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Persistency of artificial aeration at hypertrophic Lake Tuusulanjärvi: A sociohistorical analysis

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Abstract

With present-day scientific evidence challenging the efficiency of artificial aeration as an effective [illegible]es the reasons for the persistent support for this method in Finland, where about one hundred lakes are subject to this treatment. Our study employed the concepts of technological path and aeration frame to analyze the extensive restoration and aeration history of the hypertrophic Tuusulanjärvi in southern Finland. Continuously aerated since 1972, it has the longest history of aeration in Finland. Qualitative analysis of documentary and archival sources revealed that the longstanding preference for aeration in the context of increasing scientific controversy was based on its functional versatility and seemingly unproblematic applicability in regard to shifting emphasis and goal setting of restoration. Additionally, the stability of the aeration frame has been supported by the practical and emotional attachment of local residents to lake restoration, particularly aeration, and finally the problems and contradicting interests related to alternative restoration methods.

Key words: hypertrophic lake, lake restoration, restoration history, artificial aeration, technological frame, Tuusulanjärvi

1. Introduction

Anthropogenic eutrophication of lakes is currently one of the most prevalent of water-quality problems. Lake restoration is an intentional reparative activity to remedy or reverse past human-induced environmental damage. Artificial aeration is a widely used and intensively studied lake restoration technique to combat the adverse effects of eutrophication and related oxygen deficiency (anoxia) problems (see Cooke et al. 2005; Singleton and Little 2006). Aeration often aims at addressing water-quality problems associated with anoxia-induced sediment phosphorus (P) cycling. The release of P from sediments to the overlying water column, i.e. internal P loading, has commonly been attributed to oxygen deficits. Internal P loading contributes to excessive primary production and hence accelerates the eutrophication of the lake (Cooke et al. 2005).

Several studies have reviewed the impacts of aeration on lake water quality (e.g. Beutel and Horne 1999; Cooke et al. 2005; Bormans et al. 2016). An increasing number of studies question the efficiency of artificial aeration (Gächter and Wehrli, 1998; Gächter and Müller, 2003; Nürnberg et al. 2003; Liboriussen et al. 2009; Zębek 2014; Horppila et al. 2015; Kuha et al., 2016; Mallin et al. 2016). Generally, in lakes which' internal loading was not decreased, also no water quality improvement in the surface layer were observed (i.e. phytoplankton, cyanobacteria, or Chl *a* reductions). No water quality improvement can be expected unless external P load is reduced, as this controls both oxygen deficit and P release (Gächter and Wehrli, 1998; Moosmann et al., 2006).

The paradigmatic basis of oxygen-determining P release from sediments has been challenged (Hupfer and Lewandowski 2008; Tammeorg et al. accepted for publication). Additional support for the limited use of aeration in Tuusulanjärvi, the case lake of this study, was provided by our recent findings. Long-term data series showed that although anaerobic P release has decreased as a result of aeration efforts, total internal P loading has increased, due to the enhanced P release from aerobic areas (Horppila et al., 2017).

In Finland, aeration has been among the most common lake restoration methods since the early 1970s (Keto et al. 2004, 94–95). At our case lake, recent research suggests that this is likely in the future as well. When restoration stakeholders gathered in five futures workshops to ponder what the recently raised, scientifically based doubts about the effectiveness of aeration could mean for current and future practices of lake management, they nevertheless envisioned a central role of aeration in the preferred future of the lake management efforts (Nygrén 2016). At Tuusulanjärvi, lake management experts and other stakeholders considered hypolimnetic aeration as an important part of the preferable and probable lake restoration strategy up to the year 2030 (Nygrén 2016, 23–24). In this paper, we attempt to trace the reasons for the strong support for artificial aeration as a favored technique in Finland, based on the example of particularly intensively aerated Tuusulanjärvi. The socio-historical study design is based on the importance of the past for understanding contemporary phenomena and, consequently, the need to explore the question with a longer-term historical approach. Conscious human interventions for modifying and improving aquatic environments are complex processes in which ecological realities, technological possibilities, and societal practices come together (cf. Higgs 2003). Values, as well as economic, political, and social structures influence the cultural motivations for wielding tools to cope with or pursue changing environments (Gorman and Mendelsohn 2010, 272). The objective of the study was approached via the following research questions:

1) How has the choice of artificial aeration been justified at different times?

2) Why has aeration been favored over other possible restoration methods?

The study contributes to the restoration literature of aquatic, especially lacustrine, environments that have received less attention than terrestrial restoration (Gobster and Hull 2000; Higgs 2003; Egan et al. 2011; Jordan and Lubick 2011). While the results are based on the investigation of a Finnish case, the study bears wider relevance, since aeration is broadly practiced and the controversial stances on its efficiency have been recently internationally recognized. After conceptualizing long-lasting artificial aeration as a technological path with a dominant and stabilized technological frame, we contextualize the study to the case lake. Thereafter, the study materials are presented. The results of the analysis are organized in three thematic sections, after which they are discussed reflecting the literature on the stabilizing elements of paradigmatic, strategic, and sociotechnical change.

2. Methodology and empirical design

2.1 Conceptual approach

In this study, we understand artificial aeration as a broadly defined technology. Apart from the physical artefacts, it also includes the human activity of preparing and working with these technologies, the conventions and beliefs related to the activity and, finally, the knowledge related to technology (Bijker et al. 2012, xlii).

