Quantification of lake water level influences for Wawasee and Syracuse lakes: Lake and watershed water budgets for 2011, 2012, and 2013

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Abstract

In 2012, northern Indiana experienced below average rainfall and above average temperatures. Both of these factors combined to lower water levels on Wawasee and Syracuse lakes. The purpose of this expanded study was to evaluate the causes of lake level changes during normal years (taken as 2011 and 2013) and a drought year (taken as 2012). In 2012, the lake levels of Wawasee and Syracuse dropped about 18 inches below normal, and levels returned to normal by early 2013. Lake residents have expressed continued interest in the causes of changing water levels and how they can help prevent levels from falling far below normal in the future. To answer these questions, we developed water budgets for the lakes themselves as well as the watershed area around the lakes to quantify influences on these levels. Study results showed that going into the drought, total inflow into the lakes decreased by 38% from 2011 to 2012, while total outflow decreased by 28% over the same time**.** Coming out of the drought from 2012 to 2013, total inflow increased by 44% and total outflow increased by only about 6%. Precipitation was the largest inflow in all three years. Precipitation was 47% of the inflows in 2011, 41% in 2012, and 44% in 2013. In regard to outflows, the Syracuse dam outlet flow was the largest in 2011 (60%) and evaporation flow was the largest in 2012 (66%) and 2013 (49%). Residential irrigation outflow directly from the lakes was about 2% of total outflow in the non-drought years and increased to 3% of total outflow in 2012. Industrial and agricultural irrigation in the surrounding watershed by comparison was only 1% of total outflow in non-drought years and 2% in drought year. This study demonstrates that the main causes of the changing lake levels are uncontrollable factors. It also showed that irrigation systems were not as influential as first thought, but still impact the lake, especially during drought years.

Keywords: lake water levels, Kosciusko County, water budgets, Lake Wawasee, Syracuse Lake, drought, irrigation, evapotranspiration, Syracuse dam

Introduction

Of all the water on our planet, only 2.5% is freshwater, and most of this freshwater is frozen in ice or buried as groundwater such that only 1.3 % of the freshwater is surface water (Perlman, 2013). Even smaller, then, is the portion of the total water on our planet that is in freshwater lakes and streams (0.007%). Our lakes are important and rare resources.

Water around the planet is constantly in motion due to weather and circulation patterns. Water also moves more locally through the water cycle, also known as the hydrologic cycle. Water from lakes and streams evaporates into the atmosphere; this water then becomes rain through condensation in clouds and falls back to Earth, causing the cycle to start over once again.

The water cycle affects water all around the world in mostly predictable ways, but it can change from year to year and lead to unpredictable extremes. The drought of 2012 is an example of how the water cycle can change in a given year and how this change affected the U.S. and parts of Canada (Freedman, 2012). During 2012, the United States suffered a heat wave as well as low snowfall and rainfall which caused a drought in the northern and southern United States. Due to the heat and lack of rain, crops and water supplies were greatly affected. Corn and soybean crop yields declined during 2012 due to the drought. The low rainfall caused farmers to use more irrigation to water their plants, such that irrigation during 2012 was the major factor in farm success or failure (Kirk, 2012). The drought affected many areas including much of Indiana. The lack of rain not only had an effect on crops but also on lakes and streams.

Lake Wawasee, a glacially formed lake located in northern Indiana near the town of Syracuse, is the largest natural lake in Indiana. During the winter, the lake is typically frozen over and less used, while in the summer people enjoy using the lake for boating, fishing, and other recreation. Lake levels have been in constant flux historically. Over the 60 years of available historical water level data for Lake Wawasee and Syracuse Lake, levels have fallen lower than those observed in 2012 four other times, and in each case the water levels returned to normal the very next year (Figure 1).

The purpose of the present study was to reevaluate the causes of lake level changes during normal years (taken as 2011 and 2013) and a drought year (taken as 2012). In 2012, the lake levels of Wawasee and Syracuse dropped about 18 inches below normal, and levels returned to normal by early 2013. Lake residents have asked about the causes of changing water levels and how they can help prevent levels from falling far below normal in the future. Because of this, we have revised and expanded the study**.** To answer these questions, we developed water budgets for the lakes themselves as well as the watershed around the lakes to quantify influences on these levels. As part of this study, we included precipitation on land and lake surfaces, evaporation from the lake, evapotranspiration (ET) from the watershed (evaporation from the lake plus water leaving plants in the surrounding land), inflowing streams, outflowing water over the Syracuse dam, irrigation uses directly from the lake as well as from groundwater in the watershed, and groundwater flows into and from the lake.

Methods

Study sites

The areas that we focused on for this study are Lake Wawasee, Syracuse Lake, and the watershed surrounding the two lakes. Lake Wawasee and Syracuse Lake have surface areas of

3,410 and 414 acres with maximum depths of 77 and 34 feet, respectively. The average depth of Lake Wawasee is 22 feet and Syracuse Lake is 13 feet. The lakes are part of a 24,448 acre watershed, which spans two USGS HUC12 drainage areas (040500011702 and 040500011701). The primary inflows to the lakes are Launer, Dillon, and Turkey Creeks as well as the outlet of Papakeechie Lake. For the lakes' water budget, we focused on the entire lake up until the lake edge, including Wawasee and Syracuse lakes together. The watershed area includes the two lakes and their surface drainage area (Figure 2).

Data Sources

- Lake water budget
    - Precipitation – local weather station observations (CoCoRaHS, 2013)
    - Evaporation – local climate station observations (NOAA, 2011, 2012, 2013) and regional climate summaries (Charusombat et al., 2010)
    - Stream Inlets – flow measurements by Center for Lakes & Streams, Grace College and USGS gage (Station ID: 4100500)
    - Dam Outlet – records of Syracuse dam operations, Town of Syracuse and flow measurements by Center for Lakes & Streams, Grace College
    - Irrigation – survey of homeowners around the lake by Center for Lakes & Streams, Grace College
- Watershed water budget
    - Precipitation – local weather station observations (CoCoRaHS, 2013)
    - Dam Outlet – records of Syracuse dam operations, Town of Syracuse and flow measurements by Center for Lakes & Streams, Grace College
    - Evapotranspiration (ET)– watershed modeling efforts in nearby watersheds by Center for Lakes & Streams, Grace College
    - Groundwater – storage based on lake volume and other flows collected by Center for Lakes & Streams, Grace College
    - Irrigation – water usage records of major water withdrawal facilities (IDNR, 2013)

Data Analysis

Lake water budget

Precipitation inflow data was obtained for each day from Community Collaborative Rain, Hail & Snow Network (CoCoRaHS, 2013; Station ID: IN-KS-29, Syracuse 0.9 SW, Milford 0.9N, and North Webster 2.3N) for 2011, 2012, and 2013. For dates that did not have readings in Syracuse, data from Milford and North Webster were used. We then summed this data for each month as well as annual totals.

Evaporation outflow data was collected from NOAA's Climatological Data Publications for the months of April to October (NOAA, 2011, 2012, and 2013). The data used was from the pan evaporation measurements at the Winamac Station. For the remaining months we found more general information about average evaporation for regions of Indiana (Charusombat et al., 2010). Evaporation rates were taken to be zero during times of documented ice cover. In the case that there was partial ice cover in the month, a proportion of the general information was used.

The Center for Lakes & Streams measured stream inlets as lake inflows from May 2012 to December 2013. Strong correlations (r^2: Turkey Creek 0.91, Dillon Creek 0.83, and Launer 0.86) for water flow were found between these stream inlets and the Elkhart River which was measured daily throughout 2011, 2012, and 2013 by USGS (Station ID: 4100500) such that missing data was filled in using these correlations. The Papakeechie Lake outlet was found to flow at about 8% of the total flow for the three stream inlets such that missing data for this inflow was filled in using this proportion. Daily stream flows were summed for each month of 2011, 2012, and 2013.

