

In-Lake Mechanisms for Manganese Control—A Systematic Literature Review

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Abstract: An elevated concentration of manganese (Mn) in lakes is a common water quality problem faced by many water utilities. Thermal stratification is a natural phenomenon that influences the Mn concentration in lakes and can exacerbate Mn accumulation in surface water without external loading sources. While several treatment methods can be utilized to treat Mn in drinking water treatment plants, in-lake control mechanisms can be a proactive and efficient strategy for Mn control by reducing water treatment complexities and costs. Despite previous research pointing to the benefits of in-lake Mn control, the feasibility and effectiveness of the various in-lake Mn control mechanisms in lakes in different environmental conditions remains unclear. To identify and consolidate the existing research on the topic, a comprehensive, systematic literature review (SLR) was conducted. The SLR identified case studies of in-lake Mn control mechanisms in thermally stratified lakes. The identified case studies were grouped into three categories based on their goals: identification of Mn behaviour in lakes, built engineering implementations and digital solutions for process optimization and anticipation. It is critical that a site-specific understanding of Mn dynamics is obtained before implementing any built or digital solutions, because lake specific dynamics can significantly impact a solution's performance. While most reviewed mechanisms were successful in decreasing high Mn concentrations, a lack of financial and environmental cost–benefit analyses for most in-lake Mn control mechanisms was observed, which is crucial for their adoption by water authorities. The rationale of this SLR provides a summary of the benefits and limitations of the most common in-lake Mn control mechanisms, the enabling the conditions for their implementation, and the knowledge gaps and future direction for research on the topic, being valuable to support informed decision-making by water authorities managing waterbodies with high Mn concentrations.

Keywords: manganese; drinking water; in-lake control mechanisms



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1. Introduction

Elevated concentration of manganese (Mn) in lakes is a common water quality problem faced by many water utilities [1]. According to the World Health Organization guidelines, Mn concentrations in drinking water exceeding 0.4 mg/L are considered toxic [2]. In addition to the health impacts of high concentrations of Mn in drinking water, elevated concentrations of Mn can cause aesthetic impacts such as water discolouration, and unpleasant taste and odour [3].

Mn concentration in lakes is dependent on physical, chemical, and biogeochemical processes [3,4]. Dissolved oxygen (DO), redox potential and pH are water quality parameters that affect the Mn concentration and solubility [3]. Mn is often present in natural water bodies due to its common occurrence in rocks, sediments and soils. Additionally, anthropogenic activities such as mining and industrial discharge can increase natural Mn concentrations in waterbodies. A key and natural phenomena that influences the Mn

concentration in lakes is thermal stratification [5]. Thermal stratification usually results in the water column being separated into three distinct layers: epilimnion, metalimnion and the hypolimnion. Those layers have distinct chemical and physical characteristics. The dynamics of stratification and circulation patterns can vary according to the lake characteristics and climate. Lakes that are permanently stratified are called meromictic. Lakes that stratify seasonally are called either monomictic or dimictic based on the number of times the lake mixes during a year. In monomictic lakes, the stratification occurs during the summer months and the water column is completely mixed in spring and autumn. In dimictic lakes, stratification occurs twice a year.

During strong stratification, commonly during the summer and early spring, Mn tends to accumulate in the hypolimnion due to DO depletion and an increase in Mn solubility [6]. However, when the thermal stratification is broken due to decreasing air temperatures and solar radiation, usually during the winter and autumn, the vertical movement of the water column (also referred as full lake circulation or turnover) leads to the distribution of the accumulated Mn in the hypolimnion throughout the water column [7]. Periods of turnover represent a challenge to water treatment plant operators because of the risk of sharp increases of Mn concentrations in the raw water intake, despite external loading sources.

While several treatment methods to treat Mn in drinking water treatment plants exist, they are often costly and reactive solutions. In-lake control mechanisms can be a proactive and efficient strategy for Mn control by reducing water treatment complexities and costs, resulting in a reduced human health risk [8]. While there has been strong evidence and research of Mn in-lake controls, their effectiveness and feasibility in field conditions are not clear for the various environmental conditions that lakes are subjected to.

The rationale of this article is to provide a comprehensive understanding of the effectiveness, limitations and future research of in-lake Mn control mechanisms. Using a systematic literature review methodology, case studies of in-lake Mn control mechanisms in real conditions were identified and critically analysed. We start by describing the systematic literature methodology and the target data extracted from publications. The results are presented in Section 3, under two subsections: time and spatial distribution of the reviewed articles and suggested in lake Mn control mechanism. A critical discussion is then provided in Section 4 where the knowledge gaps and future directions of research are given.

2. Materials and Methods

An SLR was conducted to assess the state-of-the-art of tested and validated in-lake control mechanisms. The SLR was performed in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [9] and Pickering and Byrne [10], ensuring a reliable and reproducible assessment of the literature by clearly stating the search, inclusion and exclusion criteria, and the method of data collection, reporting and discussion [9]. The PRISMA guidelines checklist has been submitted as Supplementary Material for this journal article (Supplementary Material). However, due to the nature of this systematic literature review (SLR) not being focused on health or social aspects, it was not registered in a specific database or protocol repository.