We conceptualize continuous artificial aeration as a *technological path,* which means a process in which a specific technological option with increasingly stable interlocking of social and material elements stabilizes as a result of emergent phenomena and deliberate human actions. The path can be divided into the phases of path generation (i.e. beginning), continuation, and termination (Meyer and Schubert 2007, 29–30). While we explore the initial phase of the path, our main interests here are the continuation and stabilization phases of aeration, which help us explain the persistent support for this method. As a constitutive element of the path, we include in the analysis the concept of the *technological frame*, developed especially by Bijker (1997). With a strong analogy to the Kuhnian concept of *paradigm,* which is used to explain the stability of normal science (Kuhn 2012; see also Bijker 1997, 192), the technological frame can be used to increase our understanding of the stability of a certain choice of technology. This also follows Dosi's model of technological paradigms producing technological trajectories, which promote continuous progress on an established path instead of shifts to alternative paths (Dosi 1982).

The technological frame, or 'frame in respect to technology', refers to established ways of thinking through a common cognitive frame shared by a group of people interacting around the technology.

The frame constitutes the members' common interpretation of a technology and comprises the (technological) artefacts in addition to the knowledge, goals, and values related to this technology. Hence, the frame comprises various material, technical, social, and cognitive elements that may promote certain actions and discourage others. They tacitly or explicitly structure the frame holders' thinking, problem-solving, strategy formation, and design activities (Bijker 1997, 123–125; see also Klein and Kleinmann 2002). The formation of a technological frame necessitates social interactions of groups that move towards a shared attribution of meanings with regard to technical artefacts. Following this, a meaning can become dominant and influence the ways goals are translated into problem-solving strategies (Bijker 1997, 237). Hence, the stabilization of a technological path is conceptualized as a collective process (Meyer and Schubert 2007, 35). The concept of the technological frame is used here to increase our understanding of the *lack of change* in situations when scientific findings increasingly indicate a need for change.

2.2 Tuusulanjärvi

The study was performed in the context of a lake in southern Finland, Tuusulanjärvi, which has an extensive aeration history. The shallow lake (mean depth 3.2 m) is located approximately 40 km north of the capital, Helsinki. It belongs to the catchment of River Vantaa, where the lake also drains through an outlet, the Tuusula River. The lake surface area is roughly 6 km^2, with one main deep of 10 m depth. Two main municipal centers are located at both ends of the lake, Järvenpää in the north and Hyrylä, the main population center of the municipality of Tuusula, in the south (see Fig. 1). The cultural historically significant lake is known for a circle of prominent artists who accommodated its shores during the first half of the twentieth century and drew inspiration for their iconic national romantic works from the lake scenery (see Konttinen 2013). Tuusulanjärvi is also the largest lake in the country's most densely populated province, which increases its' recreational significance.

Figure 1. Tuusulanjärvi, its surroundings, and positions of the aerators in 1972.

The naturally eutrophic Tuusulanjärvi has been one of the most intensively and longest studied lakes in Finland. Tuusulanjärvi became a popular field lake for natural historians and scientists since the 1890s (Levander 1901). The first professor of limnology in Finland, Heikki Järnefelt (1891–1963), grew up on the shores of the lake, and was occupied with the lake throughout his career until the late 1950s (Järnefelt 1958). Signs of anthropogenic eutrophication have been observed in the lake since the 1920s, becoming more pronounced between the 1930s and 1950s and advancing in the postwar decades. The rapid deterioration in the water quality of the lake was due to intensified agriculture and an increase in centralized sewerage for a growing population. Discharges of unpurified or poorly purified municipal wastewaters into the lake resulted in excessive nutrient input and, consequently, eutrophication (Järnefelt 1958; Tolonen et al. 1990). Extensive algal blooms occurred more frequently, and potentially poisonous cyanobacteria (blue-green algae) hampered the utilization of the lake. Foul odors resulting from anoxia and fish kills were obvious signs of a degrading lake. The lake became infamous for its offensive state. Artificial aeration was initiated in 1972. Forty-five years later aeration is ongoing and has been slated for continuance at least until 2021 (KUVES 2012). In general, aeration has increased concentration of dissolved oxygen in the hypolimnion (Fig. 2). Nevertheless, the recent lake monitoring data (including fish, invertebrates) indicate still a 'bad state' of the lake, and high phosphorus concentrations in the surface layer (mean for 2006–2012 in summer, 88 $\mu g\, l^{-1}$) are of major concern

(Marttila 2013). In summer of 2006–2012, mean values for the concentrations of TN, Chl *a* and phytoplankton biomass were 1000 µg l^{-1}, 34 µg l^{-1} and 5 mg l^{-1}, respectively.

