Nutrient reduction capability of drainage water recycling storage reservoirs

by

Tyler Meyer

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Program of Study Committee:
Matthew Helmers, Major Professor
Chris Hay
Tom Isenhart

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NOMENCLATURE

DWR	Drainage Water Recycling
NO_3-N	Nitrate Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TRP	Total Reactive Phosphorus
FWC	Flow Weighted Concentration
ET	Evapotranspiration

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ABSTRACT

The midwestern corn belt is characterized by heavy cropping and substantial subsurface drainage systems. These drainage systems are a known source of both phosphorus and nitrogen from the region. Many conservation practices have been developed and implemented to help lessen the region's impacts on downstream water quality. Drainage Water Recycling (DWR) is a relatively new conservation practice designed to help capture nutrient-rich subsurface drainage and store it for later use in the growing season. DWR consists of an edge-of-field capture basin for subsurface drainage or other surface waters and a system to reapply drainage water as supplemental irrigation, such as center pivot or subsurface irrigation. Through capture and storage, these nutrients are retained in the system rather than causing downstream impacts such as algal blooms, most notably in the Gulf of Mexico. This study monitored DWR reservoirs for inflows, outflow, and nutrient concentrations throughout the 2022 and 2023 growing seasons at three locations in Central Iowa. Results exhibit a capability for reduction in nitrate-nitrogen and total nitrogen concentrations within the reservoirs with overall reduction rates for nitrogen loads of 63% to 99%. Phosphorus, however, varied greatly among locations, with a net export of phosphorus at one study site while the other two sites exhibited reduction rates of 66% to 96%.

CHAPTER 1. GENERAL INTRODUCTION

Iowa and the greater Corn Belt region of the US Midwest are dominated by agricultural lands, a primary source of nutrient pollution within the Mississippi River Basin (Spangler et al., 2020). The majority of this area, particularly in Iowa, Illinois, Indiana, and Ohio, has extensive subsurface drainage infrastructure (Fausey et al., 1995). Subsurface drainage is a significant non-point source of nitrogen, particularly nitrate-nitrogen, loads to surface waters (Baker et al., 1975; Waring et al., 2020).

Nitrogen and phosphorus nutrient pollution can lead to harmful algal blooms, also known as eutrophication (Watson et al., 2016). When this oversaturation of algae dies, the decomposition process consumes oxygen, removing it from the water column, leading to a condition known as hypoxia(Rabalais et al., 2002). Hypoxia is defined as a dissolved oxygen concentration of less than 2 mg/L. Hypoxia can be caused in any water body, but one of the largest is in the Gulf of Mexico (Rabalais et al., 2001), primarily during the spring and summer months, which coincides with peak subsurface drainage volumes in the Corn Belt (Goeken et al., 2015). The river delivers large quantities of nitrogen and phosphorus, fueling algal growth and eventually hypoxia, which has numerous ill effects on the local ecology. Many fisheries have been negatively impacted as species migrate due to the anoxic conditions and is especially harmful to shellfish species and other bottom feeders that cannot migrate (Craig & Crowder, 2005; Craig et al., 2001).

In order to address the growing issue of hypoxia and nutrient pollution, the Gulf of Mexico Watershed Nutrient Task Force was created and many Midwest states have made actions plans and established goals to reduce nutrient loads (US EPA, 2022). These action plans address both point source or industrial nutrient pollution as well as non-point source pollution which comes from the agricultural areas of the Midwest. The primary way to attain these nutrient reduction goals for non-point source nutrient sources is through voluntary implementation of in-field and edge-of-field conservation practices by farmers and landowners. Many of these conservation practices are incentivized through grants and cost-share programs through various public programs. Drainage water recycling (DWR), however, is a relatively unknown conservation practice with increasing interest that could provide its own economic incentives in addition to nutrient loss reduction. DWR is an edge-of-field practice incorporating a capture basin for subsurface drainage water and a system to pump water back onto the field for supplemental irrigation (Figure *1*). Through incorporating supplemental irrigation DWR can also be a management tool for growers to boost yields, especially in drought conditions. As the climate of many Midwest states shifts toward wetter springs with more intense rainfall events and drier summers(USGCRP, 2018) where rainfall may not fully meet crop demand, supplemental irrigation could prove a useful tool in maintaining and increasing yields throughout the region as well as potentially providing additional economic incentive beyond cost share or grants. Much of the Midwest region is already artificially drained (Fausey et al., 1995) to aid in root development by lowering the water table in wet spring months, making implementation of DWR reservoirs a potentially viable addition to these drainage systems by routing drainage into storage reservoirs rather than discharging to rivers and streams.

