Journal of Hydrology 577 (2019) 123920

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Management of minimum lake levels and impacts on flood mitigation: A case study of the Yahara Watershed, Wisconsin, USA

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ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Marco Toffolon, Associate Editor

Keywords:
Flood exposure assessment
Lake level management
Hydrologic model
Ecosystem services

ABSTRACT

Lake level regulation is commonly used to manage water resources and mitigate flood risk in watersheds with linked river–lake systems. In this study, we first assess exposure, in terms of both population and land area, to flooding impacts in the Yahara Watershed's chain of four lakes in southern Wisconsin as affected by minimum lake level management. A flooding exposure assessment shows that the areas surrounding the upstream lakes, Mendota and Monona, have dense urban areas with high populations that are exposed to flooding; Waubesa has low elevations along its lakeshore, resulting in a large potential flooding area; and the most downstream lake, Kegonsa, has a large area of surrounding cropland that is exposed to flooding but impacts a limited population. We then use a linked modeling framework of a land surface model (Agro-IBIS) and a hydrologic-routing model (THMB) to simulate daily lake level over a study period of 1994–2013 in the Yahara Watershed with different minimum lake level management strategies. Modeling results show that the peak lake levels and corresponding exposed land area and population to flooding will decrease under a lower target minimum lake level. However, at the same time, the number of days that the lake level is below winter minimum will increase, which may adversely affect ecosystem health. In addition, our sensitivity analysis indicates that reducing target minimum lake levels will help mitigate flood risk in terms of both flood magnitude and frequency. Nevertheless, this must be balanced against the need to maintain adequately high lake levels for ecosystem services and recreational functions of the lakes.

1. Introduction

Land located in close proximity to water bodies has been preferentially selected for human settlement throughout history because of fertile soils, recreation opportunities, aesthetic beauty, diverse ecosystems, clean water supply, and a means to transport goods (Di Baldassarre et al., 2010; McGranahan et al., 2007). However, surface water flooding caused by natural water bodies such as rivers and lakes is a significant natural hazard posed to society (Opperman et al., 2009). In the current century, growing population and urban footprints near water combined with trends toward increasing frequency of intense precipitation events in some regions (IPCC, 2013) has contributed to an increased exposure of people, land area, and property to flood risk (Milly et al., 2002; Pahl-Wostl, 2007). In order to manage these risks, regulating water flows and controlling water body levels with engineered control structures, such as dams, levees, and reservoirs are common management options (White, 1945; Salazar et al., 2012).

Among the various ways of managing inland water bodies, lake level regulation and management are options in watersheds with hydrologic connections between lakes, rivers, and streams. The management of levels in low-gradient natural lake chains is more challenging than the management of reservoir levels because of the complex river–lake connectivity (Lesack and March, 2010), between-lake interactions (Zhang and Werner, 2015), and water flow variability (Peters and Buttle, 2010).

Dams are a key tool for managers to maintain lake levels between targets as much as possible with the acknowledgement that extreme wet and dry periods may lead to levels outside of the target range

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https://doi.org/10.1016/j.jhydrol.2019.123920
Received 3 January 2019; Received in revised form 22 May 2019; Accepted 3 July 2019
Available online 08 July 2019

(County of Dane, 2010). In order to effectively manage flood risk in watersheds with lakes, it is important to understand lake level dynamics and the impact of management decisions related to high and low lake levels on flooding, and then use this information to design management plans based on a wide range of plausible outcomes. Management of high lake levels attempts to minimize flooding by maintaining the lake level below some target maximum, and focuses on dam operation during storm periods (Reimer and Wu, 2016). Management of low lake levels aims to maintain the lake level above some target minimum, relying on lake outflow interventions during non-extreme periods. Management of low lake levels is focused on maintaining ecosystem services such as near-shore fish spawning and river habitat provision and boat recreation (Carpenter et al., 2007). Optimal management of both high and low lake levels is challenging since low lake levels and flows also affect flood risk (Young, 1968).

Extensive studies have been performed on dam management and operation optimization. To list a few, Wang et al. (2013) developed a near real-time optimization model for flood mitigation in a river basin in China with multiple reservoirs and focused on high water level management during flood season. Ahn et al. (2018) used a modeling approach to assess the coordinated operation of dams and weirs in terms of both high and low flow management under different climate change scenarios. Ehsani et al. (2017) analyzed climate and dam management data in the northeast United States and suggested an increase of the size and number of dams in the region to mitigate flood and drought risk under climate change. These previous studies have shown the challenges of dam management and its multi-objective nature. However, study on the flood mitigation impacts of low lake level management is limited, especially in a natural river–lake coupled system.

The main objectives of this study are to assess the potential exposure to flooding in an agricultural/urban watershed containing a chain of lakes, and investigate the effect of minimum lake level management on flood mitigation using a physically-based modeling framework. In this way, our study provides new insights about flood control in river–lake coupled hydrologic systems. To accomplish this, we adapt and link a 1-D dynamic land surface model with a 2-D hydrologic routing model to simulate the streamflow and lake levels in the watershed over a 20-year period from 1994 to 2013 as they are impacted by management of minimum lake levels.

2. Study area

The Yahara Watershed (YW) is located in southern Wisconsin, home to the city of Madison, and has a drainage area of 1345 km^2 (Fig. 1). Land cover within the YW is primarily cropland (46.5% of the total area) and urban land (26.7% of the total area). The watershed had a total population around 372,000 in 2010 (U. S. Census Bureau, 2015; Carpenter et al., 2015) with 65% within the city of Madison. There are four major lakes in the watershed connected by the Yahara River: Mendota, Monona, Waubesa and Kegonsa (listed in order from upstream to downstream). This low relief chain of lakes has 2.1 m of elevation change from the upper to lower lakes, which are separated by a distance of 10.9 km.

There are three dams in the YW allowing management of lake levels (Fig. 1). In this study, we refer to dams by the lake of which they are downstream. Mendota Dam (also called Tenney Dam) is located at the outlet of Mendota and controls the outflow and lake level of Mendota. Waubesa Dam (also called Babcock Dam) is located at the outlet of Waubesa. There is no control structure and little elevation change at the outlet of Monona, so both Monona and Waubesa are controlled by Waubesa Dam. Finally, Kegonsa Dam (also called Lafollette Dam), is located at the outlet of Kegonsa. High and low lake level targets have been established for each lake based on extensive discussion between local managers, regulatory institutions, and the general public (Table 1) (County of Dane, 2010).

To better understand the effectiveness of lake level regulation, there are several models that have previously been applied in the Yahara region to simulate river–lake dynamics. Krug (1999) developed a lumped water balance model to estimate the lake outflows under both high and low lake level regulations, suggesting that to maintain a reasonable level of minimum streamflow in the chain of lakes requires active dam management, which relies on detailed computations and modeling of streamflow and lake levels in the watershed. Baird and Associates (2007) coupled a lumped land surface model (NAM) and a 1-D hydraulic routing model (MIKE 11) to study the hydrologic system and assist lake level managers. They showed that both channel roughness and dam operation would have direct impact on lake levels. Reimer and Wu (2016) developed a real-time water information system to simulate water level and flow rate in the river chain of lakes. Using their real-time hydrodynamic model, the study tested different lake level management strategies to mitigate flood risks. They found that reducing the flood duration at one lake may cause the extension of flooding at another lake. As a result, lake level management needs to involve consideration of each lake's water level to achieve the overall flood mitigation for the entire lake-chain system. These previous modeling efforts have provided physical insights of the lake-chain system and guidelines for lake level management. However, these studies have focused primarily on event and intra-annual time scales. Research is still needed to simulate lake levels over longer time scales in order to understand the effect of low lake level management on flood risk during non-extreme periods.

In addition, a number of studies have been conducted on the non-stationarity of climate in the YW that is exacerbating flood risks. Gillon et al. (2015) reported an increasing trend of precipitation in the Yahara region in terms of both annual average precipitation totals and the frequency of extreme rainfall events (e.g., 50 and 75 mm in a 24-h period). Hayden et al. (2016) conducted a storm transposition experiment in the Upper Yahara Watershed to show a potential increase of flood risk in an urbanized area under climate change. They recommended that a watershed-scale modeling effort should take place with a focus on how flood risk is impacted by lake level variability.