Daily outflow over the Syracuse dam was estimated through experimental operation of dam gates. Town of Syracuse staff manipulated the settings of the dam for us to determine water flow rates under different dam operation conditions (spillway flows, open gate flows). These estimations were used along with information about the dam operations to determine monthly outflow. Measured data collected by the Center for Lakes & Streams was used for August through December of 2013 due to an expansion of stream monitoring efforts by the center.

Irrigation estimates for homeowners living around the two lakes were based on homeowner survey results and represent outflows from the lakes. Golf courses on the lakes were also surveyed. Surveys were conducted on both lakefront residents and those that lived on the canals and channels around the lake. The percentage of people who have personal irrigation systems around the lake was determined from our surveying efforts. We then multiplied this percentage by the number of people who live around each lake (lakefront and channel front) to estimate how many operating irrigation systems there were around Lake Wawasee and Syracuse Lake. From the survey we also recorded average pump sizes, run times, and months the irrigation systems were run to get the amount of water being taken directly out of the lakes for residential irrigation. Of the three local golf courses, only Maxwelton Golf Club indicated that they pulled water from the lake for irrigation. Golf course irrigation data was available for 2013 and was added to residential irrigation withdrawal data for the lakes for this year.

Groundwater flows for the lakes were calculated by difference for all the inflows and outflows since no groundwater flow data exists for this region. Thus, groundwater flows were sometimes net inflows and sometimes net outflows in any given month.

Watershed water budget

Precipitation was the only inflow of water for the watershed budget and was calculated similarly as for the lake area only using the larger watershed size rather than lake surface area.

Outflow of water from the watershed included water leaving the watershed through the Syracuse dam. The other outflow from the watershed was ET, which was calculated by taking the ET rate times the areas of the non-lake watershed area and adding it together with the amount of evaporation from the lake area.

Groundwater storage in the watershed was determined by difference between precipitation inflow and outflows from the dam and ET as well as consideration of changes in lake volume as lake levels varied over 2011, 2012, and 2013. Irrigation water usage through industrial and agricultural wells was quantified for all major water withdrawal facilities in the watershed and totaled for each year (IDNR, 2013). There were 15 major wells in the watershed in 2011, and this increased to 16 in 2012 and 17 in 2013. The hypothetical addition of 20 new agricultural wells, in addition to the 17 wells already in the watershed, was also quantified for reference. This was accomplished by selecting the largest existing agricultural well each year in the study watershed and projecting the addition of 20 more wells pumping at that same maximum rate.

Results

Lake water budget

Average rainfall in 2011 increased during the winter until April when it reached about 3 million m^3, fell back down during June, July, and August, then rose back up for the rest of the year (Table 1; Figure 3). Precipitation was much lower in April and May for 2012 compared to 2011 and slightly higher in July and August (Figures 3 and 4). There was also a difference during the fall months in each year with higher precipitation totals in 2011 compared to 2012 and almost no rain during November 2012. Overall, annual precipitation in the drought year of 2012 was only 54% of annual precipitation in the average year of 2011 (Table 1). In 2013, the total rainfall was low in the beginning of the year and peaked in April. The year of 2013 had more precipitation in the summer than the previous two years. During the end of 2013, September through December, the total precipitation was relatively constant. Precipitation increased by 53% from 2012 to 2013.

Evaporation was always high during summer months and low to zero during the winter months. In 2011, there was zero evaporation in the months of January and February and then evaporation rates slowly increased during the summer months (Figure 3). Evaporation during the summer months (May – August) was 65%, 62%, and 57% of the annual evaporation respectively for 2011, 2012, and 2013. During the drought year, the lakes never froze completely, leading to increased evaporation during the winter months (Figure 4). The amount of evaporation during the summer months was slightly higher during the drought year (Figures 3 and 4) and annual evaporation was 24% higher for 2012 compared to 2011 (Table 1). In the beginning of 2013 the lake was not frozen. Like the previous two years, evaporation increased over the summer and decreased in the winter. There was not ice cover until halfway through December. The amount of evaporation in 2011 and 2013 was nearly identical.

In 2011 (Figure 3) the rainfall was at a normal level such that the amount of water going into the lake from the streams increased to about 4 million m^3 for May, decreased to about 180,000 m^3 for July, then increased again to a high of about 5 million m^3 for December (Table 1). Stream inflow during the 2012 drought year was much different. Stream inflows were highest during January at 2.4 million m^3 and slowly decreased during the winter months. The streams contributed more water in 2013, however not nearly as much as 2011. In general, the stream inflow in 2013 increased from January to April, where it peaked at 4 million m^3. From there it decreased steadily for the rest of the year (Figure 5). Relative contributions from each of the four stream inflows were consistent for 2011, 2012, and 2013 with Turkey Creek, Dillon Creek, Launer Creek, and the outlet of Papakeechie Lake contributing 77%, 5%, 11%, and 7% of total annual stream inflows, respectively.

The Syracuse dam is the only place where surface water directly leaves the lakes through a stream outlet. During 2011, the amount of water leaving the dam was very high, over 3 million m^3 each month, for the months of January-April (Figure 3). The amount dropped dramatically to just less than 200,000 m^3 leaving the lake for each month from June through September then rose in November and December to almost 4 million m^3 each month. The beginning of 2012 started out roughly the same as 2011 (Figure 4) except for March (1.8 million m^3) and in April the amount leaving the lakes dropped to zero and remained there for the rest of the year (Table 1). In 2013 there was zero outflow for January and February. From there it increased, peaking in May (4.2 million m^3). By August the outflow decreased rapidly and remained low to the end of the year, until December, where it jumped to 2.7 million m^3 leaving the lake.

Residential irrigation systems operated during the summer months of May through August with an average of 166,000 m^3 of water being taken out of the lake in 2011 and 2013 (Table 1). During the 2012 drought, irrigation water usage increased approximately 50% from 2011 (Figures 3 and 4) but remained a small fraction of total outflows. The addition of golf course irrigation data in 2013 increased annual irrigation by 14% compared to 2011.

Groundwater flows fluctuated broadly during the years studied. During January of 2011 about 3.4 million m^3 of water was being put into the lake from groundwater. This value decreased during the next couple months and then reversed with about 1.6 million m^3 of water leaving the lake back into the groundwater in April. The amount of water entering the lake then rose to over 2 million m^3 during the month of July. For the remaining months of 2011 the amount of water fluctuated between entering and leaving the lake (Figure 3). During the drought year in the months of January and February there was less water entering the lake (Figure 4). The volume of water entering the lake remained mostly high for March through November and did not substantially reverse flow as it did in 2011. Groundwater for 2012 remained mainly a monthly inflow to the lake and only became a monthly outflow twice, unlike 2011 (Table 1). Without this overall inflow of water through lake bottom springs, water levels could have dropped an additional 20 inches. The 2013 year began with water leaving the lake. From February to October the water was flowing into the lake in all the months. The year ended with some groundwater flowing out of the lake as it did also in 2011 and 2012.

Annual comparisons for 2011, 2012, and 2013 include total inflows and outflows to the lakes as well as relative contributions of specific inflows and outflows during drier and wetter years (Table 1; Figures 6 and 7). Total inflow into the lakes decreased by 38% from 2011 to 2012 or from about 41 million m^3 to 25 million m^3. Total outflow decreased by 28% over the same time from about 40 million m^3 to 29 million m^3. Coming out of the drought from 2012 to 2013, total inflow increased by 44% (from about 25 million m^3 to 37 million m^3) and total outflow increased by only about 6% (from about 29 million m^3 to 31 million m^3). Precipitation was the largest inflow in all three years. It was 47% of the inflows in 2011, 41% in 2012, and 44% in 2013. For outflows, the Syracuse dam flow was the largest (60%) in 2011. Evaporation flow was the largest (66%) in 2012. In 2013, evaporation was a slightly higher proportion (49%) than the water exiting through the dam (48%). Residential irrigation outflow directly from the lakes was about 2% of total outflow in 2011 and 2013. It only increased to 3% of total outflow in 2012.

