

ELUCIDATING ANTHROPOGENIC IMPACTS ON WATER QUALITY THROUGH SPATIAL
HETEROGENEITY IN THE LAURENTIAN GREAT LAKES AND THE GLOBAL FAST
FASHION INDUSTRY

KERRICE BAILEY

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE

GRADUATE PROGRAM IN BIOLOGY
YORK UNIVERSITY
TORONTO, ONTARIO

October 2024

© Kerrice Bailey, 2024

ABSTRACT

Freshwater resources are vital for human survival including for consumption, transportation, and production of goods. We explore the impact of anthropogenic activity on water quality through: 1) the spatial heterogeneity in the northern nearshore regions of the Canadian Great Lakes and 2) the state of fast fashion in the top garment producing countries: China, Bangladesh, Vietnam, Turkey, India, and Indonesia. Water quality conditions varied spatially from oligotrophic conditions in Lake Superior to eutrophic conditions with elevated concentrations of nutrients and chlorophyll-a in Lake Erie. Further, we found that policy, sustainability and wastewater are key research areas in the top garment-producing countries. However, there was variation in the number of publications, terminology, knowledge gaps, and barriers that impede more sustainable garment production in the top garment-producing countries. We suggest investments in management and education to protect and use our freshwater resources more sustainably.

DEDICATION

I dedicate this work to those who build tables where none exist.

ACKNOWLEDGEMENTS

I would like to acknowledge the people who were instrumental in supporting me throughout the production of this body of work.

First and foremost, thank you to Dr. Sapna Sharma for believing in my ideas and providing me with necessary support(s) to execute them. I hope to continue to multiply your investment. Thank you to all members of my committee, your feedback and support has been valuable and insightful.

A special thank you to Dr. Kevin Blagrove and Aman Basu for their help whenever I was met with a statistical challenge or code greater than my ability. Your help is deeply appreciated and has prepared me for new coding challenges.

Thank you to the Ontario Ministry of Environment, Conservation and Parks especially Nadine Benoit and Dr. Todd Howell. The work you do is phenomenal and the data you provided is invaluable.

Thank you to the songs and podcasts that carried me through the darkest of times. Thank you to my cat, Ash for sitting near through countless hours of meetings, studying, and work sessions.

Last but most certainly not least, thank you to my friends and family for your unwavering support throughout this process. The late-night stats sessions, coffee runs, late night pick-ups, early drop-offs, facetime calls while away at conferences along with the many other displays of love and support did not go unnoticed. I appreciate you.

TABLE OF CONTENTS

Abstract.....	ii
Dedication.....	iii
Acknowledgments.....	iv
Table of Contents.....	v
List of Tables.....	vii
List of Figures.....	viii
GENERAL INTRODUCTION.....	xi
Importance of freshwater and water quality.....	xi
Water quality conditions in the Great Lakes region.....	xi
Environmental impacts of the Fast Fashion Industry.....	xii
Water use in clothing production.....	xiii
Water consumption and degradation across industries.....	xiii
Objectives.....	xiv
CITATIONS FOR M.SC. THESIS.....	xv
REFERENCES	xvi
CHAPTER 1: Spatial heterogeneity in water quality across the northern nearshore regions of the Laurentian Great Lakes.....	1
MY CONTRIBUTION.....	2
ABSTRACT.....	3
1 INTRODUCTION.....	4
2 METHODS.....	6
2.1 Study area.....	6
2.2 Data acquisition.....	7
2.3 What are the spatial patterns in water quality across the nearshore of the Canadian Great Lakes?	9
2.4 How do land cover, site characteristics, and weather influence water quality conditions in the nearshore of the Canadian Laurentian Great Lakes?	10
3 RESULTS.....	11
3.1 What are the spatial patterns in water quality across the nearshore of the Canadian Great Lakes?	11
3.2 How do land cover, site characteristics, and weather influence water quality conditions in the nearshore of the Canadian Laurentian Great Lakes?	14
4 DISCUSSION.....	15
4.1 Spatial heterogeneity in water quality conditions.....	15
4.2 Inter-lake heterogeneity.....	16
4.3 Intra-lake heterogeneity.....	19
4.4 Drivers of spatial variability in water quality.....	21
4.5 Drivers of variability: climate change.....	21
4.6 Drivers of variability: urbanization, agriculturalization, and other land cover changes	23
4.7 Drivers of variability: Invasive mussels.....	24
5 CONCLUSION.....	25
ACKNOWLEDGEMENTS.....	27
REFERENCES.....	28
SUPPLEMENTARY MATERIALS.....	37

CHAPTER 2: A synthesis of the state of fast fashion and environmental research in the top garment-producing countries China, Bangladesh, Vietnam, India, Turkey and Indonesia.....	45
MY CONTRIBUTION.....	46
ABSTRACT.....	47
1 INTRODUCTION.....	48
1.1 Globalisation and the fashion industry.....	48
1.2 Scarcity and demands on water.....	49
1.3 Impacts on water quality and the environment.....	49
1.4 Research Questions.....	50
2 MATERIALS AND METHODS.....	50
2.1 PRISMA Method	50
2.2 Country Selection.....	51
2.3 Literature Search.....	51
2.4 Screening.....	52
2.5 Visualisation Packages.....	52
3 RESULTS.....	52
4 DISCUSSION.....	53
4.1 What are the predominant environmental impacts and research areas in each top garment-producing country as a result of fast fashion?	54
4.1.1 Fast fashion and key terminology.....	54
4.1.2 Heterogeneity in research interests.....	55
4.2 What are the knowledge gaps hindering improved environmental practices?	55
4.2.1 Research methods impacting knowledge gaps.....	55
4.2.2 Consumer knowledge contributes to research gaps.....	56
4.3 What are the primary barriers to implementing sustainable garment production in the top garment-producing countries?	56
4.3.1 Barriers are heterogenous in the way they impact each country	56
4.3.2 Key barriers.....	57
5 CONCLUSION.....	57
ACKNOWLEDGEMENTS.....	59
REFERENCES.....	60
SUPPLEMENTARY.....	64
GENERAL CONCLUSION.....	70
Future applications.....	71

LIST OF TABLES

Table 1. Means, coefficients of variation, and ranges of all nearshore water quality variables grouped by lake.

Table 2. Means, coefficients of variation, and ranges of select nearshore water quality variables grouped by region.

LIST OF FIGURES

Chapter 1:

Figure 1: Locations of 52 stations across the northern nearshore of the Great Lakes. Sites are divided into regions, as indicated. Areas of Concern (AOCs) are marked with a star. The AOC in recovery (Jackfish Bay) is marked with a plus (+) and the delisted AOC (Severn Sound) is marked with a triangle.

Figure 2: Means of 10 water quality variables (total phosphorus, nitrates and nitrites, suspended solids, chlorophyll *a*, sulphate, pH, chloride, silicate, alkalinity and DIC) by sampling site.

Figure 3: Ridge plot summaries of water quality conditions across the nearshore of the four Canadian Great Lakes, as represented by ten water quality indicators. The vertical strokes (rug plot) indicate measured values. The total number of samples collected from each lake is indicated in the right margin of each plot. Note that concentrations are presented on a log scale with an offset of 1 to allow for null detections (i.e., zeroes).

Figure 4: A Principal Component Analysis of water quality variables illustrating heterogeneity in water quality across the nearshore regions of the four Canadian Great Lakes. Generally, Principal Component Axis 1 is associated with nutrients and productivity (total phosphorus and total chlorophyll *a*), whereas Principal Component Axis 2 is dominated by silicate concentrations.

Figure 5: Redundancy analysis of water quality variables and associated drivers of weather, landcover, and sampling site characteristics in (a) spring, adjusted $R^2 = 32.1\%$, first 5 canonical axes (CA) are significant ($p < 0.05$); (b) summer, adjusted $R^2 = 32.3\%$, first 6 CA are significant (c) fall, adjusted $R^2 = 31.8\%$, first 6 CA are significant; (d) summer for reduced number of samples (based on the availability of invertebrate samples) and dreissenid abundance data, adjusted $R^2 = 33.2\%$, first 6

CA are significant. Environmental variables include depth of site (Site-Depth), sampling depth (SampleDepth), distance from the site to the nearest shoreline (i.e., distance to island or mainland; DistanceToLand), area of watershed by land cover type (Water, Treed, Grasses, Barren, Wetlands, Developed (i.e., urban, roads, etc.), Agri/Rural (i.e., agricultural and other rural)), seasonal air temperature (AirTemp), seasonal precipitation (Rain), and whether site was near a river mouth (NearRiverMouth). For summer sites with benthic invertebrate data, three species counts of *Dreissena* are summed together (*D. polymorpha*, zebra mussels; *D. bugensis*, quagga mussels; *D. sp.*, unknown species). Water sample parameters include total phosphorus (PPUT), nitrate + nitrite (NNOTUR), nitrite (NNO2UR), reactive silicate (SIO3UR), suspended solids (RSP), total chlorophyll a (CHLRAT), chlorophyll b (CHLRBT), dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), pH (PH), sulphate (SSO4UR), temperature at sample depth (SampleTemp), oxygen saturation at sample depth (SampleOxySat), cobalt (COUT), chromium (CRUT), copper (CUUT), manganese (MNUT), nickel (NIUT), titanium (TIUT), vanadium (VVUT), and zinc (ZNUT).

Chapter 2:

Figure 1: Number of garment-producing factories per capita for the top garment producing countries per 100 000 people.

Figure 2: Value of per capita clothing exports for the top garment producing countries per billion.

Figure 3: Flowchart outlining the systematic process employed in this study. This includes the key steps: Identification, Screening, Inclusion, and Full content Analysis along with the exclusion criteria.

Figure 4: Percentage of countries studied in the literature as part of the final study. Bangladesh was studied in (26), China in (23), India (10), Vietnam (6), Turkey (5), and Indonesia (1). The combinations China and India, China and Turkey, and Bangladesh, Vietnam and India, were the main countries studied in 3 separate studies.

Figure 5: Frequency of terminology used to refer to the textile and garment industry across study countries; where RMG refers to ready-made garment and RW refers to ready-wear or ready-to-wear.

Figure 6: Frequency of key themes studied across the top garment producing countries; where SDGs refers to the sustainable development goals; Green encompasses variations of the green sector including manufacturing and green innovation; and CSR refers to corporate social responsibility.

GENERAL INTRODUCTION

Importance of freshwater and water quality

We depend on freshwater resources for our basic needs and a myriad of ecosystem services. Freshwater and freshwater quality are important for drinking, cooking, bathing, agriculture and industrial processes [1]. Lakes provide key ecosystem services through energy production, fish production, transportation, and recreation and tourism [2]. Lakes are also a hub for biodiversity including: amphibians, fish, plants, phytoplankton, and mussels [3]. Thus, the abundance and maintenance of the quality of freshwater is vital. However, freshwater quality is impacted by many stressors that impact water quality such as: climate change, shoreline development and road salts [4]. In this thesis, we investigate the patterns and drivers of spatial heterogeneity in water quality conditions in the nearshore regions of the Laurentian Great Lakes, as well as the environmental impact of the fast fashion industry on water quality conditions in the top-garment producing countries.

Water quality conditions in the Great Lakes region

In the Laurentian Great Lakes region, millions depend on the Great Lakes for drinking water [5], recreational activities [6], and transportation [7]. The Great Lakes comprise 1/5th of the world's freshwater resources covering an area of 244 000 km² resulting both in high ecological and economic importance [8]. In the United States alone, over 25 million people depend on the Great Lakes for drinking water [9]. Thus It is important to understand water quality in this region for our own benefit along with the other 1861 species who depend on this vast resource [10].

On the Canadian side, Lakes Erie, Ontario, Huron and Superior are vastly different, each exhibiting their own unique set of characteristics. This is especially noticeable when comparing the largest and smallest lakes. Lake Superior is the largest and deepest with the longest retention time of 191 years [11]. Though Lake Superior is the coldest, it is also one of the fastest warming lakes in the world [12,13]. On the contrary, Lake Erie is the smallest and shallowest with a retention time of only 2.6 years. Lake Erie is also the warmest and most exposed to the impacts of agriculture and

urbanisation [14]. Lake Ontario is also greatly affected by agriculture and urbanisation as it is home to major cities such as Hamilton and Ontario. Ontario is home to over 48 000 farms totalling over 25% of all Canadian farms [15]. Nutrient levels associated with agricultural land are also strongly related to productivity and water quality indicators such as water clarity [16-18]. The physical site characteristics in conjunction with distance to human activity such as major cities and agricultural lands can impact the water quality of these lakes.

In particular, the nearshore regions are disproportionately affected as they serve as a transition between land and the open lakes, experiencing stressors from a myriad of point sources such as tributaries and landscapes [19]. This proximity to land coincides with greater susceptibility to anthropogenic stressors, such as acidification, nutrient discharge, and climate change [20,21]. Previously, there were no existing comprehensive analyses of the water quality conditions of Canadian Great Lakes nearshore regions. This thesis provides this important information for understanding and maintaining water quality conditions in the Great Lakes.

Environmental impacts of the Fast Fashion Industry

The term *fast fashion* is used to describe an approach to clothing production that encourages shortening the length of time it takes to design, produce, and get clothing items into retail stores [22]. This business model is built on the encouragement of rapid production and overconsumption of clothing made from cheap materials so that they are replaced often [22,23]. This industry is often criticized for the treatment of garment workers, the use of child labourers, and other hazardous conditions. A well-known case of the latter is the 2013 Rana Plaza factory collapse in Bangladesh. As a result of occupational safety hazards, the eight-storey plaza collapsed leading to the tragic death of over 1100 people, most of whom were garment workers [24]. The social justice issues associated with the garment industry are extremely important, but this industry is also responsible for many negative environmental impacts. This includes but is not limited to air and water quality. It was previously reported that the clothing and footwear industries were responsible for an increase from 1.0 to 1.3 Gt of carbon dioxide emissions from 2000-2015 [25].

Water use in clothing production

Water is used at many stages of clothing production. The treatment of textile fibres with chemicals and dyes over a stepwise process referred to as wet processing including singeing, desizing, scouring, bleaching, mercerizing, dyeing, printing and finishing [26]. This process uses a lot of water, energy, and chemicals to treat fibres during which a vast amount of polluted effluent is produced [27]. The fashion industry used 93 billion cubic metres of water annually; in fact, a pair of jeans could result in the use of 7500 litres of water [28]. Over 400 000 tons of reactive dyes and 8000 chemicals are used annually to dye fabrics such as cotton [29,30]. The resulting textile effluents have been associated with changes in water quality such as high chemical oxygen demand (COD) and high temperatures, along with pH and colour changes [31]. More recently, the fast fashion industry has resulted in a shift from handloom to powerloom industries as seen in Bangladesh [32]. These methodologies differ in the number of steps and where in the process textile waste or wastewater is generated, this can also differ depending on the size of the powerloom industry. For example, in the handloom industry undyed cotton yarn can be transformed to woven fabric in four steps with only one input of water. However, in a large power loom industry, this transformation happens over six steps where water is used in four [32]. The components of textile wastewater can vary, although it often contains alkalis, metals including heavy metals, and other organic compounds [33]. In many cases, untreated effluents and its toxic waste flow into surrounding rivers and streams [34]. Untreated wastewater is often associated with water quality issues such as acidification, alkalinization, and eutrophication [31].

Water consumption and degradation across industries

Industries from agriculture to clothing manufacturing impact nearby water resources including rivers, streams and lakes. This is demonstrated in the Great Lakes by variations in water quality as a result of agricultural activity, urbanization, point source pollution, and other forms of anthropogenic activity [35]. Similarly, garment production results in changes in water quality as a result of consumption of freshwater and the production of large quantities of wastewater [36]. The

prevalence of fast fashion, a growing business model encouraging increased and rapid clothing production further exacerbates this situation [22]. Along with the large volumes of water, clothing production also requires many chemicals which further degrade water quality[30]. These impacts on freshwater can primarily be seen in the countries that produce the majority of the world's clothing such as China, Bangladesh, Vietnam, Turkey, India, and Indonesia [37,38]. In this body of work, we explore the impacts of anthropogenic activity on water quality by exploring 1) spatial patterns of heterogeneity in the Great Lakes nearshores and 2) the state of environmental research in the top garment-producing countries. We use the Canadian Great Lakes in chapter 1 to form a foundational understanding of water quality and its drivers which we then extend to chapter 2 to understand how the fast fashion industry impacts freshwater resources across the globe.

Objectives

This thesis aims to explore and clarify anthropogenic impacts on the environment with a major focus on water quality. We highlight the drivers of heterogeneity in freshwater quality conditions and draw attention to the environmental impacts of the fast fashion industry. In the first chapter, we used long term data to identify spatial patterns in the northern nearshores of the Canadian Great Lakes. Using 52 nearshores sites and a total of 23 water quality variables we provided a succinct summary of water quality conditions across lakes Erie, Ontario, Huron, and Superior. We asked: (1) What is the extent, range, and magnitude of spatial heterogeneity in water quality conditions across the nearshore of the Canadian Great Lakes? and (2) How do features of anthropogenic development, sub-basin characteristics, anticipated coastal circulation, and weather influence water quality conditions in the nearshore of the Canadian Great Lakes? In the second chapter, we summarise the state of fast fashion and water quality in the top garment producing countries: Bangladesh, China, Turkey, India, Vietnam, and Indonesia. We specifically ask: 1) What are the predominant environmental impacts and research areas in each top garment-producing country as a result of fast fashion?; 2) What are the knowledge gaps hindering improved environmental practices?; and 3) What are the primary barriers to implementing sustainable garment production in the top garment-producing countries?

CITATIONS FOR M.SC. THESIS

To date, I have published the following papers on the aforementioned topics:

Blagrave, K. *, **Bailey, K.***, Basu, A., Benoit, B., Howell, T. and Sharma, S. 2023. Spatial heterogeneity in water quality across the northern nearshore regions of the Laurentian Great Lakes. *Journal of Great Lakes Research* 6: 102231. <https://doi.org/10.1016/j.jglr.2023.09.002>

***Joint first authors**

Bailey, K., Basu, A., and Sharma, S. 2022. The environmental impacts of fast fashion on water quality: A systematic review. *Water* 14, 1073. <https://doi.org/10.3390/w14071073>.

REFERENCES

- [1] “Freshwater use,” Understanding Global Change. Accessed: Aug. 29, 2024. [Online]. Available: <https://ugc.berkeley.edu/background-content/freshwater-use/>
- [2] R. W. Sterner, B. Keeler, S. Polasky, R. Poudel, K. Rhude, and M. Rogers, “Ecosystem services of Earth’s largest freshwater lakes,” *Ecosyst. Serv.*, vol. 41, p. 101046, Feb. 2020, doi: 10.1016/j.ecoser.2019.101046.
- [3] “Ponds and Lakes: A Journey Through the Life Aquatic | Learn Science at Scitable.” Accessed: Aug. 29, 2024. [Online]. Available: <https://www.nature.com/scitable/knowledge/library/ponds-and-lakes-a-journey-through-the-25982495/>
- [4] M. E. Palmer, N. D. Yan, A. M. Paterson, and R. E. Girard, “Water quality changes in south-central Ontario lakes and the role of local factors in regulating lake response to regional stressors,” *Can. J. Fish. Aquat. Sci.*, vol. 68, no. 6, pp. 1038–1050, Jun. 2011, doi: 10.1139/f2011-041.
- [5] A. Singh, L. Murison, and E. McBean, “Characteristics of nearshore water quality of Lake Ontario coast under Credit Valley Conservation Jurisdiction, Ontario, Canada,” *J. Gt. Lakes Res.*, vol. 48, no. 2, pp. 326–335, Apr. 2022, doi: 10.1016/j.jglr.2022.01.013.
- [6] N. A. Connelly and T. L. Brown, “Sportfishing Participation on Lake Ontario: Modeling the Past, Predicting the Future,” *North Am. J. Fish. Manag.*, vol. 30, no. 3, pp. 821–830, Jun. 2010, doi: 10.1577/M09-089.1.
- [7] M. Campbell†, M. J. Cooper†, K. Friedman, and W. P. Anderson, “The economy as a driver of change in the Great Lakes–St. Lawrence River basin,” *J. Gt. Lakes Res.*, vol. 41, pp. 69–83, 2015, doi: 10.1016/j.jglr.2014.11.016.
- [8] R. W. Sterner, B. Keeler, S. Polasky, R. Poudel, K. Rhude, and M. Rogers, “Ecosystem services of Earth’s largest freshwater lakes,” *Ecosyst. Serv.*, vol. 41, p. 101046, Feb. 2020, doi: 10.1016/j.ecoser.2019.101046.
- [9] W. S. Breffle, D. Muralidharan, R. P. Donovan, F. Liu, A. Mukherjee, and Y. Jin, “Socioeconomic evaluation of the impact of natural resource stressors on human-use services in the Great Lakes environment: A Lake Michigan case study,” *Resour. Policy*, vol. 38, no. 2, pp. 152–161, Jun. 2013, doi: 10.1016/j.resourpol.2012.10.004.
- [10] A. Trebitz, M. Sykes, and J. Barge, “A reference inventory for aquatic fauna of the Laurentian Great Lakes,” *J. Gt. Lakes Res.*, vol. 45, no. 6, pp. 1036–1046, Dec. 2019, doi: 10.1016/j.jglr.2019.10.004.
- [11] R. 05 US EPA, “Physical Features of the Great Lakes.” Accessed: Aug. 29, 2024. [Online]. Available: <https://www.epa.gov/greatlakes/physical-features-great-lakes>
- [12] “Lake Huron,” Great Lakes Commission. Accessed: Aug. 29, 2024. [Online]. Available: <https://www.glc.org/lakes/lake-huron/>
- [13] S. Sharma et al., “Loss of Ice Cover, Shifting Phenology, and More Extreme Events in Northern Hemisphere Lakes,” *J. Geophys. Res. Biogeosciences*, vol. 126, no. 10, p. e2021JG006348, 2021, doi: 10.1029/2021JG006348.
- [14] “Lake Erie,” Great Lakes Commission. Accessed: Aug. 29, 2024. [Online]. Available: <https://www.glc.org/lakes/lake-erie/>

- [15] . C. Government of Canada, “Ontario is an agricultural powerhouse that leads in many farming categories.” Accessed: Aug. 29, 2024. [Online]. Available: <https://www150.statcan.gc.ca/n1/pub/96-325-x/2021001/article/00006-eng.htm>
- [16] [L. Moslenko, K. Blaggrave, A. Filazzola, A. Shuvo, and S. Sharma, “Identifying the Influence of Land Cover and Human Population on Chlorophyll a Concentrations Using a Pseudo-Watershed Analytical Framework,” *Water*, vol. 12, no. 11, p. 3215, Nov. 2020, doi: 10.3390/w12113215.
- [17] A. Shuvo et al., “Total phosphorus and climate are equally important predictors of water quality in lakes,” *Aquat. Sci.*, vol. 83, no. 1, p. 16, Jan. 2021, doi: 10.1007/s00027-021-00776-w.
- [18] S. Holopainen and A. Lehtikoinen, “Role of forest ditching and agriculture on water quality: Connecting the long-term physico-chemical subsurface state of lakes with landscape and habitat structure information,” *Sci. Total Environ.*, vol. 806, p. 151477, Feb. 2022, doi: 10.1016/j.scitotenv.2021.151477.
- [19] P. M. Yurista, J. R. Kelly, and J. V. Scharold, “Great Lakes nearshore–offshore: Distinct water quality regions,” *J. Gt. Lakes Res.*, vol. 42, no. 2, pp. 375–385, Apr. 2016, doi: 10.1016/j.jglr.2015.12.002.
- [20] R. R. Goforth and S. M. Carman, “Nearshore Community Characteristics Related to Shoreline Properties in the Great Lakes,” *J. Gt. Lakes Res.*, vol. 31, pp. 113–128, Jan. 2005, doi: 10.1016/S0380-1330(05)70293-8.
- [21] J.-P. Jenny et al., “Scientists’ Warning to Humanity: Rapid degradation of the world’s large lakes,” *J. Gt. Lakes Res.*, vol. 46, no. 4, pp. 686–702, Aug. 2020, doi: 10.1016/j.jglr.2020.05.006.
- [22] R. Bick, E. Halsey, and C. C. Ekenga, “The global environmental injustice of fast fashion,” *Environ. Health*, vol. 17, no. 1, p. 92, Dec. 2018, doi: 10.1186/s12940-018-0433-7.
- [23] V. Bhardwaj and A. Fairhurst, “Fast fashion: response to changes in the fashion industry,” *Int. Rev. Retail Distrib. Consum. Res.*, vol. 20, no. 1, pp. 165–173, Feb. 2010, doi: 10.1080/09593960903498300.
- [24] “The Rana Plaza disaster ten years on: What has changed?” Accessed: Aug. 25, 2024. [Online]. Available: <https://webapps.ilo.org/infostories/en-GB/Stories/Country-Focus/rana-plaza#intro>
- [25] G. Peters, M. Li, and M. Lenzen, “The need to decelerate fast fashion in a hot climate - A global sustainability perspective on the garment industry,” *J. Clean. Prod.*, vol. 295, p. 126390, May 2021, doi: 10.1016/j.jclepro.2021.126390.
- [26] S. K. B. C. Panda, K. Sen, and S. Mukhopadhyay, “Sustainable pretreatments in textile wet processing,” *J. Clean. Prod.*, vol. 329, no. Complete, 2021, doi: 10.1016/j.jclepro.2021.129725.
- [27] M. Rahman, M. Billah, and D. Hack-Polay, “What is hindering change? Anticipating the barriers to the adoption of enzyme-based textile processing in a developing country,” *Bus. STRATEGY Dev.*, vol. 2, no. 2, pp. 137–147, Jun. 2019, doi: 10.1002/bsd2.58 WE - Emerging Sources Citation Index (ESCI).

