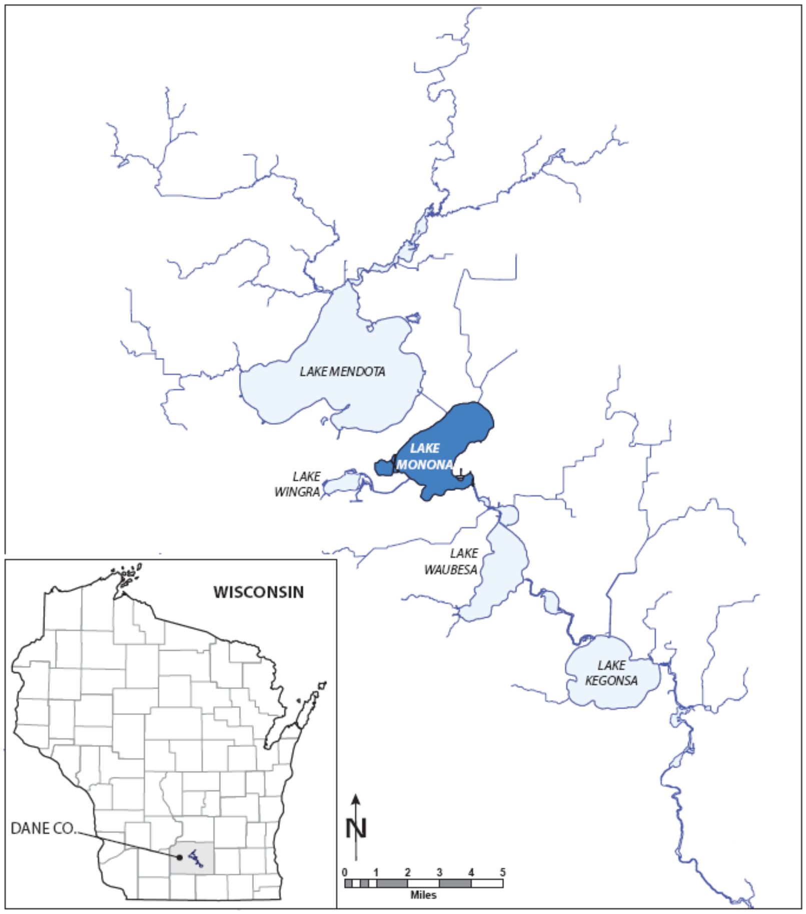
Hydrodynamic and Hydrologic Modeling for Lake Monona, Madison, WI



DNR Lake Planning Grant Final Report

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1 INTRODUCTION

1.1 Background

Monona Bay is a small, shallow, eutrophic body of water that experiences degraded water quality largely due to urbanization in the Monona Bay watershed. Runoff from roads, parking lots, and lawns carries sediment, nutrients, toxic metals, trash, and other pollutants into the lake and bay. Although current management practices such as street sweeping, installation of storm catch basins, and installation of proprietary stormwater devices have reduced some negative impacts in recent years, stormwater still significantly affects the health of the bay. Understanding the circulation patterns and transport between Monona Bay and Lake Monona is critical in assessing the retention time as it describes the mean time that water or dissolved substances spend in the lake.

Lake Monona and Monona Bay experiences much of runoff from the highly urbanized watershed. Lake Monona and Monona Bay are classified as eutrophic (i.e. nutrient rich, supporting many aquatic plants). The water quality of the lakes in the past has been impacted by municipal and industrial sewage discharges; however, the discharge is now diverted around the lake. The sewage sources have enriched Monona Bay in the water and bottom sediments which proliferates weed growth during the summer months. Also, algae blooms are prevalent in the summer due to stimulation from high levels of phosphorus. Heavy metals and organic compounds through past sewage discharge, nonpoint source pollution, applications of herbicide treatment, and atmospheric deposition. These pollutants remain intact within the bottom sediments of the lake and pose toxicity concerns for fish and other aquatic life. The contaminated sediment is a concern especially regarding future dredging efforts to ensure proper techniques to eliminate the mixing of pollutants within the water column.

In addition to pollutants/nutrients affecting Lake Monona, high inflows due to urban runoff creates flooding to surrounding residents of the lake. The release rate of water from Lake Monona is controlled by the Babcock Lock and Dam at the outlet of Lake Waubesa. While it is believed that lowering the operational water level may resolve flooding issues because of the increased storage, there is a continuous debate on this controversial issue due to the balance among social/recreational activity, ecological integrity, and economic growth. It is critical to evaluate runoff patterns and hydraulic limitations and the effect on Lake Monona water levels with hydrologic modeling and hydrodynamic analysis.

1.2 Literature review and previous studies

A preliminary analysis of Lake Monona and Monona Bay was conducted by evaluating literature and other studies aimed at assessing Lake Monona and Monona Bay. Four main studies were collected and evaluated due to their significance with work related to Lake Monona. These studies are titled (1) *Watershed Assessment and Management Plan for Monona Bay, Madison, Wisconsin*, (2) *Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Maintain Dry-Weather Flow*, (3) *Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Reduce Water Levels during Floods*, and (4) *Yahara River Watershed Rainfall-Runoff Model Final Repor*t. The aforementioned articles where the primary sources for understanding specific work to Lake Monona and the Yahara Lakes; however, additional literature was examined and reviewed for further understanding to meet the objectives of this study.

Prior studies and on-going water quality programs in the past years have focused on Lake Monona, Monona Bay, and their watersheds. Most recently, a DNR Lake Management Planning project was carried out through the efforts of faculty and graduated students involved in the 2006 UW-Madison Water Resource Management (WRM) Graduate Workshop. This study is a comprehensive assessment of Monona Bay. The objectives were to identify management strategies and gather site specific data.

Primarily, the focuses of past research and papers have been involved with the overall Yahara Lakes including Lakes Mendota, Monona, Waubesa, and Kegonsa. In 1999, the U.S. Geological Survey (USGS) published a paper titled *Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, south-Central Wisconsin, as Multipurpose Reservoirs to Maintain Dry-Weather Flow*. The goal of the study was to determine whether using the lakes as multipurpose reservoirs to maintain flow during periods of low flow would appreciably lower lake levels. Four operating alternatives were evaluated imposing a different amount of outlet flow from Lake Waubesa of: 8.5 ft^3/s, 10 ft^3/s, 30 ft^3/s, and 36 ft^3/s. The results indicated that maintaining a minimum flow of 8.5 ft^3/s resulted in lake levels higher than observed and maintaining a flow of 36 ft^3/s resulted in lake levels that were very similar to the observed minimum lake levels. However, it was impossible to maintain a flow of 36 ft^3/s (Krug, 1999). The paper discusses the Yahara lakes during dry weather flow and five years later the USGS published a paper simulating the lakes during floods.

In 2004, the USGS published a second paper on the Yahara lakes titled *Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Reduce Water Levels during Floods*. The goal of the study was to determine the degree to which modifications in the operation of the dams controlling the outlets could affect high lake levels.

The paper evaluated three alternatives while maintaining a minimum flow of 30 ft^3/s out of Lake Waubesa which are: 1. Keep lake levels as low as possible, 2. Early summer water elevations were kept closer to the middle of the regulatory ranges versus the upper limit, and 3. The low flow simulation used in the previous 1999 simulation. The results of the simulation for alternative 2 demonstrates that it is possible to lower the maximum water levels slightly but that minimum water levels would also be lowered (Krug, 2004). Since the creation of the USGS simulation models, a more comprehensive model has been developed by W.F. Baird & Associates Ltd.

In 2007, a Yahara River Watershed Rainfall-Runoff model was created as a tool to simulate current and future conditions with the Yahara Lakes watershed and how the management of the lakes would need to change to account for the changes. The numerical modeling system contains a one-dimensional model for simulating flows called MIKE11 and a module for simulating the hydrology of the watershed called NAM. The model was intended to be used to assist in the operational management of lake levels and to evaluate different impacts on lake levels such as land use changes, management practices, and control structure changes. Additional discussion of the coupled NAM and MIKE11 model and results are discussed in detail in Chapter 4.

1.3 Objectives

The objective of this study is to develop a suite of models that can predict water level and examine circulation patterns and retention time. The retention time that describes the mean to take water or dissolved substances spend in the lake will be obtained. I will build upon prior efforts and research while expanding our knowledge to include hydrodynamic flow and transport of Lake Monona including Monona Bay. Specifically hydrological budget will be carefully re-evaluated and examined. First, site-specific data is analyzed in order to create an accurate and representative model. A unit hydrograph model will be created for Lake Monona to assess runoff entering Lake Monona from storm sewers, Lake Wingra, and Starkweather Creek. Prior modeling efforts included creation of MIKE11 coupled with a rainfall-runoff model called NAM. The NAM modeling results and the Unit Hydrograph method will be compared and evaluated. Finally, a three dimensional model for Lake Monona will be created to establish the exchange rate between Lake Monona and Monona Bay and to assess the spatial changes in water level.

2 STUDY SITE AND DATA

2.1 Physical Setting

The Yahara River Watershed, located in Dane County, Wisconsin, is made up of a chain of four lakes known as Mendota, Monona, Waubesa, and Kegonsa. Lake Monona is the second largest of the chain of lakes and is located south of Lake Mendota (Figure 2.1). It is a freshwater drainage lake surrounded on three sides by the City of Madison and on the south side by the City of Monona. Lake Monona is regulated by locks in the Yahara River where it exits Lake Waubesa. Lake Monona is fed by three tributaries, including the Yahara River (from Lake Mendota), Starkweather Creek, and Wingra Creek (from Lake Wingra).

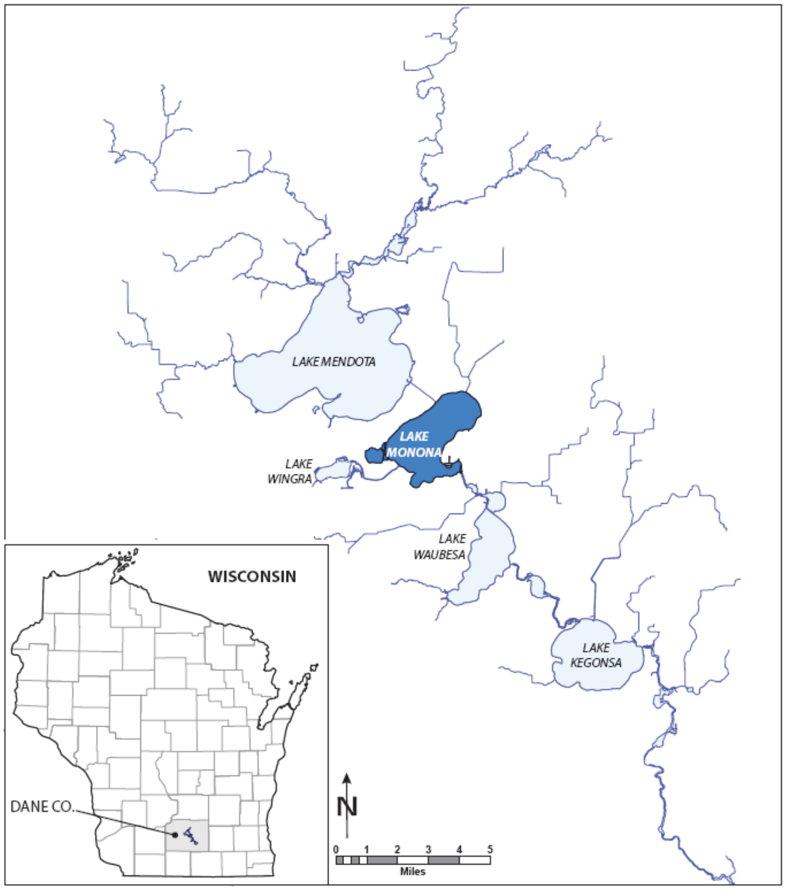


Figure 2.1: Yahara River chain of lakes

Lake Monona has a surface area of 3,274 acres (13.2 km^2). It has a mean depth of 27 feet (8 meters) and maximum depth of 64 feet (20 meters). The volume of Lake Monona is about 28 billion US gallons (110,000,000 m^3). The shoreline length is 13 miles (21 km). The Lake elevation is 845 feet (UW-Madison Limnology, 2007).

Monona Bay (Figure 2.2) is located to the southwest of Lake Monona where they are partly separated by two elevated causeways: John Nolen Drive and the Wisconsin and Southern Railroad tracks. Additionally, the causeways create two small triangular-shaped water bodies that are considered part of Monona Bay.

Figure 2.2: Monona Bay and its watershed

2.2 Site Data

There are several data sources that have been used to assist in understanding Lake Monona and to support the creation of a model. Several data sources exist that are available online that provide required information for this study. Two data sources used are Atmospheric Oceanic Sciences (AOS) data and United States Geological Survey (USGS). These data sources provided data for precipitation, speed, wind direction, air temperature, dew point temperature, relative humidity, pressure, discharge, and lake levels as shown in Table 2.1. Further, measured data was necessary to carry out the study of Lake Monona and Monona Bay. Field collected data include water level measurements, and temperature measurements as indicated in Table 2.2. The combination of available data and measured data provided detailed information to further investigate Lake Monona and Monona Bay.

Table 2.1: Readily Available Data

AVAILABLE DATA					
Parameter	**Units**	**Source**	**Sample Frequency**	**Latitude**	**Longitude**
Precipitation	inch	Dane County Airport	1 hour	43°06'35"	89°21'25"
Wind Speed	mps	AOS	1 hour	43°04'15"	89°24'27"
Wind Direction	degrees	AOS	1 hour	43°04'15"	89°24'27"
Air Temperature	Celsius	AOS	1 hour	43°04'15"	89°24'27"
Dew Point Temperature	Celsius	AOS	1 hour	43°04'15"	89°24'27"
Pressure	hectoPascals	AOS	1 hour	43°04'15"	89°24'27"
Relative Humidity	percent	AOS	1 hour	43°04'15"	89°24'27"
Discharge (Lake Mendota)	cfs	USGS 05428500	5 minutes	43°05'22"	89°21'25"
Discharge (Lake Waubesa)	cfs	USGS 05429510	5 minutes	43°00'17"	89°18'09"
Lake Monona water level	feet	USGS 05429000	15 minutes	43°03'48"	89°23'49"

Table 2.2: Field Measured Data

MEASURED DATA						
Parameter	**No. of Sensors**	**Units**	**Location**	**Sample Frequency**	**Latitude**	**Longitude**
Water Level	1	meter	Starkweather Creek	1 minute	43°05'35"	89°19'58"
Water Temperature	1	Celsius	Starkweather Creek	1 minute	43°05'35"	89°19'58"
Water Level	1	meter	Lake Monona Outlet	1 minute	43°03'00"	89°20'13"
Water Temperature	1	Celsius	Lake Monona Outlet	1 minute	43°03'00"	89°20'13"
Water Level	1	meter	Lake Monona Buoy	1 minute	43°03'43"	89°22'42"
Water Temperature	10	Celsius	Lake Monona Buoy	1 minute	43°03'43"	89°22'42"
Water Level	1	meter	Monona Bay Buoy #1	1 minute	43°03'27"	89°23'38"
Water Temperature	7	Celsius	Monona Bay Buoy #1	1 minute	43°03'27"	89°23'38"
Water Level	1	meter	Monona Bay Buoy #2	1 minute	43°03'39"	89°23'35"
Water Temperature	3	Celsius	Monona Bay Buoy #2	1 minute	43°03'39"	89°23'35"
Barometric Pressure	1	mbar	Lake Monona	1 minute	43°04'22"	89°22'58"

2.2.1 Precipitation

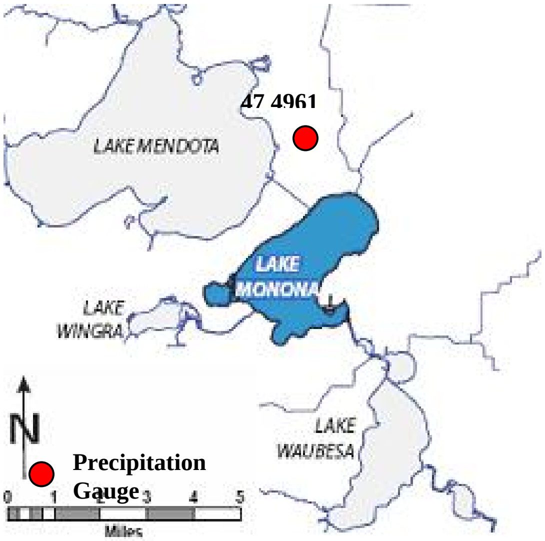


Figure 2.3: Dane County Regional Airport Precipitation Gauge

The average annual precipitation in the area of study is approximately 33 inches (Wisconsin State Climatology Office, 2008). Historical precipitation data indicates that the summer months endure about three times the amount of winter precipitation. Significant runoff into Lake Monona can be accounted during the spring melt and during summer thunderstorms. The precipitation data is the primary driving component used for any hydrologic model. Fortunately, there are several daily gauges within the Lake Monona watershed; however, there are only a few hourly gauges in the watersheds. For simplification, only one rain gauge was used to represent the watershed. The rain gauge selected was an hourly rain gauge located at the Dane County Regional Airport as shown in Figure 2.3. The selection of this gauge was made due to data adequacy and a full record of data present. The total summer rainfalls (May 1st to November 30th for the study periods are displayed in Table 3.3.

Table 2.3: Summary of Summer Rainfall Totals

Year	Rainfall Sum (in)
2004	31.5600
2005	14.7725
2006	24.9600
2007	29.2800
2008	30.2100

2.2.2 Meteorological

The study area experiences a temperate climate with an average yearly air temperature of 46°F (Wisconsin State Climatology Office, 2008). Within the Yahara watershed there is one evaporation gauge that is located to the far north of the watershed, approximately 16.1 miles from the study site. Due to the far proximity of the pan evaporation measurements to Lake Monona, evaporation was calculated from meteorological components. The meteorological data was collected from instruments located at the Atmospheric, Oceanic and Space Science Building at the corner of Dayton Street and Orchard Street at the University of Wisconsin Madison shown in Figures 2.4 and 2.5. The data obtained from this instrument were wind speed, wind direction, air temperature, dew point temperature, relative humidity, and pressure. Further explanation of determining evaporation losses is discussed later in the chapter. In addition, wind speed

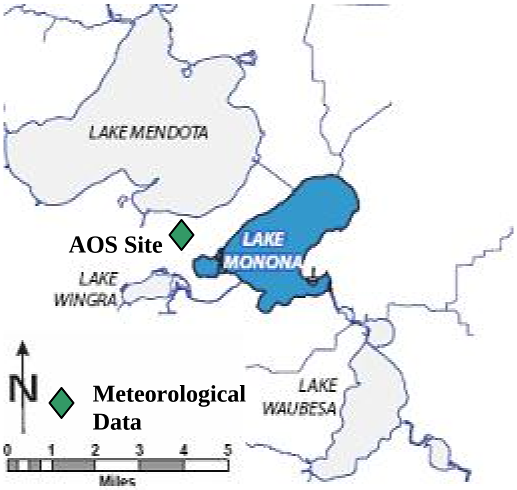


Figure 2.4: Atmospheric, Oceanic and Space Science Building Location

and direction were used to provide wind stress information necessary for hydrodynamic modeling of circulation in Lake Monona. The data from the AOS anemometer is approximately 84.9 meters above the Lake Monona water surface and was corrected to height of 10 meters above the water surface by applying the power-law wind profile as follows. However, this method of using onshore data to represent water surface conditions can often be distorted by shoreline, limited fetch, ground vegetation, and topography.

$$\frac{u}{u_0} = \left(\frac{Z}{Z_0}\right)^P \quad (1)$$

Where,

Z = instrument height

Z_0 = reference height (10 m)

u = wind speed at height Z

u_0 = wind speed at reference height (10 m)

P = coefficient (0.11)

Figure 2.5: AOS Building

2.2.3 Stream Discharge

There are two stream gauge stations maintained by the United States Geological Survey (USGS) that are relevant to the study. They are presented in Table 2.4 and presented in Figure 2.6. Discharge measurements are necessary data sets required for the hydrologic and hydrodynamic modeling applications. One of the discharge gauges measures flow from Lake Mendota traveling into Lake Monona located at the East Main Street Bridge between the two lakes. This gauge uses an acoustic velocity meter and a submersible pressure transducer. The pressure transducer is used to calculate water depth for determination of channel cross sectional area. The combination of the cross sectional area and velocity measurements produces an average cross sectional discharge and is reported by USGS. The other discharge gauge measures outflow from Lake Waubesa located on the Exchange Street Bridge at McFarland, Wisconsin. An acoustic velocity and stage system is used. The measurements of velocity and stage are then used to calculate discharge from Lake Waubesa. Currently, there is no discharge gauge measuring the release out of Lake Monona into Lake Waubesa. The methodology for establishing Lake Monona's release is discussed further in the paper. Additionally, stream gauge measurements are not recorded for Starkweather Creek, Wingra Creek, and storm sewers. For this reason, hydrologic modeling is necessary to represent discharge from these ungauged tributaries. Further explanation of alternative hydrologic modeling approaches and their results are discussed later in this chapter.

