Case Study 6 – Annex

Understanding eutrophication processes and restoring good water quality in Lake Ringsjön and Rönne å Catchment in Kattegat, Sweden[1]

[1]See full case study report for author and project information. Further information at https://aquacross.eu/content/case-study-6-understanding-eutrophication-processes-and-restoring-good-water-quality-lake

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Annex 1: Data on the Rönne catchment

History of two water associations in Sweden

History of the Rönneå River committee

The Rönneå River committee was formed in 1978 and includes representatives from eight municipalities, the County Board, the Southern Sweden Water Supply (Sydvatten), the Civil Aviation Authority, the angling association and the land-owners' organisation. The committee now exists alongside the Rönneå water council which has the wider remit under WFD. Their main focus is on monitoring water quality and reporting results to national water monitoring programme. The reports could be used for the basis of water quality measures but the committee have no political power (Franzén et al 2015).

Rönneå had previously experienced many water related problems such as flooding, drought, acidification and pollution. In 1995, the Rönneå committee set up a working group with the aim to collect money to implement water management measures. Although there was sufficient agency for this, progress was blocked by high polluting municipalities and industries (Franzén et al 2015).

The recent developments within WFD of a broader scope and stakeholder representation with the Rönneå catchment could increase the scope of water management (Franzén et al 2015).

History of the Ringsjö Lake committee

The Ringsjö Lake committee was established in 1980 to investigate the possibilities of improving Ringsjö. It covered the subcatchment of the Ringsjö lakes within the Rönneå catchment, shared by the Eslöv, Höör and Hörby municipalities. Representatives were included from the municipalities, County Board, Lund University, farmers, nature and fishery conservation organisations, Southern Sweden Water Supply (Sydvatten), and Ringsjö lake fishery company (Ringsjöfisk) (Franzén et al 2015).

The committee carried out a number of studies looking at management of manure, crop selection, crop sowing date as well municipal and individual waste water treatment. The committee's work laid the foundation for "Lex Ringsjön" in 1985, section 8a of the Environmental Protection Act that meant that Ringsjö could now be classified as an 'especially pollution sensitive area'. Regulations were then put in place for fertiliser use and storage as well as for individual sewers. These reduced the supply of phosphorus to the lake from >30t/yr to 10t/yr, although there were no visible effects on water quality. Lex Ringsjö is now included in the Environmental Code (Ringsjökommittén 1991)

Following this, the Ringsjö Lake committee implemented further projects to investigate methods to reduce the nutrients in the lake, including cultivation of aquatic plants, field trials with catch crops and a reduction fishery. Catch crops were found to be efficient in preventing nutrient leakage and reduced the amount of nutrient input required the following year, making it easier to meet the regulations for nutrient reduction (Ringsjökommittén 1991).

In 1989, a cyprinid reduction investigation was started by trawling in Satofta Basin. It was expected that a reduction in cyprinids in the lake would allow an increase in zooplankton, which would feed on the algae and improve water quality. Results were mixed, with trawling resulting in higher numbers of young fish the following year, although nutrients concentrations and water transparency did show some improvements (Hansson et al 1999). Biomanipulation is carried out today by the Ringsjö Lake water council (see chapter 1.2).

The Ringsjö Lake and Rönne River committees have worked as two separate water associations, with the Lake committee being replaced by the Lake water council in 2007 (Franzén et al 2015).

Screening data for municipalities

Table 1 Overview on population size and change in catchment municipalities, by Håkan Emilsson, 2016.

Kommun	Inhabitants 2014	Trend [avg pop change/yr]	Classification
Eslöv	32179	244	Förortskommuner till större städer
Hörby	14927	71	Förortskommuner till större städer
Höör	15770	125	Förortskommuner till större städer
Klippan	16733	74	Pendlingskommuner
Perstorp	7174	28	Varuproducerande kommuner
Svalöv	13460	49	Pendlingskommuner
Åstorp	15061	167	Förortskommuner till större städer
Ängleholm	40229	209	Pendlingskommuner
Örkelljunga	9733	23	Varuproducerande kommuner

Table 2 Overview on comprehensive plan processes in the catchments municipality, by Håkan Emilsson, 2016.

Kommun	Year of latest plan	In which phase of creating the comprehensive plan is the municipality now?
Eslöv	2001	planning for new masterplan – ready 2017
Hörby	2005	new plan has been in consultation and is now being reviewed. The suggested plan is available here: http://www.horby.se/oversiktsplan2030
Höör	2002	working on a new masterplan which was put out to consultation in 2012. Still working with the opinions expressed then (seems like people had a lot of opinions about it that weren't included)
Klippan	2013	the plan was remade 2013
Perstorp	2006	the masterplan was evaluated again 2010 and was found valid (proc. in accordance with PBL)
Svalöv	2007	masterplan from 2007, but there is a remade one (though not accepted) from 2016
Åstorp	2012	new masterplan 2012

Ängleholm	2004	making a new plan that was put out for consultation 2014 and are planned to be voted for in KF spring 2016
Örkelljunga	2008	up and running

Ecological status and nutrient data

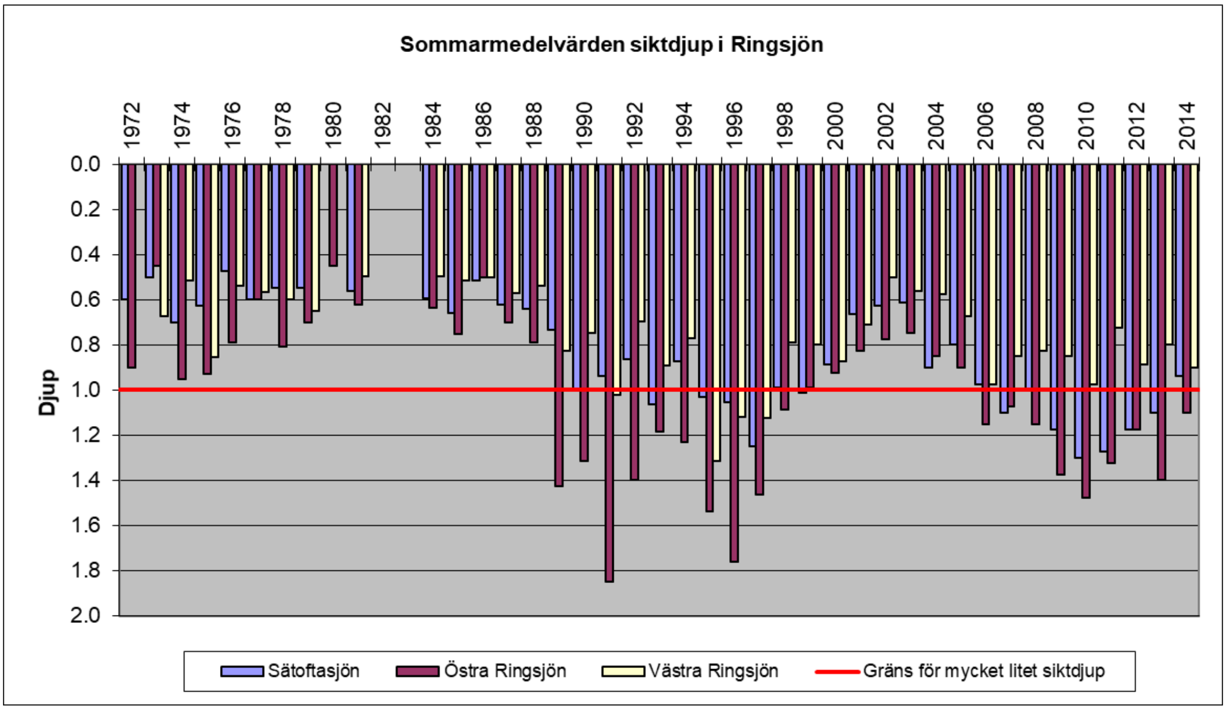


Figure 1 Mean summer Secchi depth in different locations within lake Ringsjön, measured by Ekologgruppen.

Ekologisk status och potential

Vald vattentyp: Alla ytvatten
Vald storhet: Antal
Valt dataset: Vattenförekomster övrigt vatten inklusive preliminära (2010-2015)
Vald vattentyp: Alla vattenförekomster
Cykel: Cykel 2 (2010 - 2015)

Klassning	Antal
God status	7
Måttlig status	29
Otillfredsställande status	8
Dålig ekologisk status	1
Data saknas	-
Summa	45 st

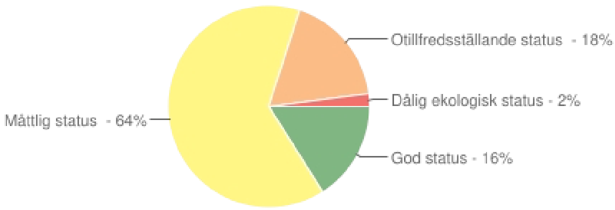


Figure 3 Overview on the 2015 evaluation of the ecological status from river segments and lakes in the Rönne catchment published in VISS (http://viss.lansstyrelsen.se/), prepared by Håkan Emilsson, 2016.