DWR systems can be designed to fit a variety of locations based on landscape and water resources and can use different irrigation systems, such as subirrigation systems or a centerpivot irrigation system. Excess rainfall is captured and stored on the landscape during wet spring months until needed for supplemental irrigation later in the year when rainfall no longer meets crop water demand, typically in the late summer months of July and August. Through the use of supplemental irrigation, there is a potential for yield benefits as well as water quality benefits. The storage period until irrigation is needed allows a reduction in nutrient concentrations through denitrification(Crumpton et al., 2020) and allowing for sediments and phosphorus to settle out (Schmadel et al., 2019).

While DWR is relatively unstudied as a practice for its potential yield benefits (Willison et al., 2021) and nutrient reduction capabilities (Reinhart et al., 2019), comparisons can be made to agricultural wetlands for nutrient reduction. Nutrient removal wetlands receive nutrient-rich water from agricultural drainage, either directly or by intercepting surface water within watersheds dominated by agricultural land use. Through storage and retention within wetlands, before continuing downstream natural processes can remove nutrients. During the retention period, sediments and phosphorus settle out, and denitrification occurs (Crumpton et al., 2020; Neely & Baker, 1989). A driving factor for nutrient reduction within wetlands is the residence time of water passing through the system. The longer the residence time, the more nutrient removal can occur (Ghosh & Gopal, 2010). Given residence time is such a key factor, wet springs with significant rainfall events can cause too much flow for the system to handle, leading to short residence times with lower nutrient reduction percentages. However, during summer months, when total flow is lower, these systems can reduce nitrate-nitrogen concentrations to near zero. Nutrient removal wetlands have been shown to reduce nitrate-nitrogen concentrations from inflow to outflow by 9% to 92% (Crumpton et al., 2020; Lemke et al., 2022).

Phosphorus capture and reduction from wetlands is less studied in comparison to nitrogen. Still, results have shown a capability for capturing and removing total phosphorus (TP) and total reactive phosphorus (TRP), also called orthophosphates, from surface waters. A 12-year study of agricultural wetlands in Illinois showed a reduction of anywhere from 32% to 95% for TRP loads(Lemke et al., 2022).

While DWR reservoirs can be functionally similar in the storage and removal process to wetlands, they are still different systems with different functions. Wetlands are meant to slow down water movement for a limited time, whereas a DWR reservoir is intended to capture and hold until used for irrigation. Due to this difference DWR reservoir will typically have a much longer retention time thus potentially having larger percent reductions but having lower total load reductions due to receiving less flow. Since subsurface drainage nutrient loads are typically highest in spring, spring filling with summer withdrawal would lead to the most significant reductions in nutrient load for DWR reservoirs. Nutrients are pumped out in irrigation water, but the fate of these nutrients is unknown. Nutrients reapplied to the field from irrigation are available for plant and microbial uptake and further reduction within the soil profile, but some may persist for eventual leaching into ground water(Colbourn & Dowdell, 1984; Sebilo et al., 2013). In systems where drainage from the irrigated area is routed into the reservoir much of the subsurface leaching will ideally enter the subsurface drainage and then reenter the reservoir. However, this will depend on the system.

Nutrient removal wetlands can be an analog to DWR reservoirs, but particularly due to depth differences, these systems can behave differently. Due to this, DWR reservoirs would likely be more similar to farm ponds or small lakes because these reservoirs are often ten or more feet deep, whereas wetlands will be much shallower. Farm ponds are similarly under studied, but one such study found a nitrate-nitrogen reduction of 64% and a total nitrogen reduction of 36% (Brunet et al., 2021). The TN reduction was much lower due to changes in nitrogen compounds, particularly an increase in particulate nitrogen, such as algal biomass and dissolved nitrogen. Like wetlands, the pond from this study was not as effective at phosphorus removal. They found only an 8% removal of TP, but it may have been up to 20% due to some unmonitored inputs (Brunet et al., 2021). While this is a pond due to depth, it still had overflow from the pond, so the residence time may not be as long as with DWR reservoirs that do not have any overflow, but it may still serve as a better analog than wetlands. However, a different study on pond nutrient reduction from Nanjing China, was done on a much smaller scale 800 m^2 pond that captured surface drainage from a tea field (W. Zhang et al., 2022). The purpose of that study was to examine N_2 Loss rates from the pond, but in doing so, they determined the nutrient losses to be roughly 45kg per year based on gaseous losses of nitrogen. The estimated nitrogen influx for this pond was 130 kg, leading to a percent reduction of 35%. Given DWR reservoirs will receive tile drainage in similarly agricultural-dominated areas, they would be expected to receive similar quantities or more nitrogen, and without any outflow, this may be the best comparison to a DWR reservoir. Still, a pond of that size would be too small for DWR storage. Thus, nutrient reduction values would likely change as the size and depth of the reservoir change. Additionally, irrigation withdrawal would also impact these reservoirs' nutrient cycles.

