategic adaptive management offers a framework for natural resource management and decision making in environmental, social and institutional situations that are characterised by variability, uncertainty, incomplete knowledge and multiple stakeholders (Biggs & Rogers 2003). Three key tenets form the basis for the management and decision-making process in strategic adaptive management: strategic and value-based planning based on scientific and societal needs and values; a learning by doing approach to management planning; and participatory engagement of all stakeholders to serve their needs, access their inputs, and secure their cooperation (Rogers et al. 2008).

Table 5. Six fundamental principles of strategic adaptive management.

1. All stakeholders are involved in an adaptive planning process to develop a vision for the desired state of an aquatic ecosystem. The desired state is expressed as the spatial-temporal heterogeneity in Values, Social, Technical, Economic, Environmental and Political (V-STEEP) conditions.
2. A vision for the desired state of aquatic ecosystem condition is translated into an objectives hierarchy.
3. Thresholds of potential concern are generated to define acceptable levels of change in aquatic ecosystem form and function.
4. Research and observations of aquatic ecosystem form and function are used to audit and understand river ecosystem condition in relation to thresholds of potential concern.
5. Management interventions are an accepted part of ecosystem processes but occur only in the context of thresholds of potential concern.
6. Learning by doing is an essential part of strategic adaptive management: knowledge of aquatic ecosystems is constantly reviewed in order to update thresholds of potential concern and management options.

Resilience thinking presents a useful social-ecological approach for understanding resilience in ecosystems, but it does not have a strong operational and implementation procedure. Strategic adaptive management provides an excellent operational procedure for managing resilience in ecosystems, but so far it has been applied to managing ecosystems where biodiversity conservation is the main goal. The ecosystem approach has a strong conceptual and scientific basis, but does not have an operational procedure associated with it within a management context. Thus, integration of the principles from each approach will provide a powerful and cutting edge basis for the components of a framework for managing for resilience in aquatic ecosystems (Parsons et al. 2009).

The principles of these three approaches are collated to form the components of a practical framework for adaptive management in aquatic ecosystems. These three building blocks have been collated into three logical levels representing the ‘why’, ‘what’ and ‘how’ of a best practice framework for managing resilience in river ecosystems (Figure 1).

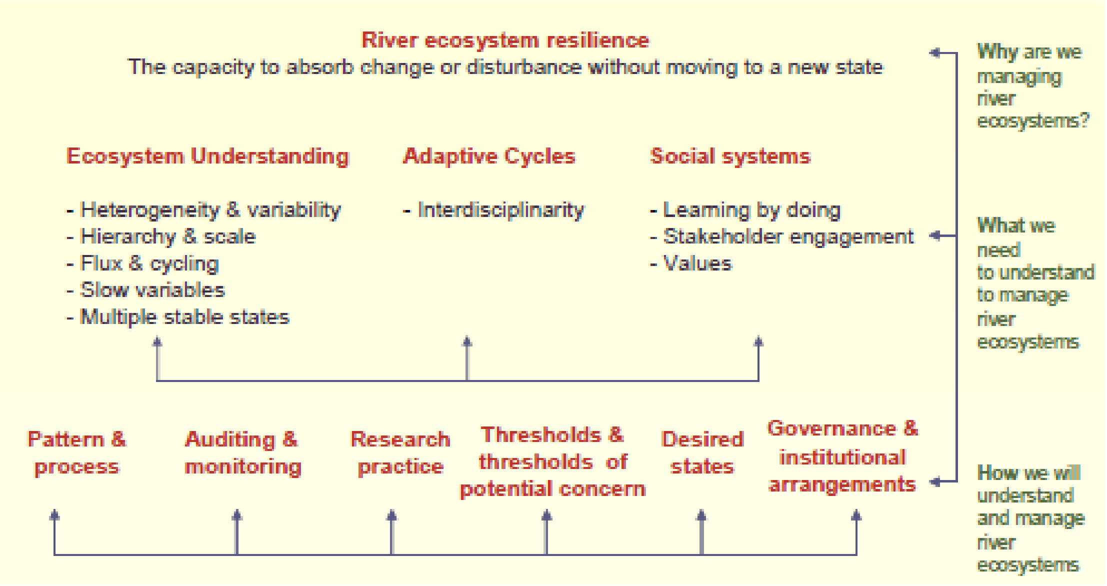


Figure 1. Components of a practical framework for managing resilience (Parsons et al. 2009).

The components listed above provide the philosophy of the framework of an approach for managing resilience in aquatic ecosystems as developed for Australian rivers by Parsons et al. (2009). It will be necessary for local water managers to develop, fill in and quantify these components for their own water bodies. It also involves developing the management, policy and governance structures and attitudes required to go about managing for resilience in aquatic river ecosystems.

3. Climate adaptation labels

The list with adaptation measures (Verdonschot & Besse 2012) comprises measures that are normally being taken by local authorities/managers in different ecoregions and water types (for all kinds of purposes). The scores in this list were used to design a practical guide for water managers. Therefore, the scores were translated into a climate adaptation label (Table 2).

Climate adaptation labels for streams and rivers

				water type						
ecosystem component/scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**stream**	**river**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
temperature	warming of surface water	cooling	(re)forestation	1		1,2,3	1,2,3	1,3,4	1,2,3,4	1,2,3
		cooling	development of a wooded bank	1		1	1	1,4	1,4	1,4
		cooling	cutting wooded bank			1	1	1,4	1,4	1,4
hydrology	change in flow regime	increase water storage capacity	drainage removal	1		2,3,4	2,3,4	2,3,4	🟨	1,3,4
		increase water storage capacity	extra irrigation	1		2,3,4	2,3,4	2,3,4	🟥	1,3,4
		increase water storage capacity	groundwater storage	1	1	3	3	2,3	3	1,3,4
		increase water storage capacity	groundwater extraction for water supply	1	1	3	3	2,3	3	1,3,4
		increase water storage capacity	improvement of infiltration in the soil, like wadi's	1	1	2,3,4	2,3,4	2,3,4	2,3,4	1,3,4
		increase water retention capacity	creation of inundation zones	1	1	2,3	2,3,4	2,3,4	2,3	2,4
		increase water retention capacity	excavation of the uper layer of the riparian zones/floodplain	1	1	2,3,4	2,3,4	2,3,4	2,3,4	1,3,4
		increase water retention	construction of	1	1	2,3	2,3,4	1,2,3	2,3	1,2,3,4

				water type						
ecosystem component/scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**stream**	**river**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
		capacity	waterretention/retention reservoirs/ponds			🟩	🟩	🟩	🟩	🟩
		increase water retention capacity	digging of high-water channels	1	1	2,3	2,3	2,3	2,3	2
		increase water retention capacity	construction of a two-stage channel	1		2,3	2,3	0	2,3	🟨
		increase water retention capacity	enlargement of the riverbed		1	2,3	2,3,4	2,3,4	2,3,4	2
		increase water retention capacity	reconnection of old meanderbeds	1	1	2,3	2,3,4	0	2,3	2,4
		increase water retention capacity	relocation of dikes to enlarge the riverbed		1	2,3	2,3,4	3,4	2,3	2,4
		restoration of the water network	restoration of natural river network	1		0	0	1,2,5	🟨	1,2,3,4
		flow restoration, improve connectivity	removal of weirs	1		1	1	1.2	1,4	1,2,3,4
		flow restoration	introduction of weirs		1	2,3	2,3,4	0	2,3	3
		flow restoration	removal of obstacles from the floodplain		1	2,3	2,3	3,4	2,3	1,2,3,4
		increase water storage capacity	construction of hydrological buffers	1		2,3,4	2,3,4	2,3,4	2,3,4	2
	change in effective moisture	flow restoration	reduction of water extractions	1		2,3	2,3	1,2,3,4	3	3,4
		increase water retention capacity	reuse of treated wastewater	1		3	3	3	3	4
		flow regulation	flood protection	1	1	2,3	2,3,4	2,3,4	2,3,4	2
morphology	erosion	channel shape	passive remeandering	1		2,3	2,3,4	2,3	3	2,4