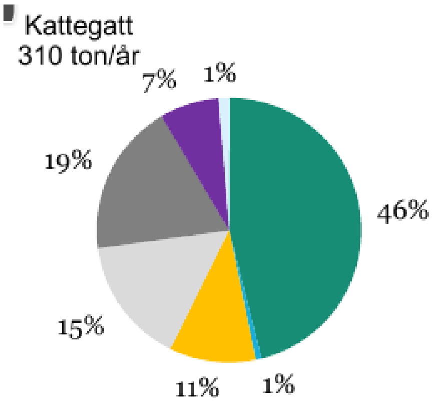


Figure 2 Anthropogenic phosphorus net load for the Kattegatt catchment in 2014 – 310 ton/year, 46 % from agriculture, 19% municipal sewage treatment, 15% private sewage treatment (Havs- och vattenmyndigheten 2016)

Table 3 Gross load of nitrogen (ton/yr) from diffuse and point sources in the Kattegatt basin (Ejhed and Olshammar 2008; Havs- och vattenmyndigheten 2016)

Gross load of nitrogen (ton/yr)	1995	2014
Farmland	23600	17500
Individual drainage	800	900
Municipal wastewater treatment plant	7300	3900

Table 4 Gross load of phosphorus (ton/yr) from diffuse and point sources in the Kattegatt basin (Ejhed and Olshammar 2008; Havs- och vattenmyndigheten 2016)

Gross load of phosphorus (ton/yr)	1995	2014
Farmland	550	580
Individual drainage	80	90
Municipal wastewater treatment plant	200	80

Reflection on EBM criteria from the CS 6 perspective

Table 5 System oriented criteria

System-oriented criteria	CS 6 responses
Ecological integrity and biodiversity	Diversity of zooplankton and macrophytes species are monitored regularly as indicators of improvement of the ecological state. This diversity is understood as a stabilizing factor for the clear water state and addressed in regular reports.
Consider ecosystem connections	The mobility of fish between the three lake basins is monitored, as well as the mobility of fish in the lower stream segments. Other connections that might be relevant are littoral zones, where human activities interfere with the structure and ability for macrophytes to establish. It is also a zone of interaction with aquatic birds.
Account for dynamic nature of ecosystems	Time series of nutrient content is annually updated in monitoring reports. External climate change scenarios are used for research, not for particular management plans. However, the general threat of warming is reflected in the motivation for regular reporting. Feedbacks among trophic levels in the lake are considered, which is why biomanipulation where planktivorous fish are reduced, is considered a viable option to restore the clear water state.
Acknowledge uncertainty	• Have not seen it explicitly discussed in reports • Structural uncertainty on fish data, when relying on individual reporting from business fishers
Appropriate Spatial and Temporal Scales	To observe changes in the lake's state, several decades of monitoring or simulation is necessary. Date on the lake goes back to 70's and models suggest that for a regime shift to the turbid state at least 10 years are necessary before the state gets fully established. The current spatial scale of the Ringsjön water council encompasses three municipalities in the lake's subcatchment. However, some links exist to the lower river stream and thus to the adjacent water council.
Distinct boundaries	Administrative (municipal) boundaries around the lake have been overcome by the water council, however, boundaries between the subcatchments are still hindering even larger collaboration.
Recognise coupled SES	To a degree, all social-ecological couplings and interactions with the lake are represented by water council members. However, there is probably no systematic reflection on whether really all relevant activities in the catchment are appropriately represented and discussed.
Consider cumulative impacts	

Policy Dimensions	Process-oriented criteria	CS 6 narrative describing the capacity of their social system and its actors
Scientific knowledge	Use of Scientific Knowledge	• Scientific knowledge from researchers at Lund university is incorporated in discussions of the water council.

		• Scientific monitoring performed by consultancies (name) are used to inform management
	Interdisciplinarity	• LimnoTip (2013-2015) and Algae Be Gone (2012-2014) are examples for earlier projects
Stakeholder involvement	For all categories	• Water council as suitable hub to link science to business – *one entry for all categories*
Management	Integrated Management	• To a degree yes. But **Fehler! Verweisquelle konnte nicht gefunden werden.** above shows where the integration has limits. For some decisions that affect the lower catchment, cross-water council decisions would be relevant, but are not possible with the current setup. Cross-sectoral collaboration would be more needed in municipalities and county administrative boards to tackle strategic questions on ES synergies and trade-offs.
	Adaptive Management	
	Apply the Precautionary Approach	
	Stakeholder involvement	*See above*
	Appropriate Monitoring	
Policy making	Decisions reflect Societal Choice	• Decisions are taken at the municipality level, and their planning documents (comprehensive plan) are collaboratively built.
	Stakeholder involvement	*See above*
	Sustainability	*Link to chapter 2?*
Social participation	Stakeholder involvement	*See above*

Table 6 Template of process-oriented criteria linked to the main actors in the social system

Annex II Stakeholder Process

Stakeholder activities overview

Table 7 Full list of activities we performed for our research in the Rönne catchment during 2015 – 2018.

Steps	Type of engagement, CS action	Outputs/outcome
1. Oct. 2015	Meeting with CS representative and former contacts who we have collaborated with (2013-2015 in previous Biodiversa project "LimnoTip")	Refinement of research questions, emphasis on 'participation' from the 7 resilience principles
2. Feb.-Jun. 2016	Pre-analysis of socio-economic data based on municipalities and water councils in the catchment: political background, demography, municipality divisions related to water regulation, phase of preparing a comprehensive plan. Visits of the annual water district and the Rönne å water council meeting.	Selection of municipalities currently interested in how to plan with ecosystem services (Annex I – 8.2, Table 2), improving contact to CS representative and making our project aims known through him to municipality mayors and water councils.
3. Sept.-Oct. 2016	Collection of participants to invite for workshops through CS representative with broad invitation letter from us, negotiation with main political representatives on participants. Selection and invitation of participants by us, sent out briefing material on ecosystem services to participants.	Participants list for workshops
4. Nov.-Dec. 2016	Workshops conducted on municipality and water council level. Interviews on municipality level to consolidate insights from workshop discussions.	Data source for answering our research questions 1 and 2, and for scenario development.
5. Jan. 2017	Follow-up information sent out to participants with a summary from the workshop discussions and option for another feedback, further interviews with selected participants on collaboration among administrative actors to support water regulation.	Refinement of data
6. Feb.-June 2017	Scenario development from workshop- generated data together with pre-analysis data	Draft of narratives for model adaptation and scenario analysis.
7. Sept-Nov 2017	Follow-up exchange with stakeholder representative, review of scenario narratives and first chapter from CS report	Refinement of scenarios to be analysed by models.
8. May 2018	Second follow-up with presentation of preliminary results at Ringsjön water council meeting[1]. Further revisions of CS report chapter 2.	Second scenario refinement and preparation of model extension and analysis (section 4.2.3).
9. Nov. 2018	Planned: presentation of final results with dissemination of Swedish summary.	Expected: continued collaboration on further research projects.

Workshops and interviews

This section presents the step-wise procedure and thinking behind the stakeholder-based scenario development for the Rönne å catchment area.

[1] http://www.seslink.org/visiting-the-ringsjon-water-council/

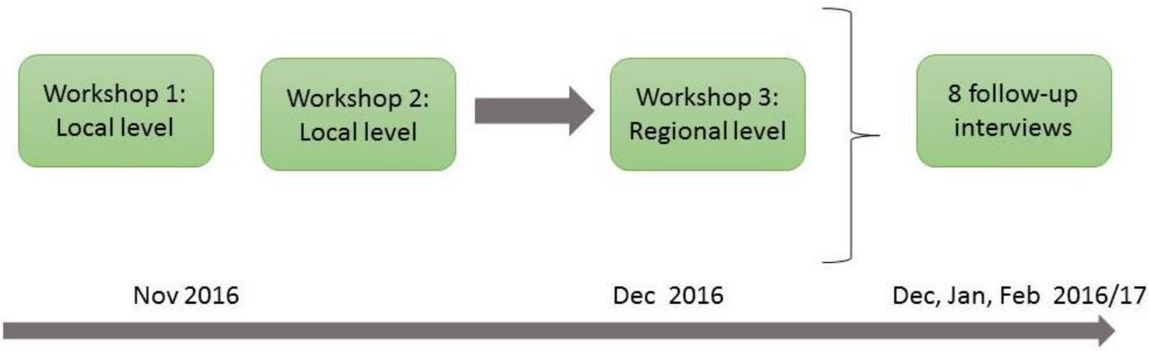


Figure 4 Shows the data collection that acted as basis for the scenario development. In total, three workshops were held and eight follow-up interviews.