In the last decade, flood management has become an important and timely issue in the YW. Usinowicz et al. (2017) document a long-term increase in flashiness for lake levels in both Mendota and Monona over the past century. Several recent events have also highlighted the challenges in flood management. In June 2008, flooding affected the YW when the region received approximately 20–35 cm of rainfall between June 1 and 15 (Budikova et al., 2010). This contributed to Monona exceeding its 100-year return period high lake level, causing substantial economic loss and property damage in Dane County (County of Dane Emergency Management, 2014). More recently, in late August through early October 2018 the entire Yahara chain of lakes was impacted by record flooding that began with a heavy 24-h rainfall event (mean of 11.5 cm over the Lake Monona watershed) on August 20. This historic event was then followed by an unusually wet September. These conditions combined with Lake Mendota water levels that were already 20–30 cm above the normal maximum level due to previously high spring and summer rainfall created an unprecedented and long-lasting water management issue. The large volume of runoff that entered Lake Mendota was slowly released through the Yahara River to minimize downstream flooding. However, given the high lake and river levels, this caused localized street closures and other flooding around businesses and homes for about 6 weeks (Verburg, 2018). Lake Monona reached a maximum level of 258.57 m, which is 19 cm higher than its 100-year return period level. Lake Waubesa also exceeded its 100-year flood level. After these flooding events, improving flood protection has once again become a major topic of discussion within the community (Elbow, 2018).

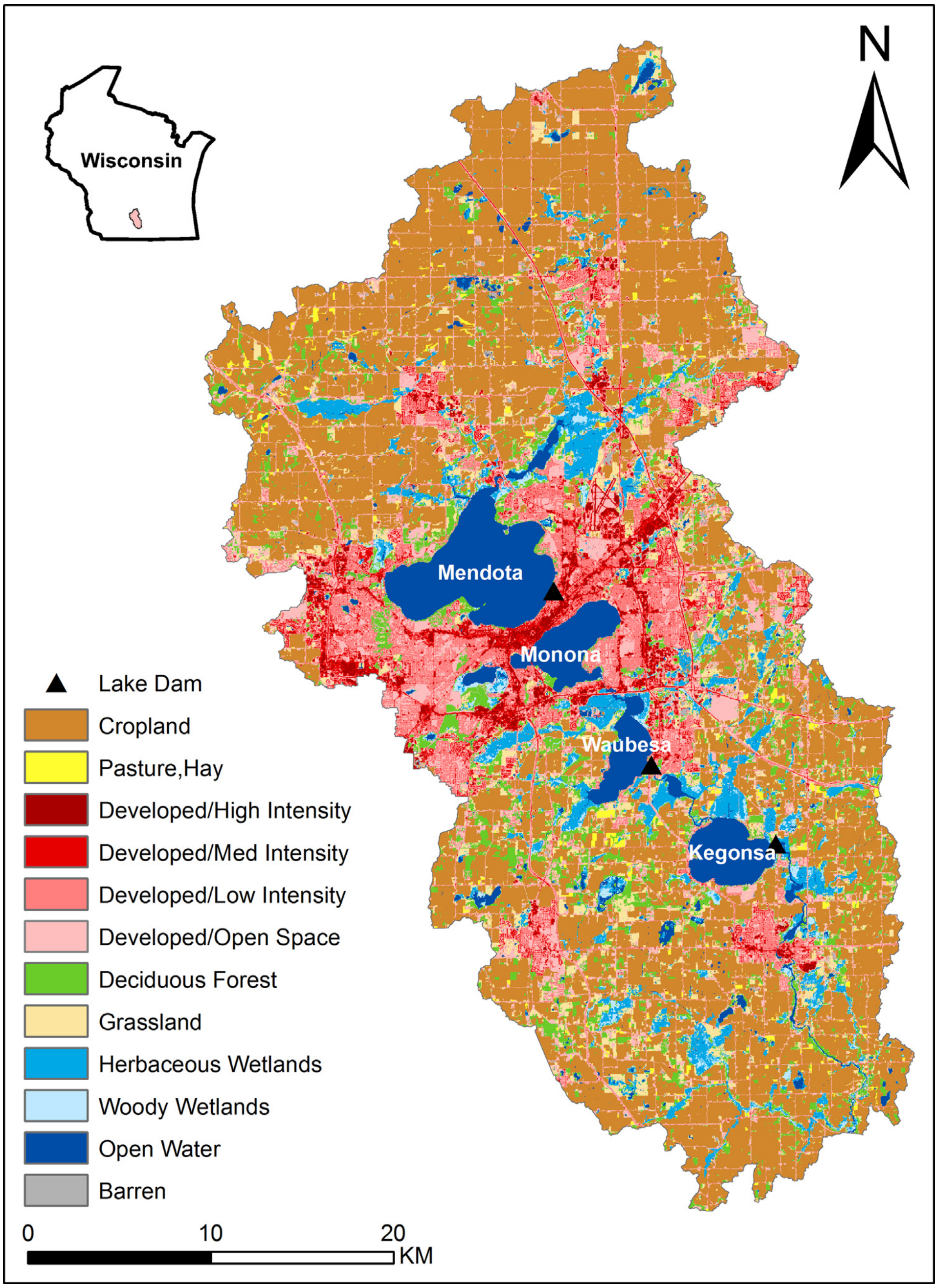

Fig. 1. Map of the Yahara Watershed.

Table 1
Lake areas and level management targets for the Yahara chain of lakes.

Lake	Mendota	Monona	Waubesa	Kegonsa
Target Maximum (m)	259.73	258.18	258.12	257.70
Target Summer Minimum (m)	258.50	257.03	256.90	256.58
Target Winter Minimum (m)	258.10	256.83	256.70	256.38
Area (km^2)	39.85	13.26	8.43	12.99
Model Summer Minimum (m)	258.70	257.15	257.15	256.70
Model Winter Minimum (m)	258.30	256.95	256.95	256.50

3. Methodology

3.1. Assessment of exposure to flooding

In order to investigate the flood risk in the YW, we conduct an assessment of exposure to flooding in the lakeshore areas. Based on Schanze et al. (2006), the term “flood risk” is defined as the probability of negative consequences caused by floods, which depends on the exposure of elements at risk to flooding. There are different methods of flood risk assessment, including the index method (Solín, 2012), mathematical modeling (Dutta et al., 2003), statistical approaches (Thieken et al., 2015), hydrologic modeling and scenario projections (Kobayashi and Takara, 2013; Sušnik et al., 2015; Vozinaki et al., 2015), and explicit damage and cost accounting based on historical events (Patankar and Patwardhan, 2016). Our approach uses a simple assessment of potential exposure to flooding of the lakeshore area of the YW, based on the relationship between lake levels and land surface elevation. First, we use historical lake level records to calculate the regulated lake level exceedance frequency of the four lakes (Fig. 2). Second, we link a digital elevation model (DEM) with population density and land use/land cover maps to estimate the potential

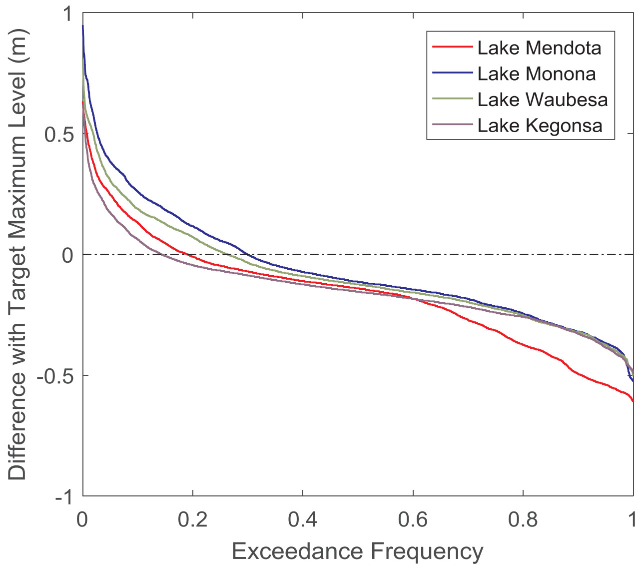

Fig. 2. Lake level exceedance frequency from 2004 to 2018 relative to target maximum lake levels.

exposure of population and land area of each lake across a range of lake levels. The potential exposure of land area is determined as the area within 1 km from the lakeshore that has an elevation lower than the target extreme lake level and is not directly protected by dams and levees (Fig. 3). The potential exposure of population is determined by multiplying each census-level block population density by the exposed area within that block. Then, the total exposed population is determined by summing all of the exposed blocks. We recognize that our measure of potential exposure of populations is an approximation since the spatial scale of the census data may not be fine enough to be able to fully capture the details of population distribution in the lakeshore area. Four extreme lake levels are used in this assessment: target maximum level, target maximum level +0.1 m, target maximum level +0.4 m, and target maximum level +0.7 m. These extreme levels are selected based on the historical lake level records (Fig. 2) to represent different levels of flood risk. For example, Lake Monona exceeded the +0.7 m lake level during the 2008 and 2018 flood events, which had major impacts on the City of Madison and surroundings.