				water type						
ecosystem component/scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**stream**	**river**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
		restoration								
		channel shape restoration	passive rebraiding	1	1	2,3	2,3,4	2,3	3	2,4
		channel shape restoration	removal of bed fixation	1		0	0	0	3	2,3,4
	change in flow regime	channel shape restoration	digging of new meanders	1	1	2,3	2,3,4	0	3	3,4
		flow restoration	reduction of the wet profile	1	1	0	0	3		3,4
		flow restoration	regulating the channel			2,3	2,3,4	0	3	3,4
	sedimentation	sediment load reduction	construction of sediment buffers	1		2,3,4	2,3,4	4	2,3,4	4
	loss of biodiversity	habitat restoration	construction of asymmetric/natural bank profiles	1	1	0	0	0	0	0
		habitat restoration	improvement of habitat heterogeneity (micromeandering)	1		0	0		3,4	0
		habitat restoration	improvement of habitat heterogeneity (pools and runs)	1		0	0	1,3,5	4	0
		habitat restoration	improvement of habitat heterogeneity (obstacles)	1	1	0	0	3,5	3,4	3
		habitat restoration	addition of species-specific structures, like fish habitats	1		0	0	1,3,5	0	0
		habitat restoration	reprofiling of banks (steep and overhanging)	1		0	0	0	0	0
	spread of alien species	habitat restoration	improvement of habitat heterogeneity			0	0	1,3,4,5	4	0
water quality		nutrient load reduction	reduction of the use of	1		4	4	4	3,4	4

				water type						
ecosystem component/scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**stream**	**river**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
			fertilizers							
		nutrient/organic/toxic load reduction	removal of point sources of pollution	1	1	4	4	4	3,4	4
		nutrient/organic/toxic load reduction	removal of sewage discharges (houses)	1		4	4	4	4	4
		nutrient/organic/toxic load reduction	reduction in sewage overflows/load	1	1	4	4	4	4	4
		nutrient/organic/toxic load reduction	improvement of sewage treatment	1		4	4	4	3,4	4
		nutrient/organic/toxic load reduction	separation of sewage and rain water overflow	1	1	4	4	4	3,4	4
		nutrient/organic/toxic load reduction	disconnection of polluted tributaries	1		4	4	4	4	3,4
		nutrient/organic load reduction	creation of helophyte filters/wetland	1		4	4	0	4	3,4
		nutrient/organic load reduction	using natural wetlands	1		4	4	0	4	3,4
		nutrient/organic load reduction	construction of horse-shoe wetlands	1		4	4	0	4	3,4
		nutrient/organic load reduction	construction of buffer zones between floodplain and agricultural land	1		4	4	4	4	3,4
		nutrient/organic/toxic load reduction	dredging		1	4	4	4	4	4
biology	loss of biodiversity	reduce direct human interference	reintroduction of species, like fish stocking	1	1	0	0	5	0	0
		habitat restoration	maintenance	1		0	0	0	0	0
floodplain	loss of	habitat restoration	digging of off-channel ponds	1		0	0	0	0	0

				water type						
ecosystem component/scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**stream**	**river**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
	biodiversity									
	change in flow regime	reduce direct human interference	reduction of maintenance	1	1	1,2,3,4,5	1,2,3,4,5	1,3	1,2,3,4	
	change in flow regime	floodplain restoration	development of a natural floodplain		1	1,2,3,4,5	1,2,3,4,5	3,4	1,2,3,4	2,3,4
connectivity	loss of biodiversity	improve connectivity	construction of fish passages	1		0	0	5	0	0
societal		outside scope	regulation of recreation pressures	1		0	0	0	0	0
		outside scope	assignment of protected areas	1	1	0	0	5	0	0

Climate adaptation labels for lakes.

				water type							
ecosystem component/ scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**small lake**	**large/ shallow lake**	**large/ deep lake**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
temperature	warming of surface water	none		1	1	1	🟨 0	🟨 0	🟨 0	🟨	🟩 1
hydrology	change in water level regime	increase water storage capacity	drainage removal	1	1	1	🟩 2,3	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟨
		increase water storage capacity	groundwater storage	1	1	1	🟨	🟩 2,3	🟩 2,3	🟩 2,3	🟨
		increase water storage capacity	improvement of infiltration in the soil, like wadi's	1		1	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟨
		increase water retention capacity	construction of waterretention/retention reservoirs/ponds	1	1		🟩 2,3	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟩 2
		increase water retention capacity	improvement of hydrological isolation			1	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟨
		increase water retention capacity	water level management	1	1	1	🟩 2,3	🟩 3,4	🟩 3,4	🟨	🟩 3,4
		increase water retention capacity	reduction of water level extractions			1	🟩 2,3	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟩 3,4
		reduce direct human interference	reduction of maintenance	1			🟩 2,3	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟨
		increase water storage capacity	construction of hydrological buffers	1			🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟩 2,3,4	🟨
		increase water storage capacity	building reservoirs	1	1		🟥 2,3	🟥 2,3,4	🟥 2,3,4	🟥 2,3,4	🟥 2
	change in effective moisture	increase water retention capacity	reduction of extractions	1			🟩 2,3	🟩 2,3	🟩 2,3	🟩 2,3	🟨
morphology	erosion	habitat restoration	protection/reconstruction of the banks (stabilisation	1		1	🟩 2,3	🟩 2,3,4	🟩 2,3,4	🟩 2,3	🟩 2,4

				water type							
ecosystem component/ scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**small lake**	**large/ shallow lake**	**large/ deep lake**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
			by vegetation)								
	siltation / low water level (due to low precipitation & high evaporation) / low freshwater inlet/ loss of connectivity	nutrient/organic/toxic load reduction	dredging	1	1	1	4	2,3,4	2,3,4	4	3,4
	loss of biodiversity	habitat restoration	improvement of bank heterogeneity/vegetation				0	2,4	2,4	4	
	loss of biodiversity	habitat restoration	construction of natural bank profiles	1		1	0	4	4	0	
water quality	eutrophication	nutrient/organic load reduction	creation of helophyte filters/wetland	1	1		4	4	4	4	4
		nutrient/organic load reduction	using natural wetlands	1			4	4	0	4	3,4
		nutrient/organic load reduction	construction of horse-shoe wetlands	1	1		4	4	4	4	4
		nutrient load reduction	freshwater inlet en flushing	1	1	1	4	4	4		4
		nutrient load reduction	reduction of the use of fertilizers	1	1		4	4	4	4	4
		nutrient/organic load reduction	construction of buffer zones with agricultural land	1	1		4	4	4	4	4
		nutrient load reduction	chemical phosphate removal			1	4	4	4	4	4
		nutrient load	fixation of phosphate in			1	4	4	4	4	

				water type							
ecosystem component/ scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**small lake**	**large/ shallow lake**	**large/ deep lake**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
		reduction	the sediment (addition binding substances)				🟩	🟩	🟩	🟩	🟨
		nutrient load reduction	introduction of zebra mussels			1	4	4	4	4	🟨
		nutrient load reduction	P-fixation	1		1	4	4	4	4	🟨
		nutrient load reduction	introducing rotting strow	1		1	4	4	4	4	🟨
	oxygen depletion	nutrient load reduction, re-oxygenation	flushing		1	1	4	4	4	4	4
	oxygen depletion by stratification	re-oxygenation	mixing		1	1	4	4	4	4	4
	eutrophication/increase toxicity	nutrient/organic/toxic load reduction	reduction in sewage overflows/load / stringent waste water treatment & control system in catchment	1	1	1	4	4	4	4	4
	eutrophication/increase toxicity	nutrient/organic/toxic load reduction	removal of point sources of pollution	1	1	1	4	4	4	4	4
	eutrophication/increase toxicity	nutrient/organic/toxic load reduction	removal of sewage discharges (houses)	1	1	1	4	4	4	4	4
	eutrophication/increase toxicity	nutrient/organic/toxic load reduction	dredging	1		1	2,3,4	2,3,4	2,3,4	4	4
	salinisation	de-salinisation	freshwater inlet/flushing	fresh water inlet/flushing	1		4	4	4	0	4
biology	loss of biodiversity	reduce direct human interference	reduction of fish biomass		1	1	4	4	4	4	4