1) Understanding the baseline.

Initially, we gathered socioeconomic, institutional and policy data to include several municipalities with similar conditions in our study. We only included municipalities that are currently updating their comprehensive (also called master) plan that states their visions and goals, as they are thinking holistically and long-term. Two municipalities were included based on our criteria, and two more were suggested by stakeholders as they collaborate on many water issues, making it four relevant municipalities for our study.

2) Preparing stakeholder workshops

The second step was to plan the workshops and link the research questions and exercises, while creating mutual benefits for researchers and stakeholders. For example, cross-scale communication is beneficial as it provides a holistic understanding of the topics and allows stakeholders to initiate new contacts. We intentionally mixed civil servants and politicians as 1) according to stakeholders, they rarely interact and, 2) they have complementing viewpoints as they are decision-makers and practitioners. We aimed to create groups with a diversity of perspectives to ensure holistic, representative and cross-scale insights in water governance. We had three workshops (geographic diversity) and, included many institutional scales (e.g. municipalities, county administrative boards) as well as different sectors (drinking water, recreation and sewage). The list of participants was created together with our local contact to ensure diversity and similar group dynamics in all workshops (to ensure cross-workshop comparability). The workshops were followed-up by 8 in-depth interviews to triangulate data, and to follow-up on interesting leads from the workshops.

3) Conducting the workshops

As we focused on creating diverse groups (with varying worldviews and opinions), we collaborated with a facilitator (from Albaeco[2]) to have respectful and fruitful discussions. We started with an introduction of ESS and how they connect to sustainable development, as a

[2] Consultancy at the science-policy interface for strategic environmental communication, science communication and education. http://www.albaeco.se/english/

benefit for the participants. Focus groups (i.e discussions in smaller groups that is specifically appropriate when one is trying to unravel a diversity of perspectives (Carey & Asbury, 2016) were created with one note-taker each to ensure high-quality data and understanding of the discussions. One workshop lasted a full day (10-16) with a total of four exercises. We designed the exercises to incrementally build an understanding of underlying conditions for aquatic ESS in place, their interrelations and the future prospect of how they are affected by policy measures. Details on the exercise design and format can be found in Annex II.

4) Analysing the results

Workshop data is used to identify interactions among ESS from planned measures and to identify actors and activities that are important to reach water related goals (presented in section 3.3). The preliminary narratives described in the following section as main output are based on researchers' understanding of the discussions (and dominating story-lines) about problems and solutions during the workshops. What are weak collaborative links? What is needed for them to create a more sustainable water governance? A local stakeholder in Höör municipality has read through the narratives and confirms that all three alternatives are plausible future scenarios, and the outcome will most likely be a mixture of all of them.

Data collection

Data from the workshops was triangulated (Mathison, 1988) through post-its and posters, notes (taken by researchers), and, follow-up interviews. The exercises were conducted in smaller groups with continuous follow-up questions to increase clarity and depth of data (e.g. "Would you mind giving us an example?" and "Could you explain further what you refer to?"), as well as link to the resilience principles.

The interviews included open-ended semi-structured questions as for example "What social and ecological components are needed to create ecosystem service x?" and "During the workshop, your group discussed the interaction between ES x and y, can you please tell me a little about that conversation?"

Workshop conceptual material

Table 8 Exercises performed to discuss ESS co-production in focus groups and later build scenarios for ESS management.

RQ	Exercise	Expected output
1. Which steps and actors characterise the co-production of aquatic ES? **- who are the beneficiaries?**	Mapping co-production from natural processes, natural structures, labour + knowledge, institutions, infrastructure, money, based on prepared poster, alternative views possible	Graph of actors, natural and social factors for an ES to become accessible for consumption for beneficiaries
2. Which interactions among ES and land uses are perceived? (in the past, now)	Create an ESS flower (representing the distribution of ESS) by giving them petals in different sizes.	Perception on the ES relative abundances.

		Discussions on interactions on a holistic level.
3. Which values / objectives are prioritised and how will they effect ESS interactions? (in natural or social side, micro- or macro-level)	Table with goals, measures and ESS	Set of objectives within each municipality, including a priority list for ESS interactions that are taken into account -> informs target for scenarios
4. What are practical rules/processes to improve decision-making and governance with respect to objectives and trade-offs?	Define vision for municipality. Discuss what measures/processes are necessary to reach vision, based on conceptual model with scales.	Defined strategies to get there. Interaction across levels - who needs to do what and its effect -> informs measures and pathways for scenarios

Workshop example outputs

Exercise 1:

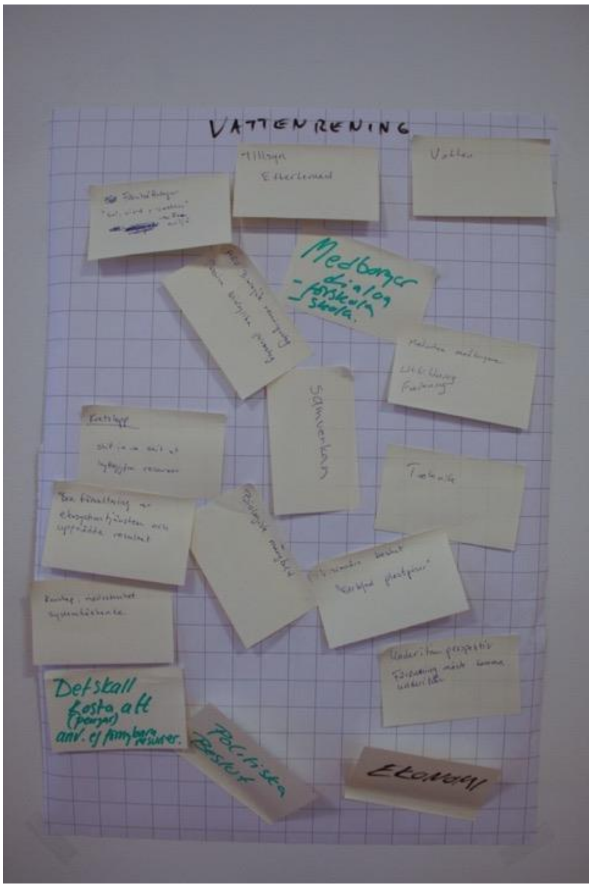


Figure 5 Example for aspects collected in the first exercise on ESS co-production, here nutrient retention at Ringsjön.