Watershed water budget

Patterns in precipitation over 2011, 2012, and 2013 for the watershed water budget were similar to results for the lake water budget (Table 2; Figures 8, 9, and 10). The watershed area and lake area have the same amount of precipitation per unit area, but since the watershed is much larger than the lakes themselves, total precipitation inputs are much larger for the watershed water budget.

Evapotranspiration (ET) was quantified over the whole watershed area and lake surface area. It increased slowly during the summer of 2011 (Figure 8). It reached its peak in July at 13 million m^3 of water leaving the watershed during this month. After July, the ET amount decreased until winter. In 2012, the same trend was observed but there was a slight decrease overall (Figure 9). In July 2012, 12 million m^3 of water left the watershed from ET. Like the previous two years, 2013 followed the same trend. It increased until July, peaked, and dropped. The peak in July 2013 was between the values observed in 2011 and 2012.

The Syracuse dam outlet data for the watershed water budget is identical to the lake water budget because all of the surface water in the area exits from the same location.

Groundwater in the watershed budget area is taken to be aquifer storage and thus not part of inflow or outflow from the watershed. These changes in aquifer storage are included for reference in context of actual inflows and outflows to the watershed. Groundwater was overall recharging the aquifer during the first 5 months of 2011. During the summer months (June-August 2011) aquifer storage decreased. For the rest of 2011 the aquifer storage increased. Groundwater storage decreased overall for 2012, unlike 2011. In the months of February to August, water was leaving the aquifer faster than it was being recharged. In June a maximum of 6.2 million m^3 of water left the aquifer. Aquifer storage decreased in all months except for January, September, October, and December (Figure 9). In 2013, groundwater storage decreased in only March, May, June, and August. The most water recharging the aquifer was in April (9.9 million m^3).

Like groundwater, significant well withdrawals in the watershed are included in this study for comparison but are not part of inflow or outflow from the watershed. Data for major water well withdrawal facilities was available for all three years studied in the report. The total amount of water taken out of the aquifer by these wells was almost 1 million m^3 of water for all of 2011 which is almost 1% of precipitation inputs to the watershed (Table 2). In 2012 there was an increase to a total of 1.4 million m^3. This accounted for 2% the precipitation for the watershed that year. It went down in 2013 to 1.0 million m^3 and accounted for 1% the precipitation. We calculated that if 20 farmers were to install additional major wells in the watershed area, an additional 8 million m^3 of water would be taken out of the aquifer per year on average. When combined with the existing wells, this would represent about 10% of annual precipitation.

Discussion

Lake water budgets

Inflows to Lake Wawasee and Syracuse Lake were higher in 2011 compared to 2012 and 2013. The amount of inflows in 2013 was just over the average of the previous two years. In 2012 the rainfall amount for the year was 10 million m^3 -- about half of the annual precipitation of 2011. Like the total amount of inflows, precipitation in 2013 was an average of the amount that fell in 2011 and 2012. The lack of rainfall in 2012 in the area caused the drought and subsequently the lake levels to fall below normal. With little snow during the winter or rain in the spring the lake was not able to replenish the water lost through evaporation, irrigation, and dam outflows. The lack of rain in 2012 also affected the stream inlets. With low rainfall around the lakes, the streams delivered less than half of the water in 2012 than they did in 2011. In the year following the drought, precipitation and stream inflows increased, but not to the same amount as in 2011. Comparison of normal years of 2011 and 2013 shows that precipitation was slightly lower in 2013, but stream inflows were substantially lower. Groundwater inputs were much higher in 2013 to compensate for lower stream inflows. The reason for this appears to be more infiltration of water into the soil and then groundwater in 2013 and more surface runoff in 2011. Precipitation data supports this as 2013 had ten rain events of greater than one inch with four of them occurring in June-September, while 2011 had seven similar events with none of them occurring during June-September. The likely explanation is that the agriculturally-dominated watershed was strongly vegetated in these summer months, and that vegetation intercepted precipitation and slowed down surface run-off to allow infiltration of water into soil rather than quick run-off over bare dirt or frozen ground at other times of the year. This increased infiltration based on timing of major rain events in 2013 allowed more inflowing water to the lakes to come in the form of groundwater rather than streams.

Outflows from evaporation and irrigation from the lakes increased in the 2012 drought year compared to the more average 2011 year. Thus, the lakes had less water entering and more water leaving which led to extremely low lake water levels in 2012. Evaporation increased in 2012 because of warmer temperatures in the Midwest. Evaporation was almost exactly the same in 2011 and 2013. In the winter of 2012 the lake was not frozen over, which allowed evaporation to occur, then high temperatures during the summer allowed for more evaporation than normal. Residential irrigation systems around the lake continued to remove water from the lake during both years. These systems were predominantly used during the summer months to water lakefront lawns. During a normal year (2011 and 2013), a lower amount (640,000 m^3 and 760,000 m^3) of water is taken directly out of the lake. Under normal year conditions this amount of water leaving the lake does not cause much concern, but irrigation activities during the drought of 2012 may have had a small impact on low lake level conditions. During the summer of 2012, almost 1 million m^3 of water were taken out of the lake from residential irrigation. Lake levels may have been affected by this residential irrigation in 2012, though groundwater inputs to the lake likely compensated for some of these losses. In order to keep their lawns properly watered, survey results showed that lake property owners used more water on their lawns in 2012 than in 2011 due to the lack of rain.

A particularly helpful way to look at the results of the present study is to translate water volumes in flows to approximate lake water level changes. For instance, in the drought year of 2012, groundwater inputs to the lake increased from 2011. Without these groundwater inputs through springs in the lake bottom during 2012, the lake level could have dropped an additional 20 inches for a total drought water level drop of 38 inches by the end of the summer in 2012. Residential and golf course irrigation used a volume of water equal to three inches of lake level during the drought year. Evaporation lost the equivalent of 38-49 inches of the lake’s water level each year.

Watershed water budgets

At the watershed scale, the only input of water to the system was precipitation. Annual watershed precipitation in 2012 was about half (54%) of annual precipitation in 2011. This decrease impacted the lakes directly through less water falling directly on the lake as well as indirectly through decreased stream flow. The precipitation increased by 53% from 2012 to 2013, almost to the amount of rain and snow that fell in 2011.

Outflows from the watershed included Syracuse dam outflows as well as ET from the watershed and lake areas. No water was leaving the area for most of 2012 through the dam. ET in 2011 accounted for 65.5 million m^3 lost, while in 2012 64.2 million m^3 of water left the watershed. Similar to 2011, 2013 ET accounted for 65.1 million m^3. Though these values changed little from 2011 to 2012, the proportion of precipitation lost to ET increased dramatically during the 2012 drought.

Groundwater in aquifer storage varied most dramatically from 2011 to 2012 and 2012 to 2013. In 2011, 33.3 million m^3 of water were being transferred into the aquifer under the surface of the watershed; whereas in 2012, the aquifer lost 6.5 million m^3 of water. Then, in 2013, 21.9 million m^3 entered the aquifer throughout the year. In a normal year, 2011, there was enough precipitation and stream flow in the watershed area to allow water to remain in the area and flow into the aquifer. In a drought year, 2012, less water was coming into the watershed from rainfall, while ET and dam outlet losses continued. 2013 allowed more water to come in and help compensate for the loss during the drought of 2011.

Wells in the watershed area likely had minimal effect on aquifer storage and therefore the lakes as well. Data from 2011 showed 955,000 m^3 of water being taken out of the aquifer and used for irrigation by farmers and industry. Data for 2012 showed that there was 1.4 million m^3 taken out. In 2013 that number decreased slightly to 1.0 million m^3. The hypothetical amount of water potentially leaving the watershed in a normal year if 20 new farmers installed wells and pumped at the maximum well rates observed in the watershed was estimated as a new total of 9 million m^3 of water removed from the aquifer. This potential increase in agriculture irrigation would be relatively small compared to the total watershed budget in a normal year, but could exacerbate low water levels to the same degree that residential irrigation currently does during drought years.

