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Urban Lakes: Ecosystem Services and Management

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by

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Abstract

Lakes provide a variety of ecosystem services and benefits that greatly contribute to urban sustainability. Despite the growing interest in integrating freshwater systems into management and policy decisions, urban lakes are often overlooked in land-use planning. Nutrient and pollutant runoff from the surrounding urbanized watershed result in water quality deterioration that negatively impact the lake ecological functions and related ecosystem services. The vulnerability and degradation of these urban ecosystems should be a matter of concern, especially considering that, in rapidly growing metropolitan areas, the demand for aesthetic and recreational services provided by urban lakes is increasing. The overall goal of this dissertation was to better characterize urban lakes and to provide a basis to improve the management of these systems.

As a first step I defined as "urban" those lakes that were completely within areas with at least 50,000 people, and in a sub-watershed with a population density of at least 1,000 people per square mile and more than 10% of impervious cover. Based on this definition, by analyzing datasets from a variety of sources, I identified and characterized 1,950 "urban" lakes and reservoirs across the continental United States. These systems presented more eutrophic and disturbed conditions than non-urban lakes. Urban lakes are also impaired by contaminants (i.e., mercury and toxic compounds) that could harm recreational users. With the exception of a few systems, most urban lakes are not actively managed, which results in degradation of these valuable resources.

In the second chapter I examined a case-study of an urban lake that has been intensively managed and monitored for the past 20 years. Intensive in-lake management

efforts successfully improved the water quality and maintained the aesthetic and recreational benefits provided by the lake. However, high nutrient loading from the surrounded watershed partially reduced the effectiveness of management efforts. An accurate phosphorus budget for the lake is necessary to effectively implement nutrient reduction strategies. This study also showed some of the challenges faced by lake managers like the coordination of multiple stakeholders and jurisdictions with conflicting goals, guarantee of consistent high-quality data in long-term monitoring programs, and ensuring that the water quality meets user's expectations.

In the third chapter, I used a new approach to analyze the impact that future urbanization could have on the water quality and ecosystem services provided by a major urban lake. I combined two modeling tools (InVEST software and a mass balance model) to estimate the amount of phosphorus runoff resulting from alternative land use management scenarios and the consequent lake water quality responses. My results highlighted the negative impacts that land use management decisions developed at the regional scale could have on the water quality of a major urban lake and the importance of incorporating small ecosystems (like lakes) into a large-scale ecosystem service trade-off analysis.

Finally, since lakes could be used to ease some of the negative consequences of urban development and climate change, I also quantified the ecological and economic value of the temperature mitigating capacity of urban lakes. Using a new modeling tool (InVEST urban cooling model), I valued the heat mitigation service provided by lakes in alleviating the urban heat island effect in a hot and dry climate. My results showed that the presence of a lake significantly mitigates air temperature and reduces electricity consumption in areas immediately adjacent to the lake under current and future climate change scenarios. The quantification of this important regulatory ecosystem service could help inform decisions on sustainable urban planning. This dissertation contributes in several ways to the existing knowledge of the social-economic value of urban lakes and have a number of implications to improve management of these important systems.

Dedication

I dedicate this work:

To Greg, without your endless support I would have not endured this journey

And

To Diego and Alex for giving me the gift of being your mom

Acknowledgements

Throughout my research and writing of this dissertation I have received a great deal of support and assistance. I would first like to thank my advisor, Dr Mark Sytsma for his guidance, patient support and insightful feedback who sharpen my thinking and made me a better scientist. He provided me with directions and most importantly he gave me the opportunity to pursue a PhD. I owe him my eternal gratitude. Thank you to my committee member Dr Elise Granek for the time she spent discussing literature and research ideas. I would also like to express my gratitude to Dr. Max Nielsen-Pincus and Dr Randy Bluffstone for being on my committee despite their busy schedules and for providing suggestions that improved the quality of my work. A special thank you to Dr Yangdong Pan for always making himself available, his endless source of statistical advice and for collaborating on one of my chapters. I am also extremely grateful to Mark Rosenkranz and the Lake Oswego Corporation for the internship opportunity and the financial support. Last but not least, thank you to my husband Stefano for his constant support and for graciously taking care of everything while I was busy working on my dissertation. Thank you to my Mom and Dad for understanding all of the time I sacrificed spending with you in order to pursue my dream of graduate training.

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Table of Contents

List of Tables

Chapter 6 Tables

List of Figures

Chapter 1 Figure

Chapter 2 Figures

Chapter 3 Figures

Chapter 4 Figures

Chapter 5

Chapter 1

Introduction

Lakes are an important feature of the urban landscape. These systems provide ecological and social ecosystem services, defined by the Millennium Ecosystem Assessment (2005) as the benefits that people receive from the environment, that greatly improve the quality of life in urban areas. Through their ecological functions, lakes provide services like fishing, water provision, biodiversity, wildlife habitat, recreational opportunity and regulation of urban climate (Schallenberg et al. 2013, Vilbaste et al. 2016). Despite their environmental and economic importance and high level of public interface, urban lakes have received little attention in the literature and are among the least protected of the world's biomes (Vreugdenhil et al. 2003).

Environmental changes driven by anthropogenic activities and urban development are posing significant pressure on aquatic ecosystems that are often detrimental to the provided ecosystem services. Urban development in the last century has increased substantially, creating challenges for preserving the balance of human-environment interactions that greatly contribute to people's well-being (Luederitz et al. 2015). Since early 1900, the urban population has grown by nearly 500 percent and as of 2010, 81 percent of the U.S. population was considered urban (U.S. Census 2013). In rapidly growing urbanized areas agricultural and wildlands are converted into urban and suburban lands (Moore et al. 2003). Residential development is associated with nutrient pollution and eutrophication of freshwater systems (Carpenter et al. 1998). The resulting disruption of the natural ecological state of these systems often leads to rapid water quality degradation with negative consequences for the services provided.

Phosphorus is usually the main limiting nutrient for lake primary production (Schindler, 1977; Boers et al. 1993). Point sources of nutrient pollution have been successfully reduced in most developed regions, however, there is still a need to implement nutrient management strategies to improve control of nonpoint sources of pollution (Carpenter et al. 1998). Productivity and water transparency is strongly influenced by the high phosphorus runoff from the surrounding watershed (Reckhow et al. 1980). High external loading of P can also lead to high P concentration in lake sediments, which contribute to internal P release. In shallow lakes internal P release can be particularly problematic as it can offset nutrient reduction strategies implemented in these systems (Scheffer, 2001).

As residential development continues to grow, and urban boundaries expand, more freshwater systems will be threatened by eutrophication. Urban lakes are also subjected to more and varied types of pollutants including mercury, metals, pesticides and antibiotics (Almakki et al. 2019; Müller et al. 2020). The influence of the surrounding drainage basin on lake ecology and water quality must be considered to successfully implement an integrated management approach. From a management perspective, freshwater systems in urban areas can be considered as a distinct class of lakes due to the impact of watershed development on lake water quality and year-round high usage (Schueler and Simpson, 2016).

Lakes have been classified based on their geomorphic origin (Hutchinson, 1957) or their trophic state (Carlson, 1997). While each lake is unique in term of size, depth, nutrient cycling and trophic state, it is unrealistic to develop management strategies to meet the conditions of each lake (Schueler and Simpson, 2016). Recent efforts have grouped lakes in categories based on common characteristics that require similar management strategies to help establish policies and regulations (USEPA 2020). Few studies have defined urban lakes based on criteria such as watershed development, surface area and average depth (Schueler and Simpson, 2001; Naselli-Flores, 2008). A better characterization of urban lakes will be an important step in refining of more specific management approaches.

Maintaining ecosystem services to sustain growing urban needs is one of the greatest challenges to the sustainable development of cities (Grunewald and Bastian, 2017). This requires gaining a better understanding of the impacts of long-term complex interactions of humans and ecosystems. One of the main constraints to the integration of freshwater systems into restoration or conservation decisions related to their use is the lack of information on their social and economic value. In urban settings, with ever escalating land values and development incentives, it is critically important to establish the impact of future development on the ecology and economic values of ecosystem services to preserve and maintain their relative worth and value to the community.

The failure to incorporate the value of natural services into land management decisions has resulted in the progressive loss of ecosystem benefits. Integrating people's perception of ecosystem services that directly enhance human wellbeing in management efforts can be an effective way to support the conservation of natural ecosystems. Among the wide variety of ecosystem services, lakes provide regulatory services like climate mitigation that offer a direct benefit to urban dwellers. These less tangible ecosystem services are complex to measure and, as a result, are less acknowledged and undervalued (Mengist et al. 2020). There is a pressing need to develop new methodologies to facilitate the valuation and integration of these valuable services into management decision processes.

Rapid urbanization is increasing the demand for the ecosystem services that urban lakes provide, while at the same time exacerbating the vulnerability of these ecosystems to anthropogenic degradation (Cumming et al. 2014). Urban lakes managers face numerous problems including lack of funding to maintain ongoing interventions and monitoring efforts, and difficulty in controlling multiple drivers of water degradation (Birch and McCaskie, 1999). The recognition of the importance of ecosystem services and values can be used to offer financial incentives for maintaining and managing these ecosystems (Deal et al, 2012). Therefore, research approaches that facilitate comprehensive analyses of ecosystem services trade-offs and incorporate a valuation of the benefits provided by these ecosystems are becoming progressively more important.

This dissertation paper covers multiple aspects of the ecological and socio-economic value of urban lakes (Figure 1). The goal of this dissertation is to inform management decisions by providing a comprehensive picture of urban lakes: from the ecosystem services, to the main drivers of change and the challenges in maintaining an adequate water quality level.

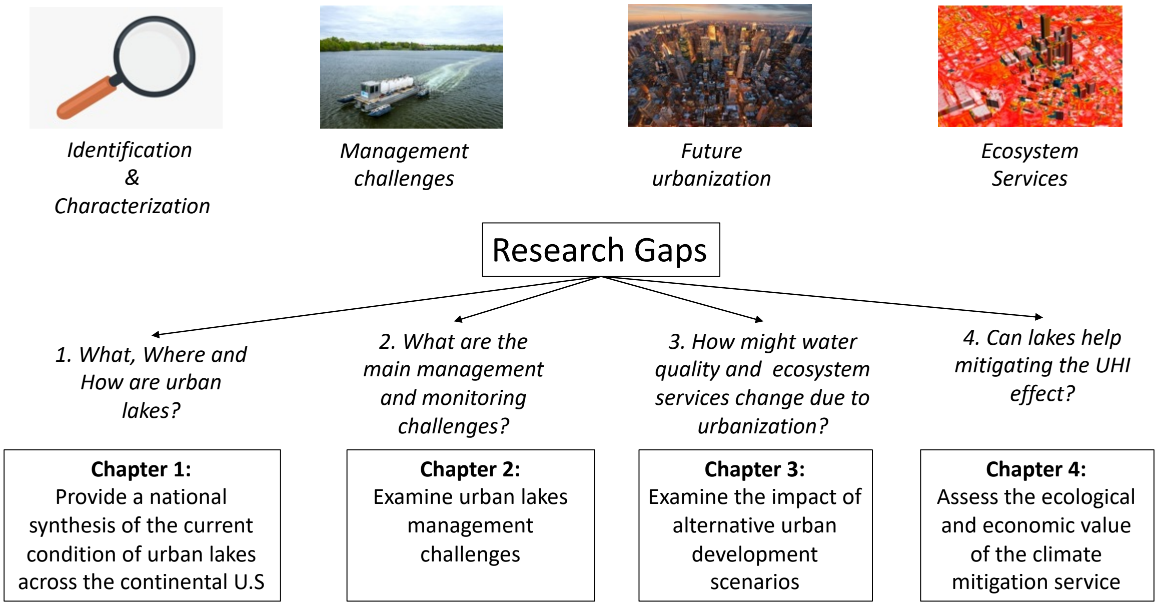

Figure 1: Conceptual diagram of research gaps.

My thesis is composed of four chapters that address the following research objectives:

1. Provide a national synthesis of the current conditions of urban lakes across the continental United States by considering physical characteristics, water quality variables, watershed land use, management actions, main problems (i.e., HABs or invasive aquatic weeds) and overview of the main ecosystem services provided.
2. Examine urban lakes monitoring and management challenges.
3. Examine changes in water quality and related freshwater ecosystem service provisions of a major urban lake under alternative urban development and land use/land cover management scenarios.
4. Assess the ecological and economic value of the climate mitigation service provided by urban lakes.

In the first chapter, I defined and identified urban lakes across the continental United States, and I provided a detailed characterization of the current conditions of these systems in terms of trophic state, cause of impairments, main ecosystem services and management information. Chapter 1 was submitted to the *Lake and Reservoir Management Journal* on January 26, 2021, by L. Costadone, and M. Sytsma, and is currently in review.

In the second chapter I presented the results of a lake long-term management effort implemented to maintain a water quality level adequate to the recreational and aesthetic benefits provided by an urban lake. Through this case study I highlighted the main challenges faced by the lake managers and the importance of integrating water quality perception of lake users in the development of a management plan targeted at preserving lake ecosystem benefits. Chapter 2 was submitted to the *Lake and Reservoir Management Journal* on February 1, 2021, by L. Costadone, M. Sytsma, Y. Pan and M. Rosenkranz and is currently in review.

In the third chapter, I assessed the consequences of alternative scenarios of urban development and land-use management policies on a major urban lake's water quality and related ecosystem services. Chapter 3 will be submitted to the *Ecosystem Services* Journal by L. Costadone, M. Sytsma.

In the last chapter of this dissertation, I used a new methodology, the InVEST Urban Cooling Model, to evaluate the ecological and economic impact of urban lakes in mitigating the urban heat island effect. Using this new modeling tool, I quantified in terms of energy saving (kwh) the heat reduction services provided by three lakes located in the Phoenix Metropolitan area under current conditions and climate change scenarios. Chapter 4 will be submitted to the *Landscape and Urban Planning* by L. Costadone, M. Sytsma.

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Chapter 2

Identification and characterization of urban lakes across the continental United States

Abstract

Urban lakes contribute to the quality of life and sustainability of urban areas by providing a variety of ecosystems services. The goals of this study were to define and identify urban lakes across the continental United States; provide a comprehensive assessment of water quality, management activities, and the main ecosystem services provided; and to determine how these systems compare to non-urban lakes. Lakes and reservoirs were identified as "urban" if they were completely within areas with at least 50,000 people, and in a sub-watershed with a population density of at least 1,000 people per square mile and more than 10% of impervious cover. We identified 1,950 urban lakes and reservoirs. Urban lakes were smaller, shallower, and in a more disturbed condition than non-urban lakes due to high Chlorophyll a concentrations, based on reference conditions for a given ecoregion. A significantly higher proportion of urban lakes were eutrophic in all ecoregions, except in the Coastal Plains, Southern Plains and Temperate Plains ecoregions. In these ecoregions, agriculture and pasture are the predominant land use, which may contribute nonpoint sources of phosphorus and influence non-urban lake water quality. Catchment geology and other environmental factors like soil type, vegetation cover or atmospheric deposition could also influence water quality. With the exception of a few systems, most urban lakes are not actively managed, which results in degradation of these valuable resources.

Introduction

Lakes in urban areas have distinct characteristics and management challenges (Schuler and Simpson 2001). Urban lakes are surrounded by watersheds with high levels of development and impervious area that increase the volume, rate, and impact the quality of runoff (Im et al. 2003). They are subjected to more and varied types of pollutants than non-urban lakes and are presumably more vulnerable to eutrophication and water quality degradation (Birch and McCaskie 1999). As residential development and urban boundaries expand, more lakes will be subjected to the unique characteristics of the urban watersheds, which will require development of urban-lake specific management approaches (Schuler and Simpson 2001, Soranno et al. 2017, Yan et al. 2018).

Although each lake is unique in terms of origin, geologic setting, size, depth, nutrient cycling, etc., categorizing lakes based on similarities can facilitate the development of management strategies that can be applied across geographical areas (USEPA 2009, Soranno et al. 2017, Hill et al. 2018). The U.S. Environmental Protection Agency (EPA) developed a lake nutrient classification approach based on ecoregions (Omernik 1987, 1988, 1995). These ecoregions are characterized by relative homogenous land use, soils, vegetation, climate and hydrology, and provide a spatial framework for freshwater ecosystem assessment, monitoring and management. This classification approach has led to ecoregion-specific water quality criteria that helped to clarify expectations and goals for protecting lakes (USEPA 2000). The common characteristics of urban watersheds, e.g., high nutrient and metals loading and flashy hydrographs, may dampen these ecoregional differences and create a distinct subset of urban lakes whose characterization may aid in management.

Lakes are an important component of urban ecosystems. They provide ecosystem services that contribute to the psychological, emotional and physical human well-being (Haase 2015, Mantler and Logan 2015, Triguero-Mas et al. 2015) as well as wildlife habitat, water supply for municipal and industrial uses, and fisheries (Schallenberg et al. 2013, Angradi et al. 2016, Allan et al. 2015). These benefits are susceptible to degradation by nutrients, metals, and sediments in urban runoff (Birch and McCaskie 1999, Keeler et al. 2012). Despite their importance, urban lakes have received little attention in the limnological literature (Naselli-Flores 2008).

In the United States, urban lakes are assumed to be in a more eutrophic state than non-urban lakes, but this assumption has never been documented. Urban lakes have not been clearly defined or identified and empirical data about these systems remain scattered throughout the scientific literature. We addressed this knowledge gap by identifying urban lakes across the continental United States and documenting their morphological characteristics, water quality issues, main ecosystem services, monitoring and management approaches.

Materials and Methods

We adopted the U.S Census Bureau definition of urban areas to map urban lakes across the continental United States. The Census Bureau uses the population threshold of 50,000 or more people and the density of 1000 people per square mile to classify urban areas. To account for the influence of urbanization on freshwater ecosystems, we integrated the Census Bureau definition of urban areas with percent impervious surface data. Most reported thresholds of water quality degradation were found when the percentage of the watershed covered by impervious surfaces exceed 10% (Arnold and Gibbons 1996, Paul and Meyer 2001, DeLuca et al. 2004). The percentage of land within each sub-watershed classified as impervious by the 2011 National Land Cover Dataset was estimated using the EnviroAtlas national map.

Watershed data were obtained from the Watershed Boundary Dataset (WBD) developed by the U.S. EPA in partnership with the U.S. Geological Survey to support water resource applications. The WBD defines six hierarchical levels of hydrologic units derived from subdivision of land surface areas into geographic polygons. Each subdivision or hydrologic unit code (HUC) represents areas that can be either a part or an entire drainage basin. Many HUCs are not true topographic watersheds or basins but, since watersheds cannot be clearly defined in many regions, several studies have adopted the HUC dataset as a convenient nationwide drainage subdivisions of surface areas (Omernik et al. 2017). We used the 12-digit Hydrologic Unit Code (HUC) as a framework to identify urban sub-watersheds.

Each sub-watershed across the continental United States was characterized in term of population density and percentage of impervious surfaces. We used the dasymetric mapping technique to accurately represent demographic data and estimate population density within watersheds (Mennis 2003). This approach has been employed for a variety of applications to accurately map population data (Mennis and Hultgren 2005). We used the EnviroAtlas national dasymetric population map to estimate population density within sub-watersheds (Pickard et al. 2015). The EnviroAtlas dataset spatially allocates population from 2010 census blocks to 30-m pixels based on land cover class and slope. To better portray population distribution, areas considered uninhabitable, such as open waters, forested lands or slopes greater than 25% were excluded from population density computation. The EnviroAtlas dasymetric map summarized population data by sub-watersheds or 12-digit hydrologic unit (HUC-12). Sub-watersheds with a population density of at least 1000 people per square mile and with more than 10% of their surface area covered by impervious surfaces were considered 'urban' and selected using ArcMap v.10.

Lake and reservoir data were derived from the National Hydrography Dataset (NHD) at the medium-resolution NHD scale (1:100,000 scale). The NHD in the format of ERSI geodatabase was retrieved from the USGS website (U.S. Geological Survey, 2019, National Hydrography Dataset (ver. USGS National Hydrography Dataset (NHD) for Hydrologic Unit (HU) 12-2001 (published February 10, 2019)), accessed August 23, 2019 at URL https://www.usgs.gov/core-science-systems/ngp/national-hydrography/access-national-hydrography-products). Lakes and reservoirs completely within previously identified urban sub-watersheds were selected using ArcMap and classified as "urban lakes".

We only considered freshwater systems; and marshes, swamps, brackish systems or meadows were excluded from the analysis. Lakes and reservoirs not identified by the Geographic Names Information System (GNIS) were also excluded from the analysis as not clearly identifiable. Urban lakes were characterized based on available information on surface area (km^2), depth (m), total phosphorus (μg/L), Chlorophyll a (Chl-*a*) (μg/L), Secchi disk transparency (m), and main ecosystem services provided. Surface area data were retrieved from the NHD. Depth and water quality data were gathered through a primary literature search, official reports, government websites, or personal communications with people directly responsible for lake water quality management. Lake water quality problems and/or management strategies adopted (either in-lake treatments or at the watershed scale) were also documented if available through online search and personal interviews. We also used water quality data from both the 2007 and 2012 National Lake Assessment reports (U.S. Environmental Protection Agency 2010, 2016) and from the Water Quality Portal (http://www.waterqualitydata.us/).

Urban lakes were classified into least-, moderate- and most-disturbed condition classes based on total phosphorus (TP) and Chl-*a* using NLA-derived thresholds developed to identify regional reference lakes (U.S. Environmental Protection Agency 2010, 2016). Trophic State Indices (TSI) (Carlson 1977) were calculated for each water body based on the available data on water transparency, TP, and Chl-*a* concentration.

A population of non-urban lakes was defined by removing urban lakes from list of lakes monitored in the National Lake Assessment surveys (2001 and 2012). This population of non-urban lakes was characterized in terms of surface area (km^2), TP (μg/L), Chl-*a* (μg/L), Secchi disk transparency (m). Information about lake depth is not readily available. To make data analysis more manageable, a sub-population of 300 non-urban lakes was identified using a proportionate, stratified-random sampling. The stratification boundaries were determined based on the surface area of urban lakes within each ecoregion. This sub-population of non-urban lakes was characterized in terms of depth (m).

Urban lakes were compared to non-urban lakes with respect to morphological conditions (surface area and depth), water quality data, trophic state, and disturbed condition. A two-sample t-test was used to determine the difference between urban and non-urban lakes depth and surface area measurements. The Kolmogorov-Smirnov Goodness of Fit test (KS test) was used to compare the distribution of the urban and non-urban lake datasets. Mann-Whitney test was used to assess the differences between urban and non-urban systems in terms of TP, Chl-*a* and Secchi transparency. Chi-square tests of independence were performed to compare the proportion of urban and non-urban lakes in the different trophic and disturbed categories. The relationship between Chl-*a* and TP was also investigated at the ecoregional level for both urban and non-urban lakes. The analysis of covariance (ANCOVA) was used to compare regression slopes.

The national geospatial dataset produced, and periodically updated, by the EPA containing the 303 (d) listed impaired waters was also included in our study. The dataset from 2015, containing 17,631 water bodies considered threatened or impaired under the Clean Water Act, was retrieved by the EPA website (https://www.epa.gov/waterdata/waters-geospatial-data-downloads). Urban lakes that were part of the 303 (d) list were selected using ArcMap. Main causes of impairments and designated water uses were recorded to further characterize water quality and ecosystem services provided by urban lakes. Frequency distribution analyses of the main ecosystem services and pollutants that cause water use impairments were performed. All data management and analyses were performed using R (R core team 2020). All mean values are reported ± the standard error.

Results

Urban lakes identification

The EnviroAtlas dasymetric dataset included 82,915 HUC-12 sub-watersheds with a population density ranging from 0 to 38,635 people per square mile. Of the 82,915 HUC-12 sub-watersheds, 1220 were selected because they contained a population density of at least 1000 people per square mile and more than 10% of watershed area covered by impervious surfaces. These sub-watersheds were considered "urban" based on the definition stated above. The National Hydrography Dataset included 444,373 bodies of water. Of these, 1950 bodies of water were completely within the identified urban watersheds and were considered "urban lakes". The majority of urban lakes were located in the Coastal Plains ecoregion regions of the United States and the fewest were in the Northern Plains ecoregion (Fig. 1).

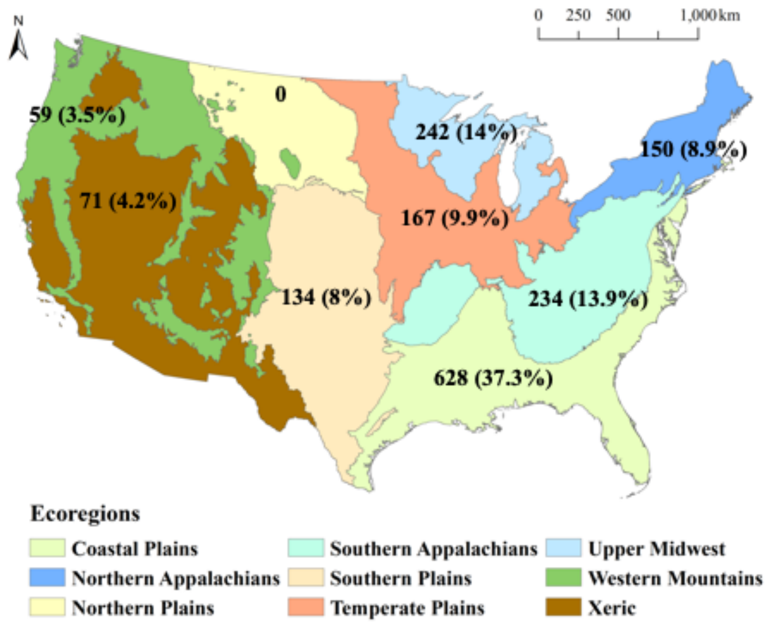

Figure 1. Map of the distribution (number and percentage) of urban lakes within each of the nine ecoregions in the continental United States.