2.1. Data Sources and Search Criteria

The search was conducted over three databases (Web of Science, ProQuest and Scopus) in July 2022. The search strategy (Table 1) was identical over all three databases and aimed to capture journal articles on the in-lake Mn control measures in thermally stratified lakes used primarily as drinking water sources.

Table 1. Search strategy of the systematic literature review.

Search Criteria	Boolean Operator	Key Words
Water quality parameter		Manganese OR Mn [TI and Abstract]
	AND	
Stratification		Stratif * OR Thermal Stratif * [TI and Abstract]
	AND	
Water supply		“Water supply” OR drink * OR potable [TI and Abstract]
	AND	
Treatment		Treat* OR Destrat * OR Oxidis * OR control OR aerat * OR “turnover” OR Manag * [TI and Abstract]
	AND	
Forecasting		Predict * OR forecast OR model * [TI and Abstract]
	AND	
Water body		lake* OR lagoon * OR pond * OR freshwater * OR reservoir * OR inland [TI and Abstract]
	AND	
Seasonality /climate		Summer OR Season OR Winter OR Temperature OR Subtropical [TI and Abstract]
	AND	
Document type		Full text journal article
	AND	
Databases		Web of Science, ProQuest and Scopus

2.2. Inclusion and Exclusion Criteria

The selection of publications for the review was carried out by subsequently screening the title, abstract and full text according to the PRISMA guidelines [9]. The inclusion and exclusion criteria were:

- (i) Studies focusing on the internal loading of Mn were included (i.e., studies on Mn external contamination sources such as mining and industrial discharge were excluded).
- (ii) Only case studies of lakes and reservoirs were included (i.e., case studies carried out on rivers and groundwater were excluded from the review).
- (iii) Only studies published in English were included.
- (iv) Only peer-reviewed journal articles were included.

2.3. Article Selection, Data Extraction and Summary

Through a systematic analysis of the selected studies, the following information and data were extracted and recorded.

- (i) Publication date
- (ii) The timeline and global distribution of reviewed articles
- (iii) Data on the characteristics of the case study lakes that influence thermal stratification and Mn circulation behaviour:
 - a. Total volume and the surface area of the lake
 - b. Stratification pattern and impact on the level of Mn
 - c. Köppen climate classification of the region in which the lake is located
- (iv) Characteristics of the suggested Mn control mechanism:
 - a. Details of the numerical models used to predict the cycle of Mn (if applied)
 - b. Data collection and sampling methodology
 - c. Advantages and disadvantages of the suggested solutions

3. Results

The search resulted in 801 journal articles, which were screened at title, abstract and full-text levels. After this process, 48 journal articles were selected for the final review (Figure 1) and categorized into three groups based on their goals.