Study Limitations

Several limitations existed for this study mainly due to lack of data sources which are important in interpreting results and conclusion. For this study we explored many data sets that were incomplete such that estimation techniques were needed to fill in missing data. In all cases, the best available scientific methods were used in estimations such that general trends and comparisons are robust while individual flow values have some uncertainty associated with them. We were able to make estimates on the amount of water leaving and entering the system for each year, but the exact amount of water in aquifer storage or groundwater flows are largely unknown. These aquifer storage estimates are further complicated by groundwater flows out of the watershed to the northwest which are thought to exist but are not quantifiable. While general study results may have broad application for other lakes in the region, the heterogeneity of geology, soils, and topographies in northern Indiana glacial lakes make application of these specific water budgets to other lakes in the region uncertain. This study does limit the implications it can have on other watershed areas but can give some insight on how to do a study like this on other lake areas throughout Indiana and other states.

Conclusion and Implications

This study demonstrates that the main causes of the changing lake levels are uncontrollable factors. Lake managers and property owners cannot control the amount of water that enters the lakes through rainfall, groundwater, and the streams, nor do they have control over how much water leaves the lake and enters the atmosphere through evaporation. Groundwater flows through springs on the lake bottom switched between inflows and outflows throughout the three years of the study. Lake managers do, however, have some control over lake levels through dam operations. The Syracuse dam has helped control the lake levels when water is able to go over the spillway, but once the levels are below the spillway there is nothing the dam can do to help at that point. Lake property owners likewise have control over water lost from the lake due to residential irrigation systems. For future drought events, it may be effective to limit irrigation systems during times of lower lake levels. The expansion of agricultural irrigation systems is something to continue to monitor. The current study showed that irrigation systems were not as influential as first thought, but still impact the lake.

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Tables

Table 1: Lake water budget for Wawasee and Syracuse lakes combined for 2011 (normal year), 2012 (drought year), and 2013 (normal year), including inflows and outflows. Irrigation outflow refers to residential and golf course irrigation systems pulling water directly from lake. Net groundwater (GW) flows vary from net inflow to lake (positive value) to net outflow from lake (negative value). All values in m^3.

		Inflows		Outflows			
Year	Month	Precipitation	Streams	Evaporation	Stream	Irrigation	Net GW
2011	Jan	448,115	135,964	0	3,571,572	0	3,381,814
	Feb	1,124,219	483,614	0	3,225,936	0	2,012,425
	Mar	1,002,363	2,518,693	589,625	3,353,578	0	816,469
	Apr	2,967,780	2,916,433	1,179,250	3,122,216	0	-1,582,747
	May	2,598,282	4,225,388	1,831,769	2,101,080	124,616	-2,766,206
	Jun	1,041,671	1,776,653	2,602,213	186,450	166,154	136,493
	Jul	1,320,761	177,400	3,180,045	192,665	166,154	2,040,703
	Aug	1,065,256	110,941	2,444,979	192,665	207,693	1,669,140
	Sep	2,468,564	90,415	1,591,988	186,450	0	-780,541
	Oct	1,808,184	494,694	1,092,772	575,591	0	548,450
	Nov	2,389,948	890,279	652,519	3,997,065	0	-996,572
	Dec	1,022,017	5,411,347	235,850	3,571,572	0	-1,837,298
2012	Jan	876,576	2,388,881	235,850	3,571,572	0	936,286
	Feb	628,934	1,518,310	235,850	3,341,148	0	1,429,754
	Mar	691,827	1,384,472	1,179,250	1,843,392	0	946,344
	Apr	467,769	619,987	1,957,556	0	0	475,478
	May	923,746	374,634	2,995,296	0	186,923	306,553
	Jun	577,833	100,171	3,262,593	0	249,231	862,213
	Jul	1,780,668	58,245	3,239,008	0	249,231	-716,603
	Aug	1,293,245	79,411	2,389,948	0	311,539	540,187
	Sep	825,475	60,341	1,658,812	0	0	1,955,961
	Oct	1,371,861	62,153	1,037,740	0	0	786,691
	Nov	172,957	66,066	707,550	0	0	862,850
	Dec	794,029	92,774	235,850	0	0	-256,631
2013	Jan	1,470,132	298,506	235,850	0	0	-349,823
	Feb	652,519	372,169	235,850	0	0	394,127
	Mar	518,870	758,388	1,179,250	160,561	0	456,875
	Apr	2,786,962	4,138,423	1,179,250	2,886,169	2,592	1,085,842
	May	1,151,735	1,425,634	2,016,518	4,226,637	134,390	3,011,534
	Jun	1,733,498	709,441	2,264,161	3,928,697	185,329	4,329,569
	Jul	2,303,469	378,801	2,275,953	857,479	184,267	635,430
	Aug	1,253,936	261,285	2,079,412	80,352	224,869	869,411
	Sep	1,238,213	71,122	1,784,599	3,240	15,271	493,776
	Oct	774,374	73,174	966,985	241	8,932	128,609
	Nov	1,092,772	132,661	707,550	5,184	0	-512,699
	Dec	959,124	379,737	117,925	2,678,400	0	1,063,143
2011	Total	19,257,160	19,231,822	15,401,011	24,276,840	664,617	2,642,129
2012	Total	10,404,920	6,805,445	19,135,304	8,756,112	996,925	8,129,083
2013	Total	15,935,605	8,999,341	15,043,305	14,826,960	755,651	11,605,793

Table 2: Watershed water budget for Wawasee and Syracuse lakes for 2011 (normal year), 2012 (drought year), and 2013 (normal year), including inflow and outflows. Evapotranspiration (ET) includes ET over land as well as evaporation over lake surfaces. Groundwater (GW) storage varied from net accumulation (positive value) to net loss (negative value) included for reference. Irrigation data included refers to current 17 major agricultural and industrial wells and hypothetical expansion of 20 new agricultural wells pumping at the maximum well rates observed in the watershed for reference. All values in m^3.

		Inflow	Outflows		GW	Irrigation	
Year	Month	Precipitation	ET	Stream	Storage	Current	Expansion
2011	Jan	2,864,835	551,284	3,571,572	-1,258,021	6,269	6,269
	Feb	7,187,218	763,317	3,225,936	3,197,966	6,288	6,288
	Mar	6,408,184	3,494,554	3,353,578	-439,948	5,558	5,558
	Apr	18,973,251	5,038,409	3,122,216	10,812,626	6,671	6,671
	May	16,611,019	7,811,346	2,101,080	6,698,593	8,010	8,010
	Jun	6,659,486	9,854,094	186,450	-3,381,059	66,572	1,113,049
	Jul	8,443,725	13,103,618	192,665	-4,852,558	400,083	4,062,752
	Aug	6,810,266	11,011,439	192,665	-4,393,838	376,174	3,908,033
	Sep	15,781,724	6,596,181	186,450	8,999,093	57,776	973,443
	Oct	11,559,862	3,573,708	575,591	7,410,563	8,642	8,642
	Nov	15,279,121	2,433,684	3,997,065	8,848,372	6,587	6,587
	Dec	6,533,835	1,274,843	3,571,572	1,687,420	7,132	7,132
2012	Jan	5,604,020	1,402,062	3,571,572	630,386	4,528	4,528
	Feb	4,020,821	1,868,533	3,341,148	-1,188,860	4,449	4,449
	Mar	4,422,904	3,787,418	1,843,392	-1,207,907	5,085	5,085
	Apr	2,990,486	6,474,127	0	-3,483,641	7,712	7,712
	May	5,905,581	8,826,617	0	-2,921,036	116,403	116,403
	Jun	3,694,130	9,899,676	0	-6,205,546	474,873	3,343,903
	Jul	11,383,951	11,784,379	0	-400,428	450,083	3,379,673
	Aug	8,267,814	8,899,686	0	-631,871	231,522	2,434,392
	Sep	5,277,328	5,115,179	0	162,149	71,693	881,683
	Oct	8,770,417	2,924,978	0	5,845,439	22,085	22,085
	Nov	1,105,726	2,107,066	0	-1,001,340	6,379	6,379
	Dec	5,076,287	1,126,420	0	3,949,867	5,815	5,815

