Environmental Science and Policy 81 (2018) 95–103

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

The past, present, and future of a lake: Interdisciplinary analysis of long-term lake restoration

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ARTICLE INFO

Keywords:
Eutrophication
Lake restoration
History
Future
DPSIR-framework
Interdisciplinarity

ABSTRACT

The history and future of the restoration efforts at the hypereutrophic southern Finnish lake, Tuusulanjärvi, are investigated. The interdisciplinary study is conducted within a modified DPSIR- framework, which allows us to both trace back and envision the future of the dynamics of the complex socio-ecological processes involved in restoration. The study covers the time period from the early 1970s up to 2030. The longitudinal study integrates environmental historical, limnological, and futures studies. The analyses reveal the multiple time scales of social and ecological processes present in long term restoration, the changing perceptions of and emphasis on restoration goals and outcomes over time, and the challenges that incidental and uncertain parameters, such as weather conditions, pose to sustainable and efficient restoration endeavors.

1. Introduction

Despite the great advances that have been made in fresh water protection, such as qualitative and quantitative improvements in waste water treatment, the anthropogenic eutrophication of lakes remains one of the most obvious and prevalent water quality problems (e.g. Schindler, 2012). Phosphorus (P) is usually the limiting nutrient for productivity in lakes, and is thus of key importance in the process of eutrophication (Schindler, 1978; Keeneleyside et al., 2012). The total phosphorus (TP) concentration in lake water is a function of the externally delivered P, lake hydraulic residence time, and the tendency of P to settle from the water column (Brett and Benjamin, 2008). Under certain conditions, settled P can be released back into the water column, providing an important internal source of P for algae (Marsden, 1989). Internal P release has been related to anoxic conditions in hypolimnetic water (Hupfer and Lewandowski, 2008), and can be induced by diffusion, bioturbation by dense fish stocks, or photosynthetically elevated water pH (e.g., Søndergaard et al., 2003; Holmroos et al., 2009).

Efforts to remedy or reverse the human-induced environmental damages of the past, known collectively as 'ecological restoration', have grown over recent decades into an acknowledged field of research, and are being put into practice on a broad scale. Restoration aims to improve the environmental quality of degraded lakes through the "re-establishment of important missing altered processes, habitats, concentrations and species [.] to attainable approximation of pre-disturbance conditions" (Cooke et al., 2005, 14). In practice, this may sometimes involve more limited goals, such as reducing systemic pressures and enabling natural recovery, but may also involve significant interventions (Keeneleyside et al., 2012). The restoration of eutrophicated lakes is usually realized via the reduction of external (i.e. originating from the lake catchment) and internal phosphorus (P) loads, aiming at reducing algal biomass (e.g., Spears et al., 2013). In the limnological approach, the relationship between chlorophyll *a* (Chl *a*), a surrogate for algal biomass, and total phosphorus (TP) has served as a framework for predicting the bio-chemical outcome of nutrient controls (Stow and Cha, 2013; Filstrup et al., 2014; Jones and Brett, 2014). As for the anthropogenic perspective on lake restoration, the roles of the culturally determined values and societally preferred functions attached to the respective lake are highlighted.

Lake restoration can be understood both as a process of transition and as a product, i.e. an outcome of these transitions (Higgs, 2003, 110–112). While the goal of the *recovery* of a disturbed ecosystem suggests the workings of autonomous natural processes, the notion of restoration as the *assisted recovery* of a lake includes both intentional human action and ecological processes which are steered or accelerated through human interventions. Human restorative actions are intentionally directed towards specific ends, including a diverse set of anticipated, observed, and interpreted outcomes of restoration activities (cf. Higgs, 2003, 110–112). Determining restoration goals, and the

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https://doi.org/10.1016/j.envsci.2017.12.015
Received 22 December 2016; Received in revised form 29 December 2017; Accepted 30 December 2017
Available online 10 January 2018

best practices to achieve these goals, are necessarily value-laden activities, as they involve human perceptions, beliefs, and emotions. They are influenced by preferences, possibilities, and knowledges that are context-dependent variables that shift over time.

While hydro-ecological literature has identified several factors contributing and confounding to the desired outcomes of aquatic restoration endeavors (Verdonschot et al., 2013), the literature is scarce on empirical cases that take into consideration both ecological and societal processes, and additionally capture the changes over time in the dynamics of these processes. We propose that by utilizing a long time span perspective we can increase our understanding of the complex and intertwined nature of the societal and ecological processes active in lake restoration, and of how these contribute to the anticipated and realized outcomes of restoration. Through the study of six decades of restoration at the hypereutrophic Lake Tuusulanjärvi, located in southern Finland – and also how the results of these efforts were perceived – we aim to answer the following research questions:

- What kind of interventions have taken place at the lake in the past, and are anticipated to take place in the future?
- What were, and will presumably be, the respective goals for restoration?
- What temporal dimensions are related to the social and ecological processes of restoration, and how did they affect both the restoration endeavors and the perceived and anticipated outcomes of that restoration?

In order to pursue these goals, we propose an interdisciplinary case study approach that benefits from multiple sets of source material, which are introduced in Section 2.2 (and in more detail in the Supplementary material appendix), together with the Drivers-Pressures-State-Impact-Responses (DPSIR)-framework, which we apply to our analysis. The results of the study are chronologically organized according to the identified key phases and significant ruptures during the six decades of restoration efforts. The changes in the relationship between Chl *a* and TP throughout these phases are analyzed. The article concludes by highlighting the multiple time scales of social and ecological processes that are inherent to long-term restoration projects, the changing perceptions of and emphasis on various restoration goals and outcomes over time, and the challenges that incidental and uncertain parameters – such as weather and climate conditions – pose to sustainable and efficient restoration endeavors.