- [28] “UN launches drive to highlight environmental cost of staying fashionable | UN News.” Accessed: Aug. 24, 2024. [Online]. Available: <https://news.un.org/en/story/2019/03/1035161>
- [29] B. Mu, L. Liu, W. Li, and Y. Yang, “High sorption of reactive dyes onto cotton controlled by chemical potential gradient for reduction of dyeing effluents,” *J. Environ. Manage.*, vol. 239, pp. 271–278, Jun. 2019, doi: 10.1016/j.jenvman.2019.03.062.
- [30] U. Nimkar, “Sustainable chemistry: A solution to the textile industry in a developing world,” *Curr. Opin. Green Sustain. Chem.*, vol. 9, pp. 13–17, Feb. 2018, doi: 10.1016/j.cogsc.2017.11.002.
- [31] L. Ayed, N. Ladhari, R. El Mzoughi, and K. Chaieb, “Decolorization and phytotoxicity reduction of reactive blue 40 dye in real textile wastewater by active consortium: Anaerobic/aerobic algal-bacterial-probiotic bioreactor,” *J. Microbiol. Methods*, vol. 181, p. 106129, Feb. 2021, doi: 10.1016/j.mimet.2020.106129.
- [32] T. Mahiat et al., “Modeling the environmental and social impacts of the handloom industry in Bangladesh through life cycle assessment,” *Model. EARTH Syst. Environ.*, vol. 9, no. 1, pp. 239–252, Mar. 2023, doi: 10.1007/s40808-022-01491-7.
- [33] J. Chu, L. Sun, F. Chen, X. Ji, Z. Tian, and L. Wang, “Assessing the environmental profit and loss of the textile industry: A case study in China,” *Ind. TEXTILA*, vol. 72, no. 1, pp. 55–61, 2021, doi: 10.35530/IT.072.01.1787 WE - Science Citation Index Expanded (SCI-EXPANDED).
- [34] F. Baehaki, R. B. Rudibyani, S. R. N. Aeni, R. Perdana, and S. N. Aqmarina, “Utilization OF Salacca zalacca seeds as chromium(vi) adsorbents,” *Periód. Tchê Quím.*, vol. 17, no. 34, pp. 200–212, Mar. 2020, doi: 10.52571/PTQ.v17.n34.2020.217_P34_pgs_200_212.pdf.
- [35] E. T. Howell, K. M. Chomicki, and G. Kaltenecker, “Patterns in water quality on Canadian shores of Lake Ontario: Correspondence with proximity to land and level of urbanization,” *J. Gt. Lakes Res.*, vol. 38, pp. 32–46, Jan. 2012, doi: 10.1016/j.jglr.2011.12.005.
- [36] L. Hossain and M. S. Khan, “Water Footprint Management for Sustainable Growth in the Bangladesh Apparel Sector,” *Water*, vol. 12, no. 10, Art. no. 10, Oct. 2020, doi: 10.3390/w12102760.
- [37] K. Bailey, A. Basu, and S. Sharma, “The Environmental Impacts of Fast Fashion on Water Quality: A Systematic Review,” *Water*, vol. 14, no. 7, p. 1073, Mar. 2022, doi: 10.3390/w14071073.
- [38] K. Niinimäki, G. Peters, H. Dahlbo, P. Perry, T. Rissanen, and A. Gwilt, “The environmental price of fast fashion,” *Nat. Rev. Earth Environ.*, vol. 1, pp. 189–200, Apr. 2020, doi: 10.1038/s43017-020-0039-9.

CHAPTER 1:

Spatial heterogeneity in water quality across the northern nearshore regions of the Laurentian Great Lakes

Kevin Blagrove^{a,*}, Kerrice Bailey^{a,*}, Aman Basu^a, Nadine Benoit^b, Todd Howell^b, and Sapna Sharma^a

^a Department of Biology, York University, 4700 Keele Street, Toronto, Ontario, Canada

^b Ontario Ministry of Environment, Conservation and Parks, 125 Resources Rd. Toronto, Ontario,
Canada

Keywords: Chlorophyll a, Nutrients, Areas of concern, Land cover, Air temperatures

MY CONTRIBUTION

The manuscript, “Spatial heterogeneity in water quality across the northern nearshore regions of the Laurentian Great Lakes” was published in the Journal of Great Lakes Research. The project was conceptualised by Kerrice Bailey, Kevin Blagrove, Aman Basu, Todd Howell and Sapna Sharma. The data was collected by Nadine Benoit and Todd Howell. The methods finalised by Kerrice Bailey, Kevin Blagrove, Aman Basu, and Sapna Sharma. Statistical analyses in R by Kerrice Bailey. Original draft written by Kerrice Bailey. Revisions from Sapna Sharma.

ABSTRACT

We provide the first comprehensive analysis of spatial heterogeneity in water quality across the Canadian nearshore regions of the Laurentian Great Lakes (LGL) with periodic sampling in the ice-free seasons from 2000 to 2019 for 24 water quality variables from 52 nearshore sites. We asked: (1) What is the extent, range, and magnitude of spatial heterogeneity in water quality conditions across the nearshore of the Canadian Great Lakes? and (2) How do features of anthropogenic development, sub-basin characteristics, anticipated coastal circulation, and weather influence water quality conditions in the nearshore of the Canadian Great Lakes? Principal Components Analysis explained 42% of the variation in water quality across the Canadian Great Lakes, with high spatial heterogeneity both within and among lakes, ranging from oligotrophic conditions in Lake Superior to eutrophic conditions in Lake Erie. Lakes Erie and Ontario generally had higher concentrations of chloride, chlorophyll a, and nutrients while higher silicate concentrations were observed in Lake Superior. Consistent patterns of degraded water quality were observed in Areas of Concern, such as Hamilton Harbour, Bay of Quinte, Nipigon Bay, and near Thunder Bay. Across the nearshore of the Canadian Great Lakes, regions with warmer air temperatures, in addition to urbanized and agricultural landscapes, were associated with deteriorated water quality. Our study highlights the importance of improving management practices across urban and agricultural landscapes, particularly in consideration of climatic change cumulatively degrading water quality conditions in the highly biologically, culturally, and socioeconomically important nearshore regions of the LGL.

1 INTRODUCTION

The Laurentian Great Lakes comprise one fifth of the world's fresh- water supply, span 244,000 km², and are home to a plethora of species (Sterner et al., 2020; Vadeboncoeur et al., 2011). These lakes are unique from other large lakes as their basins pool together in one continuous drainage basin covering an area of almost 550,000 km² (Forsyth et al., 2016). Millions of people depend on the Great Lakes for drinking water, recreational activities (Connelly and Brown, 2010), agriculture, and transportation (Campbell et al., 2015). For example, roughly 28 million people are dependent on the Great Lakes for drinking water (Environment and Climate Change Canada and the U.S. Environmental Protection Agency, 2022), and recreational activities generate over 52 billion dollars of revenue annually ("About the Lakes – Great Lakes Commission," 2023). The Great Lakes region is also home to the majority of Ontario's agricultural industry with around 60,000 farms and roughly 9.1 billion dollars in revenue ("Agriculture in the Great Lakes Basin – Stewardship and Innovation," 2016).

In addition to their economic impact, the Laurentian Great Lakes are an ecological powerhouse, with over 2200 taxa of aquatic animals identified including: 36 amphibians, 43 reptiles, 178 fishes, 476 zooplankton, and 1433 benthic invertebrates, with the highest animal diversity in Lake Erie, followed by Lakes Superior, Huron, Michigan, and Ontario (Trebitz et al., 2019). The nearshore regions of the Great Lakes host inordinate amounts of biodiversity (Vadeboncoeur et al., 2011), but the proximity of the species' habitats to terrestrial environments results in a greater susceptibility to anthropogenic stressors (Allan et al., 2013; Riseng et al., 2018). Maintaining these ecosystems is not a simple task as lakes, and in particular, the Great Lakes, are complex ecosystems with varying interacting internal and catchment-scale influences from invasive species to local climate, geology, and land cover (e.g., Allan et al., 2013; Goforth and Carman, 2005; Riseng et al., 2018; Jenny et al., 2020).

Exploration of the spatial patterns within and across the diverse environments of the Great Lakes nearshore provides an opportunity to further understand and focus efforts to mitigate the effects of a variety of environmental stressors on nearshore environments. To date, water quality assessments across the Great Lakes have been heavily weighted towards offshore regions of the Great Lakes (e.g.,

Burniston et al., 2011; Chapra et al., 2012; Yurista et al., 2016). The defining spatial features of the Great Lakes nearshore vary by lake but also within each lake across a rich mosaic of habitat types. The Laurentian Great Lakes watersheds are host to a variety of land cover types, from grasses and forests to agricultural and urban landscapes, with implications for the water quality in the lakes (Environment and Climate Change Canada and the U.S. Environmental Protection Agency, 2022). The interaction of the geography and geology of the basins and local shoreline features contribute to varying water quality conditions for each lake. Land cover changes affect the hydrology of the Great Lakes basin (Philip et al., 2022), while effluent from wastewater treatment plants and agricultural runoff has a localized influence on water quality near the input site (Howell and Benoit, 2021; Makarewicz and Howell, 2012; Michalak et al., 2013; Yurista et al., 2011). The breakdown of land cover in the Canadian Great Lakes drainage basin in 2011 was approximately 3.5% built-up land (mostly in the basins of Erie and Ontario), 11.1% agricultural land (cropland, pasture, and summerfallow), and 85.4% natural and semi-natural land which includes the 35% of the basin covered by water (i. e., rivers, lakes, reservoirs, ponds, and wetlands) (Statistics Canada, 2017).

Moreover, the Great Lakes coastal regions are sensitive to the influences of climatic change, including warming air temperatures, storm events, watershed inflows, and seasonal and annual water level fluctuations (Blagrove et al., 2022; Jenny et al. 2020; Trumpickas et al., 2015). For example, in response to warming air temperatures, summer surface water temperatures in the Great Lakes are warming faster than the global average (O'Reilly et al., 2015). In particular, the northern lakes, Superior and Huron, are warming even faster than the southern lakes (Dobiesz and Lester, 2009; O'Reilly et al., 2015), and strong heatwaves are contributing to degraded water quality conditions across lakes globally (Shuvo et al., 2021), including in Lake Ontario (Blagrove et al., 2022). Furthermore, water quality conditions can deteriorate in nearshore sites in seasons with storm events and heavy precipitation, by increasing nutrient and particulate fluxes within a lake resulting in decreasing water clarity and increasing chlorophyll a concentrations (Blagrove et al., 2022).

The geological, morphological, climatic, and land cover heterogeneity within and across each of the Great Lakes contributes to their own unique spatial properties and consequently variability in water quality. Furthermore, the heterogeneous impact of multiple anthropogenic stressors both within

the watersheds and along the shorelines of all of the Great Lakes, is concomitantly reflected in the water quality of the nearshore waters (e.g., Howell et al., 2012; Kelly et al., 2015; Makarewicz and Lewis, 2015; Stefanoff et al., 2018; Yurista et al., 2011). A comprehensive multi-year exploration of this spatial heterogeneity across a landscape of nearshore environments and across the entirety of the Canadian Great Lakes nearshore has not yet been fully realized. We aim to build a holistic view of the nearshore regions of the Canadian Great Lakes by examining the magnitude of and the reasons for spatial heterogeneity in water quality patterns across the Canadian Great Lakes' nearshore. Using a suite of 24 water quality variables for 52 nearshore sites across the Canadian Great Lakes between 2000 and 2019, we addressed the following questions: (1) What is the extent, range, and magnitude of spatial heterogeneity in water quality conditions across the nearshore of the Canadian Great Lakes? and (2) How do features of anthropogenic development (land cover), sub-basin characteristics (site depth), anticipated coastal circulation (distance from land), and weather influence water quality conditions in the nearshore of the Canadian Great Lakes?

2 METHODS

2.1 Study area

This study examined conditions in 52 diverse sites within the nearshore (defined here as waters within 5 km of shore and up to 30 m depth, with the exception of western basin of Lake Erie (16 km from shore, 10 m depth) which was selected to fill a gap in management needs) of the Great Lakes, and specifically Lakes Erie, Ontario, Huron, and Superior, which constitute the Great Lakes portion of the Ontario Ministry of the Environment, Conservation and Parks (MECP) Great Lakes nearshore monitoring network. Additional nearshore monitoring network sites within Lake St. Clair and within St. Mary's, St. Clair, Detroit, Niagara, and St. Lawrence Rivers were not included in this study. The Great Lakes nearshore sites cover a range of environmental settings including locations influenced by tributary inflows, embayments, and urban shorelines, in addition to reference sites located away from direct sources of anthropogenic influence (Electronic Supplementary Material (ESM) Table S1). A number of these sites are also within current or former Great Lakes Water

Quality Agreement Areas of Concern (Hartig and Thomas, 1988; United States and Canada, 1987; ESM Table S1).

2.2 Data acquisition

Nearshore water quality samples from Lakes Erie, Ontario, Huron, and Superior and their connecting waters have been collected and analyzed as part of the Great Lakes nearshore monitoring network since 1994 (Long et al., 2022). Here, we focus on the Great Lakes data collected after 2000. This provided for a more consistent dataset across the years, as the data prior to 2000 were not as complete with respect to the number of nearshore sites or the breadth of water sample analyses. Great Lakes nearshore water samples were collected three times during the ice-free season, during the spring, summer, and fall seasons, with each lake on a different temporal cadence: Lake Superior sampled every 6–7 years, Lake Huron sampled every 6 years, Lake Erie sampled every 2–4 years, and Lake Ontario sampled every 3 years. This included a total of 4683 water samples (most in triplicate, reducing time/spatial data to a count of 1615 samples) since 2000 across 51 Canadian and 1 American nearshore sites (Fig. 1; ESM Table S1). Surface water samples were collected as depth-integrated samples, typically sampling the entire mixed surface layer, based on in situ water column temperatures, while the bottom samples were collected as discrete samples 1 to 3 m above the lakebed. A suite of water chemistry variables was measured, including nutrient concentrations, metal concentrations, turbidity, suspended solids, chlorophyll a concentrations, conductivity, and pH (Table 1). Analyses reported in this study were conducted in the Ontario Ministry of the Environment, Conservation and Parks Environmental Monitoring and Reporting Branch laboratory in Toronto, Ontario using Ministry standard methods for surface water on whole water samples (Table S2). The exceptions were chlorophyll concentrations which were analyzed using field-filtered samples (nylon filters with a pore size of 1.2 μm), in addition to a portion of the total phosphorus data which were analyzed at the Ontario Ministry of the Environment, Conservation and Parks laboratory in Dorset, Ontario. Detection limits varied across laboratory methods. We provided detection limits within data summaries when the measured concentrations fell below these limits (Blaggrave et al. 2023). However, for our analyses, if concentrations below the detection limit were summarized, they were set to zero.

Water column profiles of temperature, specific conductivity, oxygen saturation, and turbidity were collected concurrently during all sampling events using a conductivity, temperature, and depth (CTD) sonde. Two depth-integrated means were calculated for each CTD variable for: i) the mixed surface layer and ii) the bottom of the water column profile. These depth ranges were chosen to reflect the conditions corresponding to the two collected water samples (surface depth-integrated sample and bottom discrete sample). If the nearshore waters were stratified at the time of sampling, note that neither of these two means reflects conditions within the thermocline. Furthermore, as part of the Great Lakes nearshore monitoring network, sediment samples were collected using Shipek samplers and benthic invertebrate communities were collected using Ponar samplers. Sediment samples were not analyzed as part of this study. From the benthic invertebrate data, we extracted counts of *Dreissena bugensis* (quagga mussels), *D. polymorpha* (zebra mussels), and uncategorized *Dreissena* sp.

We acquired monthly weather (air temperature (°C) and precipitation (mm)) data for each sampling site and sampling time from the University of East Anglia's Climate Research Unit (CRU) online open access database (Harris et al., 2020). CRU interpolates meteorological station measurements onto a 0.5° latitude-longitude grid, providing monthly summaries of weather variables. Using the monthly mean temperature and total precipitation, we calculated seasonal mean temperatures and total precipitation for spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November).

We used geoprocessing tools to define two distinguishing features for each nearshore site: distance from land and the local watershed land cover characteristics. Lake boundary shapefiles from HydroLAKES (Messenger et al., 2016) were used to calculate the distance from the site to the shoreline and to determine the local shoreline (ESM Appendix S1; ESM Fig. S1), while sub watershed shapefiles from Great Lakes Hydrography Database (Forsyth et al., 2016) were used to determine a watershed associated with each local shoreline. In turn, the watershed was used in combination with land cover raster data to determine watershed land cover characteristics. Land cover raster data were merged from Southern Ontario Land Resource Information System (Ontario Ministry of Natural Resources, 2015), National Land Cover Database (Wickham et al., 2021), and the Ontario

Provincial Land Cover (“Provincial land cover, Land Information Ontario,” 1999). Land cover was summarized using eight categories, specifically: water (primarily lakes), barren, agricultural/rural, developed, treed, grasses, wetlands, and other.

2.3 What are the spatial patterns in water quality across the nearshore of the Canadian Great Lakes?

To investigate the spatial patterns in water quality, we grouped the data in several ways: i) by lake (4 lakes: Erie, Ontario, Huron, Superior), by region (10 regions: Superior North, Georgian Bay North, Georgian Bay South, Huron East, Erie West, Erie Central, Erie East, Ontario Open, Hamilton Harbour, and Bay of Quinte; Fig. 1), and by sampling site (52 sites). Regions were assigned using characteristics such as geology (the Canadian Shield for Georgian Bay North/South), basin depth (Erie West/Central/East), or geographical feature (embayments for Hamilton Harbour/Bay of Quinte), independent of any other criteria. Additional regional divisions can be investigated by grouping data from individual sites. All water chemistry variables measured in concentrations were $\log_{10}$ transformed to better satisfy the assumptions of normality. As seasonal stratification at most sites was very weak, the differences between a surface and bottom sample could not be consistently defined. Thus, for all our analyses, both surface and bottom samples were used together. We used four approaches to quantify the spatial patterns in water quality across the nearshore of the Canadian Great Lakes: i) summary descriptive statistics; ii) ridge plots; iii) a Principal Component Analysis (PCA); and iv) a Linear Discriminant Analysis (LDA).

First, we calculated the mean, range, and coefficient of variation for each water chemistry variable by lake (Table 1), by region (Table 2, for a selection of variables that characterize the general features of the water body including trophic state and base chemistry), and by sampling site (Blaggrave et al., 2023), mapping the site means (Fig. 2) and site coefficients of variation (ESM Fig. S2). We also calculated Z-scores for each site and each water chemistry variable, summarizing those sites with statistical extremes (Z-score greater than 2) in ESM Table S3. The Z-score is a measure of how far values deviate from a mean: $Z = (x - \mu)/sd$. In this case, x represents the site sample value, μ is the mean of all samples from a given lake and season, and sd is the standard deviation of these same lake-

wide samples. Next, we summarized the distributions of all water chemistry variables using ridge plots, produced using kernel density estimation plots in matplotlib 3.4.2 (Hunter, 2007) in Python 3.8.5. Third, we used several Principal Component Analyses to assess how nearshore water quality varied across the four Canadian Laurentian Great Lakes, within each of the four Great Lakes, within each of the three seasons (spring, summer, and fall), and across all seasons. We retained 1101 water samples for the nearshore Great Lakes sites, based on measurements of a consistent set of water quality parameters. This included samples covering 52 sampling locations, 15 years of data, 18–185 samples per year, 10–28 samples per site, and 178 potential water quality indicator variables. Note that only variables that were directly measured from water samples were included in this analysis. We subsequently reduced the number of water quality variables based on the frequency of data available, the occurrence of zeros (i.e., removed if more than 98% of sites have zeroes), and collinearity based on Variance Inflation Factors less than five. Thus, the final dataset for the Principal Component Analyses comprised 1101 samples and 24 water quality variables across 52 sampling sites. Each water quality variable was standardized to zero mean and unit variance. Principal Component Analyses were conducted using the `sklearn.decomposition.PCA` function in Python (Pedregosa et al., 2011). Finally, we determined which of the 24 water quality variables were the most heterogeneous between lakes. We used Linear Discriminant Analysis to create a model that predicted in which lake a site is most likely situated based solely on its water quality variables. This analysis was performed using the `sklearn.discriminant_analysis.LinearDiscriminantAnalysis` function in Python (Pedregosa et al., 2011). The magnitudes of the model weights (coefficients) represented how significant each water quality variable was at defining differences between lakes and was thus a measure of heterogeneity of that variable. Five-fold cross-validation was repeated 10 times to determine the mean accuracy of the LDA classification model.

2.4 How do land cover, site characteristics, and weather influence water quality conditions in the nearshore of the Canadian Laurentian Great Lakes?

A Redundancy Analysis (RDA) was conducted to assess the association between land cover, site characteristics, and weather on water quality conditions in the nearshore of the Canadian

Laurentian Great Lakes. The response variables were the 24 water quality variables from the Principal Component Analysis, including both surface and bottom samples. The predictor variables were weather (seasonal total precipitation and air temperature), land cover (water, barren, agricultural/rural, developed, treed, grasses, wetlands, and other), invasive dreissenid mussel counts (*D. polymorpha*, *D. bugensis*, and *D. sp.*), and other site characteristics (distance from shore, lake depth at sampling site, sampling depth, day of year). The rda function in the R-based vegan community ecology package (Oksanen et al., 2022) was used to investigate how much of the variation in water quality could be explained by these environmental variables. Land cover variables, mussel counts, and distance from shore were $\log_{10}$ transformed, and all data were standardized to have a zero mean and unit variance prior to performing the RDA. Forward selection was conducted on the environmental variation for each season such that we retained the subset of environmental variables that maximized the adjusted R^2 and minimized type 1 error (Blanchet et al., 2008).

3 RESULTS

3.1 What are the spatial patterns in water quality across the nearshore of the Canadian Great Lakes?

We found evidence of high spatial variability in water quality conditions across the northern nearshore of the Great Lakes (Fig. 2 and ESM Fig. S2). Summary descriptive statistics of all water samples collected between 2000 and 2019 revealed that generally the nearshore of Lake Ontario had the highest mean concentrations of total phosphorus (mean 13.6 $\mu\text{g/L}$; coefficient of variation, CV 0.97; range < 0.2–218 $\mu\text{g/L}$), nitrates and nitrites (0.46 mg/L N; 0.24; ranges are reported in Table 1), total chlorophyll a (3.1 $\mu\text{g/L}$; 0.81), sulphate (25.1 mg/L S; 0.58), and chloride (29.0 mg/L; 0.44), followed by Lake Erie. Lake Erie had the highest total suspended solids concentration (4.66 mg/L; CV and ranges are reported in Table 1), followed by Lake Ontario and Lake Superior (both 1.7 mg/L) and Lake Huron (0.90 mg/L). In contrast, the nearshore regions of Lake Huron and Superior typically had lower concentrations of total phosphorus (3.9 $\mu\text{g/L}$ and 3.39 $\mu\text{g/L}$, respectively), nitrates and

nitrites (0.23 mg/L N, 0.31 mg/L N), total chlorophyll a (1.3 µg/L, 1.7 µg/L), sulphate (13.9 mg/L S, 4.0 mg/L S), and chloride (7.1 mg/L, 1.8 mg/L) although mean reactive silicate concentrations were higher (0.80 mg/L Si, 1.1 mg/L Si) than those observed in Lake Erie and Lake Ontario (Table 1).

Grouping the nearshore regions not simply by lake, but into 10 nearshore “regions” (Superior North, Georgian Bay North, Georgian Bay South, Huron East, Erie West, Erie Central, Erie East, Ontario Open, Hamilton Harbour, and Bay of Quinte) revealed that the Hamilton Harbour and Bay of Quinte regions, both embayments within Lake Ontario, had much higher concentrations of total phosphorus (49.33 µg/L and 24.07 µg/L, respectively) and chlorophyll a (13.01 mg/L and 7.51 mg/L, respectively) than any of the other nearshore regions, including all three of the Lake Erie nearshore regions, of interest given Lake Erie offshore waters are the most eutrophic across all Great Lakes. Following Hamilton Harbour and Bay of Quinte, the Erie West region (western basin of Lake Erie) had the next highest mean total phosphorus (14.69 µg/L) and next highest total chlorophyll a (3.08 mg/L) across all nearshore regions. Interestingly, the geographically adjacent Erie Central region (central basin of Lake Erie) had some of the lower mean nitrates and nitrites concentrations (0.14 mg/L N) across all nearshore regions, on the same order as those in the Georgian Bay North region (0.14 mg/L N) (Table 2).

Finally, in a comparison of all individual sites across all lakes (i.e., no grouping of site data into lakes or regions), we found that some of the highest mean concentrations of total phosphorus, nitrates and nitrites, suspended solids, and sulphates were found at the site near the mouth of the lower Grand River, a major tributary to the eastern basin of Lake Erie (Blagrove et al., 2023). Furthermore, across all nearshore sites, the highest mean chloride concentrations were found in Hamilton Harbour, and the nearshore sites around Toronto (Toronto Inner Harbour Humber Bay, Oakville, and Pickering) (Blagrove et al., 2023).