		Inflow	Outflows		GW	Irrigation	
Year	Month	Precipitation	ET	Stream	Storage	Current	Expansion
2013	Jan	9,398,670	782,241	0	8,616,430	7,250	7,250
	Feb	4,171,602	1,000,282	0	3,171,320	6,133	6,133
	Mar	3,317,178	4,081,626	160,561	-925,009	6,989	6,989
	Apr	17,817,265	5,045,686	2,886,169	9,885,409	14,188	14,188
	May	7,363,129	8,002,504	4,226,637	-4,866,011	22,443	22,443
	Jun	11,082,389	9,522,508	3,928,697	-2,368,815	126,771	1,300,121
	Jul	14,726,259	12,189,227	857,479	1,679,552	274,762	1,448,112
	Aug	8,016,513	10,646,816	80,352	-2,710,655	363,906	1,930,896
	Sep	7,915,992	6,783,099	3,240	1,129,653	168,475	1,992,845
	Oct	4,950,636	3,439,931	241	1,510,464	24,409	24,409
	Nov	6,986,177	2,492,083	5,184	4,488,911	10,728	10,728
	Dec	6,131,753	1,158,860	2,678,400	2,294,493	5,917	5,917
2011	Total	123,112,527	65,506,479	24,276,840	33,329,208	955,763	10,112,435
2012	Total	66,519,465	64,216,141	8,756,112	-6,452,788	1,400,627	10,212,107
2013	Total	101,877,563	65,144,862	14,826,960	21,905,741	1,031,971	6,770,031

Figures

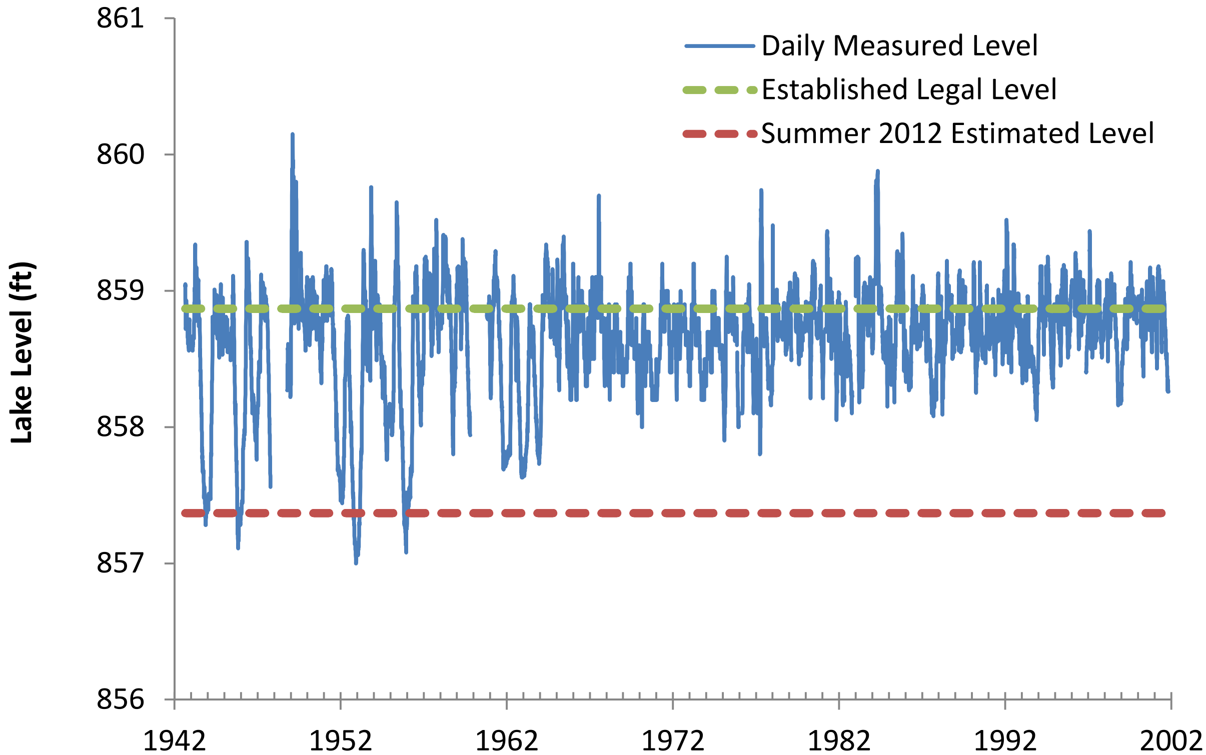

Figure 1: Daily water levels (measured in feet above sea level) for Wawasee and Syracuse lakes over period of record from 1943 to 2002. Reference lines of court-established legal level and low water mark during summer of 2012 included. Data was provided by USGS.