There has been some work on the nutrient reduction potential of wetlands in conjunction with a storage reservoir at the Ohio Wetland Reservoir Subirrigation System (WRSIS) (Barry et al., 2014). In this study, known quantities of nitrogen were fed into a wetland linked to the storage reservoir to track the potential for nitrogen loss from the system. They found an average reduction in nitrate, ammonium, and total nitrogen of 27.7%, 79.2%, and 28.5%, respectively, among the four test periods within the study. While this shows the potential to pair DWR with another nutrient reduction practice to improve the water quality of the storage reservoir, there may be additional nutrient reduction benefits from the time within the storage reservoir itself.

Some DWR reservoirs can also aid the overall drainage infrastructure, especially in places like the Des Moines Lobe, where additional subsurface infrastructure is needed to remove water from crop fields. These areas use larger subsurface drainage pipes called drainage mains because surface streams and drainage ditches might not be available for farmers to outlet drainage. Many farmers will route their drainage into these mains, sometimes overloading the infrastructure leading to inadequate draining of fields or the requirement for new drainage mains to be built. DWR can capture drainage water that would have otherwise needed to be routed into a drainage main, reducing the required capacity for these mains. Furthermore, in areas without sufficient surface water structures, such as streams or drainage ditches, to route drainage tiles for discharge, DWR reservoirs can serve as a place to discharge subsurface drainage.

There are still many questions related to the benefits and functionality for DWR systems. As outlined by Hay et al. (2021) there are five areas of study associated with DWR: hydrology of DWR systems, crop yield benefits, water quality benefits, complementary benefits, and implementation and management considerations. The primary purpose of this study is to explore the potential for water quality benefits through nutrient reduction within DWR sites in Iowa, with a secondary focus on monitoring the hydrology of the systems. This study was conducted at three DWR sites, with each location being designed differently based on topography and water resources, but all incorporate the same basic system of a storage reservoir and a centerpivot irrigation system. Given each DWR system monitored is different, this study can help draw conclusions for a broader range of sites and designs in addition to previously conducted studies on controlled drainage with subirrigation systems.

While this study focuses more on the storage reservoirs capability to reduce nutrient loads, it is still important to think about other effects on the system from irrigation. A series of studies in Canada (Drury et al., 1996, 2009a; Tan et al., 2007; Tan & Zhang, 2011) found that controlled drainage subirrigation systems reduced tile drainage volume as well as reducing the nitrate-nitrogen concentration of that tile drainage, but increased surface runoff. When compared to unrestricted drainage, controlled drainage subirrigation systems reduced nitrate-nitrogen losses by 43 to 68% (Drury et al., 1996, 2009). This reduction was due both to a decrease in average concentration, but also a decrease in total drainage volume. Later studies at the same research site found that controlled drainage subirrigation also reduced phosphorus losses from tile drainage as well. The results were a combination of flow reduction and concentration reduction, but for phosphorus, flow reduction played a larger role than concentration reduction. Fluxes of dissolved organic phosphorus, dissolved inorganic phosphorus, and total dissolved phosphorus were reduced by 18%, 47%, and 36%, respectively, over one study period and reductions of 15% particulate phosphorus and 12% total phosphorus were recorded in a follow up study (Tan et al., 2007; Tan & Zhang, 2011).

While these studies are important to understanding DWR systems, they do not directly monitor and report nutrients within the storage reservoir itself which can serve as an important tool for nutrient reduction. For the purposes of this study, DWR reservoirs were evaluated for fluxes and potential nutrient reduction of nitrate-nitrogen (NO_3-N), total nitrogen (TN), total phosphorus (TP), and total reactive phosphorus (TRP) over two years, 2022-2023.