Ridge plots further illustrated the mean and variability in key water quality variables across the nearshore regions of the four Great Lakes (Fig. 3). For example, Lakes Erie and Ontario have total phosphorus and chlorophyll a concentrations that are distinctly higher than Superior and Huron. For suspended solids concentrations, Lake Erie had the highest levels, whereas Lake Ontario suspended solids concentrations are more similar to those in Lake Superior, but with higher variability (Fig. 3).

Furthermore, there is a general decreasing pattern in reactive silicate concentrations from Superior to Huron to Erie and Ontario.

Principal Component Analysis on water quality conditions in the nearshore regions of the Canadian Great Lakes explained 42% of the variation, with PCA Axis 1 explaining 28.4% and PCA Axis 2 explaining 13.7% (Fig. 4). PCA Axis 1 was associated with total phosphorus, manganese, chlorophyll a, and suspended solids concentrations, whereas PCA Axis 2 was associated with reactive silicate and sulphate concentrations. Within the PCA biplot, Lakes Superior and Huron clearly have distinct water quality conditions typically associated with oligotrophic conditions, whereas Lakes Erie and Ontario have greater overlap in water quality conditions typically associated with mesotrophic and eutrophic conditions. Upon further examination of water quality conditions across lakes and seasons, there was no significant variation across seasons (ESM Fig. S3), but analysis on a lake by lake basis suggests each lake may have its own unique fingerprint in variation in water quality variables (ESM Fig. S3).

Linear Discriminant Analysis (LDA) identified dissolved inorganic carbon (DIC) as the water quality indicator that is the most heterogeneous across lakes. The LDA correctly assigned 88% of the 1101 nearshore samples to their corresponding lake based solely on the values of 24 water quality variables. The magnitude of water quality variable heterogeneity, as represented by the LDA model coefficients (ESM Fig. S4), varied from lake to lake, but dissolved inorganic carbon (DIC) appeared with the largest model coefficient in Superior (-7.3), Erie (4.0), and Ontario (3.2). Differences between sites in Lake Huron and sites in the rest of the lakes were primarily explained by total phosphorus which had a model coefficient of 2.0. Superior was most easily distinguishable from all other lakes, with the largest number of LDA coefficients greater than 1 (including those coefficients associated with DIC, sulphate, nitrate + nitrite, nickel, dissolved organic carbon, total suspended solids, lead, silicate, vanadium, nitrite, iron); all samples from Superior sites were well separated in the LDA plot (ESM Fig. S5).

3.2 How do land cover, site characteristics, and weather influence water quality conditions in the nearshore of the Canadian Laurentian Great Lakes?

A redundancy analysis revealed that a combination of land cover, site characteristics, and weather influence water quality conditions in the nearshore of the Laurentian Great Lakes. The redundancy analysis explained 31.8–32.3% of the variation in water quality conditions depending upon the season (Fig. 4). A subsequent redundancy analysis which included the summer dreissenid mussel count variables explained 36.0% of the variation in summer water quality conditions.

For all three seasons, air temperature and land cover types associated with development and agriculture were among the strongest drivers of variation in water quality conditions and were most closely associated with RDA axis 1. The spatial extent of the water land cover type (i.e., primarily lakes/reservoirs) within the station's watershed was also an important driver in the spring and, to a lesser extent, in the summer and fall and was most closely associated with RDA axis 2. The site depth also drove some of the variation in all three seasons and sampling timing (through the variable DayOfYear) had some influence on the variation in water quality conditions observed in the fall (see Fig. 5).

Higher concentrations of sulphate and dissolved inorganic carbon, and lower concentrations of silicate were observed in all seasons in regions with warmer air temperatures and with more urbanized and agricultural landscapes (and less water) within their watersheds. In the spring months, water temperature and concentrations of chlorophyll a, suspended solids, and total phosphorus were elevated within the waters of shallow sites, with more urbanized and wetland land cover within their local watershed. In the summer, water temperature and concentrations of chlorophyll a and suspended solids were elevated for samples collected from shallow sites and sites that had higher counts of *Dreissena polymorpha* at the time of sampling. In the fall, chlorophyll a and suspended solids concentrations were higher in shallower sites. These observations will be explored in more detail in the discussion below.

4 DISCUSSION

We present the first comprehensive twenty-year exploration of the spatial heterogeneity across the nearshore regions of the Canadian Laurentian Great Lakes. We found that water quality conditions varied across and within the Great Lakes. The lower Great Lakes (Erie and Ontario) were generally associated with higher phosphorus, chlorophyll a, and chloride concentrations. In contrast, despite having lower concentrations of these indicators, the upper Great Lakes had higher concentrations of reactive silicate. Notably, we observed consistent patterns of degraded water quality conditions in sites categorized as ‘Areas of Concern’. Across the Canadian Great Lakes, we found that the nearshore regions with warmer air temperatures, in addition to urbanized and agricultural landscapes, were associated with higher concentrations of chlorophyll a, suspended solids, dissolved inorganic carbon, and sulphates. Urbanization and higher air temperatures are intricately connected through the urban heat island effect (Oke, 1976). Furthermore, within the Laurentian Great Lakes region, the more southern lakes are typically associated with warmer air temperatures, in addition to more urban and agricultural areas. Our study highlights the importance of improving management practices across urban and agricultural landscapes in consideration of climate change and the cumulative influence of these environmental stressors on water quality.

4.1 Spatial heterogeneity in water quality conditions

Nearshore regions of the Laurentian Great Lakes often exhibit higher variability and degraded water quality conditions compared to offshore regions, as exemplified by higher mean values of trophic state indicators, such as chlorophyll a, and total phosphorus (Yurista et al., 2016). The variability in water quality within the nearshore sites is partly defined by the variability in nearshore currents. Chief among these is the degree of exchange of water with the offshore, which is highly dependent on fetch. Embayments, for example, have much lower fetch than open nearshore sites. This would have a critical local effect on water chemistry and biology, as there is reduced general circulation of water between the nearshore and the offshore. On the other hand, alongshore currents which transport water along the shoreline may introduce the open coastline to substantial variability, as local circulation may reverse direction, oscillating over the course of days (Howell et al., 2012).

Upwelling and downwelling, an additional offshore- nearshore exchange, introduce yet another source of variability in nearshore waters. In Lake Ontario, for example, upwelling and downwelling events have been observed to occur approximately every 10–12 days (Rao and Murthy, 2001). As the nearshore sites were sampled on a single day in each season, this is an extremely limited sampling of the actual circulation events, reducing our ability to interpret the effects of circulation on water quality in our dataset. However, differences between embayments and open shoreline were very much evident within our samples.

Where offshore waters have generally shown an improvement in water quality conditions (Chapra et al., 2012; Dove and Chapra, 2015), the nearshore has not always followed suit, showing declines in coastal water quality (Environment and Climate Change Canada and the U.S. Environmental Protection Agency, 2022). For example, remote sensing methods have shown that water clarity has increased across the offshore waters of most of the Great Lakes, whereas some nearshore regions experienced a reduction in water clarity (Binding et al., 2015). The same satellite observations indicate a much higher seasonal variability within the nearshore than the offshore regions (Binding et al., 2015). Here, we fill a knowledge gap in the literature by focusing on the variability in water quality conditions across the biologically, culturally, and socio-economically important nearshore regions of the Canadian Laurentian Great Lakes over two decades.

4.2 Inter-lake heterogeneity

We found distinct differences in nearshore water quality between the Great Lakes. Generally, we observed a gradient of deteriorating water quality conditions from the oligotrophic conditions in Lakes Superior and Huron to more mesotrophic and eutrophic conditions in Lakes Ontario and Erie. Previous studies have also shown inter-lake heterogeneity in offshore water quality conditions (e.g., Chapra et al., 2012; Dove and Chapra, 2015), fish species composition (Trebitz et al., 2019), phytoplankton taxa and biovolume (Cai and Reavie, 2018), and summertime lake warming (Zhong et al., 2019). In our study, we focused on water quality indicators such as water clarity (via total suspended solids), nutrients, chlorophyll a concentrations, and ions, such as chloride. Water clarity directly influences the light available for primary production within the water column. In the deep

basins, the 34-year mean water clarity increased from Ontario to Erie to Huron (Dobiesz and Lester, 2009). Moreover, offshore phosphorus and chlorophyll a concentrations in offshore waters generally decreased in concentration from the highest levels in Lakes Erie and Ontario to the lowest levels in Lake Huron and Superior (Dove and Chapra, 2015). We found similar inter-lake patterns across the nearshore sites.

Water quality conditions varied amongst the lakes and were influenced by the general characteristics of each lake and their watersheds. For example, the western basin of Lake Erie is eutrophic, warm, shallow, highly agricultural and industrialized, with high levels of biodiversity. However, the central part of the Lake Erie basin has been tied to continued water quality degradation issues, including hypoxia and algal blooms (Rowe et al., 2019). We found that the nearshore regions of Lake Erie had the lowest water clarity as indicated by the high levels of total suspended solids, with the highest suspended solids concentrations in the shallow western basin compared to the deeper meso-oligotrophic eastern basin. For Lake Ontario, large urban centers are found along the shoreline, including Toronto, Mississauga, Kingston, and Rochester, in addition to large agricultural and industrial sites, which negatively affects water quality conditions in Lake Ontario (Howell et al., 2012). Across all nearshore sites, we found the highest concentrations of total phosphorus, nitrates and nitrites, chlorophyll a, sulphate, and chloride in the nearshore of Lake Ontario. Lake Huron's shoreline consists of agricultural activity, beaches, and cottages along the southeast shores of Lake Huron, followed by more natural landscapes to the north (Lake Huron Science Committee, 2005). Both Lakes Huron and Superior generally had the lowest concentrations of water quality indicators, with the exception of reactive silicate. Silica uptake and sedimentation by diatoms is known to extract silica from the water column in eutrophic lakes (Schelske et al., 2006), leading to depleted silicate concentrations in the open waters of Lakes Erie and Ontario (Dove and Chapra, 2015). We also found lower silicate concentrations in the eutrophic/mesotrophic nearshore of the lower Great Lakes, suggesting historical parallels in diatom activity between the open and nearshore waters of these lakes. Dissolved inorganic carbon (DIC) was the most heterogeneous water quality variable across lakes in our study. We found that DIC increased from Superior to Huron to Erie and Ontario in the nearshore waters, a pattern also seen in the closely related measure of alkalinity (Chapra et al., 2012).

This pattern across lakes has been primarily attributed to the geological differences within each lake's respective watershed. The generally thinner soils on the Canadian Shield surrounding Lake Superior and some of Lake Huron supply a comparatively minimal load of carbonate to these more northern lakes as compared to Lakes Erie and Ontario (Waples et al., 2008). However, the introduction of invasive quagga mussels to the Great Lakes ecosystem has altered the natural DIC gradient across lakes. The effects of the mussels on DIC are two-fold, but generally the introduction of dreissenids has reduced the differences in DIC concentrations between Superior and the other Great Lakes. Dreissenids remove calcium and bicarbonate from the water column and thus reduce alkalinity and the bicarbonate component of DIC. At the same time, they contribute carbon dioxide (CO_2), also a component of DIC, through increased respiration, which may supersaturate the water column leading to an increase in the partial pressure of CO_2 (Lin and Guo, 2016). The effects of dreissenids on DIC are not similar across all of the Great Lakes owing to differences in their relative abundances across lakes, including the fact that dreissenids are not found in Lake Superior. Water quality variables, such as those discussed above (i.e., total phosphorus, nitrates and nitrites, total suspended solids, chlorophyll a, sulphates, chloride, silicates, and DIC) are not only indicative of the current state of the water quality but also the overall health of the ecosystem within the nearshore of each lake. Nutrient and chlorophyll a concentrations reflect the level of primary production, and concentrations of these and other water quality indicators influence pH, respiration, and community structure, ultimately driving changes such as eutrophication, algal blooms, species invasions, and acidifications (Jeppesen et al., 2005; Odum, 1985; Pick, 2016). Conversely, species invasions have influenced conditions in the nearshore. For example, the abundance of invasive dreissenids is the most important predictor of benthic algae cover and biomass in Lake Huron, wherein an increase in dreissenid mussels results in increases in algal blooms and biomass (Stefanoff et al., 2018). These observations further suggest that although nearshore conditions are heterogeneous across lakes, heterogeneity is also expected within the nearshore of each lake.

4.3 Intra-lake heterogeneity

Just as we observed differences in water quality indicators between the Great Lakes, differences in local environmental conditions within each lake led to spatial heterogeneity in observed water quality indicators within each lake. Open sites are exposed to greater offshore- nearshore exchange as compared to embayments, which are generally more protected with a lesser fetch. Water quality is also influenced by depth and distance from shore as has been found in comparisons of near and offshore water quality (Yurista et al., 2016). In Lake Erie, the western basin is much shallower than the eastern basin and thus these two basins would be expected to have different water quality conditions. Anthropogenic influences and inputs are also not homogeneous across a given lake. For example, in Lake Ontario, the Greater Toronto Area is much more densely populated than the eastern shores of the lake. The water quality conditions reflect these intra-lake differences in environmental conditions. We found significant variation in water quality conditions within each lake, especially within Erie and Ontario which showed the largest site-to-site variability for most water quality variables (refer to width of the ridge plots in Fig. 3 and ranges in Table 1). Consistent lake-wide statistical extremes of select water quality parameters (Z -score > 2 , as in Blagrove et al., 2022) were found in a selection of sites for the 2000–2019 monitoring period (ESM Table S3).

These consistent extreme conditions suggest that these sites had water quality conditions that were degraded relative to the rest of the lake's nearshore sites. Unsurprisingly, many of these sites were on the list of sites identified as Areas of Concern (AOC) as part of the 1987 update to the Great Lakes Water Quality Agreement (Hartig and Thomas, 1988; United States and Canada, 1987). In Lake Ontario, Hamilton Harbour and the Bay of Quinte are categorized as Areas of Concern. They are eutrophic embayments that have a history of harmful algal blooms with observed spatial and seasonal variance in toxin levels and algal types (Murphy et al., 2003; Watson et al., 2008). In an earlier study, Hamilton Harbour, Bay of Quinte, and Presqu'île Bay were found to have the most extreme turbidity and extreme concentrations of chlorophyll a across Lake Ontario nearshore sites (Blagrove et al., 2022). Expanding the analysis to the entirety of our nearshore dataset, we found that Hamilton Harbour had the highest concentrations of total phosphorus, chlorophyll a, nitrates and nitrites,

sulphates, and chloride, not only in Lake Ontario, but across all nearshore sites of the Canadian Great Lakes.

Lake Superior's Thunder Bay was also listed as an AOC in 1987 due to elevated bacteria and phosphorus levels, in addition to contaminated sediments, a legacy of industry and urbanization (Hartig and Thomas, 1988). The area covered by the AOC extends northwards from Thunder Bay and southwards to the north shore of Flatland Island. The Great Lakes nearshore monitoring network site near Flatland Island is located approximately 15 km south of Thunder Bay, and yet still had the highest spring total phosphorus, chlorophyll a, and chloride concentrations across all of the Lake Superior nearshore sites. Prevalent currents in Lake Superior within the nearshore waters are generally cyclonic (i.e., counterclockwise) (Bennington et al., 2010; Harrington, 1895), suggesting that the Flatland Island site is directly influenced by water quality conditions circulating from the Thunder Bay AOC.

Interestingly, the delisted (i.e., recovered) Severn Sound AOC exhibited some of the most extreme total phosphorus, chloride, chlorophyll a, and total suspended solids concentrations in Lake Huron. That is not to say that the water quality is degraded, but that conditions are still statistically extremely high, in the context of the oligotrophic Huron nearshore sites. Indeed, seasonal peak mean phosphorus and chlorophyll a concentrations of 10.2 µg/L and 5.6 µg/L, respectively are indicative of oligo-mesotrophic conditions in Severn Sound.

Additionally, sites at the mouths of rivers (i.e., Grand River in Lake Erie, Nipigon Bay in Lake Superior, French River in Georgian Bay, Lake Huron) had some of the highest total suspended solids, chloride, and/or total phosphorus concentrations within their respective lakes. Not unexpectedly, sites near mouths of tributaries have some of the most dynamic water quality conditions across the nearshore due to seasonal cycles in discharge, and the influence of precipitation and storms on flow and turbidity (Blagrove et al., 2022; Chomicki et al., 2016; Howell and Benoit, 2021). In a changing climate, it is necessary to continue monitoring these flows and their influence on the nearshore water quality, both seasonally and as they respond acutely to the effects of both extreme drought and extreme precipitation events.

4.4 Drivers of spatial variability in water quality

Water quality is moderated by a complex combination of nutrient concentrations, land cover changes, and climate. Primary production in freshwaters is generally thought to be phosphorus limited (Schindler, 1977), yet Shuvo et al. (2021) found that climate is just as important as phosphorus in predicting water quality (Shuvo et al., 2021). Likewise, precipitation and air temperature have been shown to influence water quality trends in the Great Lakes over the past century (Mahdiyan et al., 2021). In fact, primary production may be co-limited by nitrogen, other nutrients, metals, light, or temperature (Sterner, 2008) and in the offshore of Lake Superior has been well-modeled by variations in light and temperature (Sterner, 2010). Nearshore regions are more strongly impacted by many stressors that also affect offshore waters. The nearshore water quality responds more acutely to the many land-based anthropogenic stressors, including increased nutrient inputs. Although there is some exchange between the nearshore and offshore, a gradient is seen in water quality conditions from the nearshore to the offshore regions (Yurista et al., 2016). Sites across the Great Lakes nearshore are exposed to a variety of environmental conditions. Our analysis revealed that a combination of local weather, land cover, and other site-specific characteristics explained ~36% of the variation in water quality conditions in each of the seasons. In the following sections, we highlight the effects of how changes to these drivers (i.e., climate change, land cover changes, species invasions) may affect water quality.

4.5 Drivers of variability: climate change

We found that sites with warmer air temperatures were associated with increased concentrations of DIC and sulphates, regardless of the season. This is at least partly a spurious signal connected to the gradient of increasing DIC from Lakes Superior and Huron to Lakes Erie and Ontario, in line with the latitudinal gradient of colder to warmer air temperatures. However, when we classified sites by their region (e.g., Superior, Georgian Bay North, Georgian Bay South, Erie West, etc.), there still remained some variation in DIC and sulphates that was explained by air temperature differences across sites and years. Further gradients exist within each region, both in air temperature and other drivers, such as urbanization, agriculturalization, and industrialization, that could be the

source of this residual signal. Nonetheless, warming air temperature leads to warmer water temperature, which in turn is known to influence water quality (e.g., O'Reilly et al., 2015; Paerl and Huisman, 2008; Shuvo et al., 2021).

The Great Lakes are getting warmer, exceeding the warming rates of many other lakes around the world (O'Reilly et al., 2015), driven by rising annual air temperatures (Austin and Allen, 2011; Zhong et al., 2016), an increase in solar radiation (Zhong et al., 2016), and region-dependent decreases in cloud cover (Ackerman et al., 2013), which are connected to climate change. The degree of warming varies across the Great Lakes, but Lake Superior is warming the fastest, with an increase of +2.5 °C in summer surface water temperatures between 1979 and 2006 (Austin and Colman, 2007) and was identified as the second fastest warming lake in a global study (O'Reilly et al., 2015). Warming leads to a suite of ecosystem effects (Woolway et al., 2022, 2020), including increases in primary production (Shuvo et al., 2021), alterations in fish habitat (Kraemer et al., 2021; Mandrak, 1989; Sharma et al., 2007; Smith et al., 2012), and increased intensity and frequency of algal blooms (Ho et al., 2019; Paerl and Huisman, 2008), even in oligotrophic and 'cold' lakes (Reinl et al., 2023, 2021). Additionally, climate change will bring an increased frequency and intensity of heatwaves and storms (Rahmstorf and Coumou, 2011; Seneviratne et al., 2012), both of which are associated with increased primary production (Blagrove et al., 2022; Hampton et al., 2022; Stockwell et al., 2020) and reduced water clarity in the nearshore (Blagrove et al., 2022). Sites near mouths of tributaries, which we have shown already have some of the highest total suspended solids, chloride, and/or phosphorus within their respective lakes, will be especially sensitive to this increased storm activity. Climate change can also influence lake water levels (Gronewold et al., 2013; Watras et al., 2022; Woolway et al., 2020) and alter invasion risk by expanding the habitable environments for non-native species, while reducing the habitable zone for native species (Campbell et al., 2022; Van Zuiden et al., 2016; Wu et al., 2023). Interactions of environmental stressors can complicate the process of identifying how individual stressors affect lakes over time, leading to oversimplification or underestimation of effects (Danz et al., 2007; Smith et al., 2015).

4.6 Drivers of variability: urbanization, agriculturalization, and other land cover changes

We found that spatial variability of water quality is largely influenced by the degree of anthropogenic development (more urban and agricultural land cover) in areas with fewer and/or smaller lakes (less water-type land cover). This land cover influence has been seen globally in a study of over 9000 lakes by Moslenko et al. (2020). In particular, lakes with high agricultural activity and human population had the highest chlorophyll a concentrations (Moslenko et al., 2020). Changes in human activity and demographics lead to changes in land cover, which in turn have direct implications for water quality, human health, climate, and ecosystems. For example, the conversion of land cover from undisturbed to urban and agricultural contributes to lake eutrophication and degraded water quality, as urban development introduces changes to runoff and nonpoint source pollution (Cullis et al., 2019; Howell et al., 2012; Soranno et al., 1996; Tang et al., 2005). Urban lands can contribute as much as five times more suspended solids per year compared to other land cover types (Kellogg, 1997). Likewise, agricultural intensity has been strongly associated with higher nutrient levels, increased primary production, and reduced water clarity both in lakes (e.g., Holopainen and Lehtikoinen, 2022; Moslenko et al., 2020; Taranu and Gregory-Eaves, 2008) and in coastal wetlands (Treibitz et al., 2007). Using SPATIally Referenced Regressions On Watershed (SPARROW) models, Robertson and Saad (2011) found that in the Great Lakes agricultural factors resulted in 33–44% and 33–58% of phosphorus and nitrogen contributions, respectively with the exception of the low agricultural areas of Lake Superior (Robertson and Saad, 2011).

In a study of land cover changes in the US Great Lakes basin, Wolter et al. (2006) found that 49.3% of the change in watershed land cover between 1992 and 2001 was a result of undeveloped land being converted to developed land (Wolter et al., 2006). Developed lands have a high retention time (Pastor and Wolter, 2002) meaning that there is little likelihood that they will be “undeveloped” back to their original state. In combination with the declines in water quality associated with land developments, this has major implications for species whose habitat is either modified or destroyed by this development. Chief among these species are the fish who inhabit the nearshore of the Great Lakes and are thus directly impacted by changes in water quality. Important breeding sites such as coastal wetlands are negatively affected by human activities such as mining and timber harvesting, and in

some cases have been completely lost due to the impacts of urbanization, such as shoreline hardening (Trebitz et al., 2009). Furthermore, an increase in impervious surfaces as a result of urbanization may contribute to increases in surface runoff amongst other stressors, overall contributing negatively to water quality (e.g., Cheng et al., 2022).

4.7 Drivers of variability: Invasive mussels

In the late 1980s, zebra and quagga mussels were first detected in Lake Erie (Hebert et al., 1989; Mills et al., 1993) and have since spread across the Great Lakes, with the exception of Lake Superior, owing to temperature and calcium limitations (Vanderploeg et al., 2002). They have played a key role in the Great Lakes ecosystem, primarily through their filtering function, leading to alterations in habitat and community structure (Hecky et al., 2004) and systemic changes in ecological function and processes (McKenna et al., 2017). Dreissenids have further been hypothesized to be the reason behind the observed reemergence of *Cladophora*, associated with shoreline fouling and clogging water intakes in Lakes Ontario and Huron (Kuczynski et al., 2016; Stefanoff et al., 2018) via the phosphorus shunt (Hecky et al., 2004). We found that the abundance of zebra mussels (*D. polymorpha*) explained some of the variation in chlorophyll a and suspended solids concentrations in nearshore sites. A higher abundance of zebra mussels was associated with higher chlorophyll a and suspended solids concentrations in the summer. This is most likely a spurious association and does not imply a mechanistic connection. The presence of dreissenids is generally negatively correlated with chlorophyll a concentrations and suspended solids (e.g., Fahnenstiel et al., 1995; Johengen et al., 1995) and zebra mussels have been largely replaced by quagga mussels (*D. bugensis*) across much of the Great Lakes (Karatayev et al., 2014; Wilson et al., 2006). We found that the highest counts of zebra mussels were found in the Bay of Quinte in Lake Ontario and the western basin of Lake Erie. These sites also corresponded to nearshore wide extremes in chlorophyll a and suspended solid concentrations. As these sites are also the shallowest across the nearshore, this also explains the strong association we observed between shallow sites and higher chlorophyll a and suspended solids concentrations. Likewise, quagga mussels (*D. bugensis*) explained some of the variation in sulphate concentrations with a higher abundance of quagga mussels associated with higher sulphate

concentrations. Again, this is most likely a spurious association connected to covariation of quagga mussels and sulphate concentrations across lakes.