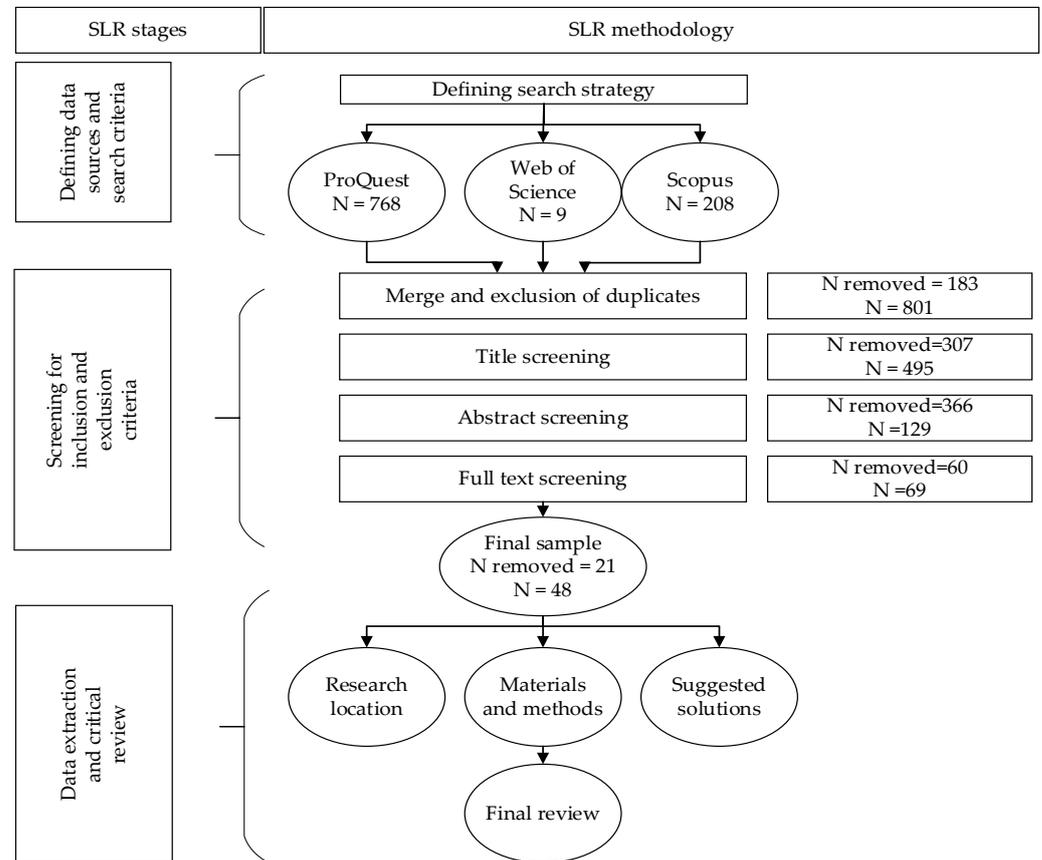


Figure 1. SLR methodology for this study based on PRISMA guidelines. “N” = number of publications.

3.1. Time and Spatial Distribution of the Reviewed Articles

The number of journal articles on Mn behaviour in lakes has progressively increased over the years. The SLR identified case studies from the 1980s to the present date (Figure 2). Most of the publications before the 2000s focused on identifying the Mn behaviour in lakes. From the mid-2000s, the studies’ focus shifted primarily to test and validate in-lake control measures and the applications of numerical models. Particularly after 2010, a sharp increase in digital solutions (data-driven modelling) to predict Mn behaviour and to optimize in-lake control measures was observed.

Most case studies are from the USA, China and Australia with 14, 11 and 8 journal articles, respectively (Figure 3), The review also included article each from the UK, Germany, Jordan, Switzerland, Italy, Greece, Spain, Morocco, Japan, Thailand, New Zealand and Romania. Three articles were not geographically specified as they discussed the theoretical foundations of the Mn behaviour ($n = 2$) or reviewed the technical aspects of a Mn control mechanism ($n = 1$).

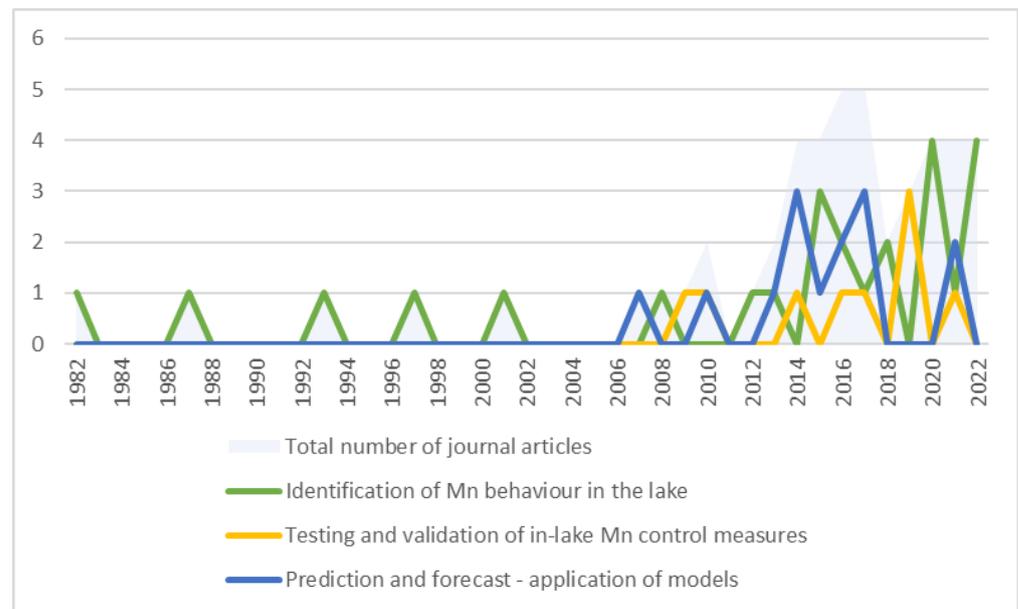


Figure 2. Time series of reviewed journal articles according to the study design.