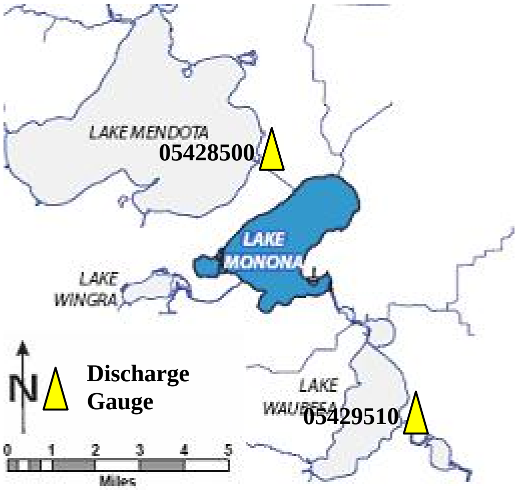


Figure 2.6: USGS Stream Gauge Measurement Locations

Table 2.4: USGS Stream Gauges

Gauge Name	Gauge Number	Sample Frequency	Instrument
Yahara River At East Main Street At Madison, WI	USGS 05428500	5 minutes	Acoustic Velocity Meter
Yahara River At Exchange Street At McFarland, WI	USGS 05429510	5 minutes	Shallow Water Acoustic Velocity Meter

2.2.4 Lake Level

There is one lake stage gauge on Lake Monona operated by the USGS. A water stage recorder is located on Monona Bay to represent Lake Monona water elevation located within Brittingham Park in Madison, Wisconsin. The location is

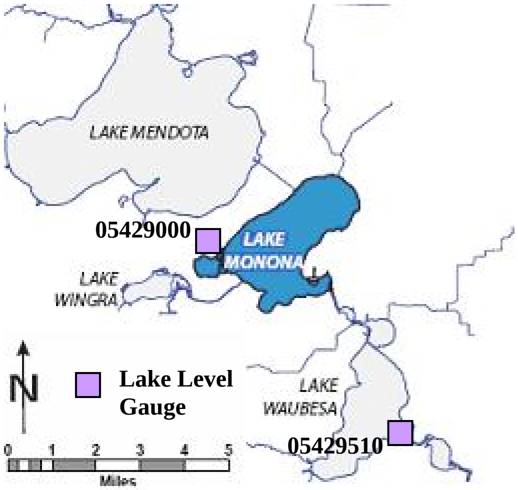


Figure 2.7: USGS Lake Level Gauge Measurement Locations

shown in Figure 3.7. The data set extends back to 1915 to the present, though the early years were not gauged continuously. To adequately calibrate the hydrologic and hydrodynamic model, Lake Monona water levels are required.

Table 2.5: USGS Lake Level Gauge

Gauge Name	Gauge Number	Sample Frequency	Instrument
Lake Monona At Madison, WI	USGS 05429000	15 minutes	Water-Stage Recorder

2.2.5 *Lake Bathymetry*

The lake bathymetry is a critical component required for the hydrodynamic model. Circulation responses to wind and flows are strongly guided by bathymetry and are usually three-dimensional in character. Hence, an accurate representation of bottom topography by the model grid is the most important and fundamental requirement for successful modeling efforts (Liu et al., 2008). The data for Lake Monona was obtained from WDNR Lake Survey Maps which were recorded in July of 1980 shown in Figure 2.8.

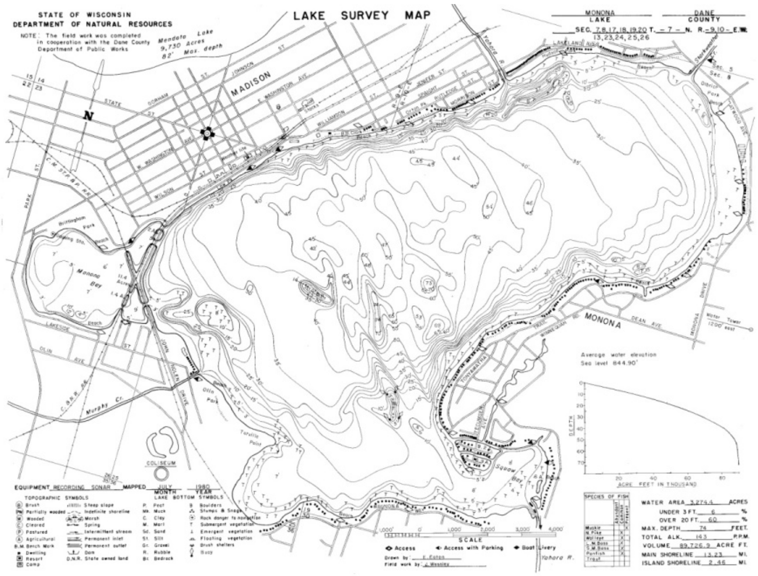


Figure 2.8: Lake Monona WDNR Survey Map

Monona Bay was surveyed by the 2006 Water Resources Management Practicum. The data for Monona Bay was obtained from this study to represent a more recent bathymetric map for Monona Bay. The bathymetric map was created by measuring the water depth at 50 meter grid spacing. The WDNR Survey Map and the Water Resources Management Study data sets were merged together to provide one current, cohesive lake bathymetry map. Finally, the mapping was adjusted to Wisconsin County Coordinate System (WCCS) to provide a reference coordinate system for future survey and bathymetric updates. The resulting bathymetric map for Lake Monona and Monona Bay is shown in Figure 3.9. The bathymetric mapping is a necessary component to the hydrodynamic model.

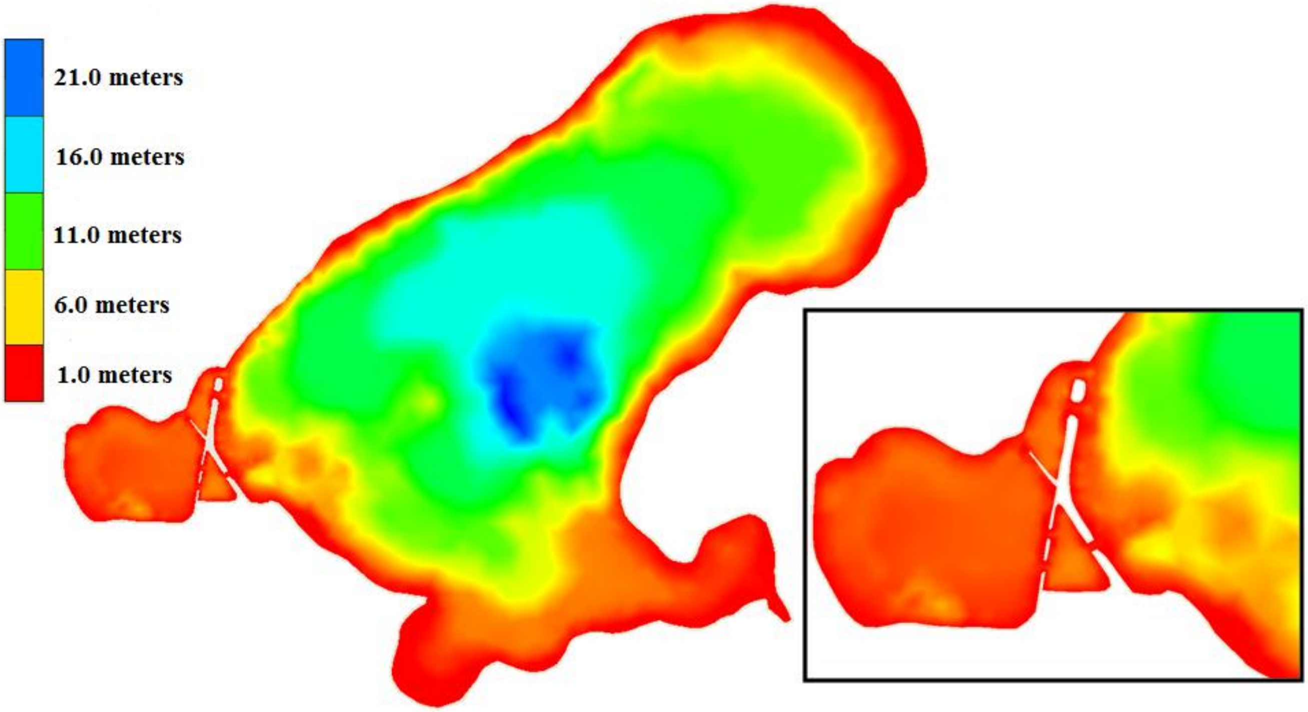


Figure 2.9: Lake Monona and Monona Bay Bathymetric Map

2.2.6 Water Level Field Measurements

Water level measurements were carried out during the summer of 2008. Four locations as illustrated in Figure 3.10 were selected to obtain spatial differences in water elevation and provide stream depth information. The instrument used is a HOBO water level logger which is a pressure based water level recording device. The instrument has an accuracy of ±0.5 cm and was sampled at a rate of 1 minute. The HOBO water level loggers provided useful information for the hydrodynamic model of spatial water levels and stream depth increases from hydrologic results.

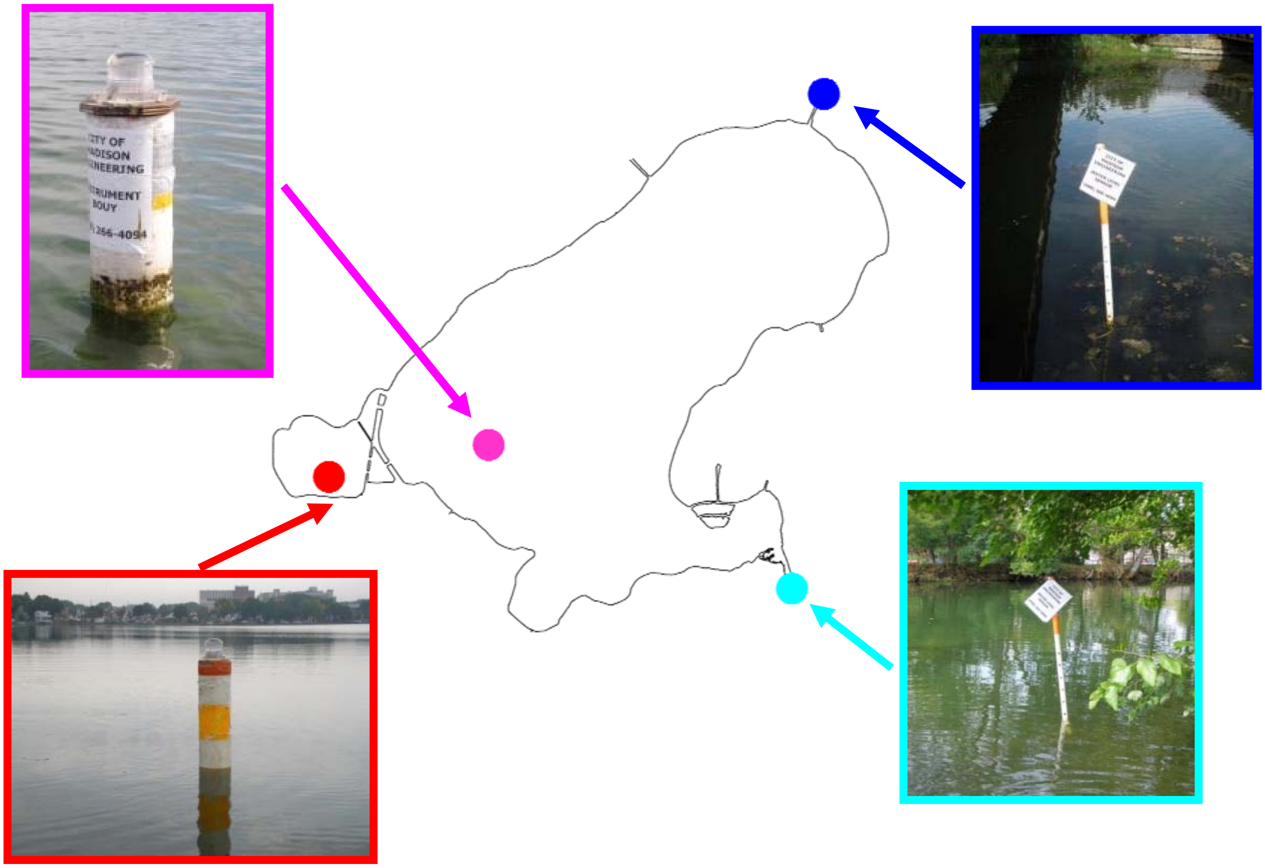


Figure 2.10: Water Level Field Measurement Locations

2.2.7 Temperature Field Measurements

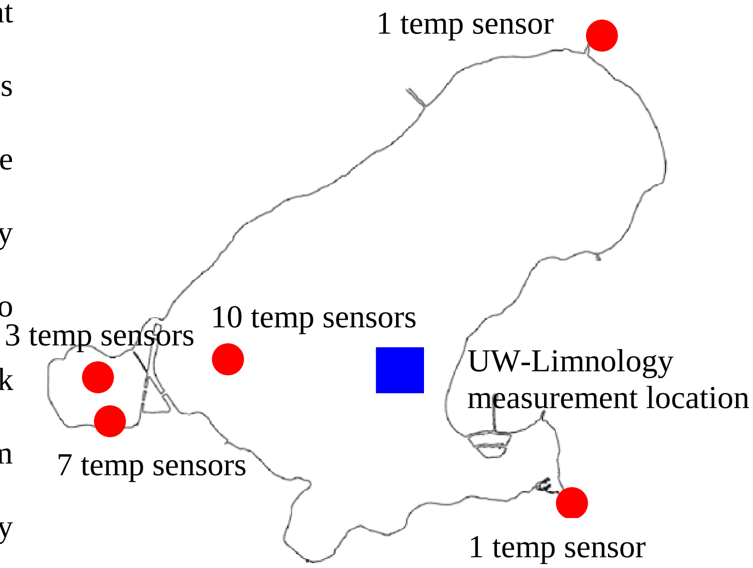


Figure 2.11: Water Temperature Field Measurement Locations

Temperature measurements were conducted at five sites in Lake Monona. Three of the sites were set up with thermistor chains to measure the water column temperature at equally vertically spaced intervals. The remaining two locations were installed at Starkweather Creek and Monona Outflow to measure the stream discharge. Additionally, the UW-limnology collects water column temperature at the deepest site in the lake. The onset of stratification occurred in May of 2008 with a depth of approximately 12 meters in the summer months as shown in Figure 2.12.

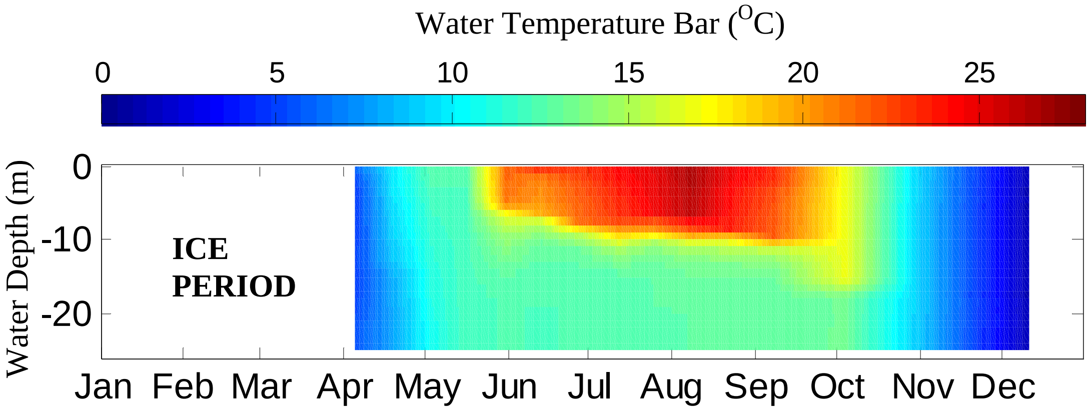


Figure 2.12: 2008 Lake Monona Water Column Temperature

It is understood that the temperature of the water is important because it plays a major influence on the biological activity and growth of aquatic organisms. The purpose of the data collection is to further hydrodynamic modeling of Lake Monona and include a thermal model. The heat transfer at the lake-atmosphere interface is influenced by heat budget components driven by meteorological variables. The lake responds through both radiative and turbulent heat transfers and heating/cooling (Leon et al., 2004). Preliminarily, a thermal model for Lake Monona was created; however, the results will not be presented within this paper due to further work required to validate the model. With future work, establishment of a thermal model for Lake Monona can be achieved. The following figures of water column temperature are presented at each of the five measured sites.

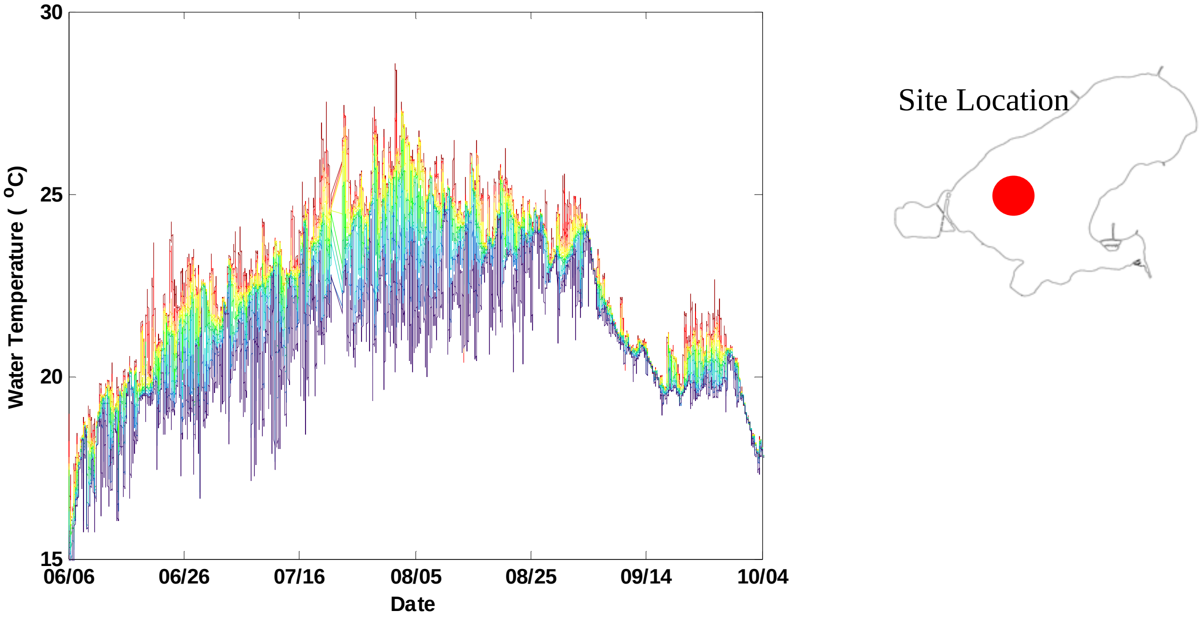


Figure 2.13: Lake Monona Thermistor Chain and Site Location

In Figure 2.13, a thermistor chain in Lake Monona was installed with 10 equally spaced temperature sensors in the water column. The average depth at the location is approximately 9.4 meters. The change in temperature from the surface to the bottom at the location can range by approximately 10 degrees Celsius.

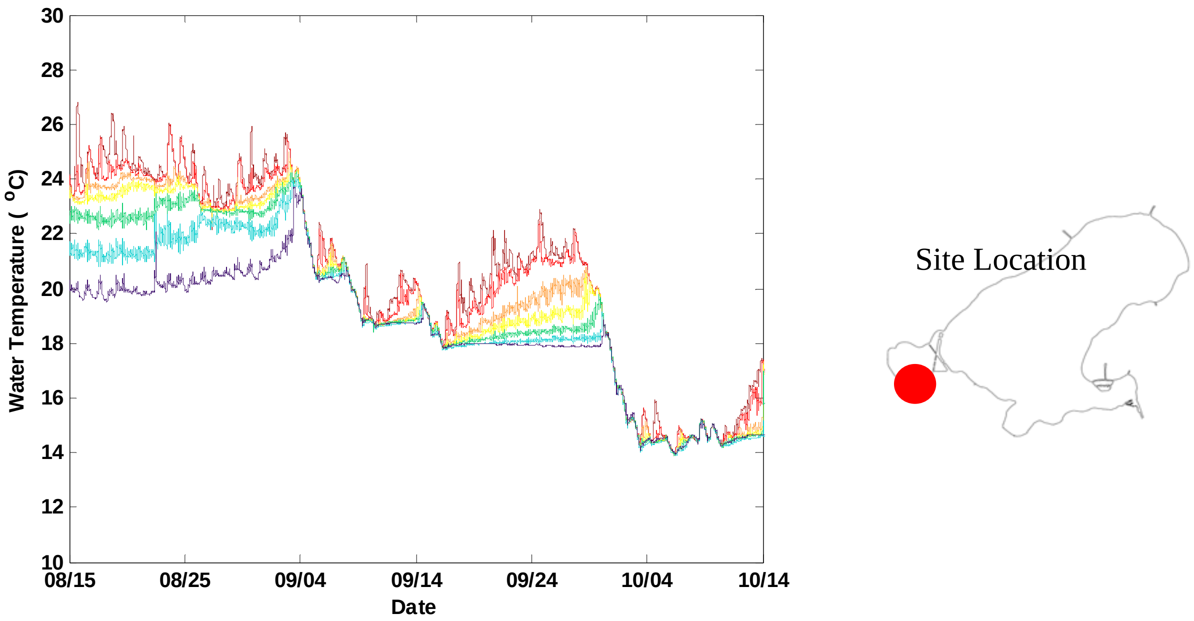


Figure 2.14: Monona Bay Site 1 Thermistor Chain and Site Location

In Figure 2.14, a thermistor chain with five temperature sensors were installed at the deepest hole in Monona Bay on the southern side. This site has been dredged in the early 1970's. Today the deep hole remains approximately 4.7 meters deep compared to the average depth of the bay being 2.2 meters. During cooling periods the water column becomes homogenous in temperature versus during heating periods the surface heats very quickly.