				water type							
ecosystem component/ scale	**climate change effect**	**adaptation strategy**	**adaptation measure**	**small lake**	**large/ shallow lake**	**large/ deep lake**	**atlantic**	**boreal**	**alpine**	**conti-nental**	**mediter-ranean**
		reduce direct human interference	fish (predatory) stocking		1	1	4	4	4	4	4
		reduce direct human interference	shellfish stocking			1	4	4		0	
		reduce direct human interference	removal of exotics		1	1	0	0	0	0	
	spread of alien species	habitat restoration	improvement of habitat heterogeneity/managing alien species	1	1	1	0	0	0	0	
floodplain	loss of biodiversity	habitat restoration	development of natural bank vegetation		1	1	0	2,4	2,4	0	
connectivity	loss of biodiversity	improve connectivity	construction of fish passages/reduction of fish migration barrieres		1	1	0	0	0	0	
		increase water retention capacity	connection of waterbody and floodplain/adjacent wetland		1	1	0	2,4	2,4	4	
societal		outside scope	regulation of recreation pressures incl. fishing		1	1	4	4	4	4	

4. Put the framework into practice

4.1 Resilience

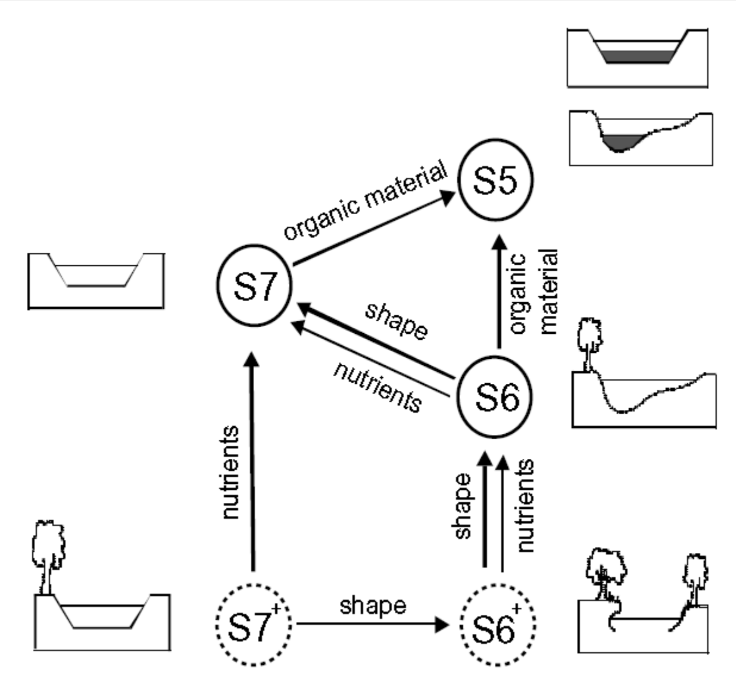
Resilience implies maintaining the capacity of aquatic ecosystems to absorb disturbance without changing to a different state. Therefore, first the desired state of an aquatic ecosystem has to be described. The desired state provides a benchmark state to aim towards. The desired state sets the environmental, biological and social parameters that are important in and for the respective aquatic ecosystem. Here, the desired state is a benchmark state, or set of states, that describe a resilient aquatic ecosystem.
The absorption of disturbances implies that the aquatic system has thresholds until which it can return to its original state. Thresholds can be used in management plans to indicate tipping points (demonstrated or potential) between alternate states. Thresholds must occur in the context of disturbance and multiple states as these are key components of resilience. Thresholds need not to be sharp boundaries between states as often states gradually fade into one another.

Desired states can represent future conditions e.g. include predicted climate change. Good examples of future conditions are the climate scenario predictions and those land use scenarios that are built on the former. Using those in water system models can provide future environmental conditions that indicate directions of change and help to define desired states.
Using, preferably quantified, the understanding of the important environmental and biological biophysical aspects of aquatic ecosystems (like, heterogeneity and variability, scale, flux and cycling, slow variables and multiple states) will help to define the biological desired state. Crucial is the knowledge on operational thresholds (actual or potential) that can switch or grade an aquatic ecosystem into an different state. This requires understanding of the type and scale of operation of the threshold. Thresholds can become more powerful on local scales when coupled with a monitoring procedure that can relate the state of the system to upper and lower limits of an acceptable state.

Ecosystems are characterised by episodic change, patchiness, cross-scale interaction and multiple equilibria, or multiple states (Gunderson & Holling 2002). More often ecosystems are treated as some type of equilibrium stable equilibrium, often resulting in surprise events and changes (Carpenter & Folke 2006). Static states as targets have shown not to lead to sustainability, but rather to collapse (Walker & Salt 2006) and therefore, ecosystems should be treated as moving targets. Especially, in an adaptive management approach there is a need for flexible desired states.

Box 1 Example of the practical description of a desired state
The figure a web of potential current and desired states; here called cenotypes. Three cenotypes, all middle reaches of streams, are currently occurring states, the coded circles, as well as their most important environmental relationships, the arrows, and some profile shapes.

Cenotype S5, at the top, represents polysaprobic or organically polluted streams. The relationships between this type and both cenotypes S7 on the left and S6 on the right are illustrated by the arrows, both related to the amount of organic material. Cenotype S7 represents β-mesosaprobic-regulated streams and is related to the cenotype S6, β-mesosaprobic seminatural streams. These are related by the parameters profile shape, thus morphology and hydrology of the stream and the catchment and nutrient concentration, and hence the intensity of agricultural activities in the watershed. A general feature in this region is the combination of intensive agricultural activity and increased discharge fluctuations by stream canalization and land drainage. Through these human activities, streams belonging to cenotype S6 can shift towards those of S7. The construction of a sewage treatment plant which discharges in a stream belonging to cenotype S6 or S7 will cause a shift towards cenotype S5.



Five cenotypes (circle with code) with their mutual relation-ships (arrows). S7: α-mesosaprobic middle reaches of regulated streams, S5: polysaprobic upper and middle reaches of natural and regulated streams, S6: α-mesosaprobic middle reaches of semi-natural streams. S6+: β-mesosaprobic middle reaches of natural streams, S7+ β-mesosaprobic middle reaches of regulated streams.

The potential desired states S6+, oligosaprobic natural streams, and S7+, oligosaprobic regulated streams, are shown. The relationship between cenotypes S6 and S6+ is mainly due to the parameters profile shape, again morphology and hydrology, and nutrient concentration. The latter is also important between cenotypes S7 and S7+. Streams which belong to cenotypes S6 or S7 can be managed in the direction of the desired states S6+ and S7+, respectively.

4.2 Ecosystem approach

The ecosystem approach is based on two important building blocks:

- 5-S-Model
- DPSIRR-chains

The 5-S-Model, a frame that divides the stream ecosystem into five major components, i.e. System conditions, Stream hydrology, Structures, Substances and Species (Verdonschot et al., 1998), is a first attempt to comprise theoretical knowledge in 'best-practice' integrated adaptive management and assessment. Integrated adaptive management and assessment comprises an ecological typology, an ecological catchment approach and a societal approach. Integrated assessment using ecological parameters includes the following.

Environmental parameters that are relevant for the structure and functioning of the ecosystem. In order to make the proper choices in integrated stream and catchment management, one has to understand the functioning and interactions (dominance and feedback) of the controlling factors. The conceptual basis for integrated assessment should therefore be embedded into a landscape ecological frame. To simplify the ecological complexity of catchment ecology the 5-S-Model, a conceptual model that provides guidelines for assessment and management, was formulated (Verdonschot et al., 1998). The main structure of this model is shown in Figure 2. The five key components are as follows:

System conditions comprise the processes related to climate (temperature, rainfall), geology and geomorphology (such as slope, soil composition). System conditions are composed of ultimate controlling factors and are boundary conditions for a stream. The system conditions set the possibilities and limits for stream ecosystem functioning. Ultimate controlling factors continuously interact with a stream at a high hierarchical scale level in space (the catchment), as well as in time (±100 years). Generally, system conditions cannot be changed by management. Human activities influence this level through, for example, atmospheric deposition and climate change. Stream rehabilitation does not focus on these factors but one has to consider the effects of these boundary conditions as well as the long-term effects of change.