Surface area

Urban lakes had surface areas ranging from 0.003 to 104.103 km^2, a median surface area of 0.06 km^2 and a mean surface area of 0.23±0.008 km^2, respectively. Lake Washington (WA) was the largest and Bulls-Eye Lake, a pond located near Chicago (IL), was the smallest urban lake in our dataset. The surface area of 76,959 non-urban lakes from the NHD ranged from 0.001 km^2 to 5004 km^2, with a median surface area of 0.087 km^2 and a mean of 1.35±0.13 km^2. Within this dataset 4 lakes, which are part of the Great Lakes, have a surface areas of more than 10,000 km^2. These lakes were excluded from the analysis.

Most urban lakes had a surface area of less than 0.1 km^2 (Fig. 2). Non-urban lakes included a higher percentage of large bodies of water (>1 km^2). The total area covered by urban lakes was 474 km^2, while the total area covered by non-urban lakes was 104,482 km^2. The independent samples t-test indicated that urban lakes were significantly smaller than non-urban lakes (t= 7.9, df=47,823, p-value < 0.0001).

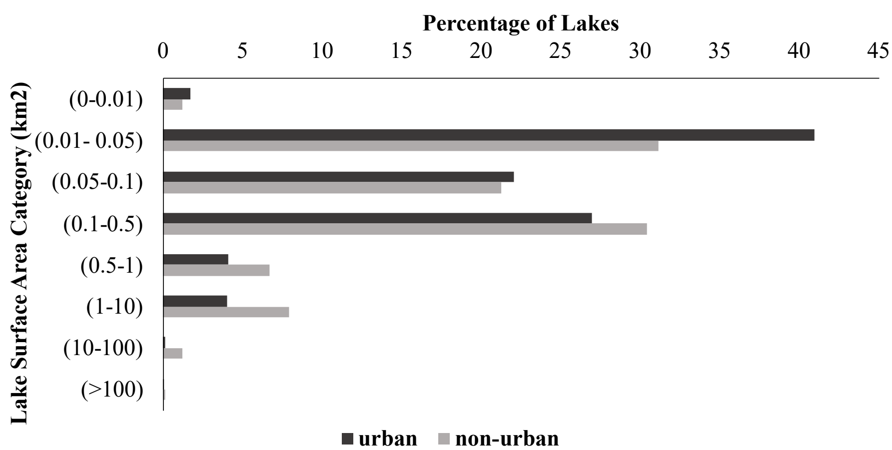

Figure 2. Percentage of urban and non-urban lakes in the continental United States per surface area category.

Depth

We found depth information for 302 of the 1950 urban lakes (Fig. 3). Urban lakes were shallow systems with maximum depths ranging from 0.9 to 65.2 m, a median value of 6.4 m and a mean value of 8.6±0.44 m. Most of the systems considered in the analysis (69.7%) had a maximum depth less than 10 m. An independent samples t-test indicated that a subset of the 302 non-urban lakes, identified using stratified-random sampling, were deeper than urban lakes ($t= 4.37$, $df=596$, p-value < 0.0001). Non-urban lakes had maximum depths ranging from 0.9 to 130.8 m, a median value of 8.2 m and a mean of 12.4±2.5 m.

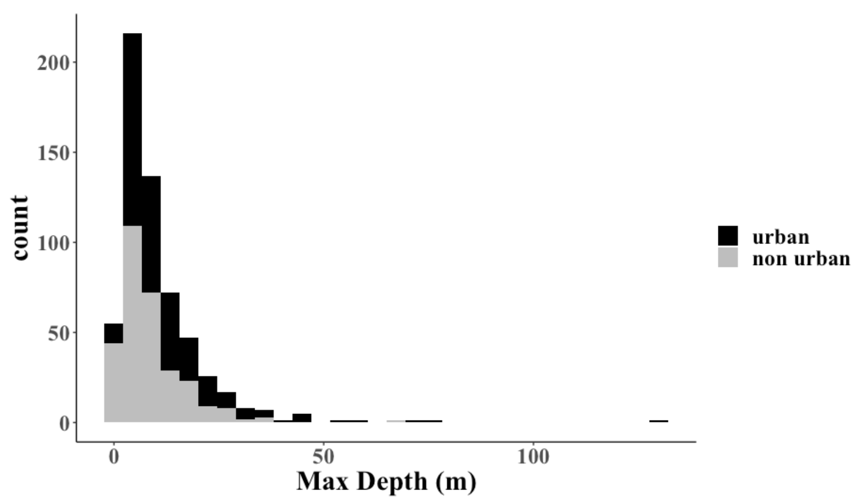

Figure 3. Urban and non-urban lakes maximum depth distribution.

Urban lakes condition

To compare the trophic state of urban and non-urban lakes we had to combine water-quality data from multiple sources. Only a subset of urban lakes had water quality data available for TP, Chl-*a* and Secchi disk transparency. The 2007 and 2012 NLA reports collected water quality data for 2066 lakes and out of these surveyed lakes only 52 where part of our list of urban lakes. Most of the water quality data were gathered by volunteer monitoring programs and retrieved from the Water Quality Portal (WQP). A small subset of information was found through primary literature search, official reports or contacting lake management companies. Some lakes included monthly samples collected over many years (e.g., Florida Water Atlas) while other lakes only had few data from sporadic samples. Secchi disk transparency information was most abundant, but only available for 489 of the 1950 urban lakes in our dataset (25%). Chl-*a* and TP information were available for 367 and 352 lakes, respectively.

The Kolmogorov-Smirnov test indicated that urban and non-urban systems have a significantly different cumulative distribution (Fig. 4) for both Secchi Disk transparency (KS = 0.105; p-value < 0.001); Chl-*a* (KS =0.21, p-value < 0.001); and TP (KS=0.11, p-value= 0.003).

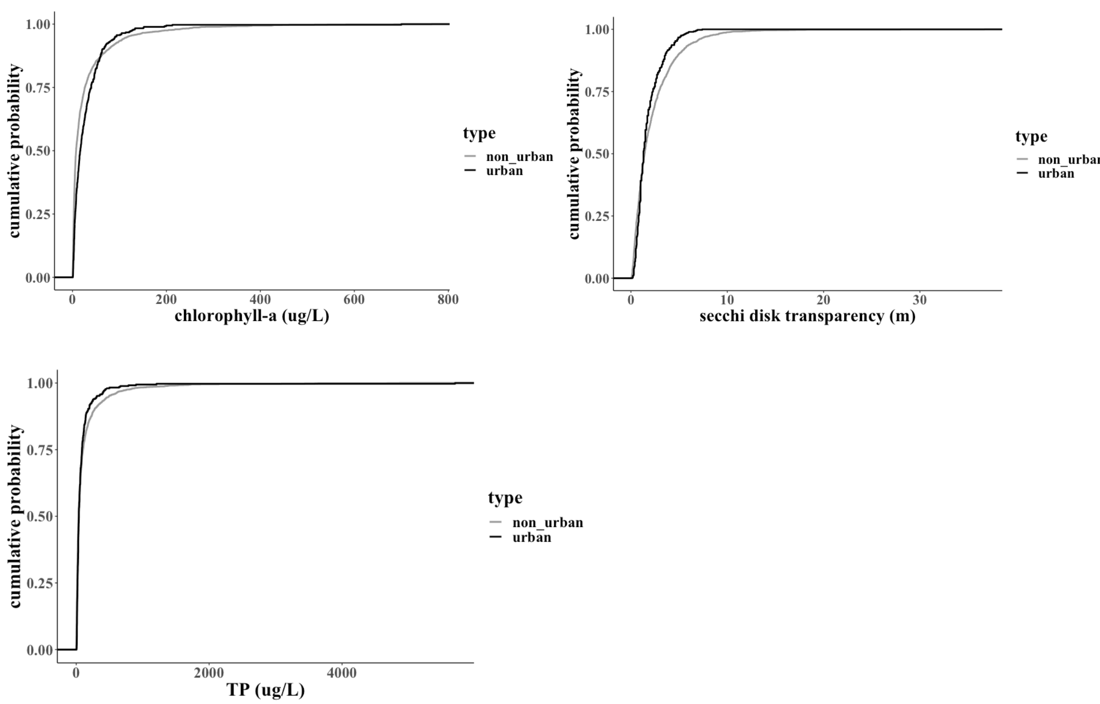

Figure 4. Cumulative distribution functions for urban lakes (black line) and non-urban lakes (grey line) for Chl-*a (*µg/L), Secchi Disk transparency (m) and TP (µg/L).

The data distribution for all the parameters we considered were skewed to the right. Both urban and non-urban groups were characterized by the presence of several hypereutrophic systems with a high concentration of TP (>1000 µg/L) and Chl-*a* (>100 µg/L) in the water column (Figure 5 A and B).

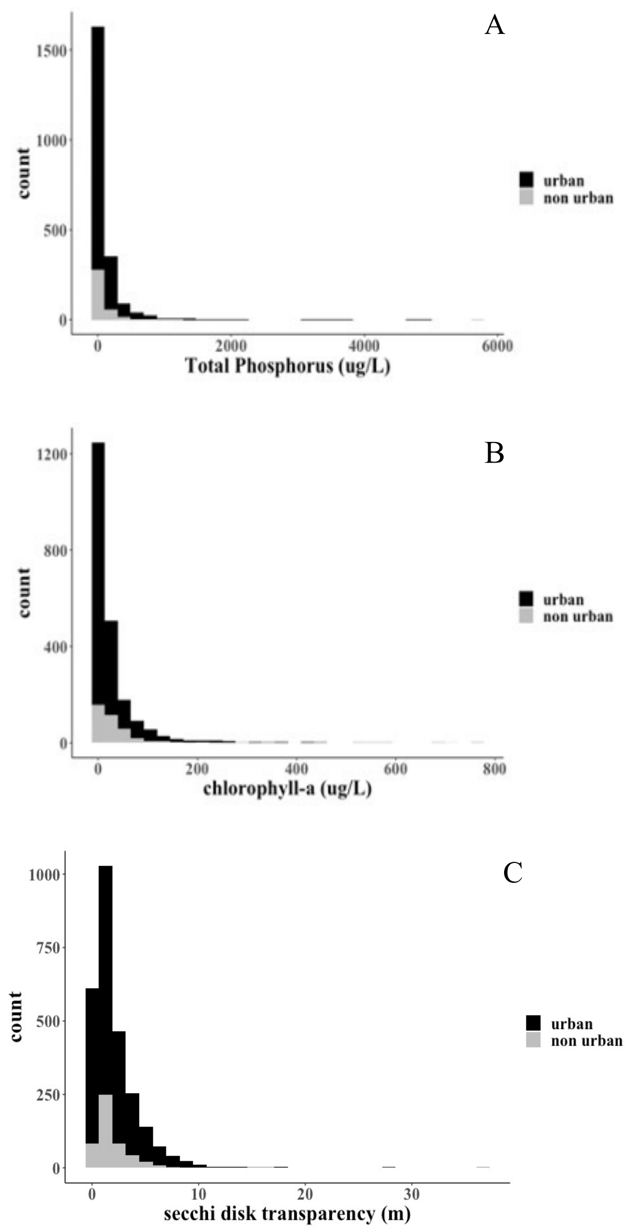

Figure 5. Urban and non-urban lakes TP (µg/L) (A); Chl-*a* (µg/L) (B); and Secchi disk transparency (m) distributions (C).

Almost 70% of urban lakes across the United States had Secchi transparency values < 2 m (Figure 5 C). Urban lakes with the lowest water transparencies were clustered in the Plains and Xeric ecoregions, while lakes located in the Mountains and Upper Midwest had the highest transparency. Compared to urban lakes, non-urban lakes were characterized by a larger proportion of lakes with a Secchi transparency exceeding 4 m, which indicates oligotrophic conditions.

The Mann-Whitney test indicated that at the national level there was a significant difference (p-value < 0.0001) between the urban and non-urban lake Chl-*a* concentrations. There were no significant differences between the values of TP and Secchi transparency between urban and non-urban lakes. The coefficient of variation in TP was higher in urban lakes than in non-urban lakes, but the coefficient of variation in Chl-*a* and Secchi transparency was higher in non-urban lakes than in urban lakes (Table 1).

Table 1. Descriptive statistics of the variables considered in this study for urban (U) and non-urban lakes (NU).

Lake	**Parameter**	**Unit**	**Number of lakes**	**Min**	**Max**	**Median**	**Mean ±SE**	**CV**
U	TP	µg/L	344	5.0	5700	40	96.7±17.3	3.7
NU	TP	µg/L	1821	1.0	4865	37	121.8±7.1	2.5
U	Chl-a	µg/L	367	1.0	700	16.7	29.91±2.5	1.6
NU	Chl-a	µg/L	1861	0.11	764.6	7.7	28.7±1.4	2.1
U	Secchi	m	489	0.15	7.4	1.3	1.75±0.1	0.8
NU	Secchi	m	2175	0.02	36.7	1.4	2.19±0.1	1.1

Based on the Carlson's Trophic State Index (TSI), urban lakes tended more towards eutrophic conditions, while non-urban lakes were more mesotrophic systems. Regional differences were identified across the nine ecoregions (Fig. 6). Results from Chi-square tests indicated that a significantly larger proportion of urban lakes were eutrophic/hypereutrophic, based on Chl-*a* concentration, than non-urban lakes in every ecoregion except in the Coastal Plains and Temperate Plains. Urban lakes also had a higher proportion of eutrophic and hypereutrophic systems at the national level ($X^2 = 9.5$, df= 3, p-value = 0.023)

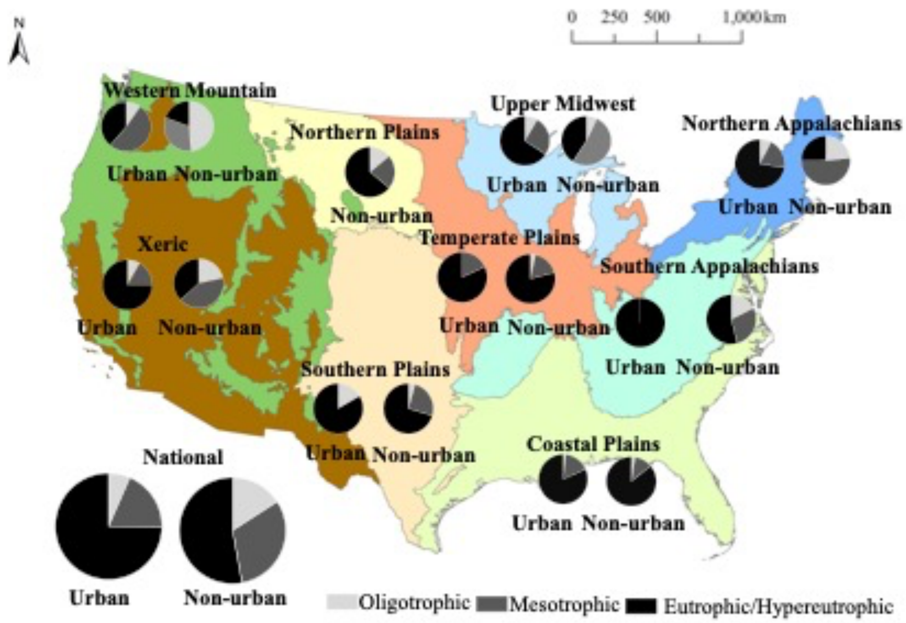

Figure 6. Trophic state classification of urban and non-urban lakes in nine ecoregions based on Chl-*a* concentration (µg/L).

A significantly larger proportion of urban lakes in urban areas in the Northern Appalachians, Southern Appalachians, Upper Midwest, and Xeric ecoregions were classified as eutrophic than in non-urban areas, based on Secchi disk transparency and TP. Interestingly, in the Coastal Plains and Temperate Plains ecoregions non-urban systems had a higher proportion of lakes classified as eutrophic based on TP concentration.

The condition of urban lakes was also evaluated based on NLA-derived benchmarks. Urban lakes had a significantly higher proportion of lakes in the Most Disturbed category based on Chl-*a* concentration than non-urban lakes in every ecoregion except in the Coastal Plains and Temperate Plains (Table 2). At the national level, urban lakes had a higher percentage of lakes in the Most Disturbed category due to high Chl-*a* values compared to non-urban systems (X^2= 6.07, df= 2, p = 0.04) (Table 2).

Table 2. Conditions of urban (U) and non-urban (NU) lakes based on Chl-*a* NLA-derived benchmarks across nine ecoregions.

Ecoregions		**Most Disturbed**	**Moderately Disturbed**	**Least Disturbed**
CPL	U	36.8	28.7	35.1
	NU	42.1	28.9	28.9
NAP	U	70	17.5	12.5
	NU	25.1	23.4	51.5
SAP	U	81.8	18.2	0
	NU	45.6	15.4	39
SPL	U	77.8	5.6	16.7
	NU	55.2	15.3	29.5
TPL	U	60.6	6.1	33.3
	NU	54.3	13.2	32.6
UWM	U	59.3	6.5	34.3
	NU	31.1	11.3	57.6
WMT	U	77.4	16.1	6.5
	NU	37.8	15.6	46.5
XER	U	58.3	16.7	25
	NU	27	12.5	60.5
NPL	U	-	-	-
	NU	54.7	3.1	42.2
NATIONAL	U	65.3	14.3	20.4
	NU	41.4	15.4	43.1

Our results indicated that urban lakes contained a significantly higher proportion of lakes in the Most Disturbed category due to high phosphorus concentrations compared to non-urban systems in the Northern Appalachians, the Upper Midwest, and the Xeric ecoregions (Table 3). The Southern Plains, Coastal Plains and Temperate plains had a significantly higher proportion of non-urban lakes in the most disturbed category.

Table 3. Percentage of urban (U) and non-urban (NU) lakes disturbance categories based on NLA-derived benchmarks for TP in nine ecoregions.

Ecoregions		**Most Disturbed**	**Moderately Disturbed**	**Least Disturbed**
CPL	U	35.3	11.8	52.9
	NU	51.3	14.7	34
NAP	U	73.5	11.8	14.7
	NU	23.9	19.3	56.7
SAP	U	33.3	50	16.7
	NU	40.7	18.1	41.2
SPL	U	60	0	40
	NU	66.5	7.6	25.9
TPL	U	32.3	9.7	58.1
	NU	53.7	17	29.3
UMW	U	55.7	17.5	26.8
	NU	22	19.3	58.7
WMT	U	15.6	15.6	68.8
	NU	19.5	17	63.5
XER	U	66.7	16.7	16.7
	NU	34.9	15.1	50
NPL	U	-	-	-
	NU	70.3	5.5	24.2
NATIONAL	U	46.6	16.6	36.8
	NU	42.5	14.8	42.6

Analysis of the phosphorus-chlorophyll relationship at the ecoregional level revealed that there was no difference in the relationship between Chl-*a* and TP in urban and non-urban lakes except in the Southern Plains, where urban lakes were more sensitive to changes in TP than non-urban lakes (Fig. 7).

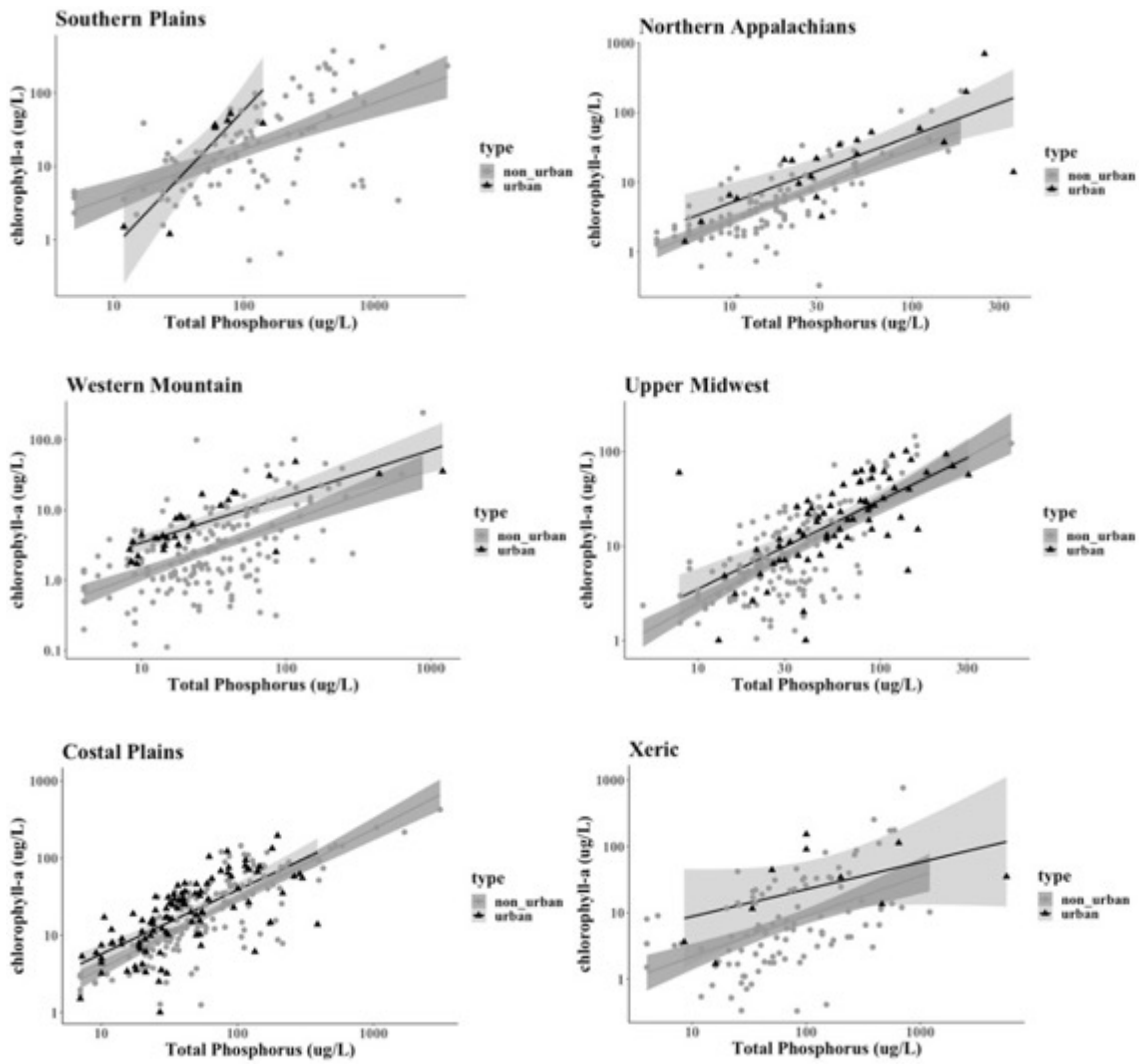

Figure 7. Log-log relationship between Chl-*a* concentration and TP concentration in the lakes within Southern Plains, Northern Appalachians, Western Mountains, Upper Midwest, Coastal Plains, and Xeric ecoregions. Each symbol represents an individual sampling data.

Causes of impairment

The EPA geospatial dataset of the impaired waters included 17,621 lakes that were defined as impaired under Section 303 (d) of the Clean Water Act across the continental United States. Out of this list, 526 lakes were identified as urban using our criteria. Very often a lake was impaired by several contaminants or causes. Excessive nutrients was the most reported cause of impairment for urban lakes listed as impaired in the 303 (d) list (Fig. 8 A). Fish tissue contamination was the second most reported problem in urban lakes. More than 12% of urban lakes were included on the 303 (d) list because mercury concentration in game fish exceeded health-based limits. Pathogen contamination was also a major water quality concern threatening recreational suitability of these lakes. Based on the national summary of impaired waters, pathogens, metals (other than mercury), and nutrients were the three most reported causes of impairment for 303 (d) listed non-urban lakes (USEPA 2016) (Fig. 8 B).

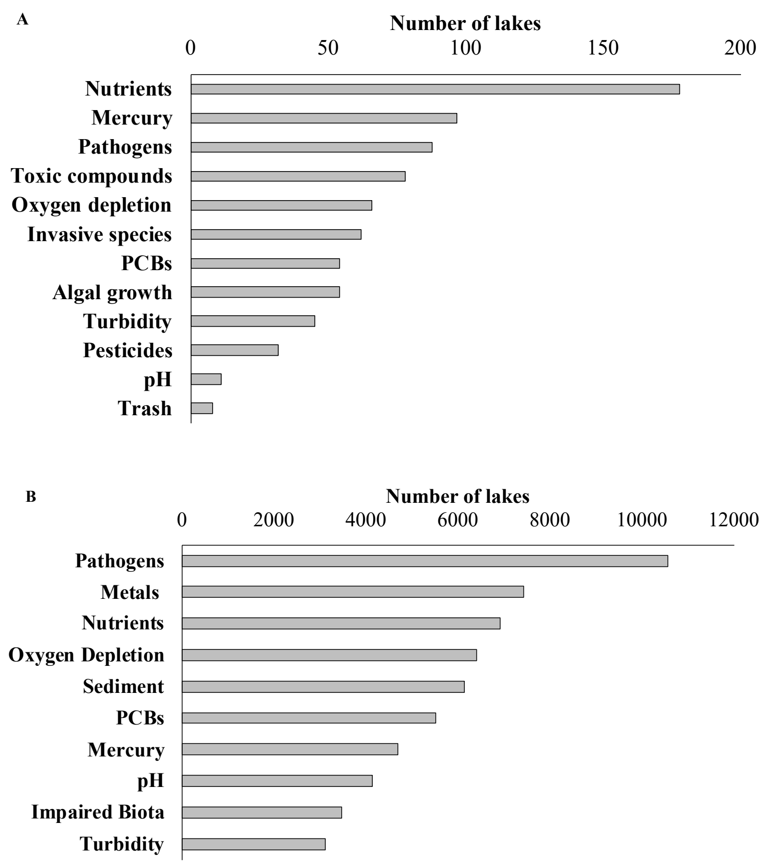

Figure 8. Ten most reported causes of impairment for 303 (d) listed urban lakes (A) and non-urban lakes (B) (from USEPA 2015 dataset).