2. Materials and methods

2.1. Case study approach

Our research design includes a longitudinal case study covering six decades (1970–2030), and an interdisciplinary approach including contributions from environmental history, limnology, and futures studies. The study was performed in the context of a southern Finnish lake with an extensive restoration history, Lake Tuusulanjärvi. It is located approximately 40 km north of the capital, Helsinki, and belongs to the catchment area of the River Vantaa, through the Tuusula River. The lake surface area comprises 6 km^2, and its mean depth is 3.2 m, with one main basin reaching 10 m depth. It has a fairly narrow (max 2 km) and extended (7–8 km long) form, with municipal centers (Järvenpää and Hyrylä) at both ends (see Fig. 1). The catchment of the lake (92 km^2) belongs to the jurisdiction of two municipalities. The populations of both Järvenpää and Hyrylä have grown continuously since the 1950s, with present totals of 41.000 and roughly 20.000 people, respectively.

Tuusulanjärvi is the largest lake in the country's most densely populated Uusimaa province and thus has considerable recreational significance. Popular uses of the lake include summer and winter swimming, fishing, boating, and ice skating; the lake is also surrounded by a scenic bike route. The lake and its shores are home to great biodiversity, and it has been included in both the National Waterfowl Habitat Protection Programme and the EU-wide Nature 2000-network, as part of the EU Habitat Directive. The aesthetic value of the lake scenery is highly prized by the growing local population.

Tuusulanjärvi is naturally eutrophic, and with the predominant clay soils in the catchment the water is greyish-brown in color. Early signs of anthropogenically inflicted eutrophication have been observed since the 1920s, becoming more pronounced between the 1930s and 1950s, and rapidly advancing in the post-WWII decades (Tolonen et al., 1990). The hypereutrophic lake has been subject to various interventionist restorative activities for more than four decades, and the current restoration efforts are expected to continue into the future, which makes Tuusulanjärvi a fruitful case to explore the socio-ecological dynamics of lake restoration over time.

2.2. Materials, methods and integrated analysis

The analysis of Tuusulanjärvi's restoration history and future prospects was performed using the systemic DPSIR framework (Fig. 2), which is a tool aiming to integrate the natural scientific and social aspects of environmental problems in order to comprehensively understand and analyze environmental change. It has been widely used since 1995, e.g. in the environmental indicator reporting of the European Environment Agency (EEA, 1995), and has thus become broadly known and applied in the European context. The model presents a causal chain of *driving forces* (D) which are linked to the underlying needs of individuals, societies, industries and the like, followed by the *pressures* (P) (e.g. emissions) that stem from fulfilling these needs. Pressures affect the physical, chemical, and/or biological *states* (S) of the environment, which in turn have *impacts* (I) on ecosystems, human health, and other functions. The *responses* (R) denote the societal actions that derive from unwanted impacts, and can be targeted at any stage of the model (Smeets and Weterings, 1999). Despite some critique directed at the framework, most importantly addressing the simplified, linear causal chains that obscure the complexity of real socio-ecological dynamics and the conceptual ambiguity of the nodal points (e.g. Lundberg, 2005; Maxim et al., 2009), in our case the value of the framework lies in its utility for providing structure to the integration of interdisciplinary analysis. Restoration is characterized through concepts present in the DPSIR-framework, such as pressures and states, making it conceptually apt to the discussion of restoration problematics (see e.g. Keeneleyside et al., 2012). Moreover, the simple structure of the framework directs the focus of analysis towards the key social and ecological factors that have formed and influenced restorative actions in the past and will also affect future actions. Since active restorative interventions are always targeted at some defined goals, which might be attached to any of the stages of the model, we included a study of these restoration goals in the overall analysis (see Tapio and Willamo, 2008).

The study is based on the individual and integrated analysis of several types of materials. The historical analysis is based on documentary material, most importantly from the local Tuusulanjärvi Water Protection Association (TWPA, *Tuusulanjärven vesiensuojeluyhdistys*), as well as from newspaper articles (for more details see the Supplement). The historical data pertaining to the Tuusulanjärvi restoration process was gathered in a heuristic process typical for environmental historical research (Winiwarter and Knoll, 2007). The various interventionist responses to the eutrophication of the lake since 1970 were first identified, after which the content of the historical documents was analyzed against the different stages included in the analytical DPSIR framework. The limnological data included records of concentrations of TP and Chl *a* for different time periods. The sources of the limnological data and applied tests are presented in Table 1, and in more detail in the Supplement.

The future prospects for Tuusulanjärvi were gathered by applying the scenario approach (e.g. Bishop et al., 2007) and the futures

Fig. 1. Lake Tuusulanjärvi, southern Finland. Locations of aerators in the 1970s are displayed in the map.

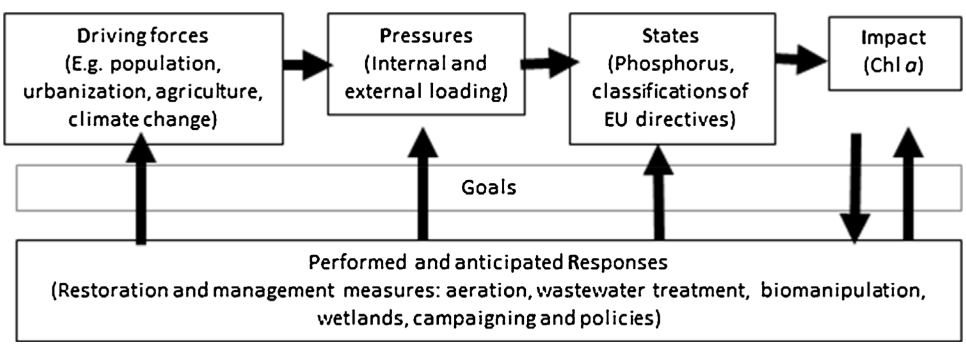

Fig. 2. The modified DPSIR-framework used for analyzing the long-term restoration of Tuusulanjärvi.