3.2. Modeling framework

After we performed the exposure assessment under different lake levels, we use a watershed-scale modeling framework to simulate the linked river-lake system in the YW with lake level management implementation to investigate the effects of the minimum lake level management on flood risk in the YW. To build this modeling framework, we adapt and link an agricultural version of the Integrated Biosphere Simulator (Agro-IBIS; Kucharik, 2003) with the Terrestrial Hydrology Model with Biogeochemistry (THMB; Coe, 1998). Agro-IBIS simulates, among other processes and quantities, surface runoff and subsurface drainage for a variety of ecosystems and land cover types. Using Agro-IBIS outputs as driver variables, THMB simulates the instream transport of water and the change of lake levels. A more detailed description of these two models is provided in the following Sections 3.3 and 3.4. This modeling framework has the capability to dynamically simulate daily streamflow and lake levels under the impacts of changing management, land use/land cover, and climate, and has been used previously in different regions and at coarser spatial scales but across larger spatial domains (Coe et al., 2002; Donner et al., 2002; Donner and Kucharik, 2003; Coe et al., 2008).

3.3. Agro-IBIS model description

Agro-IBIS is a 1-D land surface and dynamic ecosystem model that simulates the movement of water, energy, momentum, carbon, nitrogen, and phosphorus through the soil-vegetationatmosphere system (Foley, et al., 1996; Kucharik et al., 2000; Kucharik, 2003). The model has been validated across a range of ecosystems at different regions and time periods (Kucharik and Brye, 2003; Kucharik and Twine, 2007). Recently, Agro-IBIS was integrated with the soil water and energy transport routines from HYDRUS-1D (Šimůnek et al., 2013) to improve simulation of water-soil-vegetation interactions in the unsaturated zone (Soylu et al., 2014). In the YW, the updated Agro-IBIS model has previously been validated at both the field scale (Soylu et al., 2014; Zipper et al., 2015) and watershed scale (Motew et al., 2017).

3.4. THMB model description

THMB is a physically-based 2-D hydrologic routing model that combines prescribed river network information with calibrated parameterization of river morphological characteristics to simulate the flow and storage of water in hydrologic systems using linear reservoir functions (Coe, 1998; Coe, 2000). THMB has been validated in various regions and at a range of scales (Coe et al., 2002; Donner et al., 2002; Donner and Kucharik, 2003; Coe et al., 2008).

The version of THMB used for the YW is modified from the version of Coe et al., (2008) to include lake level simulation under regulation. The original lake outflow equation to compute lake outflow under unmanaged conditions (Coe, 1998) is replaced by Eq. (1):

$$Q_{out} = \begin{cases} \dfrac{\frac{2}{3}\sqrt{2g}\,CL\left(V^{\frac{3}{2}} - V_l^{\frac{3}{2}}\right)}{A_s^{\frac{3}{2}}} & V_l < V \\ Q_m & V \le V_l \end{cases} \quad (1)$$

where Q_{out} (m^3/s) is the lake outflow; g is the gravitational acceleration, 9.8 m/s^2; C is the outflow coefficient, which is obtained through calibration; L (m) is the effective length of the crest (gate width), which is given by the Wisconsin Department of Natural Resources (WDNR, 2001); V (m^3) is the current lake volume; V_l (m^3) is the management low volume; A_s (m^2) is the standard lake area; and Q_m (m^3/s) is the regulated minimum flow. In Eq. (1), the first equation is a modified version of the spillway discharge equation in Chow et al. (1988).

In our model, lake volume V is simulated at each time step in THMB, driven by meteorology and lake outflows. The initial lake levels are prescribed based on the DEM. A detailed explanation of lake volume simulation in THMB is provided by Coe (1998) and Coe et al. (2008).

The levels of V_l of each of the four lakes are calculated based on the model minimum lake levels, mimicking the target minimum lake levels in Table 1. As Table 1 shows, the minimum lake levels in the model are not the same as the target minimum lake levels. The model minimum levels are obtained through calibration, described in Section 3.5.

Standard lake area A_s is obtained from Lathrop (1992). We assume that the lake area variability is negligible for outflow calculation and therefore A_s is constant in Eq. (1).

The minimum flow rate Q_m is set to 0.1 m^3/s for all four lakes. This flow rate is the lowest among the minimum outflow requirements of the four lakes according to Krug (1999). The actual minimum flow varies with the lake level conditions, but we simplify the minimum flow rate to a constant level of 0.1 m^3/s because variability around this small discharge value does not substantially affect lake levels.

Because of the simplicity of Eq. (1), short time scale hydrodynamic processes such as backwater effects are not considered in the model. As a result, the effect of high lake level management during extreme events, which has been extensively studied (Reimer and Wu, 2016), is not investigated in this study. We focus on the contribution and impact of minimum lake level regulations to YW flood risk and evaluate these effects from 1994 to 2013.

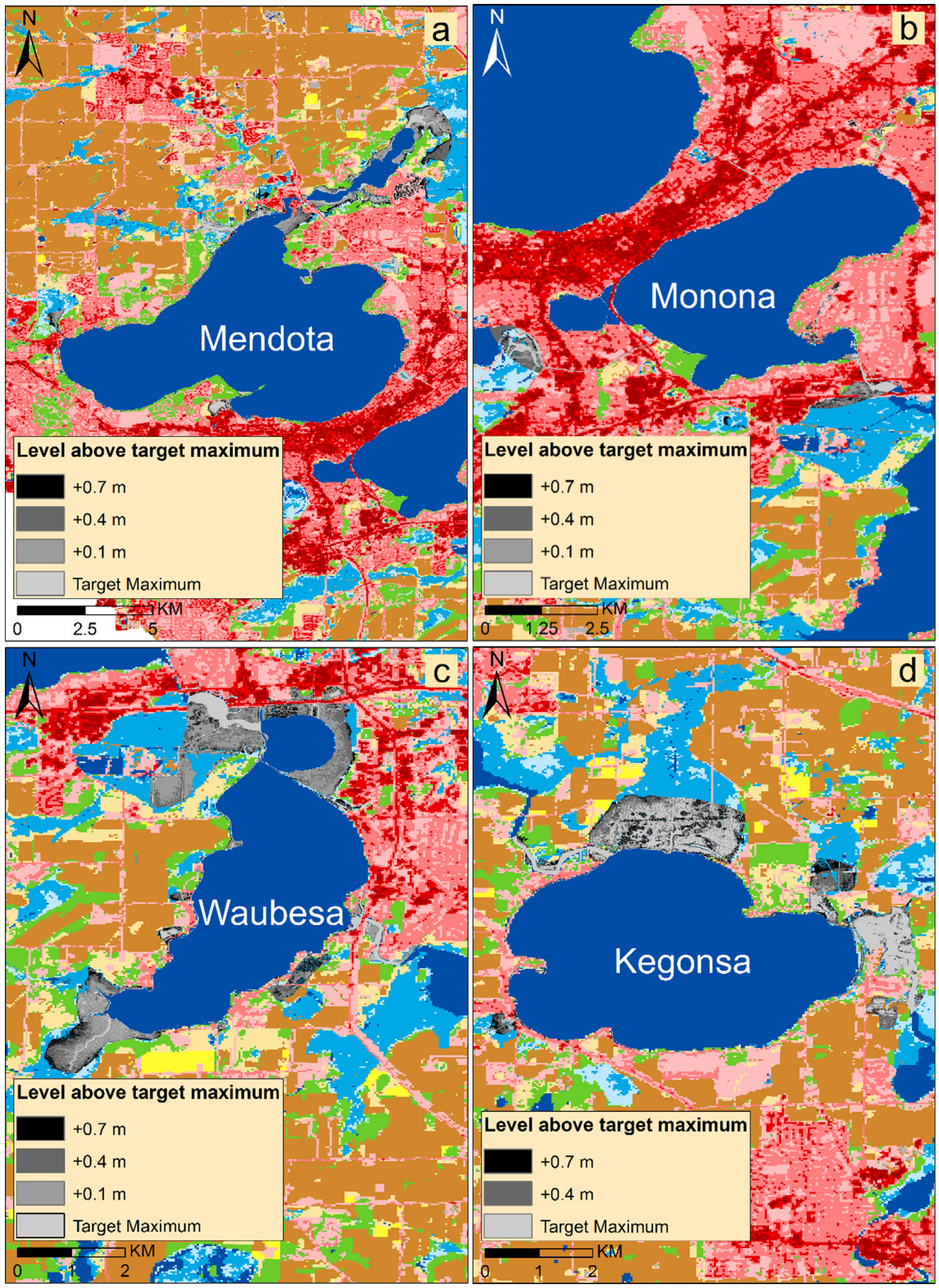

Fig. 3. Potential flood area at different extreme lake levels of the 4 lakes with land use/land cover map (a–d). The color categorization of land use/land cover types is the same as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.5. Data sources and model calibration