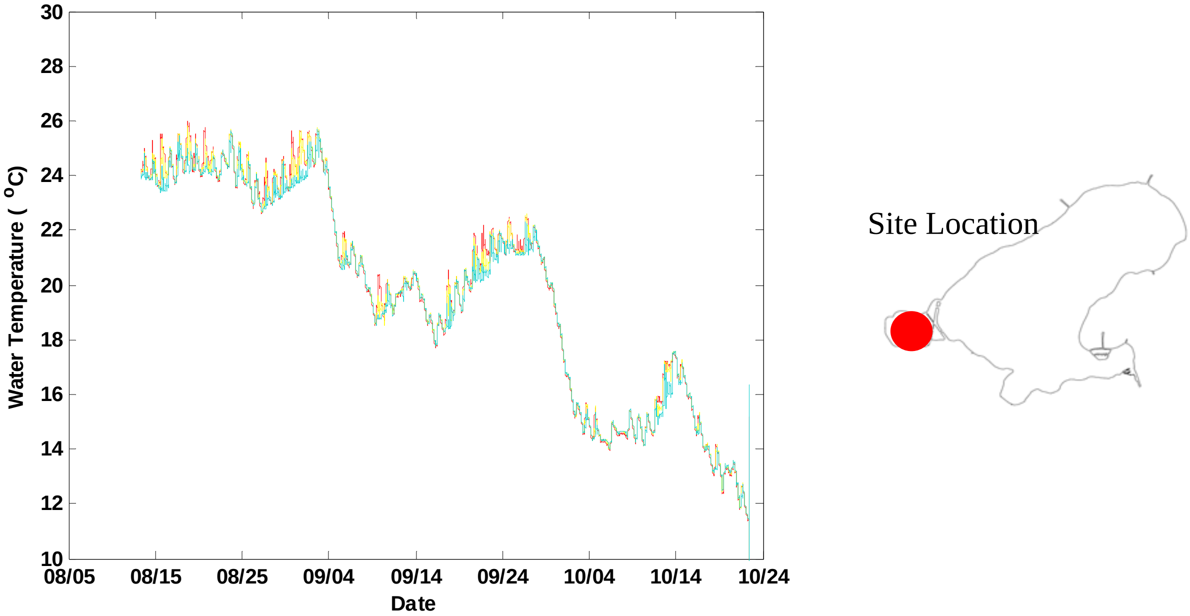


Figure 2.15: Monona Bay Site 2 Thermistor Chain and Site Location

In Figure 2.15, a thermister chain with three temperature sensors were installed within the center of Monona Bay. The approximate depth of the site is 2.2 meters. When compared to the previous site with the deep hole site (Figure 2.14), there is a smaller range of temperature variations from the surface to the bottom.

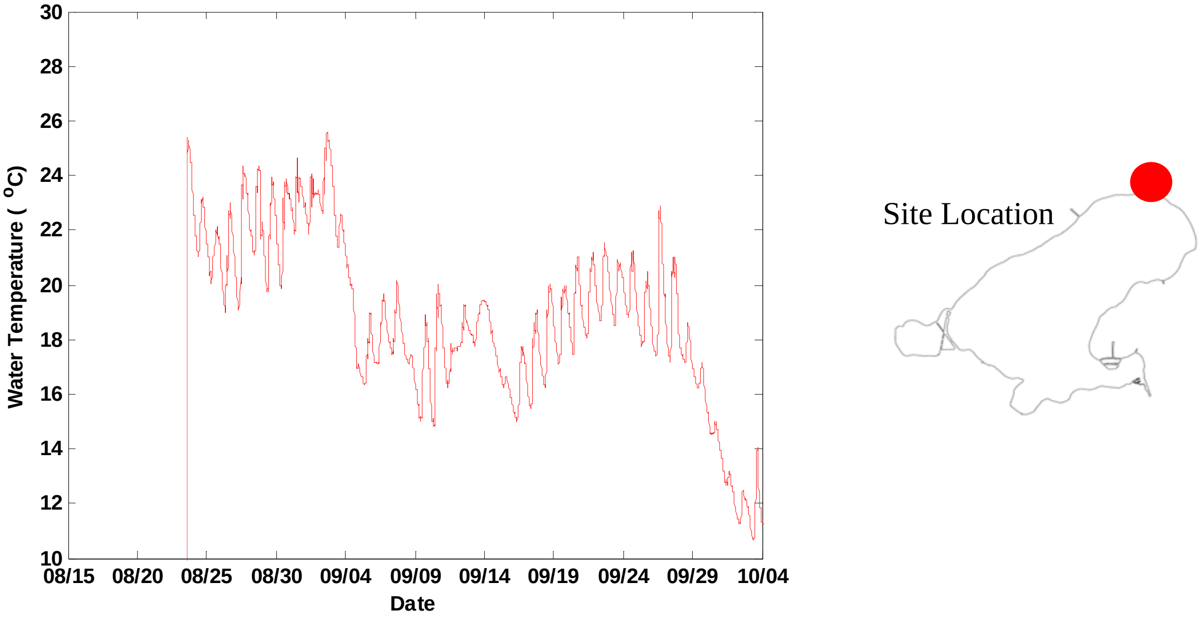


Figure 2.16: Starkweather Creek Temperature and Site Location

In Figure 2.16, one temperature sensor was installed in the channel of Starkweather Creek to provide stream temperature. The data results in a diurnal pattern of heating during the day and cooling at night.

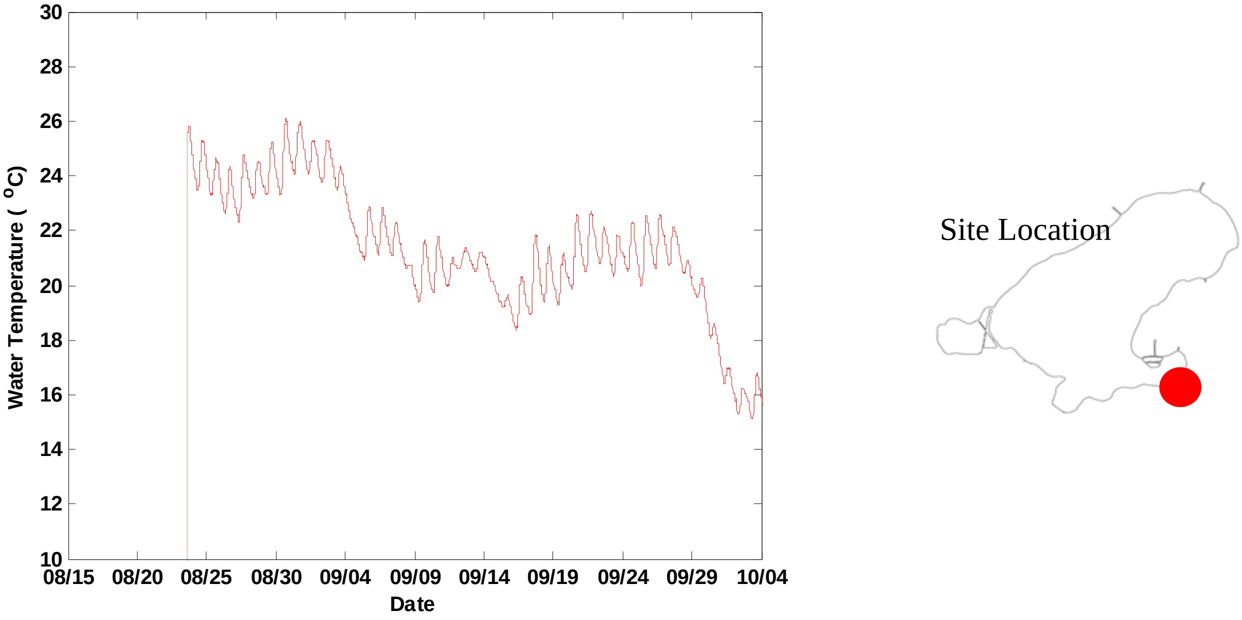


Figure 2.17: Lake Monona Outlet Temperature and Site Location

In Figure 2.17, one temperature sensor was installed at the outlet of Lake Monona to provide outlet temperature. It is shown that the outlet water temperature is much warmer than the inflow from Starkweather Creek.

3 HYDROLOGIC BUDGET

The hydrologic budget for Lake Monona is represented by the total water input to the total water output given a specified interval during a specified time period. The water balance of inputs and outputs influences the nutrient supply to the lake, the lakes resident time, and the lake's water quality. A hydrologic budget for Lake Monona was developed using three modeling approaches including unit hydrograph method, HEC-HMS model, and NAM model. A hydrologic result for each approach was conducted for five consecutive years from 2004 to 2008. Each year was evaluated from May 1st to November 30th to account for rainfall and ignore snow melt and storage. The modeling approaches divide the Lake Monona watershed into three basins: Starkweather Creek, Wingra Creek, and storm sewer outfalls.

Lake Monona has a total watershed area of 21,530 acres and its watershed is primarily urbanized. Lake Monona is fed by two tributaries including Wingra Creek from the west and Starkweather Creek from the east. The watershed area of Wingra Creek and Starkweather Creek are 4,928 acres and 11,061 acres respectively. Wingra Creek with a baseflow of approximately 3.5 cfs and Starkweather Creek with a baseflow of 1.5 cfs are both ungauged tributaries. Additional surface inputs to Lake Monona include Yahara River inflow from Lake Mendota, storm sewer inflows, and precipitation on the lake. Surface outputs from Lake Monona include evaporation and Yahara River outflow.

Starkweather Creek is composed of an East and West branch in which the confluence point is one-half mile away from Lake Monona. The East Branch of Starkweather Creek is 3.5 miles in length with an average slope of 0.09%. However, the West Branch of Starkweather Creek is 7.0 miles in length with an average slope of 0.07%. During the summer months Starkweather Creek is a backwater of Lake Monona.

Wingra Creek (Murphy Creek) is a channelized stream that flows from Lake Wingra to Lake Monona. The creek's average slope is approximately 0.04%. The creek undergoes stagnant conditions and during certain periods the creek has no flow. Lake Wingra itself is a eutrophic, productive water body that contributes nutrient rich water to Lake Monona.

3.1 INFOS Hydrologic Model

3.1.1 Unit Hydrograph Approach

The unit hydrograph method is used to represent the watershed response to rainfall. The watershed's response to rainfall depends on a variety of factors including land use, vegetation type, antecedent soil moisture content, duration of rainfall, topography, and drainage density. The unit hydrograph was introduced more than 70 years ago and its application has been noted to relate unit hydrograph shape parameters to various watershed properties (Yen et al., 1997). During the five year simulated period, land use and vegetation changes are minimal and the unit hydrograph was not adjusted year to year to account for these minor changes. The unit hydrograph used specifically for Lake Monona represents the response of the watershed for a one hour unit input of rainfall. This lump based approach does not describe the physical flow processes inside the watershed; however, the timing from rainfall inputs has been established. Therefore, the inherent assumption is that the catchbasin behaves like a linear system whose impulse response function is a unique time-invariant, linear transromation (Hoyby et al., 1999). The method used assumes the rainfall is spread uniformly over the watershed and that the rainfall is spread uniformly over time by using one rain gauge. Additionally, the method reflects the physical characteristics of the drainage basin including shape, size, slope, and also reflects the storm including pattern, intensity, and duration. The approach used assumes that basin features do not change during the modeled period so that hydrographs from storms of similar duration and pattern have a similar shape and time base. Thus the theory of superposition applies and linearity of the relation is assumed. This concept is shown in Figures 3.1 and 3.2.

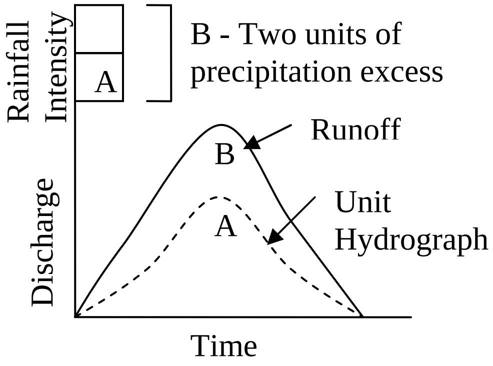


Figure 3.1: Runoff hydrograph for two units of precipitation

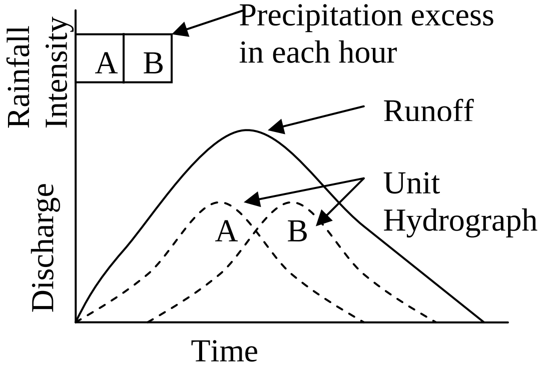


Figure 3.2: Runoff hydrograph for unit precipitation for two consecutive time periods

After completion of the unit hydrograph, the calculation of inflow can be performed based on the convolution between the rain input and the unit hydrograph output.

The unit hydrograph method was developed to establish hydrologic components for the Lake Monona watershed. Coding was developed to allow users to download data sets directly from the Internet and then run the code without needing to reformat or integrate data into a separate modeling platform. Downloaded data sets required to execute the code are Lake Monona inflow, Lake Waubesa outflow, precipitation, and AOS meteorological data. The results of the unit hydrograph method allow users to evaluate discharge and lake responses driven by precipitation data.

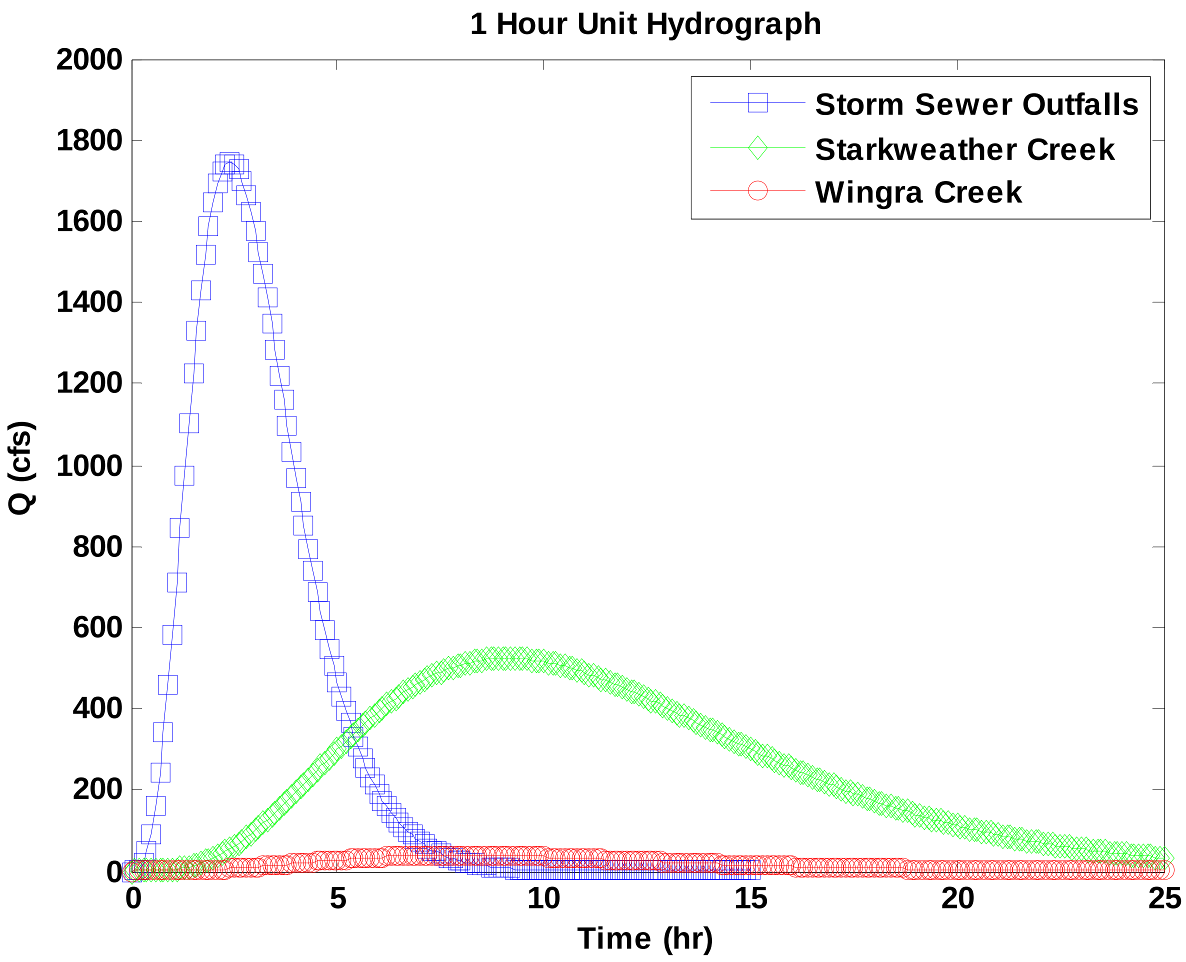


Figure 3.3: 1-Hour Unit Hydrographs for Ungauged Lake Monona Inputs

The unit hydrograph shown in Figure 4.3 provides discharge information for the ungauged inflows of Starkweather Creek, Wingra Creek, and storm sewer outfalls. The discharge values are equated to a volume based on a specified time period to produce mass balance results. The hydrologic budget for Lake Monona, equating inflow and outflow terms, was determined by the following equation:

$$I - Q = \frac{\partial S}{\partial t} \quad \text{(Continuity Equation)} \qquad (7)$$

$$\Delta S = P + Yin + W + S + O - E - Yout \quad \text{(Storage Equation)} \qquad (8)$$

$$\Delta h = \frac{\Delta S}{A} \qquad (9)$$

Where,

I = inflow

Q = Outflow

A = Lake Monona Surface Area (ac)

ΔS = change in storage (ac-ft)

Δh = change in water level (ft)

P = precipitation on lake (ac-ft)

W = Wingra Creek (ac-ft)

S = Starkweather Creek (ac-ft)

O = Storm Sewer Outfalls (ac-ft)

Yin = Yahara River Inflow (ac-ft)

Yout = Yahara River Outflow (ac-ft)

E = evaporation (ac-ft)

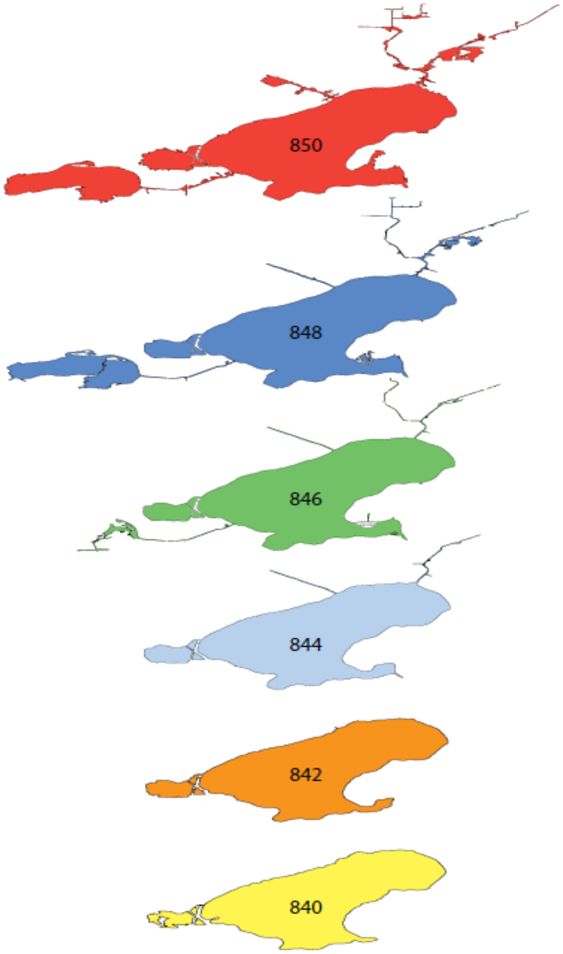


Figure 3.4: Lake Monona Surface Area

Due to backwater conditions, the surface area of Lake Monona can drastically increase as shown in Figure 3.4. A relationship was established between water elevation and surface area as shown in Figure 3.5. This relationship was necessary to determine the resulting water level change.