workshop – method, which aims to engage stakeholders in the process of creating desirable futures (Jungk and Müllert, 1986). In futures research, the future is not seen as determinate, but instead as a variety of options, and thus the aim is to produce several alternative, plausible future images or scenarios (Bell, 1997). Following this, a futures workshop was arranged to envision the future and to create alternative scenarios for managing Tuusulanjärvi through the year 2030. Alternative future states for qualitative variables based on the DPSIR framework were envisioned in groups and gathered into a matrix – a futures table. A single future state for each qualitative variable was chosen from each row of the matrix, to form a preferable, a non-preferable, and a probable future image through discussion in groups. By constructing paths from the present to the future images, future scenarios were formed. Table 1 summarizes the integration of both the

Table 1
Summary of the research materials, methods, and analyses utilized in this study, and their connection to the DPSIR-framework. A more detailed description of the methods and their application can be found in the Supplement.

	Materials	Methods/Analyses	Modified DPSIR	References
History	Archival documents; media material	Historical analysis (qualitative)	Driving forces; Pressures; Impacts; State; Responses; Goals	Winiwarter and Knoll (2007)
Limnology	Data on total Phosphorus (TP), Chl *a* (HERTTA-database)	Shapiro-Wilk test; ANOVA for repeated measurements; Games-Howell *ad hoc* test; linear regression analysis	Pressures, State, Goals	Stow and Cha (2013); Filstrup et al. (2014); Jones and Brett (2014)
Futures studies	Scenarios produced in Futures workshop (27 Oct. 2015), 15 participants	Futures workshop; Scenario method; Futures table (qualitative, participatory)	Driving forces; Pressures; State; (Impact); Goals; Responses	Jungk and Müllert (1986); Bishop et al., (2007); Lauttamäki 2016

qualitative and quantitative analyses of our case, in relation to the different dimensions of the DPSIR-framework.

While the longitudinal nature of the study entails a descriptive approach to the restoration history and anticipated future of the lake, the analysis coalesced around key phases and ruptures of the restoration history. The analysis integrates findings from environmental history, futures studies, and limnology in a novel way. Additionally, it provides an empirical, interdisciplinary application of the DPSIR-framework, which has been called for by Lewison et al. (2016). Our application of the framework includes the historicity and future relevance of the entangled social and ecological processes, answering the critique presented by Fernandez et al. (2014). As shown by Karageorgis et al. (2006), the frame is applicable to long term analysis. Our study integrates interpretations of the past – reflecting the perceptions valid *at the respective times* to avoid anachronisms – and limnological data that was acquired through present day knowledge about past conditions. The futures' analysis is likewise based on *present day* knowledge.

3. Results

The historical analysis revealed four main periods of lake restoration at Tuusulanjärvi. Along with the future orientation we used these periods to structure the chronological presentation of our results, scaffolded around the DPSIR-framework and summarized in Table 2. In the following sections, they are abbreviated with Roman numerals as follows:

I (1970–1980): Aeration utilized, but no wastewater treatment
II (1980–1996): Both aeration and wastewater treatment utilized
III (1997): Heavy algal blooms
IV (1998–2015): Multiple, simultaneous restorative measures
$V_{a–c}$ (2016–2030): Future prospects in three scenarios

3.1. Past ecological states of the lake

The analysis of the long term limnological data series shed more light on the eutrophication-related processes, with the goal of increasing our understanding of the ecological realities that have shaped the lake's past. The observed relationship between the concentrations of TP and Chl *a* from 1970 to 2015 ($R^2 = 0.359$, $p < 0.0001$; Fig. 3) depicts a pattern of increased algal biomass with TP concentration for the water in Tuusulanjärvi (Fig. 4). This pattern changes between the historical periods differentiated in the study, according to the ruptures in the lake restoration history, whereby the most noticeable changes (decrease in the Chl *a*/TP and slope of the regression line) occurred during the period IV (I: $R^2 = 0.234$, $p = 0.018$; II: $R^2 = 0.346$, $p < 0.0001$; IV: $R^2 = 0.139$, $p < 0.0001$). During period IV, the Chl *a* and TP concentrations were at their lowest ($p < 0.01$). However, there were no significant differences in the concentrations between the periods from 1970 to 1980 (I) and 1980–1996 (II). The corresponding mean values for the Chl *a*/TP for the periods I, II, and IV were 0.66, 0.52, and 0.40 respectively. Despite a high degree of inter-annual variability, the Chl *a* concentrations displayed a decreasing trend over the years 1980–1996 ($R^2 = 0.045$, $p = 0.020$) and 1998–2015 ($R^2 = 0.094$, $p < 0.001$), resulting in an overall decrease over the studied years ($R^2 = 0.250$, $p < 0.0001$; Fig. 3). Similarly, TP concentrations declined over the studied years ($R^2 = 0.166$, $p < 0.0001$).

3.2. Historical analysis

3.2.1. First aid for the 'dying lake' (I: 1970s)

The history of human responses to the hypereutrophication of Lake Tuusulanjärvi dates back to the end of the 1960s. For the local people, as well as the city of Helsinki Water Works (which used the waters downstream in the catchment as its raw water supply), the frequently occurring algal blooms, the bad smells arising as a consequence of anoxia and related H_2S- and methane release, and the occasional fish

Table 2
Analysis of long-term restoration of Tuusulanjärvi according to the DPSIR-framework. The analysis covers four decades of active interventions (periods indicated in I–IV) and future prospects up to year 2030 (alternative scenarios V_a–V_c).