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CHAPTER 2. EVALUATION OF DWR RESERVOIRS AS A NUTRIENT REDUCTION PRACTICE

Tyler Meyer[1], Matthew J. Helmers[1], Christopher H. Hay[2]

[1]Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA

[2]Iowa Soybean Association, 1255 SW Prairie Trail Pkwy, Ankeny, IA 50023, USA

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2.1 Abstract

The midwestern corn belt is characterized by heavy cropping and substantial subsurface drainage systems. These drainage systems are a known source of both phosphorus and nitrogen from the region. Many conservation practices have been developed and implemented to help lessen the region's impacts on downstream water quality. Drainage Water Recycling (DWR) is a relatively new conservation practice designed to help capture nutrient-rich subsurface drainage and store it for later use in the growing season. DWR consists of an edge-of-field capture basin for subsurface drainage or other surface waters and a system to reapply drainage water as supplemental irrigation, such as center pivot or subsurface irrigation. Through capture and storage, these nutrients are retained in the system rather than causing downstream impacts such as algal blooms, most notably in the Gulf of Mexico. This study monitored DWR reservoirs for inflows, outflow, and nutrient concentrations throughout the 2022 and 2023 growing seasons at three locations in Central Iowa. Results exhibit a capability for reduction in nitrate-nitrogen and total nitrogen concentrations within the reservoirs with overall reduction rates for nitrogen loads of 63% to 99%. Phosphorus, however, varied greatly

among locations, with a net export of phosphorus at one study site while the other two sites exhibited reduction rates of 66% to 96%.

2.2 Introduction

Drainage Water Recycling (DWR) is an emerging and understudied edge of field practice that incorporates on-farm storage of subsurface drainage water and supplemental irrigation. DWR systems are a combination of a storage reservoir that captures spring subsurface drainage, with the potential for additional flow from surface runoff or other water sources, and a way to use that stored water for supplemental irrigation later in the summer months when precipitation does not meet crop water demand. Iowa and much of the Corn Belt region require substantial subsurface drainage during wet spring months to remove water from the root zone and allow for proper plant development (Fausey et al., 1995). Given climate change trends, wet springs are expected to become more common, and summer months are expected to receive less precipitation(USGCRP, 2018). This leads to a mismatch in the timing of precipitation with crop needs. DWR captures the excess water in the spring and utilizes supplemental irrigation when the crop water needs are greater than precipitation later in the growing season, usually during the months of July and August. In constructing these reservoirs, storage is created on the landscape retaining and potentially reducing nutrient rich water that would have otherwise made its way downstream. Subsurface drainage water is known to have high quantities of nitrogen, especially nitrate-nitrogen, which can lead to algal blooms and hypoxia downstream if it enters rivers and streams (Johnston et al., 1965).

If constructed near surface waters, DWR reservoirs can pump from streams that are also high in nutrient concentration during springtime. Furthermore, other water resources can be utilized, such as pumping from drainage mains to aid reservoir spring filling. By capturing nutrient-rich drainage water, DWR can help reduce downstream impacts while allowing time for natural processes to take place, reducing nutrient concentrations within the reservoir before it is used for irrigation. DWR can serve as an additional resource to help meet nutrient reduction goals in states like Iowa and much of the Mississippi River Basin while bolstering climate change resilience through supplemental irrigation.

While this practice is relatively unstudied, nutrient removal wetlands can serve as an analog to DWR storage reservoirs. Nutrient removal wetlands receive nutrient-rich water from agricultural drainage, either directly or by intercepting surface waters, such as streams in watersheds dominated by agricultural land use. DWR can also be constructed to receive flow from these sources. Through storage and retention time within wetlands before continuing downstream, natural processes can take place to remove nutrients. During the retention period, sediments and phosphorus settle out, and denitrification begins (Crumpton et al., 2020; Neely & Baker, 1989). A driving factor for nutrient reduction within wetlands is the long residence time of water passing through the system. The longer the residence time, the more nutrient removal can occur (Ghosh & Gopal, 2010). Given residence time is such a key factor, wet springs with significant rainfall events can cause excess flow, leading to shorter residence times with lower nutrient reduction percentages. However, during summer months, when total flow is lower, these systems can reduce nutrient concentrations to near zero for nitrate-nitrogen.

Phosphorus capture and reduction from wetlands is less studied in comparison to nitrogen. Results have shown a capability for capturing and removing total phosphorus (TP) and total reactive phosphorus (TRP), also called orthophosphates, from surface waters. A 12-year study of agricultural wetlands in Illinois showed a reduction of anywhere from 32% to 95% for TRP loads (Lemke et al., 2022).

