Integrated Nowcast and Forecast Operation System (INFOS) for WINgra Best Management Plan (WIN-BMP)

Final Project Report for DNR Lake Planning Grant

Professor Chin Wu, UW-Madison Department of Civil & Environmental Engineering

John Reimer, Dane County Land & Water Resources

Greg Fries, City of Madison Engineering

(Field, laboratory, and modeling work conducted by graduate students Gary Guo and Nathan Gerdts from the Environmental Fluid Mechanics Lab, Dept. of Civil Environmental Engineering, UW-Madison under the supervision of C. Wu)

Introduction

Lake Wingra is a small, shallow eutrophic body of water that is considered to experience degraded water quality due to watershed inputs and in-situ lake conditions. When storm water enters a lake system during storm periods, suspended storm water sediment loading and transport is important to overall lake water quality. In addition, wind-induced sediment resuspension from the benthic substrate can be of great concern. From past efforts on Lake Wingra, we learned that the role of carp plays a significant role in sediment resuspension due to their foraging behaviors reducing macrophyte density. This report is intended to improve our understanding of the complex interactions of physical (watershed and waves) and biological (carp) in Lake Wingra (Figure 1) to help aid in strategies for improving water in Lake Wingra.

We investigated the role caused by the watershed (storm sewers), biologic (carp), and hydrodynamic (wind) and isolate the variables to determine their contribution to the overall lake water clarity.

Our specific tasks were to (1) quantify the contribution of sediment resuspension from hydrologic, biologic, and hydrodynamic through modeling and field measurements and (2) install a real-time observation station using the Integrated Nowcast and Forecast Operation System (INFOS).