Time	I: 1970s	II: 1980–1996	III: 1997	IV: 1998–present	V_a: Preferable scenario	V_b: Non-preferable scenario	V_c: Probable scenario
Drivers	Sanitation	History	Agriculture; history	Agriculture; land use; history	Clay soils; disturbances in sewer systems	Urbanization; climate change	Agriculture; forestry; history
Pressures	External discharges from wastewater treatment plant	External diffuse loading; internal loading, i.e. past deposits	External diffuse loading; internal loading	External diffuse loading; internal loading, mobilized through physical-chemical processes and activities of the biota	Occasional loading from point sources; natural loading	External diffuse loading; internal loading	External diffuse loading; internal loading
State	Critical	Momentary improvement; stagnated progress	Unprecedented algal bloom; "horrid"	Poor ecological state (WFD); slowly improving	Good–High	Bad– Poor	Moderate– Good
Impacts	Threat of fish kills; distress: Urge to start action	Initial optimism; research and planning	Disgust, disappointment	Motivation to continue restoration	High value and versatile use	Low biodiversity, usability and utility	Recreational use and fishing
Responses	Winter aeration	Elimination of wastewaters; winter and summer aeration; restoration plan	New social forces (Pro Tuusulanjärvi); Mixox-aeration; food web restoration	Wetland construction; detailed action plan in line with WFD	Changing cultivation techniques; buffer zone extension; artificial wetlands; urban leakage water control; repairs of the sewer network; food web restoration, macrophyte removals; aeration	No effective restoration methods in use; experiments on chemical methods and dredging	Catchment scale management; artificial wetlands; foodweb restoration; aeration
Restoration goals	Fish survival; oxygen levels > 4mg O_2/l; time winning	Recovery; recreational use; restoration of reputation;	Restore recreational and cultural value;m Sediment restoration;	Absence of cyanobacteria; "Good ecological status" (WFD)	Versatile use of the lake	Diminishing algae blooms	Safeguarding recreational use and fishing

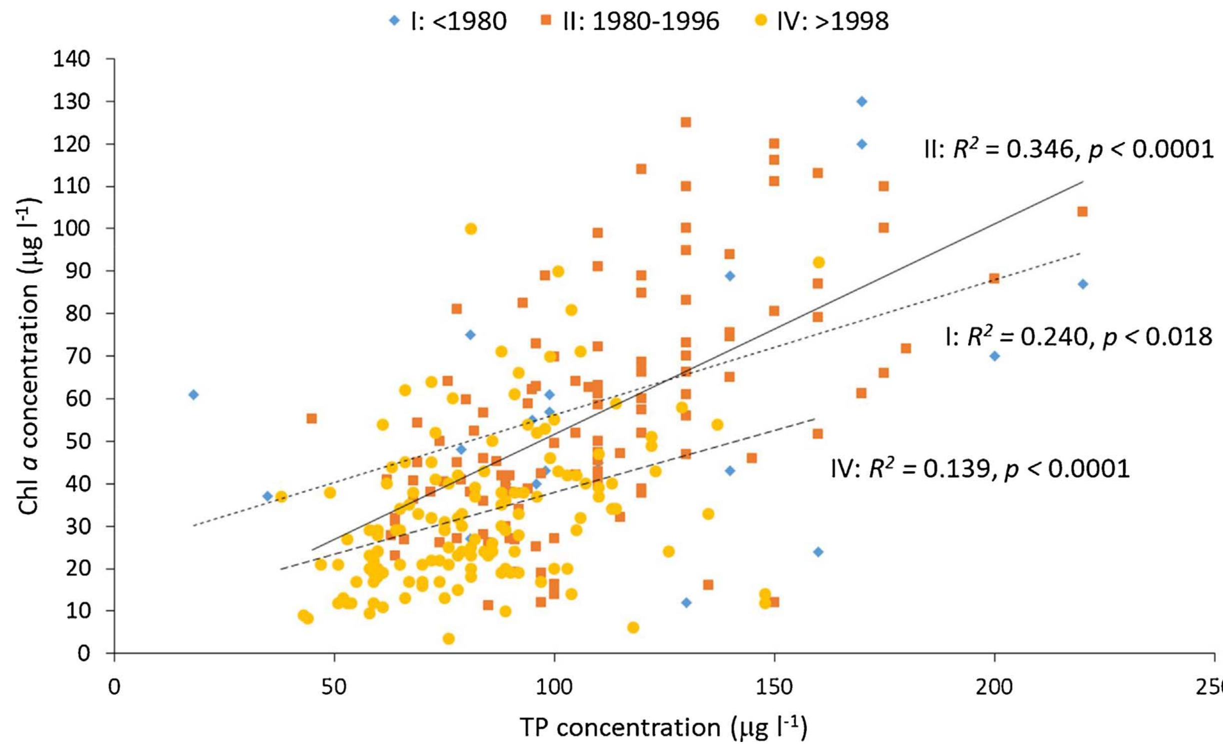

Fig. 3. Changes in the relationship between Chl *a* and TP over the periods differentiated according to the ruptures in the restoration efforts from 1970 to 2015. Year 1997 (period III) was excluded from the analysis as an outlier.

kills were all signs of a degraded lake in an unacceptable state.

The first joint meeting held to discuss the alarming state of the lake, organized in 1961, predicted a further decline of the lake, going so far as to refer to the "death of Tuusulanjärvi" (Tuusulanjärvi meeting 1961; *Maaseudun tulevaisuus,* 14 Sep 1961). Oxygen deficiency during the long winter months and the ensuing risk of fish stock destruction was the main concern. While population growth and intensified agriculture, including fertilization, were identified as important factors causing nutrient enrichment (Anttila, 1968; Harjula, 1971), the development of sanitary infrastructures and centralized sewage systems was identified as the single most important driving force causing excessive nutrient discharges (TWPA Annual report, 1976–1977). Since the elimination of these wastewaters was planned, albeit in a slow process, the immediate responses were targeted at speedy in-lake measures.