Stream hydrology characteristics are set by the system conditions. Stream hydrology comprises, at the scale level of catchment, the hydrological processes, such as infiltration, ground water flow, seepage, run off and discharge. At the level of stream and habitat, stream hydrology comprises hydraulic processes, such as current velocity and turbulence. Stream hydrology refers to the water quantity parameters. The direction of the water flow strongly influences the direction of all other parameters in the system. The two main directions of flow are one running from the boundary of the catchment towards the stream (lateral) and one running from source to mouth of the stream (longitudinal).

Structures of the stream valley and the stream itself are strongly determined by the hydrological and hydraulic processes of stream hydrology. Structures imply the morphological features of the longitudinal and transversal shape of the stream bottom, banks and bed, as well as the substrate patterns within. Structures also refer to cut off meanders, wetlands, sand deposits and others in the stream valley. The dynamics of these structures directly relate to the dynamics in hydrology and hydraulics.

Substances comprise the dissolved components, such as nutrients, organic matter, oxygen, major ions and contaminants. Substances directly follow the water flow. From catchment boundary towards the stream the amount of dissolved substances increases. In addition, from source to mouth this increase is visible. Substances refer to the water quality parameters.

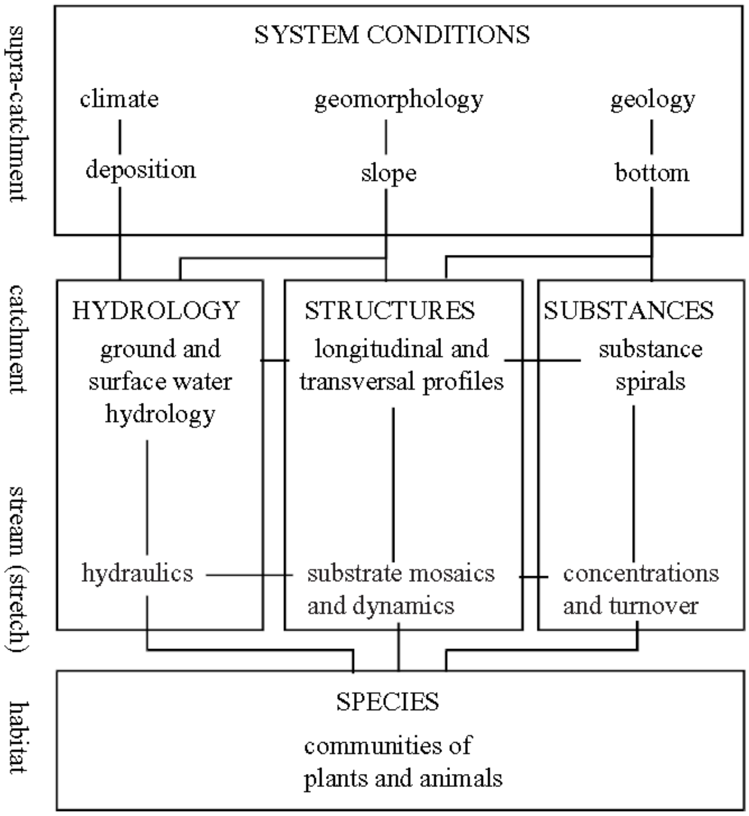
Stream hydrology, structures and substances together compose the group of controlling factors that directly determine how the stream community functions. These controlling factors take an intermediate position in between the high scale and low-scale levels, and include the latter. Species are the response to the functioning of all above-mentioned groups of controlling factors. Species and their communities are the actual goal of ecological stream management and rehabilitation.

Controlling and response characteristics are not solely related to one of the mentioned groups of factors. There are mutual interactions. Structures, for example, can respond to the action of stream hydrology but can also reduce discharge fluctuations. Alternatively, species can be adapted to stream hydrology but, for example, trees can operate on stream hydrology and morphology. Despite a dominant hierarchical effect, a feedback is always present. Thus, factors interact on different hierarchical scale levels and with different intensity.

Knowledge of the hierarchy in factors and processes acting in space and time in streams, allows us also to infer the direction and magnitude of potential changes due to human activities (Naiman et al. 1992): changes which refer to disturbance as well as to restoration, and the time involved/needed (Niemi et al. 1990). Human disturbances can be seen as a sixth 'S'; the 'S' of Steering. The disturbance and restoration of streams is steered in a negative or positive direction. Integrated adaptive management includes these aspects.

Biological parameters that are indicative for the ecological quality state of the ecosystem. Within the use of biological parameters two approaches dominate assessment:

- Indicators;
- Communities or species assemblages.



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- *Figure 2. Main structure of the 5-S-model with key factors and functional aspects (adapted from Verdonschot et al., 1998).*

The Driver-Pressure-State-Impact-Response (DPSIR) scheme provides a framework to link socio-economy with ecology (EEA 2007) and has been applied in previous similar studies (Elliott 2002, Karageorgis et al. 2005), whereas a main advantage of the scheme is its simplicity that renders the communication with non-scientists feasible (Stanners et al. 2007).

Society's food demand, for instance, is a Driver of agricultural land use. Application of fertilisers and pesticides in agricultural crops is often linked with pollution and eutrophication (Pressure) and causes water quality deterioration of adjacent rivers and lakes. Nutrients (N, P) and contaminants are being transferred with surface runoff from agricultural areas and through nutrient leaching from the soils. This has a stimulating direct effect on the growth of macrophytes and algae, but will also affect the aquatic fauna (fish, benthic invertebrates) as soon as decomposers start depleting oxygen (State). In parallel to eutrophication and contamination, rivers in agricultural landscapes are morphologically modified and hydrologically regulated (Pressure). As a result, microhabitats and flow regimes may change (State).

Following high population density and its demand for food (Driver) weirs and dams (Pressure) are built to control the ground water levels (State), but also disrupt the longitudinal connectivity of the system (State). Land use is often extended to the river banks and inhibits the development of a natural (vegetated) riparian buffer. As a consequence, the riverine fauna and flora is being disrupted, sensitive taxa disappear (Impact), and a few tolerant taxa become dominant in the system (Impact). Rivers and estuaries are easily being invaded by alien species (Impact).

To reverse degradation and to improve ecological status, restoration and mitigation measures are required. Best-practice agriculture (Response), for instance, might reduce the amount of fertilisers applied per area to the amount that is equivalent to the plant biomass produced per area. Hydromorphological conditions might be actively restored (Response) to a more diverse habitat and flow regime. Land use in the riparian zone might be abandoned (Response) to promote the natural development of a diverse riparian corridor, i.e. a mixed buffer strip with grasses, shrubs and trees.

The Response component is incomplete with respect to the objectives of this study. In parallel to the degradation side of the scheme (Pressure-State-Impact), a similar cause-effect chain can be drafted for the Management (restoration) side, i.e. a Response-State-Impact chain (Figure 3). A specific restoration measure or any other kind of ecosystem management is considered to have a positive effect on environmental conditions (State), which in turn should have a positive Impact on the biota, i.e. Recovery. In its strict sense Recovery refers to the full recovery of both community structure and function accompanied by all physical and chemical conditions prior to degradation (Henry & Amoros 1995). The extension of the DPSIR scheme with Recovery eventually results in the DPSIRR scheme, i.e. the Driver-Pressure-State-Impact-Response-Recovery chain (Feld et al. 2011).