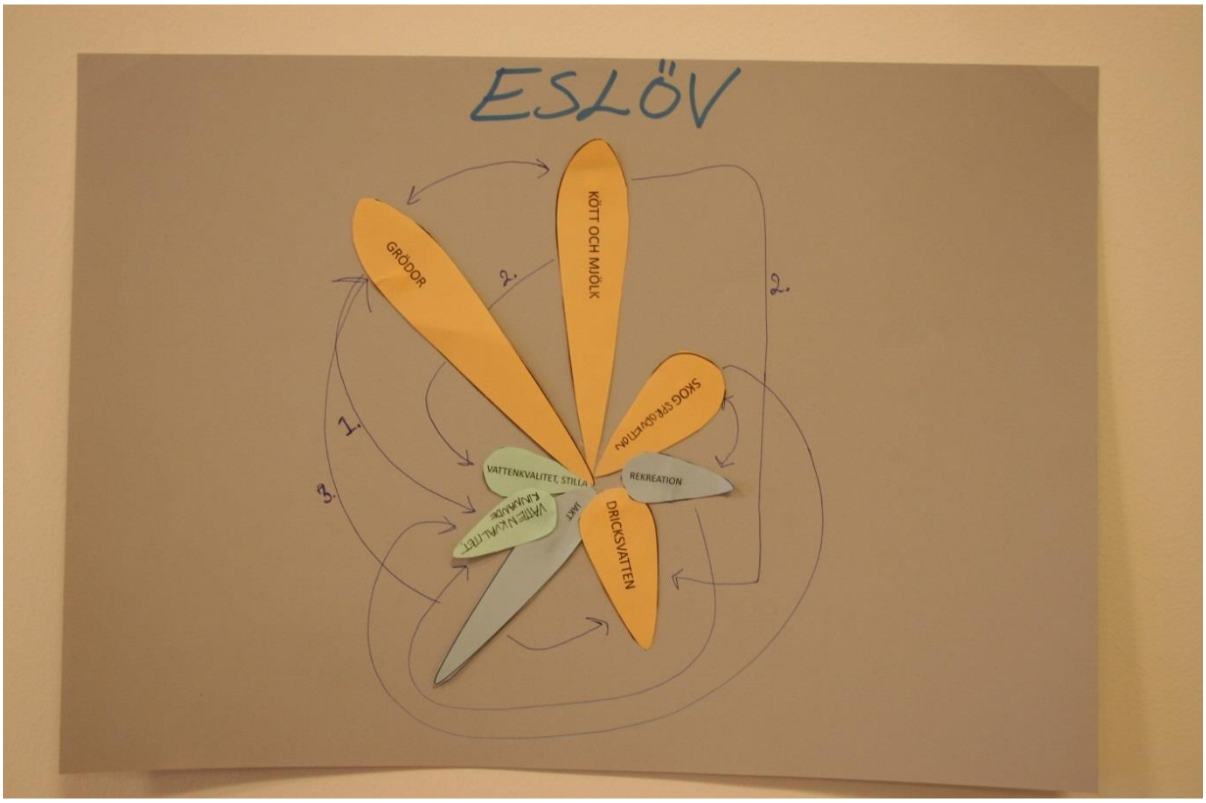
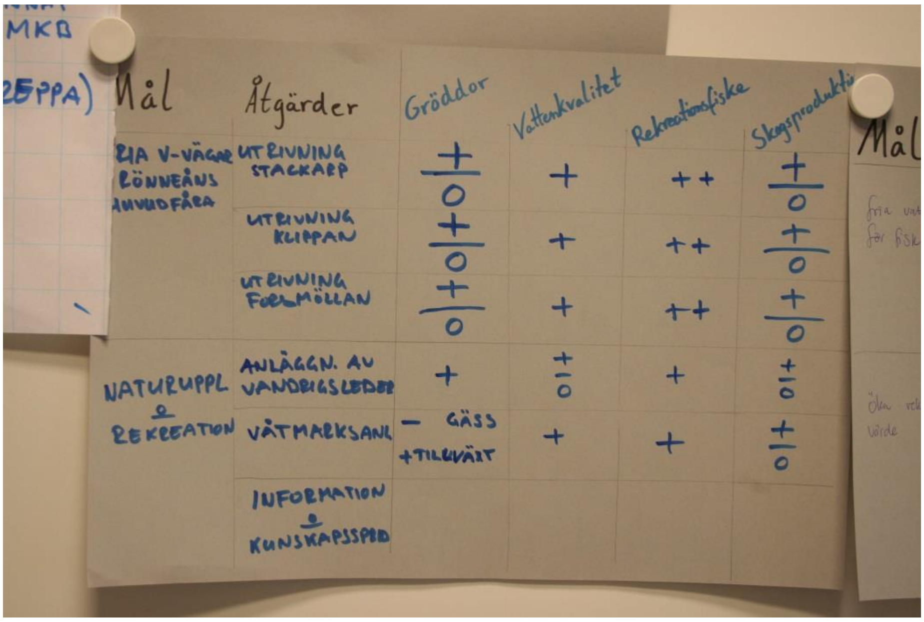


Figure 6 Example for an ESS flower assembled during focus group discussion on a stakeholder workshop in Höör, Nov 2016. Provisioning services (orange) dominated most flowers, particularly crop production, but recreation among the cultural services (blue) scored highest after eight focus group exercises altogether (from three workshops). General water quality was of greater concern than specific nutrient retention services among the regulation services (green).

Exercise 2:

Exercise 3:



Exercise 4

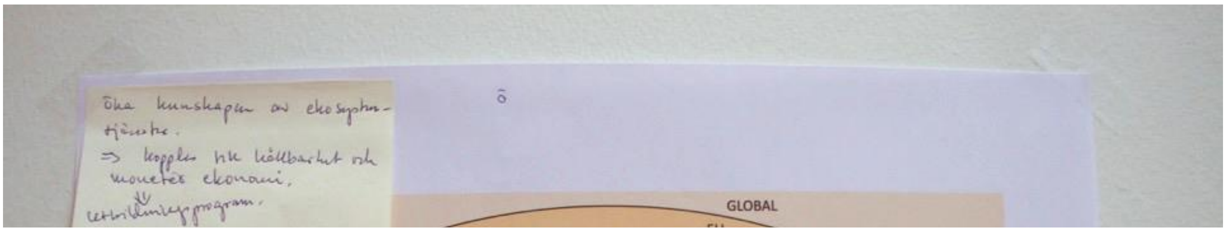


Figure 8 Result example from exercise 4 on necessary decision-making at multiple levels for improved ESS management and water governance.

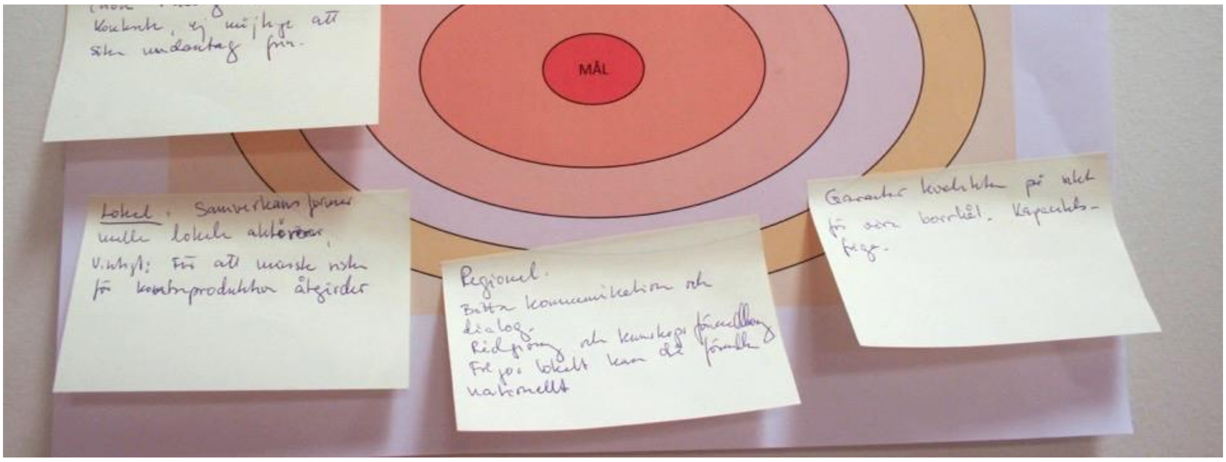
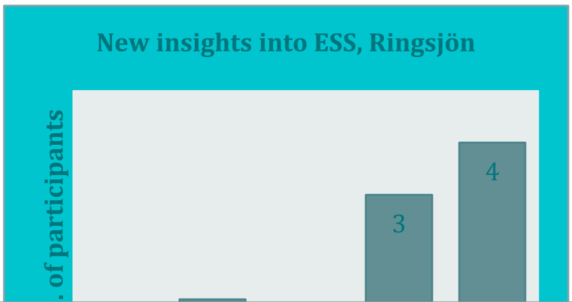


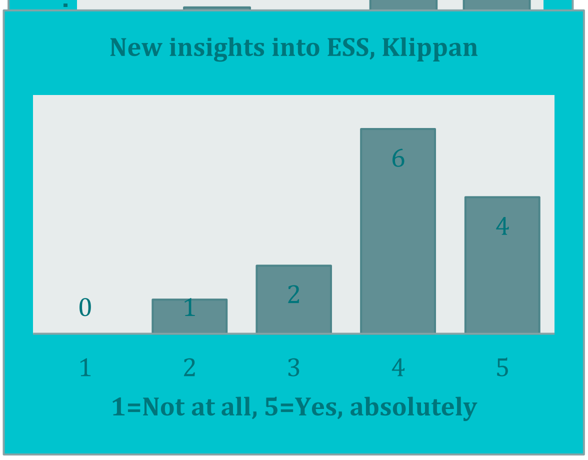
Figure 7 Example table from exercise 3 on expected effects from measures on ESS.