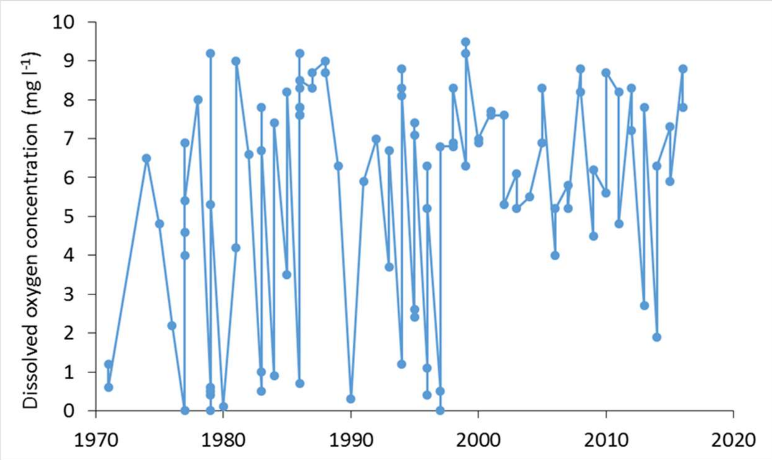

Fig. 2. The concentration of dissolved oxygen between 1970 – 2016 near the bottom in the deepest part of Tuusulanjärvi during late summer.

However, with gradually improving water quality (see Horppila et al. 2017) and investments in enhanced recreational facilities, such as surrounding scenic bike route and lakeside parks, beaches, and birding towers, the recreational use and significance of the lake has grown. Popular uses of the lake include summer and winter swimming, fishing, boating, and ice skating. The aesthetic lake scenery is highly valued among the increasing local population and mainly domestic tourists. The lake's shores host a great biodiversity and it has been included in the National Waterfowl Habitat Protection Programme and the EU-wide Nature 2000-network as part of the EU Habitat Directive.

2.3 Study material

The material for this study was gathered in a heuristic process, typical for environmental historical research (Winiwarter and Knoll 2007, 78–80). It consists of historical and contemporary documents, reports and research publications, and extensive media material. The media material was acquired through searches of the digitized archives and a media clip collection. The other materials, stored in several archival units, were produced by the various stakeholders who have been involved in aeration practices at the lake. These include the main promoters and leaders of early restoration efforts at the lake, namely the actively involved, self-educated local residents and users of the lake, grouped predominantly within the independent and voluntary-based Tuusulanjärvi Water Protection Association (TWPA). Along their independent work around the lake issue, they communicated actively and informally with the officials of the two riparian municipalities. The regional water authorities (Helsingin vesipiiri), who were most importantly responsible for the implementation of national lake management guide lines and planning, were involved in the case of Tuusulanjärvi mainly through monitoring and consultation. Since the early 1980s a federation of municipalities (Keski-Uudenmaan vesiensuojelun kuntayhtymä, KUVES) has been responsible for the water protection and restoration activities in the region. The catchment wide Water Protection Association of the River Vantaa and Helsinki Region (VHVSY) became also increasingly involved. The national Board of Waters (Vesihallitus) was only beginning to raise lake restoration on its agenda at the same time with initiation of aeration at Tuusulanjärvi, which resulted in frequent information exchange and communication. However, since restoration by large was a local decision and initiative, they remained mainly as background observers, who provided unofficial advice at request. Finland as a country with a small population had a very modest amount of well-networked restoration experts. Scientific expertise was scattered within all these organizations, thus encouraging frequent consultation and informal exchange experience-based knowledge.

The analysis of the material advanced through a merged process of qualitative content analysis and hermeneutically advancing contextualization and interpretation of the material (Winiwarter and Knoll 2007, 80; Krippendorff 2013). The focus of the content analysis was on the identification of the formative and stabilizing elements of the technological path of aeration and the *aeration frame*. Through selective close reading of the documentary material, reoccurring categories that revealed patterns were identified inductively and interpreted in the sociohistorical context of water protection and lake restoration in Finland.

3. Results

3.1 Multifunctional and indispensable aeration

Initiation of aeration at Tuusulanjärvi was clearly experimental. After the first tests in 1968 with prototype equipment, the TWPA negotiated with the conglomerate Nokia, which actively offered their newly developed equipment (Fig. 3). Due to the experimental character, the aerators were provided in the beginning for free. Only after successful evaluation of their functioning were they obtained in the municipalities for regular and continuous operation (Nokia 1972a, 23; TWPA 1972). Artificial aeration was a rather novel technique, with not much previous domestic or even international experience to draw upon (TWPA 1972). Nevertheless, it was worth a try, since it was "[..] certain that the state of Tuusulanjärvi cannot worsen from [the aeration]" (Kainulainen 1972).