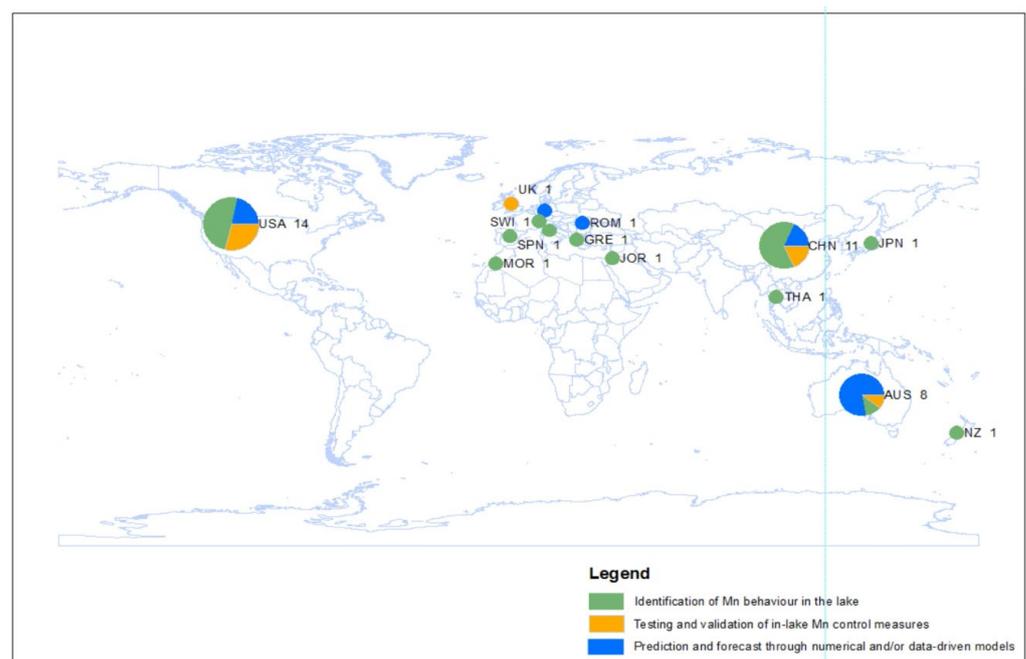


Figure 3. Geographical distribution and the number of reviewed articles. (USA = United States of America, UK = United Kingdom, GER = Germany, JOR = Jordan, SWI = Switzerland, ITA = Italy, GRE = Greece, SPN = Spain, MOR = Morocco, JPN = Japan, CHN = China, THA = Thailand, AUS = Australia, NZ = New Zealand, ROM = Romania).

3.2. Suggested In-Lake Mn Control Mechanisms

3.2.1. Identification of Mn Behaviour in the Lake

The SLR identified 25 articles that focused on investigating the Mn dynamic patterns in various lakes. These articles highlight the importance of developing a comprehensive understanding of Mn behaviour to define effective management strategies that maintain optimal water supply by reducing the Mn concentration in the raw water intake. Among those, there are two broad categories: studies that anchor the theoretical foundations of the

Mn dynamics by testing a hypothesis ($n = 2$), and studies that analysed the chemistry in specific lakes over periods of time ($n = 23$). Table 2 provides a summary of findings from the 23 studies that have been conducted to identify the lake-specific Mn dynamics. The primary objective of these studies was to investigate the seasonal and spatial variations of Mn dynamics in lakes used as a drinking water source. They focused on exploring the correlation between the lake characteristics and the Mn behaviour in the water column, to support the informed design of in-lake Mn control mechanisms.

For those studies focusing on understanding the Mn dynamics, the majority ($n = 17$) monitored only water quality, while few studies measured both water and sediment quality ($n = 6$). Commonly tested water quality parameters in these studies were pH, DO and temperature as these parameters can influence the Mn distribution and movement in the water column. Most of the case studies were on monomictic lakes ($n = 20$) and few on dimictic lakes ($n = 3$). There were few case studies on lakes with an average depth of less than 15 m ($n = 4$), and the number of case studies on deeper (average depth greater than 15 m) was 12. Lake depths are a critical factor for stratification. In shallow lakes, the water column can be easily mixed, disrupting the stratification. Stratification is more likely to occur and be sustained in deeper lakes because the temperature difference between the lake's surface and the bottom is greater, with a reduced likelihood of full vertical water mixing. The rest of the articles did not mention the average depth.

The impact of climate change on lakes and hydrology can also influence the Mn dynamics. While some studies had conducted water sampling during periods of stratification ($n = 13$), few others had conducted water sampling throughout all seasons of the year ($n = 7$). Most studies measured the DO and water temperature, and their correlation with Mn concentration. The pH level of water was also quantified in some studies. Fluctuations of temperatures and extreme weather events, such as heavy rains and floods, have been identified as key factors influencing the Mn concentration variability in drinking water lakes [11]. The Köppen climate classification was recorded as an indicator of the climatic conditions of the study areas. Most studies were conducted in humid subtropical areas where warm monomictic stratification occurs frequently with lakes stratified throughout the year ($n = 8$) [7].

Another factor that influences Mn behaviour is the sediment resuspension, which can be driven by external factors such as inflow, wind speed and direction. Sediment resuspension can significantly increase the Mn concentration in the water column [12], thus being a critical factor to consider when designing in-lake Mn control mechanisms. It is argued that climate change could intensify resuspension events, causing a water quality deterioration over a prolonged period [11]. Therefore, understanding the occurrences of extreme weather events such as floods and droughts, which can have significant impacts on the hydrologic cycle and subsequently impact the Mn concentration in lakes, is critical for resilient Mn control.

The sampling plans of the reviewed studies were recorded. The monitoring campaign of most case studies lasted less than a year, often focusing on the summer stratification period ($n = 7$) and the autumn turnover ($n = 6$). The longest recorded sampling in this review is of a study that conducted water sampling four times a year for 10 years (2005–2015) in the Mohammed Ben-Abdelkrim Khattabi (MBAK) reservoir, Morocco [13]. This finding of this long-term study includes the temporal evolution and the seasonal variations of Mn in the water column. The study identified increased Mn concentrations during periods of low water volumes [13].