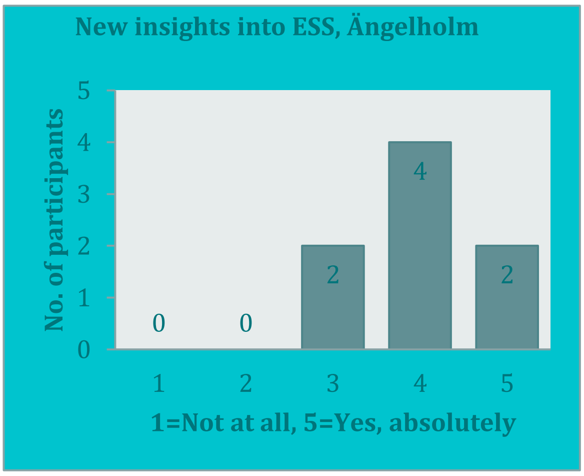
1.1.1 Short workshop evaluation

The following results from quick surveys answered by workshop participants were summarised and presented in the overall results that they received few weeks after the workshops.

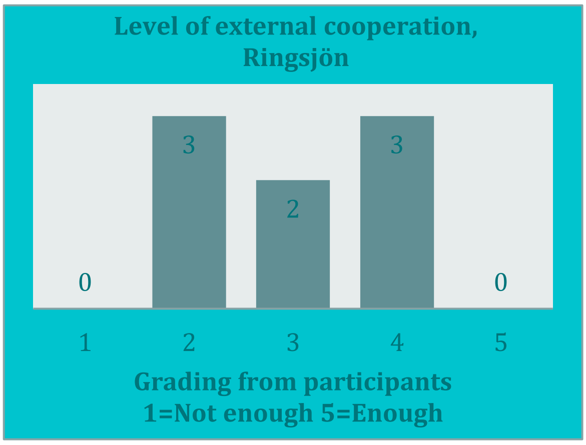
1. Did stakeholder get new insights on ESS?

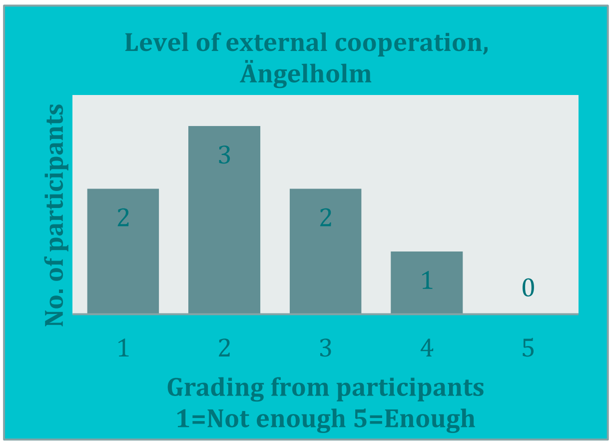


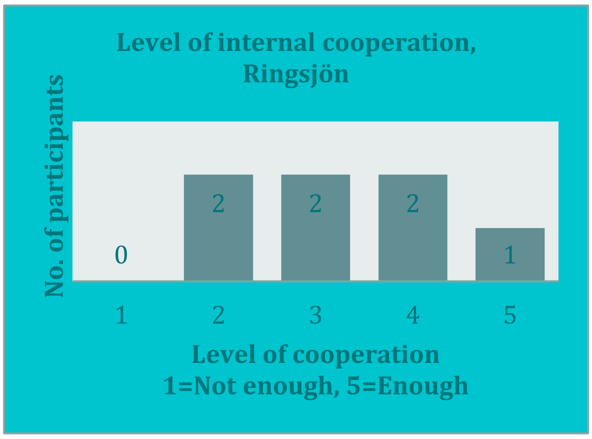


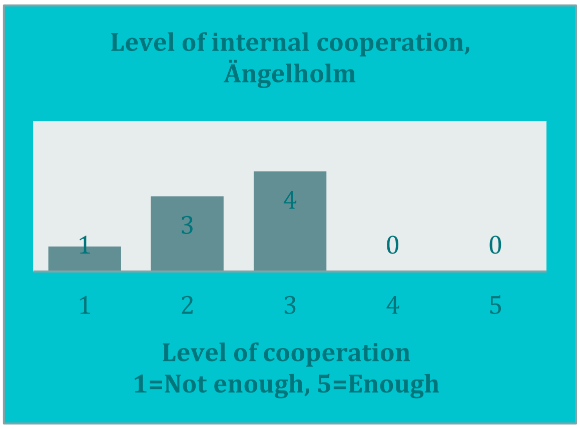


2. Level of external/internal cooperation as rated by participants

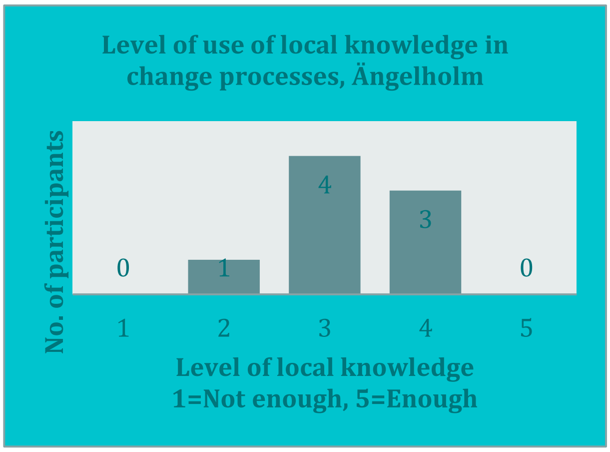


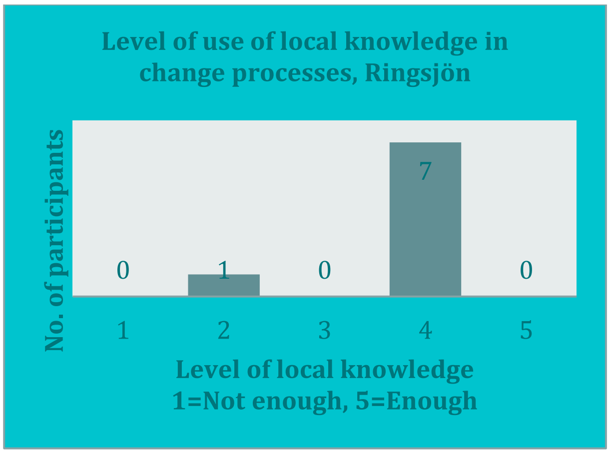




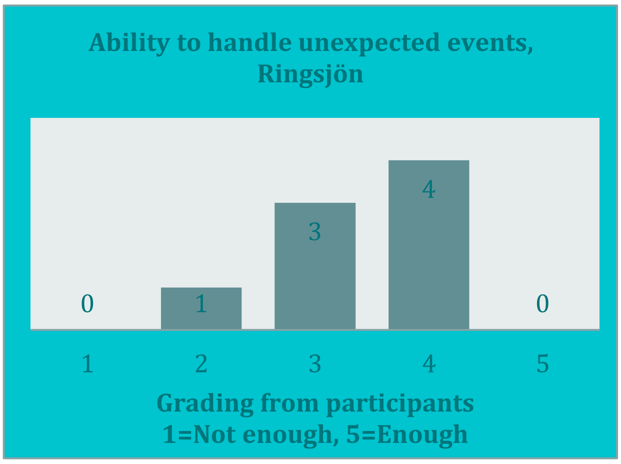


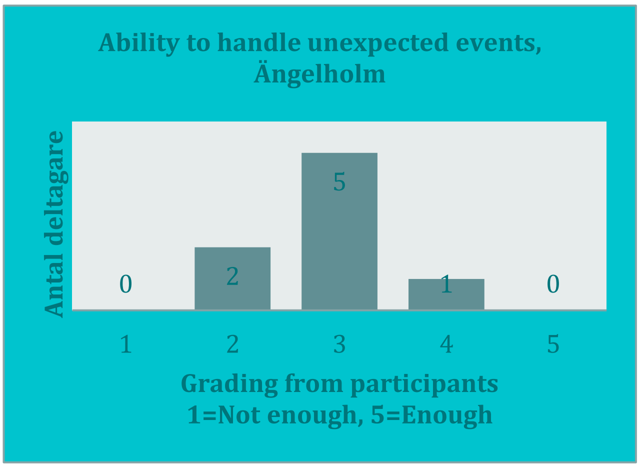
3. The use of local knowledge in processes of change





4. Ability to handle unexpected events





Annex III Assessment methods

LimnoSES model documentation

ODD+D for LimnoSES

The following documentation was prepared after the ODD+D protocol for describing human decisions in agent-based models (Müller et al. 2013), and was published together with the model code on OpenABM.org.

Overview

I.i.a What is the purpose of the study?

The main purpose of the model is to simulate social-ecological feedbacks in lake use and management systems where ecological regime shifts can occur between the turbid and the clear water state. We further aim to extend the regime shift evaluation to include social responses and regulation mechanisms of important drivers in the lake. In particular, the issues of cooperation between different interest groups and time lags of social responses to changes of the lake state play an important role.

I.i.b For whom is the model designed?