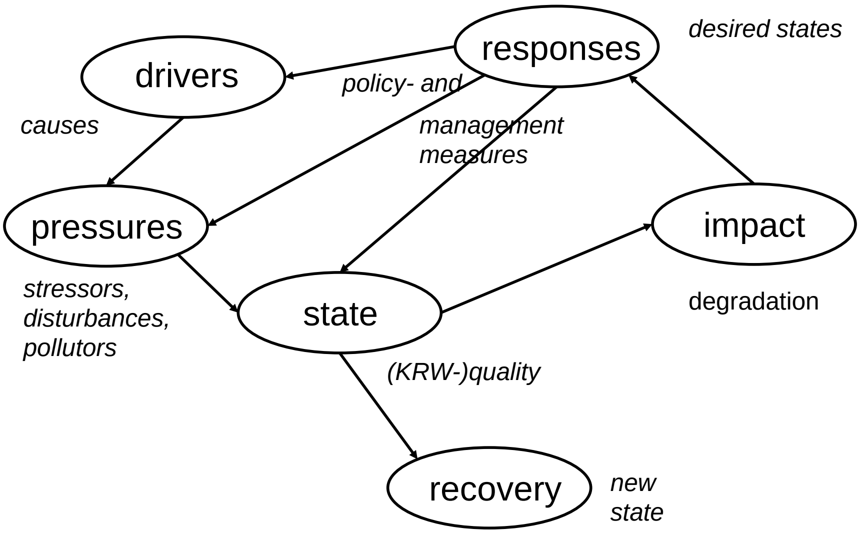


Figure 3. The Driver-Pressure-State-Impact-Response-Recovery chain (DPSIRR).

The 5-S-Model and the DPSIRR-chain are combined in one approach whereby two other important aspects are integrated: scale and hierarchy (Figure 4).

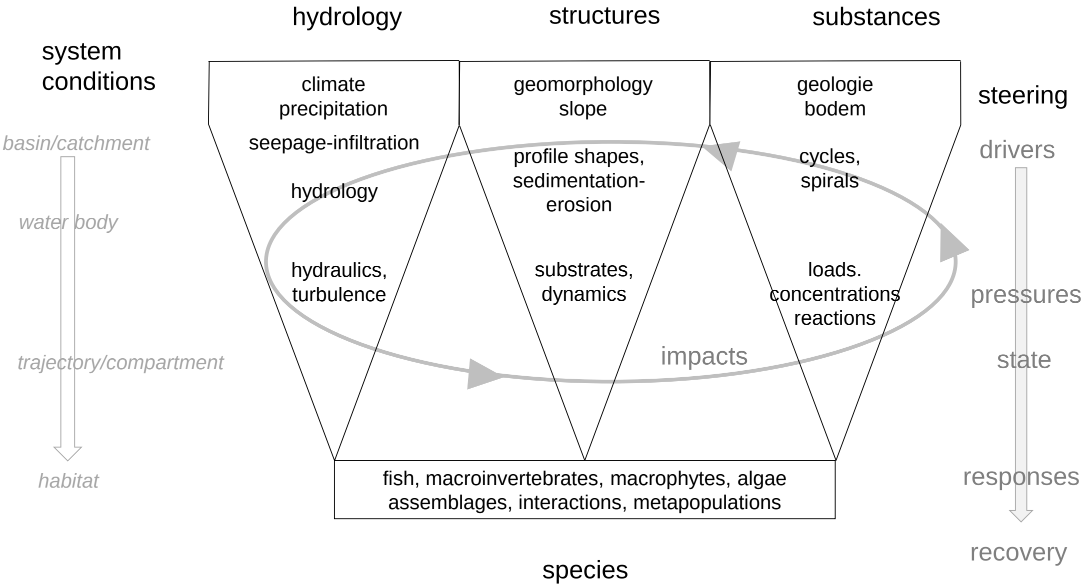


Figure 4. Integration of the 5-S-Model, the DPSIRR-chain and the components of scale and hierarchy.

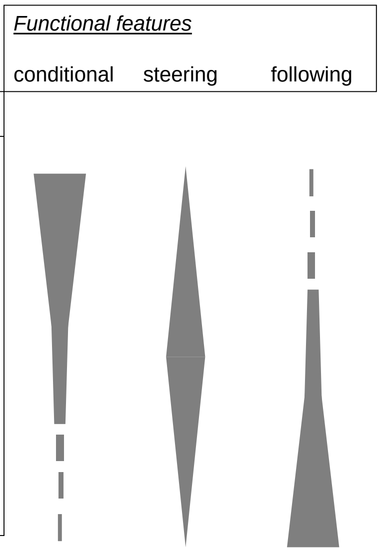
In an ecosystem approach the water managers first performs a water (eco)system analysis. Such an analysis is per definition based upon whole water basins or catchment (Verdonschot 2000). WFD water bodies can be parts of a water basin or catchment and both can comprise more water types. By applying both the 5-S-Model and DPSIRR approach scale and hierarchy become automatically part of the analysis.

Hierarchy comprises the effects of steering factors upon drivers for species and species assemblages. Hierarchy is important linking processes over different scales. Processes and factors acting at the scale of system conditions are not or hardly (climate change) influenced by human activities.
A clear distinction must be made between processes and factors that set conditions for the aquatic ecosystems (but are hardly manageable) and steering and key processes and factors that can be managed Furthermore, processes and factors are not independent from each other. For example, leave packages are depedent on current but can also act to reduce discharge peaks. Despite a dominance relation between hierarchical more important variables, like system conditions, in comparison to lower scales factors, there is always a back loop. The interactions between factors and processes within and between scales is always present but can differ in hierarchy and intensity. Knowledge of hierarchical scaled interactions can make adaptive management much more cost-effective. Managing a more dominant processes will result in a more higher effect.

The ecosystem approach that integrates the 5-S-Model and the DPSIRR-chain into one practical system analysis approach is not a rigid frame but needs to be elaborated per basin or catchment.

The relevant processes and factors that become quantified through the ecosystem approach also give way to select the measures that are needed. This selection uses the climate adaptation labels to be able to prioritise the measures.

5-S-Model	*steering factors*
System conditions	climate (temperature, precipitation) geology/geomorphology (slope, soil composition)
Hydrology	ground water, hydrology hydraulics
Structures	length en transversal profile substrate mozaieks
Substances	O_2, organic material, nutrients macro-ions, micropollutants
Species	flora, fauna



Box 2 Example of the application of the 5-S-Model

Introduction

The noble crayfish (*Astacus astacus* (Linn. 1758)) is globally threatened and listed as an endangered species. This native species is severely affected by the plague fungus (*Aphanomyces astaci* Schikora), as well as by channalization, dredging and pollution. Only a few isolated populations remained in the Netherlands. The last ten years several projects have been developed to restore the decimated crayfish population. These projects were related to reduce respectively, sewer pollution, fish predation, habitat loss, eutrophication and loss of water plants, use of herbicides, and siltation. None used an ecosystem approach, thus focused on the whole catchment and related the abiotic and biotic preferences of *A. astacus* to the abiotic and biotic characteristics of the stream ecosystem.

Study area

Two streams arise on a south-eastern slope (1.0 %) of a glacial hill-ridge at an elevation of 45 m above sea level (Rozendaalse and Beekhuizense stream). Both are spring-fed lowland streams flowing through artificial ponds. The streams are about 3-4 km long before they enter the river Rhine. The catchment (4-6 km^2) is located above an impermeable clay-layer. The groundwater above this layer feeds the streams through more concentrated (in the spring areas) and more diffuse seepage in the upper reaches and ponds. The average discharge of both streams is about 0.02 m^3/s. The bottom material consists of fluvio-glacial deposits (sand and loam). Over the last centuries, both streams were several times adapted for recreational and industrial purposes. Nowadays, the upper part of the catchment is forested (> 95 %), and the lower part is mainly urbanized or in agricultural use. Populations of *Astacus astacus* are known to occur in the Rozendaalse stream, already centuries ago. In the mid-eighties the population density show a marked decrease. The presence of the noble crayfish in the Beekhuizense stream is never reported.