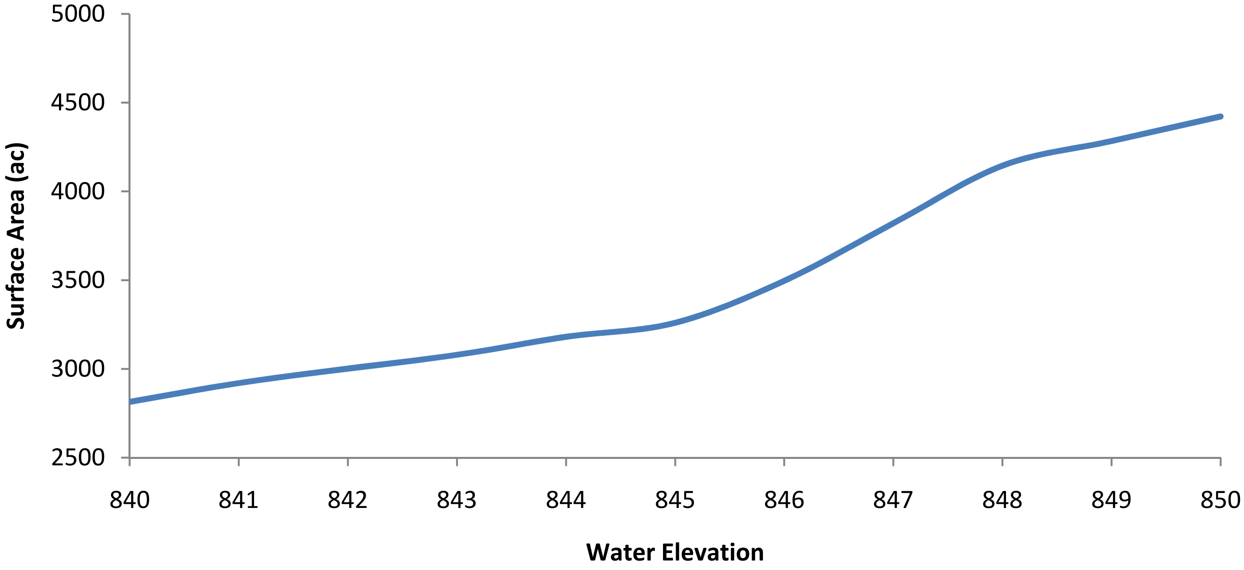


Figure 3.5: Lake Monona Surface Area versus Water Elevation

Lake Monona consists of five surface inputs including Yahara River inflow, Starkweather Creek, Wingra Creek, storm sewer discharge, and direct precipitation. Currently, discharge measurements from Lake Mendota into Lake Monona are available from the United States Geological Survey (USGS). Alternatively, ungauged inflows from Starkweather Creek, Wingra Creek, and storm sewer outfalls are calculated based on the unit hydrograph method. The rainfall is the driving component used to determine discharge values.

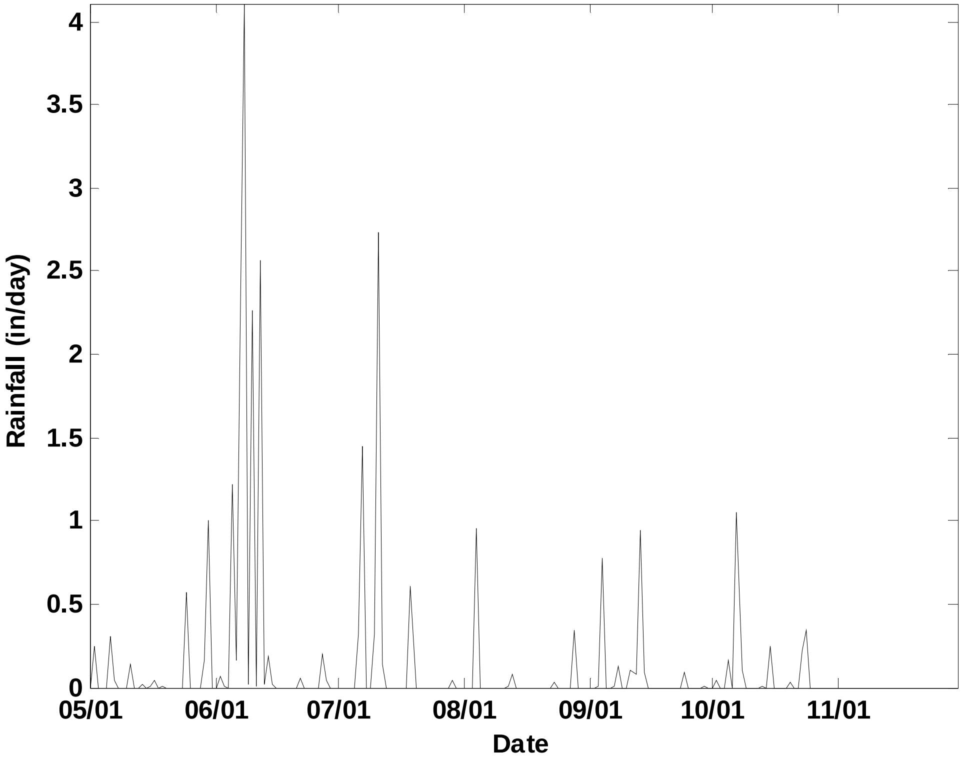


Figure 3.6: 2008 Madison, WI Rainfall

The largest storms for the summer of 2008 shown above occurred between end of May to early-July. The figures below show the discharge components for the 2008 water year which correlate with the rainfall data.

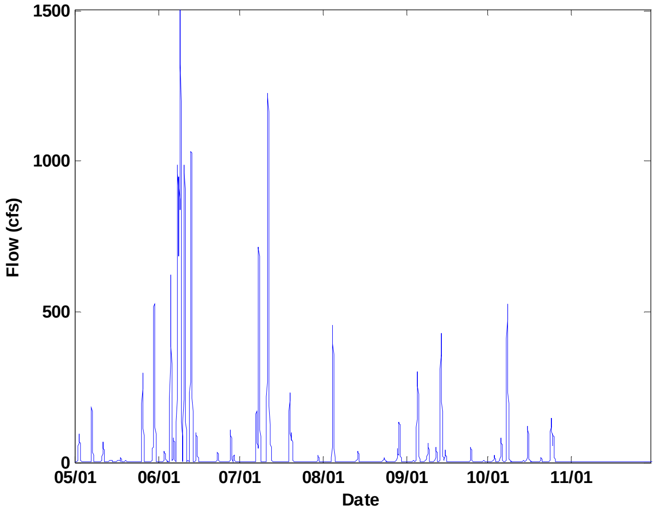


Figure 3.7: 2008 Starkweather Creek Discharge

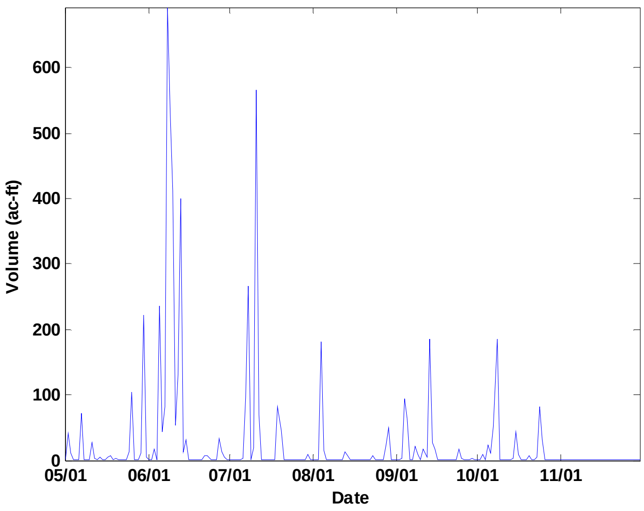


Figure 3.8: 2008 Starkweather Creek Volume

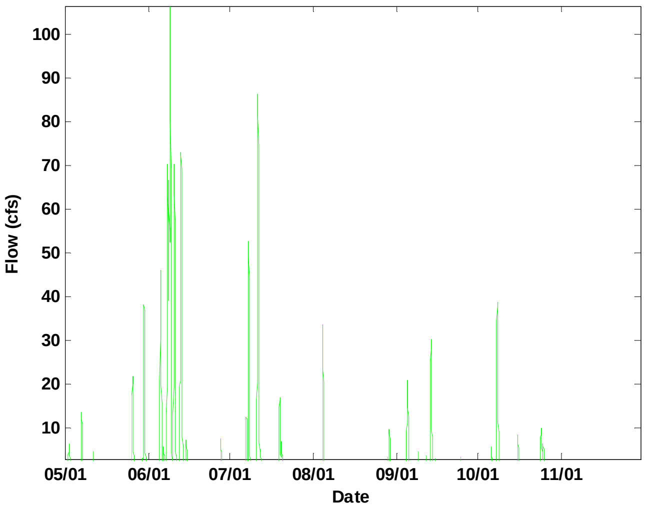


Figure 3.9: 2008 Wingra Creek Discharge

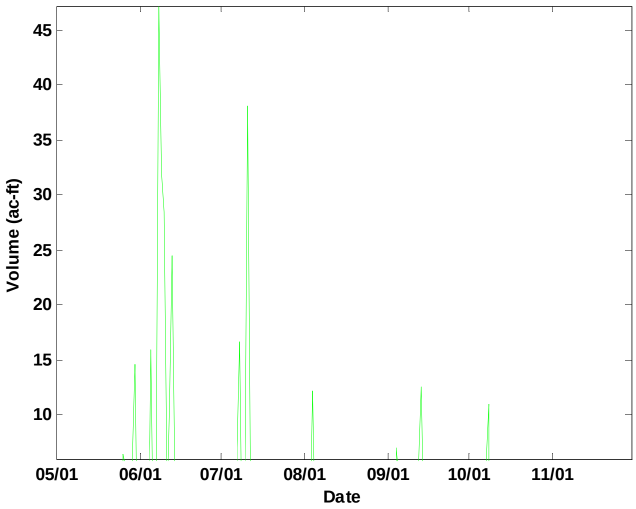


Figure 3.10: 2008 Wingra Creek Volume

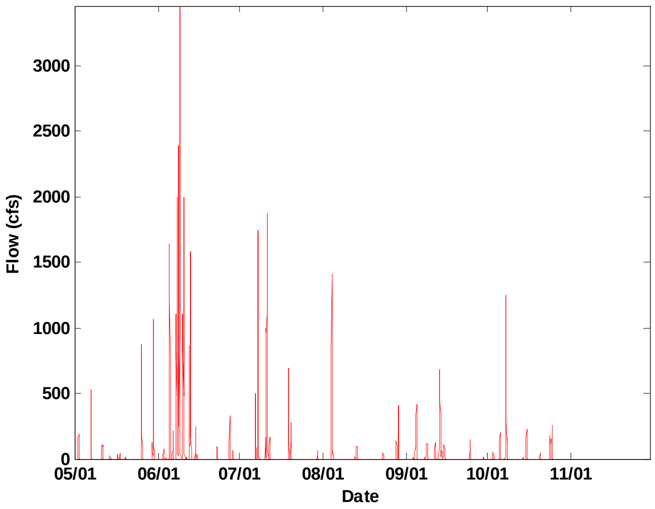


Figure 3.11: 2008 Storm Sewer Discharge

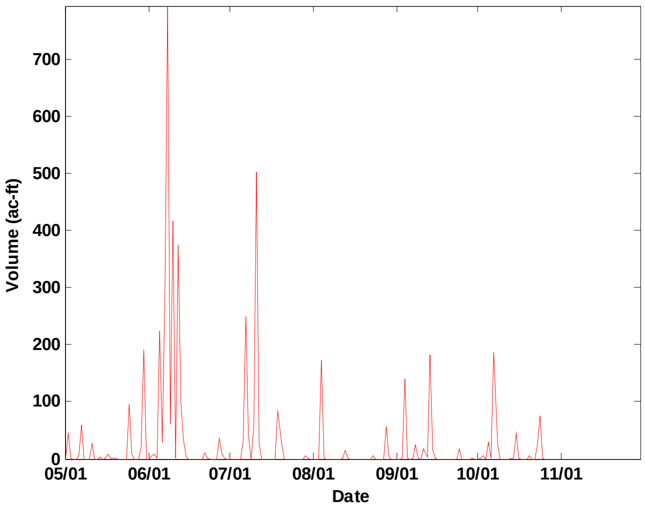


Figure 3.12: 2008 Storm Sewer Volume

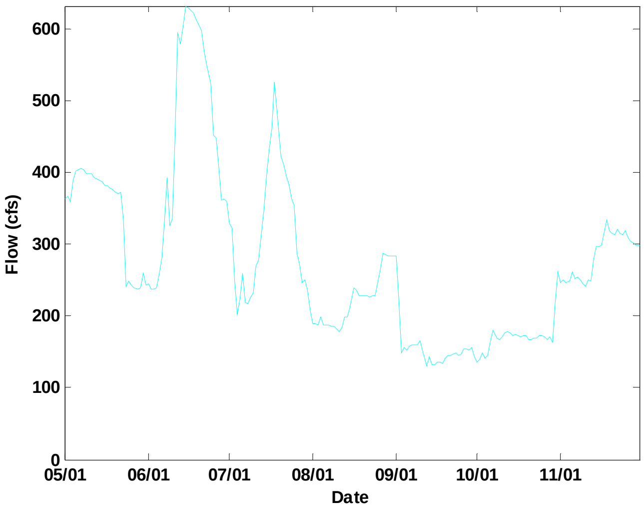


Figure 3.13: 2008 Yahara River In Discharge

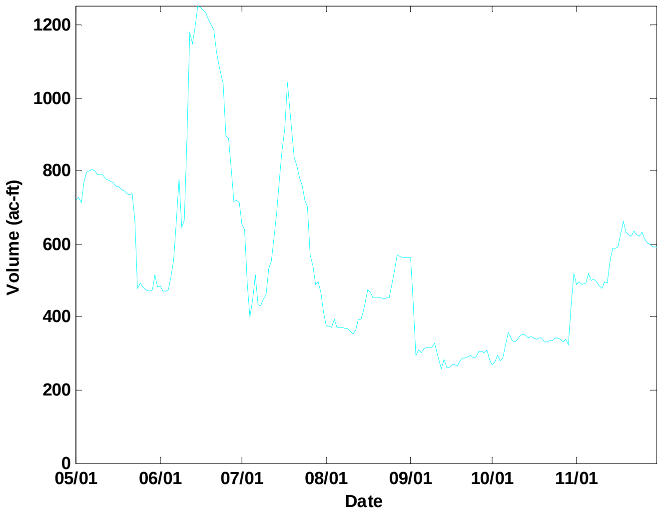


Figure 3.14: 2008Yahara River In Volume

Two components including Yahara River outflow and evaporation account for surface outputs of Lake Monona. Discharge measurements from Lake Waubesa are obtained from the United States Geological Survey (USGS).

3.1.2 Lake Monona Evaporation

The final surface output is in terms of the evaporation process over the lake surface. Evaporation occurs when a water molecule on the lake's surface gains sufficient energy to overcome molecular forces between other liquid molecules and enter the gaseous phase. Calculation of evaporation requires temperature, wind speed, pressure, and relative humidity. The evaporative flux is driven by water vapor gradients and also due to turbulent fluxes such as wind speed.

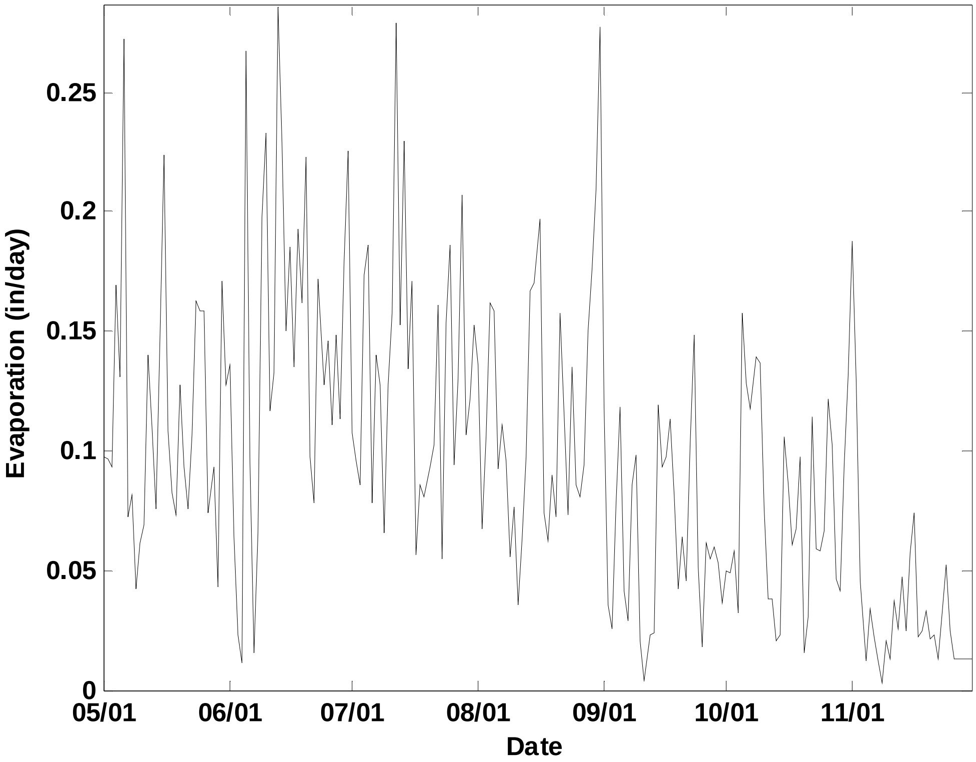


Figure 3.15: 2008 Lake Monona Daily Evaporation

3.1.3 Lake Monona Outflow

Previous models including the USGS model and the MIKE11 model have included Lakes Monona and Waubesa as one lake due to the rising and falling of the lakes in unison. The challenge with analyzing only Lake Monona's water level response is establishing the outlet discharge from Lake Monona. Two equations were applied in the form of uniform flow and unsteady flow to establish the outlet discharge as shown in the following equations. Figures 3.16 and 3.17 illustrate the 2008 Lake Monona outlet discharges and volumes.