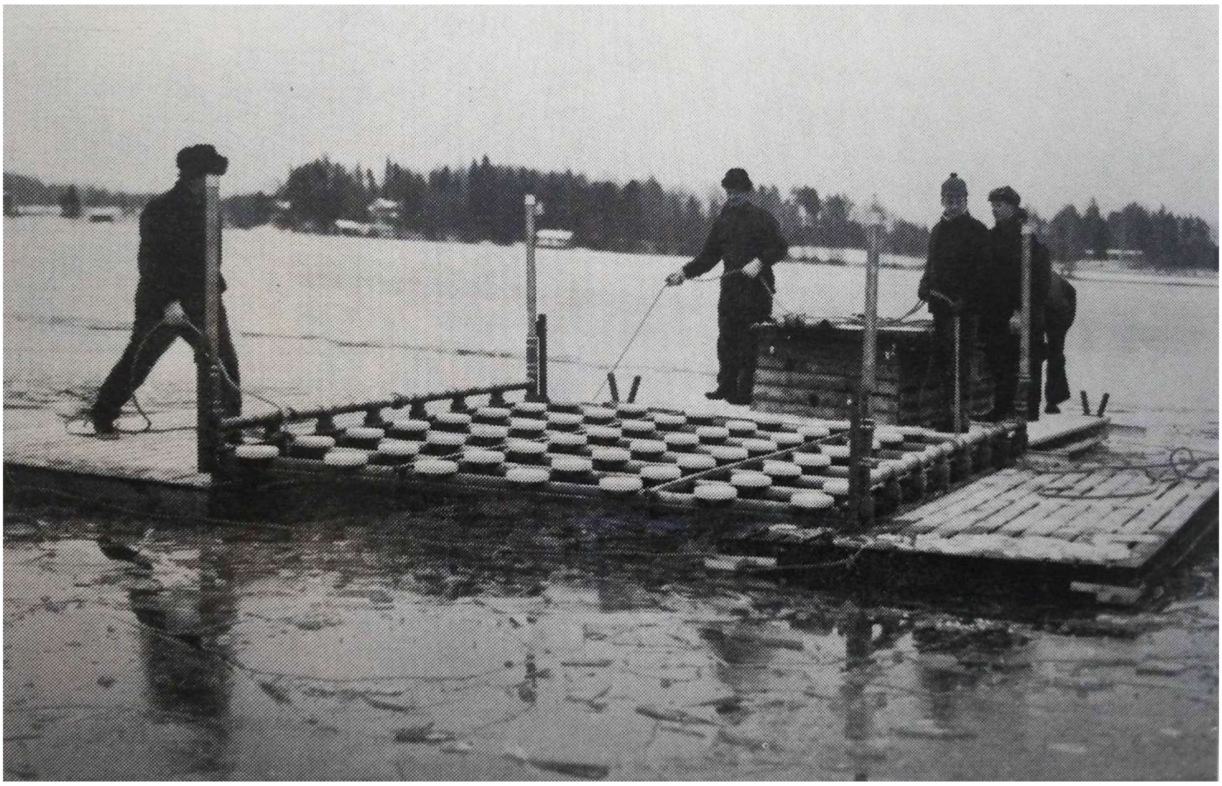

Figure 3. Nokia aerators being immersed in Tuusulanjärvi in 1972. Original published in Nokia (1972b, 29), photographer unknown, reproduced with the permission of Nokia Ltd.

Early artificial winter aeration at Tuusulanjärvi was a first-aid technique to prevent the lake from 'dying', which mainly referred to a looming total fish kill due to anoxia (Etelä-Suomen Sanomat (ESS) 4 Dec 1972; newspaper Maaseudun tulevaisuus 5 Dec 1972). The magnitude of the oxygen deficit was calculated thus enabling the translation of the eutrophication history of the lake into exact figures, and hence determining the goals for measures. The calculations suggested that the fate of the lake depended on a deficit of 200 metric tons of oxygen, whereas a limit of 4 mg l^{-1} dissolved oxygen was set as a threshold for viability (Harjula 1971). While the complex reasons for anoxia were recognized, the improvement in oxygen levels was pursued with 'direct techniques', quickly and effectively (Kangas Memo unpubl. 1969; Harjula 1971, 29). Since the eutrophication problem of the lake ecosystem was simplified to an oxygen deficit, aeration could successfully meet the objectives.

From the very beginning, aeration was interpreted as a success. It was considered so effective that by the mid-1970s when it had been established as a regular procedure at Tuusulanjärvi, it functioned as a temporary replacement for municipal wastewater treatment. A Water Court's permission for continued discharges into the lake included the condition that the oxygen levels of the lake must be maintained. In practice, this meant that the Water Court ordered aeration at the lake (Helsinki water district 1977). This was very much in line with expert statements that artificial aeration could be used to replace some wastewater treatment investments. Aeration was used to enable the relocation of wastewater treatment into the lake (newspaper Keski-Uusimaa (KeskU) 8 Mar 1973; newspaper Helsingin Sanomat (HS) 2 Apr 1980; Vesi-Eko memo, 1982).

A landmark of lake management at Tuusulanjärvi was the elimination of centralized municipal wastewater discharges in 1979. After several years of improvement observed in the state of the lake, however, the recovery process was interpreted as stagnated from 1983 onwards. The focus shifted from point sources in the watershed towards nutrient sources within the lake, at the core of which were the sediments and internal loading (TWPA Annual reports). Following this position summer aeration was initiated from 1982 on with the aim "[..] to keep the sediment surface oxic, in order to prevent the excessive release of phosphorus from it" (TWPA Annual report 1987–88). The common understanding of hypolimnetic oxygen's importance in controlling internal loading ensured a strong reliance on artificial aeration.

The temporal shift from instant and short-term prevention of fish kills, and winning of time for the lake recovery to more long-term restoration through controlling of internal loading highlighted the flexibility of aeration as a multifunctional practice. In only a single decade after the sewage diversion, it was evident that the time perspective of recovery had to be changed. With continued aeration, fish kills were avoided, but annual algal blooms even increased. Activists of the protection association and researchers were forced to admit that quick recovery was not realistic (HS 19 Aug 1990). Artificial aeration fulfilled a function of bridging the existing temporal lag characteristic of lake restoration, the frustratingly long timespan between positive results of measures and the urge to act immediately – and obtaining visible results. The increased oxygen levels due to aeration could be measured immediately, and the decreasing oxygen levels during the machinery's malfunction were instant signals of the efficiency of aeration (TWPA, Annual report 1976–1977). Aeration was thus a quick answer to problems with a long time horizon.