Artificial aeration was judged as the most suitable means to provide a technological time-out for the lake. Aeration would serve as an emergency measure, preventing fish kills and further degradation, and thus addressing the immediate impacts of eutrophication rather than the underlying pressures causing the eutrophication (TWPA Annual Report, 1969–1970; TWPA Statement, 1970). A commissioned study determined that the minimum oxygen threshold for fish survival was 4 mg O_2/l (Harjula, 1971), and the success of the aeration process was measured against these very concrete targets. After two winters, it was concluded that artificial aeration could keep up with the calculated oxygen demand, prevent both winter anoxia and fish kills, and improve the water quality (TWPA Memo, 1972; *Etelä-Suomen Sanomat*, 4 Dec 1972; *Keski-Uusimaa*, 20 Feb 1973; Numminen and Lemmelä, 1976, 20). This temporary program of first-aid aeration was an attempt to

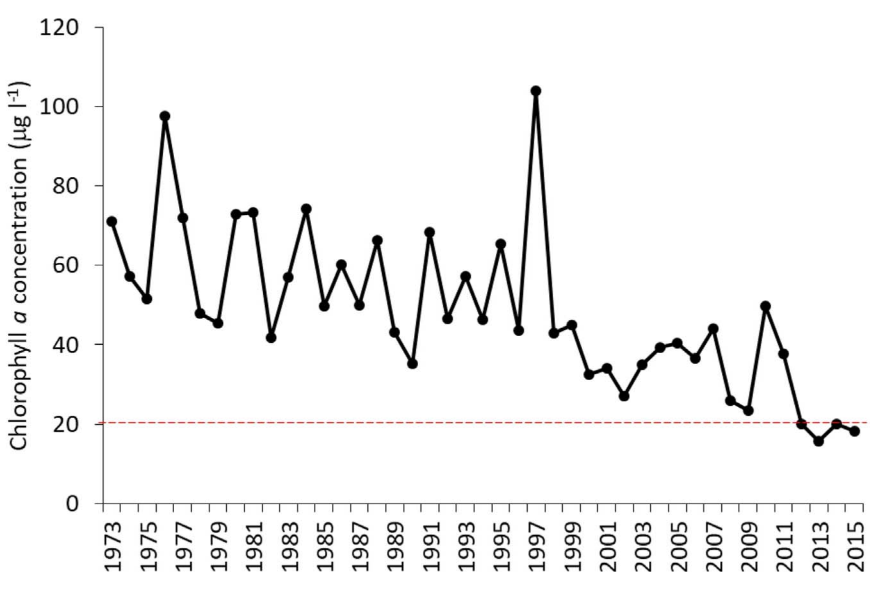

Fig. 4. Variation in epilimnetic Chl *a* concentration (average values from each growing season) in Tuusulanjärvi 1973–2015. The target value for the 'good state' is indicated with a dashed line (according to the EU Water Framework Directive).

save the lake – and especially its fish – from immediate disaster, while awaiting a final and more durable solution.

3.2.2. Shifting pressures and stagnated recovery (II: 1980–1996)

After years of delayed construction, the discharges from the wastewater treatment plant were finally diverted from the lake to a central processing plant in Helsinki in 1979. The first proper restoration plan for the lake was thus able to be completed (Keski-Uudenmaan vesiensuojelun kuntainliitto, 1984). An extensive research program was launched to identify the most suitable and effective restoration methods for the lake. The operational basis for the restoration efforts was expanded, and responsibility for the restoration was assigned to the Federation of Municipalities (KUVES, *Keski-Uudenmaan vesiensuojelun kuntayhtymä*), which would eventually cooperate closely with the local and regional water protection associations and the provincial water authorities.

While the goals of the restoration work remained rather open-ended, all plans for the future of the lake emphasized the improvement of its recreational potential. "People need to be able to enjoy the lake while swimming, fishing, rowing, sailing, or sightseeing" (*Helsingin Sanomat*, abbreviated hereafter HS, 16 Jan 1978; Kolehmainen, 1980). The scope of restoration was thus expanded accordingly. In addition to managing the oxygen levels, a more comprehensive view of the development of the lakescape as a whole gained acceptance (TWPA Plan of action, 1983–1984).

The interpretation of the state of the lake soon after the diversion of the sewage flow was ambiguous. Initial optimism was however justified, as during the summer of 1982 there was a low amount of phytoplankton biomass compared with earlier years, and no peak algal blooms whatsoever. The following winter was also good, as the warm autumn and ensuing high runoff provided surface waters rich in oxygen (TWPA Annual report, 1982–1983). However, in the summer of 1983 high concentrations of Chl *a* (Fig. 4) and large amounts of plant biomass were observed, which led to the declaration that the recovery process at Tuusulanjärvi was halted (TWPA Annual reports, 1984–1985 and 1986–1987). This unexpected setback resulted in the emergence of new perspectives on the primary pressures affecting the lake, and attention shifted to managing diffuse external loading and internal loading. While several stakeholders emphasized that diffuse sources were the single most important factor affecting the recovery of the lake (e.g. TWPA Plans of action, 1984–1985; 1986–1987), land use and agriculture were largely perceived as invariant constants that could not be addressed together with lake degradation issues (*Tuusulanjärven Viikkouutiset*, 29 Aug 1980). This difficulty in tackling the remaining external loading, especially deriving from agriculture, underscored the pressures posed by internal P loading. By the end of the 1980s, internal loading was identified as the most important component contributing to the summer algal blooms, which were particularly detrimental to recreation activities. Following this development, the general thinking, research, and planning efforts for restorative practices shifted during the 1980s towards a focus on the sediments of the lake (TWPA Annual report, 1988–1989; TWPA Plan of action, 1989–1990).