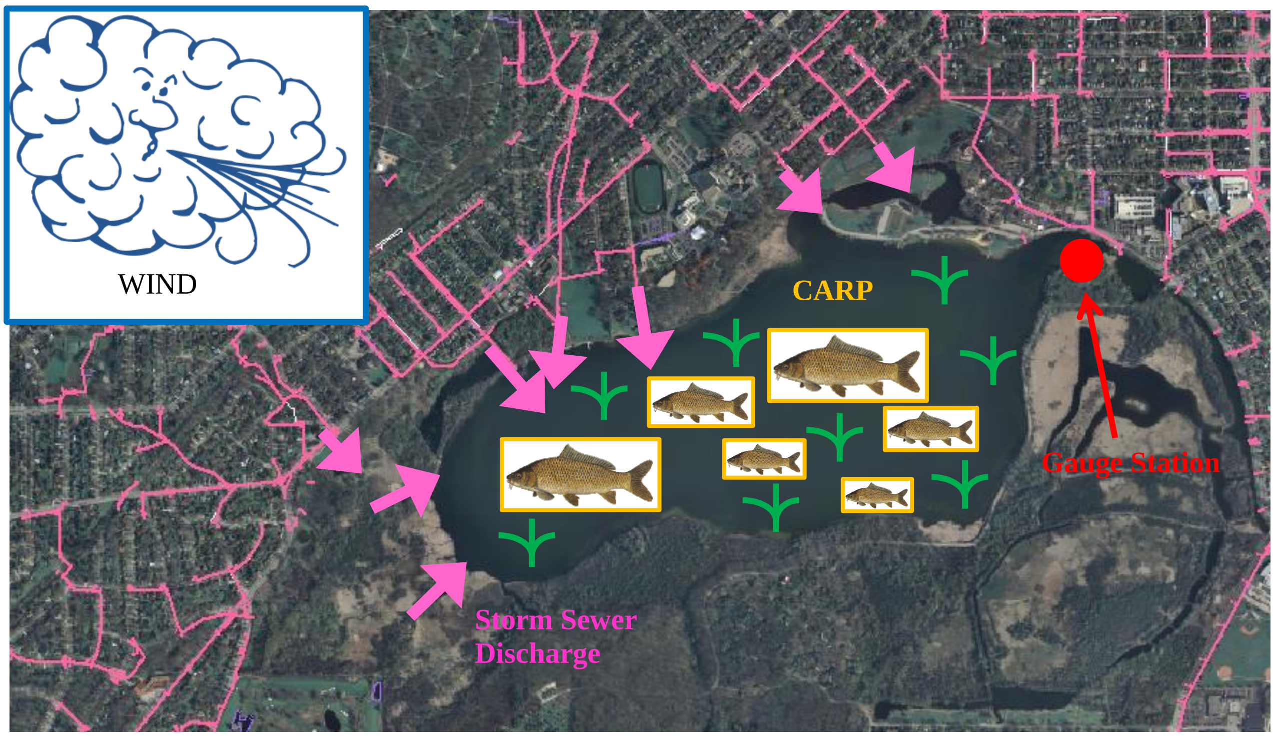

Figure 1: Lake Wingra sediment resuspension can be caused by factors including watershed (storm sewers), carp, and wind effects.

Methodology

Watershed loading

Sediment and phosphorus loads due to storm runoff into the lake are estimated using the SWAT (Soil & Water Assessment Tool) model calibrated to measurements at four main inflow locations. SWAT is a physically based distributed parameter model that simulates the hydrologic response of a watershed including capabilities to determine infiltration, evapotranspiration, stream routing, erosion, and nutrient loading. SWAT has been widely used in both agricultural and urban watersheds. The SWAT model is set up by discretizing the Lake Wingra watershed into 42 individual subwatershed basins (Figure 2a) and applying elevation data using the USGS National Elevation Dataset with 3m resolution (Figure 2b), a digital land use and land cover map using the National Land Cover Database (NLCD) from 2006, soil type data using the Soil Survey Geographic (SSURGO) Database, and climate data retrieved from the Space Science and Engineering Center (SSEC). The model considers the main storm sewer lines and streams using a combined stream system shown in Figure 2c. Streams that flow into the lake are numbered from S1 through S8. In addition, 5 ponds installed in the watershed for detention of urban runoff are included in the model (Figure 2c).