When the optimistic plans of the 1980s for quick lake recovery faded, aeration became a regular, normalized lake management procedure that was carried on in the background, while the main focus was on reducing external loading from the catchment area (TWPA, Plans of Action, e.g. 1984–1985, and 1986–1987). After an exceptionally strong, infamous algal bloom in the summer of 1997, the old aerators were replaced by destratifying Mixox 'power aerators' (TWPA Annual report 1998–1999; HS 25 Apr 1998) which pumped oxic surface water to the lake bottom. Their simple working mechanism was an innovation of the nationally well-known and influential lake restoration specialist, K. Matti Lappalainen and his company Vesi-Eko. At present, aeration is itemized as 'sediment restoration' (e.g. KUVES 2012). This indicates again its role in a process of anticipated improvement in the state of the lake, instead of simple maintenance of the status quo.

Besides that aeration seemed functionally adequate, its broad support was sustained by a generally favorable atmosphere and a perception of its indispensability. Although early experiments with artificial aerators were known (e.g. Mercier 1949; Peippo 1963), their use in lake restoration schemes were only beginning to receive more scholarly attention during the 1970s. In Finland, artificial aeration was extensively discussed in the path breaking, first comprehensive presentation about the aims and methods of freshwater restoration by the limnologist and researcher of the Finnish Board of Waters, Paavo Seppänen (Seppänen 1973). From this onset, aeration was predominantly presented in a positive light underscoring its benefits. Statements referred to favorable experiences from elsewhere, and it was seen as both realistic and economically feasible (Kangas memo 1969 unpubl.; ESS 11 Nov 1978). "Aeration is by far the most cost-efficient restoration method" declared a regional newspaper (ESS 29 Apr 1978). Experts claimed that aeration was an effectual and promising restoration method with significant future potential. A national survey on lake restoration needs verified that aeration was considered as one of the main restoration methods in Finland (Vesistöjen kunnostamistyöryhmä 1977).

Since aeration was initiated at Tuusulanjärvi, it has been unanimously declared as indispensable to the lake, without it, the lake would “suffocate” (TWPA Aeration meeting, 1 Mar 1972). Aeration was enthusiastically perceived by the stakeholders and communicated in the media as “fundamentally” important to the survival of the lake (KeskU 20 Feb 1973; KeskU 1 Mar 1973; KeskU 12 Mar 1979; KeskU 29 Aug 1979). “It is in the interest of all stakeholders to keep for the present the lake alive through aeration” (Saari and Numminen 1978). In addition to the immediate necessity, the future prospects of the lake were also relying on aeration. Recovery of the lake through aeration was a prerequisite before other measures could be put into operation (VHVSY 1978; KeskU 12 Mar 1979; KeskU 29.8.1979).

During the four decades of aeration, several positive functions have been attributed to aeration. The common denominator with all the goals attributed to aeration has been a rather monocausal and straightforward view of aeration's benefits, however reframed. As long as the various aspects and problems of the lake ecosystem have been viewed as rather separate parameters, aeration has appeared as a versatile, effective and indispensable technology for lake interventions.

3.2 Seemingly unproblematic aeration and its alternatives

Tuusulanjärvi is a multifunctional lake in which a broad variety of interests, both local and more distant, are mixed. The choice of restorative measures has been confronted with a variety of opinions, beliefs, economic realities, and imagined futures. In the context of unanimous urgency to do *something* (see Tuusula Municipal Government 1972) about the degraded lake, the broad support for aeration can also be explained with the failed attempts to introduce other, alternative restoration methods.

During the initiation of in-lake activities, withdrawal of the anoxic hypolimnetic water to the outlet of the lake, the Tuusula River, was discussed as an alternative or complimentary measure (Harjula 1971; ESS 8 Feb 1972). The regional water protection experts considered the endeavor however disproportionately costly against the anticipated benefits and the chances of success altogether

(VHVSY 1971). The plan was also opposed both by the residents, who abhorred the prospect of fouled lake water in their home river, and the influential City of Helsinki Water works, whose water supply intake was downstream and feared the deterioration of water quality and hence exacerbation of the already critical water-supply problems (Järvenpää City Government 1970). Most importantly, the withdrawal of hypolimnetic water was incompatible with hypolimnetic aeration, since withdrawal would jeopardize the benefits gained by aeration. Hypolimnetic withdrawal was seen as timely only later, but because it was estimated that aeration would be needed for a further 10–30 years, it effectively eliminated hypolimnetic withdrawal as an alternative restoration method (VHVSY 1979; VHVSY 1980).

Later, another proposal suggested the flushing of Tuusulanjärvi with pure lake water from Lake Päijänne. However, the idea was soon discarded, since the regional water authorities deemed it as too expensive in relation to the only short-time results obtainable (HS 16 Jan 1978; Keski-Uudenmaan vesiensuojelun kuntainliitto 1984).