Weather data for input to Agro-IBIS and THMB from 1986 to 2013 include daily precipitation, maximum and minimum air temperature, relative humidity, wind speed, and solar radiation. Daily precipitation observations from a National Weather Service Cooperative Observer Program (COOP) weather station at the Madison, Wisconsin airport (COOP ID: 474961) are used for the time period of 1986–2000 and applied across the watershed (NCDC, 2015). Spatially-variable, radar-derived, daily precipitation estimates (4 km × 4 km) synthesized by the National Centers for Environmental Prediction are used for the 2001–2013 time period (NCEP, 2015). Daily maximum and minimum air temperature and wind speed observations from the Madison, Wisconsin airport (COOP ID: 474961) are used for the entire time period and applied across the model domain (NCDC, 2015). Daily relative humidity and solar radiation observations for the complete study time period are obtained from a University of Wisconsin-Extension weather station in Arlington, Wisconsin, which is located in the northern YW (UW-Extension, 2014); these weather data are applied across the entire domain.

Land surface data collected for this study included land use/land cover (LULC), elevation and population data. Dynamic LULC maps are compiled to determine lake extent and annual landscape composition consisting of 17 biophysically distinct categories and interpolated to the 220 m × 220 m model grid in the period of 1986–2013 (Booth et al., 2016). The land use/land cover map of 2013 is used for the flood vulnerability assessment in this study. LiDAR-derived elevation data with a resolution of 1.5 m by 1.5 m and a vertical accuracy of 0.15 m are downloaded from the WisconsinView database (ftp://ftp.ssec.wisc.edu/pub/wisconsinview/lidar/Dane) and used to determine the

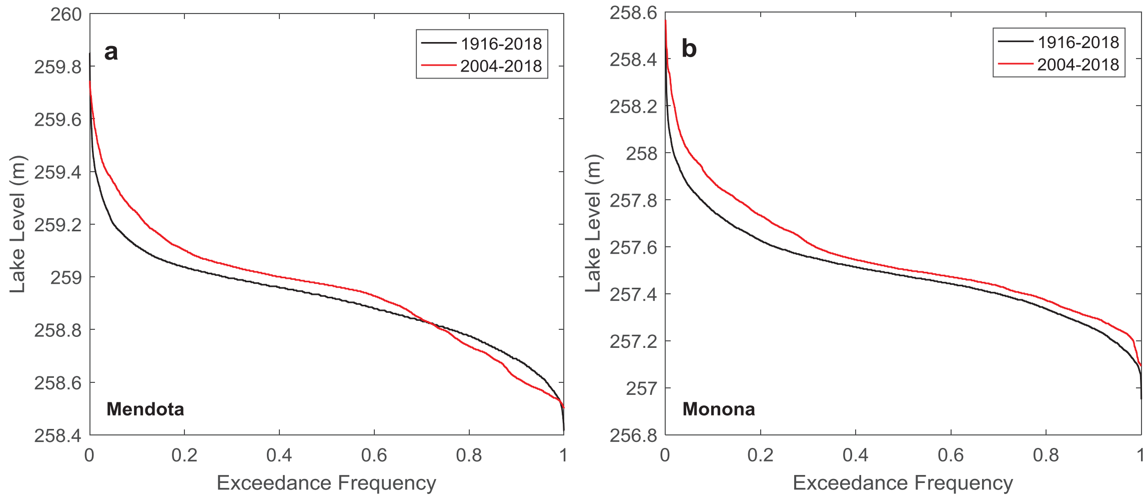

Fig. 4. Comparison of lake level exceedance frequency during 2004–2018 and in the long-term record of 1916–2017 at Mendota and Monona (a, b).

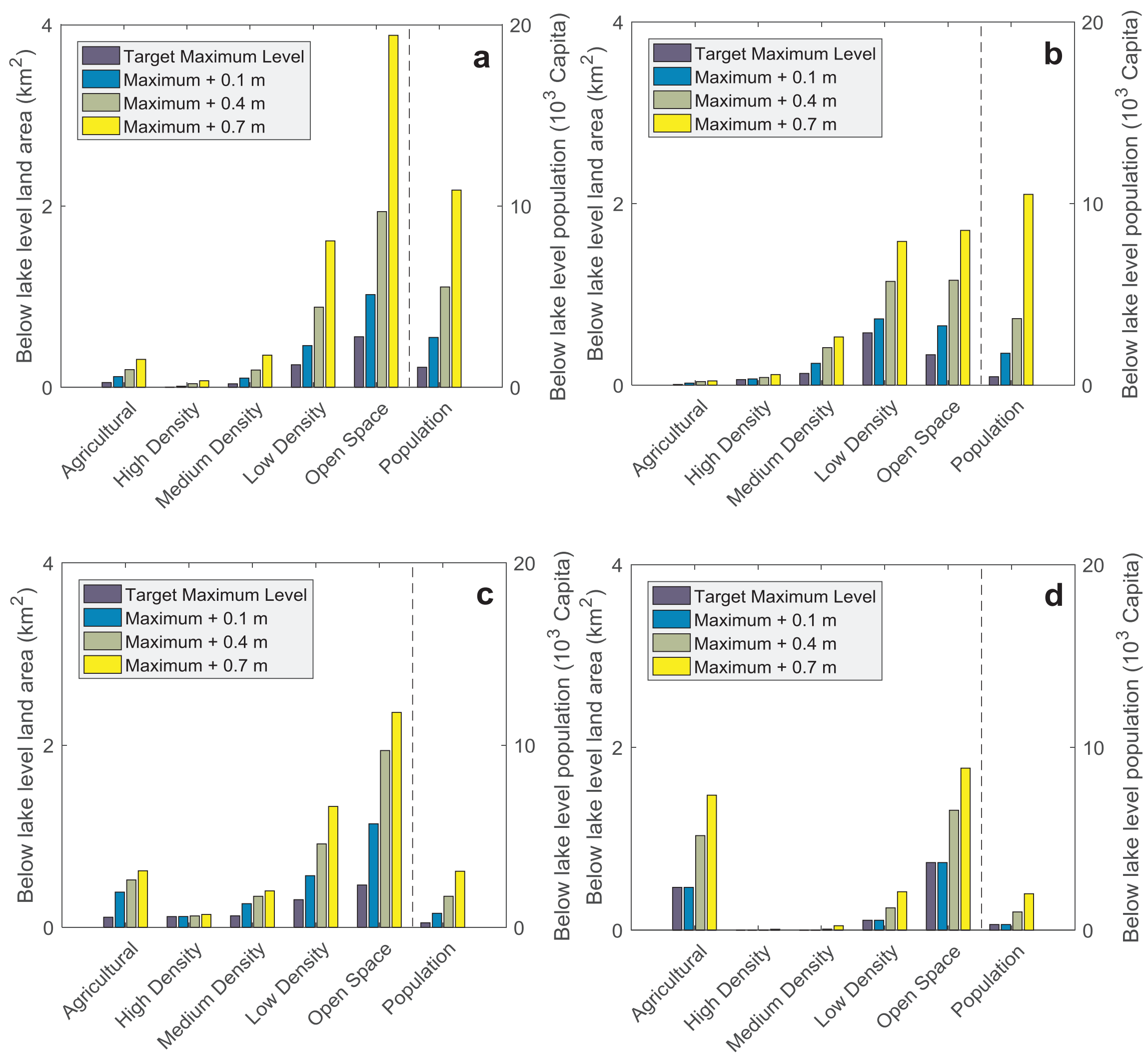

Fig. 5. Below lake level land area and population at Lake Mendota (a), Monona (b), Waubesa (c), and Kegonsa (d). Based on the historical lake level records shown in Fig. 2, we select four extreme lake levels to have a spread of flood risks with "Maximum + 0.7 m" as the most severe extreme level. For example, "Maximum + 0.7 m" occurred in Lake Monona during the 2008 and 2018 storm periods, which is considered a 100-year return period lake level. The classes of "high density", "medium density", "low density" and "open space" are different density levels of urban area.