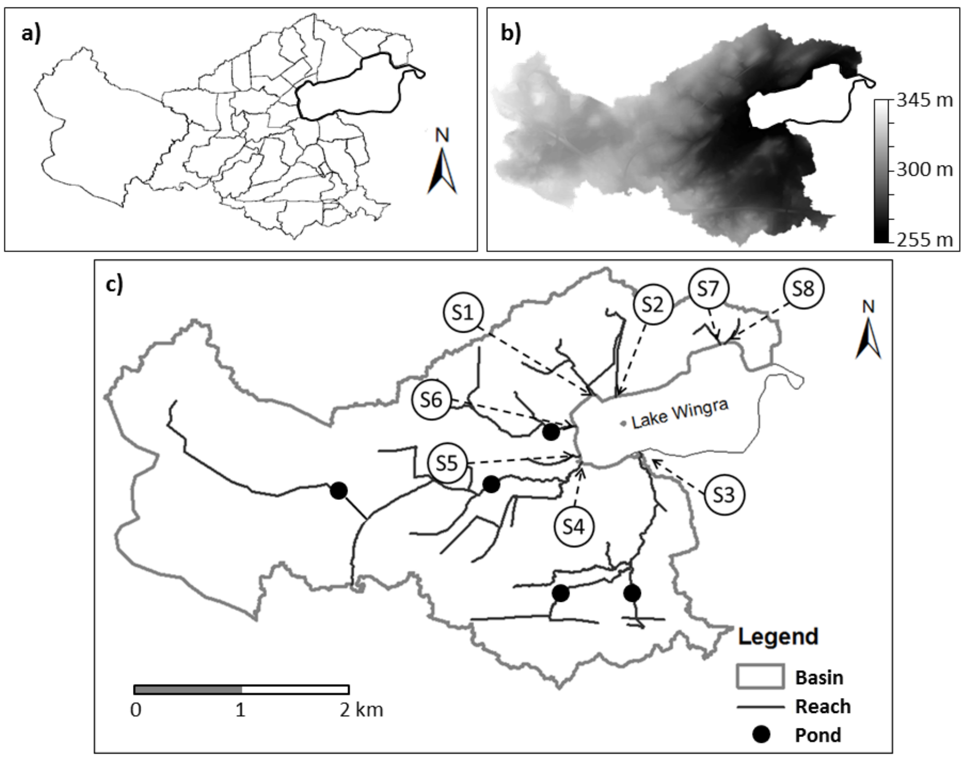

Figure 2: (a) Lake Wingra subwatershed basins; (b) elevation map; (c) watershed reaches including streams and storm sewers as well as ponds

The model was calibrated to field measurements March to June of 2014. Calibration locations include two direct storm sewer inflows labeled S1 and S2 and the two main streams, labeled S3 and S4 (Figure 2c). Together, the drainage areas of S1, S2, S3, and S4 make up 88% of the Lake Wingra watershed, while S4 accounts for the largest flow into the lake. The setup of instruments for the S4 location is shown in Figure 3. A SonTek River Surveyor (Figure 3a) was used to measure the channel cross section and instantaneous flowrate through the channel. Total flowrate measurements across the channel were used to calibrate continuous flow measurements of a SonTek IQ located in the main channel area (Figure 3b). The River Surveyor was found to measure flowrate with a standard deviation of 0.018 m^3/s (n=7). Flowrate data for storm sewers at S1, S2, and upstream of S3 were measured using an ISCO 2150 Area Velocity Flow Module and Sensor.

Model calibration was done by adjusting model parameters including Manning's n in the channels and for overland flow, as well as the fraction of directly connected impervious surface which is important for urban watersheds. Comparisons with measurements yielded goodness of fit values of NSE=0.77 (S1), 0.64 (S2), 0.5 (S3), and 0.51 (S4), while generally NSE>0.36 is considered satisfactory for hydrological models. Sediment and phosphorus concentrations are predicted from measurements at each outlet. Continuous turbidity measurements were taken using a pre-calibrated optical backscatter sensor (OBS, Figure 3c) located 20 cm from the bottom near the main channel section. In addition, an ISCO automatic water sampler (Figure 3d) was used to collect runoff samples throughout storms. The ISCO sampler automatically collected 400 mL samples at pre-set time durations, which were then later analyzed for turbidity using a Laser In-Situ Scattering and Transmissometry (LISST) instrument. The LISST and OBS were both calibrated in the lab using lake sediments to match known sediment concentrations with R^2 values of 0.99 and 0.98 respectively.

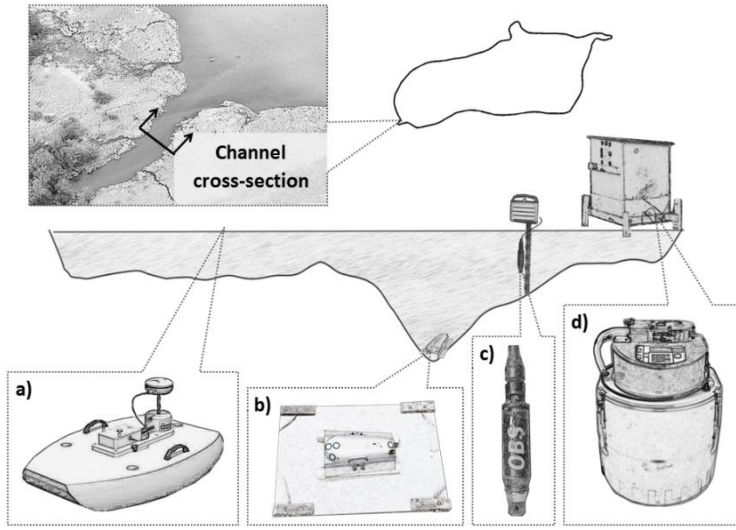

Figure3: Measurement setup used along a cross-section of the SW stream S4; (a) SonTek river surveyor, (b) SonTek IQ flow meter, (c) Optical Backscatter Sensor (OBS), and (d) ISCO automatic water sampler