5 CONCLUSION

The livelihoods of millions of people depend on the health of the Great Lakes ecosystem and thus it is critical to make every attempt to optimize lake conditions. To that end, it is important to reassess the management of the Great Lakes in the context of any new water quality research along with long term monitoring. There are numerous action plans, assessments, conferences, and committees to govern activities in the Great Lakes. Among them are the Great Lakes Water Quality Agreement, Great Lakes Water Quality Agreement Annex 1: Areas of Concern, Great Lakes Water Quality Agreement Annex 2: Lakewide Management, the International Joint Commission, and the International Association for Great Lakes Research. Continued success of management plans depends on accounting for the spatial heterogeneity among the Great Lakes and across sites on a lake-to-lake basis. In the past, the Great Lakes Water Quality Agreement (United States and Canada, 1978) was effective at reducing the phosphorus load to the Great Lakes, especially in western Lake Erie, which declined by approximately 40% (~3500 metric T/yr) between mid-1970s and the late 1980s (Nicholls and Hopkins, 1993) and even more (~40%; ~6000 metric T/yr) in Lake Ontario between the late 1960s and early 1980s (Stevens and Neilson, 1987). These changes emphasize the importance of maintaining long term monitoring programs.

Moving forward, a transdisciplinary approach to management of the Great Lakes is imperative. Scientists must work with policy makers to design sustainable management plans that align with the biological, chemical, and physical factors affecting the lake but also account for the socioeconomic and political factors that are necessary for implementing changes (Krantzberg, 2004). Furthermore, this collaboration should focus on simplifying and communicating complexities to the public who may not readily have accurate information about the delays or lag time component in relation to designing, approving, and implementing infrastructure for better lake management (Meals et al., 2010). Continually improving management plans for the Laurentian Great Lakes, in particular

accounting for the direct and indirect impacts of climate change, will improve our ability to maintain this biologically, culturally, and socioeconomically important resource.

ACKNOWLEDGEMENTS

We would like to thank the field crew at the Ontario Ministry of Environment, Conservation and Parks for collecting water quality samples from Lake Ontario over the past 25 years. Thank you to Kirill Shchapov for his helpful comments on earlier drafts of the manuscript. We further acknowledge funding from the Ontario Ministry of Environment, Conservation and Parks (2021-02-01-1569389059) and Natural Sciences and Engineering Research Council Discovery Grants to SS.

REFERENCES

- [1] About the Lakes - Great Lakes Commission [WWW Document], 2023. Great Lakes Commission des Grands Lacs. URL <https://www.glc.org/lakes/> (accessed 2.2.23).
- [2] Ackerman, S.A., Heidinger, A., Foster, M.J., Maddux, B., 2013. Satellite Regional Cloud Climatology over the Great Lakes. *Remote Sens.* 5, 6223–6240. <https://doi.org/10.3390/rs5126223>.
- [3] Agriculture in the Great Lakes Basin – Stewardship and Innovation [WWW Document], 2016. Ontario Ministry of Agriculture, Food and Rural Affairs. URL http://omafra.gov.on.ca/english/environment/facts/gl_basin.htm (accessed 2.2.23).
- [4] Allan, J.D., McIntyre, P.B., Smith, S.D.P., Halpern, B.S., Boyer, G.L., Buchsbaum, A., Burton, G.A., Campbell, L.M., Chadderton, W.L., Ciborowski, J.J.H., Doran, P.J., Eder, T., Infante, D.M., Johnson, L.B., Joseph, C.A., Marino, A.L., Prusevich, A., Read, J.G., Rose, J.B., Rutherford, E.S., Sowa, S.P., Steinman, A.D., 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. *PNAS* 110 (1), 372–377.
- [5] Austin, J.A., Allen, J., 2011. Sensitivity of summer Lake Superior thermal structure to meteorological forcing. *Limnol. Oceanogr.* 56, 1141–1154. <https://doi.org/10.4319/lo.2011.56.3.1141>.
- [6] Austin, J.A., Colman, S.M., 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. *Geophys. Res. Lett.* 34 <https://doi.org/10.1029/2006GL029021>.
- [7] Bennington, V., McKinley, G.A., Kimura, N., Wu, C.H., 2010. General circulation of Lake Superior: Mean, variability, and trends *J. Geophys. Res. Oceans* 115. <https://doi.org/10.1029/2010JC006261> from 1979 to 2006.
- [8] Binding, C., Greenberg, T., Watson, S., Rastin, S., Gould, J., 2015. Long term water clarity changes in North America’s Great Lakes from multi-sensor satellite observations. *Limnol. Oceanogr.* 60, 1976–1995. <https://doi.org/10.1002/lno.10146>.
- [9] Blagrove, K., Moslenko, L., Khan, U.T., Benoit, N., Howell, T., Sharma, S., 2022. Heatwaves and storms contribute to degraded water quality conditions in the nearshore of Lake Ontario. *J. Great Lakes Res.* 48, 903–913. <https://doi.org/10.1016/j.jglr.2022.04.008>.
- [10] Blagrove, K., Bailey, K., Basu, A., Benoit, N., Howell, T., Sharma, S., 2023. Water quality conditions for 52 stations across the northern nearshore of the Laurentian Great Lakes (2000–2019). Figshare.
- [11] Blanchet, F.G., Legendre, P., Borcard, D., 2008. Forward selection of explanatory variables. *Ecol.* 89 (9), 2623–2632.
- [12] Burniston, D., Klawunn, P., Backus, S., Hill, B., Dove, A., Waltho, J., Richardson, V., Struger, J., Bradley, L., McGoldrick, D., Marvin, C., 2011. Spatial distributions and temporal trends in pollutants in the Great Lakes 1968–2008. *Water Qual. Res. J.* 46, 269–289. <https://doi.org/10.2166/wqrjc.2012.017>.
- [13] Cai, M., Reavie, E.D., 2018. Pelagic zonation of water quality and phytoplankton in the Great Lakes. *Limnol.* 19, 127–140. <https://doi.org/10.1007/s10201-017-0526-y>.
- [14] Campbell, M., Cooper, M.J., Friedman, K., Anderson, W.P., 2015. The economy as a driver of change in the Great Lakes–St. Lawrence River basin. *J. Great Lakes Res.* 41, 69–83. <https://doi.org/10.1016/j.jglr.2014.11.016>.
- [15] Campbell, S.E., Hubbard, J.A.G., Mandrak, N.E., Liu, X., 2022. Changing community dynamics and climate alter invasion risk of freshwater fishes historically found in invasion pathways of the Laurentian Great Lakes. *Divers. Distrib.* 28 (8), 1620–1634.
- [16] Chapra, S.C., Dove, A., Warren, G.J., 2012. Long-term trends of Great Lakes major ion chemistry. *J. Great Lakes Res.* 38, 550–560. <https://doi.org/10.1016/j.jglr.2012.06.010>.

- [18] Cheng, C., Zhang, F., Shi, J., Kung, H.-T., 2022. What is the relationship between land use and surface water quality? A review and prospects from remote sensing perspective. *Environ. Sci. Pollut. Res.* 29, 56887–56907. <https://doi.org/10.1007/s11356-022-21348-x>.
- [19] Chomicki, K.M., Howell, E.T., Defield, E., Dumas, A., Taylor, W.D., 2016. Factors influencing the phosphorus distribution near the mouth of the Grand River, Ontario, Lake Erie. *J. Great Lakes Res.* 42, 549–564. <https://doi.org/10.1016/j.jglr.2016.03.014>.
- [20] Lake Huron Science Committee, 2005. Sources and mechanisms of delivery of *E. coli* (bacteria) pollution to the Lake Huron shoreline of Huron County (Report). Ontario Ministry of the Environment.
- [21] Connelly, N.A., Brown, T.L., 2010. Sportfishing Participation on Lake Ontario: Modeling the Past, Predicting the Future. *N. Am. J. Fish Manag.* 30, 821–830. <https://doi.org/10.1577/M09-089.1>.
- [22] Cullis, J.D.S., Horn, A., Rossouw, N., Fisher-Jeffes, L., Kunneke, M.M., Hoffman, W., 2019. Urbanisation, climate change and its impact on water quality and economic risks in a water scarce and rapidly urbanising catchment: case study of the Berg River Catchment. *H2Open J.* 2, 146–167. <https://doi.org/10.2166/h2oj.2019.027>.
- [23] Danz, N.P., Niemi, G.J., Regal, R.R., Hollenhorst, T., Johnson, L.B., Hanowski, J.M.,
- [24] Axler, R.P., Ciborowski, J.J.H., Hrabik, T., Brady, V.J., Kelly, J.R., Morrice, J.A., Brazner, J.C., Howe, R.W., Johnston, C.A., Host, G.E., 2007. Integrated Measures of Anthropogenic Stress in the U.S. Great Lakes Basin. *Environ. Manag.* 39, 631–647. <https://doi.org/10.1007/s00267-005-0293-0>.
- [25] Dobiesz, N.E., Lester, N.P., 2009. Changes in mid-summer water temperature and clarity across the Great Lakes between 1968 and 2002. *J. Great Lakes Res.* 35, 371–384. <https://doi.org/10.1016/j.jglr.2009.05.002>.
- [26] Dove, A., Chapra, S., 2015. Long-term trends of nutrients and trophic response variables for the Great Lakes. *Limnol. Oceanogr.* 60, 696–721. <https://doi.org/10.1002/lno.10055>.
- [27] Environment and Climate Change Canada, the U.S. Environmental Protection Agency, 2022. State of the Great Lakes - 2022 Report.
- [28] Fahnenstiel, G.L., Lang, G.A., Nalepa, T.F., Johengen, T.H., 1995. Effects of Zebra Mussel (*Dreissena polymorpha*) Colonization on Water Quality Parameters in Saginaw Bay, Lake Huron. *J. Great Lakes Res.* 21, 435–448. [https://doi.org/10.1016/S0380-1330\(95\)71057-7](https://doi.org/10.1016/S0380-1330(95)71057-7).
- [29] Forsyth, D.K., Riseng, C.M., Wehrly, K.E., Mason, L.A., Gaiot, J., Hollenhorst, T., Johnston, C.M., Wyrzykowski, C., Annis, G., Castiglione, C., Todd, K., Robertson, M., Infante, D.M., Wang, L., McKenna, J.E., Whelan, G., 2016. The Great Lakes hydrography dataset: consistent, binational watersheds for the Laurentian Great Lakes Basin. *J. Am. Water Resour. Assoc.* 52, 1068–1088. <https://doi.org/10.1111/1752-1688.12435>.
- [30] Goforth, R.R., Carman, S.M., 2005. Nearshore community characteristics related to shoreline properties in the Great Lakes. *J. Great Lakes Res.* 31, 113–128. [https://doi.org/10.1016/S0380-1330\(05\)70293-8](https://doi.org/10.1016/S0380-1330(05)70293-8).
- [31] Gronewold, A.D., Fortin, V., Lofgren, B., Clites, A., Stow, C.A., Quinn, F., 2013. Coasts, water levels, and climate change: A Great Lakes perspective. *Clim. Change* 120, 697–711. <https://doi.org/10.1007/s10584-013-0840-2>.
- [32] Hampton, S.E., Sharma, S., Brousil, M.R., Filazzola, A., 2022. Winter storms and summer calm conditions modify chlorophyll relationships with nutrients in seasonally ice covered lakes. *Ecosphere* in review.

- [33] Harrington, M.W., 1895. Surface currents of the Great Lakes: as deduced from the movements of bottle papers during the seasons of 1892, 1893, and 1894. US Department of Agriculture, Weather Bureau.
- [34] Harris, I., Osborn, T.J., Jones, P., Lister, D., 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data* 7, 1–18. <https://doi.org/10.1038/s41597-020-0453-3>.
- [35] Hartig, J.H., Thomas, R.L., 1988. Development of plans to restore degraded areas in the Great Lakes. *Environ. Manag.* 12, 327–347. <https://doi.org/10.1007/BF01867523>. Hebert, P.D.N., Muncaster, B.W., Mackie, G.L., 1989. Ecological and Genetic Studies on
- [36] *Dreissena polymorpha* (Pallas): a New Mollusc in the Great Lakes. *Can. J. Fish. Aquat. Sci.* 46, 1587–1591. <https://doi.org/10.1139/f89-202>.
- [37] Hecky, R.E., Smith, R.E., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N., Howell, T., 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* 61, 1285–1293. <https://doi.org/10.1139/f04-065>.
- [38] Ho, J.C., Michalak, A.M., Pahlevan, N., 2019. Widespread global increase in intense lake phytoplankton blooms since the 1980s. *Nat.* 574, 667–670. <https://doi.org/10.1038/s41586-019-1648-7>.
- [39] Holopainen, S., Lehtikoinen, A., 2022. Role of forest ditching and agriculture on water quality: Connecting the long-term physico-chemical subsurface state of lakes with landscape and habitat structure information. *Sci. Total Environ.* 806, 151477 <https://doi.org/10.1016/j.scitotenv.2021.151477>.
- [40] Howell, E.T., Benoit, N., 2021. Nutrient footprints on the Toronto-Mississauga waterfront of Lake Ontario. *J. Great Lakes Res.* 47, 343–365. <https://doi.org/10.1016/j.jglr.2020.11.009>.
- [41] Howell, E.T., Chomicki, K.M., Kaltenecker, G., 2012. Tributary discharge, lake circulation and lake biology as drivers of water quality in the Canadian Nearshore of Lake Ontario. *J. Great Lakes Res.* 38, 47–61. <https://doi.org/10.1016/j.jglr.2012.03.008>.
- [42] Hunter, J.D., 2007. Matplotlib: A 2D graphics environment. *Comput. Sci. Eng.* 9, 90–95. <https://doi.org/10.1109/MCSE.2007.55>.
- [43] Jenny, J.-P., Anneville, O., Arnaud, F., Baulaz, Y., Bouffard, D., Domaizon, I., Bocaniov, S.A., Ch`evre, N., Dittrich, M., Dorioz, J.-M., Dunlop, E.S., Dur, G., Guillard, J., Guinaldo, T., Jacquet, S., Jamoneau, A., Jawed, Z., Jeppesen, E., Krantzberg, G., Lenters, J., Leoni, B., Meybeck, M., Nava, V., No`ges, T., No`ges, P., Patelli, M., Pebbles, V., Perga, M.-E., Rasconi, S., Ruetz, C.R., Rudstam, L.,
- [44] Salmaso, N., Sapna, S., Straile, D., Tammeorg, O., Twiss, M.R., Uzarski, D.G., Ventel`a, A.-M., Vincent, W.F., Wilhelm, S.W., Wa`ngberg, S.-Å., Weyhenmeyer, G.A., 2020. Scientists' Warning to Humanity: Rapid degradation of the world's large lakes.
- [45] *J. Great Lakes Res.* 46 (4), 686–702.
- [46] Jeppesen, E., Sondergaard, M., Jensen, J.P., Havens, K.E., Anneville, O., Carvalho, L., Coveney, M.F., Deneke, R., Dokulil, M.T., Foy, B., Gerdeaux, D., Hampton, S.E., Hilt, S., Kangur, K., Kohler, J., Lammens, E., Lauridsen, T.L., Manca, M., Miracle, M. R., Moss, B., Noges, P., Persson, G., Phillips, G., Portielje, R., Schelske, C.L., Straile, D., Tatrai, I., Willen, E., Winder, M., 2005. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. *Freshw. Biol.* 50 (10), 1747–1771.
- [47] Johengen, T.H., Nalepa, T.F., Fahnenstiel, G.L., Goudy, G., 1995. Nutrient Changes in Saginaw Bay, Lake Huron, After the Establishment of the Zebra Mussel (*Dreissena*

- polymorpha). *J. Great Lakes Res.* 21, 449–464. [https://doi.org/10.1016/S0380-1330\(95\)71058-9](https://doi.org/10.1016/S0380-1330(95)71058-9).
- [48] Karatayev, A.Y., Burlakova, L.E., Pennuto, C., Ciborowski, J., Karatayev, V.A., Juetter, P., Clapsadl, M., 2014. Twenty five years of changes in *Dreissena* spp. populations in Lake Erie. *J. Great Lakes Res.* 40, 550–559. <https://doi.org/10.1016/j.jglr.2014.04.010>.
- [49] Kellogg, W.A., 1997. Metropolitan growth and the local role in surface water resource protection in the Lake Erie Basin. *J. Great Lakes Res.* 23, 270–285. [https://doi.org/10.1016/S0380-1330\(97\)70911-0](https://doi.org/10.1016/S0380-1330(97)70911-0).
- [50] Kelly, J.R., Yurista, P., Starry, M., Scharold, J., Bartsch, W., Cotter, A., 2015. Exploration of spatial variability in nearshore water quality using the first Great Lakes National Coastal Condition Assessment survey. *J. Great Lakes Res.* 41, 1060–1074. <https://doi.org/10.1016/j.jglr.2015.09.007>.
- [51] Kraemer, B.M., Pilla, R.M., Woolway, R.I., Anneville, O., Ban, S., Colom-Montero, W., Devlin, S.P., Dokulil, M.T., Gaiser, E.E., Hambright, K.D., Hessen, D.O., Higgins, S.N., Joehnke, K.D., Keller, W., Knoll, L.B., Leavitt, P.R., Lepori, F., Luger, M.S., Maberly, S., Müller-Navarra, D.C., Paterson, A.M., Pierson, D.C., Richardson, D.C., Rogora, M., Rusak, J.A., Sadro, S., Salmaso, N., Schmid, M., Silow, E.A., Sommaruga, R., Stelzer, J.A.A., Straile, D., Thiery, W., Timofeyev, M.A., Verburg, P., Weyhenmeyer, G.A., Adrian, R., 2021. Climate change drives widespread shifts in lake thermal habitat. *Nat. Clim. Chang.* 11, 521–529. <https://doi.org/10.1038/s41558-021-01060-3>.
- [55] Krantzberg, G., 2004. Science Must Inform Great Lakes Policy. *J. Great Lakes Res.* 30, 573–574. [https://doi.org/10.1016/S0380-1330\(04\)70373-1](https://doi.org/10.1016/S0380-1330(04)70373-1).
- [56] Kuczynski, A., Auer, M.T., Brooks, C.N., Grimm, A.G., 2016. The *Cladophora* resurgence in Lake Ontario: characterization and implications for management. *Can. J. Fish. Aquat. Sci.* 73, 999–1013. <https://doi.org/10.1139/cjfas-2015-0460>.
- [57] Lin, P., Guo, L., 2016. Do invasive quagga mussels alter CO₂ dynamics in the Laurentian Great Lakes? *Sci. Rep.* 6, 39078. <https://doi.org/10.1038/srep39078>.
- [58] Long, T., Benoit, N., Howell, T., Richman, L., Bhavsar, S.P., 2022. Spatiotemporal trends of polychlorinated biphenyls (PCBs) in surface and suspended sediments from the Lake Ontario Canadian nearshore 1994–2018: A fish consumption advisory perspective. *J. Great Lakes Res.* 48 (2), 300–314.
- [59] Mahdian, O., Filazzola, A., Molot, L.A., Gray, D., Sharma, S., 2021. Drivers of water quality changes within the Laurentian Great Lakes region over the past 40 years. *Limnol. Oceanogr.* 66, 237–254. <https://doi.org/10.1002/lno.11600>.
- [60] Makarewicz, J.C., Howell, E.T., 2012. The Lake Ontario Nearshore Study: Introduction and summary. *J. Great Lakes Res.* 38, 2–9. <https://doi.org/10.1016/j.jglr.2012.07.006>.
- [61] Makarewicz, J.C., Lewis, T.W., 2015. Exploring spatial trends and causes in Lake Ontario coastal chemistry: Nutrients and pigments. *J. Great Lakes Res.* 41, 794–800. <https://doi.org/10.1016/j.jglr.2015.04.011>.
- [62] Mandrak, N.E., 1989. Potential Invasion of the Great Lakes by Fish Species Associated with Climatic Warming. *J. Great Lakes Res.* 15, 306–316. [https://doi.org/10.1016/S0380-1330\(89\)71484-2](https://doi.org/10.1016/S0380-1330(89)71484-2).
- [63] McKenna, J.E., Chalupnicki, M., Dittman, D., Watkins, J.M., 2017. Simulation of rapid ecological change in Lake Ontario. *J. Great Lakes Res.* 43 (5), 871–889.
- [64] Meals, D.W., Dressing, S.A., Davenport, T.E., 2010. Lag time in water quality response to best management practices: A review. *J. Environ. Qual.* 39, 85–96. <https://doi.org/10.2134/jeq2009.0108>.

- [66] Messenger, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O., 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nat. Commun.* 7 <https://doi.org/10.1038/ncomms13603>.
- [67] Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., Chaffin, J.D., Cho, K., Confesor, R., Daloglu, I., Depinto, J.V., Evans, M.A., Fahnenstiel, G.L., He, L., Ho, J.C., Jenkins, L., Johengen, T.H., Kuo, K.C., Laporte, E., Liu, X., McWilliams, M.R., Moore, M.R., Posselt, D.J., Richards, R.P., Scavia, D., Steiner, A.L., Verhamme, E., Wright, D.M., Zagorski, M.A., 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *PNAS* 110, 6448–6452. <https://doi.org/10.1073/pnas.1216006110>.
- [70] Mills, E., Dermott, R., Roseman, E., Dustin, D., Mellina, E., Conn, D., Spidle, A., 1993. Colonization, Ecology, and Population Structure of the “Quagga” Mussel (*Bivalvia*: *Dreissenidae*) in the Lower Great Lakes. *Can. J. Fish. Aquat. Sci.* 50, 2305–2314. <https://doi.org/10.1139/f93-255>.
- [71] Moslenko, L., Blagrove, K., Filazzola, A., Shuvo, A., Sharma, S., 2020. Identifying the influence of land cover and human population on chlorophyll a concentrations using a pseudo-watershed analytical framework. *Water* 12 (11), 3215.
- [72] Murphy, T., Irvine, K., Guo, J., Davies, J., Murkin, H., Charlton, M., Watson, S., 2003. New microcystin concerns in the lower Great Lakes. *Water Qual. Res. J.* 38, 127–140. <https://doi.org/10.2166/wqrj.2003.008>.
- [73] Nicholls, K.H., Hopkins, G.J., 1993. Recent Changes in Lake Erie (North Shore) phytoplankton: cumulative impacts of phosphorus loading reductions and the Zebra Mussel introduction. *J. Great Lakes Res.* 19, 637–647. [https://doi.org/10.1016/S0380-1330\(93\)71251-4](https://doi.org/10.1016/S0380-1330(93)71251-4).
- [74] Odum, E.P., 1985. Trends Expected in Stressed Ecosystems. *BioSci.* 35, 419–422. doi: 10.2307/1310021.
- [75] Oke, T.R., 1976. The distinction between canopy and boundary-layer urban heat islands. *Atmosph.* 14, 268–277. <https://doi.org/10.1080/00046973.1976.9648422>.
- [76] Oksanen, J., Simpson, G.L., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O’Hara, R.B., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., Caceres, M.D., Durand, S., Evangelista, H.B.A., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M.O., Lahti, L., McGlinn, D., Ouellette, M.-H., Cunha, E.R., Smith, T., Stier, A., ter Braak, C.J.F., Weedon, J., 2022. *vegan: Community Ecology Package*.
- [77] Ontario Ministry of Natural Resources, 2015. Southern Ontario Land Resource Information System (SOLRIS) 3.0.
- [78] O’Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P., Lenters, J.D., McIntyre, P.B., Kraemer, B.M., Weyhenmeyer, G.A., Straile, D., Dong, B.o., Adrian, R., Allan, M.G., Anneville, O., Arvola, L., Austin, J., Bailey, J.L., Baron, J.S., Brookes, J.D., de Eyto, E., Dokulil, M.T., Hamilton, D.P., Havens, K., Hetherington, A.L., Higgins, S.N., Hook, S., Izmet’eva, L.R., Joehnk, K. D., Kangur, K., Kasprzak, P., Kumagai, M., Kuusisto, E., Leshkevich, G., Livingstone, D.M., MacIntyre, S., May, L., Melack, J.M., Mueller-Navarra, D.C., Naumenko, M., Noges, P., Noges, T., North, R.P., Plisnier, P.-D., Rigosi, A., Rimmer, A., Rogora, M., Rudstam, L.G., Rusak, J.A., Salmaso, N., Samal, N.R., Schindler, D.E., Schladow, S.G., Schmid, M., Schmidt, S.R., Silow, E., Soylu, M.E., Teubner, K., Verburg, P., Voutilainen, A., Watkinson, A., Williamson, C.E.,