Long-term studies can capture the temporal variations of Mn concentrations for a particular lake and may be particularly relevant to assess impacts of climate change on the Mn concentration in lakes. Future research should encompass long-term studies focusing on the correlations between Mn dynamics and climate change.

Table 2. Summary of findings from studies on the identification of Mn behaviour in the lake.

	Climate Region	Lake/Reservoir	Circulation Pattern (Monomictic (M) or Dimictic (D))	Surface Area (km ²)	Avg. Depth (m)	Water Quality	Sediment Quality	Water Quality Parameter Monitored							Sampling		Reference	
								Total Mn	Water T ⁰	Turbidity	DO	Conductivity	pH	ORP	Duration	Season		Sampling Frequency
1	Temperate climate	Lake Hume, Australia	M	202.5	41.4	X		X	X	X	X	X			6 months	Summer	Weekly	[6]
2	Humid subtropical	Falling Creek Reservoir, USA	D	0.119	4	X	X	X		X	X	X			1 year	Summer	Weekly	[14]
3	Humid continental	Lake Sebasticook, Maine USA	D	18.3	20	X		X		X					5 months	Summer/Early Autumn	Monthly	[15]
4	Mediterranean climate	Hodges Reservoir, USA	M	6	29	X	X	X		X					8 months	Autumn	Monthly	[16]
5	Humid Subtropical	Grand Lake, Oklahoma, USA	M	188.2	50	X		X		X					7 months	Winter/Spring	Monthly	[17]
6	Hot Summer Continental	Lake Erie, USA	D	25,667	19	X									1 month	Summer	Weekly	[18]
7	Humid Continental	Three Kettle Lakes, USA	M	N/A	N/A	X		X			X	X			3 months	Summer	Multiple dates at each lake	[19]
8	Humid subtropical	Arha Reservoir, China	M	4.5	13	X		X		X			X		10 months	Throughout 10 months	Once in 3 months	[6]
9	Humid Subtropical	Zhoucun Reservoir, China	M	6.5	13	X		X	X	X					3 years	Throughout the year	Weekly and every 3 days during the overturn period	[20]
10	Temperate monsoon	Wangjuan Reservoir, China	M	N/A	N/A	X	X	X		X		X			1 month	Summer	Once	[21]
11	Humid subtropical	Daheiting Reservoir, China	M	N/A	28	X		X		X					2 years	Winter	Monthly	[22]
12	Humid subtropical	Arha Reservoir, China	M	4.5	13	X				X		X			10 months	Throughout the year	N/A	[23]
13	Tropical and subtropical	Heihe Reservoir, China	M	4.55	40	X		X	X	X					2 years	Throughout the year	Monthly	[24]
14	Humid subtropical	Danjiangkou, China	M	N/A	N/A	X	X	X							3 years	Autumn/Spring	Twice a year	[25]
15	Tropical and Subtropical	El Gergal, Spain	M	2.5	15.7	X		X		X	X	X			2 years	During stratification	Biweekly	[11]

Table 2. Cont.

	Climate Region	Lake/Reservoir	Circulation Pattern (Monomictic (M) or Dimictic (D))	Surface Area (km ²)	Avg. Depth (m)	Water Quality	Sediment Quality	Water Quality Parameter Monitored							Sampling		Reference		
								Total Mn	Water T ⁰	Turbidity	DO	Conductivity	pH	ORP	Duration	Season		Sampling Frequency	
16	Hot semi-arid	Fokos Reservoir, Greece	M	N/A	N/A	X		X								1 year	Throughout the year	20 samples	[26]
17	Subcontinental	Ridracoli Reservoir, Italy	M	1035	82	X		X	X	X	X	X	X			2 years	Throughout the year	Bimonthly	[27]
18	Marine West Coast	Megget Reservoir, UK	M	2.59	N/A	X	X	X			X					1 day	Autumn	Once	[12]
19	Mediterranean	Mujib, Jordan	M	1.98	25	X			X		X					1 month	Mid-summer	Once	[28]
20	Oceanic climate with warm summers	Lake Ngapouri, New Zealand	M	0.19	24.5	X			X		X					2 years	Autumn	N/A	[29]
21	Marine West Coast	Lower Lake Zurich, Switzerland	M	88	142	X	X	X								1 year	Summer and Autumn	Every 21 days	[30]
22	Tropical savanna	Mae Thang Reservoir, Thailand	M	N/A	N/A	X			X		X		X	X		1 year	Not given	Twice	[31]
23	Dry-summer subtropical	Mohammed Ben-Abdelkrim Khattabi Reservoir, Morocco	M	N/A	N/A	X			X		X		X	X		10 years	Throughout the year	Four times a year	[13]

3.2.2. Testing and Validation of Built In-Lake Mn Control Measures

The SLR identified studies ($n = 8$) that tested or validated technologies to control high concentrations of Mn in the hypolimnion (Table 3). These studies have either used in-lake built implementations or laboratory experiments to test the effectiveness of technologies to control the Mn concentrations. The technologies focused on restoring the chemical and physical characteristics of deep waters through aeration or mixing, which reduces the accumulation of Mn in the hypolimnion. The SLR identified two techniques: water-mixing and hypolimnetic oxygenation. While some studies have not specified the devices used for hypolimnetic oxygenation, there are a few studies that have specified circular or linear bubble plume diffusers as the employed technology. Additionally, the SLR identified one article that evaluated the technical aspects of hypolimnetic oxygenation ($n = 1$) [32].