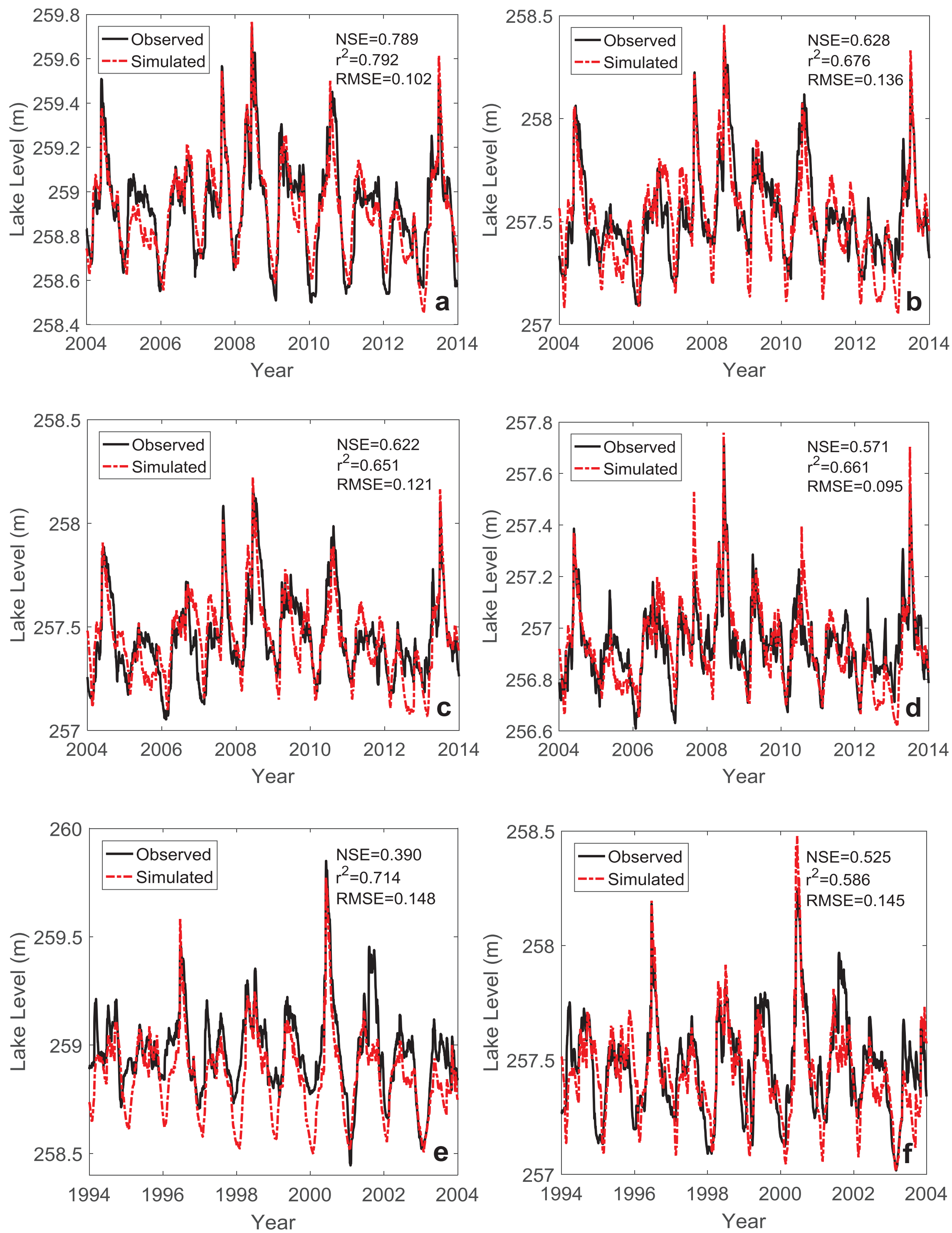

Fig. 6. Time series of observed and simulated daily lake levels for the calibration period from 2004 to 2013 at Mendota (a), Monona (b), Waubesa (c) and Kegonsa (d); and for the validation period from 1994 to 2003 at Mendota (e) and Monona (f).

potential flood-affected area. Furthermore, we collect 10 m resolution elevation data from USGS NED dataset and resample the data to 220 m spatial resolution to match Agro-IBIS. The resampled elevation data is used to derive the stream network for THMB modeling. Block-level population data was obtained from the U.S. Census Bureau to determine the number of people potentially impacted by lake flooding (U. S. Census Bureau, 2015).

For model calibration and validation purposes, observations of streamflow from six gages and lake level from four gages are obtained from the U.S. Geological Survey's National Water Information System (USGS, 2015). Streamflow simulation and realism in THMB has been discussed in-depth in previous studies (Coe et al., 2002, 2008), and therefore will not be a focus of validation here. Nevertheless, the performance of streamflow simulation will be shown in the Results section. The lake level simulation calibration in THMB is performed by comparing the observed daily lake levels with simulations, adjusting the model minimum lake levels and outflow coefficients of the four lakes. We calibrate the parameters of each lake sequentially from upstream to