While nutrient removal wetlands can serve as a proxy by which to predict the efficiency of DWR reservoirs to remove nutrients, they are still different systems and may have varying results. There has been some work on DWR nutrient reduction in conjunction with other practices such as nutrient removal wetlands and controlled drainage with subirrigation. One such study has shown the nutrient reduction potential of wetlands in conjunction with a storage reservoir for irrigation at the Ohio Wetland Reservoir Subirrigation System (WRSIS) (Barry et al., 2014). In this study, known quantities of nitrogen were fed into a wetland linked to the storage reservoir to track the potential for nitrogen loss from the system. They found an average reduction in nitrate, ammonium, and total nitrogen of 27.7%, 79.2%, and 28.5%, respectively, among the four test periods within the study.

Another set of studies examined the effect of tile drainage nutrient losses under controlled drainage and subirrigation from a storage reservoir (Drury et al., 1996, 2009a; Tan et al., 2007; Tan & Zhang, 2011). These studies found that controlled drainage subirrigation systems reduced tile drainage volume as well as reducing the nitrate-nitrogen concentration of that tile drainage, but increased the surface runoff. When compared to unrestricted drainage, the controlled drainage subirrigation systems reduced nitrate-nitrogen losses by 43 to 68% (Drury et al., 1996, 2009). This reduction was due both to a decrease in average concentration and a decrease in total drainage volume. Later studies at the same research site found that controlled drainage subirrigation also reduced phosphorus losses from tile drainage as well. The results again were a combination of flow reduction and concentration reduction, but for phosphorus, flow reduction played a larger role than concentration reduction. Fluxes of dissolved organic phosphorus dissolved inorganic phosphorus and total dissolved phosphorus were reduced by 18%, 47%, and 36%, respectively, over one study period. They found reductions of 15% particulate phosphorus and 12% total phosphorus in a follow up study (Tan et al., 2007; Tan & Zhang, 2011).

While these other studies are important to understanding DWR systems, they did not directly monitor and report nutrients within the storage reservoir itself, which can serve as an important tool for nutrient reduction. The objective of this study was to examine the ability of three different DWR systems to reduce nutrient loads from storage of water that would have otherwise continued downstream.

2.3 Methods

Site Descriptions

Three DWR locations were monitored in this study: Lake City (Figure 2), Story City (Figure 3), and Dayton (Figure 4). These locations were each designed differently and, as such, had different sampling and monitoring implementations (Table 1). The primary difference between the DWR sites in this study was the source of inflow. Story City has supplemental pumping from a creek to help fill the reservoir in the spring months, as well as a small amount of subsurface drainage inflow. The inflow tile drains about eight ha but cannot be monitored because of its position within the reservoir. The supplemental inflow from the creek is the primary influx of water, meaning no outflow is recorded at this location because pumping stops before the reservoir would require outflow. The Dayton site fills in the spring via pumping from an underground drainage main up into the storage reservoir, with no outflow given the controlled nature of the inflow. The Lake City reservoir is at an outlet of a large tile that runs nearly year-round, and given the substantial inflow, Lake City requires an outflow structure, unlike the other two locations where there is typically no outflow.

Hydrology

To create accurate water balances for each DWR reservoir, all locations were monitored continuously for pumping volume, reservoir inflow and outflow, water level, evapotranspiration, and precipitation during the growing season, mid-May to late October.

Pumping volume is monitored via electromagnetic inline flow meters fitted to inflow pump and irrigation pumping systems (McCrometer) or exterior ultrasonic flow meters attached to the inflow and irrigation pumps (Keyence). Inflows and outflows from Lake City stream channels are monitored at 5-minute intervals with submerged Doppler area velocity sensors (ISCO) combined with cross-sectional areas to calculate volumetric flow rates. Inflows and outflows were not monitored for flow or water quality during frozen periods.

Reservoir depths were monitored using submerged pressure transducers (Solinst) at 5-minute intervals throughout the season. Seepage losses were estimated by using sequences of consistent depth decreases over time. Daily seepage losses were calculated over the sequence of consistent depth change by examining the change in depth and accounting for evaporative losses. The remaining change in depth after discounting evaporative losses was attributed to seepage. The average seepage loss over the consistent depth decrease period was assumed to be the average seepage loss for the entire season.