Hypolimnetic Oxygenation (HO)

A widely used Mn control measure to minimize anoxia in the hypolimnion is direct oxygenation of this water column layer. Previous research has reviewed the impacts of Hypolimnetic Oxygenation (HO) on the chemical conditions of the bottom layers of the water column and found it as an effective method to decrease soluble Mn concentration even though did not eliminate the formation of reduced Mn [33]. Rather, it pushed the oxic-anoxic boundary out of the water column into the sediments, lowering the Mn concentration in the water column with the risks of influxes of Mn in the water column due to sediment release [32].

Understanding the spatial and temporal Mn dynamics pattern in a lake allows for the optimization of the operation of HO systems. Intermittent oxygenation has been shown to increase the system's performance [34]. The presence of Mn in the water can be used as an indicator of the effectiveness of the implemented solution. For example, Mn concentrations have been used as an indicator of the successful oxygenation of the hypolimnion of an hypereutrophic reservoir [16].

Circular or Linear Bubble Plume Diffusers

Circular or linear bubble plume diffusers are a mechanism to oxygenate the hypolimnion using a blend of water and gas called a plume [35]. Bubble plume diffusers are one of the most popular technologies for hypolimnetic oxygenation. The mechanism involves compressed air to be driven through a diffuser located near the bottom of the lake to prevent Mn accumulation in the hypolimnion. The rising columns of bubbles are supplemented with water to form a combined bubble and water plume [36] and have the ability to improve water quality in the sub-deep water system through hypolimnion oxygenation [33]. For instance, a study in Arha Reservoir, China, observed that placing circular bubble plume diffusers at the drinking water outlet area resulted in reductions of 48.9% in Mn concentration [35].

Water-Lifting Aeration (WLA)

Water-lifting aeration (WLA) is an artificial mixing mechanism that disrupts the thermal stratification and oxygenates the hypolimnion. It breaks the thermal stratification layers by mixing and changing the deoxygenated water layer at the bottom of a lake into an oxidized status. Previous research has found it to effectively decrease the Mn concentration in the water column [33,37]. This process involves lifting the anoxic bottom waters to the surface for destratification, while the oxygenated waters in the aerated region are pushed toward the bottom sediments [38].

Table 3. Summary of findings from studies on the testing and validation of in-lake Mn control measures.

	Climate Region	Lake/Reservoir	Surface Area (km ²)	Avg Depth (m)	Mn Control Measure	Initial Mn Concentration	Reduction of Mn Concentration Due to Control Measure (%)	References
1	Summer humid continental	North Twin Lake, Washington, USA	N/A	9.7	Hypolimnetic oxygenation	119 to 32 µg/L	94% on day 7 to 49% on day 17	[39]
2	Humid subtropical	Carvins Cove Reservoir, USA	2.5	23	Hypolimnetic oxygenation	N/A	97%	[34]
3	Humid subtropical	Falling Creek Reservoir, USA	0.119	4	Hypolimnetic oxygenation	N/A	39%	[40]
4	Humid subtropical	Falling Creek Reservoir, USA	0.119	4	Hypolimnetic oxygenation	N/A	39%	[41]
5	Humid subtropical	Arha Reservoir, China	4.5	13	Circular bubble plume diffusers	N/A	48.9%	[35]
6	Humid subtropical	Arha Reservoir, China	4.5	13	Circular bubble plume diffusers	N/A	48.9%	[33]
7	Humid Subtropical	Zhoucun Reservoir, China	6.5	13	Water-lifting aerators (artificial mixing)	N/A	84%	[37]
8	Humid continental	Heihe Jinpen Reservoir, China	4.55	40	Water-lifting aerators (artificial mixing)	0.13 ± 0.02 mg/L to 0.09 ± 0.01 mg/L	30.8%	[42]

The WLA has two purposes: firstly, to destabilize the stratified layers by mixing the lower and the upper layer waters, consequently increasing the DO levels in the lower-layer water; and secondly, to oxygenate the lower-layer water with the help of the aeration chamber. Two separate studies carried out in the Zhoucun Reservoir, China, and Heihe Jinpen Reservoir, China, assessed the performance of the WLA, reporting reductions of 30.8% [42] and 84% [41] in the Mn concentration. However, the WLA is a high energy intensive solution, increasing proportionally to a lake's size. Integrating artificial mixing with natural mixing can be a viable alternative to achieve energy conservation goals [42].

Overall, the reviewed case studies did not provide sufficient information on operational costs and cost–benefit analysis to support the implementation of such techniques in the field. Most of the studies also lacked information on the environmental impacts of such implementations. Future research should encompass the financial and environmental implications of these technologies, which would be beneficial for water managers' business case development.