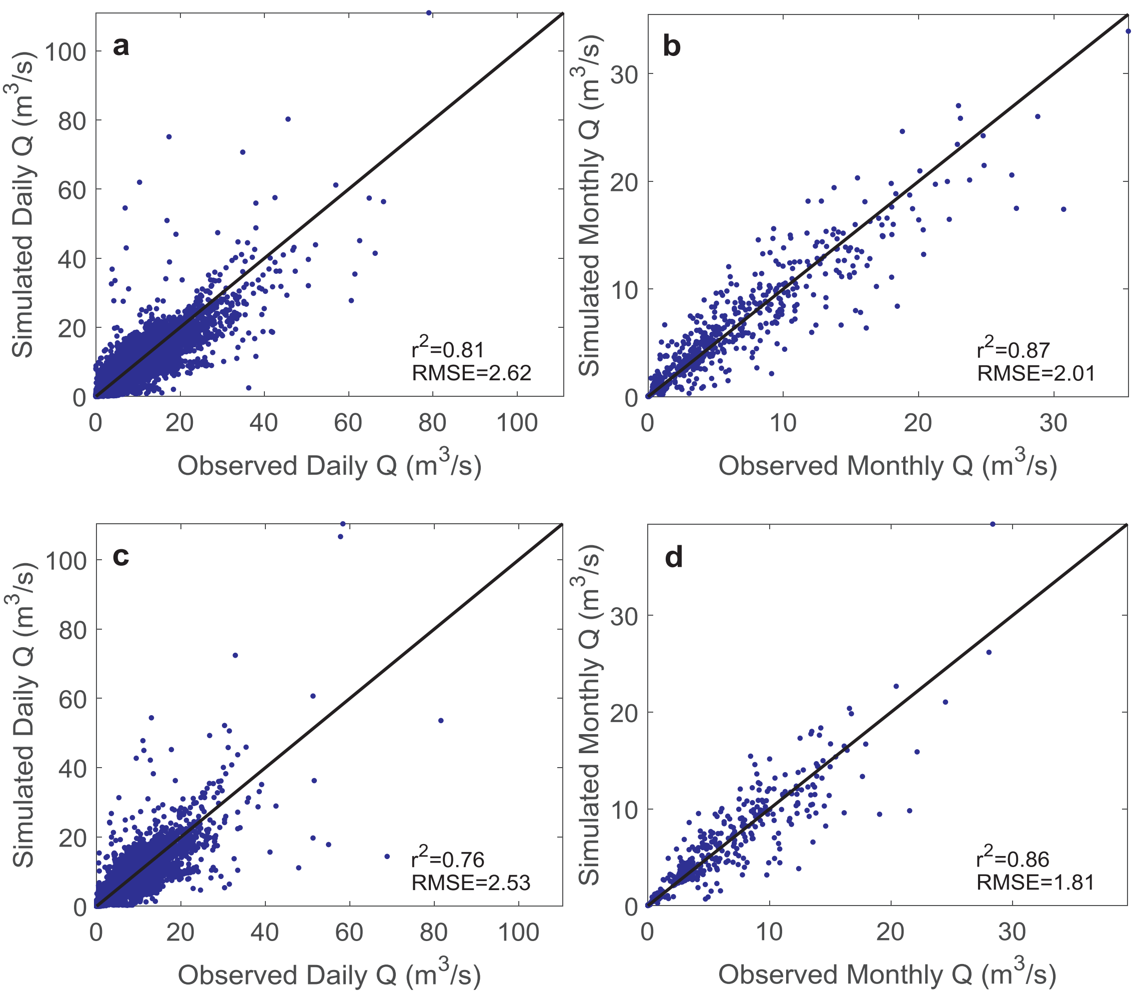

Fig. 7. Observed and simulated daily (a) and monthly (b) average flow rate in the YW in the calibration period and validation period (c, d). The data points are from 6 USGS gauge stations across the YW. The monthly performance of streamflow simulation at each of the 6 stations is shown in the Supplementary Materials (Figs. S1 and S2).

downstream. The best fit parameters are selected based on the Nash-Sutcliffe Efficiency (NSE) value of simulations. The model minimum lake levels (Table 1, rows 5 and 6) are not the same as the target minimum lake levels (Table 1, rows 2 and 3) because the target minimum lake levels are reference levels that guide management decision-making, rather than the actual minimum lake levels that are observed. We choose the period of 2004–2013 as the calibration period and 1994–2003 as the validation period.

3.6. Model simulation and sensitivity analysis

After calibration and validation, we use the calibrated model to investigate the effect of minimum lake level management on flood risk and ecosystem health. Specifically, we conduct a new simulation with a model minimum lake level 0.1 m lower than the calibrated value at Lake Mendota, representing an alternative management strategy. Then we compare this simulation result with the original modeling result, in terms of high and low lake levels. For high lake levels, we compare the potential exposure of land area and population under different peak levels, using the same method described in Section 3.1. For low lake levels, the winter target minimum levels are absolute minimums. Low winter lake levels may adversely affect hibernating aquatic species and damage fish habitats (County of Dane, 2010). Therefore, we count the number of days that the lake level is below the target winter minimum levels to evaluate the effect of minimum lake level management on ecosystem health. We select Lake Mendota for this analysis, because it is the largest lake of the four and the south side of the lakeshore area is highly urbanized. The management of lake level at Mendota is crucial to the safety and economic development of the local community, as well as the health of ecosystems in the region. This analysis is conducted during the calibration period of 2004–2013.

Furthermore, we conduct a sensitivity analysis of daily water levels under different model minimum levels at all four lakes to gain a complete picture about the impact of minimum lake level management. Using the current lake level control strategy as the base line, we evaluate 6 alternative strategies: for each of the 3 dams, we increase/decrease the minimum levels by 0.1 m respectively. The sensitivity analysis is also conducted during the calibration period of 2004–2013.

4. Results

4.1. Assessment of exposure to flooding

We first investigate the exceedance frequency of lake levels based on the historical period with data from all four lakes (2004–2018) (Fig. 2), relative to the target maximum lake levels listed in Table 1. In Fig. 2, Monona and Waubesa exceed target maximum levels most frequently; while Kegonsa and Mendota have lower exceedance frequency of target maximum levels, with Kegonsa being the lowest. Also, Mendota shows a larger range of low lake levels (approximately 0 m to −0.6 m) than the other lakes (approximately 0 m to −0.5 m), indicating low lake levels are more common in Mendota. This

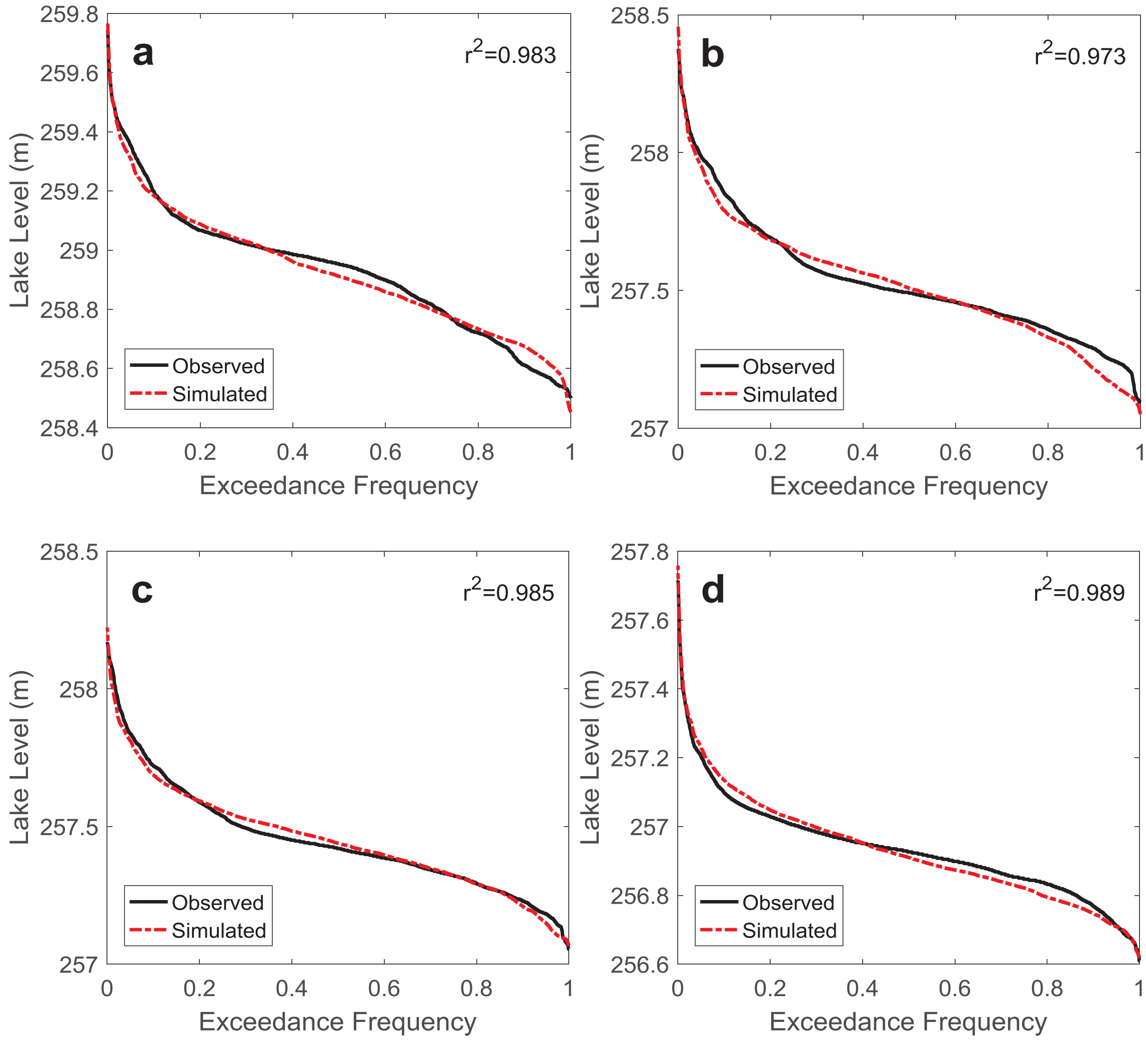

Fig. 8. Comparison of observed and simulated daily lake level of Mendota (a), Monona (b), Waubesa (c) and Kegonsa (d) in the calibration period using exceedance frequency plots.

comparison reflects the lake level range and potential flood risk of the four lakes in the 2004–2018 time period.

However, 15 years is a relatively short period to analyze lake level distributions. Therefore, we also plot the exceedance frequency curves based on long term (1916–2018) records for Mendota and Monona (only these two lakes have long term records). Both lakes show a general increasing frequency of high lake levels in the modern record compared to long-term data (Fig. 4). For example, the extreme rainfall that occurred during the first half of June 2008 caused the lake level in Monona to exceed its 100-year return period level. Also, the more recent storm event of August 2018 – coupled with heavy rainfall in May and early June (~33 cm from May 1 to June 15 2018) that increased lake levels above maximum targets – caused Monona, Waubesa, and Kegonsa to exceed their 100-year return period levels. The increase in high water level occurrences in YW is an important temporal change to note.