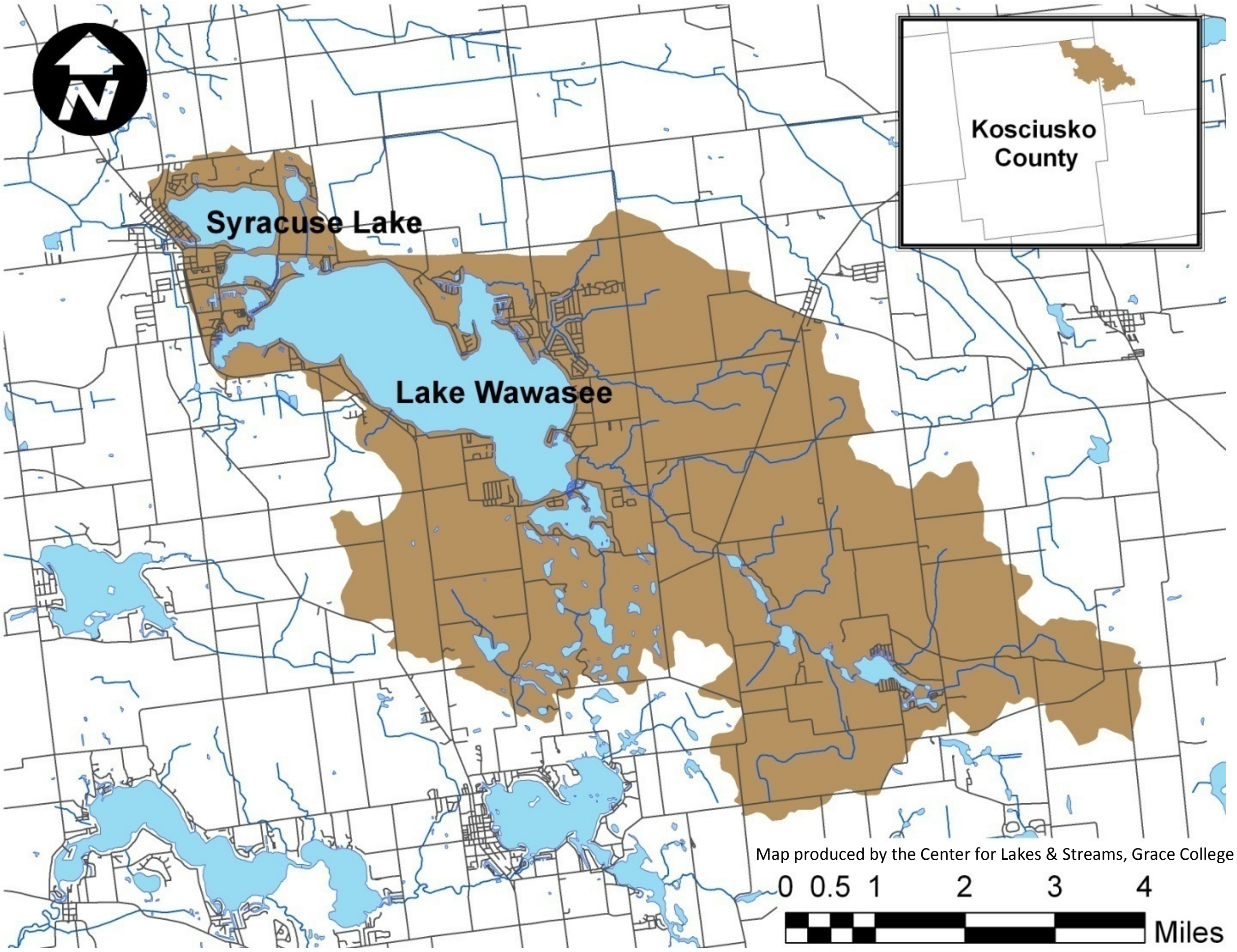

Figure 2: Watershed area for Wawasee and Syracuse. Map inset shows location of watershed in relationship to Kosciusko County boundary.

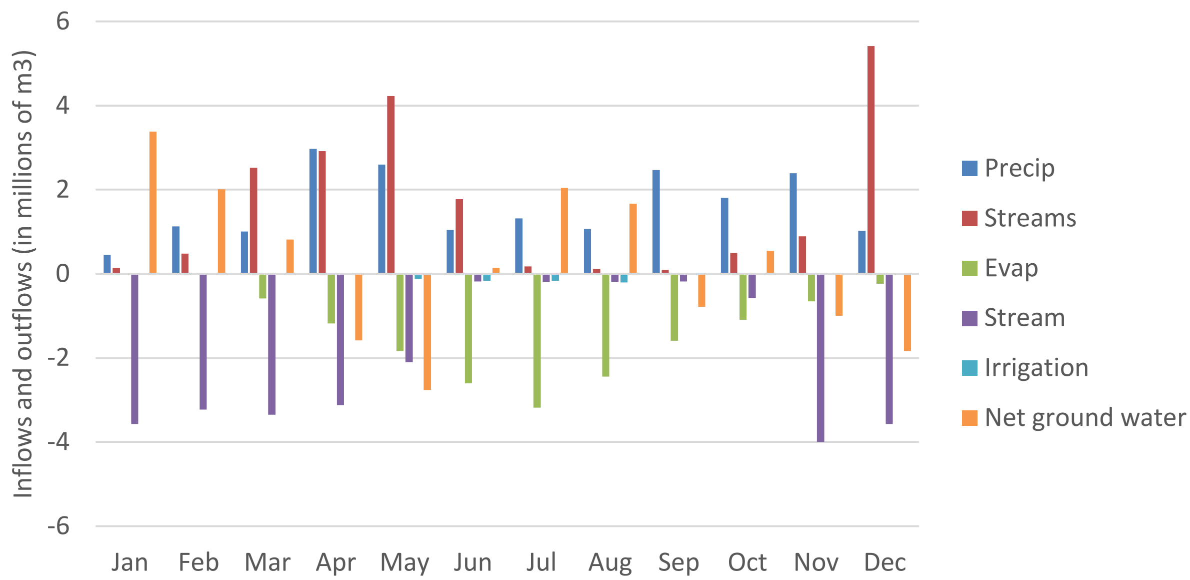

Figure 3: Lake water budget for Wawasee and Syracuse lakes combined for 2011 (normal year), including inflows and outflows. Irrigation outflow refers to residential irrigation systems pulling water directly from lake. Net groundwater (GW) flows vary from net inflow to lake (positive value) to net outflow from lake (negative value). All values in millions of m^3.

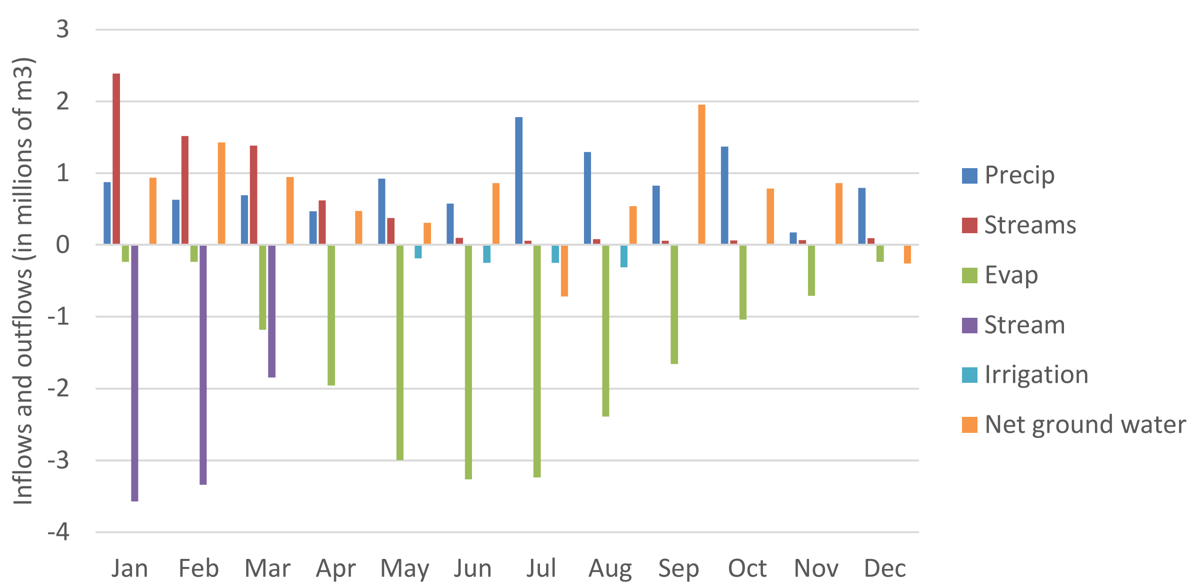

Figure 4: Lake water budget for Wawasee and Syracuse lakes combined for 2012 (drought year), including inflows and outflows. Irrigation outflow refers to residential irrigation systems pulling water directly from lake. Net groundwater (GW) flows vary from net inflow to lake (positive value) to net outflow from lake (negative value). All values in millions of m^3.