Uniform Flow

$$Q_{Monona} = \frac{A_{Monona}}{A_{Waubesa}} * \frac{R_{Monona}{}^{2/3}}{R_{Waubesa}{}^{2/3}} * Q_{Waubesa} \qquad (12)$$

$$A = w * h \qquad (13)$$

$$R = \frac{A}{P} \qquad (14)$$

$$P = 2h + w \qquad (15)$$

where,

Q_{Monona} = discharge out of Lake Monona

$Q_{Waubesa}$ = discharge out of Lake Waubesa

A_{Monona} = area of Lake Monona outlet cross section

$A_{Waubesa}$ = area of Lake Waubesa outlet cross section

w_{Monona} =width of Lake Monona cross section

$w_{Waubesa}$a = width of Lake Waubesa cross section

$h_{Waubesa}$ = Lake Waubesa stage

h_{Monona} = Lake stage at Monona outlet

R = hydraulic radius

P = wetted perimeter

Unsteady Flow

$$\frac{\partial h}{\partial t} * \frac{\partial Q}{\partial x} = 0 \qquad (16)$$

$$when\ \frac{\partial h}{\partial t} < 0, then\ Q = 0.95 * Q$$

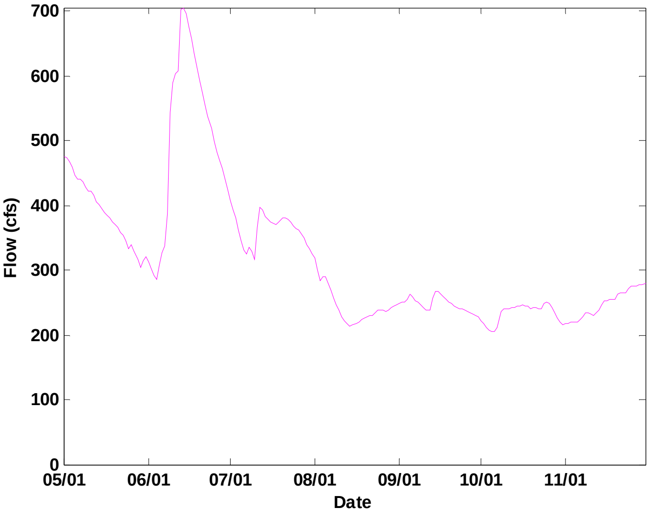


Figure 3.16: 2008 Lake Monona Outlet Discharge

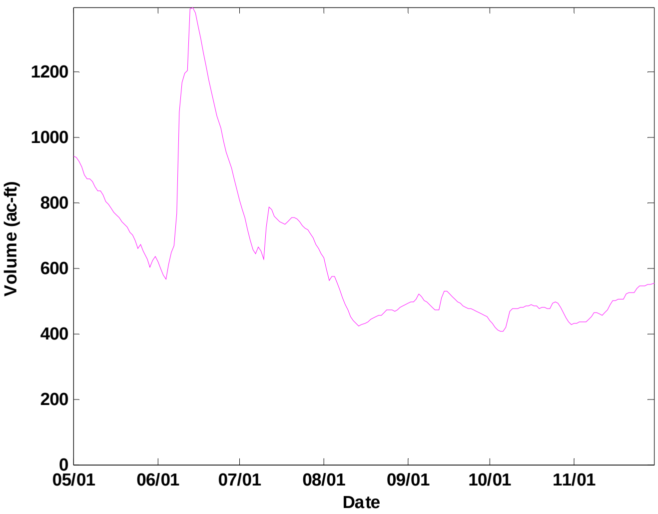


Figure 3.17: 2008 Lake Monona Outlet Volume

3.1.4 Unit Hydrograph Validation

Initially, a hydrologic budget simulation using the unit hydrograph method was carried out for the 2008 water year. Following the 2008 results, to calibrate calculated water levels with observed water levels, four years of data from 2007 to 2004 where simulated using the same model calculations while only changing input data of precipitation and gauged measurements. The goal of the validation was to confirm the unit hydrograph method could be used for past year's data for both dry and wet years. The 2008 water year (Figure 3.22) shows large variations in water levels which are also true of the water years of 2004 (Figure 3.18), 2006 (Figure 3.20), and 2007 (Figure 3.21). However, the 2005 water year (Figure 3.19) experiences relatively small variations in water levels and has considerable more dry weather flow.

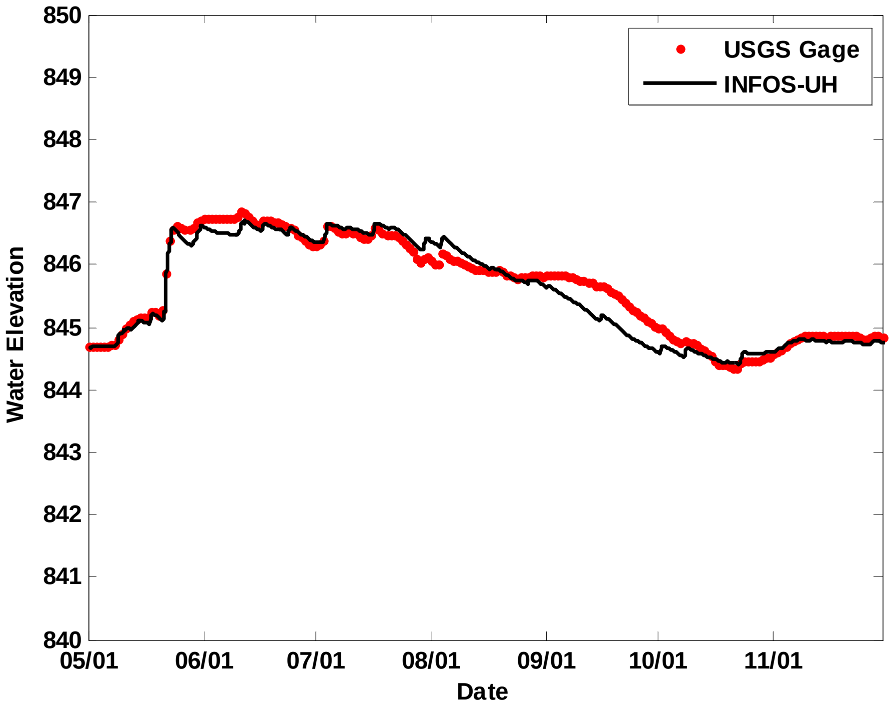


Figure 3.18 Comparison of Observed and Simulated Lake Monona Water Level in 2004

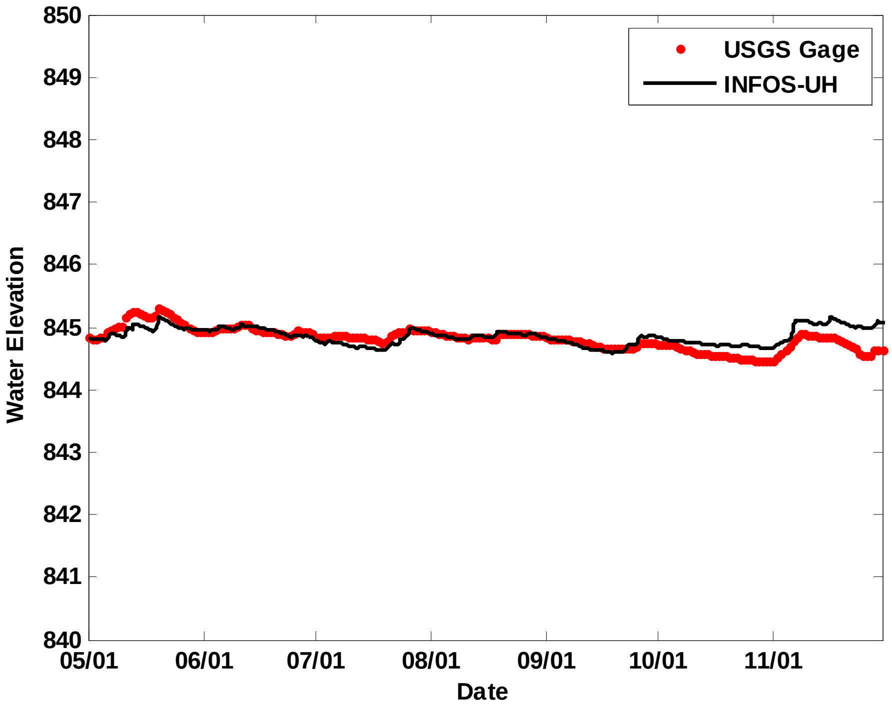


Figure 3.19: Comparison of Observed and Simulated Lake Monona Water Level in 2005

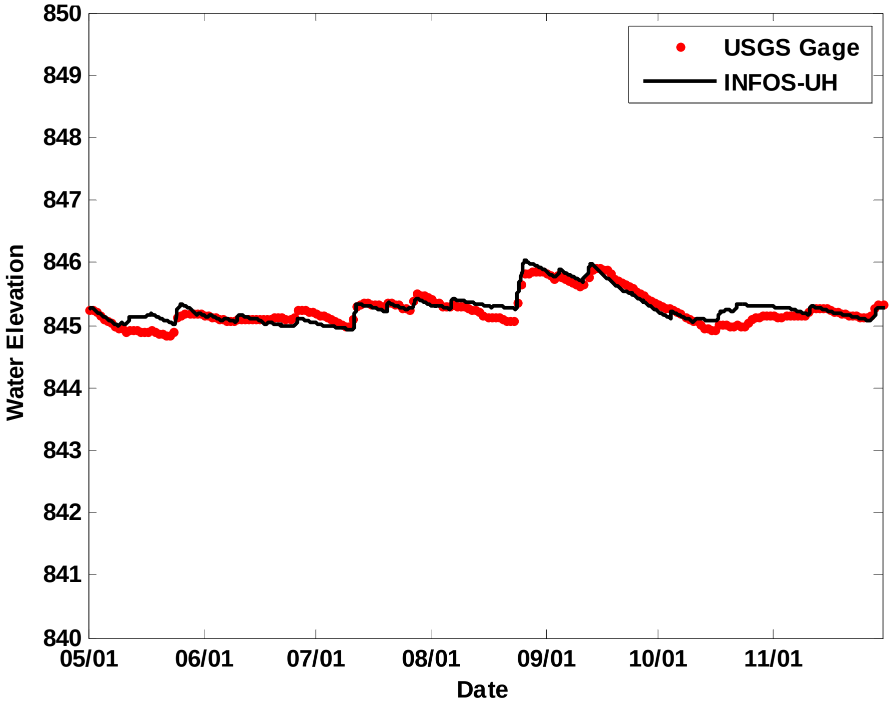


Figure 3.20: Comparison of Observed and Simulated Lake Monona Water Level in 2006

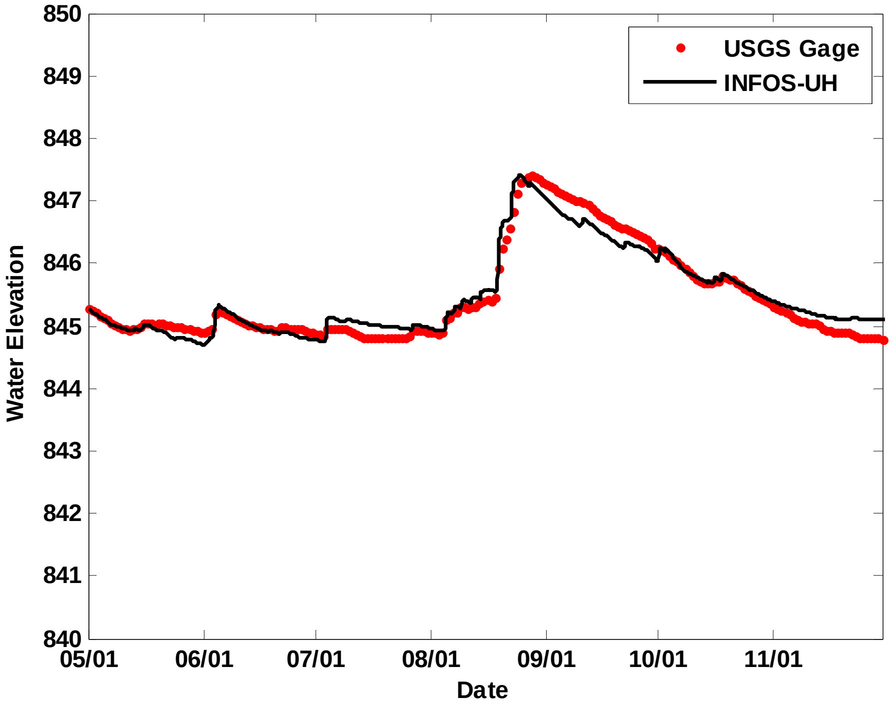


Figure 3.21: Comparison of Observed and Simulated Lake Monona Water Level in 2007

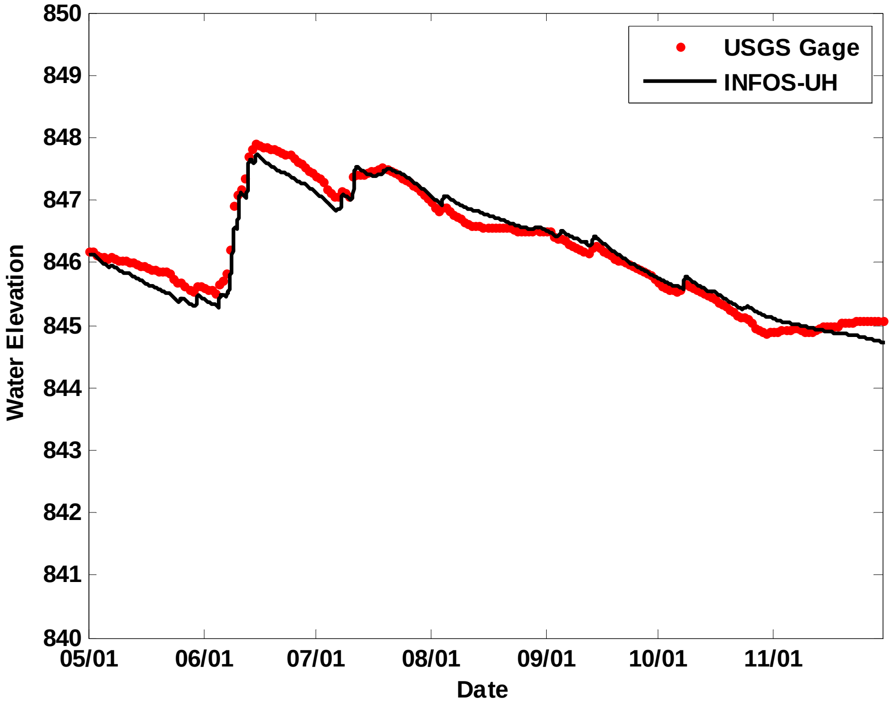


Figure 3.22: Comparison of Observed and Simulated Lake Monona Water Level in 2008

3.2 Hydrologic Modeling Results and Discussion

The unit hydrograph method is a simplified model used to describe the rainfall-runoff behavior of the watershed. The unit hydrograph model was compared during the water years defined from May 1st to November 30th. Even though only simulating the water year time period is a limitation to evaluating yearly water content, the concern for water level variations is prominent during the summer months and this was the focus for the work. The Lake Monona watershed has been seperated into three subbasins. The three subbasins used in all the modeling approaches are storm sewer outfalls, the Starkweather Creek basin, and the Wingra Creek basin.

The unit hydrograph method discussed above has been developed to include a mass balance for the hydrologic cycle of Lake Monona including evaporation losses from the changing Lake Monona surface area. The hydrologic modeling has proved to be an effective means of predicting water levels with the use of a rainfall-runoff response model.

The unit hydrograph method results for discharge and volume implications were further evaluated to assess yearly summaries for inflows to Lake Monona. Four sources of inputs of Yahara River inflow, Starkweather Creek, Wingra Creek, and storm sewer inputs were summarized. They were evaluated to assess normal flow, peak flow, normal volume, and peak volume. The normal flow and normal volume is defined as the mean value or the sum of the total discharge or input volume dived by the number of occurrences. The peak flow and peak volume is defined as the maximum daily value. The comparison of normal flow and normal volume are represented in the Figures 3.23 and 3.24.

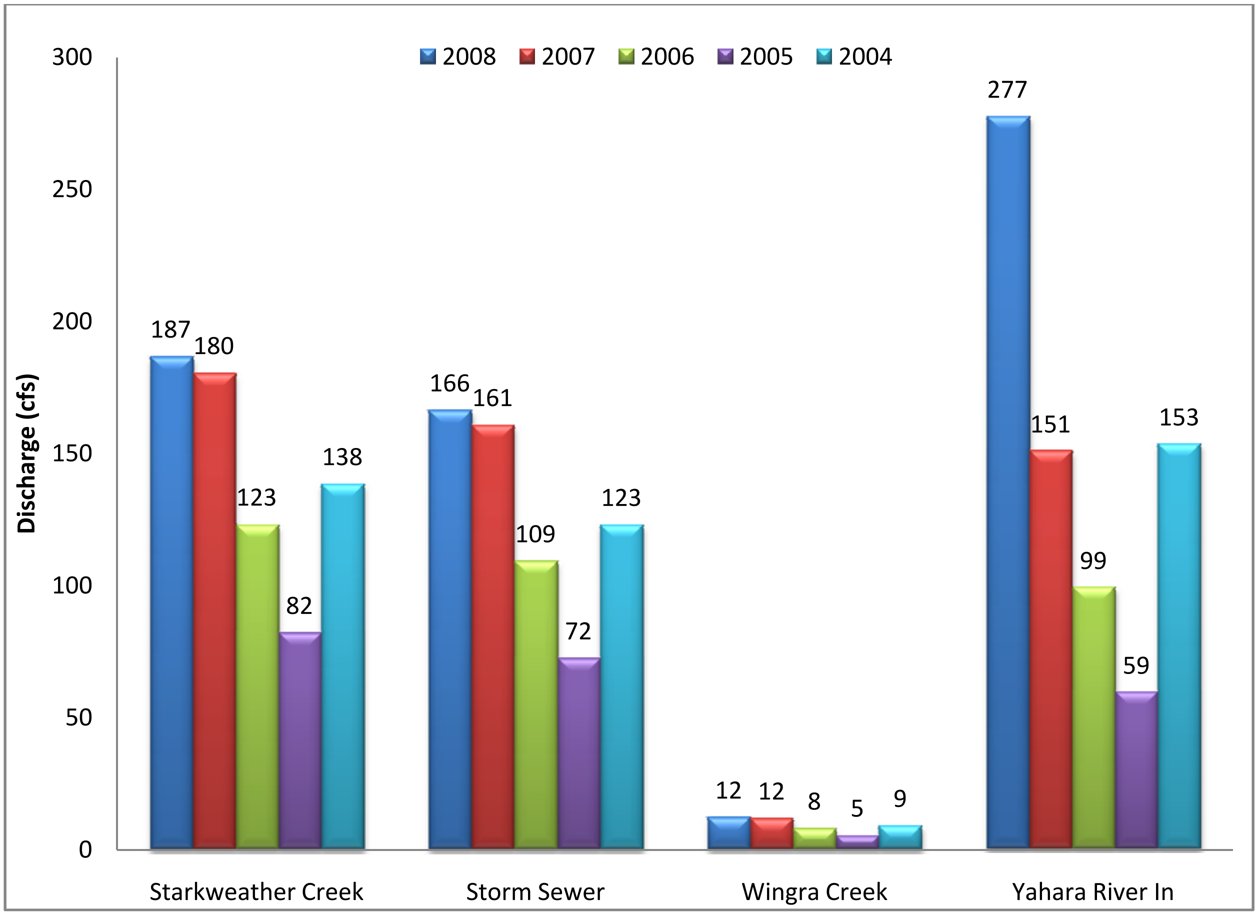


Figure 3.23: Lake Monona Source Normal Flow

Due to normal flow being represented as the mean inflow (i.e. the sum of the total inflows dived by the number of occurrences), the tributary and storm sewer values only occur during rainfall events. The normal flow for Starkweather Creek, Storm Sewer, and Yahara River are closer in magnitude when compared to Wingra Creek. The normal flow discharge of Starkweather Creek is consistently greater than the storm sewer inputs, however, when compared to the Yahara River inflow the normal flow varies based on year due to discharge contingent upon upstream gate openings.

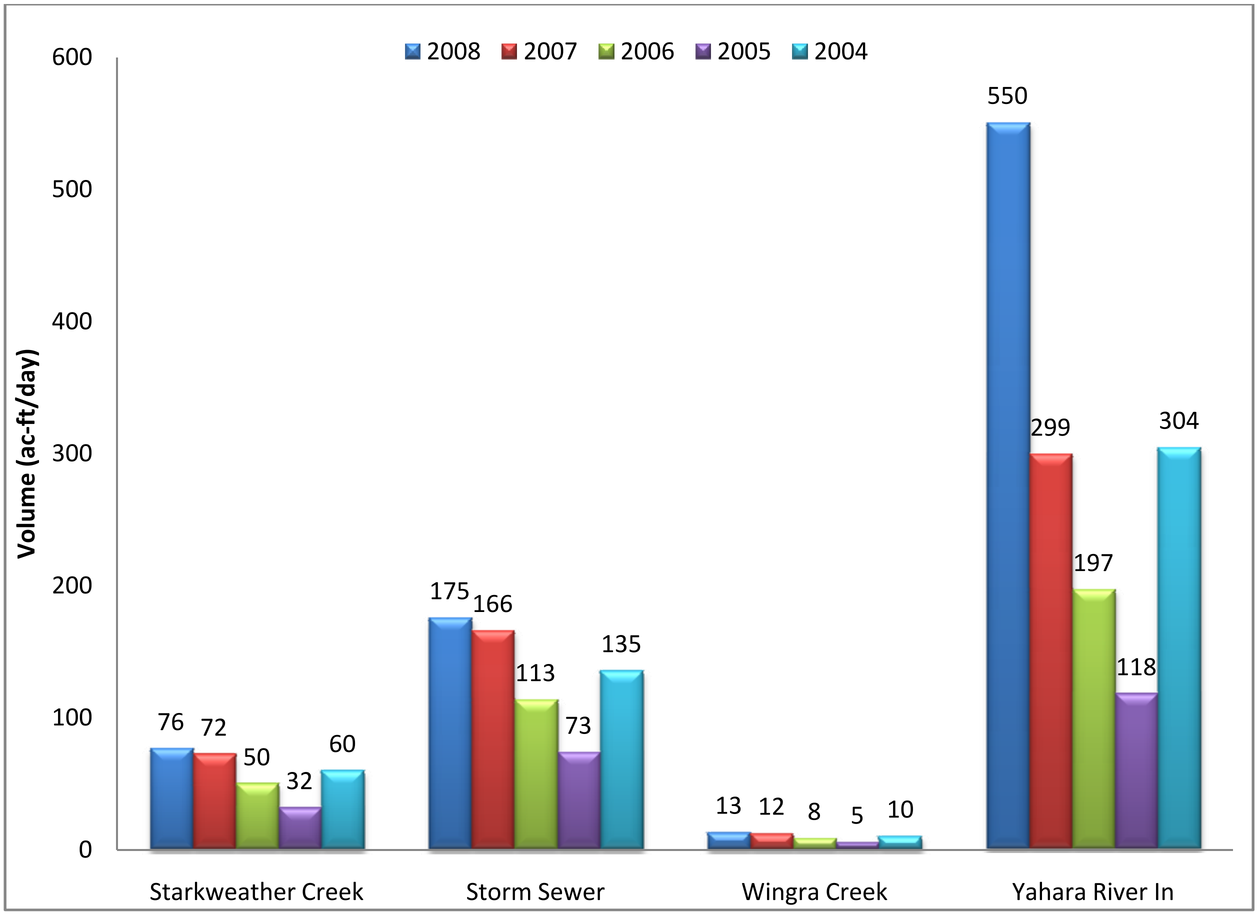


Figure 3.24: Lake Monona Source Normal Volume

The normal volume for each source input is calculated for the mean daily volume. Similar to normal flow, Starkweather Creek, Wingra Creek, and storm sewer inputs represented in the figure only occur during rain events. From a volume perspective the Yahara River provides the largest normal daily source due to the constant input from the upstream discharge from Lake Mendota.