In terms of the exposed land area and population, as expected, lakeshore areas of Mendota and Monona have the highest exposed urban area and population among the four lakes, since they are the closest to Madison's urban core (Fig. 5a and b). Waubesa has a smaller developed area and lower population density than Monona but a relatively low elevation around the lakeshore area, and therefore a larger potentially flooded area but smaller exposed population relative to Mendota and Monona (Fig. 5c). The outlying landscape surrounding Kegonsa away from the shoreline is largely undeveloped, surrounded by wetlands and croplands. Therefore, Kegonsa has the lowest exposed urban area and population and the highest exposed agricultural area (Fig. 5d).

Based on the flood exposure assessment results, the four lakes' lakeshore areas are facing varied levels of flood risk, which are closely related to the extreme lake levels. In the following sections, we use a modeling approach to investigate the impact of minimum lake level management on the daily and extreme lake levels in the YW.

4.2. Lake level model results

After calibration, the linked Agro-IBIS and THMB models simulate lake levels at a daily timestep (Fig. 6), with satisfactory values of NSE and R^2 during the calibration period for all lakes (Moriasi et al., 2007). Since lake level simulation is closely related to streamflow simulation in our modeling framework, the streamflow simulation performance is presented in Fig. 7. More detailed information about streamflow simulation, in terms of individual location performance and map of stream gauges, is provided in the Supplementary Material (Figs. S1 and S2). Model validation of lake level simulation is only performed at Mendota and Monona, since only these two lakes have a long historical record of lake levels that covers the validation period. The performance of lake level simulation in the validation period (Fig. 6e and f) is not as good as in the calibration period. One possible explanation for differing performance between the two intervals is that lake level management strategies have changed over time, even with the same target maximum

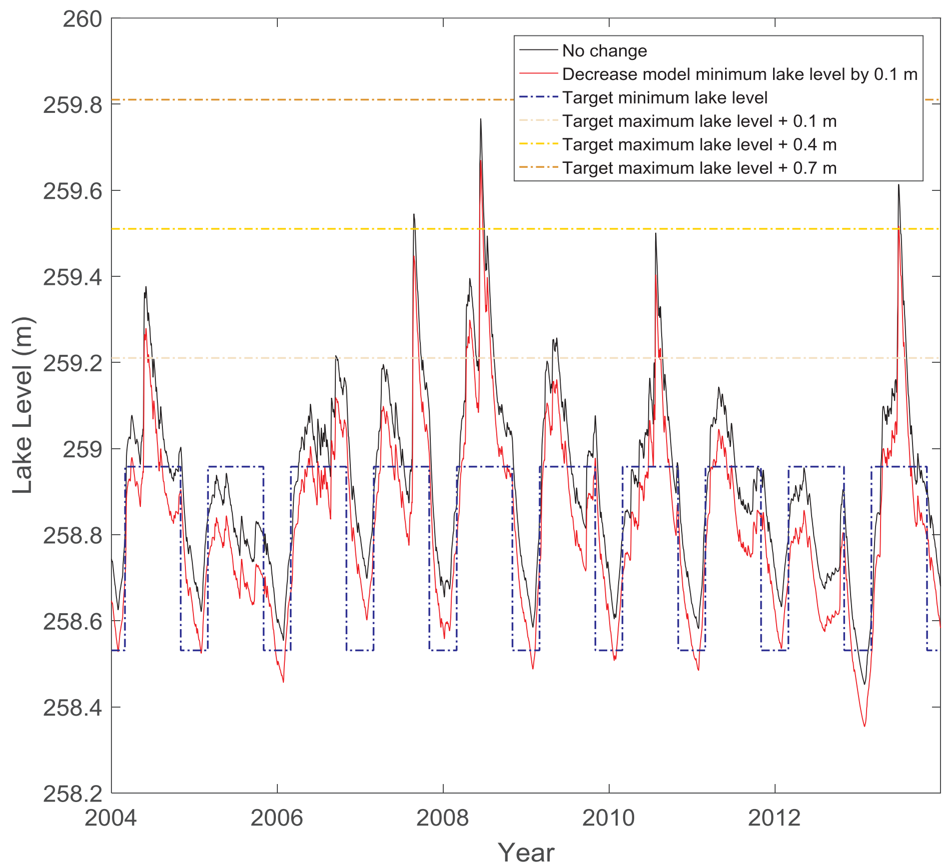

Fig. 9. Comparison of different minimum lake level management strategies at Lake Mendota.

Table 2
Impacts of minimum lake level management at Lake Mendota.

Model summer/winter minimums at Lake Mendota (m)	Peak lake level in June 2008 (m)	Exposed land area (km^2)	Exposed population	Number of days below winter minimum lake level during 2004–2013
258.70/258.30	259.77	8.04	4916	45
258.60/258.20	259.67	6.09	3403	206

and minimum lake levels, while management in our model is constant over the entire calibration and validation period. The model performance indicates that the modified spillway discharge equation (Eq. (1)) is able to simulate daily lake levels with minimum lake level management, at least under non-extreme conditions.

We also compare the observed and simulated lake level exceedance frequency curves (Fig. 8). We compute R^2 values between the frequency curves and also the percentage differences of the accumulated area of the simulated frequency curve from the observed frequency curve (dA%). The model performs well at Mendota ($R^2 = 0.983$, dA% = −0.002%, Fig. 8a). For Monona ($R^2 = 0.973$, dA% = −0.004%), the model tends to underestimate the lake level in extreme events with exceedance frequency lower than 0.2 (Fig. 8b). The model also performs well at Waubesa ($R^2 = 0.985$, dA% = 0.001%) with a similar slight underestimation of lake level for extreme events (Fig. 8c). For Kegonsa ($R^2 = 0.989$, dA% = −0.002%), the model underestimates lake levels when the exceedance frequency is higher than 0.4 (Fig. 8d). In general, the model underestimates lake levels during extreme events except for Kegonsa, where the lake level is underestimated during normal level and low level periods. This underestimation may be due to different lake level management operation decisions from event to event. Also, hydrodynamic processes, such as backwater effects, are not considered in our model, which may also cause underestimation of extreme lake levels.

4.3. Minimum lake level management impact assessment and sensitivity analysis

To quantitatively assess the effect of minimum lake level management of Lake Mendota, we conduct a comparison analysis as described in Section 3.6. By decreasing the model minimum lake level by 0.1 m, the water levels at Mendota are generally lower than the baseline condition (Fig. 9). As a result, the peak level will be lower during extreme events with this alternative management strategy, such as the one in June 2008 (Budikova et al., 2010). However, the low lake levels will be further decreased with this strategy. We use the peak lake level at mid-June 2008 as a representative event to evaluate the effect of minimum lake level management on flood risk mitigation. The peak level decreases from 259.77 m to 259.67 m with the change of model minimum lake level (Table 2). Correspondingly, the potentially exposed land area decreases from 8.04 km^2 to 6.09 km^2 and the potentially exposed population decreases from 4916 to 3403 in the Mendota lakeshore area. On the other hand, during the analysis period of 2004–2013, the total number of days that Lake Mendota is below the target winter minimum lake level increases from 45 to 203 with the new management strategy.