Ecosystem services and management

Urban lakes considered in this study contributed to the resilience and sustainability of urban areas by providing a variety of ecosystem services and benefits (Fig. 9). Based on the extensive search through reports, primary literature or personal communications with management entities we found that lakes within urban areas were the central feature of many residential developments and provided cultural ecosystem services (i.e., recreational and fishing opportunities or aesthetic enjoyment). The non-material benefits that people obtain from lakes were related to recreational uses and included a range of activities such as fishing, swimming, boating or kayaking. Urban lakes also provided aesthetic benefits to both waterfront residents and tourists. In addition, these systems were important in supporting terrestrial and aquatic wildlife habitat and supplying water for both industrial and municipal uses. These ecosystem services closely matched the designated use categories defined under the Clean Water Act and identified though the 303 (d) list of impaired urban lakes.

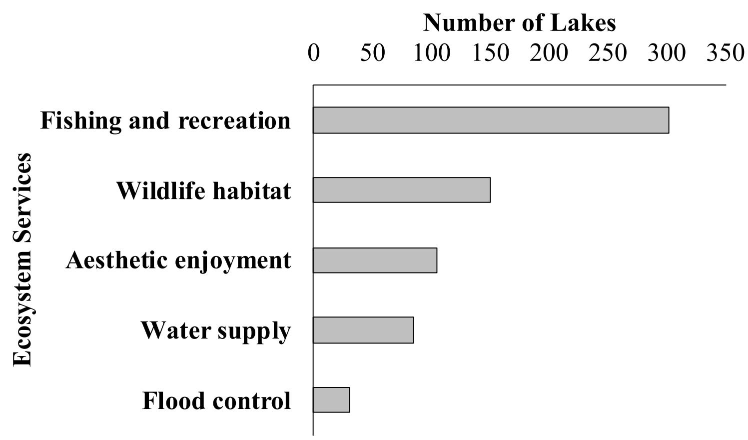

Figure 9. Ecosystem services provided by urban lakes identified in this study.

Management activities for urban lakes were rarely reported in the literature or in official reports. We found in-lake management information for 10% of the urban lakes. Alum treatments, sediment dredging, herbicide treatments to control invasive aquatic plants, and fish stocking were the most frequent in-lake management activities reported (Fig. 10). Watershed-level restoration and management efforts were reported for 30% of the urban lakes.

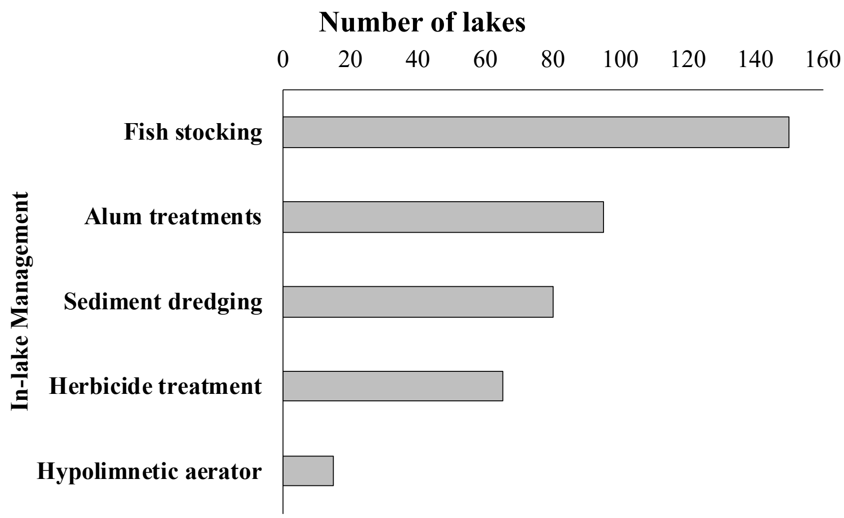

Figure 10. In-lake management activities reported by some of the urban lakes considered in this study.

Discussion and Conclusions

Lakes within urban watersheds were more eutrophic than non-urban lakes, except in agriculture dominated ecoregions, where agricultural land uses are a greater source of nutrients than urban land uses (Coulter et al. 2004; Lenat and Crawford 1994). In the Coastal Plains and Temperate Plains ecoregions, which have a long history of agriculture and high densities of livestock operations, a higher proportion of lakes in the most disturbed condition based on phosphorus concentration were non-urban. In these ecoregions, decades of fertilizer application and manure runoff have resulted in accumulation of P in soils and sediments that provide a long-term source of P to surface water (Motew et al. 2017) and may have overwhelmed best management practices adopted at the watershed scale (Meals et al. 2010). In these areas other potential causes like geology, soil type or vegetation could also influence water quality.

We were only able to obtain limited data and characterize a small subset of urban lakes. Data limitations may account for some of the apparently conflicting trophic state classifications. For example, more urban lakes than non-urban lakes were classified as eutrophic or disturbed based on consideration of Chl-*a* concentration than from TP concentration. Urban TP data was more variable than the non-urban data, and non-urban Chl-*a* data was more variable than urban data. We combined datasets drawn from different sources to characterize urban lakes, and differences in the sampling timing and frequency between TP and Chl-*a* datasets could have biased the results and influenced the summary statistics and our results.

Phytoplankton productivity in shallow lakes is less likely to be light limited and therefore shallow lakes are more responsive to nutrient enrichment and prone to higher productivity. As indicated by Phillips (2008), lake depth can influence the nutrient-chlorophyll relationship since chlorophyll response to nutrients significantly increases as depth decreases. Light limitation in deep lakes can diminish Chl-*a* yield despite high TP concentrations (Stauffer 1991). Chlorophyll response to a given total phosphorus concentration can be influenced by a number of factors including the nitrogen to phosphorus (N:P) ratio (Filstrup and Downing 2017). A reduced response to P would be expected in N-limited lakes with TP concentrations greater than 100 µg/L (Smith and Shapiro 1981).

The Chl-*a* response to increasing P concentration was more sensitive in urban lakes than in non-urban lakes in the Southern Plains ecoregion. The Southern Plains ecoregion was characterized by a high number of non-urban lakes with a TP concentration >100 µg/L. We did not consider total nitrogen data in our study because this information was not commonly available. As a result, we cannot investigate the TN:TP ratio, but nitrogen limitation could be an important factor in the lower sensitivity of non-urban lakes in the Southern Plains to increasing P concentration. We only found a difference in the TP/Chl-*a* relationship between urban and non-urban lakes in the Southern Plains ecoregion, which indicates that urban lakes respond differently to TP reduction than non-urban lakes in this ecoregion. Future studies should investigate the relationship between TP and Chl-*a* in urban lakes to assess any possible management implications.

Recreational (fishing, boating, swimming), wildlife habitat, and aesthetic benefits were the most common ecosystem services provided by urban lakes. Recreation and aesthetic benefits are related to visual perceptions of water quality. More than 70% of urban lakes across the United States had water transparency <1.5 m, which indicates eutrophic or hypereutrophic conditions. Angradi et al (2018) reported that Secchi transparency of <1 m is associated with poor recreational benefits. Based on this threshold, most urban lakes had low recreational and aesthetic appeal in every ecoregion except in the Western Mountain. Urban lakes are not providing the level of ecosystem services and benefits they could provide if water quality were improved through better management.

Urban lakes face a wide array of problems that also need to be considered in watershed management and planning programs. The EPA 303 (d) data for urban lakes indicated that they were mostly impaired by contaminants like excessive nutrients, mercury contaminations and toxic compounds that pose a serious health threat to people engaging in recreational activities in these lakes. Dynamics of mercury and toxic compounds in urbanized areas is still poorly understood, which can lead to management and sustainability issues (Taylor and Owens 2009). Furthermore, urban development will likely exacerbate the presence of these contaminants (Li et al. 2013). More targeted management may, therefore, be necessary to address the particular challenges urban lakes are facing.

We used population density and percentage of impervious surface metrics define "urban watershed". In common usage, the term "urban" also captures a complex mix of attributes like diverse development patterns, land use policies, socio-economic, and microclimatic conditions. These additional variables also influence urban lake water quality. Although we used a simple definition of "urban", our results offer important insights into both the trophic state and the socio-ecological value of these valuable urban ecosystems.

Management information for most urban lakes is either not reported or not available. Given their presence in urban areas with high population density and demand for recreational and aesthetic ecosystem services and the anticipated increase in urbanization in the future, there is a clear need for better limnological monitoring of urban lakes to inform management and protect the ecosystem services they provide (Allan et al. 2015). Lakes in urban areas also warrant special attention because they play an important role in urban resilience and environmental justice (Raymond et al. 2016). More comprehensive characterization of urban lakes is necessary to fully assess whether urban lakes demonstrate unique limnological features that require an urban lake-specific management approach.

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Chapter 3

Effect of management on water quality and perception of ecosystem services provided by an urban lake

Abstract

Integrating water quality perceptions of lake users into management efforts can be an effective way of developing and evaluating management plans targeted at preserving lake ecosystem benefits. We present a case study of Oswego Lake (OR), an urban lake that has been intensively managed for the past twenty years to preserve valuable aesthetic and recreational benefits. We combined the analysis of a long-term water quality dataset with survey data to assess if management efforts over time successfully met the expectations of people using the lake. The synergistic impact of both in-lake and watershed management activities significantly reduced whole lake nutrient concentrations, however, high external phosphorus loading from native soil sources and the surrounding urbanized watershed significantly contributed to episodes of cyanobacteria blooms during the summer and partially limited in-lake management efforts. Although there was no statistically significant change in water transparency over the twenty-year management period, 60% of the survey respondents thought the water quality had improved since they started using the lake. The lake was also perceived as "suitable" for aesthetic and recreational enjoyment by users. As with other lakes in highly developed urban watersheds, Oswego Lake requires on-going interventions to maintain adequate water quality. Management challenges include coordination of multiple stakeholders and jurisdictions with sometimes conflicting goals and constituencies, maintaining a long-term monitoring program that can produce consistent high-quality data necessary for

evaluating the efficacy of management activities, and keeping in touch with user groups to ensure that lake water quality meets expectations.

Introduction

Lakes in urban areas contribute to the quality of life by providing opportunities for recreation, social and physical activities that are directly associated with human wellbeing, and psychological benefits (Volker and Kistemann 2011, Foley and Kistemann 2015). These freshwater systems also have a high economic value by enhancing the appeal of residential real estate (Nicholls and Crompton 2018). The popularity of urban lakes and the demand for related ecosystem services, defined as the benefits that people receive from the natural environment, is increasing as a result of rapid urban development (Walker and Lucke 2019). Despite their importance, lakes in many urban areas have degraded due to the excess nutrient and pollutant runoff from the surrounding watershed (Huser et al. 2016, Welch et al. 2019). Changes in water quality and the resultant reduction of ecosystem services and benefits directly impacts human well-being (Keeler et al. 2012). Maintaining or restoring water quality necessary to preserve these systems and guarantee the provision of ecosystem services is, therefore, increasingly important.

Very few lakes are managed and regularly monitored to ensure the water quality is maintained to an appropriate level to maximize the provision of ecosystem services. Resource constraints often result in lake management that is reactive to specific problems, such as cultural eutrophication, presence of invasive aquatic macrophytes (Walker and Lucke 2019), or one-dimensional management for specific services, such as fisheries. Lakes are complex systems and maintenance of a suite of ecosystem services, particularly in urban lakes, requires ongoing integrated catchment and/or in-lake interventions (Cooke et al. 2005). The implementation of a management approach that integrates the provision of multiple ecosystem services is endorsed by many researchers and resource managers but still rarely executed (Elliff and Kikuchi 2015, Biggs et al. 2016).

Recent studies have highlighted the importance of linking water quality indicators to recreational benefits to develop management plans targeted at preserving lake ecosystem benefits (Angradi et al. 2018). Smeltzer and Heiskary (1990) linked user perception of lake water quality to eutrophication-related measurements to highlight the importance of using lake user surveys in developing region-specific or even lake-specific management applications. We present a case study of an urban lake that has been intensively managed and routinely monitored during the past twenty years to preserve its aesthetic and recreational benefits. Using survey data we assessed whether lake management has met the water quality expectations of lake users.

The lake is mainly used for water-related recreation activities by people that live near and around the lake and significantly contributes to the appeal and value of waterfront residential properties. Historically high phosphorus concentration in the lake caused cyanobacterial blooms and lake closure due to risk of toxins. An annual mean total phosphorus concentration of approximately 20 μg/L was established as a management objective to maintain water quality desired by users and prevent cyanobacteria blooms.

The overall goal of this study was to examine whether in-lake management practices complemented by efforts to reduce nonpoint nutrient pollution from the watershed successfully maintained water quality adequate to preserve the ecosystem services provided by this urban lake. We analyzed a long-term dataset that included several water quality parameters to identify and evaluate trends in the lake's water quality that could influence recreational benefits with a focus on the potential effects of different management practices. We aimed to determine whether management activities can successfully reduce nutrient concentrations, the cyanobacteria population, and improve the recreational benefits in a lake in a high-density urban watershed.

Materials and Methods

Study site description

Oswego Lake (45°24'34"N, 122°41'47"W, Fig. 1) is located in northwest Oregon, approximately 13 km south of the city of Portland. The lake was formed naturally 13,000-15,000 years ago by the Missoula Floods. In the 1921 the lake was dammed and in the following century development started in the area surrounding the lake. Today the lake is completely surrounded by the City of Lake Oswego and has a watershed area of 18 km^2 that is dominated by urban areas (68%) and forest cover (19%). The climate in the region is characterized by wet, mild winters and dry, warm summers with annual average precipitation of 962.1 mm, falling mostly during late fall to early spring as rain (Franczyk and Chang 2009).

Figure 1. Map of Oswego Lake and its watershed boundary.

Oswego Lake has a total area of 1.7 km^2 and consists of 1 deep basin, 2 shallow basins, and 2 canals. It has a maximum depth of 16.7 m and a mean depth of 7.9 m. The lake is a mesotrophic, monomictic lake with thermal stratification that usually occurs from March or April to October. The lake's hydrologic system includes one outflow to the Willamette River, 3 inflows, and approximately 70 storm water outfalls (Grund 2018). Water is imported from the Tualatin River via a regulated canal to maintain water level during the summer. The Tualatin River drains an 1844 km^2 basin characterized by highly developed urban and agricultural areas. In addition to runoff from the different land uses, the high native-soil phosphorus (P) concentrations are also a nonpoint source for the high (>100 mg P/kg) Tualatin River P concentration (Abrams and Jarell 1995).

Total maximum daily loads (TMDLs) for ammonia-nitrogen and total P were developed for the Tualatin River basin in 1988. The implementation of the TMDLs reduced nutrient loading to the Tualatin River and consequently to the lake during the summer (ODEQ 2001) but only partially benefited management efforts. Johnson (2009) showed that during storm events large amounts of sediment and P were still transported within the watershed and significantly contributed to the lake nutrient enrichment. The inflow of nutrient- and sediment-rich water has resulted in the accumulation of P-rich sediments in the lake (ODEQ 2001).

The Lake Oswego Corporation (LOC), a non-profit organization, manages the lake. Access to the lake is regulated through easements. Approximately 3000 homes within the watershed have land deeds that provide lake access and lakefront easements for boating and recreational use of the lake. The 693 properties bordering the lake and canals are referred to as “shareholder” properties as they are issued voting stock proportionately based on the linear length of their property’s lake frontage.

Management history

Numerous in-lake management techniques have been applied to reduce the lake phosphorus concentration, to control blooms, and maintain the recreational value of the lake (Fig. 2). Prior to 2000, copper sulfate was routinely applied to reduce the algal abundance. This practice was stopped in 2000 in consideration of the possible adverse effects of copper on the aquatic environment. Hypolimnetic aerators were installed in 2001 to increase oxygen concentration in the hypolimnion and reduce P release from sediments. Surface alum applications started in the summer of 2005. In the last fifteen years, an average of 157,000 kg of alum were applied through the summer. Water flow though the main canal from the Tualatin River has been progressively reduced starting from 2010 to control the external P inputs. Results from a previous study showed that management efforts caused summer phytoplankton assemblages to switch from cyanobacteria dominance (2000-2005) to diatom and chlorophyte dominance (2006-2013) (Grund 2018).

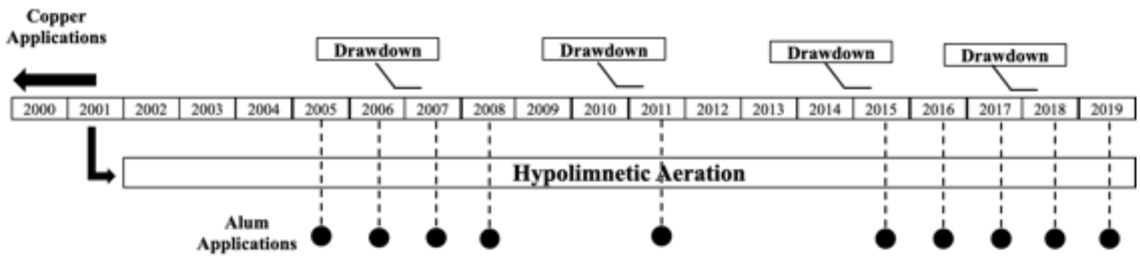

Figure 2. In-lake management action in Oswego Lake.

Other lake and watershed activities have influenced lake water quality. The lake was drawdown four times in the past 14 years for seawall and dock maintenance. In 2010 the Oswego Lake Watershed Council was formed to improve the watershed, with a focus on restoring streambanks with native vegetation. Several storm water best management practices (e.g., wet retention ponds, dry detention ponds, swales, and infiltration rain gardens), and bank stabilization through promotion of native vegetation and removal of invasive species along stream banks have also been implemented to reduce nutrient loading to the lake.

Water quality monitoring program

A long-term monitoring program was established in 1999 to track changes in water quality and evaluate the impacts of management activities. Physical, chemical and biological parameters were measured weekly or biweekly at 6 sampling locations (Fig. 3). Here, we only considered data collected at the Main Lake Central location (MLC) since over time the water quality in both canals and in Lakewood Bay, West Bay and at the Outlet followed the same trends of the MLC

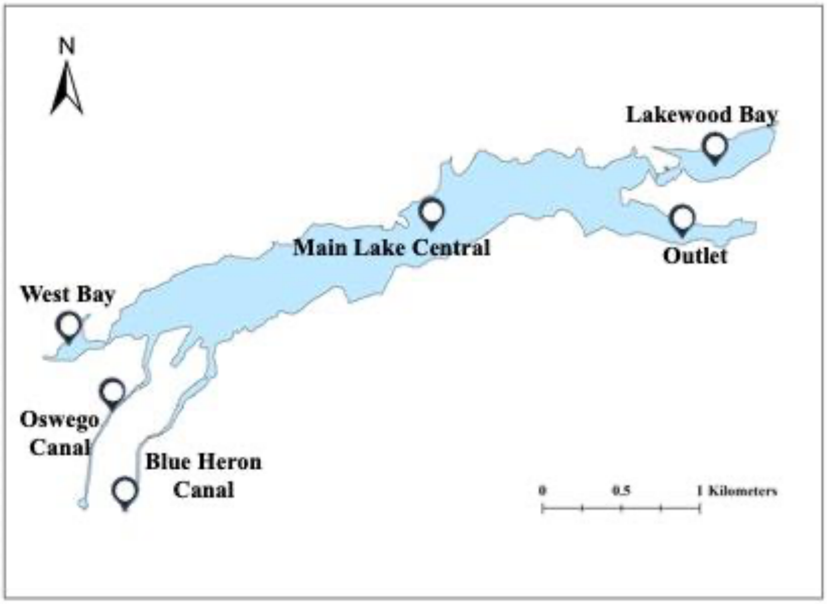

Figure 3. Routine sampling locations in Oswego Lake.

Profiles of temperature, pH, percent saturation of dissolved oxygen, and specific conductivity were recorded at every meter from surface to 14 m using YSI 6600 multiparameter water quality sonde, which was calibrated according to manufacturer's recommendations prior to each sampling event. Transparency was measured with a 20-cm black and white Secchi disk. Water samples for chemical and biological analyses were collected using a Kemmerer sampler from specific depths. The epilimnion and the hypolimnion were characterized with a depth-integrated composite with equal volumes (333 ml) from 1, 3, and 5 m and 10, 12, and 14 m, respectively. A separate sample was collected at 14 m to characterize the water quality near the bottom of the lake.

Water for analysis of total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate+nitrite nitrogen (NO_3^-+NO_2^-) and total ammonia nitrogen

(NH_4^+) and iron (Fe) were collected in acid-washed bottles, kept in a dark cooler in the field, and shipped overnight to Aquatic Research, Inc. (ARI) in Seattle, Washington. Samples were analyzed using the ascorbic acid method to determine TP and SRP (detection limits of 0.002 mg/L for TP and 0.001 mg/L for SRP), the persulfate digestion method to determine TN (detection limit of 0.05 mg/L) and the ion chromatographic method to determine NO_3^-+NO_2^- (detection limit of 0.001 mg/L) (APHA, 2012). Inductively coupled plasma-atomic emission spectrometry was used to analyze the presence of Fe in water samples (detection limit of 0.01 mg/L) (EPA 1994) and the 4500 NH_3 method was used to determine NH_4^+ (detection limit of 0.01 mg/L). Duplicate samples were also included in the analysis as a quality control measure.

Chlorophyll a (Chl-*a*) samples were obtained on the day of collection by filtering 200-300 mL of water with the addition of 1 mL of saturated magnesium carbonate ($MgCO_3$) solution through glass-fiber filters with a 0.45 μm nominal pore size. Chl-*a* was extracted in 90% acetone and determined with a spectrophotometer as described in Standard Methods (APHA, 2012). Phytoplankton samples (500 mL each) were stored in opaque bottles, preserved with 3 mL Lugol's solution per sample, kept in a dark cooler in the field, and shipped overnight to a commercial laboratory for identification. Phytoplankton identification was made to species level where possible. Samples were processed by one laboratory from 1999 to 2013 and by a different laboratory after 2014.

User Survey

We used data from surveys conducted in 2017 and 2020 to evaluate the relationship between recreational and aesthetic benefits and water quality perceptions and expectations. Data were collected using an Internet-based survey. A link to complete the surveys was sent by email to both shareholders and easement members. Invitation emails were sent to 923 shareholders and easement members in November 2017 and in June 2020. Reminder emails were sent after 4 weeks. The 2017 survey identified the benefits that people enjoy the most from Oswego Lake and assessed lake users' attitude towards management efforts. The survey conducted in 2017 also assessed the level of satisfaction toward the lake management services provided by the LOC. Respondents were also asked to describe the benefits and recreational opportunities they enjoy from using the lake (i.e., aesthetic enjoyment, boating, non-contact recreational opportunities or swimming).

The survey conducted in 2020 assessed lake users' water quality perceptions, main concerns, and attitudes towards management efforts. Since it was difficult for people to gauge levels of water quality, we described various scenarios of recreational impairment due to aesthetic problems or the presence of algae blooms. Participants were asked if the aesthetic and recreational benefits provided by the lake were slightly or substantially reduced by the visual presence of algae or if these uses were nearly impossible. Participants were also asked to rate the lake water quality and express their opinion on the suitability of Oswego Lake for recreational and aesthetic enjoyment during the summer. For this study we specifically analyzed questions regarding people's perception of water quality to assess if they thought it improved, remained the same or got worse. Surveys were designed and analyzed using Qualtrics software.

Statistical Analysis

Data analysis was performed using R Statistical Software (R Development Core Team 2020). The seasonal Mann-Kendall test was used to detect the presence of positive or negative trends in the monthly average values of the water quality data. Median slope of all ranked seasonal regression slopes was calculated to estimate the magnitude of trend (Helsel and Hirsh 1992). The mean values of each water quality parameter that showed a significant monotonic trend was used as the dependent variable in the generalized least-square model to assess the influence of management interventions on water quality. Independent variables included surface aluminum application, hypolimnetic aeration and drawdown events. The partial autocorrelation function (PACF) was used to identify the order of the autoregressive model. The best fitted model was based on autocorrelation plots. A chi-square test of independence was used to test if people's perception of water quality was linked to the length of residence time.

Results

Water quality

Hypolimnetic aerators altered the temperature and dissolved oxygen profiles in the lake (Fig. 4). Hypolimnetic aeration caused the thermocline to drop from 4-5 m before aeration to 6-7 m after the onset of aeration. Before aeration the oxygen concentration was <2 mg/L after the onset of thermal stratification and the anoxic depth started at the metalimnion. Aeration decreased both the length of time of low oxygen concentration and the anoxic volume of the hypolimnion. Mean annual nutrient concentrations in the water column of the lake decreased following the onset of hypolimnetic aeration (Fig. 5).

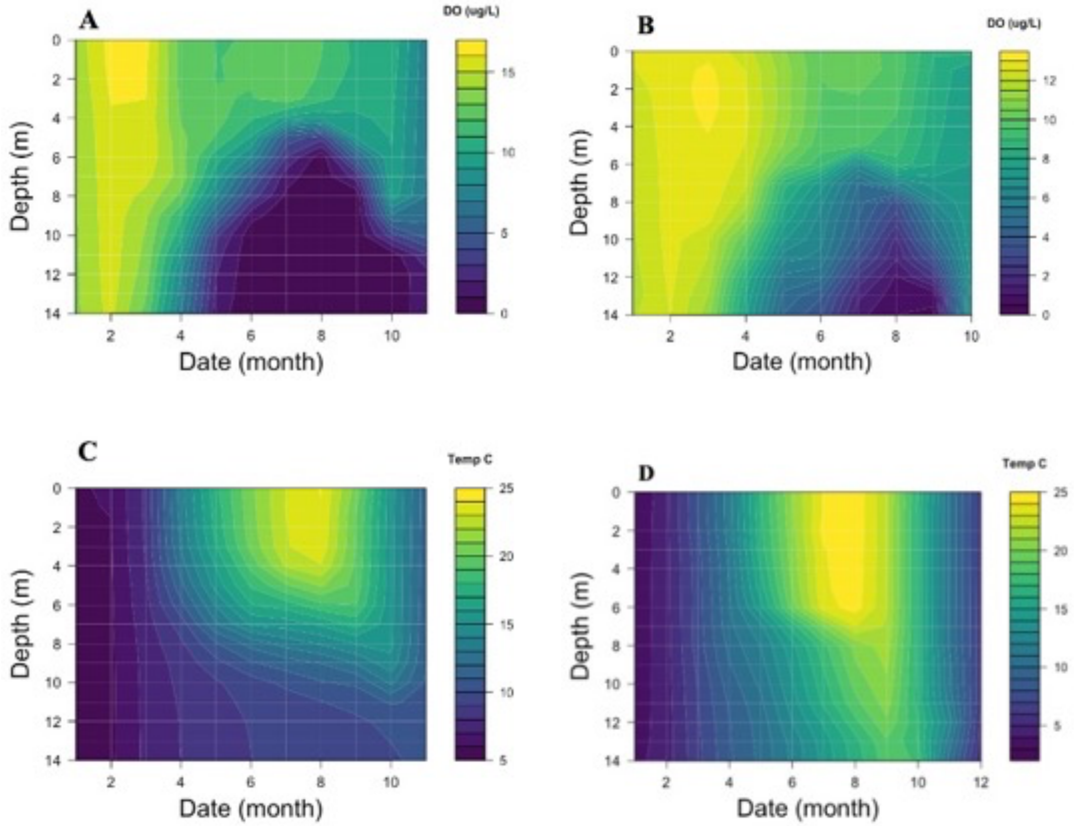

Figure 4. Water temperature and dissolved oxygen (DO) isopleths for the years before (2000) and after (2017) the installation of the aerator. A (DO 2000); B (DO 2017); C (Temperature 2000); D (Temperature 2017).