For scientists of different disciplinary backgrounds who contribute to research on lake management and look for a deeper understanding of the interplay between social and ecological dynamics.

I.ii.a What kinds of entities are in the model?

The model consists of a social and an ecological submodel. The following descriptions describe both submodels separately (see for a graphical overview (Figure 18).

Ecological entities: The ecological submodel represents the lake that includes the stocks for a predator and a prey fish species (pike – *Esox Lucius* and bream – *Abramis brama* respectively). The density of macrophytes is estimated as a function from bream.

Social entities: One agent represents the municipality and its function to regulate sewage treatment and potentially enforce the upgrade of sewage treatment systems from private house owners. Hundred agents represent private house owners that release nutrients to the lake and decide on potential upgrade of their sewage treatment system.

I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterised?

Ecological entities: The two fish species are represented as stock densities and characterised by growth, mortality and interaction rates. (see for details and numbers section III.iv.b)

Social entities: The municipalities legislation activity can be triggered by monitoring that the pike density drops below a threshold. The house owners have an onsite sewage system (OSS) that can be upgraded. House owners are characterised by a willingness-to-upgrade that can be increased by information through neighbours who upgraded their sewage system ('social engagement') or through regular checks by the municipality ('central enforcement').

I.ii.c What are the exogenous factors/drivers of the model?

Ecological submodel: The food web in the lake is driven by the amount of nutrients which can be a time series for nutrient increase/decrease scenarios. In the coupled model, the amount of nutrients is subject to the number of households that release insufficiently treated sewage water into the lake.

Social submodel: The abundance of pike is monitored by the municipality to estimate the necessity to regulate private sewage treatment. As soon as the pike level drops below a threshold, this triggers regulation and informing the private house owners about the need to upgrade their sewage system.

I.ii.d If applicable, how is space included in the model?

Not included within functions. Lake area and coastal area is only differentiated for visualization purposes.

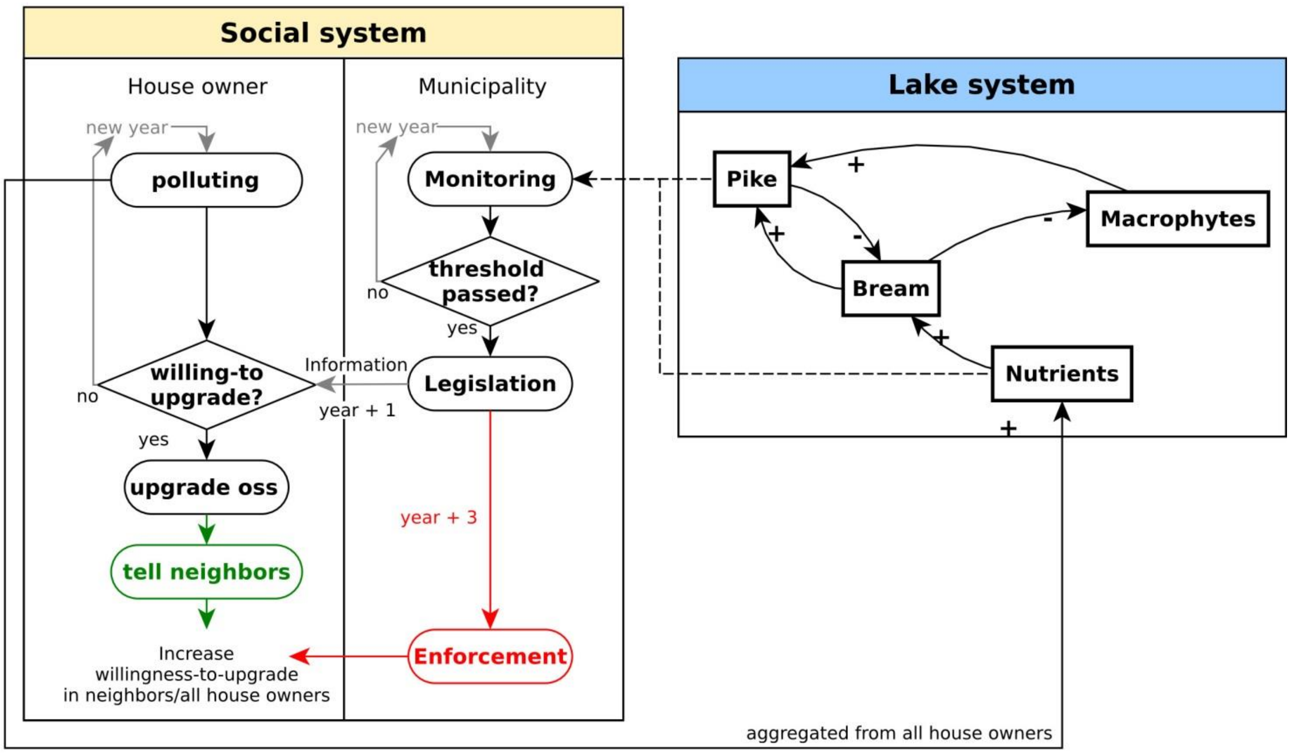


Figure 10 Graphical representation of the LimnoSES model

I.ii.e What are the temporal and spatial resolutions and extents of the model?

The ecological submodel runs on daily time steps, the social submodel on annual time steps. Thus, the processes of monitoring/legislation and house owner decisions about upgrading the private sewage system are made once per year.

I.iii.a What entity does what, and in what order?

Pollution: House owners release nutrients through their OSS and in case they were informed about the need to upgrade the OSS, they decide whether they do this investment (can be done only once). If they upgrade their OSS in the 'social engagement' scenario, they inform their neighbours about their modernization which increases their willingness to upgrade.

Ecosystem dynamics: Nutrients affect the system dynamics of lake: fish and macrophytes

Regulation: The Municipality evaluates monitoring results and starts the legislation for private sewage treatment when the threshold level of pike is passed. As a consequence, house owners are informed about the new law and the need to modernise their OSS. For the 'central enforcement' scenario, municipal inspectors are sent out to check on the installed OSS and they motivate house owners which increases their willingness to upgrade.

Design concepts

II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?

The model addresses social-ecological interactions and therefore includes a social and an ecological submodel that describe the specific subsystem characteristics. The main interactions are monitoring of the lake's state and potential pollution of the lake by applying insufficient sewage treatment installations.

The ecological submodel is a reimplementation of a minimum model that enables regime shifts between the clear and the turbid state of the lake (M. Scheffer 1989). The social submodel is based on assumptions on social norms that in some situations might overwrite the purely economic reasons for a certain behaviour. The case is in general informed by current lake management practices in Sweden and regulation of OSS treatment systems (Wallin et al 2013).

II.i.b On what assumptions is/are the agents' decision model(s) based?

The municipalities decision on regulating private sewage treatment is based on simple thresholds assumed to trigger their response. House owner agents instead are assumed to take individual decisions when requested to upgrade their sewage system. They find themselves in a high-cost low-benefit situation and tend to avoid timely upgrade of their OSS (expressed by the variable willingness-to-upgrade).

II.i.c Why is/are certain decision model(s) chosen?

Due to a lack of empirical evidence, only the simplest assumptions are used here: a probability called willingness-to-upgrade that determines when house owners upgrade their OSS.

II.i.d If the model/submodel (e.g. the decision model) is based on empirical data, where do the data come from?

Not applicable yet.

II.i.e At which level of aggregation were the data available?

Not applicable.

II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?

Subjects are individual house owner agents.

II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?

Not applicable.

II.ii.c How do agents make their decisions?

Decision making is triggered by the information about sewage regulations from the municipality. Then current value for the willingness-to-upgrade is the probability with which they decide about the OSS update.

II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?

The willingness-to-update can be changing through interventions, either through horizontal information from neighbours that recently updated their OSS or vertical through the municipality that sends out inspectors to check for the current state of the installed OSS. In both scenarios, the willingness-to-upgrade is increased by 50% but it cannot exceed 1.

II.ii.e Do social norms or cultural values play a role in the decision-making process?

In some cases, inspectors were sent by municipalities to check the current installation and support upgrading ('central enforcement').

II.ii.f Do spatial aspects play a role in the decision process?

No

II.ii.g Do temporal aspects play a role in the decision process?

Yes, the willingness-to-upgrade is increased either through stochastic interaction with neighbours or by central enforcement (inspector checks) from the municipality. So, with increasing values for the willingness-to-upgrade, the probability for upgrades increases over the course of one simulation.

II.ii.h To which extent and how is uncertainty included in the agents' decision rules?

Not applicable.

II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?

Not applicable.

II.iii.b Is collective learning implemented in the model?

Not applicable.

II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?