3.2.3. Prediction and Forecasts—The Application of Models (Digital Solutions)

The SLR identified studies ($n = 13$) where digital models have been applied to improve water quality planning in lakes (Table 4). The integration of both the empirical data collection and hydrodynamic simulations is a valuable tool to test and validate the Mn dynamics [43]. Digital models can be categorized as either forecasting or predictive models based on the goal. The goal of forecasting models is to anticipate short-term fluctuations, usually focused on operational aspects [44]. Predictive models, on the other hand, model longer-term anticipations focused on future scenarios [44]. There are two broad modelling approaches used to forecast or predict Mn concentration in lakes: process-based (PB) models compute known principles, theories and the empirical knowledge of hydrology and physics through a mathematical equation, while data-driven (DD) models are based on monitoring data and identifying statistical trends and patterns of Mn dynamics [44].

Forecasting Models

Forecasting models can be used to accurately predict the Mn concentration in lakes in the short term. For example, Zhang et al. [6] utilized a 3D model to predict the variations in the thermal structure of Tarago's Reservoir, Australia. The model was used to predict the seasonal change and the impact of DO variability on the peak concentrations of Mn in the epilimnion.

Forecasting models have also utilized the data collected through Vertical Profiling Systems (VPSs). A VPS is an automatic data recording system set up to continuously monitor the water quality along the water column, often measuring various water quality parameters such as water temperature, DO, pH, conductivity and redox potential [3], which can be used to develop cost-efficient DD models when compared to traditional grab sampling data acquisition [7]. For instance, the VPS-based Mn early warning system developed for the Advancetown Lake, Queensland, Australia, could forecast the Mn concentration in the epilimnion 7 days in advance [7], which enabled the water authority to proactively manage the Mn peaks.

Predictive Models

Predictive models have been used to simulate future scenarios, such as optimizing the performance of an implemented in-lake control solution. For example, Castelletti et al. [43] used a PB model to simulate changes in the water quality of the Googong Reservoir, Australia, by changing the location of already deployed mixers or oxygenators. The results of the study indicate significant improvements in the water quality by changing already installed mixers and locations for two new mixers. This resulted in an improved performance without additional cost. The authors suggest that the methodology can be replicated in other locations if a PB model is calibrated to the new location. Likewise, the models have been used to predict the effectiveness of a linear bubble diffuser system on thermal stratification [45], and assess how the hydrological variability would impact the performance of diffused aeration [46].

Weber et al. [47] utilized a model to predict the Mn concentration along the water column of the Dhuenn Reservoir, Germany. The results were used to determine the best withdrawal height depending on parameters such as the hypolimnetic DO concentrations and the water temperature. Similarly, numerical models have been used to predict the effect of seasonality and daily meteorological variations on the water column temperature and Mn concentration in the epilimnion [48]. Similarly to built implementations to control Mn, the SLR identified a lack of cost–benefit analysis of developing and maintaining digital models when compared to other alternatives.

Table 4. Summary of the findings from studies on prediction and forecast—the application of models (digital solutions).

	Climate Region	Lake/Reservoir	Surface Area (km ²)	Avg Depth (m)	DD/PB	Phenomenon That the Model Predicts	Water Quality Parameter Inputs										Goal of the Model		References
							Temperature	DO	Water Level	Air temperature	Wind Direction	Wind Speed	pH	Conductivity	ORP	Turbidity	Prediction of Mn	Optimization of a Control Measure	
1	Temperate oceanic climate	The Tarago Reservoir, Australia	3.6	23	DD	The simulation of the distribution of Mn in a monomictic water reservoir	X	X									X		[6]
2	Humid subtropical climate	Advancetown Lake, Australia	15	48	DD	Simulation of the seasonal and spatial variability of Mn		X		X							X		[7]
3	Humid subtropical climate	Advancetown Lake, Australia	15	48	DD	Simulation of the seasonal and spatial variability of Mn	X	X					X	X	X	X	X		[49]
4	Oceanic climate	Googong Reservoir, Australia	6.96	N/A	PB	The optimal efficiency of the mixers												X	[43]
5	Humid subtropical climate	Advancetown Lake, Australia	15	48	PB	Simulation of the seasonal and spatial variability of Mn	X	X			X		X	X			X		[3]
6	Humid subtropical climate	Advancetown Lake, Australia	15	48	PB	Simulation of the seasonal and spatial variability of Mn 7 days ahead											X		[49]
7	Humid subtropical climate	Advancetown Lake, Australia	15	48	PB	Simulation of the seasonal and spatial variability of Mn 7 days ahead	X	X			X						X		[50]
8	Humid subtropical	Leesville Lake, USA	13.2	23	DD	Simulation of the seasonal and spatial variability of Mn	X	X					X				X		[1]
9	Moderate oceanic climate	San Vicente Reservoir, USA	6.4	57.9	PB	Simulate the effect of operation of a linear diffuser oxygenation system on thermal stratification.	X	X										X	[45]
10	Dry-summer subtropical	Walnut Canyon Reservoir, USA	N/A	N/A	PB	Predict association between water temperature and water quality												X	[46]
11	Temperate monsoon	Wangjuan Reservoir, China	N/A	N/A	DD	Simulation of the seasonal and spatial variability of Mn—impact of air temperature, water level, wind speed, wind direction			X	X	X	X					X		[51]
12	Mediterranean climate region	Dhuenn Reservoir, Germany	N/A	53	PB	Water balance, vertical stratification, mixing, heat exchange and the effect of inflows/outflows	X	X										X	[47]
13	Humid continental	Firiza-Strimtori Reservoir, Romania	168	N/A	DD	Simulation of the seasonal and spatial variability of heavy metals including Mn											X		[52]
11	Temperate monsoon	Wangjuan Reservoir, China	N/A	N/A	DD	Simulation of the seasonal and spatial variability of Mn—impact of air temperature, water level, wind speed, wind direction			X	X	X	X					X		[51]
12	Mediterranean climate region	Dhuenn Reservoir, Germany	N/A	53	PB	Water balance, vertical stratification, mixing, heat exchange and the effect of inflows/outflows	X	X										X	[47]
13	Humid continental	Firiza-Strimtori Reservoir, Romania	168	N/A	DD	Simulation of the seasonal and spatial variability of heavy metals including Mn											X		[52]