Objectives

The questions from water and nature management institutions to improve the population of A. astacus are:

1. How can we protect and increase the A. astacus population in the Rozendaalse stream?
2. Are there possibilities to introduce and establish an A. astacus population in the Beekhuizense stream?

To answer these questions the 5-S-model is used.

Application of the 5-S-model

In order to generate the proper answers, the controlling processes, factors and their hierarchy according to the 5-S-model, acting in both streams are weighted against the abiotic and biotic demands of *A. astacus*. To simplify this weighing process only those factors important to the crayfish are taken into account. Here, only the components of stream hydrology and structures are shown, the full analysis can be found in Verdonschot et al. 1998.

Stream hydrology

The relation between *A. astacus* and stream hydrology is summed up in table below. The ground water supply is large enough to overcome dry periods and to guarantee a permanent discharge throughout the year. Only, in very dry successive years the upper most part of the Rozendaalse stream dries up. The development of coniferious forest in the catchment could be a cause of reduction of water supply. *A. astacus* inhabits slow flowing waters (current speed < 30 cm/s), which is related to a suitable oxygen regime. This condition is met in both streams.

Suitability of the Rozendaalse and Beekhuizense stream for A. astacus with respect to stream hydrology.

Stream hydrology	**Controlling factors**	*parameters*	*conditions A. astacus*	*habitat Rozendaalse stream*	*Beekhuizense stream*	*Rozendaalse stream*	*suitability Beekhuizense stream*
	Ground water	*supply*	continous	continuous	continuous	suited	suited
	Hydrology	*maximum depth m*	< 30	0,80	0,95	suited	suited
		surface ha	< 50	ponds < 50	ponds < 50	suited	suited
	Hydraulics	*current cm/s*	< 30	10-30	5-45	suited	suited

	running	+++	+++	+++	suited	suited
	stagnant	+++	+++	++	suited	suited

Legend: +++/--- strong (positive or negative) preference, ++/-- (positive or negative) preference, +/- low (positive or negative preference) with respect to A. astacus and respectively, abundant/never, present/incidental and occurring with respect to the streams.

Structures

The presence of weirs in the streams prevent crayfish to migrate upstream, but also isolate the remaining population and prevent competitors (and the crayfish plague fungus) to move in. The weirs also prevent a natural colonisation of the Beekhuizense stream, which would be possible because both streams join downstream. *A. astacus* is often found in meandering streams, with a large variation in current patterns and substrates mosaics to provide shelter and food for all life stages. A structured bank profile offers crayfish places to hide and a loamy bank is preferred to dig burrows. An undercut loamy bank with roots, branches, fallen trees and stones offers optimal habitat conditions. *A. astacus* also prefers shaded banks. Vegetation both serves as food and offers shelter, especially for young stages. Both, the Rozendaalse and Beekhuizense stream have a quite straight longitudinal profile and an often fixed, especially in the Rozendaalse stream, transversal profile. The substrate diversity is low in both streams. Also, trees lack for the larger part of the Rozendaalse stream and vegetation is scarcely developed. The Beekhuizense stream is more suited. It is more shaded and the banks offer a more diverse mosaic of structures. Still, the lack of vegetation and the sparse amount of structures in the latter stream again offer a less optimal habitat condition for the crayfish.

Suitability of the Rozendaalse and Beekhuizense stream for A. astacus with respect to structures.

Structures	**Controlling factors**	*parameters*	*habitat conditions A. astacus*	*references*	*Rozendaalse stream*	*Beekhuizense stream*	*suitability Rozendaalse stream*	*Beekhuizense stream suitability*
	Longitudinal profile	*meandering*	+++	24	+	+	insufficient	insufficient
	Transversal profile	*bank variability*	+++	26	-	+	very insufficient	insufficient
		undercut banks	+++	26	-	+/-	very insufficient	locally suited
		shade	+++	26	-	+/-	very insufficient	insufficient
		burrows	+++	30	+/-	++	very insufficient	very insufficient
		shelter	+++	31	+/-	++/-	very insufficient	locally sufficient
	Substrate mosaics	*silt*	+	26	+/+++	++/+	locally insufficient	suited
		stones	+++	25	+	+	insufficient	insufficient

	gravel	+++	30	+	+	insufficient	insufficient
	sand	+++	26	++	+++	suited	suited
	leaves	+++	26	+++	+++	suited	suited
	roots	+++	32	-	+/-	very insufficient	very insufficient
	wood	+++	26	-	+	very insufficient	insufficient
	vegetation	30-80%	24	< 5%	< 10%	very insufficient	insufficient
	detritus	+++	31	+	+/-	insufficient	insufficient

Legend: +++/--- strong (positive or negative) preference, ++/-- (positive or negative) preference, +/- low (positive or negative preference) with respect to A. astacus and respectively, abundant/never, present/incidental and occurring with respect to the streams.

Conclusions

Structures in the Rozendaalse stream are very insufficient to provide an optimal amount of hiding places for the noble crayfish. The longitudinal profile is too straight and the transversal profile too often fixed. Also shading is limited. Locally, the bottom contains too much silt. Therefore, the following measures are by means of the 5-S-model, deduced:

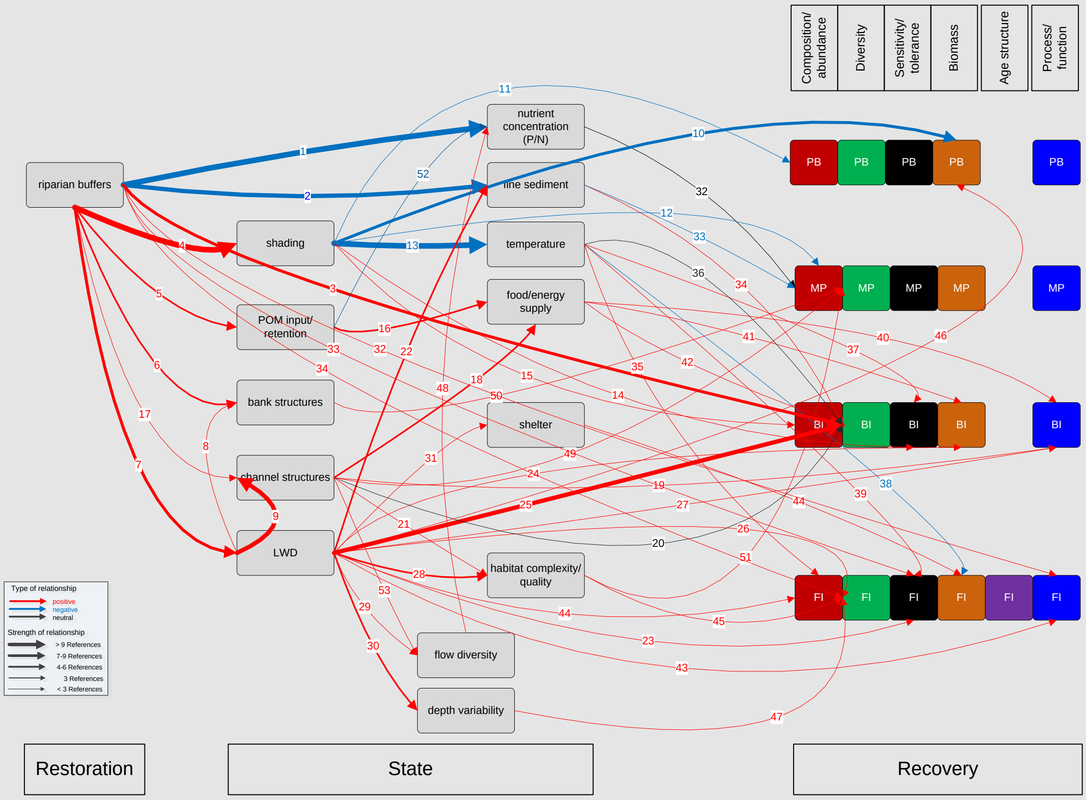
- prevent drying up (and in the long term stimulate the development of deciduous instead of coniferous forest in the catchment),
- remove artificial bank stabilization,
- install artificial structures by means of natural materials on the short term and - plant elders (*Alnus glutinosa*) to stimulate the development of structures in the long term,
- prevent the removal of vegetation and organic structures like debris dams, branches and leaf packages by omitting maintenance,
- stimulate vegetation development in the ponds by removing bottom dwelling fishes, omitting removal of vegetation and locally reducing input of fertilizers,
- prevent the inflow of sewer and toxic substances, and
- monitor the crayfish population as well as its abiotic and biotic habitat conditions.