To systematically investigate the impact of minimum lake level management changes on daily lake levels in the YW, we perform a sensitivity analysis on model minimum lake levels. For each lake, the

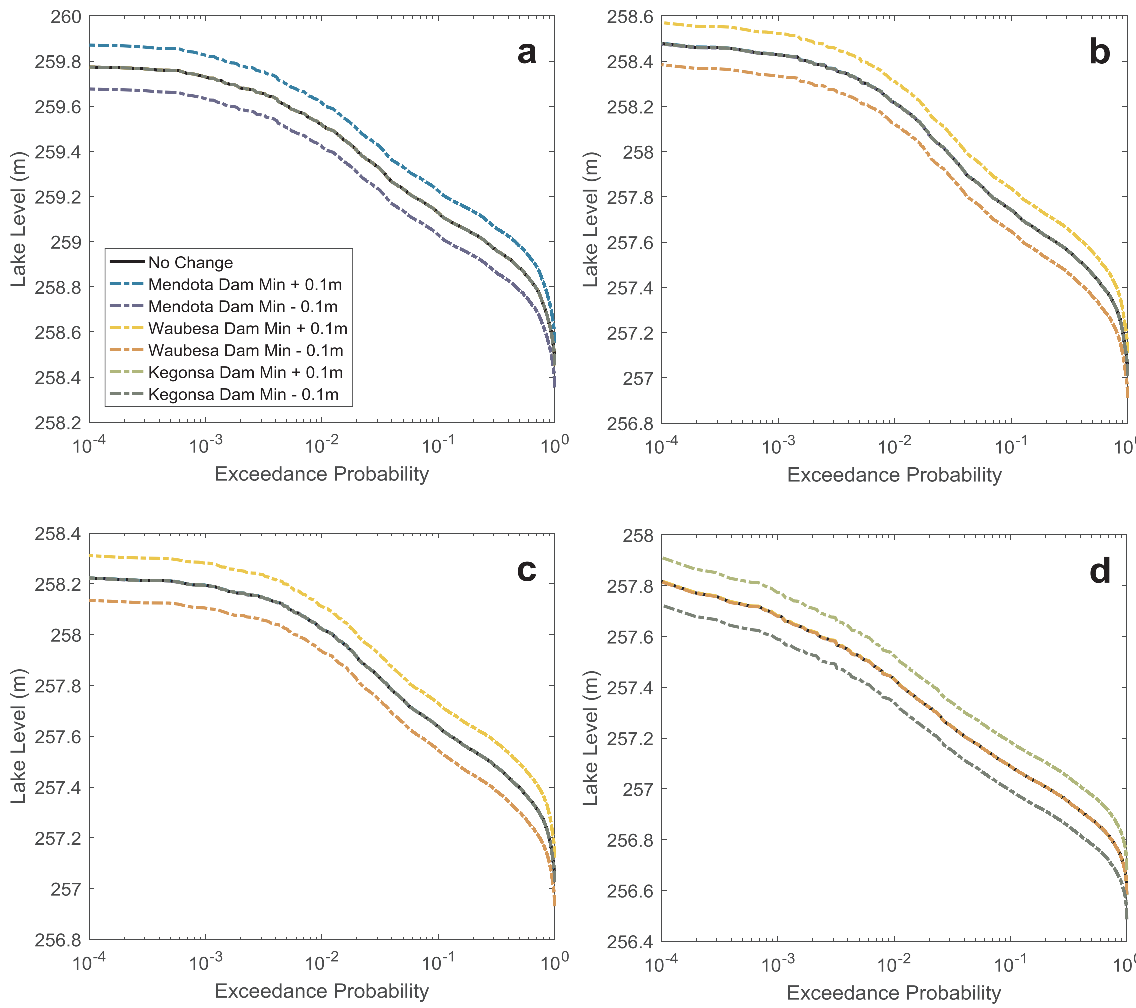

Fig. 10. Sensitivity analysis results of different minimum lake level management changes at Mendota (a), Monona (b), Waubesa (c) and Kegonsa (d). In order to emphasize the differences of high lake level events among the curves, we use semi-logarithmic scale.

daily lake levels under different model minimum lake levels are compared using exceedance frequency curves. For all four lakes, the minimum levels significantly affect daily levels; increasing or decreasing the minimum level by 0.1 m will lead to a nearly uniform increase or decrease of the lake level by 0.1 m, respectively (Fig. 10). However, changes in the upstream dam minimum levels show little to no effect on lake levels in downstream lakes.

5. Discussion

5.1. A balance between flood control and other ecosystem services

Based on our modeling and analysis results, we observe that reducing model minimum lake levels has a relatively uniform effect on daily lake levels, one that mitigates flood risk but may make the minimum lake level requirements for ecological or recreational services harder to achieve. While our study focused on the response of flooding to minimum lake level management, the Yahara lakes have diverse functions. Lakes provide aquatic habitats for a variety of species and support recreational activities, such as boating, fishing and swimming (Qiu and Turner, 2013; Qiu et al., 2018a,b). As a result, lake level management faces a complex challenge to maintain the balance among different lake functions which require different water levels (YLAG2, 2012). This is a general management dilemma both in the YW and in many lake-catchment systems around the world (i.e., Christensen et al., 2016; Yang et al., 2016; Hyatt et al., 2015), and has long been identified as "a formidable task" (Young, 1968; Day and Weisz, 1976; Morales-Hernández, et al., 2013). To optimize the multifunctional lake level management, a comprehensive assessment of the impacts of lake levels on competing interests is required.

5.2. The importance of high lake level management

Controlling for high lake levels associated with extreme rainfall and high runoff events is another important perspective of lake level management. The timing and amount of water release from the three local dams in the YW are critical for flood control during and after extreme rainfall, which changes from event to event. In order to simulate flood control during extreme events, a hydrodynamic model with high spatial and temporal resolution is required; this is not the functional purpose of our model. In future studies, we would like to combine our watershed modeling framework with a hydrodynamic model, such as the Integrated Nowcast and Forecast Operation System (INFOS) (Reimer and Wu, 2016) to investigate the effects of both long-term minimum lake level regulations and the impacts of lake level management during extreme rainfall and subsequent runoff events in the YW.

5.3. Other possible drivers of change on lake level management

A particularly challenging aspect of lake level management is that stakeholders in the YW have varying opinions on what are the most important lake level management goals. Residents in the lakeshore area may favor flood protection (Wisconsin Initiative on Climate Change Impacts, 2011), while offshore residents are concerned more about the health of the lake ecosystem and accessibility of recreational activities in the lakes (Carpenter et al., 2007). As a result, the interaction between people's preferences may also affect lake level management in the YW. In order to investigate this interaction, socioeconomic information, such as flood insurance, economic growth, and/or public perceptions are required (Di Baldassarre, et al., 2017), which is a potential future research need to further integrate socio-hydrologic feedbacks (Sivapalan et al., 2012). In addition, changes in climate and land use/land cover may alter streamflow into the lakes. The impact of climate change and land use/land cover change on flood risk and lake level management is an on-going research endeavor following this study.

6. Conclusions

In this study, we assessed the potential exposure to flooding of the lakeshore areas in the YW. Based on historical records, Monona has the highest frequency of exceeding its target maximum lake level among the four lakes. Furthermore, of the four lakes, Mendota and Monona have relatively high exposed populations. In terms of exposed land area, Mendota, Monona and Waubesa all have a large amount of exposed urban area.

We then investigated the effect of lake regulation and management on lake levels with a focus on management of target minimum levels, using a modeling approach. With the calibrated modeling framework, we compared the high and low water levels at Lake Mendota under two different model minimum lake levels. By decreasing the model minimum level by 0.1 m, the simulated peak water level in the major flood event of Mid-June 2008 will decrease by about 0.1 m, and as a result, the exposed land area and population in lakeshore area of Mendota will decrease by 24.3% and 30.8% respectively. However, decreasing the model minimum level by 0.1 m will also cause an increase of the number of days that Lake Mendota is below the target winter minimum level from 45 to 206 during the study period of 2004–2013, which may have adverse effects on local aquatic ecosystems. We also conducted a sensitivity analysis on model minimum lake levels at all four lakes and demonstrated that decreasing model minimum lake levels will reduce the frequency of extremely high lake levels. Results indicate that focusing on management of minimum lake levels will have a direct effect on high water levels with a 10 cm change in minimum lake level translating to nearly a 10 cm drop in water level across the spectrum of exceedance frequencies on all four lakes.

Recognition of the control of minimum water level management in lake chains may help mitigate flood risks in the YW and other similar watersheds. However, lower minimum levels will also reduce lake levels during dry periods, potentially impacting recreational activities and lake ecosystems. Managing lake levels requires consideration of trade-offs between flood protection and other ecosystem services, and optimizing lake level management will require a comprehensive assessment of the impacts of lake levels on competing interests.

Future research should attempt to link our watershed model with hydrodynamic models in order to investigate 1) the effectiveness of maximum lake level control during extreme events, another lake level management challenge; and 2) the impact of climate change and land use/land cover change on flood risk in the YW.

Declaration of Competing Interest

None.

Acknowledgements

We acknowledge funding from the US National Science Foundation, including the Water Sustainability and Climate (DEB-1038759) and Long Term Ecological Research (DEB-1440297) programs. We thank Kai Tsuruta for giving helpful advice on THMB modeling.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.123920.

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