- [87] Zhang, G., 2015. Rapid and highly variable warming of lake surface waters around the globe. *Geophys. Res. Lett.* 42 (24) <https://doi.org/10.1002/2015GL066235>.
- [88] Paerl, H.W., Huisman, J., 2008. Climate - Blooms like it hot. *Sci.* 320, 57–58. <https://doi.org/10.1126/science.1155398>.
- [89] Pastor, J., Wolter, P., 2002. Mapping and modeling forest change in a Boreal Landscape. *Proc. NASA LCLUC Science Team Meeting.* 19–21.
- [90] Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A.,
- [91] Cournapeau, D., Brucher, M., Perrot, M., Duchesnay, E., 2011. Scikit-learn: Machine Learning in Python. *J. Mach. Learn. Res.* 12, 2825–2830.
- [92] Philip, E., Rudra, R.P., Goel, P.K., Ahmed, S.I., 2022. Investigation of the long-term trends in the streamflow due to climate change and urbanization for a Great Lakes Watershed. *Atmosph.* 13, 225. <https://doi.org/10.3390/atmos13020225>.
- [93] Pick, F.R., 2016. Blooming algae: a Canadian perspective on the rise of toxic cyanobacteria. *Can. J. Fish. Aquat. Sci.* 73, 1149–1158. <https://doi.org/10.1139/cjfas-2015-0470>.
- [94] Provincial land cover, Land Information Ontario [WWW Document], 1999. Ontario GeoHub. URL <https://geohub.lio.gov.on.ca/datasets/provincial-land-cover> (accessed 6.24.22).
- [95] Rahmstorf, S., Coumou, D., 2011. Increase of extreme events in a warming world. *PNAS* 108, 17905–17909. <https://doi.org/10.1073/pnas.1101766108>.
- [96] Rao, Y.R., Murthy, C.R., 2001. Nearshore currents and turbulent exchange processes during upwelling and downwelling events in Lake Ontario. *J. Geophys Res. Oceans* 106, 2667–2678. <https://doi.org/10.1029/2000JC900149>.
- [97] Reinl, K.L., Brookes, J.D., Carey, C.C., Harris, T.D., Ibelings, B.W., Morales-Williams, A. M., De Senerpont Domis, L.N., Atkins, K.S., Isles, P.D.F., Mesman, J.P., North, R.L., Rudstam, L.G., Stelzer, J.A.A., Venkiteswaran, J.J., Yokota, K., Zhan, Q., 2021.
- [98] Cyanobacterial blooms in oligotrophic lakes: Shifting the high-nutrient paradigm. *Freshw. Biol.* 66, 1846–1859. <https://doi.org/10.1111/fwb.13791>.
- [99] Reinl, K.L., Harris, T.D., North, R.L., Almela, P., Berger, S.A., Bizic, M., Burnet, S.H.,
- [100] Grossart, H.-P., Ibelings, B.W., Jakobsson, E., Knoll, L.B., Lafrancois, B.M., McElarney, Y., Morales-Williams, A.M., Obertegger, U., Ogashawara, I., Paule- Mercado, M.C., Peierls, B.L., Rusak, J.A., Sarkar, S., Sharma, S., Trout-Haney, J.V., Urrutia-Cordero, P., Venkiteswaran, J.J., Wain, D.J., Warner, K., Weyhenmeyer, G. A., Yokota, K., 2023. Blooms also like it cold. *Limnol. Oceanogr. Lett.* 8 (4), 546–564.
- [101] Riseng, C.M., Wehrly, K.E., Wang, L.i., Rutherford, E.S., McKenna, J.E., Johnson, L.B., Mason, L.A., Castiglione, C., Hollenhorst, T.P., Sparks-Jackson, B.L., Sowa, S.P., 2018. Ecosystem classification and mapping of the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* 75 (10), 1693–1712.
- [102] Robertson, D.M., Saad, D.A., 2011. Nutrient Inputs to the Laurentian Great Lakes by Source and Watershed Estimated Using SPARROW Watershed Models. *J. Am. Water Resour. Assoc.* 47, 1011–1033.
- [103] Rowe, M.D., Anderson, E.J., Beletsky, D., Stow, C.A., Moegling, S.D., Chaffin, J.D., May, J.C., Collingsworth, P.D., Jabbari, A., Ackerman, J.D., 2019. Coastal upwelling influences hypoxia spatial patterns and Nearshore Dynamics in Lake Erie. *J. Geophys Res. Oceans* 124, 6154–6175. <https://doi.org/10.1029/2019JC015192>.
- [104] Schelske, C.L., Stoermer, E.F., Kenney, W.F., 2006. Historic low-level phosphorus enrichment in the Great Lakes inferred from biogenic silica accumulation in sediments. *Limnol. Oceanogr.* 51, 728–748. https://doi.org/10.4319/lo.2006.51.1_part_2.0728.
- [105]
- [106]

- [107] Schindler, D.W., 1977. Evolution of Phosphorus Limitation in Lakes. *Sci.* 195, 260–262. <https://doi.org/10.1126/science.195.4275.260>.
- [108] Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., Rusticucci, M., Semenov, V., Alexander, L.V., Allen, S., Benito, G., Cavazos, T., Clague, J., Conway, D., Della-Marta, P.M., Gerber, M., Gong, S., Goswami, B.N., Hemer, M., Huggel, C., van den Hurk, B., Kharin, V.V., Kitoh, A., Tank, A.M.G.K., Li, G., Mason, S., McGuire, W., van Oldenborgh, G.J., Orłowsky, B.,
- [109] Smith, S., Thiaw, W., Velegrakis, A., Yiou, P., Zhang, T., Zhou, T., Zwiers, F.W., 2012. Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B., Barros, V., Stocker, T.F., Dahe, Q., Dokken, D.J., Ebi, K.
- [110] L., Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M., Midgley, P.
- [111] M. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109–230.
- [112] Sharma, S., Jackson, D.A., Minns, C.K., Shuter, B.J., 2007. Will northern fish populations be in hot water because of climate change? *Glob. Chang. Biol.* 13, 2052–2064. <https://doi.org/10.1111/j.1365-2486.2007.01426.x>.
- [113] Shuvo, A., O'Reilly, C.M., Blagrove, K., Ewins, C., Filazzola, A., Gray, D., Mahdiyan, O., Moslenko, L., Quinlan, R., Sharma, S., 2021. Total phosphorus and climate are equally important predictors of water quality in lakes. *Aquat. Sci.* 83 <https://doi.org/10.1007/s00027-021-00776-w>.
- [114] Smith, A.L., Hewitt, N., Klenk, N., Bazely, D.R., Yan, N., Wood, S., Henriques, I., MacLellan, J.I., Lipsig-Mummé, C., 2012. Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world. *Environ. Rev.* 20, 1–16. <https://doi.org/10.1139/a11-020>.
- [115] Smith, S.D.P., McIntyre, P.B., Halpern, B.S., Cooke, R.M., Marino, A.L., Boyer, G.L., Buchsbaum, A., Burton, G.A., Campbell, L.M., Ciborowski, J.J.H., Doran, P.J., Infante, D.M., Johnson, L.B., Read, J.G., Rose, J.B., Rutherford, E.S., Steinman, A.D., Allan, J.D., 2015. Rating impacts in a multi-stressor world: a quantitative assessment of 50 stressors affecting the Great Lakes. *Ecol. Appl.* 25 (3), 717–728.
- [116] Soranno, P.A., Hubler, S.L., Carpenter, S.R., Lathrop, R.C., 1996. Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. *Ecol. Appl.* 6, 865–878. <https://doi.org/10.2307/2269490>.
- [117] Statistics Canada, 2017. *Human Activity and the Environment: Freshwater in Canada*
- [118] (No. 16-201– X).
- [119] Stefanoff, S., Vogt, R.J., Howell, T., Sharma, S., 2018. Phytoplankton and benthic algal response to ecosystem engineers and multiple stressors in the nearshore of Lake Huron. *J. Great Lakes Res.* 44, 447–457. <https://doi.org/10.1016/j.jglr.2018.02.009>.
- [120] Sterner, R.W., 2008. On the phosphorus limitation paradigm for Lakes. *Int. Rev.*
- [121] *Hydrobiol.* 93, 433–445. <https://doi.org/10.1002/iroh.200811068>.
- [122] Sterner, R.W., 2010. In situ-measured primary production in Lake Superior. *J. Great Lakes Res.* 36, 139–149. <https://doi.org/10.1016/j.jglr.2009.12.007>.
- [123] Sterner, R.W., Keeler, B., Polasky, S., Poudel, R., Rhude, K., Rogers, M., 2020. Ecosystem services of Earth's largest freshwater lakes. *Ecosyst. Serv.* 41, 101046 <https://doi.org/10.1016/j.ecoser.2019.101046>.

- [124] Stevens, R.J.J., Neilson, M.A., 1987. Response of Lake Ontario to Reductions in Phosphorus Load, 1967–82. *Can. J. Fish. Aquat. Sci.* 44, 2059–2068. <https://doi.org/10.1139/f87-255>.
- [125] Stockwell, J.D., Doubek, J.P., Adrian, R., Anneville, O., Carey, C.C., Carvalho, L., Domis, L.N.D.S., Dur, G., Frassl, M.A., Grossart, H.-P., Ibelings, B.W., Lajeunesse, M.
- [126] J., Lewandowska, A.M., Llames, M.E., Matsuzaki, S.-I.-S., Nodine, E.R., Noges, P.,
- [127] Patil, V.P., Pomati, F., Rinke, K., Rudstam, L.G., Rusak, J.A., Salmaso, N., Seltmann, C.T., Straile, D., Thackeray, S.J., Thiery, W., Urrutia-Cordero, P.,
- [128] Venail, P., Verburg, P., Woolway, R.I., Zohary, T., Andersen, M.R., Bhattacharya, R., Hejzlar, J., Janatian, N., Kpodonu, A.T.N.K., Williamson, T.J., Wilson, H.L., 2020. Storm impacts on phytoplankton community dynamics in lakes. *Glob. Chang. Biol.* 26, 2756–2784. <https://doi.org/10.1111/gcb.15033>.
- [129] Tang, Z., Engel, B.A., Pijanowski, B.C., Lim, K.J., 2005. Forecasting land use change and its environmental impact at a watershed scale. *J. Environ. Manag.* 76, 35–45. <https://doi.org/10.1016/j.jenvman.2005.01.006>.
- [130] Taranu, Z.E., Gregory-Eaves, I., 2008. Quantifying relationships among phosphorus, agriculture, and lake depth at an inter-regional scale. *Ecosyst.* 11, 715–725. <https://doi.org/10.1007/s10021-008-9153-0>.
- [131] Trebitz, A.S., Brazner, J.C., Cotter, A.M., Knuth, M.L., Morrice, J.A., Peterson, G.S., Sierszen, M.E., Thompson, J.A., Kelly, J.R., 2007. Water quality in great lakes coastal wetlands: basin-wide patterns and responses to an anthropogenic disturbance gradient. *J. Great Lakes Res.* 33, 67–85. [https://doi.org/10.3394/0380-1330\(2007\)33\[67:WQIGLC\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2007)33[67:WQIGLC]2.0.CO;2).
- [132] Trebitz, A.S., Brazner, J.C., Danz, N.P., Pearson, M.S., Peterson, G.S., Tanner, D.K., Taylor, D.L., West, C.W., Hollenhorst, T.P., 2009. Geographic, anthropogenic, and habitat influences on Great Lakes coastal wetland fish assemblages. *Can. J. Fish. Aquat. Sci.* 66, 1328–1342. <https://doi.org/10.1139/F09-089>.
- [133] Trebitz, A., Sykes, M., Barge, J., 2019. A reference inventory for aquatic fauna of the Laurentian Great Lakes. *J. Great Lakes Res.* 45, 1036–1046. <https://doi.org/10.1016/j.jglr.2019.10.004>.
- [134] Trumpickas, J., Shuter, B.J., Minns, C.K., Cyr, H., 2015. Characterizing patterns of nearshore water temperature variation in the North American Great Lakes and assessing sensitivities to climate change. *J. Great Lakes Res.* 41, 53–64. <https://doi.org/10.1016/j.jglr.2014.11.024>.
- [135] United States and Canada, 1978. Great Lakes Water Quality Agreement [WWW Document]. URL <https://www.ijc.org/en/who/mission/glwqa> (accessed 4.1.23).
- [136] United States and Canada, 1987. Great Lakes Water Quality Agreement [WWW Document]. URL <https://www.ijc.org/en/who/mission/glwqa> (accessed 4.1.23).
- [137] Vadeboncoeur, Y., McIntyre, P., Vander Zanden, M., 2011. Borders of biodiversity: life at the edge of the world's large lakes. *BioSci.* 61, 526–537. <https://doi.org/10.1525/bio.2011.61.7.7>.
- [138] Van Zuiden, T.M., Chen, M.M., Stefanoff, S., Lopez, L., Sharma, S., Leung, B., 2016.
- [139] Projected impacts of climate change on three freshwater fishes and potential novel competitive interactions. *Divers. Distrib.* 22 (5), 603–614.
- [140] Vanderploeg, H.A., Nalepa, T.F., Jude, D.J., Mills, E.L., Holeck, K.T., Liebig, J.R.,
- [141] Grigorovich, I.A., Ojaveer, H., 2002. Dispersal and emerging ecological impacts of Ponto-Caspian species in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* 59, 1209–1228. <https://doi.org/10.1139/f02-087>.
- [142] Waples, J.T., Eadie, B., Klump, J.V., Squires, M., Cotner, J., McKinley, G., 2008. The Laurentian Great Lakes, in: Report of the North American Margins Working Group for the U.S. Carbon Cycle Scientific Steering Group and Interagency Working Group. Presented at the North American Continental Margins: A Synthesis and Planning Workshop.

- [143] Watras, C.J., Heald, E., Teng, H.Y., Rubsam, J., Asplund, T., 2022. Extreme water level rise across the upper Laurentian Great Lakes region: citizen science documentation 2010–2020. *J. Great Lakes Res.* 48, 1135–1139. <https://doi.org/10.1016/j.jglr.2022.06.005>.
- [144] Watson, S.B., Ridal, J., Boyer, G.L., 2008. Taste and odour and cyanobacterial toxins: impairment, prediction, and management in the Great Lakes. *Can. J. Fish. Aquat. Sci.* 65, 1779–1796. <https://doi.org/10.1139/F08-084>.
- [145] Wickham, J., Stehman, S.V., Sorenson, D.G., Gass, L., Dewitz, J.A., 2021. Thematic accuracy assessment of the NLCD 2016 land cover for the conterminous United States. *Remote Sens. Environ.* 257, 112357 <https://doi.org/10.1016/j.rse.2021.112357>.
- [146] Wilson, K.A., Todd Howell, E., Jackson, D.A., 2006. Replacement of Zebra Mussels by Quagga Mussels in the Canadian Nearshore of Lake Ontario: the Importance of Substrate, Round Goby Abundance, and Upwelling Frequency. *J. Great Lakes Res.* 32, 11–28. [https://doi.org/10.3394/0380-1330\(2006\)32\[11:ROZMBQ\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2006)32[11:ROZMBQ]2.0.CO;2).
- [147] Wolter, P.T., Johnston, C.A., Niemi, G.J., 2006. Land Use Land Cover Change in the U.S. Great Lakes Basin 1992 to 2001. *J. Great Lakes Res.* 32, 607–628. [https://doi.org/10.3394/0380-1330\(2006\)32\[607:LULCCI\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2006)32[607:LULCCI]2.0.CO;2).
- [148] Woolway, R., Sharma, S., Smol, J., 2022. Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioSci.* doi: 10.1093/biosci/biac052.
- [149] Woolway, R.I., Kraemer, B.M., Lenters, J.D., Merchant, C.J., O'Reilly, C.M., Sharma, S., 2020. Global lake responses to climate change. *Nat. Rev. Earth & Environ.* 1, 388–403. <https://doi.org/10.1038/s43017-020-0067-5>.
- [150] Wu, T., Imrit, M.A., Movahedinia, Z., Kong, J., Woolway, R.I., Sharma, S., 2023. Climate tracking by freshwater fishes suggests that fish diversity in temperate lakes may be increasingly threatened by climate warming. *Divers. Distrib.* 29 (2), 300–315.
- [151] Yurista, P., Kelly, J., Miller, S., 2011. Lake Superior: Nearshore variability and a landscape driver concept. *Aquat. Ecosyst. Health Manag.* 14, 345–355. <https://doi.org/10.1080/14634988.2011.624942>.
- [152] Yurista, P.M., Kelly, J.R., Scharold, J.V., 2016. Great Lakes nearshore–offshore: Distinct water quality regions. *J. Great Lakes Res.* 42, 375–385. <https://doi.org/10.1016/j.jglr.2015.12.002>.
- [153] Zhong, Y., Notaro, M., Vavrus, S.J., Foster, M.J., 2016. Recent accelerated warming of the Laurentian Great Lakes: Physical drivers. *Limnol. Oceanogr.* 61, 1762–1786. <https://doi.org/10.1002/lno.10331>.
- [154] Zhong, Y., Notaro, M., Vavrus, S.J., 2019. Spatially variable warming of the Laurentian Great Lakes: an interaction of bathymetry and climate. *Clim. Dyn.* 52, 5833–5848. <https://doi.org/10.1007/s00382-018-4481-z>.

SUPPLEMENTARY TABLES

Table 1. Means, coefficients of variation, and ranges of all nearshore water quality variables grouped by lake.

Indicator	Unit	Superior			Huron			Erie			Ontario		
		Mean	CV	Range	Mean	CV	Range	Mean	CV	Range	Mean	CV	Range
Phosphorus; total	µg/L	3.28	0.64	<0.2–15.2	3.93	0.86	<0.2–95.0	12.34	0.61	<0.2–84.0	13.56	0.87	<0.2–217.8
Nitrogen; nitrate + nitrite	mg/L N	0.31	0.05	0.04–0.40	0.23	0.12	<0.005–2.58	0.25	0.17	<0.005–2.34	0.46	0.24	<0.005–2.96
Nitrogen; nitrite	mg/L N	0.003	0.00	<0.001–0.01	0.003	0.00	<0.001–0.01	0.006	0.00	<0.001–0.04	0.010	0.02	<0.001–0.22
Silicon; reactive silicate	mg/L Si	1.10	0.08	0.86–1.90	0.80	0.16	0.32–2.36	0.41	0.22	<0.02–2.56	0.46	0.25	<0.02–4.08
Solids; suspended	mg/L	1.66	0.58	<0.5–19.0	0.89	0.49	<0.5–27.9	4.66	0.85	<0.5–45.5	1.67	0.72	<0.5–34.0
Turbidity	NTU	1.05	0.50	0.10–6.46	0.71	0.32	0.09–9.02	4.81	0.96	0.25–54.60	1.37	0.59	<0.05–28.80
Secchi depth	m	6.65	0.54	1.0–18.0	8.03	0.54	1.0–27.4	2.97	0.68	0.0–9.0	5.89	0.65	0.0–20.4
Chlorophyll <i>a</i>	µg/L	0.91	0.57	<0.01–45.0	0.42	0.50	<0.01–6.0	1.86	0.82	<0.01–16.0	2.10	1.01	<0.01–32.1
Total Chlorophyll <i>a</i>	µg/L	1.66	0.39	0.49–51.00	1.27	0.41	<0.02–7.90	2.85	0.58	<0.02–22.60	3.10	0.81	<0.02–39.20
Chlorophyll <i>b</i>	µg/L	0.07	0.18	<0.01–9.5	0.05	0.12	<0.01–4.2	0.14	0.15	<0.01–0.9	0.17	0.23	<0.01–5.5
Carbon; dissolved inorganic	mg/L	10.67	0.10	8.5–16.0	16.43	0.29	2.2–38.8	22.48	0.15	2.3–47.2	22.80	0.08	18.3–33.0
Carbon; dissolved organic	mg/L	1.85	0.25	1.1–5.5	2.20	0.24	1.1–6.0	2.07	0.13	0.4–5.3	2.41	0.24	1.5–7.1
Alkalinity; total fixed endpt	mg/L CaCO ₃	44.88	0.10	33.8–66.7	69.29	0.30	12.2–145.0	92.23	0.11	70.0–172.0	96.79	0.08	79.6–149.0
pH	–	7.97	0.02	7.59–8.34	8.10	0.02	7.27–8.50	8.25	0.01	7.72–8.54	8.20	0.02	7.80–8.67
pH (CTD sonde)	–	7.92	0.05	6.68–8.54	8.60	0.10	7.11–11.79	8.37	0.06	6.43–9.58	8.24	0.06	6.70–9.54
Sulphate	mg/L S	4.02	0.35	1.6–36.7	13.92	0.21	5.7–33.8	21.09	0.18	15.5–54.4	25.08	0.58	<0.5–57.0
Strontium	µg/L	22.69	0.05	18.2–25.7	91.39	0.30	27.2–346.0	152.54	0.24	89.7–515.0	192.23	0.37	<0.01–536.0
Hardness	mg/L	46.10	0.10	36.0–66.8	83.66	0.29	16.2–208.0	113.35	0.12	84.0–240.0	122.78	0.12	90.0–214.0
Calcium	mg/L	13.69	0.10	10.5–20.6	22.81	0.27	4.4–53.5	31.51	0.13	21.8–67.1	35.03	0.11	25.3–60.1
Potassium	mg/L	0.53	0.03	0.36–0.75	0.88	0.07	<0.01–2.01	1.39	0.10	0.91–2.75	1.77	0.21	0.47–4.71
Chloride	mg/L	1.82	0.23	0.3–5.8	7.13	0.21	3.1–23.0	15.51	0.34	1.1–49.8	28.95	0.44	9.8–148.0
Conductivity	µS/cm	101.28	0.08	83–140	186.70	0.24	58–389	272.97	0.13	212–591	330.69	0.21	210–806
Specific conductivity, 25°C (CTD sonde)	µS/cm	69.48	0.20	41.40–121.37	137.94	0.27	27.65–303.51	217.64	0.20	156.00–484.86	257.36	0.34	159.40–662.97
Temperature (CTD sonde)	°C	10.79	0.02	2.35–21.17	12.75	0.02	4.02–24.36	14.32	0.02	2.64–26.86	11.28	0.02	3.42–25.02
Oxygen saturation (CTD sonde)	%	96.72	0.15	0.00–110.34	98.99	0.11	15.33–131.09	95.98	0.10	34.66–117.05	92.49	0.17	1.32–128.66
Iron	µg/L	17.99	4.02	<1.0–183	13.12	3.62	<1.0–160	58.95	4.55	<1.0–695	18.10	3.99	<1.0–397
Aluminum	µg/L	17.29	1.14	0.9–116.0	10.39	1.07	<0.01–108.0	42.09	1.35	2.7–597.0	10.70	1.52	<0.01–283.0
Barium	µg/L	9.66	0.07	8.3–13.7	13.90	0.14	9.5–24.8	20.24	0.16	14.3–35.1	24.43	0.21	<0.01–42.0
Cobalt	µg/L	0.00	0.00	<0.01–0.0	0.01	0.03	<0.01–0.2	0.02	0.05	<0.01–0.4	0.02	0.05	<0.01–0.3
Chromium	µg/L	0.10	0.19	<0.1–0.9	0.26	0.27	<0.1–2.7	0.30	0.31	<0.1–2.7	0.51	0.39	<0.1–4.8
Copper	µg/L	0.76	0.42	<0.09–3.6	0.43	0.25	<0.09–2.4	0.86	0.34	<0.09–4.7	0.98	0.30	<0.09–4.1
Manganese	µg/L	1.69	0.67	<0.1–25.2	3.16	0.87	<0.1–163.0	5.19	0.93	<0.1–166.0	15.67	1.87	<0.1–1030.0
Molybdenum	µg/L	0.01	0.03	<0.1–0.2	0.20	0.17	<0.1–0.6	0.99	0.18	<0.1–1.9	1.38	0.31	<0.1–6.4
Sodium	mg/L	1.77	0.17	1.28–10.80	4.43	0.19	2.40–13.50	9.17	0.26	4.50–26.50	17.01	0.44	5.72–82.00
Nickel	µg/L	0.01	0.06	<0.1–0.7	0.55	0.30	<0.1–6.8	0.64	0.20	<0.1–2.4	0.73	0.27	<0.1–4.4
Lead	µg/L	0.00	0.00	<0.01–0.00	0.03	0.06	<0.01–1.00	0.12	0.18	<0.01–2.15	0.07	0.13	<0.01–1.70
Titanium	µg/L	0.53	0.49	<0.06–4.3	0.43	0.28	<0.06–3.9	1.03	0.57	<0.06–21.7	0.58	0.42	<0.06–11.3
Vanadium	µg/L	0.22	0.13	<0.01–0.61	0.20	0.15	<0.01–0.98	0.36	0.14	<0.01–2.01	0.36	0.17	<0.01–1.13
Zinc	µg/L	1.04	0.57	<0.1–12.8	1.04	0.48	<0.1–3.8	1.36	0.53	<0.1–18.2	1.67	0.56	<0.1–10.7

Table 2. Means, coefficients of variation, and ranges of select nearshore water quality variables grouped by region.