Physical resuspension

The loading of sediment from wind-induced resuspension was evaluated by applying a wave model (WWMIII) with critical shear stress and erosion rate measurements within the lake. The wave model was enhanced to account for the effects of vegetation on waves because it affects the nearshore bottom shear stress. Bottom shear stress from waves is estimated throughout the lake for varying wind events using the calibrated lake model. Output shear stress values are used to estimate sediment resuspension rates using critical shear stress and erosion rates measured in the lake with a portable sediment flume. The portable sediment flume, Figure 4, is a $2m \times 0.1m \times 0.1m$ Plexiglas flume with an open bottom section to allow controlled in-situ testing of erosion rates at varying amounts of applied shear stress. Each of the sites exhibited minimal sediment resuspension until the critical shear stress was reached.

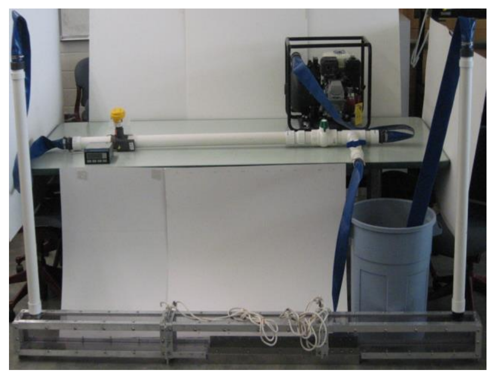

Figure 4: Portable Sediment Flume

Carp resuspension

The impacts of carp on sediment resuspension and phosphorus release were isolated using an enclosure experiment. Two square impermeable 2.3 m^2 enclosures and one large permeable 37.2 m^2 enclosure were installed in the southwest corner of Lake Wingra at a depth of approximately 1.2 meters, Figure 5. Using one of the small enclosures as a reference, varying densities of carp were kept in the other enclosure to isolate and test carp bioturbation impacts on turbidity and phosphorus concentrations. The impermeable enclosures allowed testing of phosphorus concentrations, while the large permeable enclosure enabled turbidity response measurements from lower densities of carp. An in-situ relationship between carp density and concentration of suspended sediment was performed. The relationship was then applied to the entire lake based on the carp population.

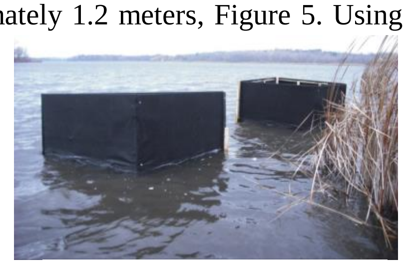

Figure 5: Carp Enclosure

Results

Runoff loading

The average loading of sediment and phosphorus from watershed runoff is estimated by applying the SWAT model to simulate runoff flowrates for the 12 year period from 2002-2013. By estimating continuous flowrates and concentrations, the total loading from each outlet is integrated to yield daily average results. Average daily runoff loads of total flow volume and sediment are shown in Figure 6a and loading of total phosphorus and orthophosphate are shown in Figure 6b. Error bars show the 95% confidence limits for each load. The sediment load mimics the trend as flowrate, but loads from basins with settling ponds yielded a smaller ratio of sediment to runoff volume than storm sewers S1 and S2 without settling ponds. The average total loading from the days with precipitation greater than 1 cm are estimated to be 28,000 kg (95% confidence interval from 15,000 to 41,000 kg) of sediment and 44.1 kg (C.I. from 23 to 65 kg) total phosphorus, and 22.7 kg (C.I. from 14 to 31 kg) is released as orthophosphate. On average throughout the season, storm runoff is estimated to contribute a daily load of 2,540 kg of sediment (C.I. from 1360 to 3720 kg), and 4.0 kg total phosphorus (C.I. from 2.1 to 5.9 kg), where 2.1 kg is orthophosphate (C.I. from 1.3 to 2.8 kg).