Concerning introduction of *A. astacus* in the Beekhuizense stream should, according to the use of the 5-S-model, the following be considered:

- introduction can only take place in isolated systems like the Beekhuizense stream above the weirs to prevent contamination with the plague fungus,
- introduction is only allowed when abiotic and biotic conditions are suited, for the Beekhuizense stream this implies;
- further improvement of natural structures, especially in the ponds.

Box 3 Example of a part of a DPSIRR chain

Water quality improvement by riparian buffers in high- and low-energy streams primarily aims at buffering the adverse impacts of intensive agricultural land use adjacent to streams and rivers. A differentiation between high- and low-energy streams was made a priori and based on the assumption that both natural riparian buffer conditions and typical land uses adjacent to a stream reach differ depending on the stream and floodplain gradients. In both cases, however, a sufficiently wide and ideally mixed riparian vegetation strip at both sides of a stream is considered to retain plant nutrients (e.g., nitrogen and phosphorous components), fine sediments and toxic substances (e.g., pesticides) that enter streams via surface runoff from adjacent agricultural areas. Riparian trees provide shade and organic material (leaf litter, wood) that have various affects on in-stream biota.



Part of a DPSIRR chain. Water quality improvement by riparian buffers in low-energy streams. Thickness of arrows equivalent to the number of references.

Forty-eight references met the review criteria and were used to construct a DPSIRR chain for riparian buffers in low-energy streams. The restoration of riparian vegetation either referred to active measures, i.e. the instalment of riparian buffers or to passive restoration by allowing riparian buffer strips to establish either with fencing (to exclude large herbivores) or without fencing. In general, mixed riparian buffers consisting of trees, shrubs and grass strips are, considered to be most effective in the retention of fine sediments and nutrients from both surface runoff and the upper groundwater layer. Results and suggestions on the minimum width and length of riparian vegetation to effectively buffer fine sediments and nutrients are highly variable in the restoration literature. One review, for instance, reported a width range of 3–200 m. The authors concluded from their review that a minimum width of 15 m on either side of a stream was sufficient to protect streams under most conditions, while a minimum buffer width of at least 30 m on either side has been found to provide also shading comparable to old-growth riparian forest. Buffers of 30 m width were found to be successful in maintaining macroinvertebrate background levels in Californian streams adjacent to logging activities. Another author suggested a function to calculate the minimum buffer width based on the riparian slope.

Results of the minimum buffer length are less frequent in the literature. From modelling studies in New Zealand is was concluded that the minimum length of riparian buffers was 1–5 km for first-order streams versus 10–20 km for fifth-order streams in order to achieve reductions of up to 5° C water temperature. Based on 16 studies that also provided information on the length of the studied sites or reaches, this was less than 500 m for two thirds of the studies; four references had study sites >1 km length.

4.3 Strategic adaptive management

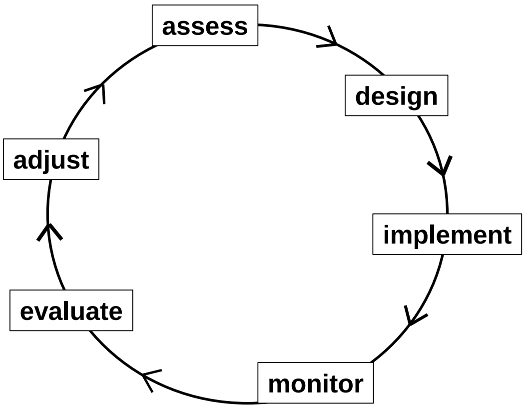
Introduction

What to accomplish through strategic adaptive management (Nyberg 1999)?

- find better ways of meeting objectives
- identify key gaps in understanding
- improve understanding of ecosystem responses, thresholds and dynamics, in order to adapt practices to fit changing social values and ecological conditions
- gain reliable feedback about effectiveness of alternative policies/practices
- encourage innovation and learning
- pass on information and knowledge gained through experience
- foster an organizational culture that emphasizes learning and responsiveness
- in some cases, adaptive management may also help detect cumulative, long-term, large scale, and emergent effects of actions

Brian Nyberg published in 1999 a practical manual for strategic adaptive management. The following paragraph is adapted using this practical manual as guideline (Nyberg 1999).

Strategic adaptive management involves six main steps:



1) problem assessment,
2) design of the plan,
3) implementation,
4) monitoring,
5) evaluation,
6) adjustment.

These six steps provide a structured approach to strategic adaptive management. The steps are not rigid rules but indicative to give freedom for creative thinking ty that is essential for dealing effectively with change and uncertainty. The way each step is dealt with always depends on the local current and future condition of the respective water body under study and on the alternatives offered by those involved in the application. The following guidelines indicate directions in thinking, are meant to stimulate thoughts and hopefully open discussions amongst those involved.

- Step 1 (problem assessment) is often done in one or more (facilitated) workshops. Participants define the scope of the management problem, synthesize existing knowledge about the system, and explore the potential outcomes of alternative management actions. Explicit forecasts are made about outcomes, in order to assess which measures are most likely to meet management objectives. During this exploration and forecasting process, key gaps in understanding of the system (i.e., those that limit the ability to predict outcomes) are identified.
- Step 2 (design) involves designing a management plan and monitoring program that will provide reliable feedback about the effectiveness of the chosen actions. Ideally, the plan should also be designed to yield information that will fill the key gaps in understanding identified in Step 1. It is useful to evaluate one or more proposed plans or designs, on the basis of costs, risks, informativeness and ability to meet management objectives.
- In Step 3 (implementation), the plan is put into practice.
- In Step 4 (monitoring), indicators are monitored to determine how effective actions are in meeting management objectives, and to test the hypothesised relationships that formed the basis for the forecasts.
- Step 5 (evaluation) involves comparing the actual outcomes to forecasts and interpreting the reasons underlying any differences.
- In Step 6 (adjustment), practices, objectives, and the models used to make forecasts are adjusted to reflect new understanding. Understanding gained in the each of these six steps may lead to reassessment of the problem, new questions, and new options to try in a continual cycle of improvement.

In reality, some of the steps outlined will overlap; some will have to be revisited; some may be better done in more detail than others. All steps should be planned in advance, though it may be necessary to modify them later. All six steps are essential to adaptive management. Omission of one or more will hamper the ability to learn from management actions. In addition, documenting the key elements of each step, and communicating results are crucial to building a "legacy of knowledge", especially for projects that extend over a long time.

Step 1 Assess

To assess a problem one or more facilitated (expert and/or stakeholder and/or combined) workshops can be organised. Keep the following in mind:

- Problem assessment is an iterative process thus be willing to return to earlier steps, use alternatives, e.g. in aims, scales or management options. Avoid defining a problem in terms of preconceived solutions, since this would limit the development of imaginative alternatives.
- Bring together knowledge experts (scientists), policy-makers, managers (those who will plan, implement, monitor, evaluate), local people affected by plans and others who will be affected by the decisions.
- Synthesize existing knowledge by developing a (conceptual) model (a simple diagram or graph or a simulation or existing model) of the system, and then use the model to explore different management options.
- The complexity of the problem decides the number of people involved. Complex problems sometimes need outside facilitators.
- Document all major steps in the process including functional relationships, models, key uncertainties; reasoning behind the choice of management plan, monitoring program and expected outcomes; methods, sites, treatments; participants and their roles and responsibilities.
- Facilitate learning creates success. Project leaders play a crucial leadership role in encouraging the conditions that facilitate strategic adaptive management. In particular, institutional environment and individual attitudes are as critical to effective strategic adaptive management and learning as the actual steps followed. There is an extensive body of literature that discusses "organizational learning";

On forehand synthesize existing knowledge about the aquatic ecosystem. Understanding of complex and dynamic aquatic ecosystems will always be incomplete. However, not all gaps in understanding necessarily need to be filled in order to decide between alternative adaptive management actions. For example, where different assumptions lead to the same forecast, or to the same choice of management measure, there is no need to resolve the uncertainty about which assumption is "correct".