The perhaps most ambitious in-lake restoration measure discussed was to cover the detrimental sediments with clay. It was intensively and carefully studied during the 1990s. Apart from the lack of funding for the costly project, water protection experts criticized it for being useless if external nutrient discharges could not be terminated (HS 27 May 1996). Additionally, local fishermen opposed the plan, since they anticipated negative effects on the feeding of fish at the shores, where the healthy sediment was to be collected for the cover (HS 21 May 1994).

After the catastrophic algae blooms of summer 1997, one of the rapidly implemented measures was foodweb restoration via effective fishing (e.g. roach and bream). Food web management aimed to strengthen herbivorous zooplankton, thus increasing the consumption of phytoplankton and to decrease the release of nutrients from the sediment due to bioturbation. Food web management was praised by the authorities and restoration activists as effective and indispensable. However, the local fishermen criticized and resisted the fishing campaigns and some fishing corporations went as far as temporarily prohibiting food web management in their governed waters. They saw it as harming stocks of the most valuable fish, especially the zander, whose population had declined occasionally (TWPA Annual report 2002–2003; HS 11 Jul 2002; HS 13 Oct 2011; Tuusulanjärvi restoration team 2012b). Indeed, the analysis of about 40-year long history of lake restoration revealed the effectiveness of food web management that was indicated by decreased Chl:TP ratio of the lake water subsequently to the application of the practice (Horppila et al., 2017).

In summary, several alternative or complimentary in-lake restoration methods were proposed and investigated at Tuusulanjärvi, however, they were discarded due to economic considerations and doubts about their efficiency. The only materialized alternative, fish removal, has been severely criticized by the influential community of fishermen and a cause for local conflict. These failures to find credible alternatives underscore the seemingly unproblematic nature of aeration. The only possible drawback of aeration was related to its actual operation, such as the melted holes in the ice cover (Vesistöjen kunnostamistyöryhmä 1977, 9). At Tuusulanjärvi, even this turned out advantageously. Birdwatchers enjoyed the new kinds of birdlife they attracted, and the ice holes became favored spots for winter fishermen and -women (TWPA Annual report 1973–1974; HS 18 Feb 2003). While other proposed restoration measures were several times criticized for the anticipated short duration of effectiveness, the need for ongoing aeration was not problematized.

The consistently positive stance toward aeration has been prevalent at Tuusulanjärvi, despite notions of the problems related to it. A restoration plan of 1984 raised the issue of aerator-induced turbulence, which during winter would prevent sedimentation and cause turbidity, and at the sediment-water interface would increase P release and circulation to the productive layer. The solution perceived was enhanced measuring of oxygen levels for improved timing of aeration (Keski-Uudenmaan vesiensuojelun kuntainliitto 1984, 139). During the early 1990s, these very same reservations were raised anew and again, the problems were to be solved by more thorough monitoring and temporal fine tuning for the operation of the machinery (TWPA Annual report 1992–1993; TWPA Plan of action 1993–1994). The most recent concerns against aeration relate to the water temperature increase caused by currently used aerators and its effects on the smelt stock, which in turn is the favored prey of the valued zander (Niemistö et al. 2016). In conclusion a "balancing between sufficient oxygen levels and cool hypolimnetic temperatures" (Project Tuusulanjärvi 2015) was needed. Yet again, the solution was temporal fine tuning, using ever more sophisticated machinery. To achieve this, since 2015, oxygen levels have been measured on a real-time basis to allow immediate reaction to undesired conditions (Luodedata). The closer examination of the limnological data showed that currently used destratification has increased the concentration of oxygen and decreased the concentration of soluble P in deep water, but at the same time it has accelerated P release from aerobic bottoms (Horppila et al., 2017). In numerous case studies, destratification has been reported to favor algal growth either via aeration-triggered increase in water temperature (e.g. Zebek 2014) or enhanced recycling of nutrients from the lake bottom (e.g., Nürnberg et al. 2003; Mallin et al. 2016). In Tuusulanjärvi, no such implications were observed, as food web management has compensated for the enhanced P-cycling (Horppila et al. 2017).

Despite the repeatedly raised concerns about the unwanted and unanticipated negative effects of aeration on the lake ecosystem, the principle of aeration and the underlying scientific paradigm have not been questioned by the stakeholders. Eventual disadvantages are circumvented, and moreover, it is attracting ever more technological equipment and more nuanced monitoring. This is in line with the lake's technologized history and the widely shared technological frame supporting it.

3.3 Local attachment through participation

In Finland, many regional water protection associations, with interest in entire watersheds, have been founded since the early 1960s. The initiative, however, stemmed from the municipalities and other official institutions. As for Tuusulanjärvi, the local residents, mostly from around the lake, were among the first in the country to found an officially registered voluntary grass-root association for the protection of a local lake in 1966 (TWPA Annual report 1972–1973; KeskU 18 Nov 1981). It became a driving and influential actor in restoration endeavors.

The TWPA activists evaluated various options for restoration methods, negotiated with contractors for the aeration machinery, and were in charge of practical operations during the experimental phase. Even when the municipalities took over the maintenance of the equipment, the association activists played an important role in the practices. They observed the functioning of the machinery, provided assistance in its operation, reported technical failures, informed the public via events and local media, and cooperated with other stakeholders (TWPA Annual report 1973–1974).