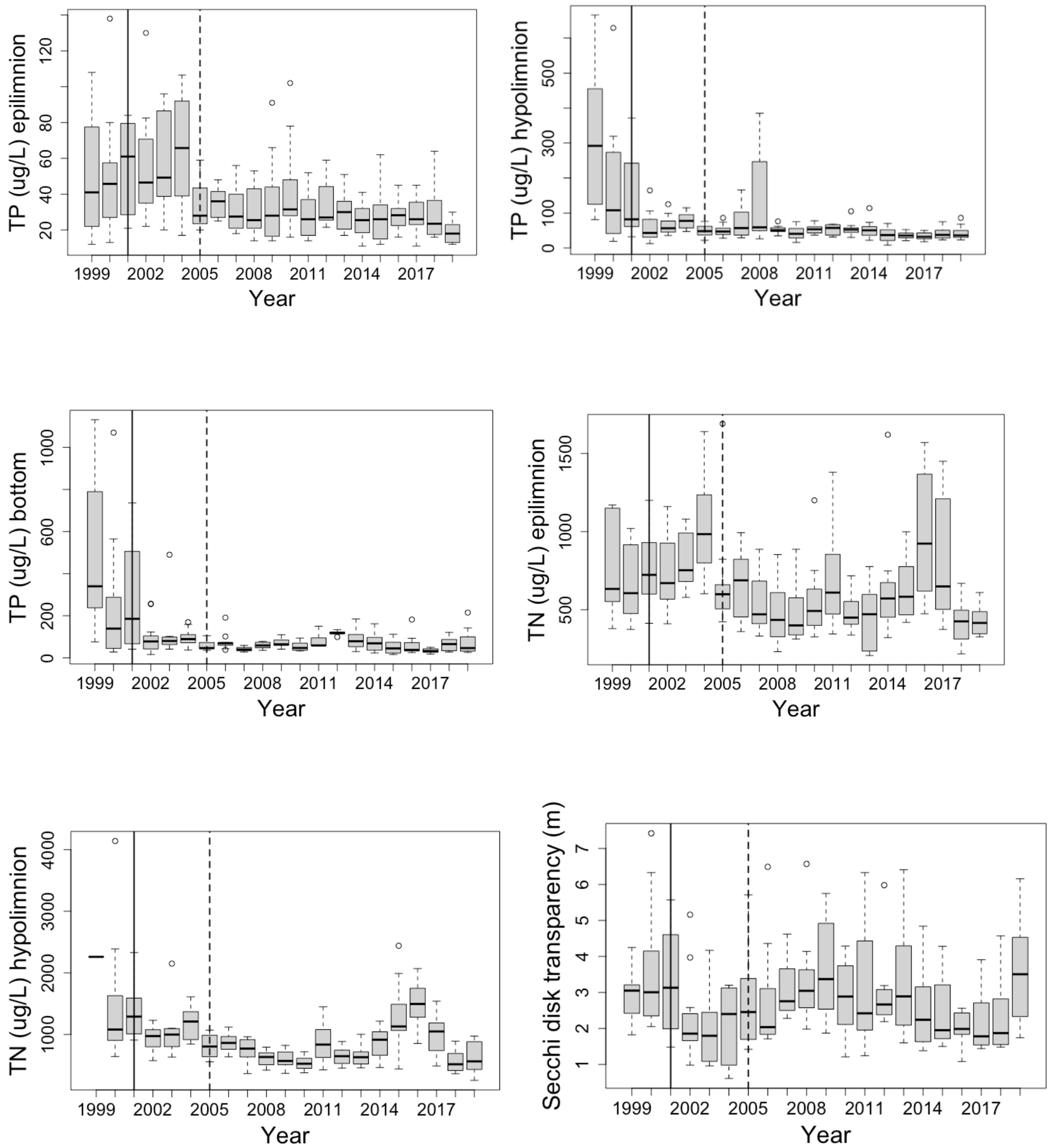

Figure 5: Year-to-year variation of the selected water quality variables. Solid and bold dashed lines represent the onset of hypolimnetic aerators and surface alum treatments, respectively. The boxes illustrate the interquartile range. The horizontal line represents the median. The vertical lines illustrate the maximal and minimal values excluding outliers, and the dots represent outliers.

Varying degree of reductions in nutrient concentrations were observed after the implementation of in-management efforts. Comparison between the pre-treatment years

(2001-2005) and post treatments years (2006-2019) averages revealed that epilimnetic TP declined by 45.5%. In the hypolimnion the largest year-to-year decrease occurred when hypolimnetic aeration began in 2001. Post-treatment average showed hypolimnetic TP was reduced by 72.9%. From pre-treatment conditions, average TP concentrations in the samples collected at 14 m, which was within 1 m from the bottom of the lake, decreased 70.6% after treatments. Mean SRP concentration declined 73.6% in the epilimnion and 60.3% in the hypolimnion following hypolimnetic aeration and alum treatments. Mean TN concentration declined 25.3% in the epilimnion and 40.9% in the hypolimnion. Alum treatments significantly reduced the proportion of cyanobacteria in the phytoplankton community. The average summer Secchi disk transparency (May to September) showed no statistical changes. The lowest Secchi depths were measured during summer 2003 as a consequence of *Microcystis* bloom events. Mean Fe, NH_4^+ and NO_3^-+NO_2^- concentrations also showed no statistical changes.

Input of the Tualatin River water influenced Oswego Lake water quality. Spikes in TN and cyanobacteria concentrations were measured during years when the headgate that regulates the inflow of water from the river was opened earlier than usual to raise the lake water level. In 2006 there was an increase in TP concentration in samples collected at 14 m, probably because one aerator compressor was down most of the summer and the first alum application was delayed until late August. The Mann-Kendall test and Sen's Slope estimator applied on the 1999-2019 datasets indicated that there were statistically significant negative trends for TP (epilimnion, hypolimnion and bottom), TN (epilimnion and hypolimnion), SRP (epilimnion and hypolimnion) The analysis also revealed the percentage of cyanobacteria showed a statistically significant negative trend following the implementation of alum treatments (2005 to 2019) (Table 1). Turbidity, Secchi depth and Chl-*a* concentration did not show any significant trends.

Table 1. Descriptive statistics of the water quality variables considered in the study collected in the epilimnion (epi), hypolimnion (hypo), and near the bottom of the lake. *Statistically significant trends over time.

Variables	**Unit**	**Median**	**Mean**	**Min**	**Max**	**Seasonal Sens slope**	**Trends**	**Kendall-tau**
TP (epi)	μg/l	30.15	37.82	11 (2014)	138 (2000)	-1.28	↓*	-0.394
SRP (epi)	μg/l	2.0	6.233	0 (2014)	63 (2011)	-0.11	↓*	-0.417
TN (epi)	μg/l	577.5	654.4	207 (2013)	1690 (2003)	-12.67	↓*	-0.247
TP (hypo)	μg/l	50	74.44	8.0 (2015)	660 (1999)	-2.12	↓*	-0.35
SRP (hypo)	μg/l	4.66	16.6	0 (2014)	297 (2008)	-2.12	↓*	-0.5
TN (hypo)	μg/l	841	919	255 (2019)	4140 (2000)	-23.14	↓*	-0.3
Secchi	m	2.53	2.954	0.61 (2004)	7.42 (2000)	-0.011		-0.05
Cyanobacteria (2005-2019)	percent	42.7	45.5	0 (2008)	98.5 (2016)	-0.69	↓*	-0.48
TP (bottom)	μg/l	66	108.89	16 (2002)	1131.5(1999)	-3	↓*	-0.355

The GLS regression models identified possible management drivers for the trends in water quality parameters included in the analysis. Alum surface application was the most important predictor of change of TP concentration in the water column (epilimnion, hypolimnion and bottom), SRP in the epilimnion and reduction in the percentage of cyanobacteria ($P < 0.05$). The hypolimnetic aerator was important in explaining the variation of TP in both the hypolimnion and bottom ($P < 0.05$) (Table 2).

Table 2. GLS regression model results (p-values). *Statistically significant trends (P<0.05).

	Hypolimnetic aerator	Alum application	Drawdown
TP epilimnion	0.58	**0.015***	0.38
TP hypolimnion	**< 0.01***	**0.023***	0.49
TP bottom	**< 0.01***	**< 0.01***	0.10
TN epilimnion	0.97	0.44	0.71
TN hypolimnion	0.34	0.59	0.48
Cyanobacteria	0.59	**0.03***	0.18
SRP epilimnion	0.31	**0.016***	0.43
SRP hypolimnion	0.13	0.41	0.44

Survey results

The response rate for the surveys conducted in 2017 was 65.5% and 56% for the surveys conducted in 2020. The vast majority of respondents in the study (99.8%) lived in a waterfront property and 53.6% of them have lived near Oswego Lake for more than 15 years. People were generally satisfied with the lake management services provided by the LOC. Based on the 2017 survey, the majority of the respondents (77%) reported being "very satisfied" with the quality of services and lake management, 20% are "somewhat satisfied", and only 1% were "not too satisfied". In both years the surveys were anonymous so we could not assess if survey respondents were the same.

All the ecosystem services and benefits values reported to be important by the respondents were directly related to water quality. The majority of the respondents reported that aesthetic enjoyment of the lake was the preferred benefit followed by boating, non-contact recreational and socializing opportunities. Few people valued swimming. Fishing is not a common use of the lake (Fig. 6).

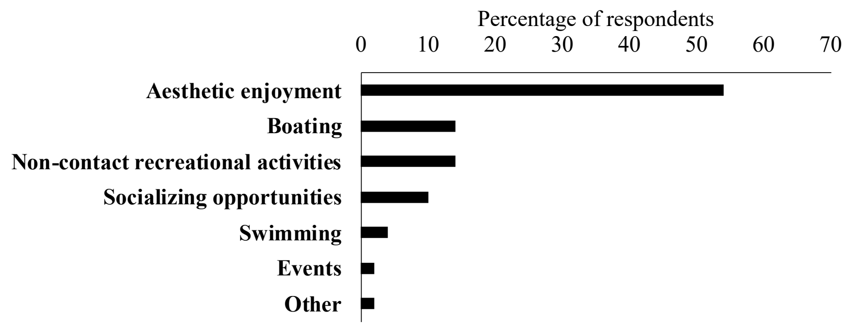

Figure 6. Benefits and recreational opportunities provided by Oswego Lake based on the 2007 survey results.

In 2020, more than 60% of the people that have access to the lake thought the water quality had improved since they started using the lake. Only 5% of those surveyed reported that it had gotten worse (Fig. 7).

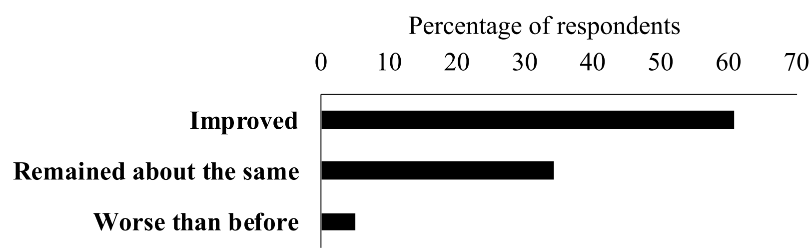

Figure 7. Perception of Oswego Lake water quality based on the 2020 survey results.

The majority of the respondents (57.3%) rated the lake water quality as “good”, 10% consider the water quality “excellent” and 30% “acceptable”. Only 2.5% of the respondents considered lake water quality as “poor”. Results of the Chi-square test indicated that the user’s perception of water quality was not linked to the length of time people lived in a property near the lake. Forty-four percent of the respondents replied that during the summer the lake water only presents very minor aesthetic problems, and it is excellent for swimming, boating and aesthetic enjoyment. Swimming and aesthetic enjoyment were found to be slightly impaired because of visual presence of algae by

39.5% of the lake users; 4.1% reported that the swimmability and enjoyment of the lake during the summer was substantially reduced because of the algal abundance and for 0.9% of the respondents these uses were nearly impossible. Based on the survey results, keeping the lake safe by reducing the frequency of algae blooms was the first concern of people using the lake.

Discussion and Conclusions

The combination of management practices, such as hypolimnetic aeration and alum treatment, significantly reduced the TP concentration in the lake water column. Consistent with the literature, this study found that in-lake measures are the most feasible management strategies to reduce nutrient concentrations in urban lakes (Huser et al. 2016). While the effectiveness of alum addition to reduce P cycling in lakes is well established (Huser et al. 2016), the effects of hypolimnetic aeration on phosphorus reduction are somewhat contradictory; positive (Ashley 2011, Bryant et al. 2011), negative (Niemistö et al. 2016), or non-significant effects (Schauser and Chorus 2007) have been published. Our results showed a significant initial decline in hypolimnetic TP following the onset of aeration. Due to the overlap between treatments we could not separate the role of the alum treatment and hypolimnetic aeration in nutrient reduction.

We only considered the potential impact of in-lake management efforts (i.e., alum treatments, hypolimnetic aeration and drawdown events) in our analysis. Results from a previous study (Grund 2018) showed that environmental variables, like temperature and rainfall events, did not influence water quality variables over a 20-year period. Watershed management activities were also carried out in coincidence with the in-lake management efforts. In addition to the TMDL to reduce phosphorus loadings across the Tualatin River subbasin, storm water treatment facilities, measures to control erosion during construction, and practices to reduce the use and loss of phosphorus from homes, gardens, farms, forests, and businesses are also implemented at the watershed scale.

Oswego Lake, based on findings from Chapter 2, is an unusual urban lake due to the large amount of available data and intensive management efforts. To prevent blooms frequent alum treatments are applied. Our results confirmed that intensive in-lake and watershed management actions can improve water quality and maintain ecosystem services and recreational benefits in a lake in a highly developed urban area. Although TP concentration declined as a result of management efforts, it remained above the management target of 20 µg/L, which was set by the LOC as a potential threshold to control the onset of cyanobacteria blooms. Despite the high level of management efforts, water clarity didn't show any significant improvement.

An accurate phosphorus budget that identifies the relative importance of different phosphorus sources and allows implementation of management actions that provide the most effective control of nutrient loading is necessary for effective urban lake management (Hobbie et al. 2017, Brito et al. 2018, Faridmarandi et al. 2021). Inflow of nutrient-rich river water contributed to high external P loading that partially counteracted in-lake management efforts. Artificial mixing altered the thermal structure of the lake by causing a thermocline deepening and higher hypolimnetic temperature. Higher temperature increases the activity of microorganisms that enhance the mineralization of organic matter. This process can alter the redox potential of the sediment, which may favor the release of Fe/Al-P or Ca-P (Wang et al. 2015).

Coordination and cooperation of the often multiple management entities and jurisdictions in urban lake watersheds is critical to a comprehensive management strategy, but implementing nutrient management solutions that resolve conflicting upstream and downstream interests among local stakeholders is challenging and often beyond the control of urban lake managers. Urban lake managers also faced the challenge of reconciling differences among multiple lake users with contrasting agendas and priorities that can influence lake water quality. Effective management requires finding a balance between users' preference and needs, and lake water quality. For instance, drawdowns provide opportunities for lake and facility maintenance, but the consequence of water level fluctuations can influence water quality (Bakker and Hilt 2016, Pan et al. 2018). Maintaining a steady water level in the lake during the summer requires importing water from the river, which counteract management efforts.

This study supports evidence from previous observations that user survey data can inform data-driven management decisions and could provide a basis for establishing water quality standard and phosphorus criteria (Heiskary and Walker 1988, Heiskary 1990, Smeltzer and Heiskary 1990, Hoyer et al. 2004). Since water clarity is the most easily understood lake water characteristic by non-expert audiences (Angradi et al. 2018) we used this attribute to assess people's perception toward management efforts in maintaining lake recreational suitability. Despite lack of a statistically significance improvement, most Oswego Lake users considered water transparency adequate to provide the recreational and aesthetic benefits they valued. Although measuring water quality is an important element of an effective lake management program, monitoring user perception of water quality may be equally important, and could be critical for setting management goals to ensure that the ecosystem services that people value are maintained. Careful design of survey questions to ensure reliable and unambiguous responses is necessary to gauge changes in user perceptions over time.

Long-term, high quality data are necessary for evaluating the efficacy of management activities. Staff and analyst turnover can compromise data quality, and variation in data introduced by changing methods can limit the ability of a monitoring program to detect lake response to management (Cao and Hawkins 2011). In Oswego Lake, a detailed field sampling procedure manual is used as a reference guide to assist in both field and laboratory procedures, however, a quality assurance project plan (QAPP) that outlines sampling, analysis methods and data quality assurance protocols would ensure more consistent and useful data collection.

Differences in phytoplankton analysts made it difficult to evaluate how management influenced the phytoplankton community. This is particularly problematic when toxic cyanobacteria were a management concern. Conventional counting of phytoplankton by microscopy, as used in Oswego Lake, is often sensitive to identification and enumeration skills of plankton taxonomists (Embleton et al. 2003, Irfanullah 2006, Manoylov 2014). The declining number of trained taxonomists poses a serious limitation to the microscopic identification and quantification of phytoplankton species. A QAPP that specifies taxonomic sufficiency (Jones 2008) and details methods used for collection, preparation, and counting of biological samples is necessary for the collection of information useful for the evaluation of management goals. Alternatively, use of DNA barcoding may provide a more consistent assessment of community composition (Zwart et al. 2005, Kormas et al. 2011, Anand et al. 2019).

This study provides the opportunity to make recommendations that could have a number of important implications for future practice. Maintaining an adequate level of lake water quality to guarantee the delivery of ecosystem services requires ongoing management interventions and monitoring efforts. A limitation of the Oswego Lake management is the lack of implementation of data-driven management strategies to more successfully achieve management objects. A systematic, adaptive management approach for improving resource management may prove more effective in maintaining and improving lake water quality. Available monitoring data can be used to gain insights about the impacts of past management actions and to improve future management efforts.

The importance of adopting an ecosystem-based management approach to preserve urban lakes from degradation and guarantee the supply of ecosystem services is widely acknowledged (Hartig and Vallentyne 1989), although these efforts are often constrained by resource limitations. Surveys can be an effective instrument to assess which ecosystem services and benefits are mostly valued by lake users, if they are carefully structured and repeated over time. Incorporating people's perception of ecosystem services that directly enhance human wellbeing into management plans can offer a valuable argument to support the conservation of these natural ecosystems.

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Chapter 4

Effect of alternative urban development scenarios on the water quality and ecosystem services provided by a major urban lake

Abstract

Land use management decisions developed at the regional scale that are intended to optimize environmental quality could have negative results at a local scale. We downscaled three regional urban growth scenarios to a watershed scale and assessed how different regional land-use scenarios can impact important ecosystem services provided by a major urban lake. The scenario that depicted more aggressive growth within an urban growth boundary at the regional scale resulted in a high-density development in the area surrounding the lake at the watershed scale. This type of development resulted in an increase of more than 30% in external phosphorus input to the lake over current conditions. Higher external phosphorus input will likely lead to water quality deterioration with detrimental consequences for the ecosystem services provided by the lake. Our model forecasted a reduction of 3 to 4 m in lake water transparency, which will diminish recreational benefits provided by the lake and degrade wildlife habitat. Implementation of nutrient management practices in the lake watershed will be necessary to offset the negative impact of urbanization on water quality and related ecosystem services resulting from regional scale planning. Land-use policies developed at regional scales should consider tradeoffs that impact highly valued local sources of ecosystem services.

Introduction

Lakes are a multifunctional component of the urban space and an important source of ecosystem services, such as recreation, fishing, drinking water, and wildlife habitat (Grizzetti et al. 2016; Shallenberg et al. 2013). Environmental changes driven by urban development put pressure on aquatic ecosystems and can lead to degradation of ecosystem services (Keeler et al. 2012; Carstens and Amer, 2019). Rapid urbanization increases the demand for ecosystem services urban lakes provide and exacerbates the vulnerability of these ecosystems to anthropogenic degradation. Maintaining ecosystem services to sustain growing urban needs is one of the greatest challenges to the sustainable development of cities (Grunewald and Bastian, 2017). The failure to forecast the impact of future urbanization on ecosystem services lakes provide could result in the progressive loss of benefits.

A regional scale approach for the management of diverse ecosystems present in a region risks overlooking individual habitat conservation goals and can result in local environmental degradation (Agardy, 2005). Future projections of urban expansion are usually developed for large areas. The specific impact of large-scale policy and management decisions on individual ecosystem is seldom described (Villarreal et al. 2017, Schultz et al. 2019, Gibson et al. 2000). Considering the consequences of management plans developed at the regional scale on local patterns of development is important to effectively manage landscape and preserve valuable ecosystem services. Recognizing and addressing these contextual impacts of policies and land use management decisions is important to ensure a sustainable and resilient environment in the future (Cumming et al. 2006, Turner et al. 2001; Bai et al. 2010).

Understanding how alternative spatial configurations of urban development at the watershed scale can influence lake water quality and the provision of ecosystem services is essential for developing a sustainable and integrated water resource management approach. While the linkages between the percentage of impervious surface or population density within a watershed and lake water deterioration is well-established, these aggregated measures of urbanization only account for a portion of the water quality variability (Alberti et al. 2007). Urban development patterns (e.g. clustered versus dispersed development) at the watershed scale should also be considered when describing the impact of urbanization on the water quality of freshwater systems (Johnson et al. 1997; Wu, 2008).

Rapid urbanization and the consequential increase in impervious area can alter flows of nutrients, pollutants, and sediment that are major threats to lakes (Vorosmarty et al. 2000; Tong and Chen, 2002). Nutrient runoff is mainly driven by land cover (Hoyer and Chang, 2014). In rapidly growing urbanized areas agricultural and wildland areas are converted into urban and suburban lands (Moore et al. 2003). Highly developed areas are characterized by high nutrient export and therefore, can contribute substantially to the loading of nutrients to aquatic systems (Winter and Duthie, 2000; Carstens and Amer, 2019). The analysis of alternative urban growth scenarios is often used to understand possible ecosystem service trade-offs resulting from specific policies or management decisions (Pickard et al. 2017). Even though significant progress in modeling the impact of land use composition on water quality has been made, the response of ecosystems services to alternative patterns of urbanization has not been directly quantified.

The Puget Sound Basin (Washington State, USA) is rich in natural resources, including forests, wetlands, lakes, shorelines and rivers that provide a suite of economically valuable ecosystem services to residents (Zank et al. 2016). Urbanization has substantially altered the landscape of the region and driven changes that have negatively impacted multiple ecosystem services and functions (Cuo et al. 2009). Preserving these ecosystem services across the region is one of the key challenges in planning for a sustainable future. Here, we aimed to quantify the consequences of alternative land policy and management scenarios, developed to assess plausible future development trajectories at the regional scale, on the water quality and ecosystem services provided by Lake Sammamish, a major urban lake in the Puget Sound region. The overall goal of this study was to address the following research questions:

I. Will water quality of Lake Sammamish differ under alternative urban development scenarios?

II. How might water-related ecosystem services change due to water quality deterioration caused by the projected urban growth?

III. What management actions should be implemented to preserve the lake water quality?

Materials and Methods

Study area

Lake Sammamish (longitude 122°05’ W, latitude 47°36’ N) is a freshwater system located 13 km east of Seattle, Washington (USA) (Fig.1). The lake is located in one of the fastest developing regions of the United States, the Puget Sound. This region has experienced high population growth over the past 50 years, and it is expected to grow by about 1.8 million people and to add 830,000 households by 2050 (Hepinstall-

Cymerman et al. 2013). Puget Sound is a multi-jurisdictional region that encompasses several units of government including municipalities and communities. Multiple stakeholders are present across the region.

Lake Sammamish is an important recreation destination that attracts more than a million people every year (Herzog, 2007). It also provides important habitat for aquatic and terrestrial wildlife including several salmon species, warm water fish, and migratory birds (Zank et al. 2016). The lake watershed area is 235 km^2 and land use includes developed areas, forest land, grassland, wetlands and water areas. The lake is surrounded by four cities: Sammamish, Issaquah, Bellevue and Redmond.