The workshop includes the following 6 steps:

1.1 Define the (initial) scope of the problem.

- Identify processes and factors that are affected by the current or future stressor(s), including (future) management actions of short-term and long-term, cumulative and large-scale effects.
- Define the spatial scale and temporal scale to be considered.
- Define the processes and range of factors (i.e., values) and their sensitivity under current or future stress (e.g., consider risk of (further) degradation).
- Identify the (management) problem.

1.2 Define measurable management objectives (desired states).

- Describe a quantified desired state and extract objectives.

- Identify key indicators for each objective. Indicators are measurable attributes of ecosystem behaviour that are relevant to the aims, responsive to management actions; allow weighing management options and, assessing outcomes. Indicators respond at different temporal (short, medium, long term) and spatial scales (e.g., site, landscape, region).
- Take into account the cost and practicality of measuring each indicator.

1.3 Identify possible management measures

- Select potential measures.
- Use the climate adaptation label to optimize measure selection.

1.4 Explore the potential outcomes of alternative management measures.

- Develop a range of plausible management measures.
- Develop a conceptual model of the aquatic ecosystem that provides (i) insight in linkages and functional relationships between different measures and indicators, (ii) information about changes over time and space and (iii) be able to assess the integrated consequences of a suite of measures.
- Use the model (whether it is a simulation model or conceptual model) to explore the effects of alternative measures (gaming). Draw impact hypothesis diagrams for a given measure.
- Make explicit forecasts about outcomes of measures in terms of responses of indicators in order to assess which measures are most likely to meet management objectives.

1.6 Identify and assess key gaps in understanding (key uncertainties).

- Through exploring alternatives and forecasting responses, key gaps in understanding of the system will emerge. Express these key uncertainties as alternative hypotheses of system function.
- Consider the relationship between measure(s) and indicators over a range of conditions (i.e., how will an indicator respond to different degrees of a treatment?).
- Assess the sensitivity of forecasts and management choices to alternative hypotheses. If different hypotheses lead to different forecasts or management choices, then it is worthwhile designing a management experiment that will discriminate between them (sensitivity analysis).

Step 2 Design

If measures are selected a management plan and monitoring program that is informative and provide reliable feedback are designed. The most informative plans are those that are deliberately designed as management experiments, to discriminate between the alternative hypotheses formulated in Step 1 (active adaptive management). Typically, this involves comparing a range of management measures. The alternative, passive adaptive management is to assume that the most plausible hypothesis is true, and then implement the measure(s) that will have the best outcome. Active adaptive management usually provides feedback that is more reliable and less ambiguous than passive adaptive management. However, passive adaptive management may be the best (or only) alternative where:

- it is impossible or impractical to design a powerful experiment;
- the ecological costs of testing a range of actions is unacceptably high;
- there is a high level of certainty and agreement about which hypothesis is true, and thus which action is best;
- past actions or natural disturbances provide reliable information about response over a range of conditions.

In some cases it may be valuable to test measures in a pilot project before testing them at a larger scale, in order to narrow the range of plausible measures, and refine methodologies. At this stage it is also important to plan (i) how the monitoring data will be managed and analysed, (ii) how measures and objectives will be adjusted, and (iii) how information will be communicated.

2.1 Design the adaptive management plan.

- Consider a number of management options, e.g., the passive approach, the active approach, or a (range of) pilot(s).
- Ideally, a well-designed management experiment should include controls; replication of treatments in space and time; allocation of treatments to control for bias and environmental gradients, and to ensure statistical independence; and evaluation of confidence levels and power.
- Evaluate the proposed management plan or plans, on the basis of ability to meet long term objectives, ecological and economic costs, risk of negative outcomes, and ability to fill key gaps in understanding. Decide which proposed plan to implement.

2.2 Design the monitoring protocol.

- Design a monitoring program and specify:
    - the type and amount of baseline (pre-treatment) data required;
    - frequency, timing, and duration of monitoring;
    - indicators to be monitored at each interval;
    - appropriate spatial scales for monitoring different indicators;
    - who is responsible for undertaking different aspects of monitoring.

2.4 Plan the data management and analysis.

- Specify method(s) that will be used to analyse data.
- Set up system for managing data over the long term (e.g., storage, analysis, access).
- Agree on who will interpret data and who will have access to it.

2.5 State how adaptive management measures and/or objectives will be adjusted.

- Identify who needs what information when in order to make timely changes.
- Define the intensity and degree of response in an indicator that will trigger a change in management measures or objectives.

- Adjustments should reflect the trade-off between the costs of acting if preliminary results later prove to be incorrect, and the costs of not acting if they later prove to be correct.

2.6 Set up system to communicate results and information.

Step 3 Implement the management plan

3.1 Implement the adaptive management measures

- Implement the management measures according to the plan.
- Sometimes it may be necessary to deviate from the original plan: decide when and what types of deviations are acceptable. Ensure that these deviations are clear and accepted by all partners.

Step 4 Monitor

Monitoring is still too often neglected in conventional management, yet it is critical to improvement. Monitoring allows you to assess how measures actually affect indicators. This information then allows you to evaluate the effectiveness of alternative measures, adjust ideas/hypotheses of how the aquatic ecosystem functions, and take appropriate corrective action. Monitoring can also determine if measures were implemented as planned, and may detect "surprising" events.

4.1 Monitor implementation and document any deviations from plan.

- Follow the monitoring protocol designed in Step 2.
- Sometimes it may be necessary to deviate from the original plan: decide when and what types of deviations are acceptable. Ensure that these deviations are clear and accepted by all partners.
- Did we do what we planned (implementation or compliance)?

Step 5 Evaluate

For evaluation the monitoring data are analysed and the actual results compared to forecasts made in Step 1. The evaluation should explain why results occurred and include recommendations for future action. Outcomes can be the result of the management measure(s), confounding factors not under your control, or both. The strength of the results depends on the design of the management experiment and monitoring program. Negative or unexpected outcomes can be as informative as positive, predicted outcomes. Results, whether expected or unexpected, must be documented and communicated, so that knowledge and experience are passed on to others facing similar problems.

5.1 Compare actual outcomes to forecasts made in Step 1.

- Were the objectives met (effectiveness)?? If not, why not?
- Evaluate the reasons underlying any differences between actual and forecasted outcomes.
- Evaluate to what degree tested hypotheses are supported by the results.

5.2 Document results and communicate them to others facing similar management issues.

Step 6 Adjust

The information gathered in the preceding five steps is used to verify or update the conceptual ideas/models used to make the initial forecasts, and adjust management measures as necessary. Objectives are reviewed and adjusted to ensure that they remain consistent with overall objectives. In order to facilitate change, participants should consider at the outset (i.e., in Step 2) how measures might be adjusted. Often, new information will suggest new management solutions, or new questions to answer or leading to another cycle of assessment, design, implementation, monitoring and evaluation. Furthermore, management experiments may yield some useful information that was not anticipated. Well-defined feedback loops must ensure that information is used promptly and appropriately.

6.1 Adjust subsequent management decisions and policies, and re-evaluate objectives, as necessary.

- Identify where uncertainties have been reduced, and where they remain unresolved.
- Adjust the (conceptual) model used to forecast outcomes (Step 1) so that it reflects the hypothesis supported by results.
- In deciding what adjustments to make, consider the reasons underlying differences between expected and actual outcomes (Step 5).
- Future measures should be based on which hypothesis of ecosystem function was supported by the results.

6.4 Make new predictions, design new management experiments, test new options.

- i.e., return to step 1 or 2
- In future management experiments, address unresolved or newly-identified uncertainties that affect predicted outcomes and decisions about which measures to implement.

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