The same method could not be used for determining seepage at Lake City as the reservoir depth was too inconsistent. Instead, to estimate seepage losses at the Lake City location, a water budget was constructed based on inflow, outflow, irrigation withdrawal, evaporative loss, and storage change. The reservoir level showed similar depths at season start and end. Given no change in depth, the change was storage is considered negligible, allowing for the construction of equation 1. The system was assumed to be at steady state during this time period due to no change in storage, allowing total inflows to equal total outflows:

$$S_V = I_V - O_V - W_V - ET_V \quad (1)$$

where S_v is Seepage volume, I_V is inflow volume, O_V is outflow volume, W_V is irrigation withdrawal volume, and ET_V is evaporation volume. Once total seepage was determined, it was assumed to be a constant daily rate throughout the season.

Precipitation data were collected on location with tipping bucket rain gauges and cross-referenced with Iowa Environmental Mesonet in cases of equipment malfunction. The nearest Mesonet station was used to calculate the 30-year average rainfall for each location. Lake City used the IA7161 Rockwell City station, Story City used the IATAME Ames Area station and Dayton used the IA3623 Harcourt Station data until 2019 when it was shut down and the IEM rainfall GIS estimate based on the latitude and longitude of the site. Evapotranspiration data were acquired from Iowa Environmental Mesonet and cross-referenced with a satellite-based estimate of ET from OpenET.org.

Water Sampling and Analysis

Water quality samples were collected at all inflows and outflows of the reservoirs as well as from within the reservoirs from May to November in 2022 and April to October in 2023. Samples were collected using autosamplers (Teledyne ISCO) set to take one 100 ml sample every six hours and composite four samples over a 24-hour period for a total sample volume of 400ml. Samples were preserved in the field using acidified bottles with H_2SO_4 (sulfuric acid) to ensure ph < 2 (Phipps & Crumpton, 1994). Within the reservoir, the water intake was attached to a float and suspended six inches under the surface so as not to intake surface algae and other surface particulates. The reservoirs were assumed to be well mixed, and nutrient concentrations were used to estimate nutrients within irrigation withdrawals. Inflows and outflows were sampled with stream bed-mounted intakes suspended above the surface to avoid sediment uptake. Site maps, including sampler locations, can be seen in Figures 2, 3, and 4.

Additionally, manual grab samples were taken from all locations once per week. Grab samples were used for redundancy and during periods when the flow was too low for autosampler intake. During supplemental pumping from the creek at Story City, grab samples were taken from the creek as an approximation for inflow nutrient concentrations.

All samples were preserved with appropriate volumes of sulfuric acid and analyzed at the ISU Wetlands Research Lab for concentrations of nitrate-nitrogen (NO_3-N), total nitrogen (TN), total phosphorus (TP), and total reactive phosphorus (TRP). A detailed description of the nitrate-nitrogen and total nitrogen analysis process can be found in Crumpton (1992). Total phosphorus and total reactive phosphorus analysis used a method described by Murphy and Riley (1962) and later modified in AWWA (1998).

Data Analysis

Samples were taken at all locations throughout the season for nutrient concentrations. In events of equipment malfunction or inadequate samples, linear interpolation was used to estimate nutrient concentrations for missing data. With the exception of an equipment error resulting in no day-to-day irrigation pumping volume at Lake City prior to 6/29/2022, where linear interpolation could not be used. In this case, an inline totalizer logged the total irrigation pumping, which was averaged over the irrigation period to determine nutrient loads within early irrigation withdrawal.

Nutrient load reductions are determined from inflow minus outflow minus seepage losses:

$$I_N - O_N - S_N = R \quad (2)$$

where I_N is inflow nutrient load, O_N is outflow nutrient load, S_N is assumed seepage losses from the reservoir, and R is total reduction. However, nutrients are also withdrawn from the reservoir within the supplemental irrigation outflow. While these nutrients do not directly enter surface waters, there is still the potential of these nutrients leaching through the soil profile into drainage systems or groundwater and eventually reaching surface waters. There would, however, be substantial time for further nutrient reduction within the soil profile. Therefore, it was assumed these nutrients did not reenter surface waterways. Given this study was only on center pivot irrigation, the nutrients likely had time to be further reduced in the field following irrigation application as well as being lost through plant uptake. During this time, some amount of nitrogen and phosphorus will likely be bound in the soil profile from mineralization, immobilization, or sorption in addition to further reduction (Sebilo et al., 2013). Without knowing the fate of nutrients within irrigation water, those nutrients were not factored into the total reduction as an additional outflow. Further research would be needed to properly determine the fate of these nutrients within each system to find the true nutrient reduction. For the purposes of this study, nutrients within the withdrawal are counted as part of the total nutrient reduction.