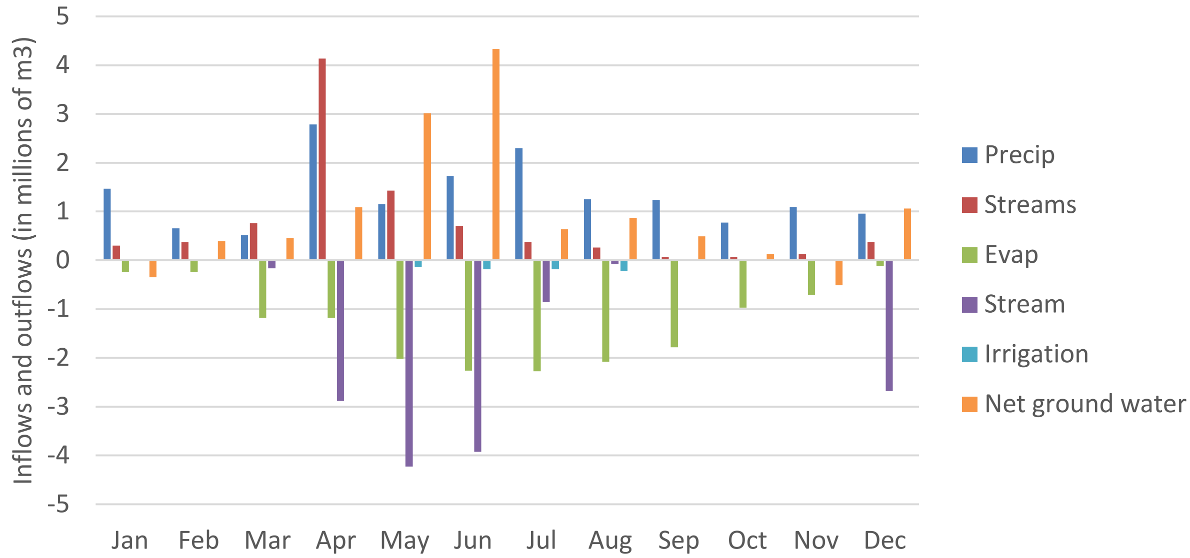

Figure 5: Lake water budget for Wawasee and Syracuse lakes combined for 2013 (average year), including inflows and outflows. Irrigation outflow refers to residential and golf course irrigation systems pulling water directly from lake. Net groundwater (GW) flows vary from net inflow to lake (positive value) to net outflow from lake (negative value). All values in millions of m^3.

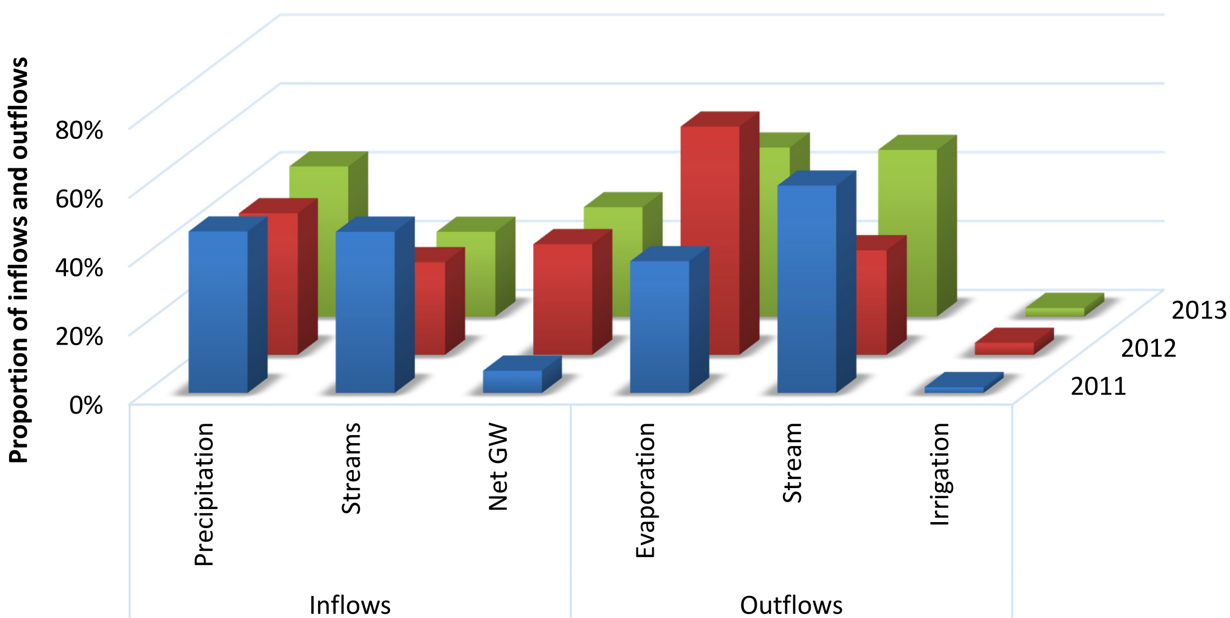

Figure 6: Percentages of inflows and outflows for annual lake water budget for Wawasee and Syracuse lakes combined for 2011 (normal year), 2012 (drought year), and 2013 (normal year). Irrigation outflow refers to residential and golf course irrigation systems pulling water directly from lake. Groundwater was a net inflow over the entirety of all years.

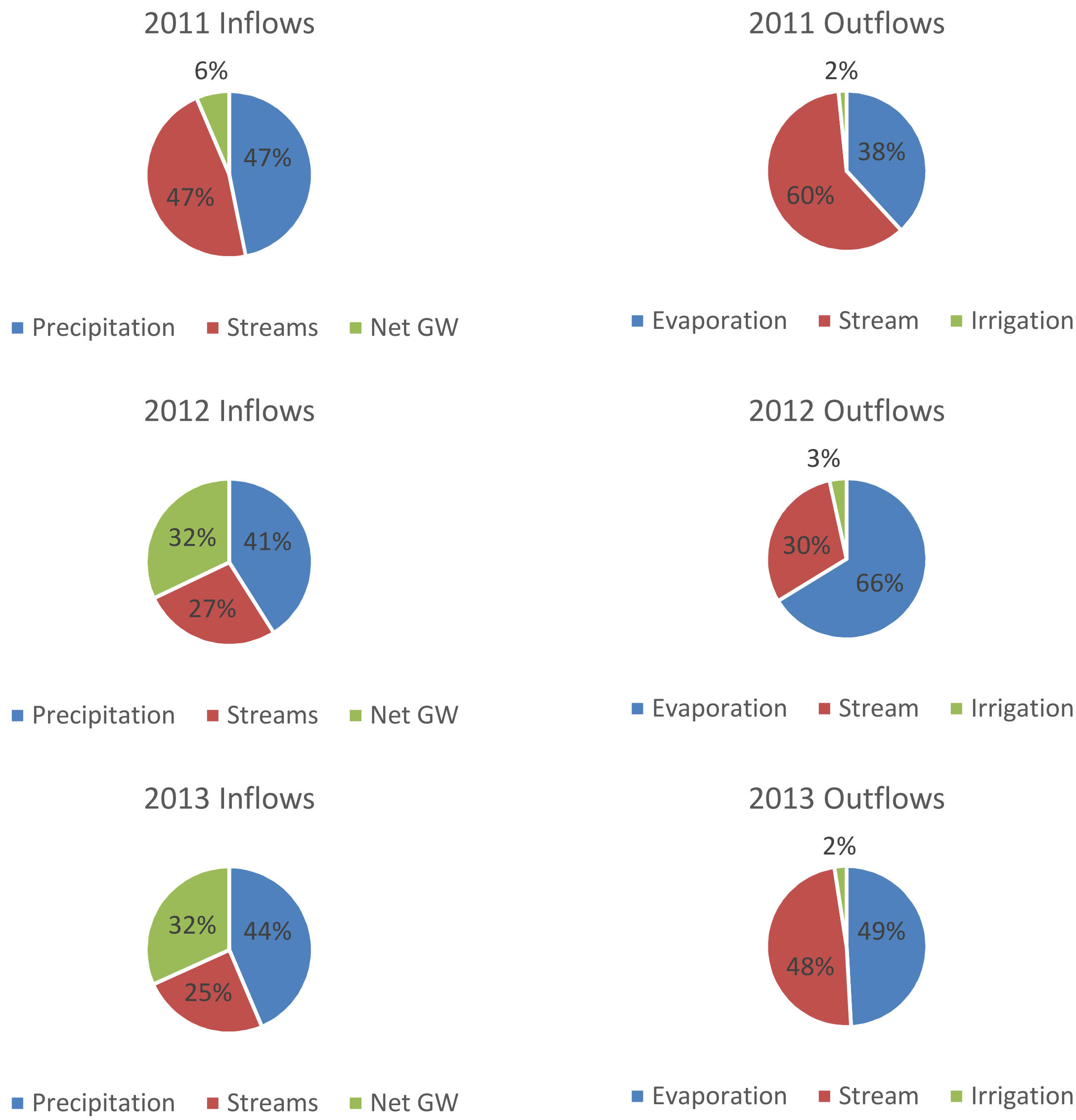

Figure 7: Percentages of inflows and outflows for annual lake water budget for Wawasee and Syracuse lakes combined for 2011 (normal year), 2012 (drought year), and 2013 (normal year). Irrigation outflow refers to residential and golf course irrigation systems pulling water directly from lake. Groundwater (GW) was a net inflow over the entirety of all years studied.