Not applicable.

II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?

Not applicable.

II.iv.c What is the spatial scale of sensing?

Not applicable.

II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?

The municipality receives annual updates on the current nutrient content in the lake, it does not read daily variations.

II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?

No.

II.v.a Which data do the agents use to predict future conditions?

Not applicable.

II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?

Not applicable.

II.v.c Might agents be erroneous in the prediction process, and how is it implemented?

Not applicable.

II.vi.a Are interactions among agents and entities assumed as direct or indirect?

In the scenario of 'social engagement', the horizontal information exchange about OSS update is considered to be direct.

II.vi.b On what do the interactions depend?

On the spatial distance, we assumed a neighbourhood radius of three units.

II.vi.c If the interactions involve communication, how are such communications represented?

No communication is modelled.

II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?

Not applicable.

II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?

No

II.vii.b How are collectives represented?

Not relevant

II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?

The willingness-to-upgrade can vary during the ‘social engagement’ scenario.

II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?

No.

II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?

Not applicable.

II.x.a What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?

Not applicable.

II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)

The aggregated pollution from private house owners is calculated from the number of not-updated OSS. Further, the time that is needed from the year house owners are informed to the year when all house owners updated their OSS is recorded.

Details

III.i.a How has the model been implemented?

The ecological submodel was first implemented in Matlab Grind to identify suitable value ranges for the alternative stable states. The coupled model was then implemented in NetLogo 6.0.1 where the ecological submodel was reproduced within the system dynamics editor. The social submodel was implemented with the common NetLogo interface.

III.i.b Is the model accessible, and if so where?

LimnoSES is published through openabm.org, current model versions are also available under https://bitbucket.org/seslink/limnoses.

III.ii.a) What is the initial state of the model world, i.e. at time t = 0 of a simulation run? b) Is the initialization always the same, or is it allowed to vary among simulations? c) Are the initial values chosen arbitrarily or based on data?

For the ecological submodel test, we initialised the lake variables either for the turbid or the clear state:

Table 9 Lake variables used in the LimnoSES model

State	**Nutrients**	**Pike** [$g \cdot m^{-2}$]	**Bream** [$g \cdot m^{-2}$]
Clear	0.7	2.6	25.8
turbid	2.5	0.04	84

The values stem from two independent implementations, one in Matlab where we identified stable states numerically and one from a reimplementation NetLogo.

III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?

No

III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?

1. House owners release nutrients

Assumptions: We have a total number of households (*h*) that may contribute to eutrophication of the lake through untreated sewage leaking into the catchment.

A minimum threshold of polluting households is tolerated (*tl*) that does not lead to increases in nutrients in the lake

The number of affectors above this threshold *tl* translates linearly into an amount of sewage-water with a maximum value 0.1

If less than the threshold *tl* is polluting, the difference is contributing in the same way (linearly) to reduction of nutrients until the initial nutrient level is reached. This means that at a *tl* of 50% and 80% of households upgraded the OSS, 30% of the maximal change value of nutrients is applied to reduce the current nutrient level in the lake. Tolerance values lower than 50% would indicate that a slower maximum decrease in nutrients is possible than increases.

$$f(affectors) = -\frac{tl \cdot sewage_{max}}{h-tl} + \frac{sewage_{max}}{h-tl} \cdot affectors$$

Table 10 Parameters to calculate individual sewage nutrient input into the lake

Parameter	comment	Value [per year]
$sewage_{max}$		0.1
tl	Tolerance level of polluting households	50 [%]
h	Total number of households	100

2. System dynamics at the lake

$$\frac{dbream}{dt} = ib + r \cdot \left(\frac{nutr}{nutr + H_1}\right) \cdot bream - cb \cdot bream^2 - \frac{bream^2}{bream^2 + H_4^2} \cdot pike \cdot predation_{rate}$$

$$\frac{dpike}{dt} = ip + pike \cdot predation_{rate} \cdot predation_{efficiency} \cdot \left(\frac{bream^2}{bream^2 + H_4^2}\right) \cdot \left(\frac{V}{V + H_2}\right) - pike \cdot mortality - cp \cdot pike^2$$

3. Municipality regulation

0) baseline: immediate response to pike threshold means that houseowners are directly informed and they have a uniformly distributed willingness-to-upgrade

a) 'central enforcement': we assume centralised, regular monitoring activities of the lake water quality. When it is perceived as necessary, new rules are developed, such as "Lex Ringsjön". This asks houseowners to install particular private sewage systems and they are regularly checked whether their installation works sufficiently or not. So all houseowners receive the information about the new law at the same time but their compliance rate is low.

b) 'social engagement': individual houseowners perceive the state of the lake through swimming or fishing activities. Since they are educated, they also see the necessity to upgrade their sewage system but this 'mind shift' may happen at certain events and not for all houseowner at once. But as soon as they see their neighbour doing it, the compliance rate is high.

III.iv.b What are the model parameters, their dimensions and reference values?

Table 11 Ecological parameters and values from an ecological minimal model (Scheffer 1989).

Parameter	comment	Value [per year]	Value [per day]
r_bream		2.74 g/year	7.5*10^-3 day^-1
Predation_rate	maximum predation rate of pike	18.25 year^-1	prmax: 0.05 day^-1
Predation_efficiency	pike conversion efficiency to growth	0.1	0.1
Mortality pike		0.82	2.25*10^-3 day^-1
Cb [cp]	Intraspecific competition constant for bream [pike]	0.0274 m^2 g^-1 year^-1, [0.1]	7.5*10^-5 day^-1 [2.75*10^-4 day^-1]
Im	Immigration	0.009 g m^-2 day^-1	0.00002
H1 H2 H3 H4	Half saturation constants on how - nutrients supports bream growing - vegetation hampers pike reproduce - bream disturbs vegetation as total - bream predation supports pike growth	0.5 (dimension less) 10 % 20 g/m^2 15 g/m^2	0.5 (dimension less) 10 % 20 g/m^2 15 g/m^2

III.iv.c How were the submodels designed or chosen, and how were they parameterised and then tested?

1. Find out whether submodels exhibit multiple stable states, determine initial conditions that lead to stable state (Python script 1 to check via isoclines?!)

2. Check: How do parameter changes affect equilibrium? Which parameters allow for large or only small changes while keeping the characteristics of the system? (Python script 2 to analyse NetLogo outcome)

3. How do links/interrelations between different minimal models change the system stability?

4. Extend this test (2./3.) to include social processes, variables.

Table 12 Implemented experiments in the NetLogo BehaviorSpace to test and validate model assumptions, analyse the sensitivity of patterns towards input variation, and to explore model behaviour in extended experiments.

Test or experiment	Hypothesis and assumptions	Observed effects	Follow up question

I: “Rtipping” – Transient nutrient in-/decrease	Hysteresis	Sudden shifts in bream and pike abundance appear, but it is dependent on the rate of nutrient change.	Why is the rate only affecting eutrophication and not restoration?
II: “TurbidityResponse” a) start with turbid state	Social pressure between houseowners works faster than top-down rule enforcement	Yes, but only in conditions were the initial willingness-to-upgrade is greater than 0.2	In what way would results differ in a fully coupled system?
III: “FullRestoration”	Social response lags may cause even larger lags in restoring the pike level	Pike restoration time increases non-linearly with the social time lag	Where does the variability between runs originate?

Survey questions on resilience principles in Aquacross case study assessments

A. Setting the frame (3)

1. **CAS thinking:** Complex adaptive systems are made up of many interacting components that are individually and collectively adapting to change, enabling them to self-organise and evolve, and often yielding emergent properties at different scales (Norberg and Cumming 2008). CAS may shift between alternative regimes, often abruptly and irreversibly (Scheffer et al. 2001).