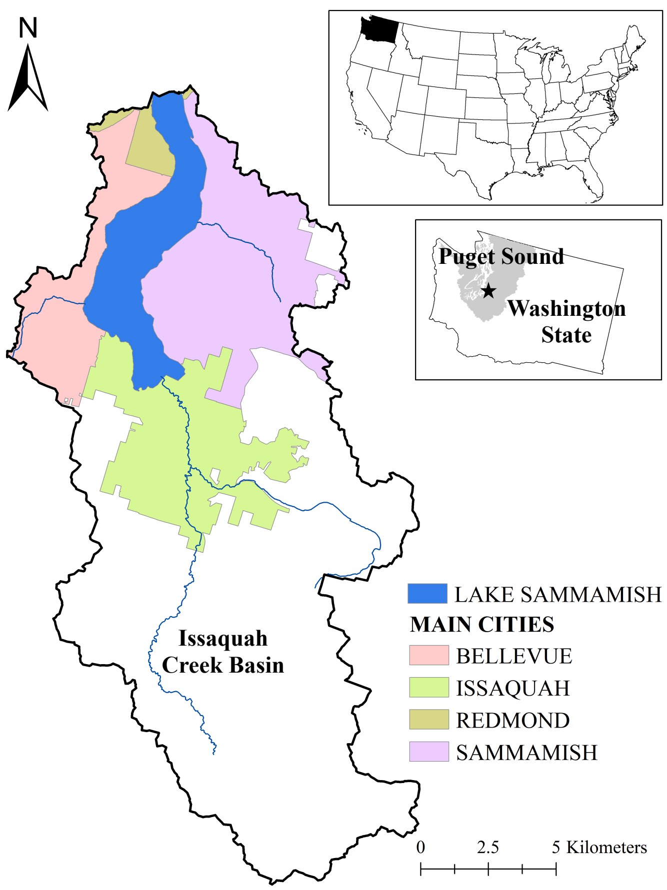

Figure 1. Lake Sammamish watershed and main cities surrounding the lake.

Lake Sammamish has a surface area of 19.8 km^2 with a mean and maximum depths of 16.5 and 32 m, respectively. It is a moderately productive system that thermally stratifies from April to October. The lake water quality has been consistently monitored since 1964 by the Municipality of Metropolitan Seattle (METRO) (Welch and Bouchard, 2014). Nutrient runoff and point sources of pollution negatively impacted the lake water quality for decades (Welch et al. 2019). In the mid-1960s sewage and wastewater were diverted from the lake to reduce the external total phosphorus load by about 35%. Watershed protection plans were also implemented to maintain an acceptable level of water transparency and the lake water quality slowly recovered over time (Welch et al. 2019). In the past four decades, recreational beneficiaries of Lake Sammamish have become accustomed to a lake water clarity of almost 6 m.

Urban development scenarios

Urban development scenario data used in this study were derived from three alternative policies and management scenarios generated by Bolte and Vache (2010). The three scenarios, based on different levels of land conversion and development, depicted a representation of future urban growth for the year 2070 in the Puget Sound region. A high land-conversion scenario (HLC) simulated permissive development under relaxed environmental management rules. This scenario significantly reduced development constraints on those lands zoned for agriculture, forestry and low-density development. In this representation of future land use, new land was converted to developed areas following an urban sprawl pattern and the new population growth was accommodated outside the urban growth areas (UGAs) rather than inside developed areas.

The low land-conversion (LLC) scenario limited the conversion of resource lands to residential uses and simulated clustered urban growth patterns concentrated within the UGAs. This scenario also precluded new coastline development. The intermediate land-conversion (ILC) scenario modeled growth under current development patterns and environmental management rules. The ILC scenario allocated 60 to 80 percent of new growth within UGAs and resulted in a moderate conversion level of agricultural and forested lands to residential. Only private lands were considered for development; no public lands were converted in any scenario.

Each scenario included a set of spatially explicit land-use/land-cover (LULC) raster grid maps of the Puget Sound Region at 30-meter resolution. Each map, including 16 different cover classes, was clipped to the Lake Sammamish watershed for the analysis. To assess multi-scale differences among scenarios, we compared the percentage of each LULC class depicted by each scenario at the regional, sub-basin and watershed levels.

InVEST Nutrient Delivery Ratio Model

The InVEST Nutrient Delivery Ratio (NDR) modeling tool (version 3.7.0), developed by the Natural Capital Project, was used to assess the impact of the three alternative LULC scenarios on the phosphorus (P) runoff across the lake watershed. The InVEST model is widely used to map nutrient sources (phosphorus and nitrogen) and their transport through the watershed using a mass balance approach (Yang et al. 2019; Tallis et al. 2013). Phosphorus availability is typically the most important determinant of lake productivity and water quality (Schindler et al. 2016). We only considered the annual total phosphorus (TP) export outputs from the InVEST model because phytoplankton growth in Lake Sammamish is P-limited and increasing P concentrations could lead to higher chlorophyll-a concentration and lower transparency (Perkins, 1997).

The InVEST NDR model quantifies phosphorus loads from LULC-specific nutrient retention coefficients using the land cover type export coefficient method as described by Sharp et al. 2016. P export coefficients used in this study were derived from an extensive literature search for values relevant to the study site. Since major point sources were diverted out of the basin in the 1970s, it was not necessary to adjust the model output with estimated loads from point sources. The InVEST model was calibrated using available observed TP concentrations measured to estimate total annual nutrient load across the Lake Sammamish watershed, as described by Hoyer and Chang (2014). Spatially explicit model inputs required for the model were manipulated and processed in ArcGIS (v10.3 ESRI, Redlands, CA).

Lake water quality model

The seasonal mass balance TP model developed by Perkins et al. (1997) was used to forecast Lake Sammamish water quality response to the external P inputs generate by the InVEST model based on the future urban development scenarios. This model simulated whole lake TP based on the following equation.

$$\frac{dTP}{dt} = Jext + Jint - S - Q(TP) \qquad \text{(kg/month)} \qquad \text{Eq. 1}$$

Where dTP = change in lake TP per month

J_{ext} = external loading from runoff, precipitation and groundwater

J_{int} = internal loading from bottom sediments

S = sedimentation loss

Q = hydraulic outflow

Total phosphorus export values generated by the InVEST model were used as external inputs (J_{ext}). External loadings also included TP inputs from precipitation, estimated from historic data, and ground water sources. Ground water input into Lake Sammamish was estimated from both hydraulic data and ground water P concentration. The internal loading was calculated as described by Perkins (1997).

Lake sediments can be an important, internal, source of P to a lake. Long term external loading of P can enrich sediments and result in elevated internal P loading. Following wastewater diversion, the sediment P-release rate dropped to ~2.5 mg/m^2 per day, and it has remained stable since 2005 (Welch, 2019). Annual whole-lake TP has remained stable in Lake Sammamish over the past decade, primarily because of this reduction of internal P loading (King County, 2014). This condition might not hold in the future as an increase in external loading could restore a high sediment P concentration and trigger higher internal P loading. To assess the consequences of higher internal loading on lake water quality, predictions of future whole-lake TP concentrations were also developed based upon a historic higher sediment release rate value (3.5 mg/m^2 per day) for each scenario (Welch et al. 2019).

The model was calibrated using observed whole-lake TP concentrations for the 1971-1975, 1981-1986, 1999-2004, and 2005-2011 time periods as described by Perkins et al. 1997. Future water quality was simulated using empirical relationships between TP, chl-*a* and Secchi disk transparency developed from past Lake Sammamish data (Perkins, 1997). Carlson's Trophic State Index (TSI) (Carlson, 1977) was calculated to identify the lake trophic condition under different urban development scenarios.

Watershed management information

Spatial distribution of stormwater facilities including pipes, ditches, swales, ponds, underground tanks and vaults distributed across the Lake Sammamish watershed were retrieved from the King County GIS data hub. We performed an overlay map analysis with each of the TP scenario outputs to assess which areas of the watershed could potentially require more stormwater facilities to compensate for an increase in P runoff.

Results

Urban development scenario analysis

Our analysis of the three future urban development scenarios conducted at the regional, sub-basin, and watershed scales revealed key differences. At the regional scale and across each of the sub-basins, the scenario that depicted the highest land conversion (HLC) showed the largest increase in landscape transitions to residential development from agricultural and forested areas compared to the other scenarios. This scenario, which assumed loose environmental regulations and low-density expansion patterns, also allowed more development of the nearshore areas, which at the regional and sub-basin scales resulted in more population growth allocated to the Puget Sound coastline.

The LLC scenario, which assumed an aggressive set of policies to contain the growth within existing urban areas, resulted in a clustered development pattern, mostly occurring within the UGAs. At the regional and sub-basin scales this scenario resulted in the smallest degree of land cover change, transition to impervious areas, and retention of more forest. The ILC scenario showed a degree of transition to urban developed areas intermediate between the HLC and LLC scenarios. Differences among scenarios were quite evident in the South-Central Sub-basin, where the Lake Sammamish watershed is located (Fig. 2).

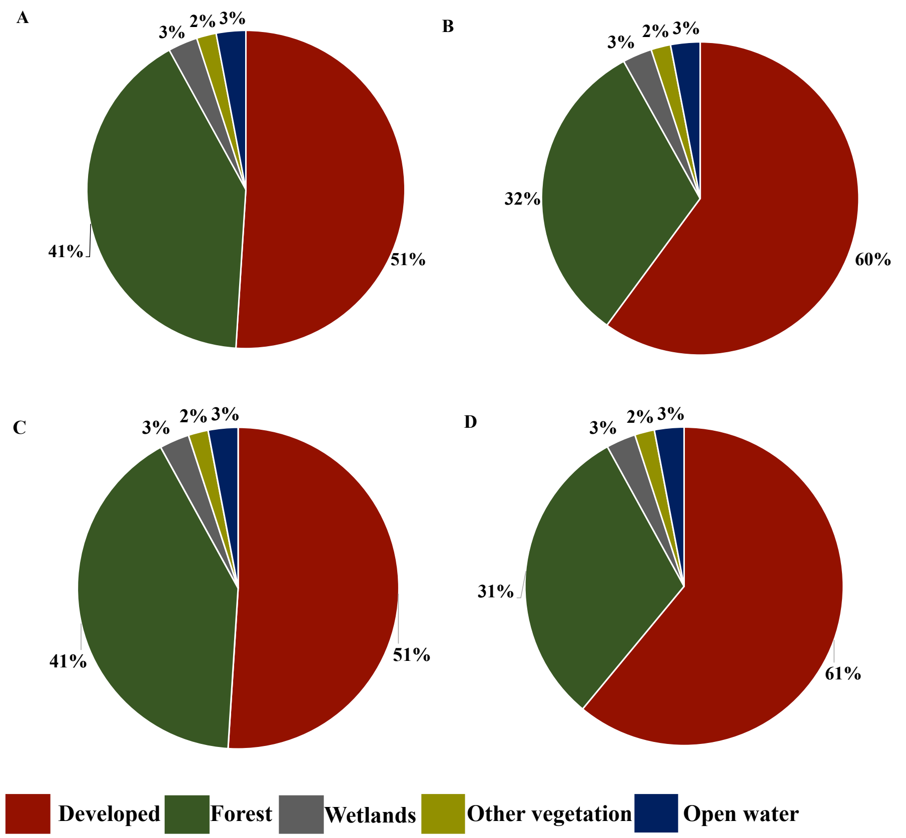

Figure 2. South Central sub-basin Land Use/Land Cover for A (baseline 2006); B (ILC); C (LLC) and D (HLC).

These patterns of landscape development were not consistent at the watershed scale, where urban development dynamics varied among scenarios (Fig. 3). Both the ILC and LLC resulted in a higher concentration of medium-and high-intensity development than the HLC. The clustered urban development depicted by ILC and LLC scenarios mostly occurred in the areas adjacent to the lake (Fig. 4 B and C), where the developed low- and medium-intensity areas transitioned to medium- and high-intensity development, respectively.

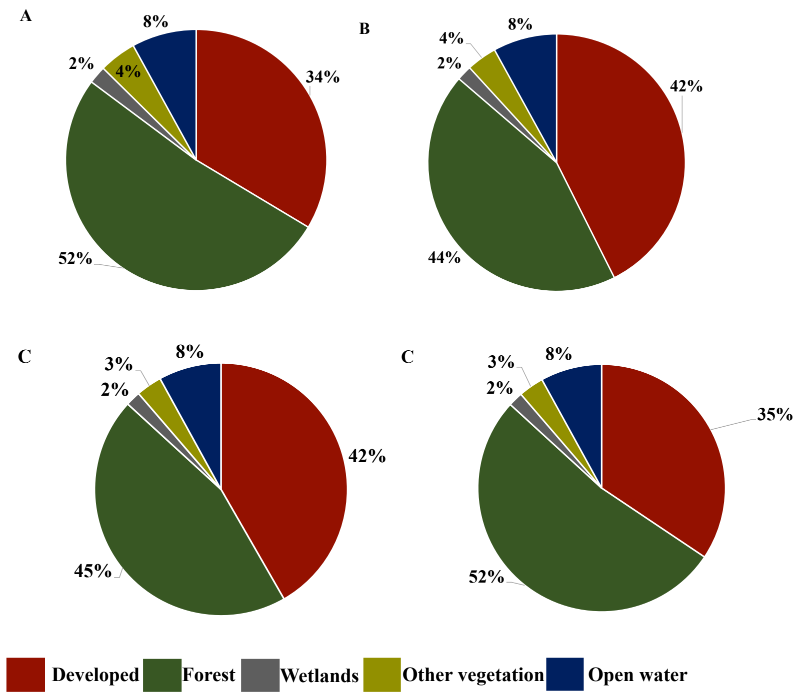

Figure 3. Lake Sammamish watershed LULC for A (baseline 2006); B (ILC); C (LLC) and D (HLC).

The HLC scenario depicts a future urban development mostly based on high conversion of land outside UGAs. This scenario emphasized the redevelopment of areas zoned for agriculture or forestry for residential uses. Within the watershed the areas for agriculture were too small to make a significant difference and the forested areas are mostly on public land and therefore were not considered for conversion. As a result, the HLC scenario resulted in less land converted to developed areas and retention of more forested areas within the watershed. Within the Lake Sammamish watershed there were also fewer alternatives for accommodating future growth outside the UGAs compared to other areas of the Puget Sound region. Therefore, counter intuitively, the urban sprawl pattern captured by HLC scenario resulted in an overall lower amount of urban development in the lake watershed than both the ILC and the LLC scenarios. All three scenarios depicted an increase in urban development within the Issaquah Creek Basin. The ILC and HLC scenarios also resulted in urban growth development in the Southeast part of the watershed (around the Issaquah Highlands).

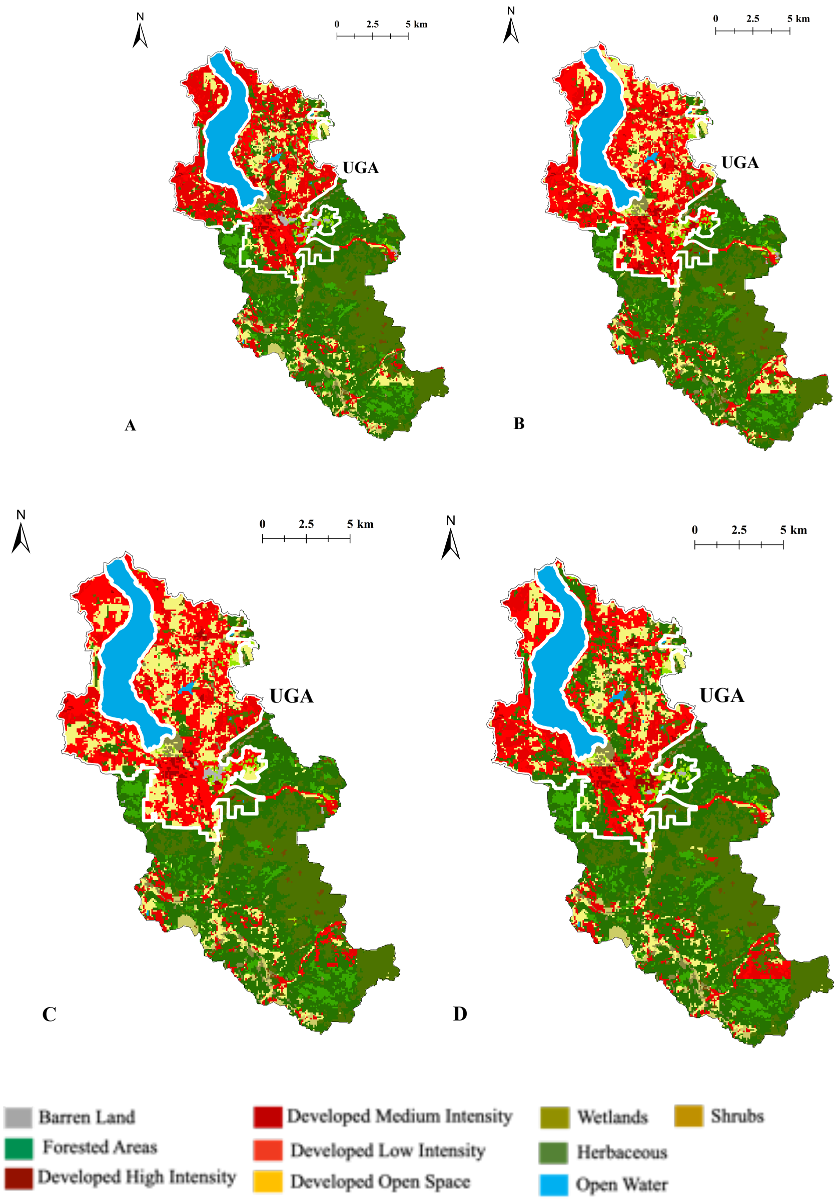

Figure 4: Land-use/Land-cover for year 2006 and 2060 under three different development scenarios (A= 2006; B= ILC and C= LLC; D= HLC). The white line marks the urban growth area (UGA).

InVEST results

After calibration, the values of TP export generated by the InVEST NDR model using the baseline 2006 LULC map were comparable to empirical observations (-0.05%). The InVEST model predicted the highest TP outputs for the LLC and ILC scenarios, that presented a higher percentage of medium- and high-intensity development (Table 1). These land-use classes contributed the most to P runoff within the watershed because of the large footprint of impervious areas, between 50-79% and 80-100%, respectively.

Table 1. TP loading under baseline conditions (2006) and predicted in 2070 under three different LULC management scenarios.

Scenario	TP export (kg/ha/year)	% difference
2006-2010 (empirical observation)	10,098	
Baseline 2006	10,093	- 0.05%
Intermediate Land Conversion 2070	13,293	+ 32%
Low Land Conversion 2070	12,576	+ 24.6%
High Land Conversion 2070	10,362	+ 2.6%

Lake Sammamish water quality response

The simulated whole-lake TP concentrations closely aligned with the observed lake values used to calibrate the model (Fig. 5). Whole-lake TP concentrations predicted by the model were influenced by external and internal loading predictions. The highest increase in whole lake TP concentration (+ 73%) occurred under the ILC and high internal loading scenario (Fig. 6). The Lake Sammamish Water Quality Management Plan sets limit of 22 μg/L annual mean total phosphorus (King County, 2014). This goal was not met under any scenario. The trophic state of the lake will likely shift toward eutrophic condition (TSI>50) under every scenario (Table 2).

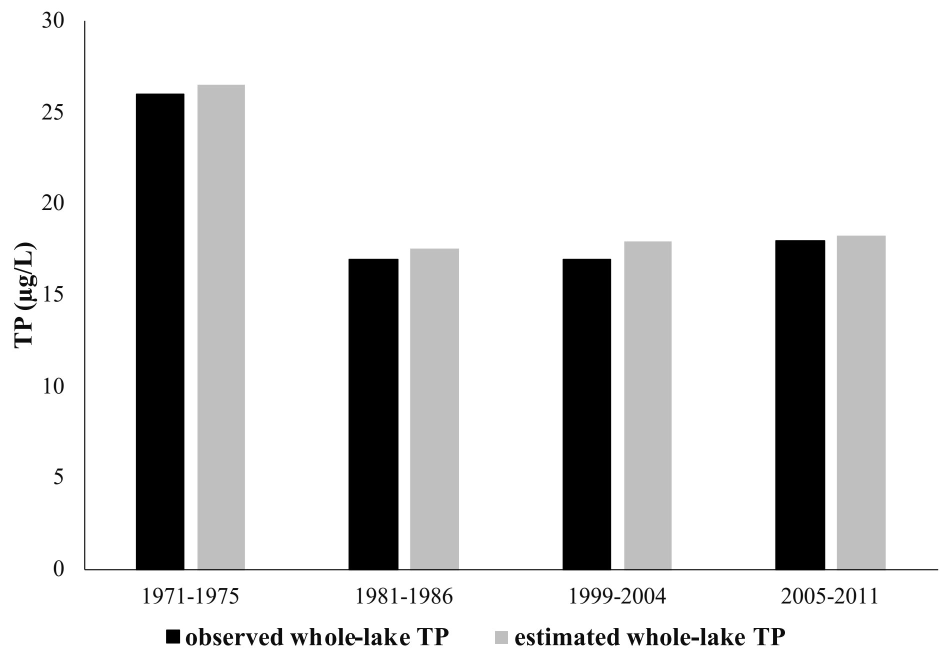

Figure 5. Observed and model-predicted whole lake TP concentrations (µg/L).

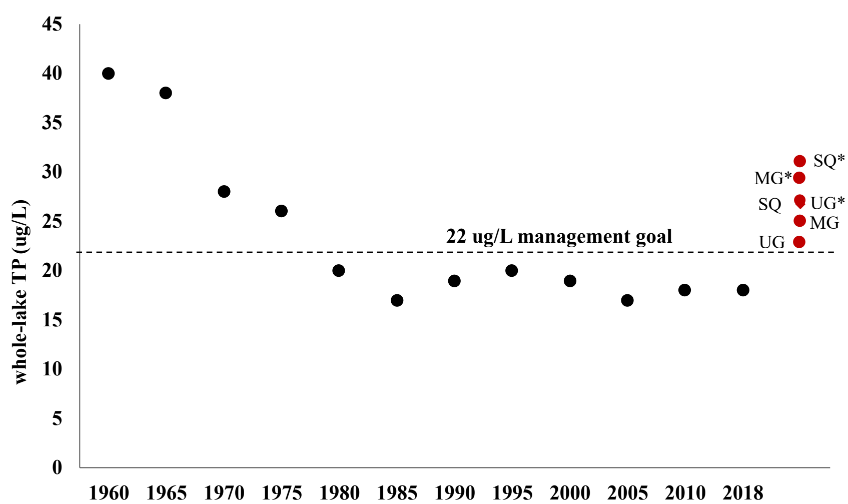

Figure 6: Mean observed and simulated annual whole lake TP (ug/L) concentrations. Red dots refer to whole lake TP values estimated under various LULC scenarios in Lake Sammamish (* Refers to whole lake TP estimated under higher internal loading conditions for the year 2070).

Table 2. Whole-lake TP concentrations as predicted by the mass balance model for various LULC scenarios (* Refers to whole lake TP estimated under higher internal loading conditions).

LULC scenario	TP (μg/L)	% change	TSI	State
Observed 2006	17.9		46	Mesotrophic
Calibrated 2006	18.25	+1.95	46	Mesotrophic
ILC 2070	26.8	+ 48.3	52	Eutrophic
LLC 2070	25.1	+ 41	51	Eutrophic
HLC 2070	22.8	+ 16.6	49	Mesotrophic/Eutrophic
*ILC 2070**	31.12	+73	54	Eutrophic
*LLC 2070**	29.4	+63	53	Eutrophic
*HLC 2070**	27.1	+50%	52	Eutrophic

Values of chlorophyll-a (chl-*a*) estimated based on the empirical relationship between chl-*a* and TP will likely increase under every LULC and internal loading scenario. The highest increase in chl-*a* concentration (+91.7%) was estimated under the ILC scenario with high internal loading, while the lowest increase (+5.5%) will likely occur under the HLC scenario. As a result, the lake management goal of 2.8 ug/L of chl-*a* will probably not be met under any scenario (Fig. 7).

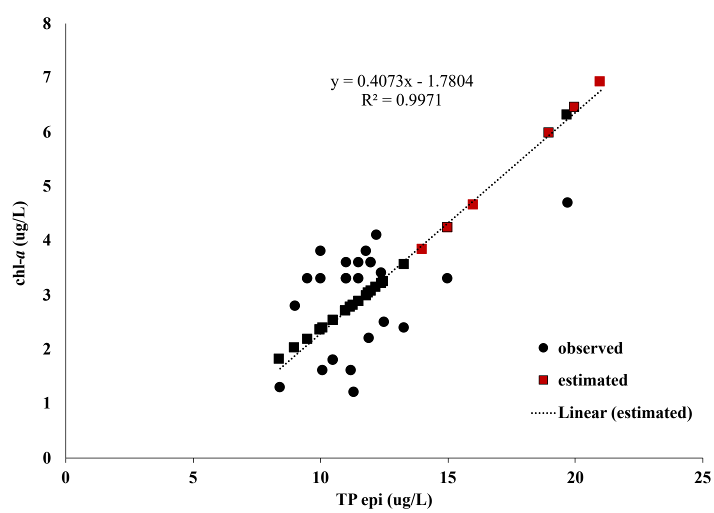

Figure 7. Observed and simulated annual summer (June-Sep) epilimnetic TP and chl-*a* values. Red squares refer to value estimated under different LULC management scenarios (LLC, HLC and ILC) and under higher internal loading (LLC*, HLC* and ILC*) for the year 2070.

Estimates of Secchi disk transparency were derived from the regression model between transparency and epilimnetic concentrations of chl-*a* developed by Carlson (1997). Future projections based on the LULC scenarios forecasted a reduction in water transparency ranging between 3 and 4 m. The lowest water clarity conditions will likely occur under the ILC scenario with high internal loading scenario, which predicted a transparency value of 2.1 m. The goal of 4 m water transparency will likely not be met under any scenario (Fig. 8).