Indicator	Unit	Superior North			Georgian Bay North			Georgian Bay South			Huron East			Erie West		
		Mean	CV	Range	Mean	CV	Range	Mean	CV	Range	Mean	CV	Range	Mean	CV	Range
Phosphorus: total	µg/L	3.28	0.64	<0.2–15.2	5.08	0.58	<0.2–14.0	1.91	0.83	<0.2–8.0	3.78	0.88	<0.2–95.0	14.69	0.61	3.0–54.0
Nitrogen: nitrate + nitrite	mg/L N	0.31	0.05	0.04–0.40	0.14	0.07	<0.005–0.31	0.27	0.12	0.06–2.58	0.30	0.13	<0.005–1.35	0.34	0.17	<0.005–1.48
Silicon: reactive silicate	mg/L Si	1.10	0.08	0.86–1.90	0.94	0.19	0.32–2.36	0.67	0.07	0.44–0.90	0.72	0.11	0.38–2.00	0.74	0.16	0.22–2.56
Solids: suspended	mg/L	1.66	0.58	<0.5–19.0	1.13	0.43	<0.5–27.9	0.40	0.36	<0.5–2.4	0.89	0.55	<0.5–8.0	6.81	0.69	0.8–45.5
Total Chlorophyll <i>a</i>	µg/L	1.66	0.39	0.49–51.00	1.97	0.39	0.40–7.90	0.68	0.27	<0.02–6.90	0.78	0.25	<0.02–3.00	4.08	0.57	0.50–17.00
Carbon: dissolved inorganic	mg/L	10.67	0.10	8.5–16.0	13.00	0.31	2.2–19.1	17.48	0.05	15.4–20.2	19.84	0.11	16.8–38.8	20.76	0.06	18.2–24.7
Alkalinity: total fixed endpt	mg/L CaCO ₃	44.88	0.10	33.8–66.7	54.85	0.31	12.2–80.8	73.34	0.06	63.3–80.4	83.85	0.11	65.4–145.0	85.68	0.08	70.0–107.0
pH	–	7.97	0.02	7.59–8.34	7.97	0.03	7.27–8.39	8.16	0.01	7.90–8.34	8.21	0.01	7.87–8.50	8.24	0.01	8.04–8.47
Sulphate	mg/L S	4.02	0.35	1.6–36.7	11.36	0.18	5.7–14.7	14.47	0.03	13.8–15.0	16.59	0.12	13.9–33.8	17.49	0.09	15.5–24.4
Chloride	mg/L	1.82	0.23	0.3–5.8	7.64	0.31	3.1–23.0	6.54	0.06	5.8–7.8	6.88	0.11	5.6–11.6	11.13	0.22	7.6–22.2
Indicator	Unit	Erie Central			Erie East			Ontario Open			Hamilton Harbour			Bay of Quinte		
		Mean	CV	Range	Mean	CV	Range	Mean	CV	Range	Mean	CV	Range	Mean	CV	Range
Phosphorus: total	µg/L	13.88	0.64	3.0–41.5	9.77	0.53	<0.2–84.0	9.46	0.66	<0.2–56.0	49.33	0.50	22.0–217.8	24.07	0.54	10.8–74.5
Nitrogen: nitrate + nitrite	mg/L N	0.14	0.06	0.02–0.35	0.24	0.19	<0.005–2.34	0.35	0.10	<0.005–0.84	1.85	0.20	0.69–2.96	0.07	0.06	<0.005–0.19
Silicon: reactive silicate	mg/L Si	0.29	0.15	<0.02–1.00	0.22	0.13	<0.02–1.12	0.39	0.19	<0.02–3.02	0.42	0.27	<0.02–1.42	1.61	0.27	0.52–4.08
Solids: suspended	mg/L	4.78	0.81	0.6–28.7	2.95	0.76	<0.5–41.8	1.13	0.58	<0.5–17.5	4.14	0.33	2.0–13.8	6.52	0.88	1.1–34.0
Total Chlorophyll <i>a</i>	µg/L	2.81	0.59	<0.02–22.60	1.93	0.45	<0.02–16.40	1.87	0.55	<0.02–20.90	13.01	0.96	0.75–39.20	7.51	0.91	1.10–30.20
Carbon: dissolved inorganic	mg/L	22.43	0.24	2.3–24.4	23.83	0.12	19.9–47.2	22.32	0.05	18.3–33.0	26.61	0.10	21.3–32.4	24.54	0.09	19.5–29.0
Alkalinity: total fixed end	mg/L CaCO ₃	92.86	0.07	79.0–101.0	96.94	0.12	75.6–172.0	94.69	0.05	79.6–149.0	113.09	0.11	90.1–139.0	105.11	0.09	84.6–125.0
pH	–	8.23	0.02	7.72–8.54	8.27	0.01	7.75–8.47	8.20	0.01	7.92–8.67	8.16	0.03	7.80–8.64	8.26	0.02	8.07–8.67
Sulphate	mg/L S	21.36	0.06	19.5–23.9	23.71	0.17	19.9–54.4	24.15	0.49	<0.5–30.4	46.58	0.15	32.0–57.0	7.36	0.19	5.3–10.9
Chloride	mg/L	15.77	0.05	13.9–17.1	18.75	0.36	1.1–49.8	24.38	0.21	16.0–96.0	86.84	0.33	41.0–148.0	13.70	0.13	9.8–17.9

FIGURES

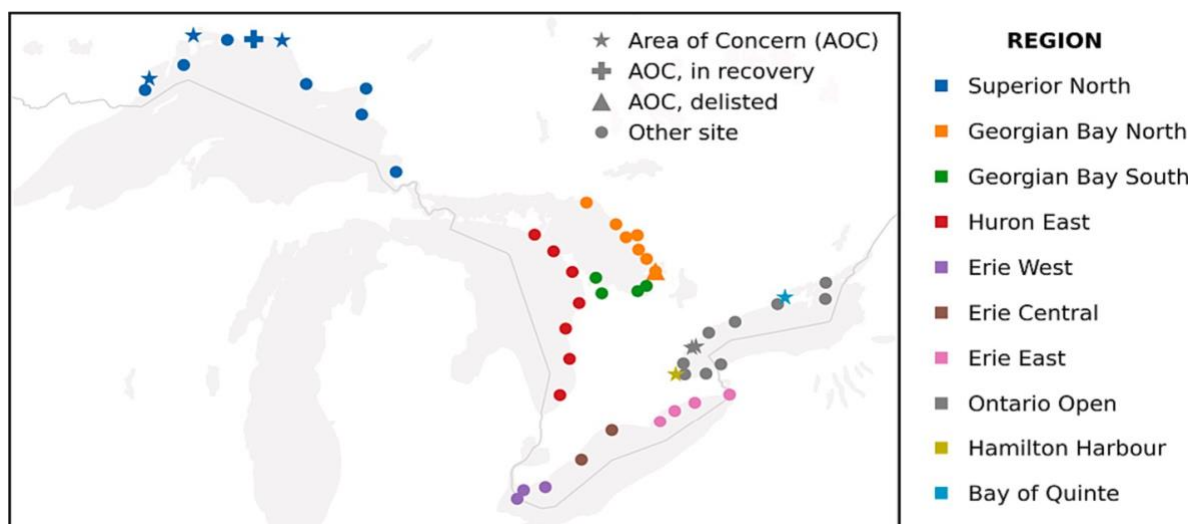


Figure 1: Locations of 52 stations across the northern nearshore of the Great Lakes. Sites are divided into regions, as indicated. Areas of Concern (AOCs) are marked with a star. The AOC in recovery (Jackfish Bay) is marked with a plus (+) and the delisted AOC (Severn Sound) is marked with a triangle.

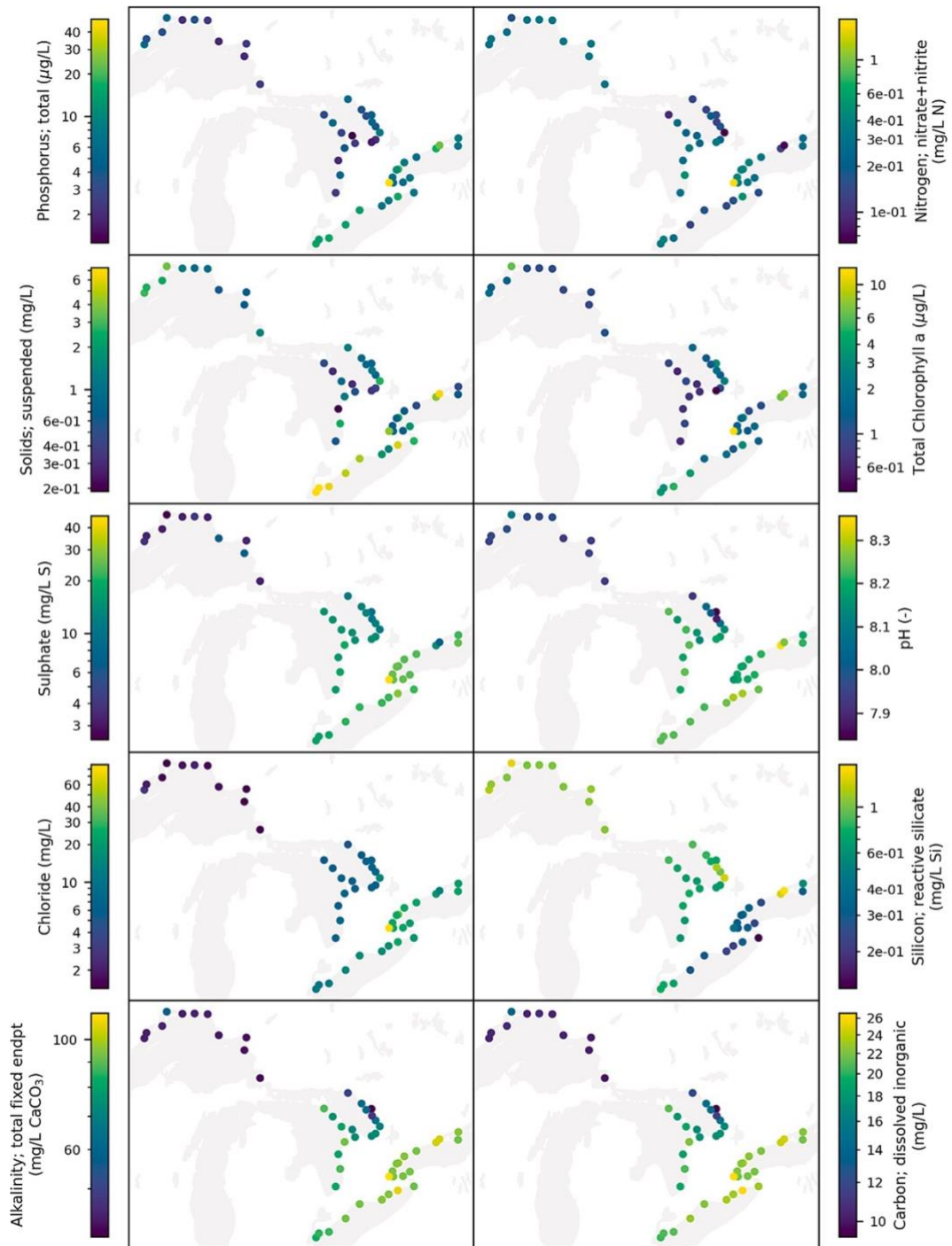


Figure 2: Means of 10 water quality variables (total phosphorus, nitrates and nitrites, suspended solids, chlorophyll *a*, sulphate, pH, chloride, silicate, alkalinity and DIC) by sampling site.

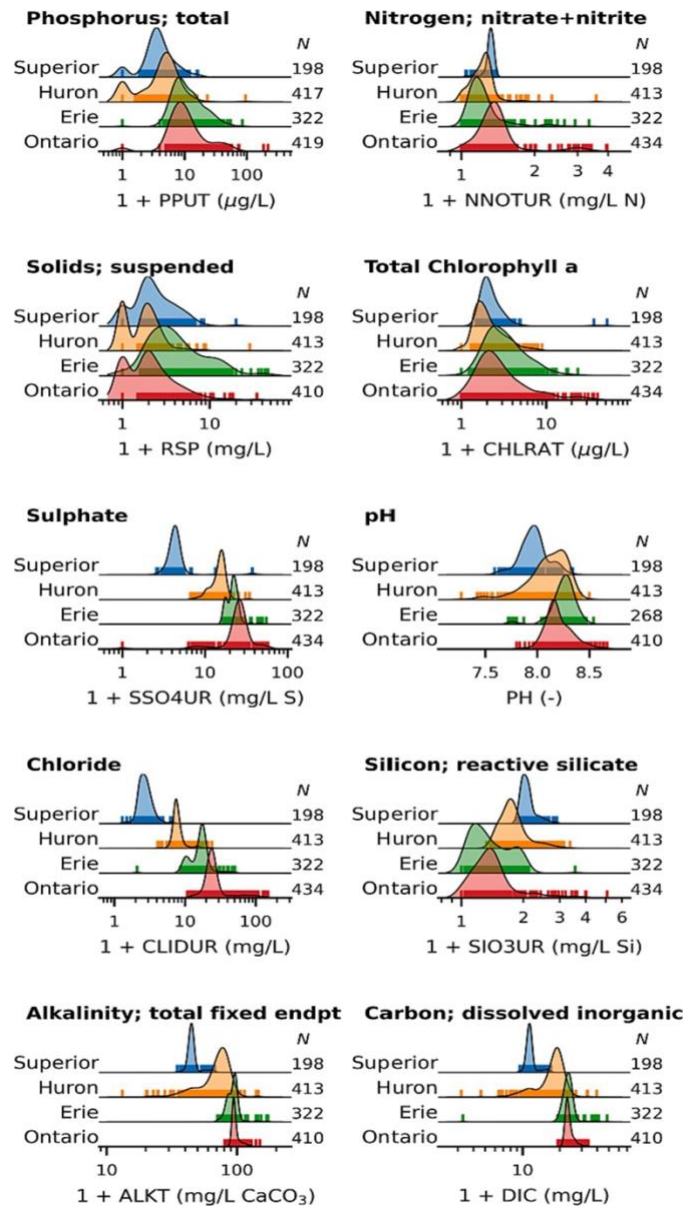


Figure 3: Ridge plot summaries of water quality conditions across the nearshore of the four Canadian Great Lakes, as represented by ten water quality indicators. The vertical strokes (rug plot) indicate measured values. The total number of samples collected from each lake is indicated in the right margin of each plot. Note that concentrations are presented on a log scale with an offset of 1 to allow for null detections (i.e., zeroes).

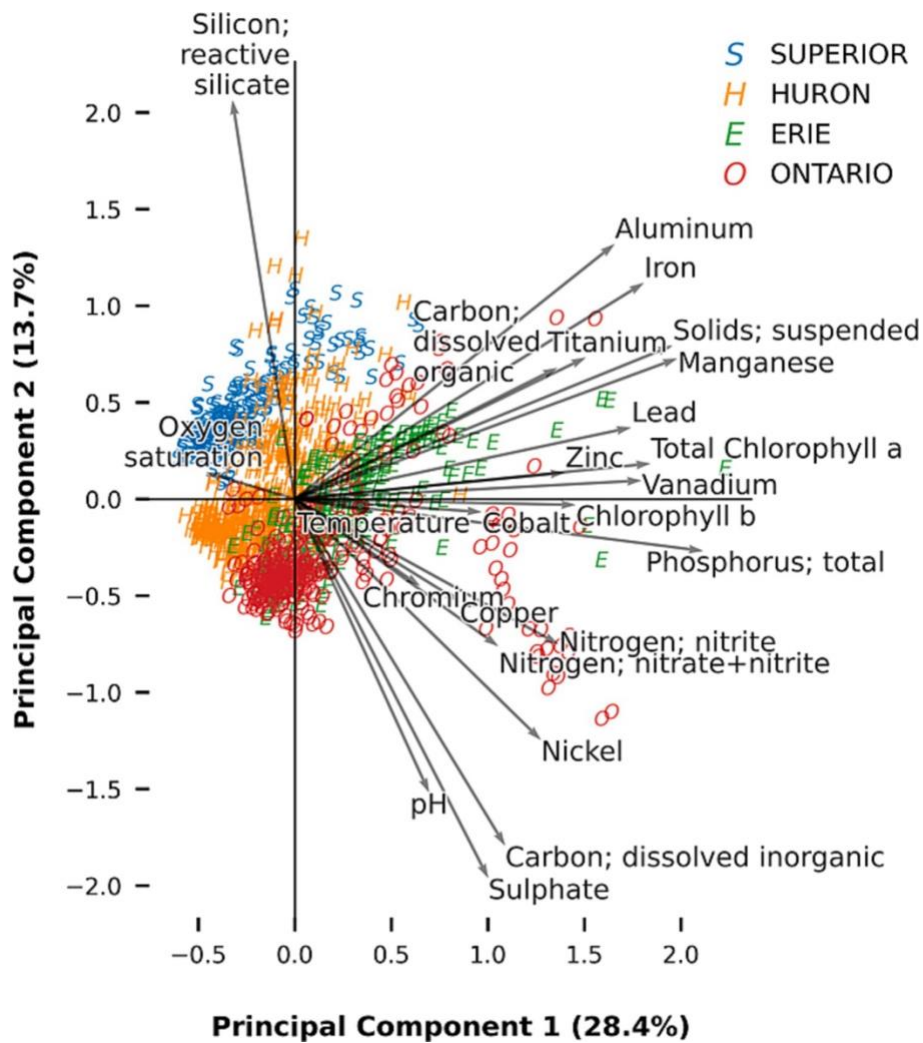


Figure 4: A Principal Component Analysis of water quality variables illustrating heterogeneity in water quality across the nearshore regions of the four Canadian Great Lakes. Generally, Principal Component Axis 1 is associated with nutrients and productivity (total phosphorus and total chlorophyll *a*), whereas Principal Component Axis 2 is dominated by silicate concentrations.

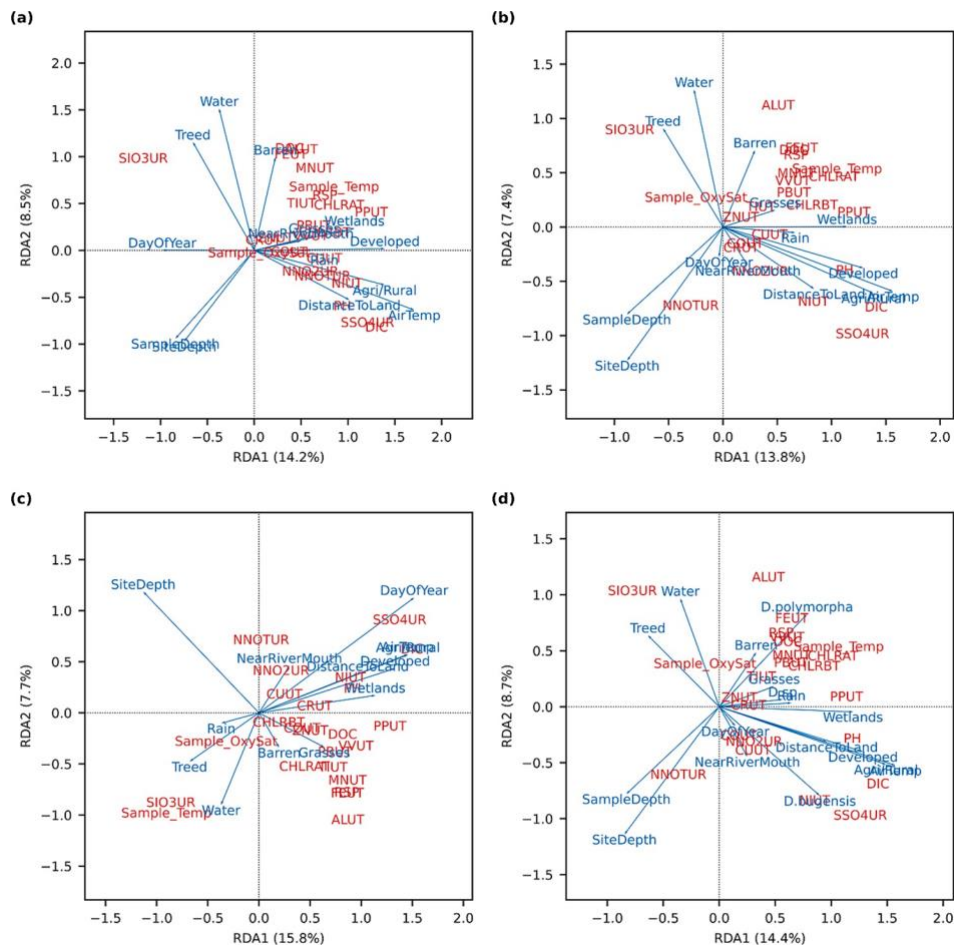


Figure 5: Redundancy analysis of water quality variables and associated drivers of weather, landcover, and sampling site characteristics in (a) spring, adjusted $R^2 = 32.1\%$, first 5 canonical axes (CA) are significant ($p < 0.05$); (b) summer, adjusted $R^2 = 32.3\%$, first 6 CA are significant (c) fall, adjusted $R^2 = 31.8\%$, first 6 CA are significant; (d) summer for reduced number of samples (based on the availability of invertebrate samples) and dreissenid abundance data, adjusted $R^2 = 33.2\%$, first 6 CA are significant. Environmental variables include depth of site (Site-Depth), sampling depth (SampleDepth), distance from the site to the nearest shoreline (i.e., distance to island or mainland; DistanceToLand), area of watershed by land cover type (Water, Treed, Grasses, Barren, Wetlands, Developed (i.e., urban, roads, etc.), Agri/Rural (i.e., agricultural and other rural)), seasonal air temperature (AirTemp), seasonal precipitation (Rain), and whether site was near a river mouth (NearRiverMouth). For summer sites with benthic invertebrate data, three species counts of *Dreissena* are summed together (*D. polymorpha*, zebra mussels; *D. bugensis*, quagga mussels; *D. sp*, unknown

species). Water sample parameters include total phosphorus (PPUT), nitrate + nitrite (NNOTUR), nitrite (NNO2UR), reactive silicate (SIO3UR), suspended solids (RSP), total chlorophyll a (CHLRAT), chlorophyll b (CHLRBT), dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), pH (PH), sulphate (SSO4UR), temperature at sample depth (SampleTemp), oxygen saturation at sample depth (SampleOxySat), cobalt (COUT), chromium (CRUT), copper (CUUT), manganese (MNUT), nickel (NIUT), titanium (TIUT), vanadium (VVUT), and zinc (ZNUT).

CHAPTER 2:

A synthesis of the state of fast fashion and environmental research in the top garment-producing countries China, Bangladesh, Vietnam, India, Turkey and Indonesia

Keywords: fast fashion, water quality, garment production, garment manufacturing, barriers, sustainability

MY CONTRIBUTION

Project conceptualised by Kerrice Bailey, Aman Basu, and Sapna Sharma. Data collected by Kerrice Bailey. Methods finalised by Kerrice Bailey, Aman Basu, and Sapna Sharma. Statistical analyses in R studio by Kerrice Bailey. Original draft written by Kerrice Bailey. Revisions from Sapna Sharma.

ABSTRACT

The growth of the fast fashion industry has accelerated over the last 5 decades, leading to serious environmental repercussions. This industry has placed immense pressure on water resources, impacting both water quantity and quality. Furthermore, the fashion industry has been credited with generating 20% of global wastewater and 8% of global greenhouse gas emissions. In this systematic review, we identify China, Bangladesh, Vietnam, Turkey, India, and Indonesia as top garment-producing countries. We aim to answer the following research questions: 1) What are the predominant environmental impacts and research areas in each of the top garment-producing countries as a result of fast fashion?; 2) What are the knowledge gaps hindering improved environmental practices?; and 3) What are the primary barriers to implementing sustainable garment production in the top garment-producing countries? In our systematic review, we identified 2318 studies, of which 68 studies were relevant to our research questions. We identified policy, sustainability and wastewater as key research areas across all the top garment-producing countries. We believe that a lack of empirical research methods and consumer knowledge on the environmental impacts of fast fashion are key knowledge gaps hindering improved environmental practices. We recognised that there are complex relationships affecting the interactions of barriers and are heterogeneous in the way they impact each garment-producing country. We offer potential solutions, such as investments in education and infrastructure to aid in the progression towards a more sustainable garment-producing industry.

1 INTRODUCTION

The garment industry is a fast-growing, lucrative industry, with widespread consequences for environmental health. Increases in garment production, fuelled by what is referred to as fast fashion, poses major environmental challenges, including generating 8% of global carbon emissions [1]. The fast fashion industry is the second-most polluting industry globally, notorious for its tremendous water usage and degradation of water quality, generating 20% of global wastewater [2]. Fibre production fuels the garment industry. Global fibre production grew from 8.3 to 14.6 kilograms per person from 1975 to 2022, and the total fibre production is projected to grow to 147 million tonnes by 2030 [3]. China, Bangladesh, Vietnam, Turkey, India, and Indonesia are among the top 10 exporters of clothing, according to the 2023 World Trade Statistical Review [4]. There are over 400 000 garment factories in Indonesia, 4400 in Vietnam, and up to 59 000 in Turkey (Figure 1). In 2022, China alone made up 31.7% of all global clothing exports, valued at \$182 billion USD [(Figure 2), 4]. The top importers are from the European Union, China, the United States of America, Japan, the United Kingdom, and Canada [4].

1.1 Globalisation and the fashion industry

Increases in garment production are driven by globalisation and the fast fashion model, which encourages a cycle of buying and replacing clothing over a short period of time. Due to globalisation, goods are increasingly produced in one country and then shipped to another, even around the globe. Much of the clothing worn in Canada and the United States has been fashioned in Asia. For example, Moazzem et al. [3] demonstrated how shirts and jackets that have been produced in garment-producing countries, such as: China, Bangladesh, Vietnam, Indonesia, India and Cambodia (from greatest to least contribution), are transported for distribution in Australia. However, these items were sometimes transported back overseas to Asia for re-use. In addition, popular brands, including Zara, H&M, and Gap, have historically outsourced production to low to middle income countries, avoiding strict environmental regulations [5]. These companies capitalise on decreased production costs tied to lower worker wages and cheaply made clothing [6]. In low to middle income countries, garment industry workers can earn less in a month than a worker in the United States would make in a single

day [7]. This globalisation pathway allows consumer countries to offload the environmental consequences of production to the countries in which garments are manufactured [8].

1.2 Scarcity and demands on water

The clothing industry has widespread environmental repercussions in countries that cultivate, process, and manufacture clothing to be exported. Fibre production requires copious amounts of energy, water, fertilisers, and pesticides, along with the use of additional chemicals during the production of synthetic fibres and textile finishing [9]. For example, cotton consumption alone requires 256 Gm³ of water annually, which primarily consists of blue water (fresh surface water and groundwater) [10]. This is concerning as global freshwater demands are increasing, yet freshwater insecurity is rising with scarcer and more polluted freshwater resources [11-14]. In 2021, 2.3 billion people were living in countries experiencing water stress and lacked sufficient access to clean water [15]. In fact, a 1% increase in global water demand has been observed annually over the last 40 years [16]. The global demand for water is expected to continue to increase over the next 20 years, especially with development along transboundary rivers; for example, China exacerbating water related issues in countries such as Bangladesh and India [17]. With these demands on water resources, it is important to monitor how textile production impacts both water quantity and quality.