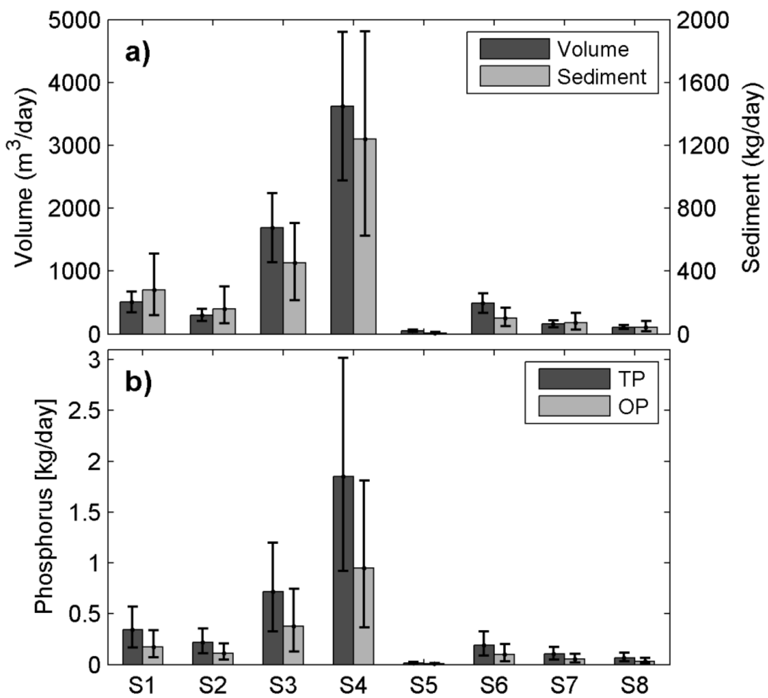

Figure 6: Average daily runoff loading of water volume (a), sediment (a), total phosphorus (b), and orthophosphorus (b); ranges show inter-annual variability from 2002-2013.

Physical resuspension

The sediment resuspension from wind is estimated by relating measured stress-erosion relationships from the lake with modeled bottom shear stress from waves under varying wind conditions. The total resuspension is calculated for ideal steady state wind cases in 8 directions, N, NE, E, SE, S, SW, W, and NW, using wind speeds from 1 to 12 m/s. A two hour wind event duration was selected based on calculations of time to fully develop waves. Total resuspension values for each wind event are shown in Figure 7a. Wind speeds less than 6 m/s show little resuspension, while larger winds significantly increase total resuspended loads. Lake Wingra has a long wind fetch in the east-west directions which leads to strong waves; however, low sediment resuspension occurs due to sheltering from shore vegetation. Figure 7b shows the probability of each wind event based on historic summer wind data for Madison, WI. As shown the occurrence of significant wind-induced resuspension in the lake is rare.