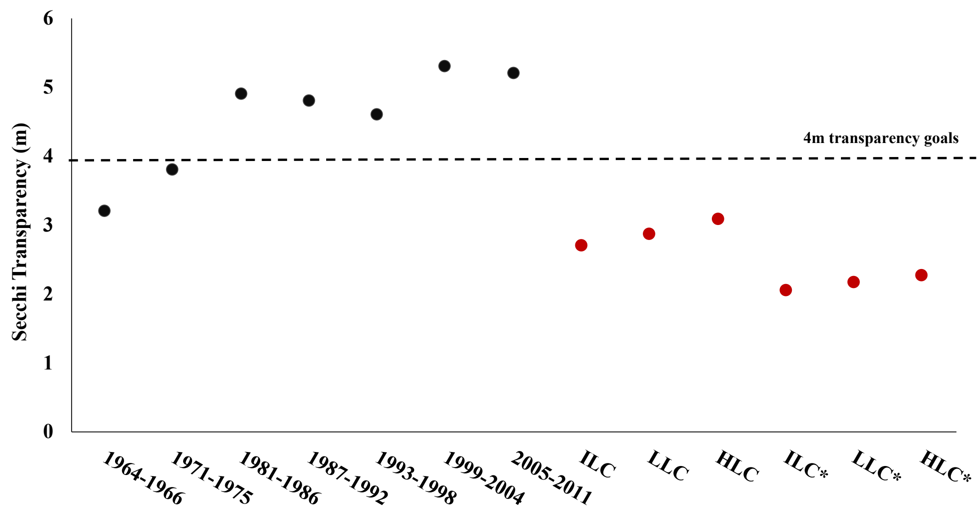

Figure 8. Observed and estimated transparency values. Red dots refer to values estimated under different LULC management scenarios (LLC, HLC and ILC) and under higher internal loading (LLC*, HLC* and ILC*)

Watershed management

We found 104 stormwater facilities within the Lake Sammamish watershed (Fig. 9). A plurality (41.3%) of stormwater facilities were located in the Issaquah Creek Basin, 14% were at the fringe of the UGA in the Eastern part of the watershed, and 14.4% were within the UGAs. We estimated that future urban development will increase TP runoff by up to 3000 kg/ha/year. Based on our spatial analysis, under the ILC and LLC scenarios more stormwater facilities should be added within the UGAs on the east side of the watershed to mitigate the increased TP runoff.

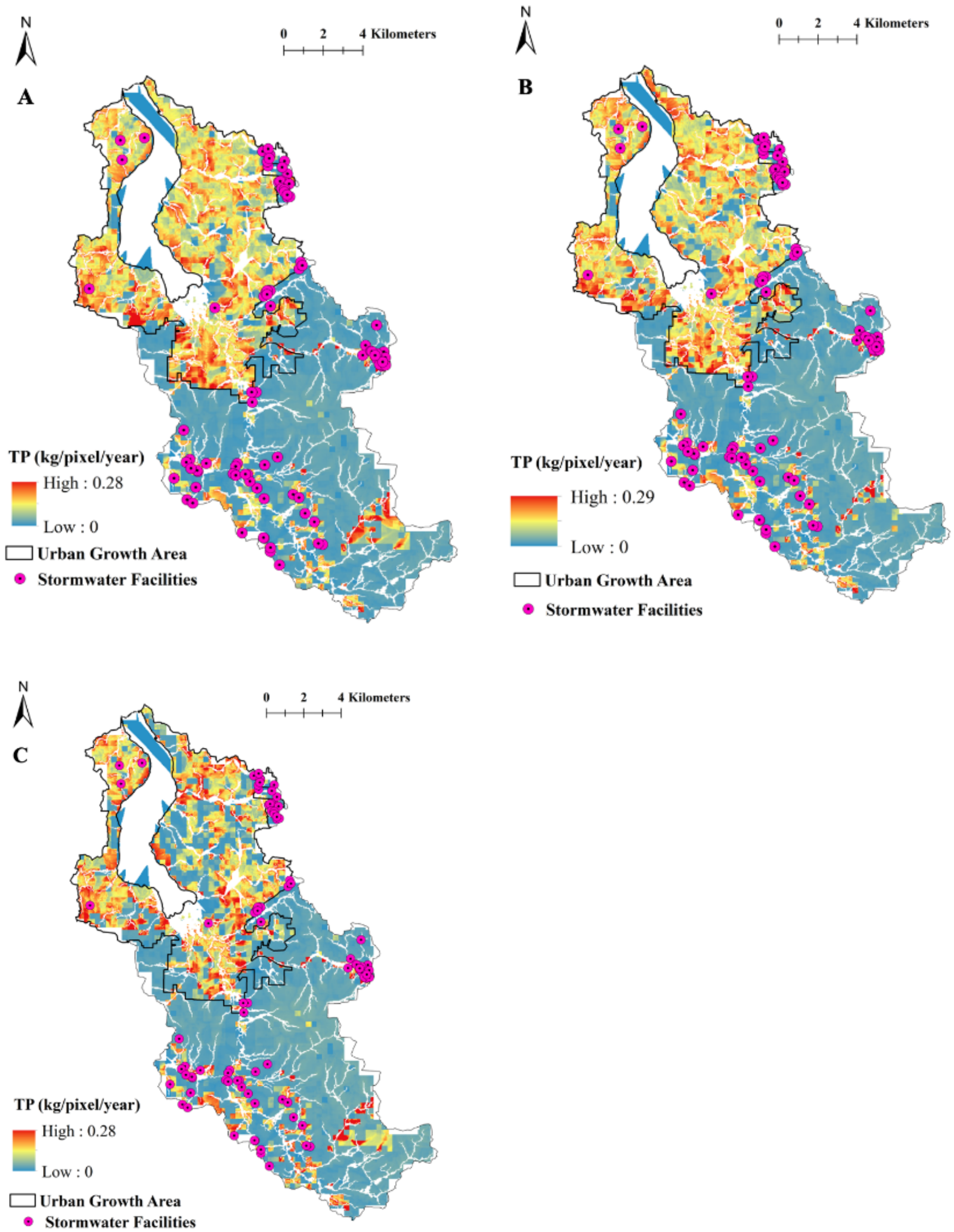

Figure 9. Stormwater facilities and spatial distribution of the variation in export of phosphorus in the Lake Sammamish watershed under the ILC(A), LLC (B) and HLC(C) scenarios.

Discussion and Conclusions

We found that the future urban scenario that, at the regional scale, limited the conversion of resource lands and concentrated more growth within the UGAs resulted in the highest percentage of urban development in the lake watershed. Restricting urban growth within urban growth areas translated in an aggregated residential growth with a larger concentration of multi-storied and higher-density development. This scenario had the most detrimental effect on the lake water quality because land use classes with a high proportion of impervious surfaces are an important factor in contributing to the P runoff. Our results support previous findings that the expansion of impervious surfaces can facilitate the runoff of nutrients and pollutants with negative consequences for aquatic systems (Dams et al. 2013; Liu et al. 2013; Brabec et al. 2002; Alberti et al. 2007; Kim et al. 2016).

Outcomes from different scenarios reflected the availability of both convertible lands and shoreline areas within the different sub-basins of the Puget Sound region. Within the Lake Sammamish watershed there was limited convertible lands and only one urban growth area. Since the HLC scenario has the smallest portion of growth in UGAs, this pattern of development resulted in the lower development expansion and TP runoff. One of the simplifying assumptions of the scenarios developed by Bolte and Vache (2010) was that the UGAs don't expand over the next 50-60 years. Our results highlight the importance of considering how UGAs need to be developed or expanded to accommodate future growth.

As this study has shown, consideration of the multiple ecosystem services and benefits provided by individual habitats and ecosystems (in this case Lake Sammamish) in larger scale analysis of ecosystem service trade-offs is necessary to prevent unintended loss of highly valued ecosystem services. It is generally assumed that clustered growth is better than sprawl and unconstrained growth (Robinson et al. 2005). However, ecosystem services that are centralized (e.g., a lake) rather than dispersed may be disproportionately negatively impacted by high-density development (Nielsen-Pincus et al. 2010). The contradiction between standard assumptions and the impacts of high-density development on some ecosystem services could help justify multi-criteria analyses (Goldberg et al. 2011).

The jurisdictional complexity of a large region like Puget Sound and lack of coordination between local and regional authorities could be obstacles to the execution of sustainable ecosystem management decisions. Wide variation in LULC patterns throughout the Puget Sound region and local limitations in the conversion or redevelopment of resource lands are reflected in the scenario outcomes. Across the entire Puget Sound, most of the new development was allocated in the western part of the South-Central sub-basin, where large areas of low-density residential zoning and private forested lands were available to accommodate new growth. Within the Lake Sammamish watershed, local constraints limited new land-use development and resulted in more growth concentrated within the UGA adjacent to the lake.

Our results highlight the importance of capturing difference in rules and regulations when implementing future land-use development plans that encompass multiple jurisdictions across a large region. Determining the most appropriate strategy for balancing new residential development and habitat conservation requires the adoption of multiple strategies and a portfolio of policies (Goldberg et al, 2011). Policymakers and urban managers may need to take additional regulatory measures to offset potential negative effects of regional policies that are overall useful but could have negative repercussions on individual habitat. Our analysis demonstrated how targeted conservation actions should be undertaken to protect key ecosystems and local communities from land-use decisions made in a regional context.

Future urban development will likely increase Lake Sammamish productivity, reduce water transparency, and diminish the recreational benefits, such as swimmability, recreational value and aesthetic appeal provided by the lake. Thresholds in recreational benefit depend on the user's perception of water clarity and its acceptability for recreational activities (Angradi et al. 2018). People are usually accustomed to the prevailing condition of lakes in their region and form their water quality expectations accordingly (Smeltzer and Heiskary, 1990; Heiskary and Walker, 1988). In the past four decades, recreational beneficiaries of Lake Sammamish have become accustomed to a lake water clarity of almost 6 m; and the forecasted reduction of 2-3 m in lake water quality will likely have detrimental consequences for the recreational benefits provided by this important aquatic system.

Projected changes in lake water quality could also negatively impact salmon habitat, offsetting restoration efforts for this regionally iconic species. Kokanee salmon, a landlocked sockeye salmon, is native to the Lake Sammamish watershed and a species of conservation concern (Young et al. 2004). Eutrophication causes alteration of the dissolved oxygen regime and food webs in lakes, which result in habitat loss and significant changes in biodiversity (Ansari et al. 2010). Salmonid species are particularly vulnerable to water quality deterioration (Müller 1992). The population of Kokanee salmon has been rapidly declining in the past decade probably due, among other causes, to lake water impairment (temperature and dissolved oxygen) (Berge and Higgins, 2003). Increased eutrophication caused by urban development in the watershed could exacerbate this decline.

Our results indicate that current strategies implemented to control phosphorus input into Lake Sammamish might need to be expanded in the future to accommodate urban development in the watershed. In the past 40 years nutrient management from non-point sources has been necessary to control Lake Sammamish water quality deterioration and preserve ecosystem service benefits (Welch et al. 2019). We estimated that future development will likely increase phosphorus runoff by approximately 20-30%. Storm water treatment facilities, measures to control erosion during construction, and practices to reduce the use and loss of phosphorus from homes, gardens, farms, forests, and businesses are necessary to protect lake water quality from future development and guarantee the provision of important ecosystem services. Further research should explore the placement and cost of implementing these measures to mitigate predicted decline in water quality.

Our analysis also confirmed the importance of forest conservation within the watershed. The negative influence of impervious surfaces on water quality was exacerbated in the scenarios where land use conversion to accommodate urban development happened at the expenses of forested lands, wetlands and other forms of vegetation that provided high nutrient retention services. Despite restrictions to converting public forested lands adopted in each regional planning scenario, the ILC and LLC scenarios resulted a reduction in private forested areas within the UGA around Lake

Sammamish and a significant increase in TP runoff.

Model structure and assumptions in the development of the LULC scenarios could have influenced our results. The NDR model requires a small number of parameters and can be highly sensitive to errors in the empirical input parameters, which could greatly impact final ecosystem service estimate. Compared to other more complex hydrologic models, the InVEST model doesn't capture the processes of nutrient cycling through the landscape but describes the long-term, steady-state flow of nutrients. After calibration, the model provided estimates of the TP export across the watershed close to those derived from empirical data. Assumptions adopted by Bolte and Vache (2010) when they developed the LULC scenarios could also have substantially influenced the outcomes, e.g., road networks and UGA's were considered fixed through the analysis and population growth was assumed to be the same in all scenarios.

Land-use managers must account for tradeoffs between ecosystem services while trying to balance the goals of different stakeholders. Our results showed that regional development scenarios that restrict development of some areas (e.g. the Puget Sound coastline) are likely to preserve some ecosystem services but can lead to degradation of ecosystem service production and delivery in other areas and at more local scales. A comprehensive multi-scale understanding of the consequences of alternative urban development trajectories is necessary to inform land use planning policies to ensure that highly valued, local ecosystem services are maintained.

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Chapter 5

Lakes can mitigate the urban heat island effect

Abstract

Rapid urbanization and climate change are exacerbating the negative consequences of the urban heat island effect (UHI). Nature-based solutions can mitigate these negative effects and help guarantee a sustainable and livable urban environment. Evaporative cooling by lakes could be one such solution, particularly in hot and dry climates. The aim of this study was to evaluate the ecological and economic impact of artificial lakes in mitigating the UHI phenomenon under current conditions and future climate change scenarios. We used the InVEST urban cooling model to quantify the energy savings provided by artificial lakes within the Phoenix, Arizona (USA) Metropolitan area. The influence of lakes in mitigating the UHI was compared to three alternative land use/land cover types: a city park, and low-density and hi-density development urban scenarios. Our results showed that the presence of a lake significantly mitigated the air temperature and reduced electricity consumption. The potential to moderate air temperature was most evident within 250 m of the lake. The heat reduction service provided by a lake could contribute an energy savings up to 57.1% with respect to the scenario characterized by high-density development. During the hottest months of the year houses adjacent to a lake could save up to 70% in electricity consumption compared to houses within a buffer zone 750 m from the lake. Our results indicated that the presence of a lake could also be beneficial in mitigating increased temperatures forecasted by climate change scenarios. This research can inform decisions on sustainable urban planning and water use in a desert city.

Introduction

As global population becomes increasingly urbanized, ways to increase urban resilience, promote sustainability, and mitigate negative consequences of urbanization are needed (Greenwalt et al., 2018). The urban heat island (UHI) effect is the condition that results in higher temperature within the urban areas compared to the surrounding rural areas (Cosgrove & Berkelhammer, 2018). This phenomenon poses a serious threat to human health by exacerbating the risk of heat-related mortality (Manoli et al., 2019). UHI effects will become even stronger under forecasted climate change scenarios because of higher temperatures and longer, more severe heat waves (Kershaw, Sanderson, Coley, & Eames, 2010). Higher temperature may also increase the need for air conditioning to cool urban buildings with a surge in energy usage. This will increase energy costs and pollution levels (Oke 1995; Kolokotroni, Gowreesunker, & Giridharan 2012; Arifwidodo & Chandrasiri, 2015).

Nature-based solutions, such as parks, vegetation, and bodies of water, are strategies for mitigating UHI effects and reducing the negative implications of heat stress on human wellbeing (Yu et al., 2020). The efficacy of urban vegetation in reducing energy consumption by buildings has been quantified (McPherson & Simpson, 2003; Abdel-Azi, Alshboul & Al Kurdi, 2015; Zardo, Geneletti, Perez-Soba & Van Eupen, 2017); however, the economic benefits that lakes can provide in mitigating the UHI have not. Lakes are an important component of urban sustainability. They provide recreational, aesthetic, and flood control benefits to urban residents. They also influence the microclimate through evaporative cooling (Hathway & Sharples, 2012). Although the role lakes can play in alleviating UHI has been recognized, research results are contradictory. While some studies have found that lakes in urban areas can function as cooling islands during the summer by reducing the surrounding temperature (Lee, Oh & Seo, 2016; Sun & Chen, 2012; Sun, Chen, Chen, & Lu, 2012; Cosgrove & Berkelhammer, 2018), others report opposite findings (Targino, Coraiola, & Krecl, 2019; Theeuwes, Solcerová, & Steeneveld, 2013).

Understanding of how site-specific microclimatic conditions can influence the cooling effects of lakes is still limited. Lakes lower the air temperature through evaporation, which depends on the vapor pressure deficit between the overlying air and lake evaporating surface (Gianniou & Antonopoulos, 2007). The cooling effect is dependent upon lake morphological characteristics (i.e., size, shape and depth) and is influenced by microclimate, and as a consequence is site-specific (Manteghi, Remaz Ossen & Lamit, 2015). Lakes are most likely to be effective in mitigating high urban temperature through evapotranspiration in hot and dry climates (Wang, Zhang, Ding, Qin, & Yang, 2020).

In desert cities numerous artificial lakes have been created to aesthetically improve residential developments and property values, and to provide open spaces, and recreational opportunities (Larson & Grimm, 2012; Larson & Perrings, 2013). Water is a scarce commodity in these areas, and rapid population growth and climate change may require urban planners and managers to reassess the luxury use of water in these man-made lakes, potentially allocating the water to more pressing needs. A better assessment of the ecological and economic value that these lakes have in UHI mitigation could offer a justification for the allocation and management of water to lakes. A further quantification of the regulating ecosystem services provided by these systems could also inform homeowner choices.

Traditional methods to assess the UHI include in situ observation and/or remote sensing data. A new software package, the InVEST urban cooling model, allows simulation of the spatial distribution of cooling capacity associated with cooling islands, like parks and water bodies, based on physical mechanisms that contribute to the heat mitigation (shade, evapotranspiration and albedo) (Sharp et al., 2020). This model presents some advantages relative to traditional UHI quantification approaches. Biophysical mechanisms that drive the emergence of UHIs are represented explicitly in the model, which allows for a physical interpretation of the parameters of the model (Bosh et al., 2020). Once the model is calibrated for a given city it can be used to evaluate synthetic scenarios (i.e., alternative land use/land cover or climate change scenarios) and also allow valuation of the heat reduction service in terms of reduced electricity use for cooling.

A new approach to quantification of regulating ecosystem services is increasingly important for optimizing the effectiveness of nature-based solutions in mitigating consequences of rapid urbanization and climate change. Using a novel methodology, we addressed three research questions: 1) What is the ecological and economic impact of lakes in mitigating UHI effect in a desert city? 2) How does future climate change affect the cooling capacity of urban lakes? 3) What is the role of landscape spatial pattern in mitigating or exacerbating UHI?

Materials and Methods

Study site

We quantified the efficacy of urban lakes in mitigating the UHI effect in three different neighborhoods within the Phoenix, USA, metropolitan area. Metropolitan Phoenix, located in the arid American Southwest, is in a valley approximately 340 m above sea level characterized by hot and dry summers. The region receives <180 mm of annual precipitation. In July maximum temperatures regularly exceed 40 C (Connors, Galletti & Chow, 2013). Phoenix is among the most rapidly growing cities in the United States (Chow, Brennan, & Brazel, 2012). Between 2000 and 2010 land use conversion to residential development resulted in growth of almost 30% in area and a population that exceeded four million (Redman & Kinzig, 2008; U.S. Census Bureau, 2010). The expansion of impervious surface areas associated with urban development has contributed to higher daily low temperature and has exacerbated the UHI effect (Guhathakurta & Gober, 2007).

Three neighborhoods located in Tempe, Mesa and Phoenix (AZ) characterized by the presence of artificial lakes were selected as study sites to assess the heat mitigation values provided by these water systems (Fig. 1).

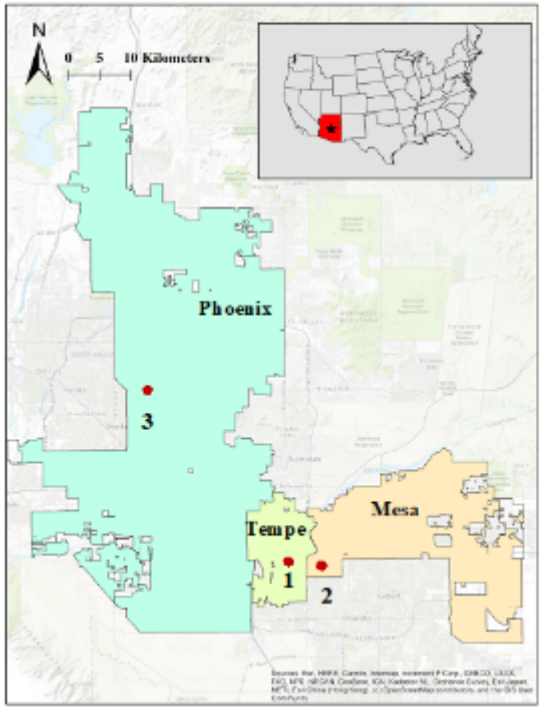

Figure 1. Study sites within Phoenix metropolitan areas (US). Site 1 (Lake of Tempe), site 2 (Dobson Lakes), and site 3 (Biltmore Lake).

The first neighborhood (414620.81E, 3693278N) was characterized by the presence of two adjacent artificial lakes named "Lake of Tempe" (Fig. 2). The land use/land cover (LULC) within the study site was characterized mostly by imperious surfaces (92%), with the highest percentage of medium and high intensity development in the 500 and 750 m buffers. The Lake of Tempe with a surface area of 0.17 km^2 covered about 5% of the overall study site (Fig.3).

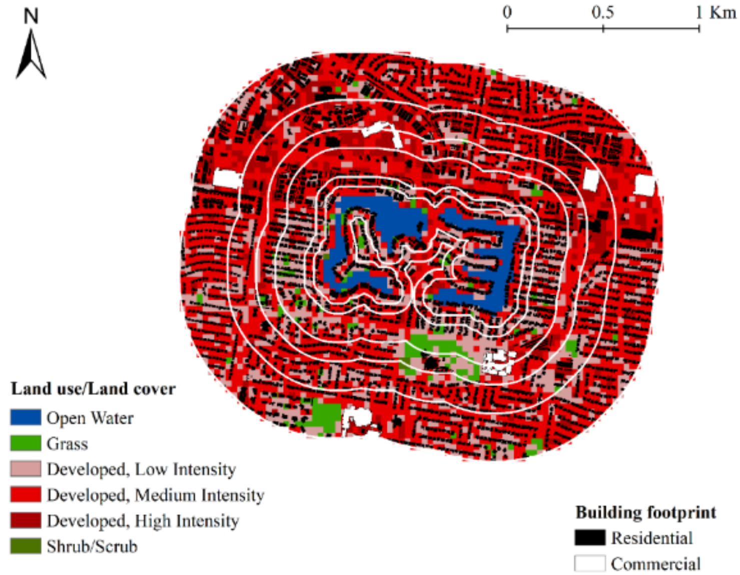

Figure 2. Land use/land cover and residential and commercial development around the Lake of Tempe. The white lines represent the 50, 100, 250, 350, 500, and 750 m buffer border lines.

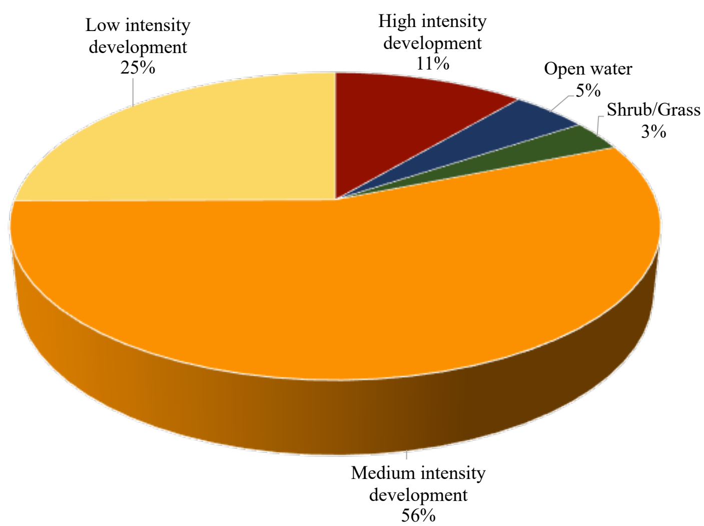

Figure 3. Percentage of different land use/land cover within the Lake of Tempe study site.

The lake was surrounded by residential development, commercial buildings and schools with areas ranging from 14.2 to 28,877.5 m^2, a median area of 238.4 m^2 and an average size of 310±13.5 m^2. The majority (92.6%) of the residential buildings had an area of less than 500 m^2 (Table 1). An elementary school and several commercial buildings were located within the 500 and 750 m buffer areas (Figure 2). The household income of the neighborhood where the Lake of Tempe is located ranged between \$65,000 and \$74,000 (Census Bureau, 2010).

Table 1. Average surface area (m^2) ± standard error of the commercial and residential development within each of the buffer areas around the Lake of Tempe.

Buffer distance (m)	Average surface area (m^2)
50	320.8±14.5
100	298.9±14.1
250	312±28.3
350	384.3±58.3
500	351.2±31.9
750	324.7±27.2

The Dobson Ranch neighborhood is located in Mesa (AZ) (418268.31E, 3693080N). Dobson Ranch was developed around a system of ten lakes commonly known as “Dobson Lakes” (Fig.4). The LULC within the Dobson Lakes study site encompassed areas covered by imperious surfaces (87.6%). The lakes, with a total surface area of 0.36 km^2, covered about 3%, and the golf course and grass/herbaceous areas covered almost 10% of the study site (Fig. 5).

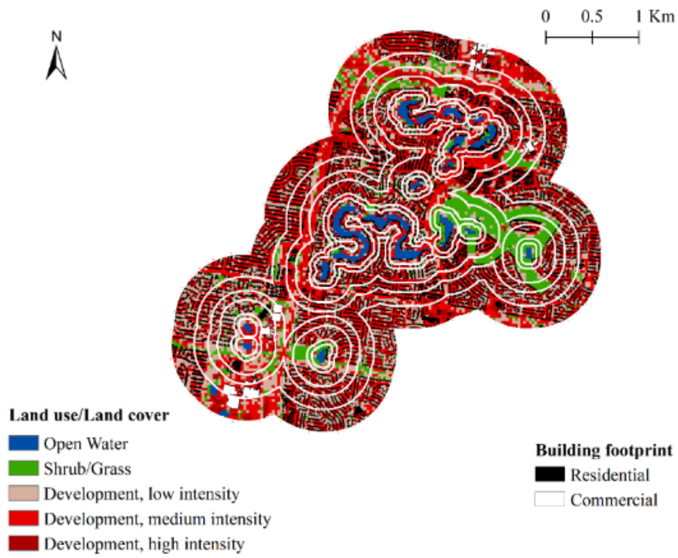

Figure 4. Land use/land cover and residential and commercial development around the Dobson Lakes. The white lines represent the 50, 100, 250, 350, 500, and 750 m buffer border lines.