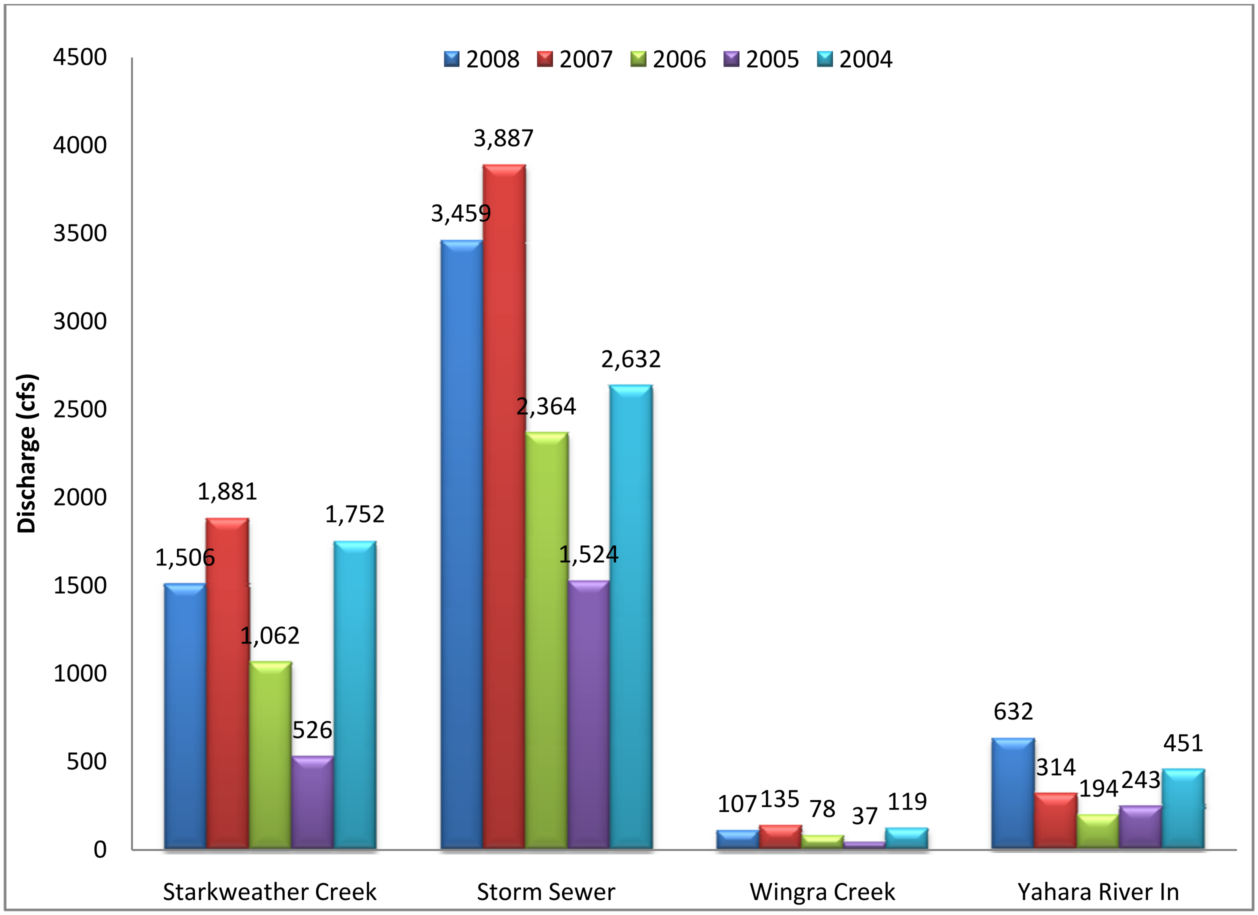


Figure 3.25: Lake Monona Source Peak Flow

The peak flow for the storm sewer inputs and Starkweather creek far exceed both the Yahara River inflow and Wingra Creek. The peak flow is determined as the maximum discharge into Lake Monona and thus the Starkweather Creek, Storm Sewer, and Wingra Creek maximum discharges only occur during or shortly after rain events. The Wingra Creek peak discharge is less than the other three inputs due to its small watershed, dam structure, and Lake Wingra providing storage and reducing the peak outflow. Similarly, the Yahara River discharge does not exhibit large discharge rates due to its constant, controlled release from the Tenney Locks.

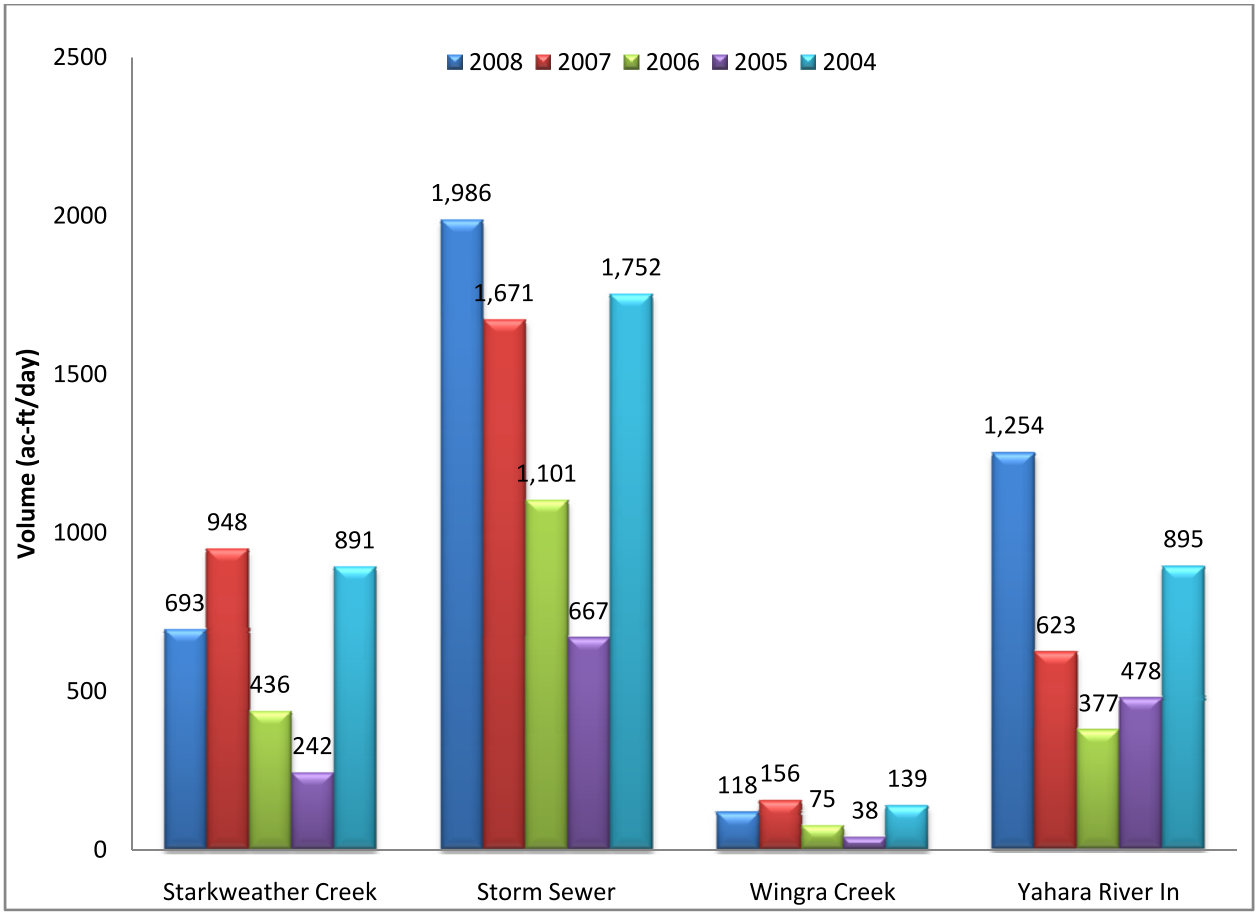


Figure 3.26: Lake Monona Source Peak Volume

4 HYDRODYNAMIC MODEL

Numerical models have become important tools in evaluating the response of complex water systems. During the last decade many 3D hydrodynamic models have been developed at different research institutions. Most circulation codes solve for some form of the Navier-Stokes equations with conservation equations for water volume. Typical codes are based on either structured grids or unstructured grids and use finite difference, finite element, or finite volume approaches. The model selected in this application is Finite Volume Coastal Ocean (FVCOM). The ability of FVCOM to accurately solve scalar conservation equation, in addition to the topological flexibility and simplicity of coding makes FVCOM suitable for studying Lake Monona circulation and spatial water level.

4.1 Model Description

FVCOM is an unstructured grid, finite volume, 3D circulation model. FVCOM is solved numerically by flux calculation using the integral from of the governing equations over an unstructured triangular grid. FVCOM combines the best attributes such as computational efficiency of finite difference methods and geometric flexibility in finite element models. It includes the Mellor and Yamada 2.5 level closure scheme for parameterization of vertical eddy viscosity. The MY-2.5 level model uses a prognostic equation for turbulent kinetic energy and turbulence macroscale (Mellor and Yamada, 1982). The variables are three components of velocity, temperature, salinity, turbulence kinetic energy, and turbulence macroscale. It has a wetting-drying option which is important to accurately simulate hydrodynamics in flooded areas. The momentum equations are nonlinear and incorporate a variable Coriolis parameter. FVCOM discretizes the integral form of the governing equations. For computational efficiency, the vertically integrated equations of the external mode are separated from the vertical structure of the internal mode.

4.2 Model Inputs

4.2.1 Computational Grid

A Cartesian grid with an average horizontal spacing of approximately 30 meters and 5 equally spaced vertical layers were used for Lake Monona. Fine resolution was imposed at specific areas including along the shore for longshore currents, between Lake Monona and Monona Bay for exchange, and at the outlet of Lake Monona for lake release.

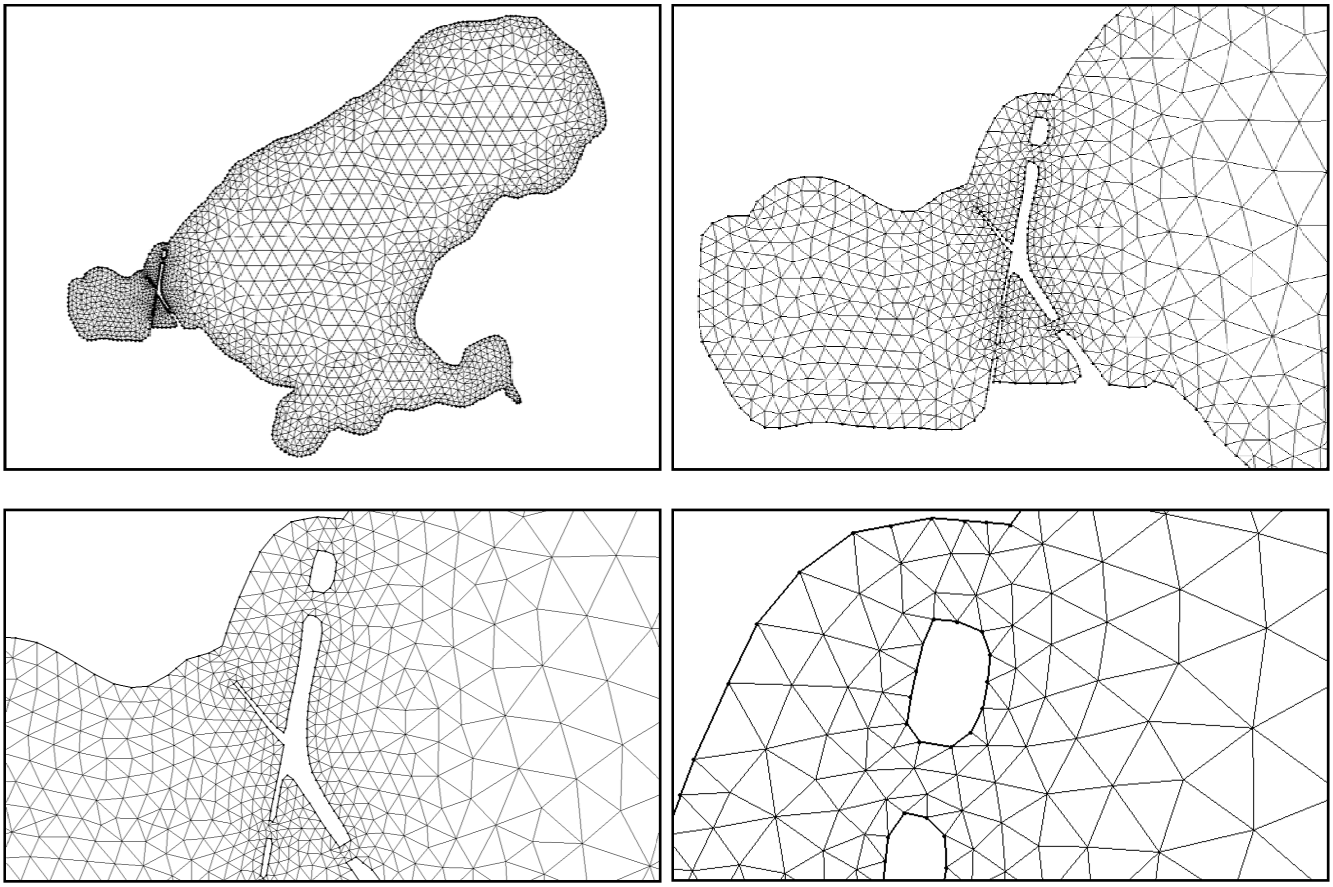


Figure 4.1: Lake Monona Computational Grid

4.2.2 Initial Conditions

Lake Monona was initiated with the starting water elevation at the time of model run for each simulation. The model was run in barotropic mode with a homogenous water column temperature of 20 degrees Celsius. The water currents at the initial condition were set to zero. The entire model forcing functions were ramped from zero to their full values in approximately one day.

4.2.3 Boundary Conditions

The surface boundary conditions for Lake Monona were prescribed with hourly wind speed, wind direction, precipitation, and evaporation obtained from the Atmospheric and Oceanic Sciences Building. River discharge nodes were input from a combination of USGS gauge measurements and hydrologic computed discharges. Only one stream gauge is measured for the input from the Yahara River into Lake Monona. The remaining sources including Starkweather Creek, Wingra Creek, storm sewer outfalls, the Yahara River Outflow were computed using the unit hydrograph method and introduced into the hydrodynamic model. All river discharge inputs were prescribed on an hourly time step. A second simulation was constructed using water level as the outlet boundary condition. Field measurements of water level were gathered in the summer of 2008. Figure 5.5 shows the field measured data in blue and the USGS water level measurements for Lake Monona upstream and Lake Waubesa downstream in green and blue, respectively.

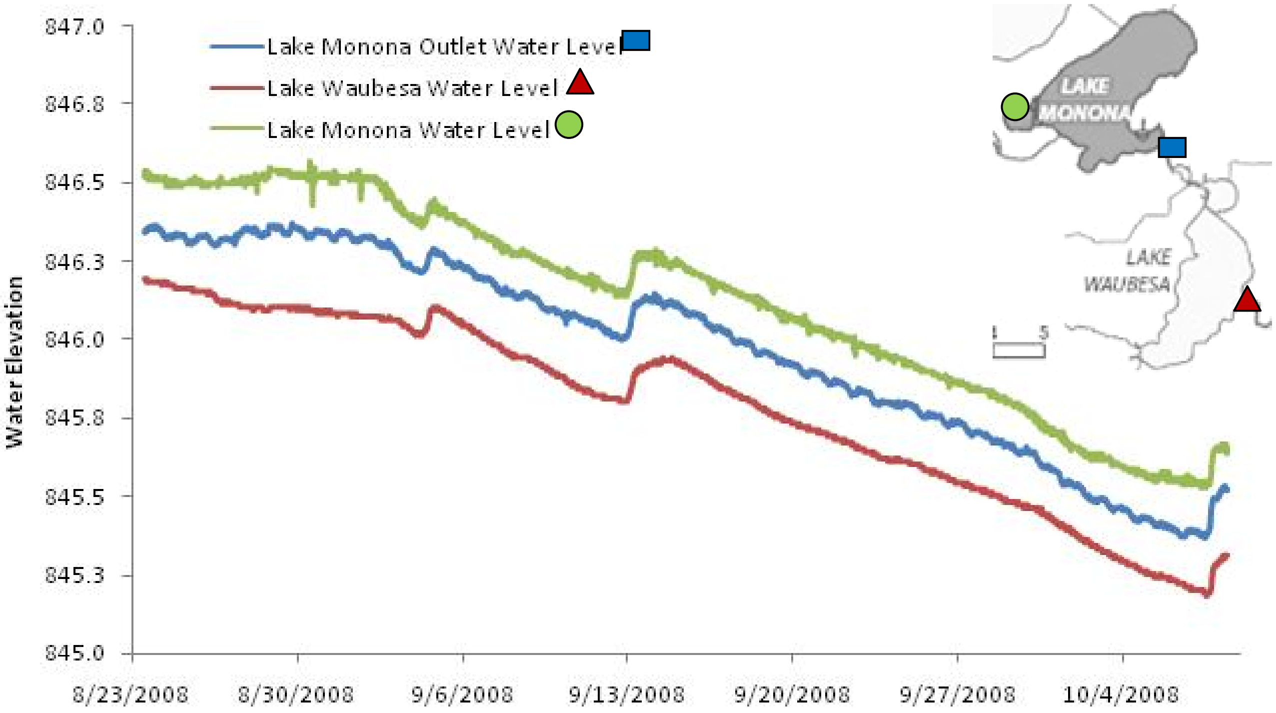


Figure 4.2: Lake Monona, Monona Outlet, and Lake Waubesa Water Levels

4.3 Model Simulations

Hydrodynamic simulations were carried out to: (1) model spatial water surface elevations, (2) evaluate wind induced circulation, (3) validate hydrologic outlet discharge, and (4) identify zones of hydraulic controlled versus wind controlled velocity.

4.4 Model Results

4.4.1 Spatial Water Surface Elevation

Four water level measurements were installed and the current USGS Lake gauges were used to provide spatial information for Lake Monona. The model was run using input forcings generated from hydrologic modeling. The purpose of this simulation is to validate the hydrologic inputs and their impact to channel levels as well as over the spatial domain. The results are shown in Figures 4.3

through 4.7 where the values from the hydrodynamic model compared to observed measurements are in good agreement.