Since the scientific understanding linked internal phosphorus loading to anoxic sediment surfaces, it was thought that persevering aeration was needed to tackle the pressure from internal loading (Sandman, 1977). As a result, starting in 1982 regular summer aeration was carried out, with the explicit goal of keeping the sediment surface aerated in order to counter the flux of phosphorus from the sediment to the water, and its availability to algae (TWPA Annual reports, 1987–1988; 1991–1992).

Over the course of the following years, several plans were made to put additional measures into place to accelerate recovery. However, as the changing state of the lake was obscured by the high inter-annual variation of local conditions, most importantly observed through the intensity of algal blooms (Fig. 4), it did not show any clear tendencies towards improvement over the next roughly 15 years. Thus, it was repeatedly concluded that non-point source loading, particularly from agriculture, needed to be tackled as "an indispensable precondition before any other large concrete restoration projects can or should be started at Tuusulanjärvi" (TWPA Annual report, 1994–1995; also *HS,* 6 Mar 1996; *HS,* 27 May 1996).

3.2.3. Algae summer 1997 (III)

The summer of 1997 was characterized by an exceptionally long period of heat and windless days, which triggered unprecedented algae growth all across the coastal waters and lakes of Finland. The situation was poor nationwide, and also Tuusulanjärvi was covered with a latex-like green slime, shocking and disgusting to the locals (see Fig. 4; also e.g. *HS,* 24 Jul 1997; Tuusulanjärvi-meeting, 1997). In the aftermath of this catastrophe, there was immediate pressure to introduce a broad selection of restoration techniques on a rapid schedule, which would yield quick results. "The restoration [of Tuusulanjärvi] now requires all possible measures" (Tuusulanjärvi-meeting, 1997; *HS,* 2 Sep 1997; *HS,* 25 Apr 1998).

A strong local initiative, named 'Pro Tuusulanjärvi', emerged to encourage and enhance restoration efforts. As a result, along with continued campaigns to reduce diffuse loading from the catchment, several in-lake measures were implemented. Despite some critical opposition from local fishermen, the mass removal of fish as part of a new program of food web management was started in the autumn 1997. New, more effective "power-aeration" (*HS,* 25 Apr 1998) was introduced, aiming at decreasing internal P loading and "improving the state of the sediment" (TWPA Annual report, 2003–2004). In addition, a program of wetland construction designed to trap nutrient inflows away from the catchment was begun, with the first wetland inaugurated in 2001. The restoration of Tuusulanjärvi attained unprecedented public attention during this time, and the quick implementation of concrete restorative measures increased the general sense of optimism about the future prospects for the lake.

3.2.4. Intensive restoration (IV: 1998–present)

The "algae summer" of 1997 triggered a new phase of restoration at the lake. In addition to considerable funding being allocated to restoration, the creation of new, permanent organizational arrangements and the Finnish accession to the European Community (European Union) in 1995 also had significant influence on the restorative efforts. The EU's Water Framework Directive (WFD), in force since 2000, introduced new modes of assessing the state of the lake, and also new targets for the respective restoration of the lake (Directive 2000/60/EC). To conform to the ambitious objective of achieving a comprehensive "good ecological status" for all surface waters, specific goals addressing the quality of the biological community, the hydrological characteristics of the lake, and its chemical characteristics were established for Tuusulanjärvi.

As Fig. 4 shows, there has been a high degree of yearly variation in Chl *a* throughout the recent history of Tuusulanjärvi, which blurs the evaluations of longer-term trends. The interpretations presented in the public about the state of the lake and its future were also characterized by discrepancies (e.g. *HS,* 12 May 1999; *HS,* 21 Oct 2000; TWPA Annual report, 1999–2000 and TWPA Plan of action, 2000–2001). It only proved possible to make very vague statements about the direction and extent of the recovery (TWPA Newsletter, 11 Apr 2006). While the ecological state of the lake is at present (year 2017) still considered "poor" according to the criteria of the WFD, indicators point to a slowly improving state (see Section 3.1). The temporal variation between temporary (undesired) states and more lasting recovery trends continues to provoke uncertainty about the success of restoration efforts after more than two decades of intensive work. This underlines the need to recognize the extensive chronological perspective required for restoration, despite being carried out in a cultural atmosphere expecting quick and clearly apparent results.

During the current, intensive restoration phase, the work at

Tuusulanjärvi has become an established practice of the responsible organizations and municipalities. The implementation of a variety of measures covering a broad spectrum continues, and these have shifted from acute interventions to normalized management measures. Recently raised concerns about the negative effects of the destratifying aeration through temperature changes in the hypolimnion, and the related harmful effects on fish and summer nutrient flows (Horppila et al., 2017), has led to efforts to change the aeration procedure, especially regarding its timing and duration (KUVES, 2015). In general, the emphasis of the restorative measures at the lake is on the primary necessity to reduce external, diffuse phosphorus loading from the catchment. This includes dispersed settlement wastewaters, urban surface waters, and most importantly phosphorus leakage from agriculture (KUVES, 2012).

3.3. The future of restoration at Tuusulanjärvi (V: present – 2030)

While the ecological part of this study is based on a scientific understanding of the human impact on the lake, and the historical part of the study on an analysis of social facts and human perceptions, the futures study is necessarily based on human perceptions only, as there are no facts about the future. The alternative future scenarios for Tuusulanjärvi (period V, 2016–2030) are hence based on future envisioning by the stakeholders. In the futures workshop, the stakeholders produced three distinct future scenarios for Tuusulanjärvi: a preferable, non-preferable and probable one (denoted as scenario V_a, V_b and V_c, respectively).