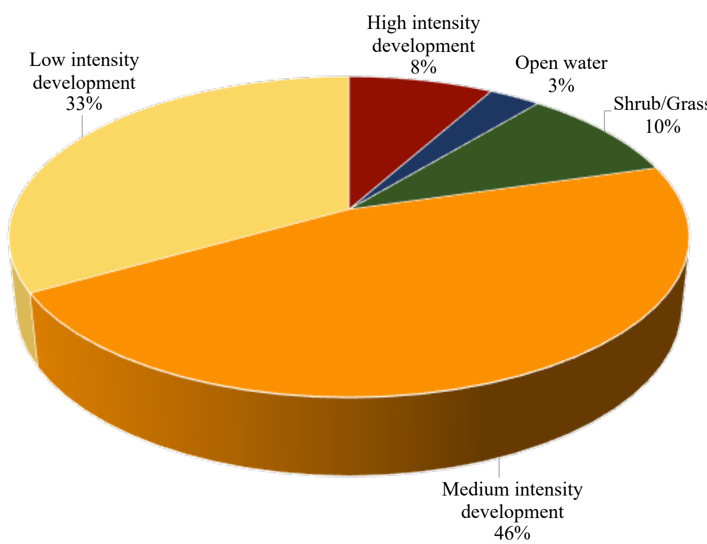

Figure 5. Percentage of different land use/land cover within the Dobson Lakes study site.

The area adjacent to the lake was characterized by single-family homes and condominiums with areas ranging from 3.6 to 60,563 m^2, a median surface area of 235.6

m^2 and an average size of 289 ±11.1 m^2 (Table 2). Several schools, churches and commercial buildings were also located within the study site, mostly within the 500-750 m buffer areas (Figure 4). The household income of the neighborhood where the Dobson Lakes are located ranged between $74,000 and $87,000 (Census Bureau, 2010).

Table 2. Average surface area (m^2) ± standard error of the commercial and residential development within each of the buffer areas around Dobson Lakes.

Buffer distance (m)	Average surface area (m^2)
50	292.4±14.7
100	323.4±22.3
250	303.1±12.2
350	320.4±16.9
500	348.6±45.9
750	298.5±28.3

The third neighborhood we studied was located near lake Biltmore Village, Phoenix (AZ) (396035.08E, 3717249.96N). This neighborhood is a residential, low-income area with a household income ranging from $32,000 to $40,000 (Fig. 6). The LULC within the study site was characterized mostly by imperious surfaces (90%) and shrub/grass (7.3%) (Fig. 7). The Biltmore Lake with a surface area of 0.07 km^2 covered 2.4% of the overall study site.

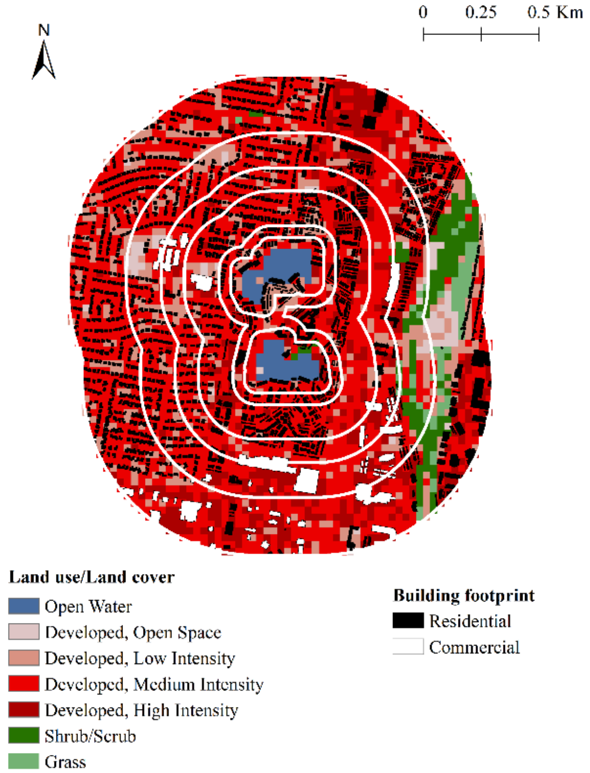

Figure 6. Land use/land cover and residential and commercial development around the Biltmore Lake. The white lines represent the 50, 100, 250, 350, 500, and 750 m buffer border lines.

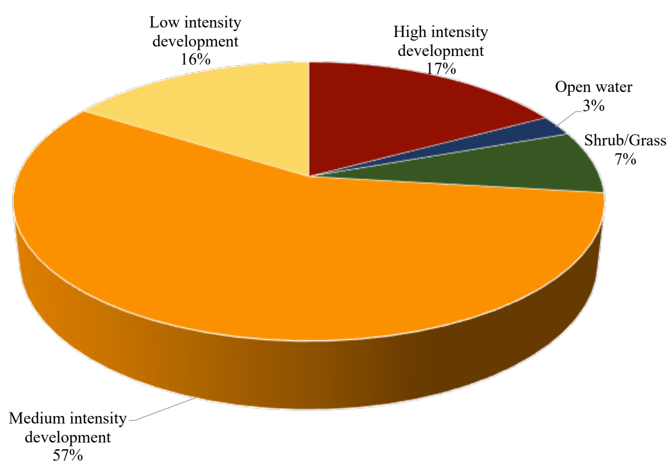

Figure 7. Percentage of different land use/land cover within the Biltmore Lake study site.

The area considered in this study was characterized as a mix of small residential buildings, condominiums and commercials development with a surface areas ranging from 19.7 to 11,769 m^2, a median surface area of 214.8 m^2 and an average size of 319 ±14.6 m^2 (Table 3). Several commercial buildings were located within 500 and 750m buffers (Figure 6).

Table 3. Average surface area (m^2) ± standard error of the commercial and residential development within each of the buffer areas Lake Biltmore Lake.

Buffer distance (m)	Average surface area (m^2)
50	340±30.2
100	290±39.7
250	306±23.8
350	441±67.6
500	375±49.3
750	330±22.6

InVEST Urban Cooling Model

The average cooling capacity of each lake was calculated using the InVEST Urban Cooling Model (version 3.9.0). The InVEST Urban Cooling Model simulated the spatial distribution of air temperature for each pixel of the study site based on the physical mechanisms that contribute to the heat mitigation (shade, evapotranspiration and albedo). The model uses city-scale magnitude of urban heat island effect (UHI_{max}) and the rural reference temperature (T_{ref}) to estimate the heat reduction service. We retrieved values of UHI_{max} from the literature (Brazel et al., 2007) and T_{ref} from weather station data.

The main inputs to the model were a land use/land (LULC) cover raster map of the study area, a reference evapotranspiration raster and a biophysical table containing information on each LULC class of the map (Sharp et al., 2020). Values relative to the air temperature mixing radius (r_{mix}), cooling distance area (d_{cool}) over which a body of water or a park could have a cooling effect and the weights attributed to the shading, albedo and evapotranspiration parameters were also required. For these parameters the default values suggested by the InVEST model were adjusted during the calibration steps.

LULC data were retrieved from the National Land Cover Database (NLCD) 2016 edition (available on www.mrlc.gov). Evapotranspiration raster data for the reference period of July and August 2018 were retrieved from the Global Potential Evapotranspiration database (Trabucco & Zomer, 2019). The building footprints vector required for energy saving evaluation was retrieved from the Arizona State University map and geospatial hub (available on https://lib.asu.edu/geo). All the coefficients required to run the model were retrieved from an extensive literature search and adjusted based on the model calibration results.

The value of temperature reduction linked to the cooling effect of the presence of water was assessed in terms of energy saving from reduced electricity consumption using the relationship between energy consumption and temperature as indicated by Santamouris et al. (2015). For energy saving valuations the InVEST model required information on energy consumption for each building type. The average monthly residential electricity use per household in Phoenix Metropolitan Area is about 1061 kwh (US EIA’s 2009 Residential Energy Consumption Survey). Since air conditioning accounts for a quarter of the energy consumed, we estimated that 265.3 kwh/month are consumed for air conditioning by an average single-family house. From the building footprint vector we calculated that the median size of a single-family house within the study sites was around 170 m^2; therefore, we estimated an energy consumption rate of 1.5 kwh/m^2/month (US EIA 2018).

The model was calibrated and evaluated on a per-pixel basis as described by Bosh et al. (2020) and Hamel et al. (2020) using both land surface temperature and temperature measured from local weather stations. Land surface temperature (LST) data were extracted from LANDSAT 8 images taken on July and August 2018 and published on the USGS Earth Resource Observation and Science (EROS) Center. Estimation of the LST from Landsat 8 images followed the methods described by Bosh et al. (2020). We assembled a dataset of air temperature measurements in the study areas by combining data from stations operated by the University of Arizona, University of Utah, NOAA and Maricopa County. Since July and August are the two hottest months in Phoenix, we calibrated the model considering mean temperatures for both months of July and August 2018.

Potential interactions between the UHI effects and projected changes in temperature were considered under two climate change scenarios. A low emission scenario (RCP 4.5) forecasting a temperature increase of 3.3 C and a high emission scenario (RCP 8.5) forecasting a temperature increase of 5 C according to Garfin, Jardine, Merideth, Black, & LeRoy (2013) were assessed. Future potential evapotranspiration raster maps under both scenarios were retrieved from the NASA Earth Exchange (NEX) downscaled climate projections (available on https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-dcp30). Spatially explicit model inputs required for the InVEST Urban Cooling Model (v3.7.0) were manipulated and processed in ArcGIS (v10.3 ESRI, Redlands, CA).

The value of the lakes in mitigating the UHI was assessed using a marginal value approach. Lake surface area was converted into three alternative LULC types: a city park, a low-density development and a clustered high-density developed urban scenario. The high-density development scenario was selected to mimic the landscape configuration of the low-income neighborhood within the Phoenix Metropolitan area mostly characterized by impervious areas. We performed a marginal value assessment by determining the difference in the heat mitigation provided by the lake versus the heat mitigation provided by different LULC scenarios as described by Lonsdorf, Nootenboom, Janke & Horgan (2021). The value of the cooling capacity of each lake and LULC types in mitigating the HUI effect was estimated in buffer zones of 50, 100, 250, 350, 500, and 750 m. Analysis of covariance (ANCOVA) was used to examine differences in the mean values of energy savings within each buffer area with each of the LULC types. Values of energy savings for 100 randomly selected houses within each of the buffers were used as response variables in the ANCOVA models. All data management and analyses were performed using R (R core team 2020). The results reported refer to summer monthly values.

Results

Average cooling capacity

The Urban Cooling InVEST model was sensitive to the air temperature mixing radius (r_{mix}), cooling distance area (d_{cool}) and the weights attributed to the shading, albedo and evapotranspiration parameters. As a part of model calibration, we selected the model with the highest correlation (r^2=0.61) and the smallest mean absolute error (MAE=2.45) between the InVEST outputs, the land surface temperature measured from the LANDSAT data and the temperature data from the weather stations. The InVEST outputs of average cooling capacity and air temperature (T_{air}) confirmed the significant influence that the LULC has on urban thermal comfort. The highest values of simulated T_{air} occurred in the medium and high density developed areas, whereas the lowest temperatures were found in the areas located near water bodies or green areas.

Results from the ANCOVA analyses indicated that there was no homogeneity of slopes and there was a significant difference in temperature between LULC scenarios along a distance gradient in every study site (p-value $<2.2e-16$; F-statistic: 183 and DD: 2395) (Fig. 8). The average temperature was significantly lower in the LULC scenario that incorporated the presence of a lake or a city park compared to the simulated scenarios were the surface area covered by the lake was substituted by a low- and high-density development. Both the lake or city park had the same mitigating effect on T_{air}. The cooling effect significantly (p-value <0.001) decreased along the distance gradient.

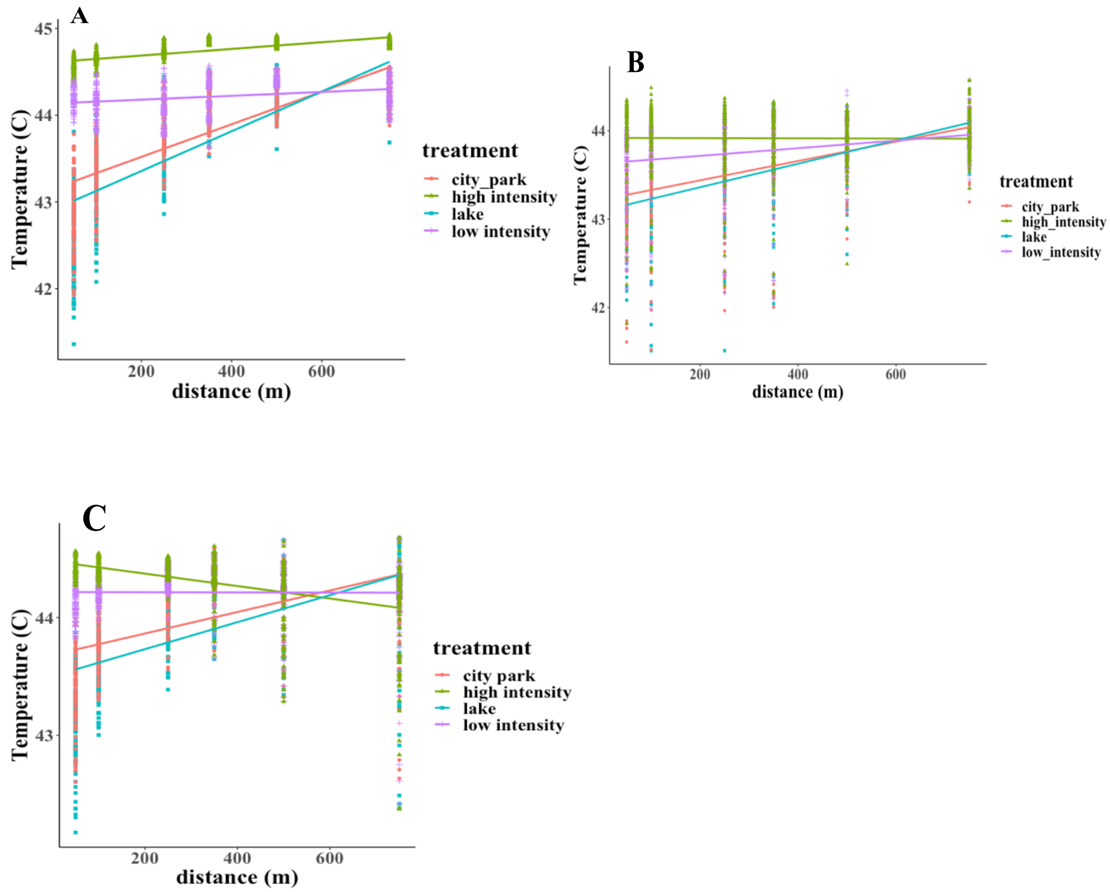

Figure 8. ANCOVA results of the temperature differences between LULC along a distance gradient for the Lake of Tempe (A), Dobson Lakes (B) and Biltmore Lake (C).

The air temperature outputs presented valuable information on how the thermal comfort provided by either lakes or city parks dissipated across each study site (Fig. 9). The potential of the Lake of Tempe to moderate air temperature through the cooling effects of ET was mostly visible within the 250 m buffer around the lake (Fig. 9 A). The green areas in the southern part of the study site also provided a small cooling service that became more evident in the low- and high-density scenarios.

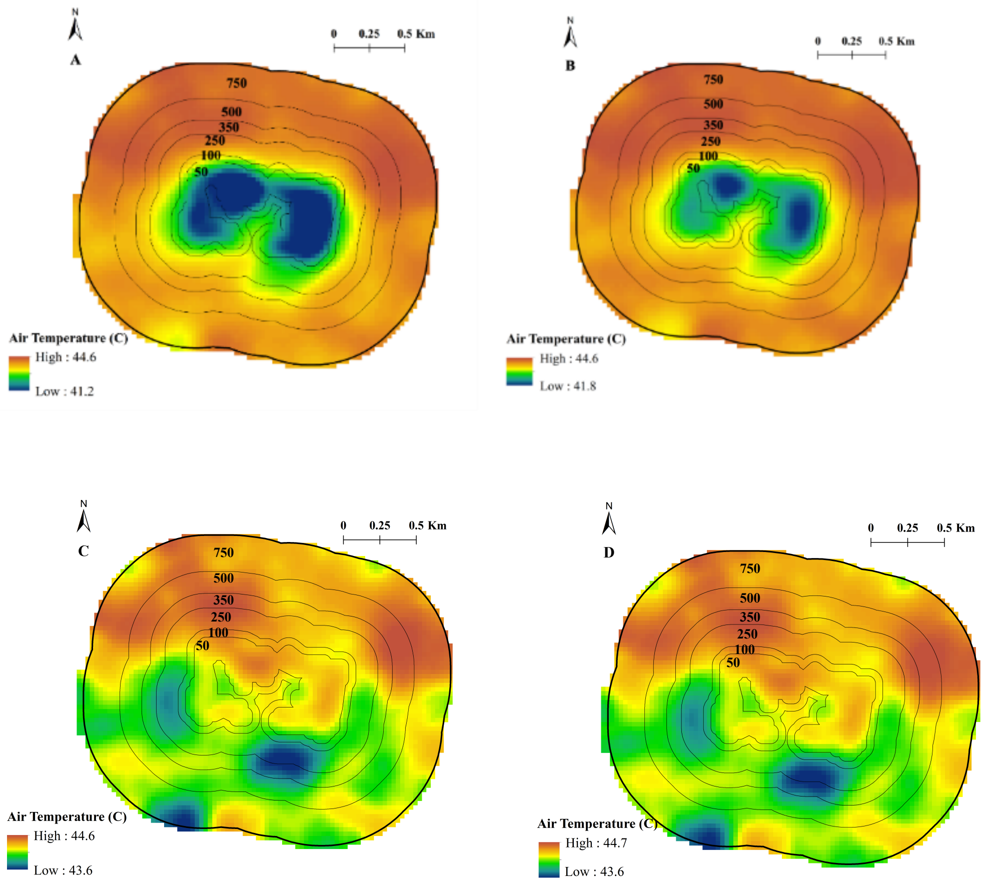

Figure 9. Air temperature map for the Lake of Tempe study site. (A) lake, (B) city park, (c) low-intensity, (D) high-intensity. The black lines represent the 50, 100, 250, 350, 500, and 750 m buffer border lines.

The temperature within the 50m buffer around the Lake of Tempe was 2.5 C cooler than the overall average temperature, while the temperatures within the 100 and 250 m buffer were 1.6 and 0.9 C lower than the average, respectively. Areas within the 350-500 and 750 m buffer that were characterized by the higher percentage of impervious surfaces resulted in the warmest temperatures (Fig. 10).

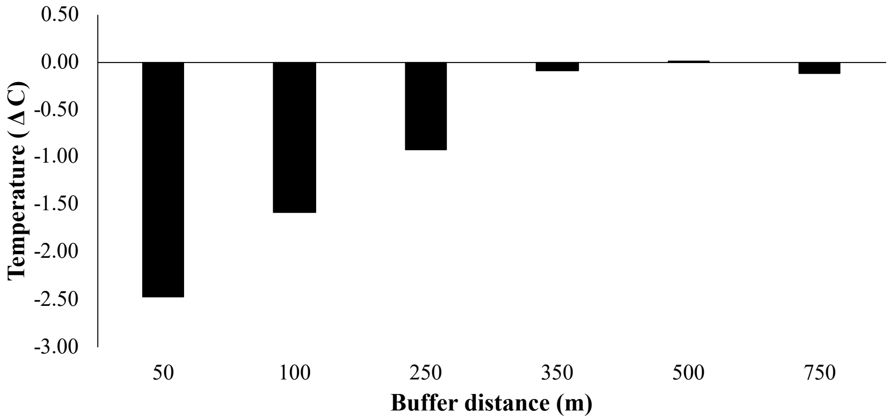

Figure 10. Bar plot of the difference between the average temperature of the study site and the temperature within each of the buffer areas considered around the Lake of Tempe.

Around Dobson Lakes, the influence of lakes in moderating air temperature was mostly visible within the 100-250 m buffer while the impact of the golf course was visible within the 500 m buffer on the east side of the Lakes (Fig. 11). This site was characterized by the highest presence of green spaces which resulted in pockets of cooler air throughout the 750 m buffer area.

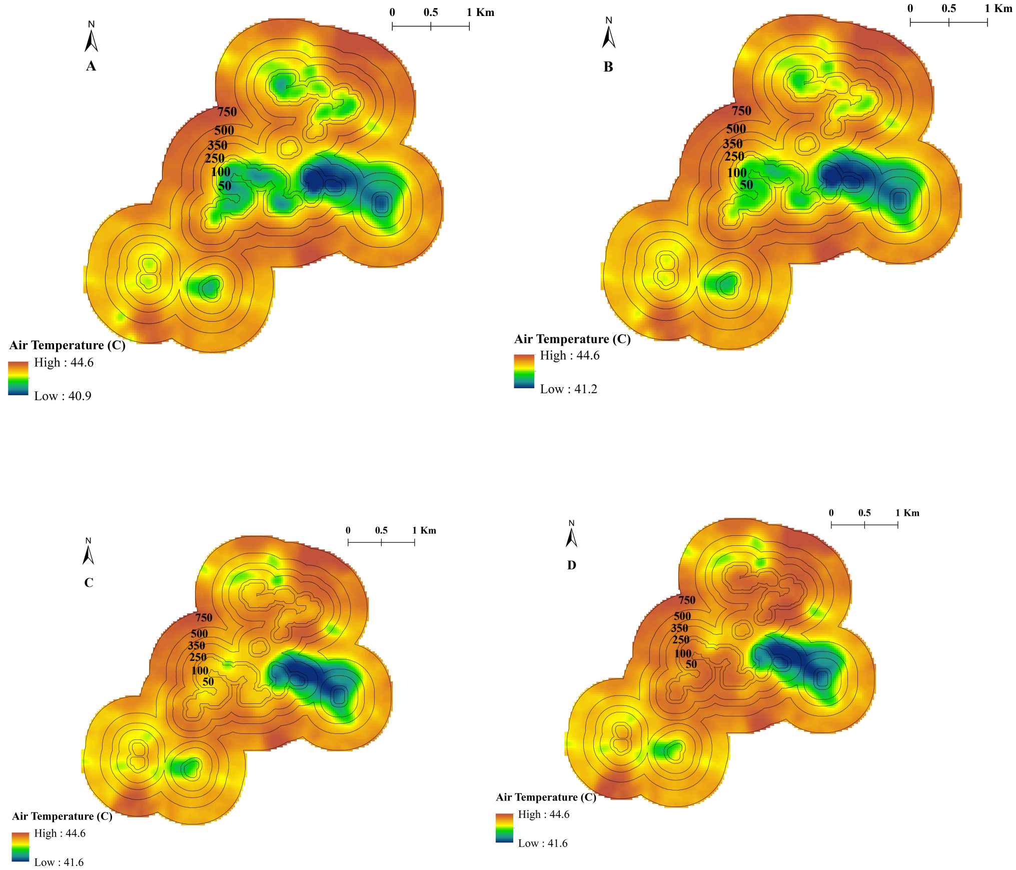

Figure 11. Air temperature map for the Dobson Lakes study site. (A) lake, (B) city park, (c) low-intensity, (D) high-intensity. The black lines represent the 50, 100, 250, 350, 500, and 750 m buffer border lines.

The temperature within the 50 m buffer around the Dobson Lakes was 0.26 C cooler than the average temperature, while areas within 500 m buffer characterized by the combined presence of water and grass/herbaceous land cover resulted in the coolest temperature (Fig. 12).

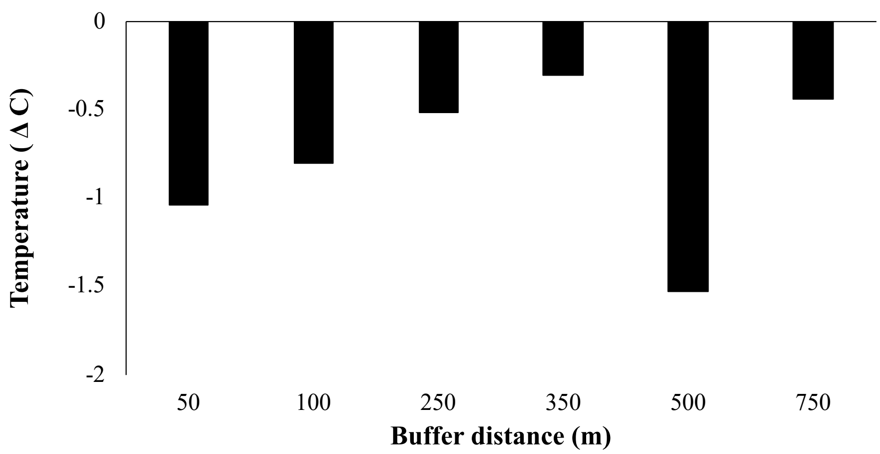

Figure 12. Bar plot of the difference between the average temperature of the study site and the temperature within each of the buffer areas considered around the Dobson Lakes.

The thermal comfort provided by Biltmore Lake dissipated within the 200 m buffer. The influence of the grass/herbaceous and shrubs areas in moderating air temperature was visible within the 500 and 750 m buffer in the east side of the lake (Fig. 13).