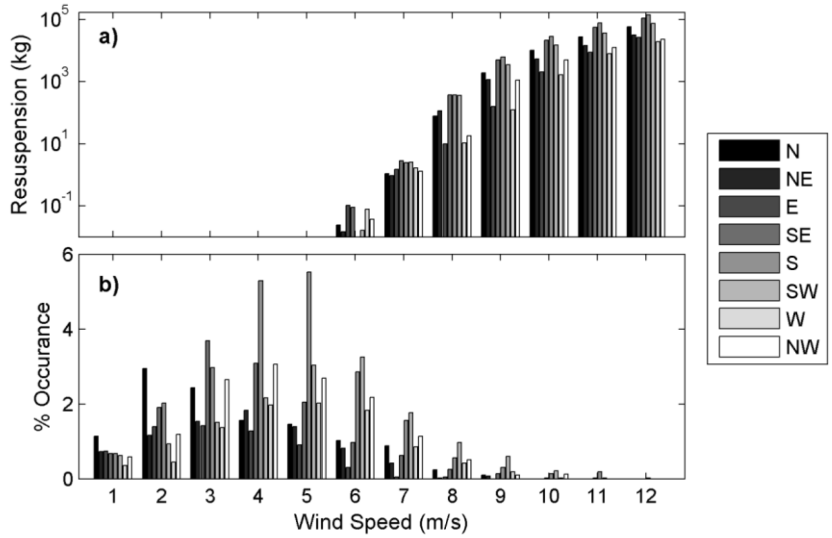

Figure 7: Resuspended sediment for each two hour wind event (a) and wind event probability (b)

Carp resuspension

The effect of carp on sediment and phosphorus in the water column is illustrated by plotting sediment and phosphorus concentrations with respect to varying densities of carp (Figure 8). The y-intercept values are taken from the reference enclosure with no carp. Significant correlations were found between carp density and sediment concentration. A trend for suspended sediment concentration was fit using a second order polynomial with least squares regression. Similarly, total phosphorus and orthophosphate were found to vary linearly with increases in carp density.

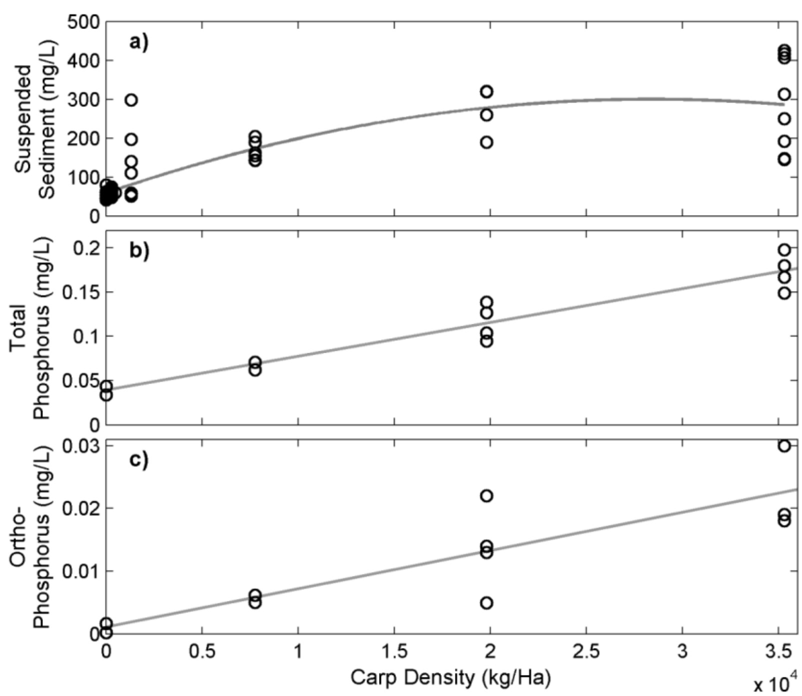

Figure 8: Measured relationships between carp density and (a) turbidity, (b) total phosphorus, and (c) orthophosphate

Relative loading

The total daily loading of sediment and total phosphorus into Lake Wingra is compared among the three primary sources (watershed runoff, wind resuspension, and carp) to evaluate the relative loading from each source in the lake. Three scenarios are considered for comparison including an average (i) 'clear day' when no rain occurs, (ii) 'rain day' when an average rain event occurs, and (iii) an 'average' day based on weather data throughout the summer months from June through September. The loading from each source under each scenario is shown as percentage pie plots in Figure 8. During an average summer clear day, a direct comparison of internal loading shows that carp bioturbation is expected to cause over 93% of sediment into the water column while wind resuspension supplies roughly 7%. Similarly, since the total phosphorus is related to suspended sediment, carp are also predicted to provide the most total phosphorus into the water column. The average rain day scenario shows a comparison of the pulse load of sediment and phosphorus that comes from external loading compared with internal loading. The rain day load was estimated as an average load from all the summer days that rained at least 1 cm. The results show that during a rain event the external loading can provide around 68% of the sediment loaded into the lake that day and 91% of the total phosphorus. On average throughout the summer months, carp are estimated to provide the majority of sediment (78%) while carp and runoff each provide about half (48%) of the total phosphorus loaded into the water column.