In the preferable scenario (V_a), the main drivers of the external pressures at Tuusulanjärvi are natural nutrient loading from clay soils and occasional disturbances in nearby sewer systems. The external loading of nutrients has been successfully reduced by changing cultivation techniques, extending buffer zones, building artificial wetlands, controlling urban leakage waters, and repairing the sewer network. Due to climate change, the duration of the ice cover during the winter has been reduced and winds have intensified, consequently improved the oxygen conditions of the lake. The state of the lake is good-high, and thus the target of EU Water Framework Directive has been reached. In addition, the scope of the management response system is expanded to include the whole catchment area. As a result, lake management is taken into account in the land use planning of the catchment, and a variety of actors are involved in the management of the lake. The restoration palette still includes food web restoration, macrophyte removals, and aeration, but in a less intensive manner. The lake is greatly valued for recreation, swimming, and fishing, and the lakeside community takes an active part in the restorative process to ensure the proper use of the lake.

In the non-preferable scenario (V_b), enhanced urbanization and climate change are increasingly relevant driving forces. The leakage of urban surface waters, and increased precipitation and run-off, has resulted in increased external nutrient loading and eutrophication. The status of the water is bad-poor, there are algae blooms during the summer, and the biodiversity has declined. There is a general disbelief that lake management and restoration efforts can improve the quality of the lake water, as the formerly extensively used aeration techniques have been shown to be ineffective. Funding for restoration is difficult to obtain, as there are no demonstrably effective methods available and the restoration efforts are generally considered to be a waste of resources. There have been some experiments with chemical methods and dredging, but without encouraging results.

In the probable scenario (V_c), agriculture and forestry are the principal driving forces for pressures on Tuusulanjärvi. Precipitation and run-offs have increased due to climate change, but efforts to reduce external nutrient loading from the dispersed settlement wastewaters, agriculture, and urban surface waters have been effective. The status of the lake is moderate-good in the year 2030. Safeguarding recreational use and fishing are the most important goals for the management of the lake, and there is a wide public recognition of the lake restoration program. Funding for lake restoration has decreased from its current levels, but is still available for certain responses and research. Catchment scale management has been effective, artificial wetlands have been built, and foodweb restoration efforts continue as earlier. There have been doubts about the effectiveness of aeration, but it is still carried out as it has in the past.

4. Discussion and conclusions

The fact that multiple underlying human-ecological factors have been simultaneously influencing the degradation of Tuusulanjärvi is evident; however, society has focused on different individual factors over time. At first, attention was focused on the obvious and unambiguous point sources, the municipal wastewaters, driven by advances in urban sanitation (period I). After the elimination of these wastewaters, the historicity of the "unforgiving" lake (*HS,* 19 August 1990) and its degradation was strongly highlighted, and attention shifted to the historical accumulations of P in sediments. While agriculture had been implicitly acknowledged as an important source for nutrients for some time, until the late 1980s agricultural water pollution was a "non-issue" in Finland (Jokinen, 2000). Thus, internal P loading, or "legacy P" (Sharpley et al., 2013), was increasingly highlighted as a major driving force for eutrophication at Tuusulanjärvi, especially during period II (1980–1996). It is also believed that it will remain an important driving force in the future scenarios of period V (2016–2030). However, in the preferred future scenario V_a diffuse external loading is of particular importance. Recent analyses of sediment cores from Tuusulanjärvi indicate the potential importance of past depositions as a source of P, extending as long as at least 20 upcoming years (Horppila et al., 2017).

This temporally dynamic property of phosphorus in the lake ecosystem has important ecological and social implications for the restorative responses implemented at the lake. As in many lakes worldwide, a strong relationship between Chl *a* and TP suggests the potential importance of P loading (from both external and internal sources) for productivity in Tuusulanjärvi. This is supported by the changing patterns in the concentrations of Chl *a* that occurred in response to restoration measures applied in the lake targeting a reduction in P loading. Recent studies in Tuusulanjärvi showed that reduced external P loading (as a result of wastewater diversion in 1979) was followed by a considerable increase in the internal P loading (Horppila et al., 2017). This could possibly explain why no significant changes in the concentrations of Chl *a* and TP between periods I and II were observed, and agrees with the recognition of internal P loading as a main pressure, as revealed by the historical analysis. The flux of P from sediments and the decreasing water quality were attributed to the oxygen deficits, and were thus countered by continuous and expanded, seemingly unproblematic summer aeration programs (see Schönach et al., 2017). However, our analysis of the long-term limnological data series revealed the major contribution made by aerobic release to internal P loading (Horppila et al., 2017). Thus, despite initial assumptions, aeration could not lead to a significant improvement in the quality of the lake water.

In the preferable future scenario V_a, stakeholders anticipated positive implications of climate change on the sediment, via improved oxygen conditions due to intensified winds and the shortening of the ice-cover period. This assumption can be questioned, however, since the aerobic release of P from sediments, and thus internal P loading, are likely to increase in response to these projected changes in weather conditions. In general, climate change has been thought to intensify eutrophication symptoms by increasing the supply and internal recycling of nutrients (Jeppesen et al., 2009; Moss et al., 2011). Thus, climate change can be seen as a new threat, possibly becoming a significant driving force in the future. This also expands the concept of 'driving force' in the DPSIR-framework. Originally, it referred to human actions producing pressures on natural environments, but our analysis highlights the impracticability of differentiating human action from natural changes. Adding natural factors to the anthropocentric DPSIR-based analysis is necessary in order to capture the socio-ecological complexity inherent in restoration processes. This is particularly evident in regard to the yearly varying weather conditions. Studies in Tuusulanjärvi demonstrated the effect of these weather variations on the temporal dynamics of pressures (Horppila et al., 2017). Moreover, exceptional weather events − such as those at Tuusulanjärvi associated with the crisis of 1997 − provide powerful examples of how the intertwined nature of temporally varying and often overlapping social and ecological processes can often have great societal influence on long-standing restoration efforts.