4. Discussion

A key finding of this SLR is the importance of conducting comprehensive research to identify the nuances and complexities of Mn behaviour in lakes. Complex interactions between the lake shape, size, depth, climate, biogeochemical processes and site geology result in a unique behaviour of Mn in lakes [14]. Therefore, it is crucial that site-specific studies on Mn dynamics patterns pertaining to a lake are conducted to identify the site-specific solutions.

There is also an evident research interest on the impacts of climate change on water quality [11]. For example, there have been studies carried out on the impacts of the increasing frequency of extreme rainfall events on the stratification structure and anoxic conditions of lakes [24]. The variability caused by climate change in rainfall patterns, air temperature and extreme weather events affects the behaviour of Mn in lakes, posing a challenge to water utilities. These climatic conditions affect the hydrological conditions of lakes, resulting in changes in Mn dynamics. It is essential to identify spatial and temporal Mn dynamics in the lake of interest, and the key factors that influence Mn dynamics. More long-term studies focusing on climate change impacts on stratification and changes in Mn dynamics are needed to enable resilient Mn management.

The second category of articles aimed to test and validate built in-lake technologies that have been implemented and/or laboratory experiments. Such technologies that were tested and/or validated had two objectives: the mixing of the layers and the oxygenation of the water column. Among the oxygenation mechanisms, hypolimnetic oxygenation has received great attention for its higher efficiency and fewer undesirable effects [32]. The most popular technologies for hypolimnetic oxygenation are circular or linear bubble plume diffusers [33,39]. These studies report a significant decrease in the Mn concentration in the water column. They also highlight the importance of identifying site-specific spatial and temporal Mn dynamics. This understanding would enable the intermittent operation of these systems to optimize efficiency while achieving financial benefits [1]. However, the SLR found limited evidence to quantify the financial benefits, which should be the focus of future research.

The third set of articles encompass digital solutions to anticipate the Mn concentration and dynamics in lakes. These digital solutions can significantly decrease laboratory costs while simultaneously boosting treatment adaptation response times. Some studies aimed at forecasting the Mn dynamics to support operation and response to undesired events, while other studies aim to optimize the performance of implemented built in-lake control measures (e.g., aerators). DD models have shown great potential to support Mn proactive management through accurate short-term forecasts, but they heavily rely on large datasets of good quality, meaning that cheap and reliable methods to measure water quality parameters are crucial for their development.

5. Conclusions

This SLR identified in-lake Mn control mechanisms through a review of case studies. The reviewed studies had three distinct goals: (i) monitoring the water and sediment quality to identify the spatial and temporal Mn dynamics; (ii) testing or validating built in-lake Mn control mechanisms; and (iii) the development and validation of digital solutions, to anticipate Mn concentration and dynamics in lakes.

In-lake control mechanisms of Mn can result in significant water quality benefits for water utilities by decreasing the Mn concentration in the raw water intake of water treatment plants. Identifying Mn dynamics in lakes is crucial for designing effective, efficient and targeted in-lake control mechanisms. It is also crucial that the impacts of climate change on hydrology and water quality are considered to enable resilient Mn management, which should be the focus of future research.

The SLR identified that built in-lake Mn control mechanisms (e.g., aerating and/or mixing the lake's stratified layers) can effectively decrease a high Mn concentration, even

though there is a lack of evidence about their cost–benefit compared to other control strategies. Additionally, digital solutions were identified as an effective Mn control mechanism, through either PB or DD models. Sufficient quantity and quality of data are crucial for digital solutions success, thus cheap and reliable data acquisition methods can foster their adoption by reducing costs. Future research should focus on reporting financial and environmental benefits of in-lake Mn control mechanisms compared to Mn treatment in water treatment plants to support informed decision-making of the water authorities managing lakes susceptible to high Mn concentrations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su15118785/s1>.

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