2.4 Results and Discussion

The DWR reservoirs, inflows, and outflows were monitored for nitrate-nitrogen (NO_3-N), total nitrogen (TN), total phosphorus (TP), and total reactive phosphorus (TRP) throughout the ice-free period in 2022 and 2023. While all three monitored locations are DWR systems, they will each be reported separately due to design differences between them.

Precipitation

Throughout the study period, sites received average or below-average rainfall (Table 2). In 2022, Story City received above-average precipitation in the spring months, particularly in June, where 21 cm of precipitation was recorded, significantly above the area average of 13 cm for June. However, precipitation was below average from July to October, ending in an overall average year for rainfall. Lake City, on the other hand, received below-average precipitation for the entire year. Over the growing season from May to October, Lake City received 21 cm less rainfall in 2022 than in an average year. Additionally, 2023 received average to below-average precipitation during the growing season at all locations; most notably, the months of April and May were drier than average at all sites. Overall, the sampling years of 2022 and 2023 and the years immediately preceding this study had below-average precipitation for the DWR locations. The dry conditions could have led to different results than if sampling occurred in wet years. Further monitoring for different climate conditions would be beneficial to determine nutrient reduction efficacy with more precipitation.

Hydrology

Lake City

Lake City received 121,571 cubic meters (99 acre-feet) of inflow during 2022 (Table 3). Irrigation withdrawal and reservoir overflow to the stream channel account for the majority of outgoing water flux, accounting for 38% and 37% of total inflows, respectively. Throughout the growing season, 45,697 cubic meters (37 acre-feet) of water was extracted from the reservoir for irrigation, resulting in 21 cm (8.3 in) of supplemental irrigation per hectare over 21.5 hectares (53 acres).

Reservoir overflow to the stream channel, totaling 45,206 cubic meters (37 acre-feet), occurred almost exclusively in the spring months prior to irrigation withdrawal. In 2022, 81% of reservoir overflow came before irrigation started, with the majority being the result of one six-day flow event that accounted for 56% of all outgoing stream flow. This same event only accounted for 32% of total inflows. Significant flow events reduce reservoir retention time, which can lead to lesser nutrient reduction; however, even with increased flows, only 64% of total inflows during the event exited within the same time frame, indicating 36% of those inflows were retained within the reservoir for a longer duration allowing for nutrient reduction before exiting the system (Fisher & Acreman, 2004; Pavlineri et al., 2017).

The remaining 25% of inflows were lost through seepage and evaporative losses from the reservoir. Daily water fluxes from 2022 can be seen in Figure 5. Seepage and evaporation are not shown due to small daily totals. Due to an equipment error, irrigation values from 6/17/22 to 6/28/22 were calculated by averaging a totalized flow over those days. Between 6/17 and 7/11, the irrigation withdrawal lowered the reservoir level to a point where the next significant inflow event resulted in little to no reservoir overflow. Following the start of irrigation withdrawal, the reservoir level was consistently below the outflow weir, resulting in little to no measurable outflow for most of the monitoring period. It was not until late in the season, after irrigation ended, that the reservoir was refilled completely, and outflow began again, at which point monitoring stopped due to freezing temperatures. After the inflow event in mid-July, very little inflow was measured for the rest of the season.

In 2023, the reservoir received less inflow than the previous year, with most of the inflow coming after July. Lake City had a drier-than-average spring, particularly in May, which would have led to less tile drainage, which is the primary source of inflow for this reservoir. Over the sampling period, the reservoir received 79,901 cubic meters (65 acre-feet) of inflow, most of which was in late summer into fall. Irrigation withdrawal occurred throughout most of the season, from June to September, totaling 38,969 cubic meters (32 acre-feet), equating to 18.2 cm per hectare (7.2 inches per acre). With the lower amount of inflow, there was only 6,029 cubic meters (4.9 acre-feet) of reservoir overflow measured during the season, most of which was in the months of May and June before the majority of irrigation withdrawal which is considerably less than 2022 (Table 3 and Figure 6).

Story City

In comparison to Lake City, Story City is a more contained system with little to no outflow in any given year. The primary inflow of this reservoir is from supplemental pumping from an adjacent stream. However, a small tile drains roughly eight hectares (20 acres) into the reservoir, but the position within the reservoir made it too difficult to monitor. While unmonitored, this tile flow is still contributing to nutrients within the reservoir but cannot be accounted for in overall reduction.