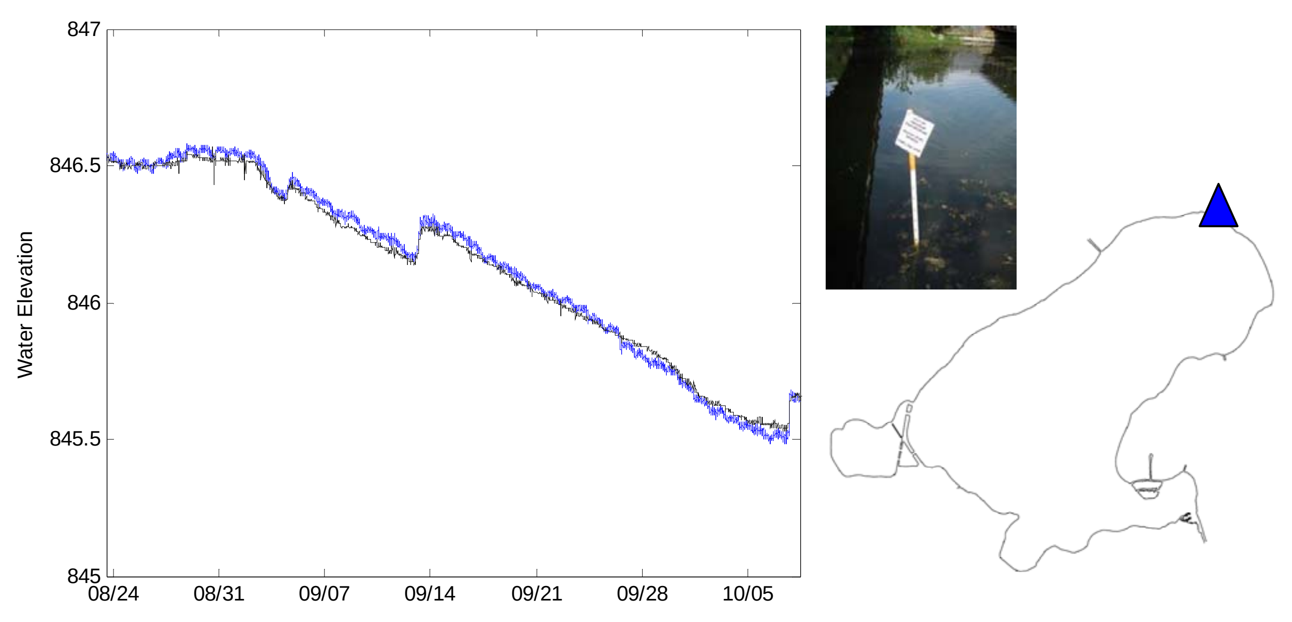


Figure 4.3: Starkweather Creek Measured Water Elevation and Hydrodynamic Water Level

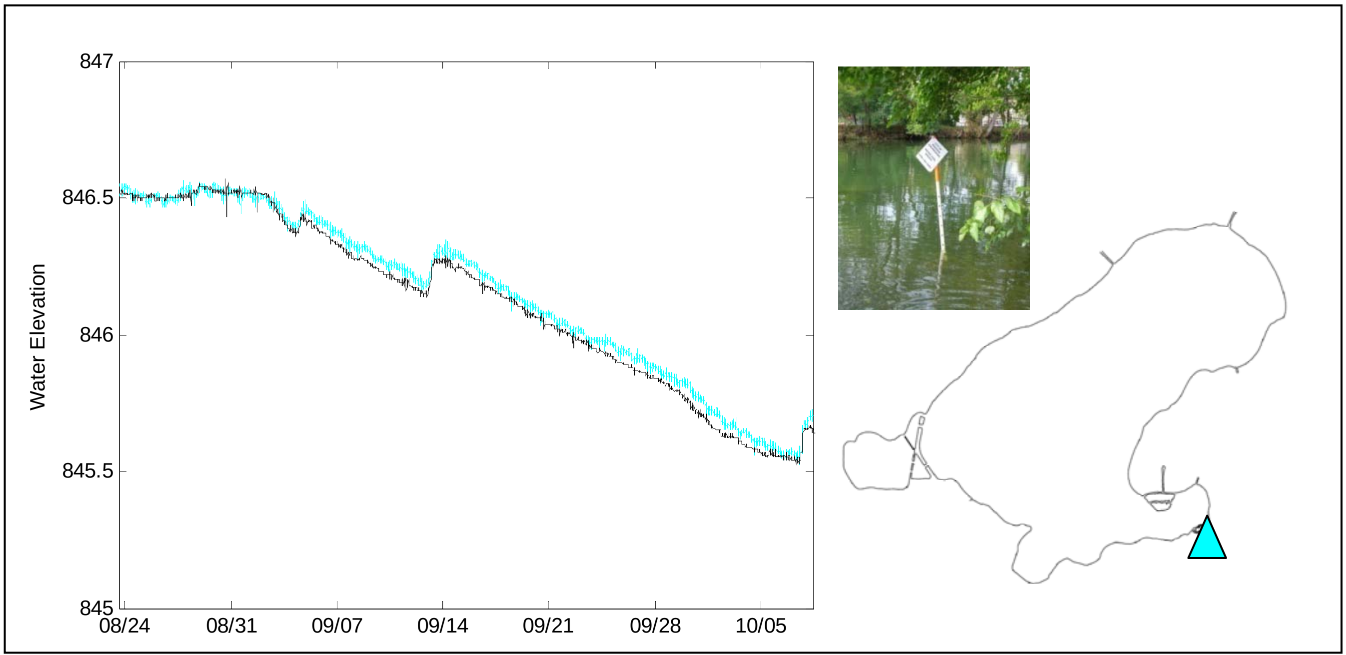


Figure 4.4: Lake Monona Outlet Measured Water Elevation and Hydrodynamic Water Level

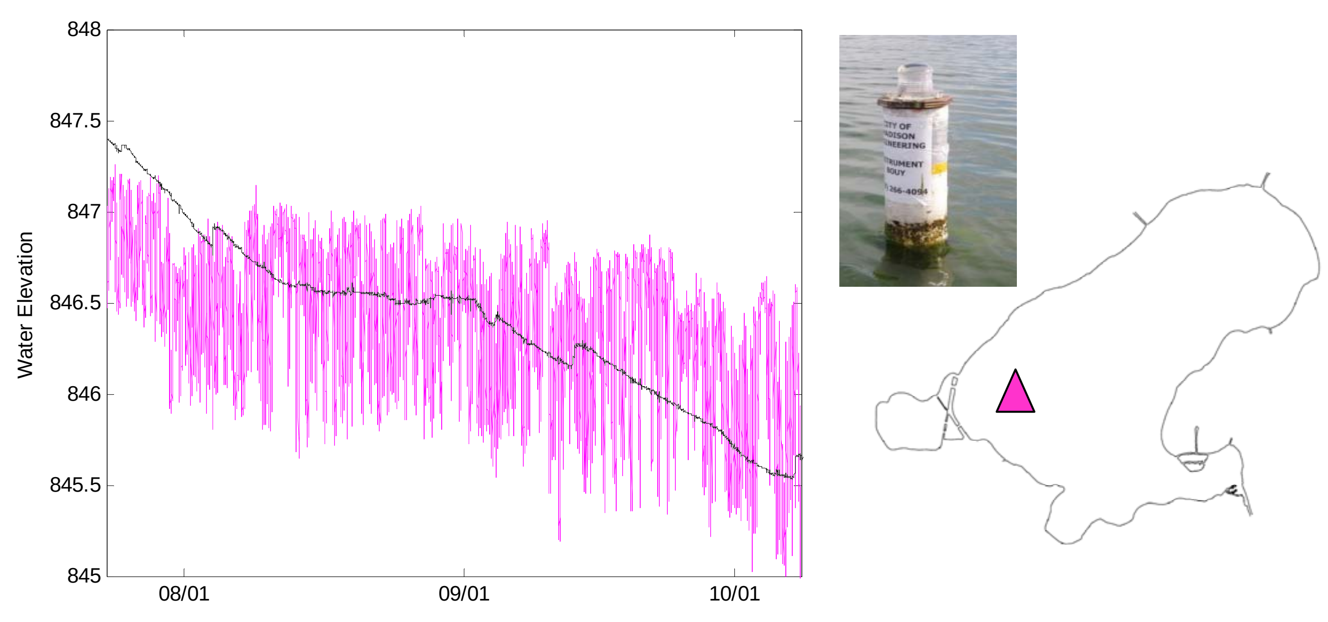


Figure 4.5: Lake Monona Measured Water Elevation and Hydrodynamic Water Level

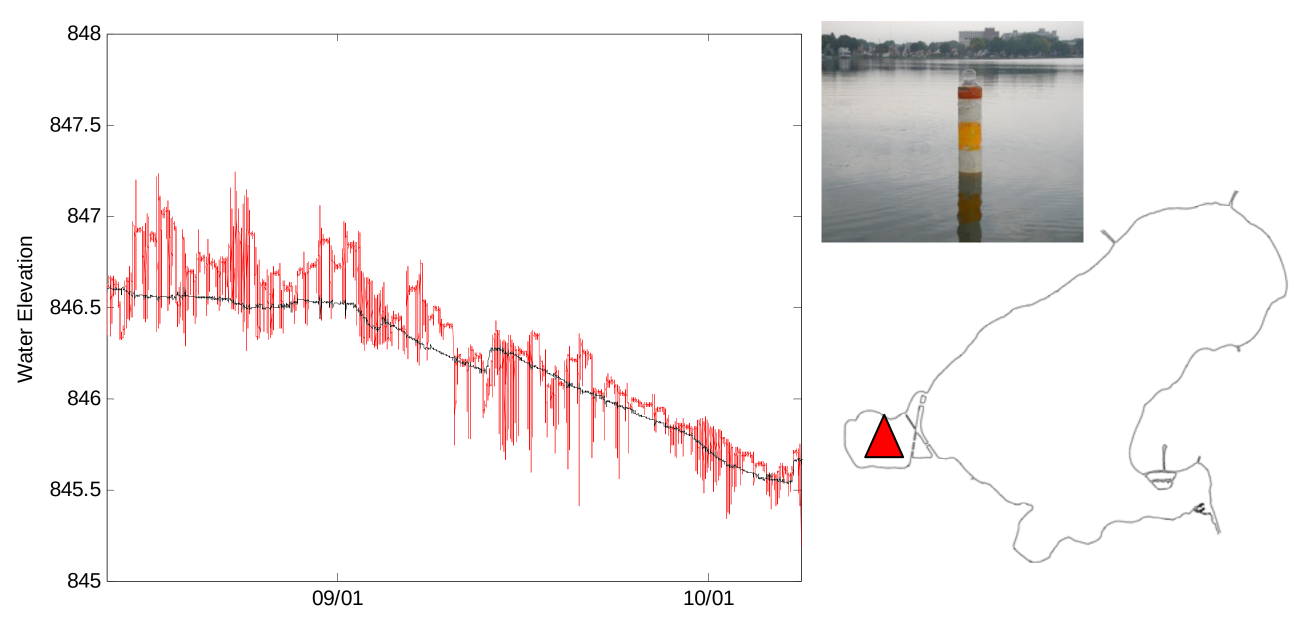


Figure 4.6: Monona Bay Measured Water Elevation and Hydrodynamic Water Level

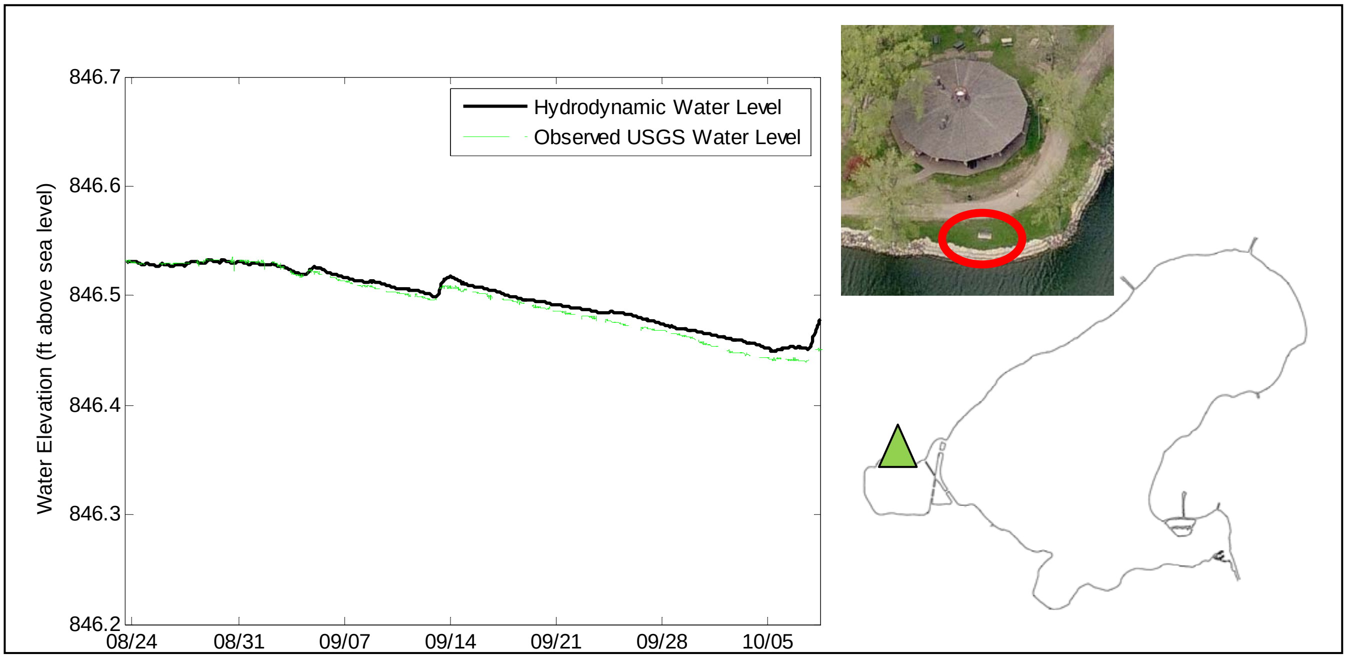


Figure 4.7: USGS Measured Water Elevation and Hydrodynamic Water Level

4.4.2 Wind Induced Circulation

One of the outcomes of a three dimensional hydrodynamic model is the lake circulation driven by wind forcing. The model was constructed with a uniform wind field applied over the computational domain. Overall, current orientations are strongly guided by bathymetry and coastal geomorphology similarily shown by Black et al. (2000). Predominately, large currents are apparent near the shore dominated by longshore currents resulting from the high energy zone associated with the shallow water depth. Dominant circulation patterns have shown to play an important role in the horizontal transport of heat, sediment, and nutrients (Leon et al., 2007).

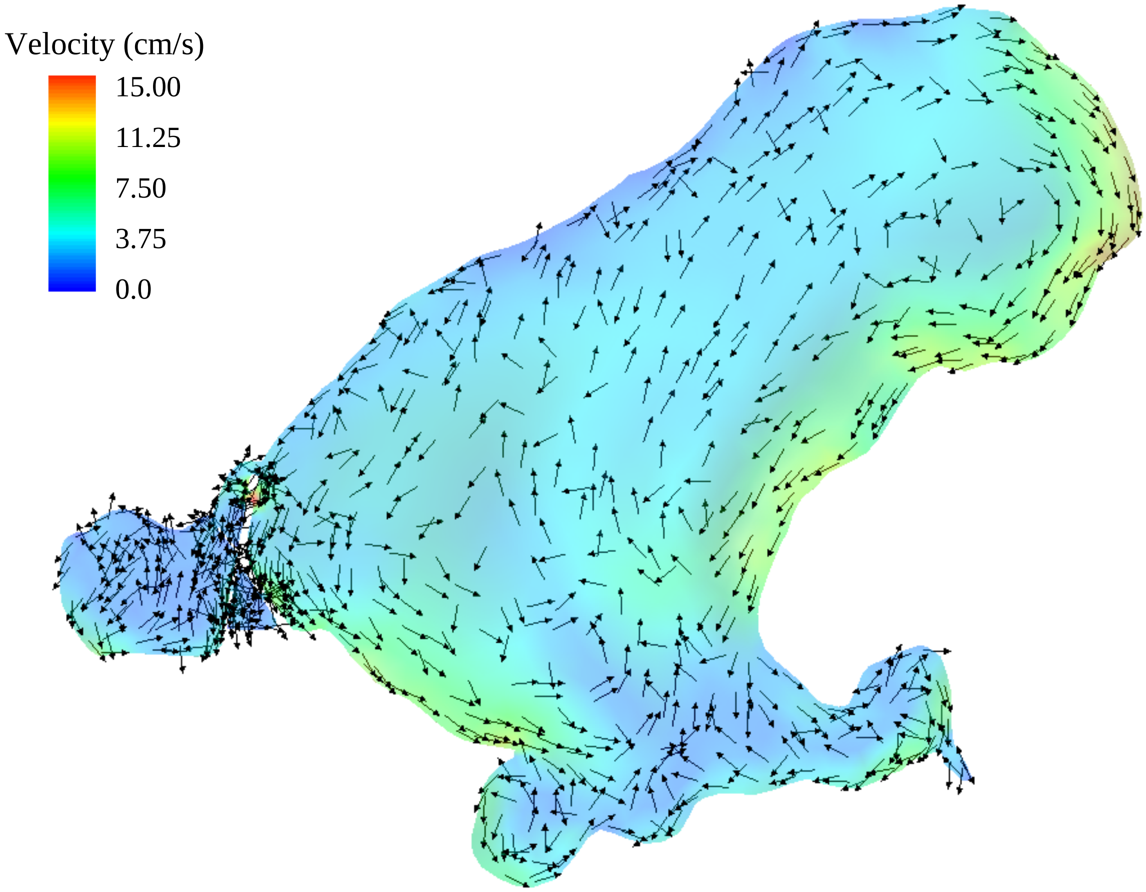


Figure 4.8: Surface circulation patter for May 12, 2008 for Lake Monona

4.4.3 Outlet Water Level Boundary Condition

The hydrodynamic model was simulated to evaluate calculated outlet discharge from uniform and unsteady calculations as described in Chapter 3. The model was imposed with forcing conditions of wind speed and river input nodes. Previously, outlet discharge out of Lake Monona used calculated discharge determined from uniform and unsteady flow calculations. However, the downstream boundary condition has been modified from discharge to water level.

A simulation of employing the open boundary treatment to Lake Monona was constructed at the outlet of Lake Monona. The resulting discharge was plotted to the corresponding hydrologic discharge shown in Figure 4.9. The hydrodynamic discharge results show an oscillated pattern as compared to the hydrologic discharge calculation. The hydrologic discharge is calculated from using downstream lock discharge information in which the physical discharge at the outlet may not be captured. The hydrologic discharge calculation can be used as an effective tool to evaluate Lake Monona water levels; however, it lacks the ability to capture true discharge values. Hence, the hydrodynamic model can be used as a tool to obtain channel discharges at user selected points.

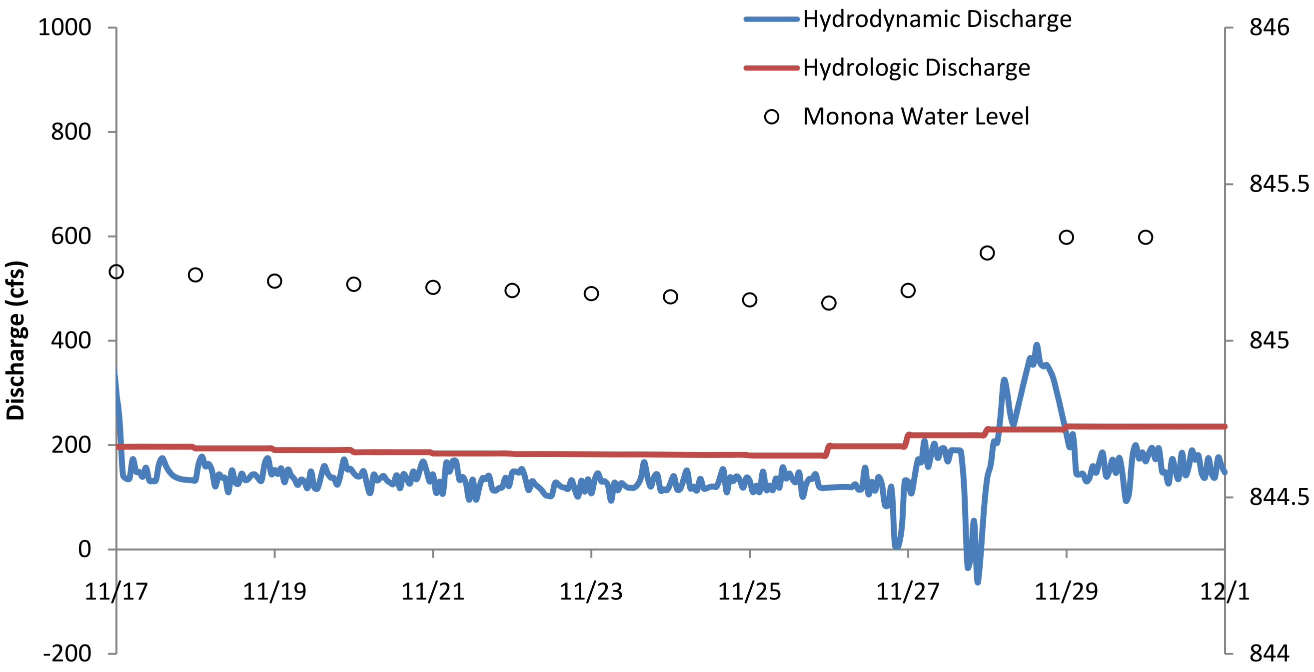


Figure 4.9: 2006 Lake Monona Outlet Discharge Comparison of Hydrodynamic and Hydrologic Results

4.4.4 *Zones of Hydraulic Controlled versus Wind Controlled Velocity*

Five years from 2004 to 2008 were simulated with the hydrodynamic model. From the five simulated years, the peak discharge results are shown in Table 4.1. The peak discharge time was established for when the storm sewer outflow reported a maximum value over the time series due to its only contribution to Monona Bay. Other peak discharges reported in Table 4.1 correspond to the same storm identified for the storm sewer input; however, the timing for the peak are not the same due to their individual hydrographs and peak to discharge.