The aerators, "artificial gills" (Brochure 1977), that enable the respiration of the otherwise dying lake "gasping for air" (HS 25 Apr 1998) are powerful verbal images of concerned locals resuscitating their valued home lake (KeskU 12 Mar 1979; KeskU 5 May 1979; HS 19 Aug 1990). Through this activism, the lake was to be elevated to the dignity it deserved as a national cultural monument (Brochure 1977). Aeration at Tuusulanjärvi was erected as a model case for stakeholder engagement and fruitful cooperation between locals and municipal officials in local water protection initiatives (Numminen and Lemmelä 1976). The case received widespread public acclaim through newspaper articles and professional journals, and it was used as a benchmark for other anticipated lake restoration projects (ESS 4 Mar 1972; ESS 20 Jan 1973; ESS 2 Aug 1973; Seppänen 1976). The minister responsible for environmental issues visited the association and inspected the aeration project in February 1983 (TWPA Annual report 1982–1983). The exceptional efforts were publicly recognized when the association was granted a reward for its toil for the future prosperity of the lake (KeskU 18 Nov 1981). Aeration also merited international significance. Delegates from abroad visited the site and explored the aeration facilities (TWPA Annual report, 1972–1973; ESS 25 Jul 1973). The Finnish National Broadcasting Company reported about aeration in its international program (TWPA Annual report 1973–1974). Finns proudly boasted about themselves as pioneers in lake aeration with Tuusulanjärvi as their show case (Seppänen 1976, 270; HS 2 Apr 1980).

Besides the association, the broader public was actively engaged for the sake of the lake. The exceptional general interest was demonstrated by a thematic event gathering some 500 participants (TWPA Annual report 1978–1979). The trend in public participation and engagement culminated in the summer of 1997, when a new broader-based initiative, "Pro Tuusulanjärvi", was founded in the aftermath of the infamous algae catastrophe. It included a petition for restoration support that was signed by nearly 9000 participants. New innovative ways to support the cause of the lake were made use of. Donation of the recycling pledge of bottles, collectable at every grocery store in the area, was enabled (TWPA Annual report 1998–1999). A local bakery donated a portion of the money earned from bread to support improvement of the lake (Tuusulanjärvi restoration team 2012a). Thus, fund raising for the protection and restoration of Tuusulanjärvi was performed by fusing the efforts into the everyday life of the broader public. Large audiences were involved and lake restoration evolved into a social space of interaction and proof of strong local commitment to a shared and imagined future of the lake. The nomination of the lake in 2011 as the Official Provincial Lake was a manifestation of the successful work done at the local level (HS 13 Oct 2011).

4. Stability of the aeration frame in lake restoration

Lake Tuusulanjärvi has an exceptionally extensive restoration history that has been largely supported among various stakeholders (Reunanen 2005, 29). This is not surprising, since lake restoration aims at a rather universally shared core value of 'clean water', however it is defined at a given time (Dizard 2010, 161). The great pressure to do *something* for the degraded lake was based on its importance as a local natural amenity, recreational haven, and a site harboring nationally significant cultural heritage.

Despite that recent studies cast scientifically based doubts about the effectiveness of aeration as a restoration method, the stakeholders have envisioned a central role of aeration in the future lake management efforts (Nygrén 2016). Science and technology studies suggest that science-based practices are formed around paradigms that represent standard assumptions, theoretical premises, and norms of disciplines (Kuhn 2012). The paradigms are difficult to change, especially when they are rooted in societal practices. The role of internal P loading in the eutrophication process and the efficiency of aeration in solving the problem can be considered as paradigms. New scientific knowledge does not immediately translate into paradigm change or revised action, but four filters need to be passed before change can occur (see Ansoff and MacDonnell 1990; Geels and Schot 2007): 1) A *surveillance filter* means that reliable data are needed to show that the old paradigm no longer functions; 2) A *mental filter* means that the data available are interpreted in the light of the dominant paradigm, and strong support is needed before the mental models of researchers and practitioners can change; 3) A *power filter* means that certain actors are either emotionally or economically dependent on current practices and tend to explain the new research results away or explicitly oppose change; 4) An *institutional filter* means that science-based practices are institutionalized in a regime that affects current practices via previous decisions, policies, markets, and technological lock-in. Our results here and the study by Nygrén (2016) suggest that the contested views over the efficiency of artificial aeration as a lake restoration method is currently affecting the technological path of aeration only in regard to the first filter. The more than 40 years of ongoing aeration show a dominant aeration frame that contributes to a stabilized technological path of artificial aeration as a continued lake intervention method. Currently, the mental, power, and institutional filters are not being passed. Rather, this study has revealed several processes and mechanisms that contribute to the stabilization of aeration as the technological path for restoration at Tuusulanjärvi. The path is supported by a dominant aeration frame composed of various material, technical, cognitive, and social elements (Bijker 1997, 123–125) that were described in the previous sections.