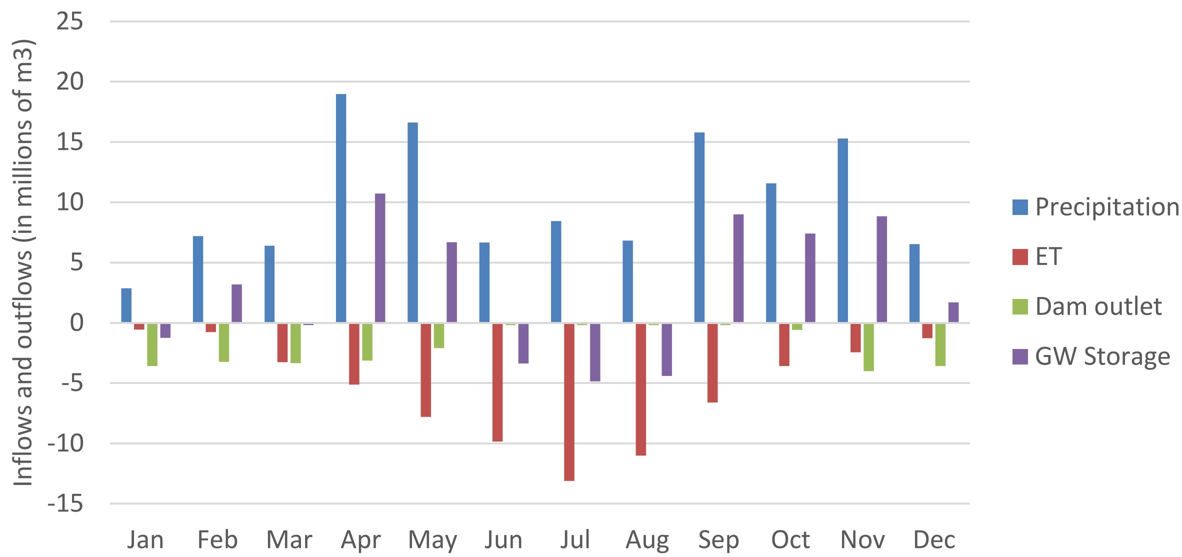

Figure 8: Watershed water budget for Wawasee and Syracuse lakes for 2011 (normal year), including inflows and outflows. Evapotranspiration (ET) includes ET over land as well as evaporation over lake surfaces. Groundwater (GW) storage varied from net accumulation (positive value) to net loss (negative value) included for reference. All values in millions of m^3.

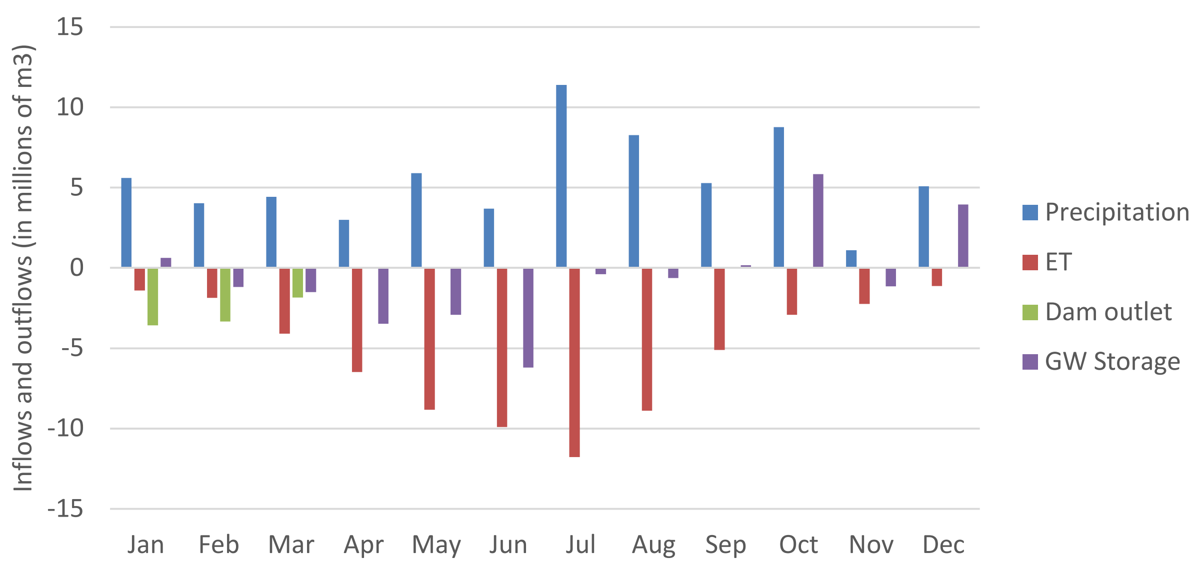

Figure 9: Watershed water budget for Wawasee and Syracuse lakes for 2012 (drought year), including inflows and outflows. Evapotranspiration (ET) includes ET over land as well as evaporation over lake surfaces. Groundwater (GW) storage varied from net accumulation (positive value) to net loss (negative value) included for reference. All values in millions of m^3.

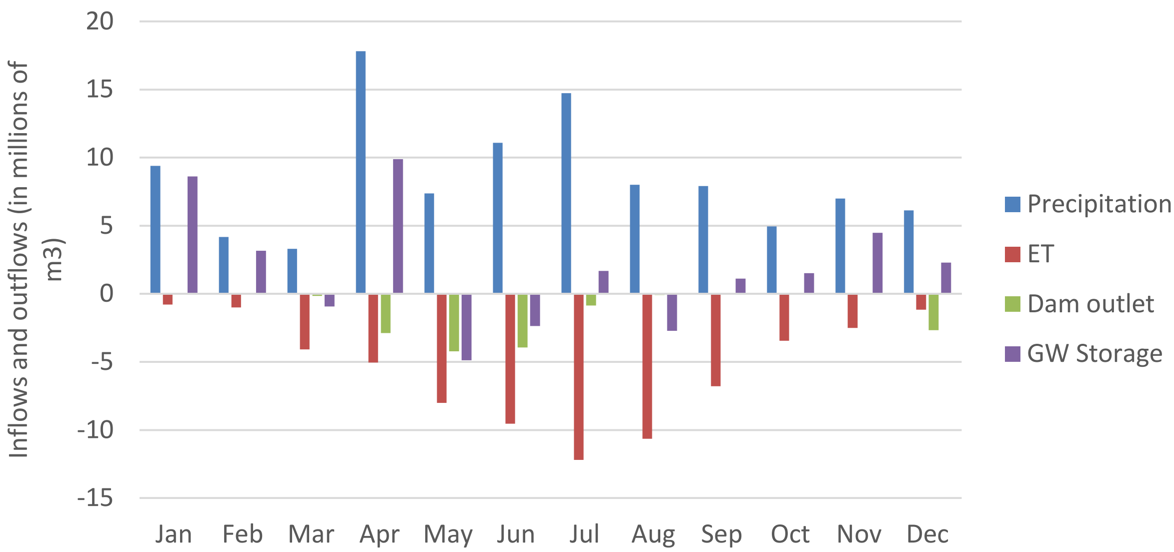

Figure 10: Watershed water budget for Wawasee and Syracuse lakes for 2013 (normal year), including inflows and outflows. Evapotranspiration (ET) includes ET over land as well as evaporation over lake surfaces. Groundwater (GW) storage varied from net accumulation (positive value) to net loss (negative value) included for reference. All values in millions of m^3.