To which degree have complex adaptive system characteristics been accounted for in your study on the management of ecosystems or ESS? We break this question down into the following complementary characteristics:

a. What are the trends (either social or biophysical) in the system that the management tries to hinder or to support? [open]

   Trends that the management tries to hinder:
   - producing unsustainable outcomes

   Trends that the management tries to support:
   - the exploitation of natural resources has been rationed to ensure the sufficiency of each of the resources
   - considering the interaction between the various uses of ecosystem services for a sustainable use and safeguarding of ecosystem services
   - restoration of degraded resources or sites
   - integration of multiple knowledge sources and engaging those actors who understand, manage and benefit from the services
   - Maintains or enhances of the ecosystems resilience and the valuable flow of services they provide

b. What are the major social or biophysical uncertainties that actors managing ESS have to cope with? (differentiate between stakeholder views and scientific judgement) [open]
   - How some ecosystems and their services may be adversely affected by human development

c. How have these uncertainties been dealt with? [open]
   - Pluralism - collaboration across scientific disciplines to construct support process and tools for decision-making
   -

d. What abrupt changes in ecosystem state have happened in the past? Can you describe how they happened? [open] Which thresholds, beyond which the ecosystem or the delivery of ESS will change abruptly, are you or stakeholders aware of? (non-linearity) [open]

e. Do you think current management practice [Likert scale]
   i. considers managing for multiple species and their interactions
   ii. pays attention to possible thresholds
   iii. tries out new approaches to adapt to new conditions

f. Do you think managing multiple species, potential thresholds, or adaptive management will make the delivery of ES more sustainable? Please explain [open]

2. **Slow variables and feedbacks:** Feedbacks occur when a change in a particular variable, process or signal leads to changes in other variables that eventually loop back to affect the original variable, process or signal. Slow variables are variables that change on time scales that are much slower than the typical time scales in focus. Slow variables can obscure feedbacks while driving the system towards a threshold (e.g. phosphorous accumulation in lake sediments).

a. What are key slow variables (e.g. eutrophication is slow and reinforces service provision from turbid water) and feedbacks (e.g. actors realizing that sewage treatment that is not controlled for may release further nutrients) that in your opinion affect the current supply of ESS?
   b. Which feedbacks are critical to restore or maintain a desirable state?
   c. Which slow variables need to be addressed in order to enhance the provision of ES e.g. by shifting the system from its current state towards a more desirable one?
   d. Which feedbacks that are affected by major drivers of ESS supply need more attention (e.g. regulation of sewage treatment adapted to the ecological state and socially reinforced)
   e. [Option: use the same questions for the eco- or social system rather than the whole]
3. What are the **boundaries of the social-ecological system (SES)** you study? (to evaluate the degree of systems thinking for ecosystem based management as in (Borgström et al. 2015)
   a. In terms of spatial, temporal and organizational level?
   b. At which scales and levels is the system regularly monitored?
   c. At which scales and at what level are management goals formulated?
   d. Do you see relevant processes from question 1 or 2 that might require different management scales or levels? Please explain [open]

B. Walk-through the AQUACROSS concept (8)

This is the main section of the survey, addressing specifically each arrow within the AQUACROSS concept. Arrows and questions are numbered according to the following figure, so you can jump to the question that you personally like to start with. (Next question brings you there)[inserted in the form]

Which ecosystem services or biodiversity characteristics are important for your case?

Table for ecosystem services (for each service the following questions are then applied): (e.g. provision of …, regulation of …, or cultural service of ...)

1. 'Ecosystem services': How is this flow characterised?
   a. Is this flow considered as provisioning, regulating or cultural?
   b. Is the use of the ES formally regulated? (yes (private, common), no;
   c. How is access to the service regulated? (e.g. through seasonal closures in a fishery, quotas or market-based instruments)
   d. Which institutions (formal or informal set of rules) are managing the flow?
   e. What is the spatial (local, diffuse, clear/unclear boundaries) and temporal (continuous, discrete (frequency?)) characteristic of this flow?
   f. Degree of non-natural capital involved to provide this service? (choose among < 25%, 25-% 50%, 50% - 75%, > 75%) (Palomo et al. 2016)
2. 'Benefits from ES': Who benefits from the service?
   a. Who are the actors that benefit from the ESS? Which actors affect the provision of the ESS? [end of table]
   - Do the perceptions about the benefits of ES differ between different actor groups? (e.g. invasive species seen as an income and employment opportunity vs as a threat for biodiversity)
   - Are you aware of tradeoffs between actors that affect the provision of an ES and those that benefit from it?

Resilience principles:

- Redundancy: Can ES be provided through alternative ecosystem processes or alternative social processes (e.g. recycling, desalination and reuse instead of freshwater)?

3. 'Social processes':
    - In which social interactions are rules for either the co-production or use of the service negotiated? (options to tick) Resource user - resource user, resource user - communal organization, communal organization, communal - regional/national organization, national organization, other
    - Can you describe what those interactions and their purpose are?

Resilience principles:

- Participation: Which stakeholders are involved in the management of the SES?
- Learning: are there platforms or processes that facilitate learning from managing and using the ES among different stakeholders? Is there room for experimentation with new management approaches?
- Connectivity: Are actors that manage, affect a particular ES connected with each other?
- How is the provision of the ES affected by other ES/ecological processes?
- Polycentric governance: Which degree of polycentricity is observed for the policy making process on managing the environment and its use? (Galaz et al. 2012)

4. 'Drivers of ecosystems' change': How are decisions about managing the ecosystem reached?
    a. What are the main drivers of ecosystem change? Differentiate between drivers that actors within the SES can influence and those they cannot
    b. What are the spatial scales or social levels of organization associated with one or more drivers?

Resilience principles:

c. Diversity: is a diversity of actors involved in decision making that affects those drivers?

d. Learning: is new knowledge from learning entering the decision process

(option to answer the same section for another example, or allow a set of services from the beginning)

Demand:

Name one example service or a group of services for which the following questions are then applied when applicable: (e.g. conserving habitat for a particular species)

5. 'Pressures'
    a. What is the spatial (local, diffuse, clear/unclear boundaries) and temporal (continuous, discrete (frequency?)) characteristic of this pressure flow? (examples should address typical threats that one would want the system to be resilient to)
    b. Which institution (formal or informal set of rules) is regulating this pressure? Or is it missing and the pressure is rather emergent from several unintended drivers?
6. 'Ecosystems' structure'
    a. What kind of intended or unintended changes are observed in the ecosystem's structure? Have there been abrupt changes in ecosystem state? If so why?
    b. Connectivity: To which degree is connectivity among ecosystem components important to maintain or change ecosystem functions or the supply of ES? (e.g. new connections - invasive species, or decreasing habitat connectivity hampering fish life cycles)
    c. Diversity: Where are redundant or diverse traits, species, or functional groups important for sustaining services despite pressures?
7. 'Ecological processes'
    a. How is ecological adaptation reinforcing a trend or buffering against a change in structure? (e.g. competition among cod and sprat reinforced cod decline)

b. Which feedback process do you see essential to sustain particular ecosystem functions? (e.g. macrophytes providing shelter and nursery for piscivore fish, keeps a lake in a clear state)

8. 'Ecosystem functions'
   a. How are ecosystem functions linked to a potential ecosystem service?
   b. Are changes in ecosystems structure affecting its capacity to provide more and a more varied array of ecosystems services? (Yes/ not, refer to current and potential services, explain)

Resilience principles evaluation for CS 6

Table 13 List of resilience principles in the order of how they appeared in our CS survey and relate to the AQUACROSS concept.

Resilience principle	Characteristic question	Relation to AQUACROSS concept	CS 6 specific insight
Foster complex adaptive systems thinking	Which are the major social or biophysical uncertainties in managing the SES?	Frames the whole SES and helps to identify the boundaries of the system to be managed.	The complex phenomenon of interest is the regime shift between a clear and turbid lake state.
Manage slow variables and feedbacks	What are key slow variables and feedbacks that affect current ESS supply?	Pure ecological and pure social feedbacks are considered, however, social-ecological feedbacks only via supply and demand connections. The speed of drivers (in relation to the targeted response) is not specified.	Slow driver eutrophication and ecological feedbacks linked to lake states are well known, but social feedbacks on restoration not yet.
Broaden participation	What kind of stakeholders are involved in the management of ESS?	Participation matters in three processes: the way how ESS benefits are accessed, social processes, and humans drive ecosystem change.	This issue raised the highest interest among stakeholders, since collaboration among stakeholders in water councils differ a lot, for instance, by how proposals are handled on annual meetings.
Encourage learning	Are their platforms that facilitate learning from using or managing ESS?	Via social processes.	Interviews revealed the water council as a suitable platform for learning on multiple perspectives and techniques in water management.
Promote polycentric governance	Which degree of polycentricism is observed for policy implementation?	Via social processes and decision making on drivers.	Water governance in Sweden is an example for high polycentrism with a high degree of horizontal and a smaller degree of vertical coordination. This is shown, e.g. by the mix of policies that are locally relevant.
Maintain diversity and redundancy	How are the diversity of species and a diversity of stakeholders considered in actual decision making?	Mainly via ecological diversity, not explicitly on social diversity.	There is no clear relation between the desirable state of the lake and the degree of biodiversity reinforcing the clear state. Social diversity is represented, but its role in managing ESS is not clear.
Manage connectivity	How are actors and ecosystem components connected via ESS?	Potentially integrated in ecosystem structure.	Relevant for the upstream-downstream relation, the river network transporting and accumulating nutrients, and ESS interactions.

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