One key problem of anthropogenic eutrophication and the resulting lake degradation is linked with the sheer complexity of lake ecosystems. The manifold ways the problem appears to observers lead to different perceptions of the symptoms and different parameters used for (re)formulation of the problem. As Bijker (1997) proposed, problem redefinition is a mechanism for increasing the stability of a chosen technology. The case shows that the use of aeration was justified during the decades with a multiple, simultaneously, and consecutively occurring set of goals that aeration was able to fit. Fish survival, in-lake wastewater treatment, prevention of internal loading, bridging temporal lags in the lengthy process of lake recovery, lake management, and sediment restoration presented shifting emphasis and a broad set of meanings that were attached to aeration. Thus, the stability of aeration is based on its functional versatility, adaptability as a problem-solving strategy, and the various attributes that have all fitted in its operation and the problem definitions related to hypereutrophication. In addition to these beneficial attributes in favor of aeration in the dominating technological frame, it has been easy to implement in comparison to other methods. As a seemingly non-invasive method it does not require any special water permits, thus diminishing the administrative burden related to its implementation. It is also a comparatively inexpensive pursuit compared to the alternatives, which makes it an attractive option for municipalities, constantly struggling with budgetary constraints. The initial investment costs can be moderated by adjusting the amount of aerators, and since the maintenance demerges over the years of operation, the annual budgetary burden seems acceptable.

The case of Tuusulanjärvi shows a strong community attachment to the lake. The local support of the general public is crucial to the success of the restoration projects (Cairns 2006). As Higgs (2003, 4) stated, people connect more deeply with natural processes when they engage in hands-on activities. Local community support for lake restoration at Tuusulanjärvi in general, and aeration in particular, has been profound. The operation of the aeration equipment has offered local residents ways to interact concretely in the restoration process over time. The joint restoration efforts can be interpreted as a two-way relationship, as Light (2000 64–65) formulated: "restoring [nature, or here: the lake] restores the human connection to nature by restoring the part of culture that has historically contained a connection to nature." The more than century long tradition of scientific inquiry at the lake, the return of the recreational use and valuation of the lake, and the justification of exceptional restoration efforts with the cultural-historical importance of the lake are indicators of a continuous process of reworking the community's relationship with its lake.

Since the initiation of aeration, the local community has been attached both practically and emotionally to it, which affects their perceptions of alternatives or the option of withdrawing from it altogether. "People with a high degree of inclusion in a technological frame will find it difficult to imagine other ways of dealing with the world, of using these things radically differently or even not using them at all" (Bijker 2007, 122). The scientifically based doubts that currently are cast over the efficiency of Tuusulanjärvi aeration, which has been done for four decades with active engagement of the local community, including hundreds of hours of voluntary work, can be cause for anxiety and distress. The prospect of the decades long work and investments in competencies sinking with the ending of aeration thus probably contributes to the stabilization of the existing practice (cf. Geels and Schot 2007). In addition to the practical engagement in aeration, an emotional attachment supports the frame. The use of powerful images in support of the chosen technology has been identified as a stabilizing mechanism (Geels 2006). In the case of Tuusulanjärvi, these emotionally laden images were produced through the heroic narrative about a suffocating lake that is being rescued. This increases the positive and uncritical stance towards aeration and hence contributes to the stabilization of it as a technological frame. We suggest that instead of technological path dependency (cf. David 1985; Arthur 1989) a *mental path dependency* contributes to the persistent support for aeration at Tuusulanjärvi. While no economic, infrastructural or organizational costs prevent the termination of aeration, the persistency of the technological path is attributed to the strong, historically evolved mindset ("lock-in") of the various stakeholders which is supportive of restoration through aeration. While the case of Tuusulanjärvi shows how the extraordinary local engagement in restoration endeavors contributed to the stabilization of the aeration frame, this cultural aspect is often lacking from frameworks describing sociotechnical change.

While stabilizing elements contribute to the persistence of support for aeration, a lack of destabilizing mechanisms also influences the dominant position of aeration. The case revealed that problems related to aeration, potentially destabilizing elements, have been repeatedly solved through temporal fine tuning and ever more sophisticated monitoring. This is in line with Geels' (2006) observation that actors resist radical change and instead dedicate activities towards incremental improvements along existing trajectories. Cognitive routines underscored by the perception of the indispensable role of aeration prevent departing from the aeration frame altogether. The existence and articulation of noteworthy alternatives has been identified as one destabilizing mechanism (Geels 2006). In the case presented here, the other restoration methods proposed were strongly disputed (see section 3.2), and thus discarded. As has been identified elsewhere, the importance of inoffensiveness of restoration practices has been crucial at Tuusulanjärvi. Attitudes of civil servants reveal that as long as it does not irritate anyone, lake restoration is considered a harmless activity that is broadly supported (Reunanen 2005, 45). To summarize, aeration has been a largely supported measure and favored because the lack of effectively competing alternative methods, and because aeration was perceived as unproblematic and inoffensive, indispensable, and economically feasible in comparison to other measures. Additionally, a strong mental attachment of the community supports continuous aeration.

This study was based on the rather obvious postulation that the past matters in our present day choices of interventions with the environment. With increasing scientific evidence against the efficiency of aeration as a lake restoration method, further studies are needed on the practical implications of shaking scientific paradigms, sociotechnical change of restoration, and alternate terminations of the technological path and the destabilization of a technological frame.

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Archival and other unpublished material

The archival material of the Tuusulanjärvi Water Protection Association is stored in a poorly organized state at the City Archives of Järvenpää. The material there is compiled in folders that are inconsistently named and only indicatively reflect the respective folder content.

Järvenpää city archive (JCA)

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