Table 4.1: Yearly Peak Discharges

Year	Date	Yahara Inflow (cfs)	Starkweather Creek (cfs)	Wingra Creek (cfs)	Storm Sewer Outfall Sum (cfs)	Yahara Outflow (cfs)
2004	05/21	145.0	1093.4	93.2	2015.1	269.5
2005	05/18	70.0	214.5	27.0	1029.6	219.0
2006	05/23	149.0	323.0	39.1	1619.3	142.5
2007	08/21	240.0	816.8	55.4	1849.5	227.4
2008	06/09	326.0	1124.5	78.7	2593.2	452.6

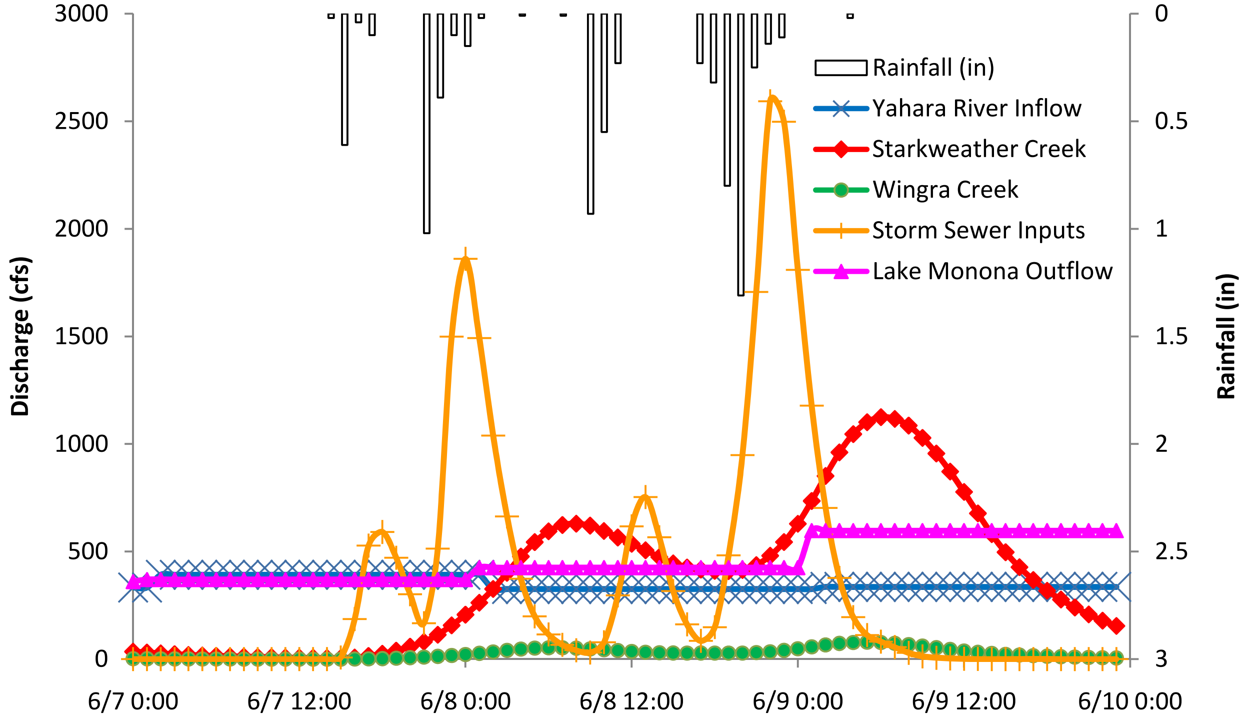
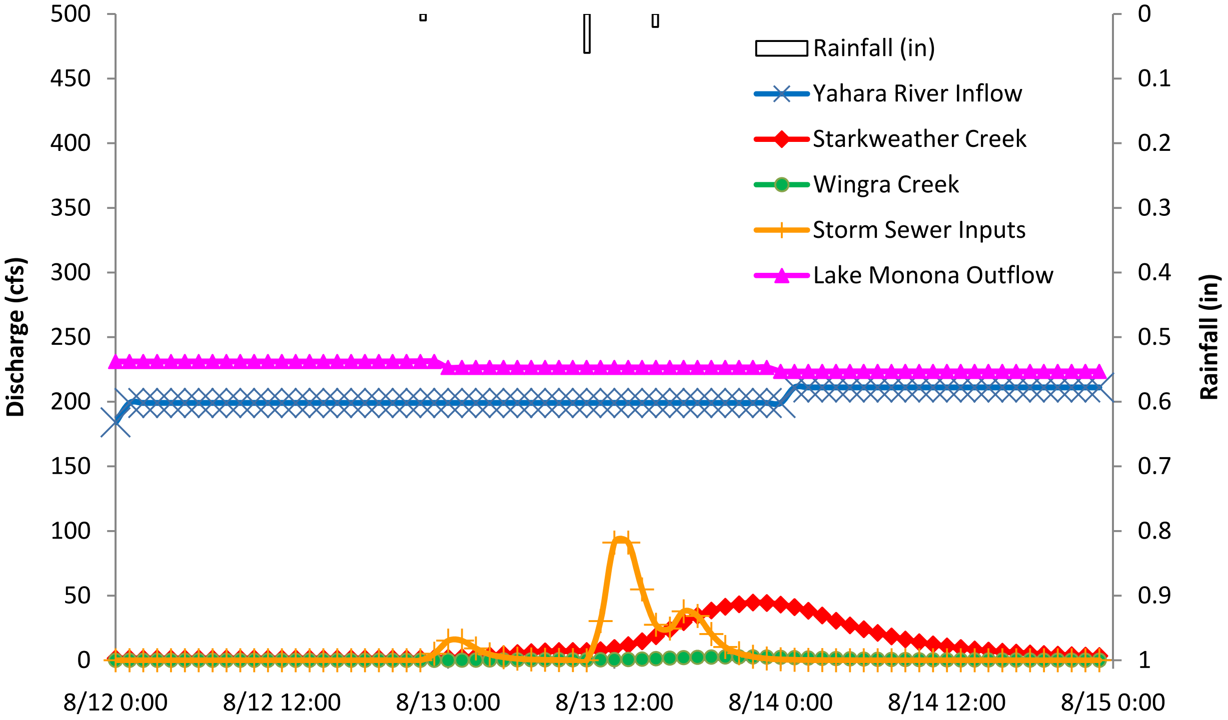


Figure 4.10: 2008 Lake Monona Hydrographs for High Flow Simulation



4.11: 2008 Lake Monona Hydrographs for Low Flow Simulation

From the five year data set, the peak discharge occurs on June 9th, 2008 and this time period is selected to be analyzed. Two hydrodynamic simulations were run to evaluate wind controlled areas versus hydraulic controlled areas. All model scenarios have been run with hydrologic inputs in which the source of inflow to Monona Bay is in the release of storm sewer discharge. Further a low flow simulation was analyzed from the hydrographs shown in Figure 5.15. Figures 5.16 and 5.17 show that the outlet channel of Lake Monona experiences high velocities and can be characterized as hydraulically controlled. Additionally, the connection between Monona Bay and Lake Monona is evaluated for wind controlled or hydraulic controlled transfer. This assessment was conducted to understand the transfer between Lake Monona and Monona Bay during storm events and any flushing during these periods. The analysis for Monona Bay transport required imposing no surface wind boundary condition to compare the velocity with wind forcing shown in Figure 5.17. As shown in Figure 5.17, the majority of the flux to and from Monona Bay is dominated by wind environments. Further a low flow simulation was assessed (Figures 5.18 and 5.19) to confirm the hydraulic controlled area of the outlet of Lake Monona.

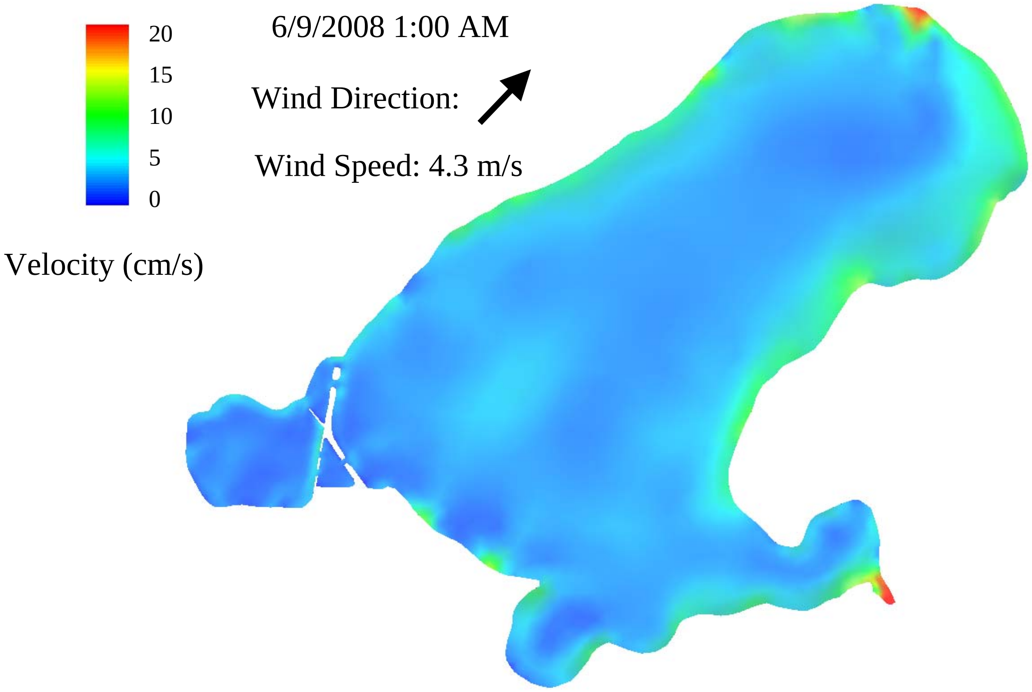


Figure 4.12: Lake Monona High Flow Surface Velocity with Wind

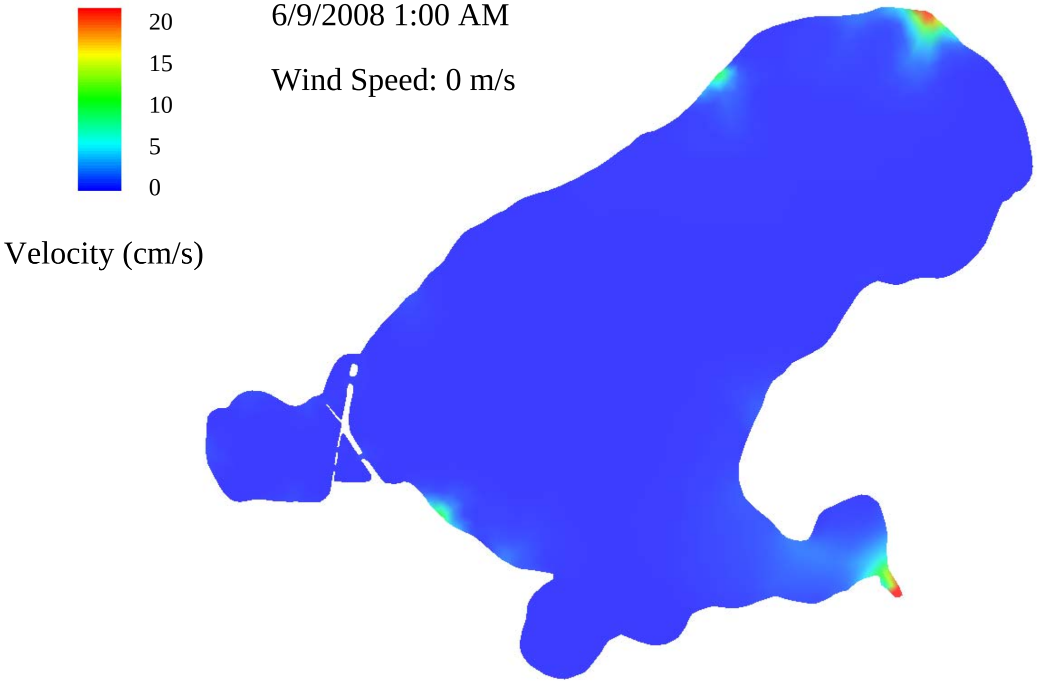


Figure 4.13: Lake Monona High Flow Surface Velocity with No Wind

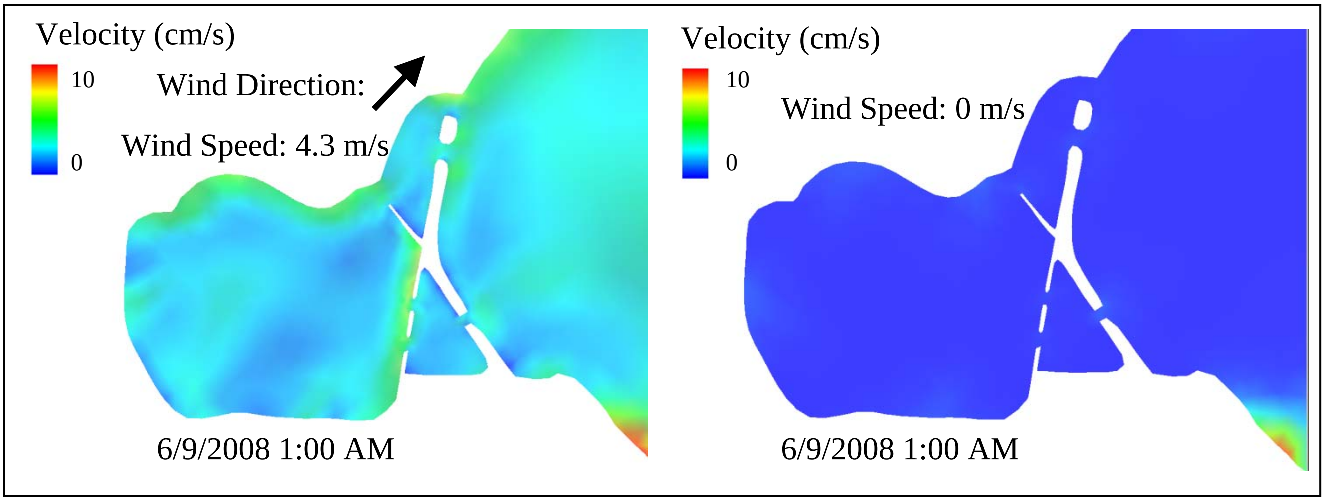


Figure 4.14: Monona Bay High Flow Surface Velocity Compared with and without Wind Boundary Condition

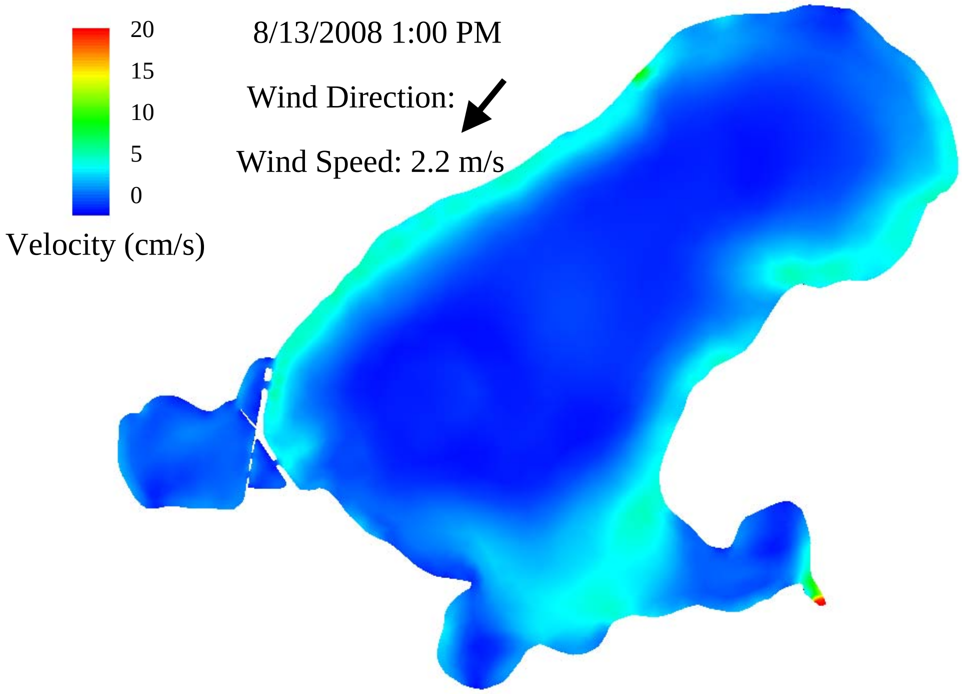


Figure 4.15: Lake Monona Low Flow Surface Velocity with Wind

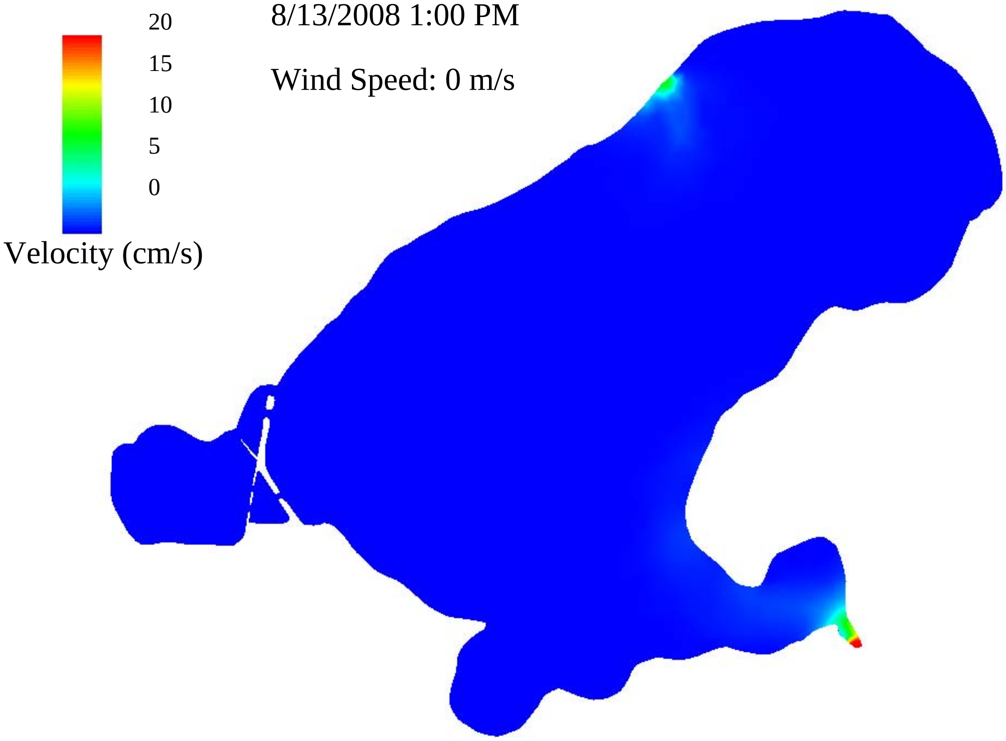


Figure 4.16: Lake Monona Low Flow Surface Velocity with No Wind

5 SUMMARY

This study successfully developed a suite of models that can predict water level and examine circulation patterns for Lake Monona. From literature review, this work has built upon prior efforts and research while expanding our knowledge to include hydrodynamic flow and transport of Lake Monona including Monona Bay. Specifically hydrological budgets were carefully evaluated and examined due this primary requirement for all model platforms. First, site-specific data was analyzed in order to create an accurate and representative model. A unit hydrograph model was established for Lake Monona to assess runoff entering Lake Monona from storm sewers, Lake Wingra, and Starkweather Creek. Prior modeling efforts included creation of MIKE11 coupled with a rainfall-runoff model called NAM. Additionally, a HEC-HMS model for the Lake Monona watershed was created. The Unit Hydrograph model, NAM model, and HEC-HMS models were compared and evaluated in terms of discharge and lake levels. Finally, a three dimensional model for Lake Monona was created to study spatial water level changes, wind driven circulation, Lake Monona discharge, and wind versus hydraulic controlled areas.

This study has shown that lake levels and flows can be accurately predicted by several modeling techniques. Hence, the work has been demonstrated using retrospective data sets, yet the concepts could be easily translated to real-time systems. The system would require live data streams to provide initial model conditions followed by continuous boundary conditions. By providing real-time numerical results, the hydrologic model can provide nowcast and forecast predictions for ungauged stream discharges to drive hydrodynamic modeling efforts. Additionally, the hydrodynamic model can be utilized in a manner to provide spatial water level information as well as outputting stream discharge from within the model domain. This Interactive and Nowcast/Forecast Operational System (INFOS) would provide beneficial information to lake managers, operators, and recreational users.

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