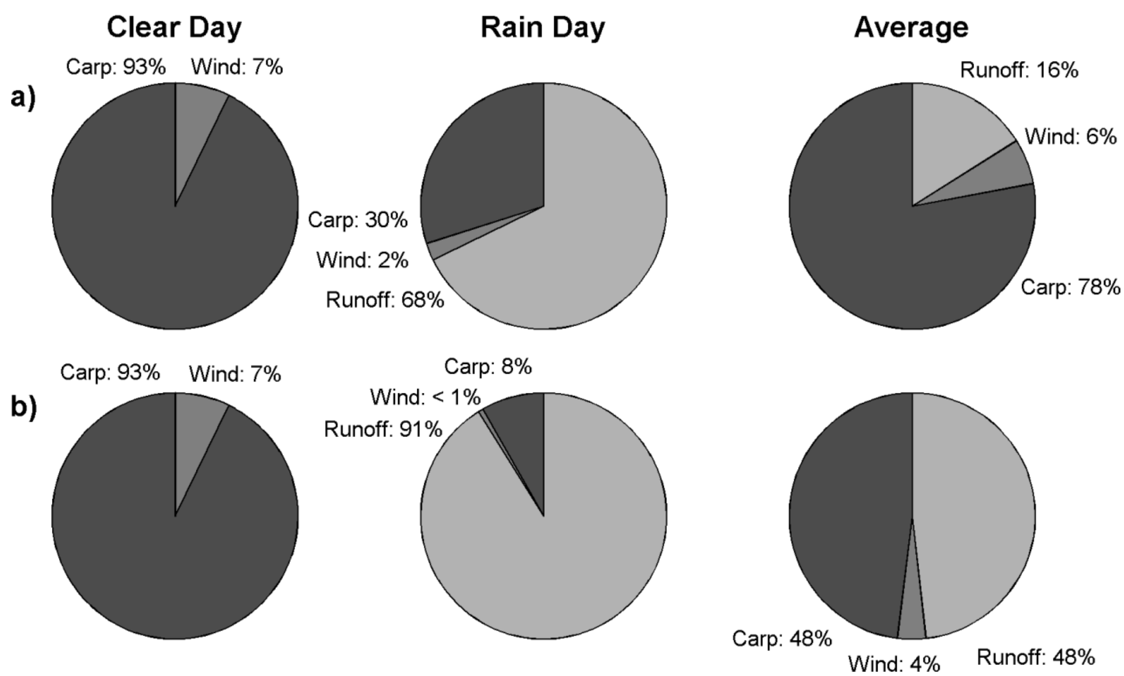

Figure 8: Daily loading percentages of sediment (a) and total phosphorus (b) from runoff, carp, and wind on an average clear day, rain day, and seasonal average day

Lake Wingra Observation Station

A real-time observation station was installed at the outlet of Lake Wingra, just upstream of the dam. The station provides a measurement of water level, outflow discharge, and water temperature. All data is displayed through the Integrated Nowcast/Forecast Operation System (INFOS) to the community (Figure 9). This project has provided the first real-time observation station for Lake Wingra. The data is archived on the INFOS server and is available for future studies or information for Lake Wingra.