1.3 Impacts on water quality and the environment

There are many impacts on water quality associated with the garment and textile industries as water is essential for textile wet processing. Textile manufacturing has been linked to water alkalization, a result of sodium hydroxide use in the dyeing processes of viscose [18]. Textile manufacturing has also been linked to water eutrophication and scarcity in the production of both virgin and recycled polyester fabrics [19]. The highest levels of carbon emissions and water consumption are associated with denim and cotton fibre production [20]. In some cases, countries, such as Bangladesh, China and India, will import cotton including in the form of cotton yarn and woven cotton [21]. While fast fashion aims to replace traditional processes with faster production and manufacturing, this often leads to processes that are even more energy and water intensive. Mahiat et

al. [22] found that hand looming for knitting processes was more efficient than power looming. In fact, hand looming reduces global warming and energy potential by a factor of 4. However, the power loom industry performs better than the handloom industry socially, being associated with better ‘salary and work time’ and ‘health and safety’, although the heavy metal chromium VI is often used in dyeing processes. In Indonesia, the Citarum River, a staple community water source, receives 349 000 tons of liquid waste including chromium VI [23]. Chromium is highly toxic, leading to an array of diseases in humans.

1.4 Research Questions

Sustainable fashion consumption is well studied in the literature [24], in addition to corporate social responsibility [25], and attitudes towards Ecological Purchase Intention [26,27]. Yet, to our knowledge, a complete synthesis of the impacts of fast fashion on the environment in the top garment-producing countries: China, Bangladesh, Vietnam, Turkey, India, and Indonesia has yet to be realised. Using a systematic review approach, we focus on the top garment producing countries and ask the following **research questions**: 1) What are the predominant environmental impacts and research areas in each top garment-producing country as a result of fast fashion?; 2) What are the knowledge gaps hindering improved environmental practices?; and 3) What are the primary barriers to implementing sustainable garment production in the top garment-producing countries?

2 MATERIALS AND METHODS

2.1 PRISMA Method

This research was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method as reference. The PRISMA method consists of a list of 27 items to facilitate a systematic review that is transparent and bias-free [28]. The key steps for this approach are: 1) identification of research papers, 2) screening of those studies, and 3) inclusion of relevant studies, followed by a meta-analysis (Figure 3). We systematically screened all literature using

specific inclusion criteria, first based on the title and abstract and second with a full text checklist full text review.

2.2 Country Selection

Previously, we reviewed the state of fast fashion and its effects on the environment [29]. We identified China as a main contributor of water quality related research, focusing on topics such as: sustainability, water, textile industry, water footprint textile, water assessment and dyeing. Similarly, we identified India as contributing to fast fashion. Based on the results of our former study, and the countries often cited as top garment producers and exporters, we selected China, Bangladesh, Vietnam, Turkey, India, and Indonesia for the scope of this study [29-31]. China, India and Turkey also ranked 1st, 2nd and 7th in top countries producing cotton in 2021-2022 [32].

2.3 Literature Search

We identified relevant literature to be screened using the multidisciplinary databases *Web of Science* [33] and *Scopus* [34]. The following search command was used to identify the primary dataset:

(TS) = (Garment OR apparel OR ready to wear OR ready-made garments OR clothing OR fast-fashion OR fast fashion) AND TS = (Chin* OR India* OR Bangladesh OR Bengali OR Turk* OR Vietnam* OR Indonesia*) AND TS = (environmen* OR climate OR sustainab*).

The final search was conducted on **October 18th, 2023**, resulting in a total of 2389 results, with 1414 results from *Web of Science* [33] and 975 results from *Scopus* [34]. The article information for the results were downloaded and loaded into Rayyan [35], which we used to identify and resolve 150 duplicates. This left 2318 sources to be screened.

2.4 Screening

The titles and abstracts of the resulting 2318 articles were screened using the inclusion and exclusion criteria. The aim was to obtain all sources capturing the themes of sustainability in fashion or the impacts of the garment industry on the environment in the top garment-producing countries. Articles were included if they were related to fast fashion, the garment industry, ready-wear garments, one or more of the identified top garment-producing countries, and if they were also related to the environment, sustainability, climate, water quality, and/or land use changes in some capacity. Articles were excluded if they primarily focused on economics (e.g. sustainable marketing), supply chain management (e.g. supplier evaluations), and/or purchasing behaviours (e.g. the effect of COVID-19, the effect of store atmosphere on purchases) with little environmental component or were outside the countries identified as top garment producers. A total of 68 articles were subjected to full text content analysis. For the 68 articles, we recorded the occurrence of: country, key terminologies, key themes, methods, water types covered, footprints studied (water or carbon), and types of barriers to sustainability. Terminology was recorded as present if there was at least one mention. Key themes were recorded if there were at least two sentences describing the theme.

2.5 Visualisation Packages

R studio (Version 2024.04.2+764) was then used for the heatmaps of the key terminologies and key themes. We used tidyverse for data visualisation [36]. We also used the package scales for visualisation [37].

3 RESULTS

Of the 2389 items retrieved from Web of Science and Scopus, 210 passed the title and abstract screening, and 68 passed full text screening. We included this 68 for full content analysis (Figure 3). The included articles were published between March 2008 and October 2023. Bangladesh and China produced the most articles with 26 and 23 articles, respectively; this was followed by India (10), Vietnam (6), Turkey (5), and Indonesia (1). There was 1 publication mentioning China and India, 1 mentioning China and Turkey, and 1 mentioning Bangladesh, Vietnam and India.

In terms of the primary terminology used, ‘textile industry’ was the most prevalent, mentioned in 51 publications followed by ‘garment industry’ (24), ‘RMG’ (ready-made garment) or ‘ready-to-wear’ (22), ‘fast fashion’ (11) and ‘fashion industry’ (7) (Figure 5). The key themes based on the number of articles mentioned in the publications are as follows: policy (40), sustainability (39), wastewater (37), air pollution (19), wastewater effluents (17), ‘green’ (17), waste management (13) and sustainable/ sustainability management (12) (Figure 6). The other themes were less explored with each represented the following number of times: barriers (10), sustainable development goals (9), and corporate social responsibility (8) (Figure 6).

The primary research methods fell into the categories of case studies (including interviews, surveys, or questionnaires), followed closely by literature reviews and others (including multiregional input output modelling, carbon footprint calculation, and environmental process methodology). In relation to water, water footprint was mentioned in 11 studies in comparison to the 5 studies that examined carbon footprint. Many studies also mentioned an environmental footprint. The grey, blue, and ground water types were equally mentioned across publications with 4 publications referencing each. Of the publications that mentioned barriers to sustainability and/or textile research, 22 mentioned infrastructure or technological barriers, 20 mentioned knowledge or information shortage as a barrier, 12 mentioned policy or regulation and 11 mentioned resource/lack of incentive or some other economic factor (Figure 6).

4 DISCUSSION

Our study comprehensively and systematically assessed the current state of research on environmental impacts of fast fashion in the top garment-producing countries. Though limited to studies published in English, our dataset covered 15 years of literature published in English between March 2008 and October 2023. We identified the key terminologies, themes, research methods, and barriers to more sustainable fashion. Our results indicate that the use of the term “fast fashion” is still fairly new as our dataset includes the years from March 2008 to October 2023. However, our previous study indicated that the terminology is on the rise [29]. Textile industry is the most prominently used term amongst researchers. We identified the key themes in the current literature as policy, wastewater,

and sustainability, all of which are insightful for the impacts of this growing area of research. Based on our findings, we recommend the implementation of training programs for factory managers and employees. These should run in conjunction with programs dedicated to increasing public knowledge on the environmental impacts of the garment industry. We believe that this will help to close the existing knowledge gaps surrounding fast fashion. These changes will ultimately work to remove some of the existing barriers, such as lack of infrastructure or knowledge shortage. All in all, these changes will contribute to a more sustainable garment production in the top garment-producing countries.

4.1 What are the predominant environmental impacts and research areas in each top garment-producing country as a result of fast fashion?

4.1.1 Fast fashion and key terminology

The term ‘fast fashion’ was originally coined and used by the New York Times in the 1990s; particularly referencing Zara’s goal to reduce design to retail time to only 15 days [38]. We were interested in the use of the term fast fashion, because tracking changes in language over time provides a more accurate description of the current state of the industry. Of the 68 studies included, 12 specifically used the term fast fashion though at varying frequencies throughout the texts [22,29,39-48]. However, there is heterogeneity in the terminology being used to refer to the fashion industry. We found that the most common terminology was ‘textile industry’ followed by ‘garment industry.’ Though conveying the same idea as fast fashion, iterations of ‘ready-to-wear’ or ‘ready-made garments’ were more popular than the usage of the term fast fashion. In fact, fast fashion placed second last to the term ‘fashion industry’. Outside the common terminology, countries also have their own terminology for waste or ideologies around the topic. ‘Jhut’ is one term used to describe waste fabric products in Bangladesh [38]. Garment industry is the terminology used most often to refer to the production of clothing, however, ‘ready-made’ or ‘ready-wear’ is most often used to specify concepts surrounding fast fashion.

4.1.2 Heterogeneity in research interests

We observed some differences in the research interests related to each country. However, the primary themes covered across all the studies were policy, wastewater, and sustainability. The studies in Bangladesh were primarily focused on policy (20), sustainability (17) and wastewater (11). We found Bangladesh to be the leader of garment related research published in journals, closely followed by China (Figure 4). China is a major producer of garments and a key player in textile and garment-related research as we previously identified [29]. Yet previous research consistently shows that China faces water scarcity. With researchers increasingly publishing and citing papers on urban water scarcity from 2002 to 2022 [46]. This scarcity has been associated with the distribution of water resources, rapid industrialization, and economic development, along with poor water resource management [49]. Thus, it is important to note that China is actively researching its water scarcity and the impacts of the textile and garment industry. It is particularly concerning that Indonesia was only represented twice in this study though the country plays a large role in clothing manufacturing globally [23,45]. Yet Indonesia has the highest number of garment factories per capita (per 100 000) people (Figure 1). This implies that there is a gap between the amount of research in comparison to the cumulative environmental impacts on water quality.

4.2 What are the knowledge gaps hindering improved environmental practices?

4.2.1 Research methods impacting knowledge gaps

Notably, we found limited research on wastewater sampling in this developing field of research, highlighting a key knowledge gap for this polluting and water-intensive industry. In fact, the majority of the existing research was found to be in the form of literature or systematic reviews. We recorded 11 articles in which water footprint was addressed and 5 in which carbon footprint was addressed. However, this only accounts for 16% and 7% of the literature, highlighting a key research gap in relation to the impacts of fast fashion.

4.2.2 Consumer knowledge contributes to research gaps

Though the focus of this study was not the purchase intention or preferences of customers, we noticed the lack of integration of consumer knowledge in the evaluated studies. For example, customers have the most influence in affecting environmental adaptations and company managers have the most influence over implementation of more sustainable garment production according to Nguyen et al. [50]. Similarly, Wang and Yang [51] found that green managerial innovation was the most important factor influencing implementation of greener practices in China's garment manufacturing industry. Thus, garment factory-managers will not make changes towards more sustainable production until consumers request it. However, many consumers will go unaware that they have the power to contribute to more sustainable garment production by voicing concern. This lack of consumer knowledge on garment related environmental issues results in a cyclic conundrum.

4.3 What are the primary barriers to implementing sustainable garment production in the top garment-producing countries?

4.3.1 Barriers are heterogeneous in the way they impact each country

Similar barriers to sustainability in fashion are experienced across the six countries of this study. The barriers are often intersecting, displaying cause and effect, and working as a feedback loop. Ponnambalam et al. [41] identified 30 barriers to sustainable garment production which were divided into 17 cause barriers and 13 effect barriers displaying the causal relationship between barriers. For example, poor knowledge of recycled products can lead to low desire for them and further reduce the likelihood that manufacturers or firms will make the effort to produce them. Similarly, Tumpa et al. [52] compiled a list of 15 barriers to green supply chain management in Bangladesh and used hierarchical cluster analysis to identify 6 different barrier clusters. Based on their analysis, the demand for green textiles is low owing to low consumer awareness as consumers tend to prioritise the cost and the longevity of the product over any green attributes. And as a result, we also noticed a low research interest in green related topics in this field of research (Figure 6).

4.3.2 Key barriers

Barriers can generally be summarised into the following groups: infrastructure and technology, knowledge/information shortage, policy, and lack of incentive and other economic factors. We found that the most common barrier to more sustainable practices within the textile and garment industry based on our dataset was a lack of infrastructure and technology. In some cases, the introduction of new infrastructure and technology can be extremely costly, sometimes requiring regular production to be halted for weeks at a time. We identified knowledge/information shortage as another common barrier impeding more sustainable garment manufacturing. Multiple knowledge-based barriers may play a role including lack of knowledge on sustainable manufacturing adoption, education and training system, circular economy awareness, theoretical knowledge, and technical knowhow [53]. In general, matters concerning policy can be extremely complicated. For example, there are many stakeholders in the textile and garment industry who influence decisions. In Vietnam, the Ministry of Industry and Trade (MOIT) and Ministry of Natural Resources and Environment (MONRE) are the predominant national stakeholders at the national level of the policy network, but other stakeholders also exist at the local level [50]. Thus, although we found that policy is a key research area, we acknowledge that there are many obstacles to implementing regulations for more sustainable clothing production at various levels of government.

5 CONCLUSION

The water intensive garment manufacturing process occurs prior to consumers receiving their clothing items. Thus, we believe it is important to identify the major environmental impacts and the barriers to more sustainable clothing production. We aim to contribute to the scientific and peer reviewed literature raising awareness to this growing and increasingly important issue. Based on our study, most of the research on the top garment-producing countries are focused on Bangladesh and China. We identified the key research themes including policy, sustainability, and wastewater. We recognised research methods and consumer knowledge on environmental impacts of fast fashion as key knowledge gaps hindering more sustainable garment production. Though there are complex relationships at play, we found infrastructure and knowledge gaps as key barriers faced when

attempting to move from a fast fashion model to a more sustainable and slow fashion approach. We recommend the funding and implementation of training programs for factory workers and management along with other incentives to encourage this often-costly transition. These investments will hopefully help to reduce and narrow the existing knowledge gaps for both manufacturers and consumers.

ACKNOWLEDGEMENTS

The authors would like to thank members of the Sharma lab primarily Aman, Arnab, Faith, Phoenix, and Josh. Additional thanks to my committee members Adeyemi Olusola and Carol Bucking, and supervisor, Sapna Sharma.

REFERENCES

- [1] “UN Alliance For Sustainable Fashion addresses damage of ‘fast fashion.’” Accessed: Aug. 24, 2024. [Online]. Available: <https://www.unep.org/news-and-stories/press-release/un-alliance-sustainable-fashion-addresses-damage-fast-fashion>
- [2] “UN launches drive to highlight environmental cost of staying fashionable | UN News.” Accessed: Aug. 24, 2024. [Online]. Available: <https://news.un.org/en/story/2019/03/1035161>
- [3] S. Moazzem, E. Crossin, F. Daver, and L. Wang, “Assessing environmental impact reduction opportunities through life cycle assessment of apparel products,” *Sustain. Prod. Consum.*, vol. 28, pp. 663–674, Oct. 2021, doi: 10.1016/j.spc.2021.06.015.
- [4] “World Trade Statistical Review 2023”.
- [5] N. Tokatli, “Global sourcing: insights from the global clothing industry—the case of Zara, a fast fashion retailer,” *J. Econ. Geogr.*, vol. 8, no. 1, pp. 21–38, Jan. 2008, doi: 10.1093/jeg/lbm035.
- [6] R. Bick, E. Halsey, and C. C. Ekenga, “The global environmental injustice of fast fashion,” *Environ. Health*, vol. 17, no. 1, p. 92, Dec. 2018, doi: 10.1186/s12940-018-0433-7.
- [7] “Effects of Economic Globalization.” Accessed: May 03, 2024. [Online]. Available: <https://education.nationalgeographic.org/resource/effects-economic-globalization>
- [8] K. Niinimäki, G. Peters, H. Dahlbo, P. Perry, T. Rissanen, and A. Gwilt, “The environmental price of fast fashion,” *Nat. Rev. Earth Environ.*, vol. 1, no. 4, pp. 189–200, Apr. 2020, doi: 10.1038/s43017-020-0039-9.
- [9] M. D. Stanescu, “State of the art of post-consumer textile waste upcycling to reach the zero waste milestone,” *Environ. Sci. Pollut. Res.*, vol. 28, no. 12, pp. 14253–14270, Mar. 2021, doi: 10.1007/s11356-021-12416-9.
- [10] A. K. Chapagain, A. Y. Hoekstra, H. H. G. Savenije, and R. Gautam, “The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries,” *Ecol. Econ.*, vol. 60, no. 1, pp. 186–203, Nov. 2006, doi: 10.1016/j.ecolecon.2005.11.027.
- [11] M. Kummu *et al.*, “The world’s road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability,” *Sci. Rep.*, vol. 6, no. 1, p. 38495, Dec. 2016, doi: 10.1038/srep38495.
- [12] S. N. Gosling and N. W. Arnell, “A global assessment of the impact of climate change on water scarcity,” *Clim. Change*, vol. 134, no. 3, pp. 371–385, Feb. 2016, doi: 10.1007/s10584-013-0853-x.
- [13] Y. Wada, L. P. H. van Beek, D. Viviroli, H. H. Dürr, R. Weingartner, and M. F. P. Bierkens, “Global monthly water stress: 2. Water demand and severity of water stress,” *Water Resour. Res.*, vol. 47, no. 7, 2011, doi: 10.1029/2010WR009792.
- [14] M. Wang *et al.*, “A triple increase in global river basins with water scarcity due to future pollution,” *Nat. Commun.*, vol. 15, no. 1, p. 880, Feb. 2024, doi: 10.1038/s41467-024-44947-3.
- [15] “Summary Progress Update 2021: SDG 6 — water and sanitation for all,” UN-Water. Accessed: Aug. 25, 2024. [Online]. Available: <https://www.unwater.org/publications/summary-progress-update-2021-sdg-6-water-and-sanitation-all>
- [16] “384655eng.pdf.” Accessed: Aug. 25, 2024. [Online]. Available: https://unesdoc.unesco.org/in/documentViewer.xhtml?v=2.1.196&id=p::usmarcdef_0000384655&file=/in/rest/annotationSVC/DownloadWatermarkedAttachment/attach_import_23cb4b75-369e-4074-ba2f-1fc01354338b%3F_%3D384655eng.pdf&updateUrl=updateUrl5092&ark=/ark:/48223/pf0000384655/PDF/384655eng.pdf.multi&fullScreen=true&locale=en#WWDR%202023%20EN%20report%20v01.indd%3A.411487%3A4562

- [17] "NIC_2021-02489_Future_of_Water_18nov21_UNSOURCED.pdf." Accessed: May 03, 2024. [Online]. Available: https://www.dni.gov/files/images/globalTrends/GT2040/NIC_2021-02489_Future_of_Water_18nov21_UNSOURCED.pdf
- [18] F. Chen, Y. Shen, S. Liu, Y. Yang, and L. Wang, "WATER FOOTPRINT OF TEXTILE INDUSTRY: A CASE STUDY OF CHINA," *Environ. Eng. Manag. J.*, vol. 20, no. 2, pp. 237–245, 2021, doi: 10.30638/eemj.2021.024.
- [19] W. Qian, X. Ji, P. Xu, and L. Wang, "Carbon footprint and water footprint assessment of virgin and recycled polyester textiles," *Text. Res. J.*, vol. 91, no. 21–22, pp. 2468–2475, Nov. 2021, doi: 10.1177/00405175211006213.
- [20] M. Zhao *et al.*, "Virtual carbon and water flows embodied in global fashion trade - a case study of denim products," *J. Clean. Prod.*, vol. 303, p. 127080, Jun. 2021, doi: 10.1016/j.jclepro.2021.127080.
- [21] L. Hossain and M. S. Khan, "Water footprint management for sustainable growth in the bangladesh apparel sector," *Water Switz.*, vol. 12, no. 10, 2020, doi: 10.3390/w12102760.
- [22] T. Mahiat *et al.*, "Modeling the environmental and social impacts of the handloom industry in Bangladesh through life cycle assessment," *Model. Earth Syst. Environ.*, vol. 9, no. 1, pp. 239–252, 2023, doi: 10.1007/s40808-022-01491-7.
- [23] F. Baehaki, R. B. Rudibyani, S. R. N. Aeni, R. Perdana, and S. N. Aqmarina, "Utilization of Salacca zalacca seeds as chromium(vi) adsorbents," *Periód. Tchê Quím.*, vol. 17, no. 34, pp. 200–212, Mar. 2020, doi: 10.52571/PTQ.v17.n34.2020.217_P34_pgs_200_212.pdf.
- [24] C. S. Dabas and C. Whang, "A systematic review of drivers of sustainable fashion consumption: 25 years of research evolution," *J. Glob. Fash. Mark.*, vol. 13, no. 2, pp. 151–167, Apr. 2022, doi: 10.1080/20932685.2021.2016063.
- [25] M. Z. Haque and F. Azmat, "Corporate social responsibility, economic globalization and developing countries: A case study of the ready made garments industry in Bangladesh," *Sustain. Account. Manag. Policy J.*, vol. 6, no. 2, pp. 166–189, 2015, doi: 10.1108/SAMPJ-04-2014-0028.
- [26] N. Kim and K. Lee, "Environmental Consciousness, Purchase Intention, and Actual Purchase Behavior of Eco-Friendly Products: The Moderating Impact of Situational Context," *Int. J. Environ. Res. Public. Health*, vol. 20, no. 7, p. 5312, Mar. 2023, doi: 10.3390/ijerph20075312.
- [27] G. Sandhya and S. K. Mahapatra, "Thematic Analysis to Assess Indian Consumers Purchase Intention for Organic Apparel," *Qual. Rep.*, vol. 23, no. 8, pp. 1962–1982, Aug. 2018, Accessed: Apr. 03, 2024. [Online]. Available: <https://www.proquest.com/docview/2231810234/abstract/51E1D34A498B4570PQ/1>
- [28] M. J. Page *et al.*, "PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews," *The BMJ*, vol. 372, p. n160, Mar. 2021, doi: 10.1136/bmj.n160.
- [29] K. Bailey, A. Basu, and S. Sharma, "The Environmental Impacts of Fast Fashion on Water Quality: A Systematic Review," *Water*, vol. 14, no. 7, p. 1073, Mar. 2022, doi: 10.3390/w14071073.
- [30] G. Peters, M. Li, and M. Lenzen, "The need to decelerate fast fashion in a hot climate - A global sustainability perspective on the garment industry," *J. Clean. Prod.*, vol. 295, p. 126390, May 2021, doi: 10.1016/j.jclepro.2021.126390.
- [31] A. G. R. Ananthashankar, "Production, Characterization and Treatment of Textile Effluents: A Critical Review," *J. Chem. Eng. Process Technol.*, vol. 05, no. 01, 2013, doi: 10.4172/2157-7048.1000182.
- [32] "From fields to fabric: the leading cotton producing countries around the world," Development Aid. Accessed: Aug. 26, 2024. [Online]. Available: <https://www.developmentaid.org/news->

- stream/post/168472/top-cotton-producing-countries-in-the-world
- [33] “Web of Science platform,” Clarivate. Accessed: May 03, 2024. [Online]. Available: <https://clarivate.com/products/scientific-and-academic-research/research-discovery-and-workflow-solutions/webofscience-platform/>
 - [34] “Scopus - Search for an author profile.” Accessed: May 03, 2024. [Online]. Available: <https://www-scopus-com.ezproxy.library.yorku.ca/freelookup/form/author.uri>
 - [35] M. Ouzzani, H. Hammady, Z. Fedorowicz, and A. Elmagarmid, “Rayyan — a web and mobile app for systematic reviews” *Systematic Reviews*, 2016, 5:210, DOI: 10.1186/s13643-016-0384-4. Accessed: Aug. 26, 2024. [Online]. Available: <https://www.rayyan.ai/cite/>
 - [36] H. Wickham *et al.*, “Welcome to the Tidyverse,” *J. Open Source Softw.*, vol. 4, no. 43, p. 1686, Nov. 2019, doi: 10.21105/joss.01686.
 - [37] H. Wickham and D. Seidel (2022). scales: Scale Functions for VisualizationR package version 1.2.1. <https://CRAN.R-project.org/package=scales>
 - [38] R. Maiti, “Fast Fashion: Its Detrimental Effect on the Environment,” *Earth.Org*. Accessed: Aug. 26, 2024. [Online]. Available: <https://earth.org/fast-fashions-detrimental-effect-on-the-environment/>
 - [39] M. Shamsuzzaman, M. Islam, H. Ul Hasan, A. Khan, and A. Sayem, “Mapping environmental sustainability of knitted textile production facilities,” *J. Clean. Prod.*, vol. 405, Jun. 2023, doi: 10.1016/j.jclepro.2023.136900.
 - [40] M. Roushan, “Study on the use of fabric wastes as an energy source for boiler by incineration process,” *Energy Sources Part Recovery Util. Environ. Eff.*, pp. 1–12, Dec. 2020, doi: 10.1080/15567036.2020.1856236.
 - [41] S. G. Ponnambalam, B. Sankaranarayanan, K. Karuppiyah, S. Thinakaran, P. Chandravelu, and H. L. Lam, “Analysing the Barriers Involved in Recycling the Textile Waste in India Using Fuzzy DEMATEL,” *Sustainability*, vol. 15, no. 11, Art. no. 11, Jan. 2023, doi: 10.3390/su15118864.
 - [42] A. Erdil and E. Taçgin, “Potential Risks and Their Analysis of the Apparel & Textile Industry in Turkey: A Quality-Oriented Sustainability Approach,” *FIBRES Text. East. Eur.*, vol. 26, no. 6, pp. 30–42, Nov. 2018, doi: 10.5604/01.3001.0012.2526 WE - Science Citation Index Expanded (SCI-EXPANDED).
 - [43] A. Vishwakarma, M. Meena, G. Dangayach, and D. S. Gupta, “Identification of Challenges & Practices of Sustainability in Indian Apparel and Textile Industries,” 2022, pp. 149–156. doi: 10.1007/978-981-16-5281-3_14.
 - [44] B. Xu, Q. Chen, B. Fu, R. Zheng, and J. Fan, “Current Situation and Construction of Recycling System in China for Post-Consumer Textile Waste,” *Sustainability*, vol. 14, no. 24, Art. no. 24, Jan. 2022, doi: 10.3390/su142416635.
 - [45] M. Al Alam *et al.*, “Taking stock of the share of global environmental burden of knitwear production in Bangladesh: Constructing the life cycle inventory,” *J. Clean. Prod.*, vol. 412, Aug. 2023, doi: 10.1016/j.jclepro.2023.137376.
 - [46] R. Nayak, M. Akbari, and S. Maleki Far, “Recent sustainable trends in Vietnam’s fashion supply chain,” *J. Clean. Prod.*, vol. 225, pp. 291–303, Jul. 2019, doi: 10.1016/j.jclepro.2019.03.239.
 - [47] A. Erdil, “An Evaluation on Lifecycle of Products in Textile Industry of Turkey through Quality Function Deployment and Pareto Analysis,” *Procedia Comput. Sci.*, vol. 158, pp. 735–744, Jan. 2019, doi: 10.1016/j.procs.2019.09.109.
 - [48] W. Ba, D. Wang, B. Gong, Y. Dai, Z. Yang, and Z. Liu, “Urban water scarcity in China: A systematic review of research advances and future directions,” *Appl. Geogr.*, vol. 159, p. 103069, Oct. 2023, doi: 10.1016/j.apgeog.2023.103069.