Exceptional situations such as these, underscored by enhanced media attention, can manifest as states that eventually influence the broader perceptions of the lake environment, and also the ensuing responses to these perceived states. The algae catastrophe (1997) was preceded by a record high (292% above long-term averages) precipitation, and thus P inflow, in November of 1996 (FMI statistics), and then an above-average period of warmth during the summer months. This exceptional and unprecedented crisis resulted in societal impacts that triggered extensive responses over a broad spectrum, both in the immediate time frame and in the longer term. Similarly, Lyytimöki (2012, 410) has identified the year as a critical discourse moment for the entire Finnish debate on eutrophication. At Tuusulanjärvi, the crisis induced restoration activities that resulted in pronounced changes in the ecological state of the lake, as indicated by the significantly decreased concentrations of TP and Chl *a*. A considerable decrease in Chl *a*/TP-ratio can be associated with the more intense algal grazing by filter feeders (zooplankton), resulting from biomanipulation efforts (Mazumder, 1994; Jones and Brett, 2014). Additionally, the introduction of wetlands with the aim of reducing the nutrient supply from diffuse sources could also have contributed to observed changes in the water quality.

After 1997, the appearance of algae, and consequently its impact on the recreational potential of the lake, has become an accepted measure and indicator of the state and water quality of the lake (Leväarkisto, 2016). The human eye can easily detect the green hue of lakes associated with algae at Chl *a* concentrations of $10\,\mu g\,l^{-1}$, and it is thus easy to visually assess the extent of the algae and its changes over time (Jones and Brett, 2014). At Tuusulanjärvi, the Chl *a* concentration exceeded this level on many occasions over the course of the study period. The overall decrease in TP and Chl *a* concentrations indicates a gradual improvement in the state of Tuusulanjärvi, despite counteractive effects of climate change (increase in temperature, water level, wind speed). Hence, the restoration efforts implemented so far seem to have played an important and positive role. Horppila et al. (2017) concluded that the further reduction of the external P loading would ensure the further improvement of the lake water quality. The use of measures designed to reverse the release of P from sediments should be reconsidered, as aeration based on destratification seems to rather increase the P flux from the sediments. These conclusions are in line with what is foreseen for the next 15 years under the probable scenario.

The DPSIR-framework emphasizes the impacts of environmental changes on the utilization of the affected environment. A lake's 'good state' has been and continues to be valuable to citizens through its ecosystem services. In addition to the impacts on recreational opportunities, our historical analysis also revealed important emotional impacts that the changing state of the lake evoked in the populace. In the anticipated future, the emotional bond with the lake is also stressed as an important factor. As Eric Higgs (2003, 58) puts it, restoration is "synonymous with the restoration of hope". The improving state of the lake invigorates the hope for an even better future, and provides a basis for continuous restorative efforts.

Our analysis reveals that the different restorative interventions implemented at the lake have not been responses to static perceptions of the overarching problem, but rather outcomes of intertwined social and ecological processes which are fused with context-bound interpretations of the problem and its desired futures.

While the overall aim of improving the state of the lake, and making it a valuable body of water again after decades of hypereutrophication, has remained unchanged, the manifestation of the 'good state' and 'value' of the lake has differed over the course of the long period of work at the lake. The often outspoken aims reflect shifting perceptions, and an emphasis on understanding the reasons for and impacts of eutrophication. The historically shifting focus on multiple goal has been based on different perceptions of the future of the lake, which in turn reflect shifting societal preferences and conditions, such as economic valuation through fishing (period I, the 1970s) or recreation (since period II, the 1980s), and goals diffused through international or domestic policies (especially since WFD in 2000, period IV). The different goals set for restoration activities often support each other, however recent findings concerning the negative effects of destratifying aeration on valuable fish stocks (through increased hypolimnetic temperatures) shows how not all restoration goals are always compatible.

The differing emphasis on various restoration goals, and the differing indicators used to judge the success of various restorative measures, make the restoration process prone to obscuring the outcomes of individual measures, and thus leave ample room for interpretative differences about the success of individual interventions. In order to proceed with a successful restoration program, the various stakeholders with their vested interests need "to understand and balance all of the competing forces contributing to the symptoms considered to be undesirable by observers" (Thornton et al., 2013, 308). These competing forces and symptoms, however, are open to various interpretations and differences in emphasis, which also change over time. Similarly, the interpretations of the state of the lake are blurred through a diversity of indicators, including both quantitative indicators and qualitative judgements. The seasonally determined practical observation of the quality of the lake (presence of algae, pleasantness for swimming) triggered short-term judgements about the state of the lake, while at the same time it was also highlighted that recovery is a process of long duration. The evaluation of the lake state under these circumstances depended on the availability of a point comparison, and also on the definition of the selected criteria and indicators. Snapshot-like comparisons to previous states, or focusing on a single, quantitative parameter, such as oxygen concentrations, narrowed the assessment and resulted in highly varying opinions among the different stakeholders concerning the state of the lake.

To conclude, our case study of Tuusulanjärvi shows how interdisciplinary and long-term analysis 1) enables an increased understanding of the socio-ecological dynamics of lake restoration, 2) addresses challenges related to these endeavors, and 3) reveals important insights into the restoration process that might otherwise remain obscured with a narrower scope. The historicity of the lake is present in the restoration process in many ways. The driving forces of lake degradation can be uncovered from the historical record, and the historical states of the lake affect the goals set for future restoration by comparison. Present-day methods allow us to gain new knowledge about the past of the lake, while present-day understandings and perceptions influence the anticipated futures of the lake.

Funding

This work was supported by the Academy of Finland [grant numbers 263468, 263464 and 263305].

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2017.12.015.

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