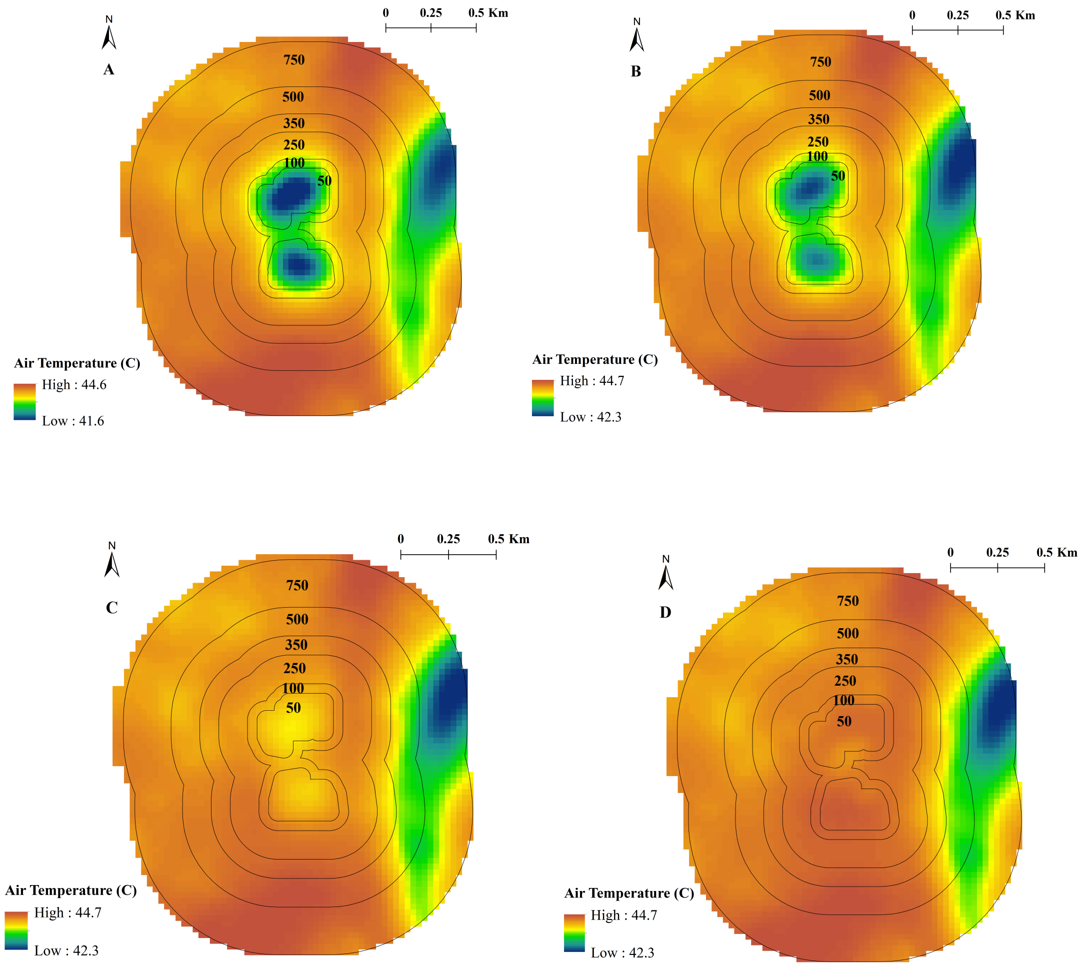

Figure 13. Air temperature map for the Biltmore Lake study site. (A) lake, (B) city park, (c) low-intensity, (D) high-intensity. The black lines represent the 50, 100, 250, 350, 500, and 750 m buffer border lines.

The temperature within the 50 m buffer around Biltmore Lake was 1.7 C cooler than the average temperature of the study site, while the temperatures within the 100 and 250 m buffer were 0.8 and 0. 6 C cooler, respectively. Areas within the 750 m buffer characterized by the presence of a park and irrigated herbaceous land cover was 1.5 C cooler than the average temperature (Fig. 14).

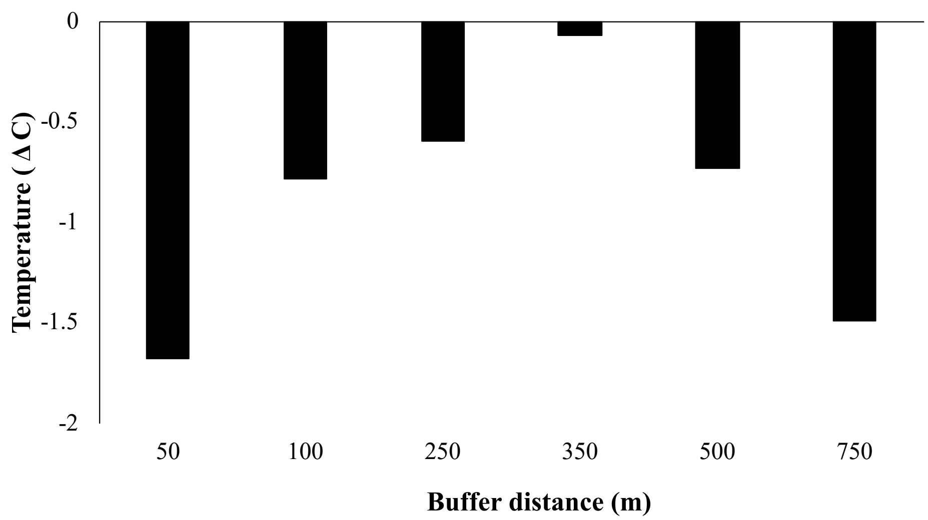

Figure 14. Bar plot of the difference between the average temperature of the study site and the temperature within each of the buffer areas considered around the Biltmore Lake.

Average energy saving

Variation in temperature linked to the different LULC classes directly influenced the energy use. Our results indicated that a lake and a city park provided a heat reduction service (kwh/m^2) significantly different from the low and high-intensity development. The heat reduction service significantly decreased along the distance gradient (p-value <0.001) (Fig. 15).

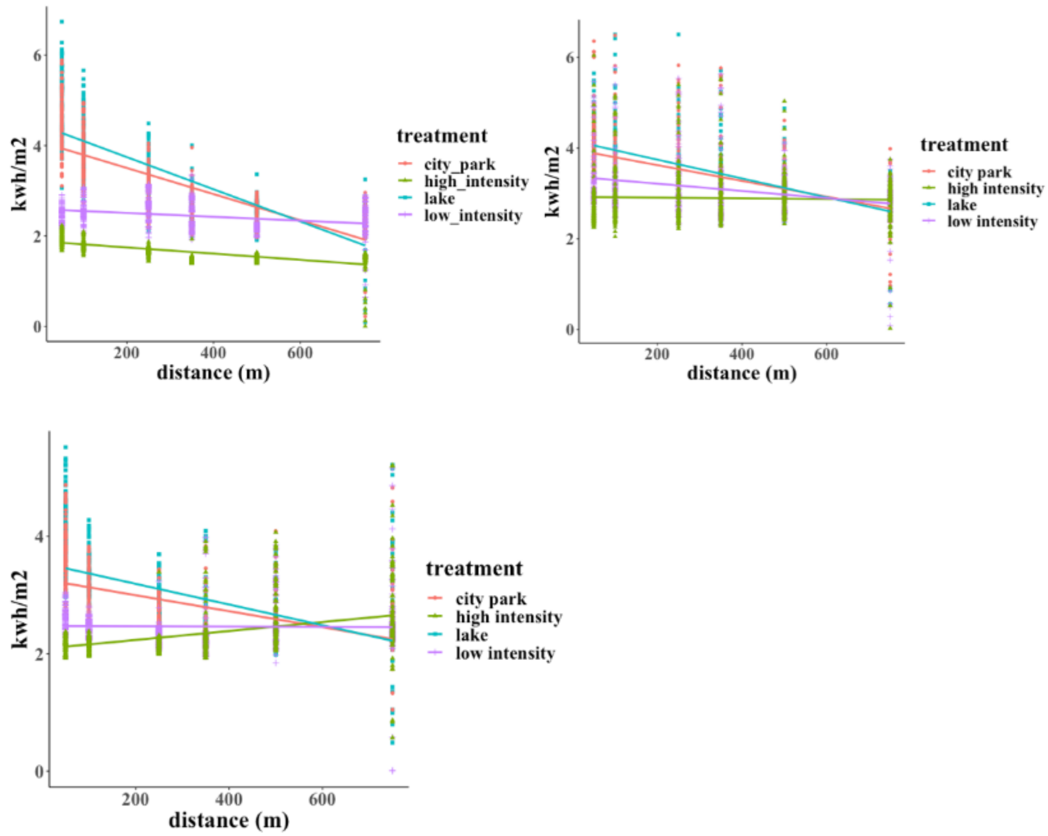

Figure 15. ANCOVA results of the heat reduction (kwh/m^2) differences between LULC types along a distance gradient for the Lake of Tempe (A), Dobson Lakes (B) and Biltmore Lake (C).

Overall, the Lake of Tempe provided a mean energy savings from reduced electricity consumption (kwh) of 17.6% with respect to the low-density development scenario and 57.1% with respect to the high-density development scenario. Residential units within the 50 m buffer around the lake saved 26.5% more than houses within the 100 m buffer and 74% more than houses within the 750 m buffer (Table 4).

Table 4. Average energy saving (kwh/m^2) ± standard error provided by different LULC scenarios within each buffer areas around the Lake of Tempe.

	Lake	City Park	Low Density	High Density
50m	5.02±0.04	4.5±0.032	2.5±0.009	1.9±0.007
100m	4.1±0.033	3.8±0.03	2.6±0.01	1.8±0.005
250m	3.2±0.02	3.1±0.02	2.6±0.01	1.6±0.004
350m	2.5±0.018	2.5±0.02	2.5±0.02	1.5±0.004
500m	2.43±0.01	2.43±0.01	2.4±0.01	1.4±0.002
750m	2.31±0.01	2.3±0.01	2.3±0.01	1.5±0.007

The Dobson Lakes provided a mean energy saving (kwh) across the entire study site of 8.3% and 10.9% compared to the low-and high-density development scenarios. Residential units within the 50 m buffer around the Dobson Lakes saved 13.9% more electricity than houses within the 100 m buffer, and 42% more than houses within the 750 m buffer (Table 5).

Table 5. Average energy saving (kwh/m^2) ± standard error provided by different LULC scenarios within each buffer areas around the Dobson Lakes.

	Lake	City Park	Low Density	High Density
50m	4.6±0.03	4.2±0.03	3.0±0.02	2.8±0.02
100m	4.0±0.02	3.8±0.02	3.2±0.02	2.9±0.02
250m	3.5±0.02	3.4±0.02	3.2±0.02	3.1±0.02
350m	3.2±0.02	3.2±0.02	3.1±0.02	3.1±0.02
500m	3.0±0.01	3.0±0.01	2.9±0.02	2.9±0.01
750m	3.0±0.01	2.8±0.001	2.7±0.001	2.8±0.01
Overall	3.5±0.03	3.5±0.03	3.1±0.02	2.9±0.02

Biltmore Lake provided a mean energy saving (kwh) across the entire study site of 8.5% and 11.6% compared to the low-and high-density development scenarios. Residential units adjacent to the lake saved 16.2% more than houses within the 100 m buffer and 46.2% more than houses within the 750 m buffer (Table 6).

Table 6. Average energy saving (kwh/m^2) ± standard error provided by different LULC scenarios within each buffer areas around the Biltmore Lake

	Lake	City Park	Low Density	High Density
50m	4.0±0.05	3.7±0.04	2.6±0.02	2.2±0.01
100m	3.4±0.03	3.1±0.02	2.4±0.01	2.1±0.01
250m	2.7±0.02	2.6±0.01	2.3±0.01	2.2±0.01
350m	2.4±0.02	2.4±0.02	2.4±0.03	2.3±0.03
500m	2.6±0.02	2.6±0.02	2.6±0.02	2.6±0.02
750m	2.5±0.02	2.5±0.02	2.5±0.02	2.5±0.02
Overall	2.9±0.03	2.8±0.02	2.5±0.01	2.3±0.02

Climate change

Higher temperatures forecasted by both climate change scenarios considered in this study will cause an increase in energy consumption. Based on our results, the presence of a lake could provide a significant cooling mitigation impact (p-value < 0.05), in terms of energy savings (kwh/m^2), under both the low and high emission scenarios. There was no difference in energy savings between the low and high emissions scenarios. The Lake of Tempe could lower the energy consumption by 8.9%; the Dobson Lakes could provide a 5.7% energy saving, mostly within a 100 m buffer, and the Biltmore Lake would reduce electricity consumption by 9.8% (Figure 16).

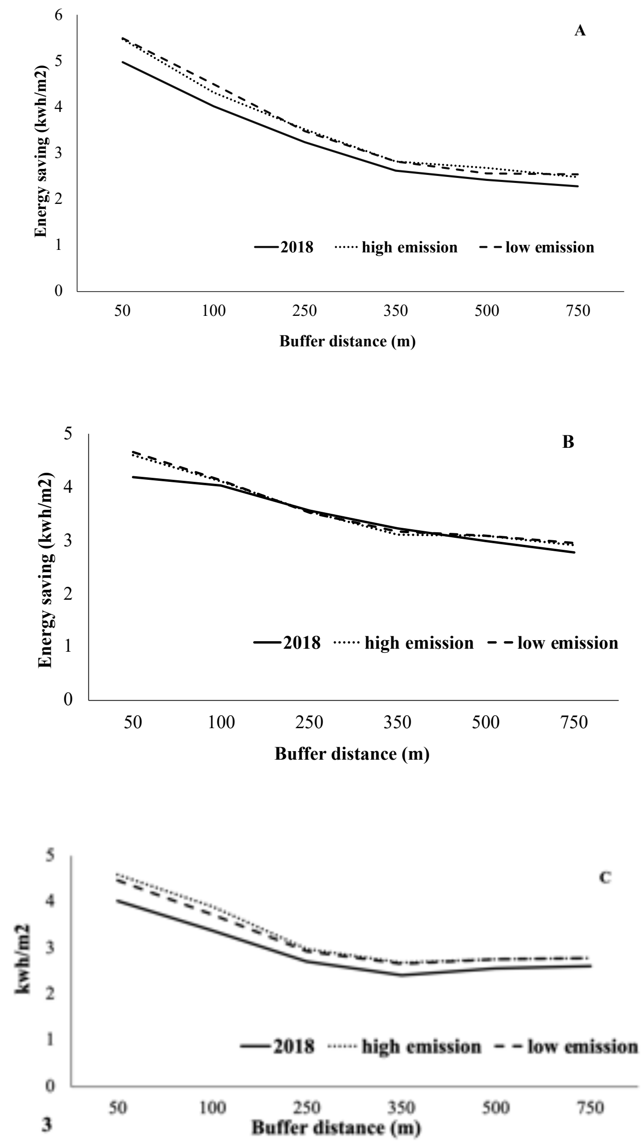

Figure 16. Energy saving (kwh/m^2) provided by the Lake of Tempe (A), Dobson Lakes (B), and Biltmore Lake (C) under high and low emission climate change scenarios compared to 2018.

Discussion and Conclusions

Results from our analysis indicate that the presence of a lake could significantly influence air temperature and mitigate UHI effects in some urban areas. Lakes represent an effective approach to reduce heat exposure and energy consumption in the hot, dry climate of Phoenix, Arizona. One of the lakes we studied lowered the surrounding temperature by up to 2.5 C and reduced energy use by 57% compared to high intensity development. Similar results were also reported by Taha (1997) who found that lake evapotranspiration can create a thermal oasis by lowering the temperature up to 2-4 C. These benefits were ancillary to the purpose of the lakes studied. We also found that distance from the lakeshore or the presence of green irrigated areas have a significant effect on the level of cooling. Intentional engineering of lake shape and landscape design could provide even greater mitigation of UHI effects (Yang, Ran, Zhang & Wang, 2020).

Thermal comfort provided by the lakes reduced energy demand. We estimated energy savings from reduced electricity consumption using averaged values for household energy use and ambient temperature. Energy consumption is influenced by a variety of other factors, including building characteristics, the efficiency of cooling appliances, and the behavior of building users (Li et al. 2019). Houses in low-income communities may be characterized by less effective insulation and structural conditions than those in higher income communities, which could result in greater energy use per unit area (Hernandez & Phillips, 2015). Consideration of these factors would provide a more precise estimate of building energy consumption and the value of nature-based solutions in addressing environmental justice disparities between socioeconomic groups.

The InVEST model showed how neighborhood landscapes influence the spatial pattern of air temperature. The Dobson Lakes area is a high-income neighborhood characterized by a higher percentage of irrigated green spaces compared to the other two study sites. The presence of a large golf course and green spaces throughout the Dobson Lake area provided additional cooling benefits. The presence of these green spaces lowered the surface temperature nearly one degree. These findings are in line with previous studies showing that the air temperature near green spaces can be cooler than surrounding built-up areas and that these cooling effects can extend hundreds of meters from the green space boundaries (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Spronken-Smith, Oke, & Lowry, 2000).

The use of spatially explicit models that estimate the cooling capacity of the urban fabric can help make informed decision on where to site new blue and green areas to maximize the potential cooling benefits. These models are a powerful tools to improve our mechanistic knowledge of ecosystems and can be useful in explaining the effects of LULC dynamics. The scenario-based analyses we used helped our understanding of the role that landscape architecture plays on microclimate mitigation. The scenario where the lake surface was substituted with a low or a high-density development simulated the impact of UHI in low-income neighborhoods. These neighborhoods are more vulnerable to the UHI affects because they tend to have more impervious surface and less and smaller-sized parks and green spaces (Harlan, Brazel, Prashad, Stefanov, & Larsen 2006; Wen, Zhang, Harris, Holt, & Croft, 2013).

Consistent with the literature, we found that a landscape architecture that guarantees a more equitable distribution of blue and green spaces, like in the Dobson Lakes neighborhood, could improve urban sustainability and climate resiliency. Promoting environmental justice through landscape designs that provide more equitable access to ecosystem services is a major challenge (Wolch, Byrne, & Newell, 2014). In the Biltmore Lake study site the presence of a large area covered by irrigated grass, shrubs and trees also provided a thermal comfort but within an area with little residential development. This finding confirmed the importance of accurately planning landscape configuration (i.e. by allocating cooling islands where urban dwellers could benefit the most) to more effectively mitigate the negative impacts of HUI.

As cities are becoming more vulnerable to climate change, the implementation of nature-based solutions to mitigate heat-wave impact is necessary for long-term sustainable development. Forecasted higher temperatures will likely increase the need for cooling, electricity and urban water demand, exacerbating greenhouse gas emissions and air pollution (Ortiz, Gonzalez & Lin, 2016). We considered a low and high emission climate change scenario to capture the extreme range of effects. The high emission scenario (RCP 8.5) represents a very high baseline emission scenario that mimic the worst-case outcomes. Our results showed that lakes are effective in mitigating air temperature and reducing energy consumption in some urban areas and that these benefits are enhanced under both future climate change scenarios.

The positive ecological and economic impact that artificial lakes can have on the UHI effect should be incorporated into sustainable land use planning but only after careful consideration of all the advantages and disadvantages. Although lakes are not a natural features of the Phoenix Metropolitan Area, numerous artificial lakes have been designed mostly for recreational uses or aesthetic enjoyment (Larson and Grim, 2012). As we have shown, these lakes also provide cooling benefits that results in substantial energy savings. However, since water is a valuable commodity, particularly in a desert city such as Phoenix, before using water for cooling purposes an accurate valuation of the water-use trade-offs is necessary. In a desert city like Phoenix, more than 60% of all the residential water use is for landscaping and other outdoor uses and the UHI effect is increasing the demand for private water use with environmental and economic consequences (Guhathakurta & Gober, 2007). With escalating pressures from climate change, demographic and economic development, governmental and regional planning agencies may need to reassess current water use allotment and potentially reassigning water uses to more pressing municipal needs. Future research should focus on assessing the tradeoff between cooling impact and water security to make more informed decisions on water allocation to sustain multiple ecosystem services.

The urban cooling model we used has limitations. To calibrate the model, we modified the required parameters using coefficients retrieved from the literature and the user guide (Sharp et al. 2020) because site-specific values based on direct measurements were unavailable. Additionally, the model simplifies the air mixing and the cooling effects of blue/green spaces, which could cause considerable deviations from the observed values in complex terrains (Bosh et al. 2020). The City of Phoenix is characterized by a flat topography and an urban geometry that mostly includes low buildings. In this case model simplification probably did not cause large deviations between observed and modeled distribution of air temperature. We explored UHI intensity based on daytime temperature and we focused on summertime data. We calibrated the model with the most widely used satellite data (Landsat) that only has daytime data. Several studies have confirmed that the UHI intensity can vary greatly between day and night, therefore future research should also estimate nighttime UHI intensity for a more comprehensive evaluation.

Despite these limitations, the urban cooling model is a relatively user-friendly tool useful for estimating the economic value of alternative LULC in providing temperature mitigation. Less tangible ecosystem services like climate mitigation are complex to measure and the availability of a model that accurately simulates air temperature helps overcoming major shortcomings of studies based on purely empirical techniques. Once calibrated to local conditions, the model could be easily applied to other cities with different microclimates, which can help exploring the UHI phenomena and support the design of mitigation strategies. Understanding the role of green or blue areas in mitigating air temperature is important as the outcomes can be directly translated into urban planning. Implementation of models that support the evaluation of ecosystem functions under alternative land use and climate change scenarios is critical to the adoption of nature-based solutions and sustainable development.

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Chapter 6

Conclusions

This is the first dissertation to offer a comprehensive characterization of urban lakes across the continental United States. I identified main monitoring and management challenges; quantified the impact that future urbanization could have on water quality and related ecosystem services; and assessed the ecological and economic value of urban lakes in mitigating the UHI effect. Findings from my studies make several contributions to the current literature on the social-ecological importance of urban lakes and strengthen the idea that these ecosystems should be prioritized in monitoring and management efforts.

Despite their recognized importance, urban lakes have received scant attention in the literature. Here, I compiled a comprehensive dataset with information on morphological parameters, water quality, ecosystem services, management activities and causes of impairment. While gathering information throughout the scientific literature, agency reports, government websites or personal communications with people directly responsible for lake management, gaps in the available data became evident. Data availability widely varied across ecoregions. Urban lakes in some ecoregions like the Xeric or the Southern Plains had less data available. Lakes in these ecoregions were also more sporadically monitored. Because of limitations in available data I was only able to characterize a subset of about 25% of the urban lakes identified in my study. Findings from my study are based on a relatively limited number of lakes, future efforts should focus on improving monitoring of urban lakes to further characterize these systems and confirm the disturbed state of urban lakes.

Several research gaps still remain to be investigated (Table 1). A better characterization urban lakes by collecting more consistent ecological data is necessary to assess if these systems are supporting the delivery of crucial ecosystem services. A natural progression of this work should focus on further quantifying the socio-economic value of the ecosystem services provided by urban lakes. One of the main constraints to the integration of freshwater systems into restoration or conservation decisions related to their use is the lack of information on their economic value. Quantifying the economic value of freshwater ecosystem services and benefits can offer a powerful justification for investment in restoration and management projects.

Table 1. Future research and management recommendations .

Research Gap	Research and Management Recommendations
Economic valuation of urban lakes	Identification and economic valuation all the ecosystem services (both market and nonmarket services)
Socio-ecological valuation of urban lake	Identification of people recreational preferences and quantification of lake visitation rates
Implement ecosystem-based management approach	Improve the adoption of ecosystem-based management approach
Better quantify the role that lakes can play in local climate regulation	Assess the role lakes can play in mitigating air temperature under a variety of local microclimates and considering multiple lakes morphological characteristics (i.e., size, depth, water, shoreline development index)
Socio-environmental justice issues	Examine how different socio-economic groups have lower (or higher) access to urban lakes

Future research should also focus on mapping all the ecosystem services (both market and nonmarket services) provided by urban lakes that contribute to social well-being and environmental sustainability in urban areas. Gaining a better understanding of recreational preferences and visitation rates will be also crucial for a sustainable urban planning and management. Finally, future work will also need to address socio-environmental justice issues by assessing how different groups can face discrimination in accessing ecosystem services provided by urban lakes.

Urban watershed are complex socio-ecological systems where the consequences of landscape planning might impact ecosystems differently. My research has shown that a challenge in preserving the ecological functions of individual ecosystems like urban lakes is to balance new residential development with habitat conservation. Before implementing specific land-use planning approaches, identifying potential ecological outcomes on individual habitats is crucial to avoid the loss of important ecosystem services. My analysis highlighted the importance and complexity of integrating multiple ecosystem services into large scale land-use plans. The adoption of a community-based management approach at the watershed-scale is widely acknowledged but still rarely executed (Tissot et al. 2009). Overcoming the challenges to reconcile differences among multiple stakeholders and lake users with contrasting agendas and goals is a crucial priority to implement an ecosystem-and community-based management approach.

This dissertation also provides the opportunity to make management recommendations. As indicated in chapter 3, the lack of implementation of data-driven management strategies limits water quality improvement. Lake managers need to adopt a systematic adaptive management approach for improving resource management. Available monitoring data should be used to gain insights about the impacts of past management actions and to ameliorate future outcomes.

The use of modelling tools to better understand the impact of alternative configurations of urban development patterns on the lake water quality is essential for developing a sustainable and integrated management approach. This dissertation also provides a new set of tools that could aid management efforts. I refined a new approach by combining two modeling tools (InVEST NDR and a mass-balance water quality model) to assess the impact of alternative land-use/land cover scenarios on the water quality and related ecosystem services provided by a major urban lake. I also adapted a modeling tool developed to estimate the cooling capacity of green areas to value the heat mitigation service provided by lakes. These relatively easy-to-use modeling tools could help resource managers in the implementation of an ecosystem-based management approach.

Tools for spatially modelling ecosystem services require the input of model specific parameters that are often retrieved from the literature or adapted from similar studies. To reduce these limitations, I suggest that further studies should be conducted to gather site-specific parameters (i.e specific coefficients to estimate cooling capacity or the nutrient retention efficiency for different LULC classes) across a range of geographic and microclimatic conditions. Models that simulate possible ecosystem service trade-offs require the input of raster datasets with the representation of future land use land cover. These data are not widely available, therefore more work needs to be done to provide datasets with projections of land use land cover change to use in modeling studies.

Among other ecosystem services, I demonstrated that urban lakes also play an important role in influencing the microclimate and reducing temperature through evapotranspiration. By using a new methodology, I assessed the ecological and economic values of lakes in mitigating UHI under both present and future climate change conditions. My analysis focused on lakes within a desert-like city characterized by a hot and dry climate. This study adds to our understanding of how lakes could be used as a solution to mitigate UHI effects. Future research should also explore the economic value of lakes in mitigating air temperature under different microclimatic conditions.

Throughout the four chapters of this dissertation I better characterized urban lakes and provided the basis to improve and justify management activities aimed at preserving these important systems. This dissertation highlights the importance of improving monitoring; adopting an ecosystem-based management approach; and modelling the impact of future urbanization to implement nutrient management efforts across the watershed. Restoring and maintaining urban lakes could help address some of the challenges that societies face, like climate change and environmental justice.

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