- [49] Y. Jiang, “China’s water scarcity,” *J. Environ. Manage.*, vol. 90, no. 11, pp. 3185–3196, Aug. 2009, doi: 10.1016/j.jenvman.2009.04.016.
- [50] N. Nguyen, R. Beeton, and A. Halog, “Who Influence the Environmental Adaptation Process of Small and Medium Sized Textile and Garment Companies in Vietnam?,” 2014, pp. 189–207. doi: 10.1007/978-981-287-110-7_7.
- [51] Y. Wang and Y. Yang, “Analyzing the green innovation practices based on sustainability performance indicators: a Chinese manufacturing industry case,” *Environ. Sci. Pollut. Res.*, vol. 28, no. 1, pp. 1181–1203, Jan. 2021, doi: 10.1007/s11356-020-10531-7.
- [52] T. J. Tumpa, S. M. Ali, Md. H. Rahman, S. K. Paul, P. Chowdhury, and S. A. Rehman Khan, “Barriers to green supply chain management: An emerging economy context,” *J. Clean. Prod.*, vol. 236, p. 117617, Nov. 2019, doi: 10.1016/j.jclepro.2019.117617.
- [53] R. Chourasiya, S. Pandey, and R. K. Malviya, “Investigation and Assessment of the Barriers to Sustainable Manufacturing Adoption in the Indian Textile Industry,” *Process Integr. Optim. Sustain.*, vol. 8, no. 1, pp. 81–109, Mar. 2024, doi: 10.1007/s41660-023-00353-8.

FIGURES

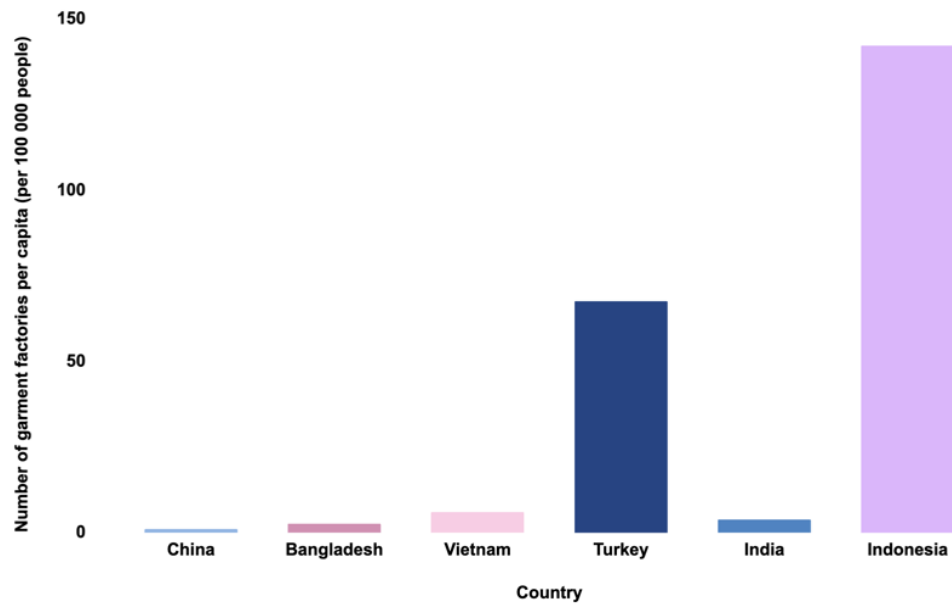


Figure 1: Number of garment-producing factories per capita for the top garment producing countries per 100 000 people.

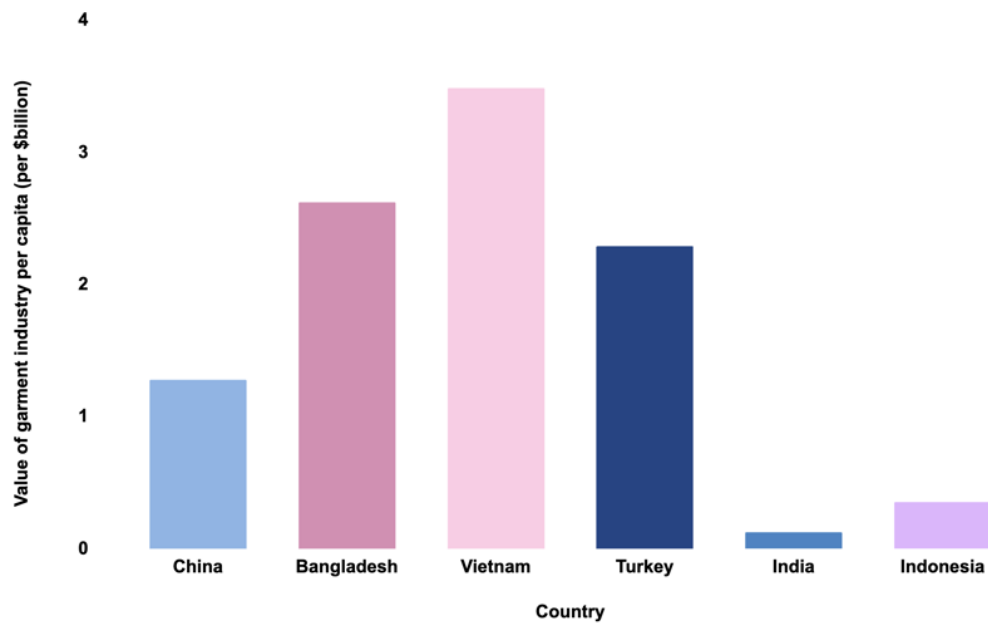


Figure 2: Value of per capita clothing exports for the top garment producing countries per billion.

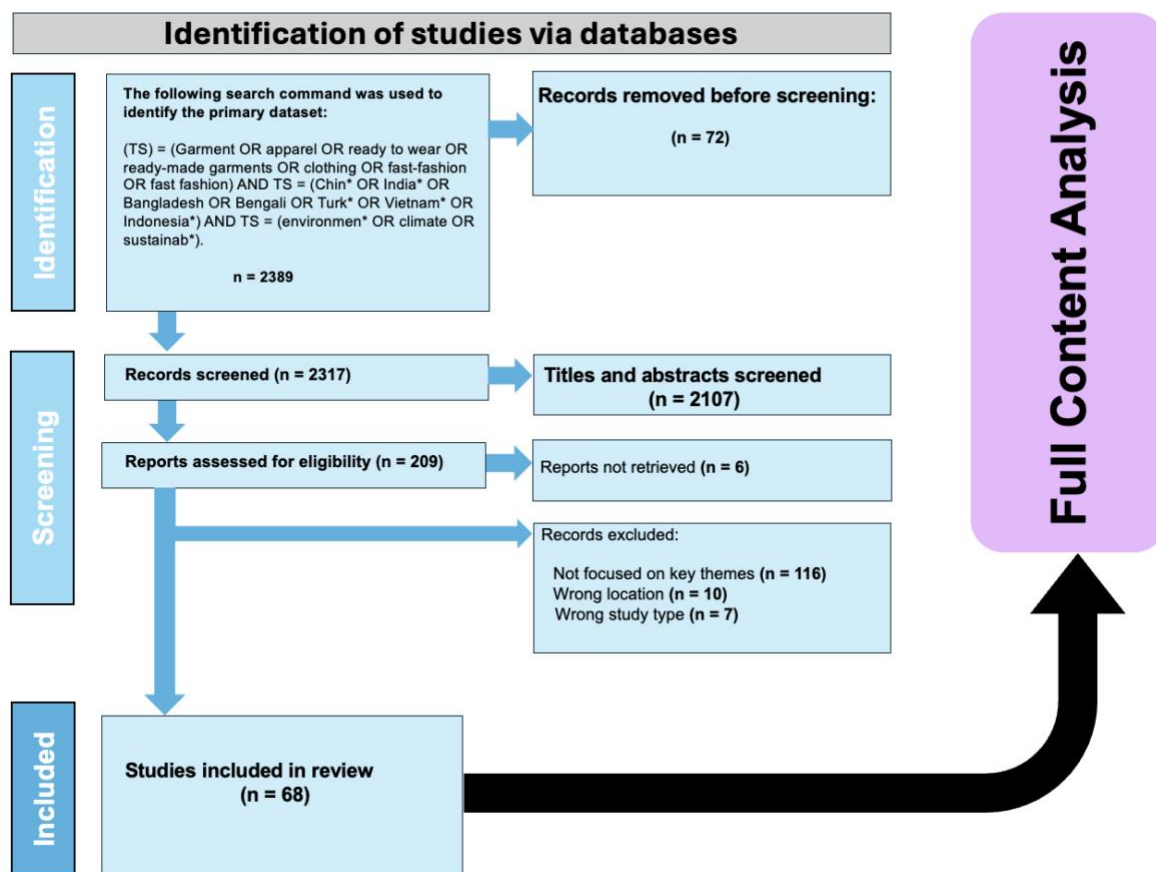


Figure 3: Flowchart outlining the systematic process employed in this study. This includes the key steps: Identification, Screening, Inclusion, and Full content Analysis along with the exclusion criteria.

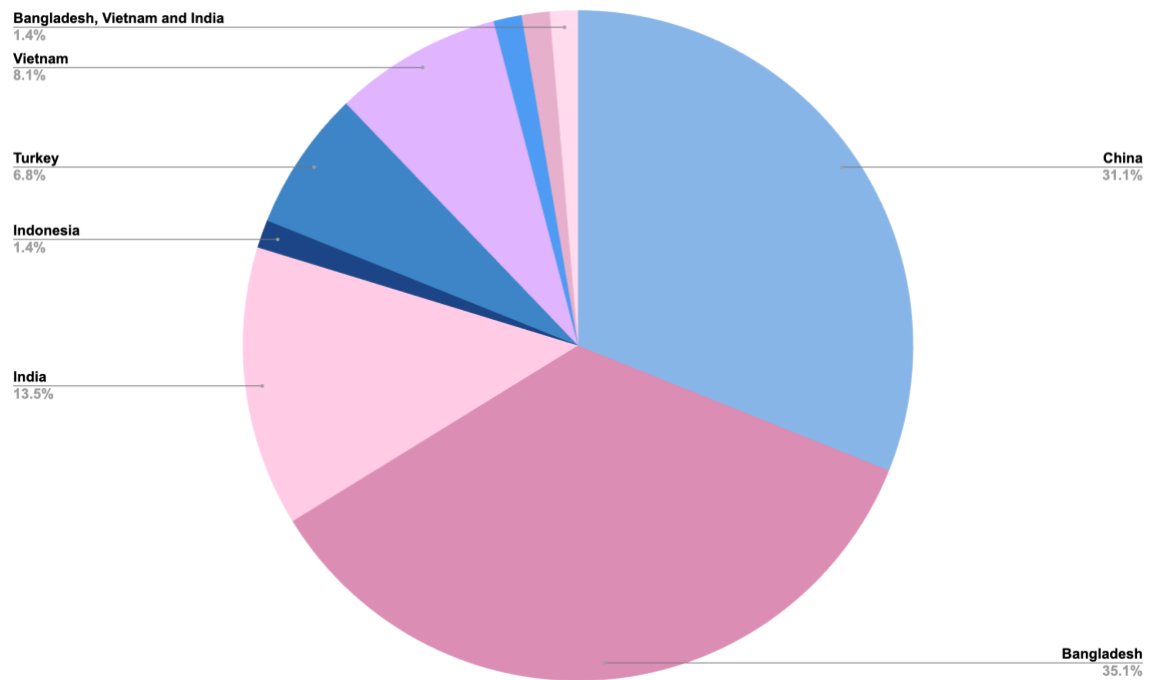


Figure 4: Percentage of countries studied in the literature as part of the final study. Bangladesh was studied in (26), China in (23), India (10), Vietnam (6), Turkey (5), and Indonesia (1). The combinations China and India, China and Turkey, and Bangladesh, Vietnam and India, were the main countries studied in 3 separate studies.

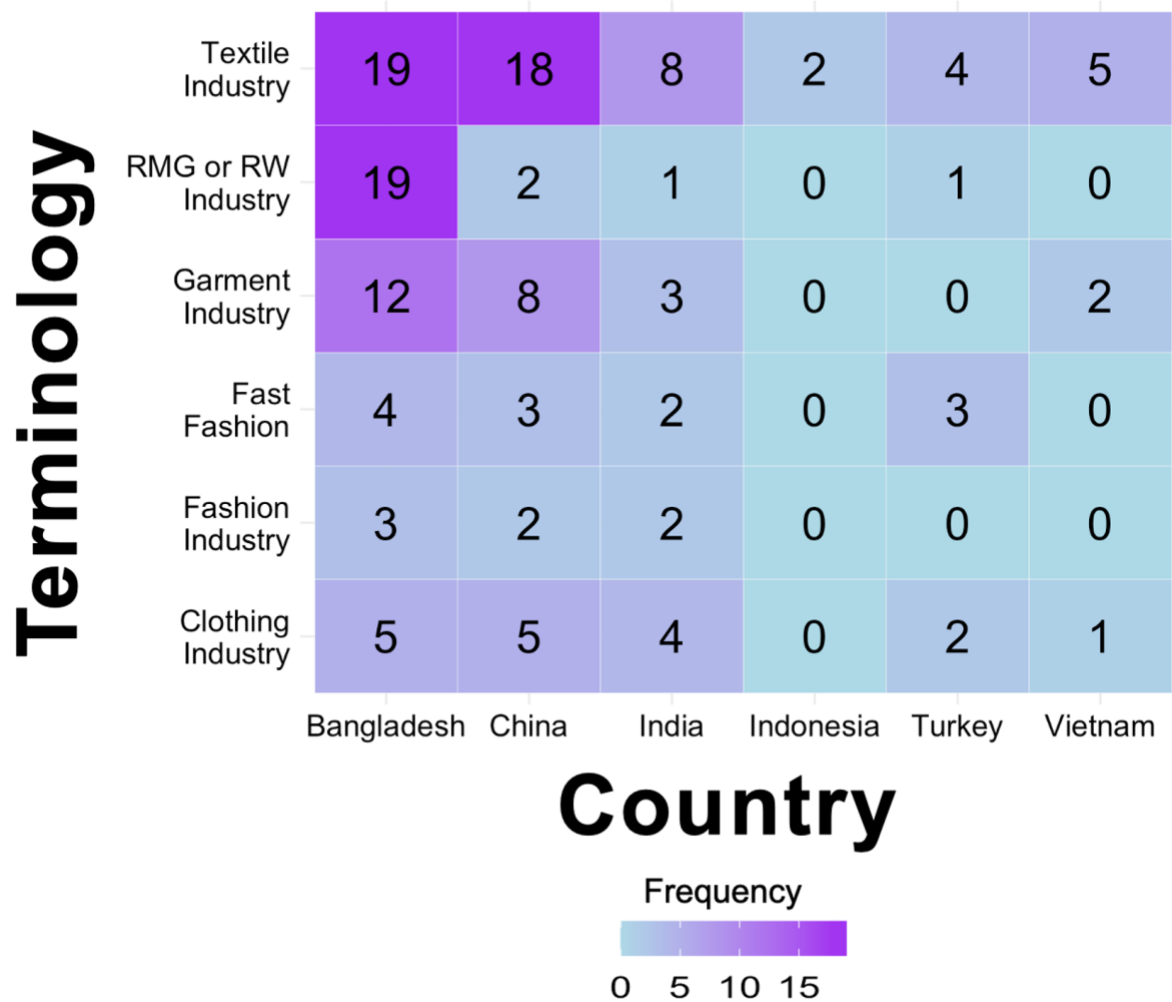


Figure 5: Frequency of terminology used to refer to the textile and garment industry across study countries; where RMG refers to ready-made garment and RW refers to ready-wear or ready-to-wear.

Key Themes

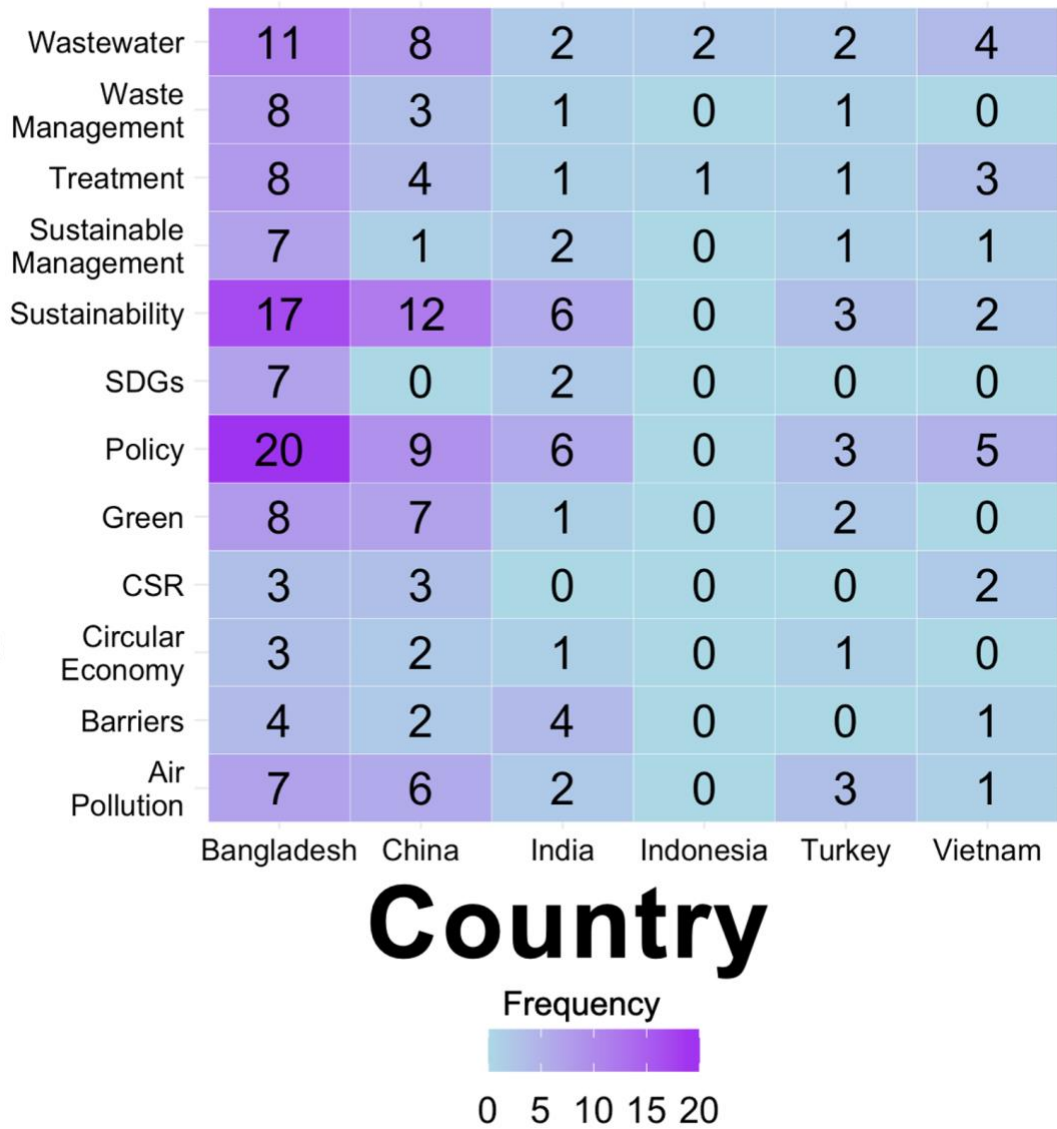


Figure 6: Frequency of key themes studied across the top garment producing countries; where SDGs refers to the sustainable development goals; Green encompasses variations of the green sector including manufacturing and green innovation; and CSR refers to corporate social responsibility.

GENERAL CONCLUSION

In the first chapter, we examined the patterns and drivers of water quality conditions across the nearshore regions of the Canadian Laurentian Great Lakes. Using long term data obtained from the Ontario Ministry of Environment, Conservation and Parks we provided an analysis of spatial heterogeneity in water quality across the Great Lakes from 2000 to 2019. We analysed 1101 water samples collected during the ice-free seasons using a combination of analyses, including descriptive statistics, principal component analysis, and redundancy analysis. We found evidence of spatial heterogeneity in water quality conditions across the Great Lakes. We observed differences in the chemical compositions of the lakes. Most notably, we observed higher concentrations of nutrients, chlorophyll-a, and chloride in lakes Erie and Ontario. Conversely, the northern Great Lakes had lower concentrations of nutrients. Our Principal Component Analysis explained 42% of the variation in water quality conditions in the Canadian Great Lakes nearshore. The first principal component explained 28.4% of the variation whereas the second principal component explained 13.7% of the variation. The first principal component was primarily associated with nutrient related variables such as chlorophyll-a; whereas the second principal component was associated with silica. Lastly, we found that degraded nearshore Great Lakes water quality was associated with warmer air temperatures, agricultural, and urbanised landscapes. We highlight the significance of improving management practices for better maintenance of urban and agricultural landscapes, as it relates to climate and water quality degradation in the northern nearshore regions of the Great Lakes region.

In the second chapter, we explored the state of fast fashion research in relation to impacts on the environment and water quality. We identified the predominant research areas, the key knowledge gaps and the key barriers to more sustainable garment production. We found that ‘textile industry’ and ‘ready-made garment’ or ‘ready-wear’ were the key terminologies used when referring to the clothing industry in the top garment-producing countries. However, we did note that the predominant barriers in this industry included lack of adequate infrastructure and lack of knowledge, which tend to have varying interconnectedness with causal relationships. Of the top garment-producing countries, we noted that the majority of the research published in English was focused on Bangladesh and China, although the majority of fast fashion was produced in Vietnam. In addition, Indonesia had the most

garment factories of the included countries yet was the focus of the least amount of research. Though the primary topics studied included policy, sustainability and wastewater. Though wastewater is discussed generally, there is a lack of studies that sample textile effluents to identify and quantify its components. An increase in these methods is needed to fill the knowledge gaps related to the environmental impacts of fast fashion. The current research practices in this field primarily focus on case studies and reviews but we implore research to take on more empirical research such as sampling and quantifying the contents of textile effluents as well as considering consumer knowledge.

Future applications

Observable shifts in water quality degradation in the Great Lakes such as the delisting of specific Areas of Concern occurred because of widespread and frequent environmental monitoring, reoccurring environmental assessments, implementing environmental management strategies, and developing data-driven regulations and policy to improve water quality in the Laurentian Great Lakes. We believe a similar multi-disciplinary and data-driven approach to improving water quality would benefit each of the top garment-producing countries. In both cases, we recommend changes to management including a transdisciplinary approach and investments into increasing public awareness of anthropogenic activity on water quality. In terms of the Laurentian Great Lakes, scientists and policymakers need to continue to work together to create sustainable and timely management plans. In terms of the fast fashion industry, it is imperative that managers and other factory workers receive the knowledge and funding to replace the current practices with more sustainable options. For each garment-producing country, consistent wastewater sampling at and near treatment plants are recommended. It is also imperative that governments and factory managers work to increase transparency in data collection and sharing.

The amalgamation of the chapters in this thesis aim to elucidate the relationship between anthropogenic activity and water quality using the examples of the Laurentian Great Lakes and the global fast fashion industry. Both chapters reveal that anthropogenic activity impacts water quality through landscape changes as a result of agriculture, developed land types, and both the manufacturing and processing of textiles for clothing. Water quality is impacted by many stressors including nutrients in runoff and untreated effluents.