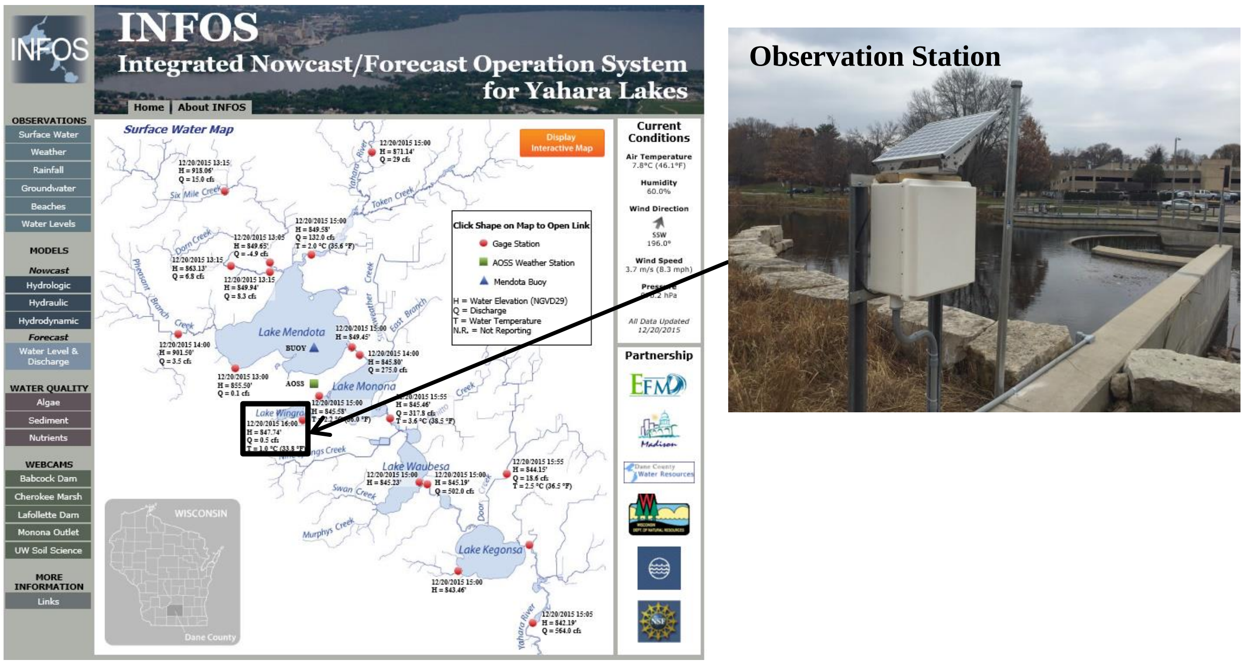

Figure 9: Lake Wingra real-time observation station is displayed through INFOS

Summary

Loading sources (watershed, wind, and carp) for sediment and phosphorus in Lake Wingra were evaluated. Daily loads from the sources are estimated from empirical relationships using direct. Watershed loads were determined by measuring flowrates and sediment/phosphorus concentrations from four main inlets into Lake Wingra. Wind-induced resuspension loads were determined by relating wind events to measured changes in sediment concentration in the lake. Carp bioturbation loads were measured directly by using an enclosure with varying amounts of carp.

The study found that carp resuspension caused the most suspended sediment in the water column, with the watershed runoff delivering the most phosphorus. Comparing clear days when no runoff enters the lake, carp are found to provide significantly more internal loading (93%) of both sediment and phosphorus into the lake than wind resuspension (7%). Wind was observed to have minimal effect on turbidity levels due to the small fetch length that limits wave growth as well as dense nearshore vegetation that protects sediment in shallow areas. During the average rain event, runoff provides the largest percentage of loading into the lake for both sediment (68%) and phosphorus (91%). The higher relative contribution of phosphorus from storm runoff is caused by runoff sediments correlating with much higher concentrations of phosphorus than internally resuspended sediments within the lake. Averaged throughout the season carp are estimated to contribute the majority of sediment (78%) followed by runoff (16%), while carp and runoff provide roughly equal loading of total phosphorus (48%) into the lake. The observed loading budgets are intended to aid with future lake management practices.

A real-time observation station for water levels, discharge, and water temperature was installed for Lake Wingra. The observation data is displayed through the Integrated Nowcast/Forecast Operation System (INFOS). INOFS provides an archive of all data that may also be used to support future studies or aid in lake management strategies.