In 2022, the Story City Reservoir was filled primarily through supplemental pumping from a creek early in the growing season when stream flow was enough to accommodate withdrawal. In 2022, 17,364 cubic meters (14 acre-feet) of water was pumped into the reservoir over 48 days from mid-July to late August. The initial pumping accounted for 7,800 cubic meters (6.3 acre-feet) over eight days; after a week-long break in pumping, the remaining 9,600 cubic meters (7.7 acre-feet) of inflow came over the following month. Almost all irrigation withdrawal was done in August, during which time 19,595 cubic meters (15.8 acre-feet) of water was withdrawn from the reservoir to supplement crop water demand (Table 3). Daily inflow pumping and irrigation withdrawal water fluxes are shown in Figure 7. Irrigation use was equivalent to 8.8 cm (3.5 inches) over 23.5 hectares (60 acres) of irrigated area. Aside from irrigation withdrawal, which was not factored in as a potential export of nutrients, the only outflow of nutrients from this reservoir is due to seepage losses.

In 2023, there was no supplemental pumping to fill the reservoir. There would have been a combination of surface flow and unmonitored tile flow to refill the reservoir. Unfortunately, these fluxes were unmonitored, leading to an incapability of calculating any amount of reduction. However, reservoir nutrient concentration, irrigation withdrawal, and seepage were still monitored. In 2023, irrigation withdrawal totaled 15,701 cubic meters (12.8 acre-feet), which took place in July and August, amounting to 6.5 cm per hectare (2.6 inches per acre) of supplemental irrigation. Along with seepage losses, these were the only flows from the reservoir in 2023.

Dayton

The Dayton reservoir was constructed above a drainage main, which serves as the source for all the inflow into the reservoir via pumping upward from the main. This location was still under construction during 2022 and thus only has data for 2023. In 2023, 38,210 cubic meters (31 acre-feet) of water was pumped out of the drainage main to fill the reservoir, primarily from the months of March to May. Like with the Story City reservoir, irrigation withdrawal is the only major outflow of water from this reservoir. Throughout August the reservoir was emptied entirely from irrigation withdrawal. There was an irrigation withdrawal of 31,078 cubic meters (25 acre-feet) used to irrigate the 42.5 hectares (105 acres), which amounts to 7.3 cm per hectare (2.9 inches per acre) supplemental irrigation used. The only other outflow is from seepage losses and evaporation, with seepage being the only source of nutrient export (Table 3 and Figure 8).

Nutrient Dynamics

Lake City

In 2022, nutrient concentration monitoring lasted 172 days from May to November, over which time the average inflow concentration was near 16 mg/L nitrate-nitrogen and total nitrogen. Inflow total nitrogen was primarily in the form of nitrate-nitrogen. While the reservoir overflow concentrations were lower with averages of 11 mg/L nitrate-nitrogen and 13 mg/L total nitrogen. Reservoir concentrations were even lower, especially in the later half of the season when nitrate-nitrogen concentrations dropped below 1 mg/L while total nitrogen stayed marginally higher around 2-3 mg/L. Day-to-day measured nitrate-nitrogen and total nitrogen concentrations can be seen in Figure 9.

Nitrate-nitrogen and total nitrogen concentrations varied throughout the season but were consistently lower in the reservoir and outflow than from inflow, indicating nitrogen loss within the reservoir. Reservoir concentration levels were used to estimate outgoing nutrients within irrigation withdrawal based on the assumption the reservoir was well mixed. On average, reservoir and outflow concentrations were within less than 1mg/L of one another for NO_3-N and TN, indicating similar concentrations between the sampling location in the reservoir and in the outflow stream.

In 2023, nitrate-nitrogen concentrations were much lower in the reservoir and outflow compared to 2022. While the nitrate-nitrogen concentration was low within the reservoir and stream outflow, total nitrogen concentrations were often double that of nitrate. In 2023, the average concentration within the reservoir was 0.75 mg/L and 3.25 mg/L of NO_3-N and TN, respectively, while inflow concentrations remained around 12 mg/L throughout the season. Outflow concentrations closely followed reservoir concentrations for nitrate-nitrogen, but total nitrogen was often much higher in the outflow. The cause of the difference in TN is unknown but could be a result of livestock waste as the outflow channel is open to cattle during the year (Figure 10).

Phosphorus concentrations, while variable, did increase in outflows within irrigation withdrawal and stream outflows relative to inflow concentrations, with the exception of irrigation withdrawal TRP, which was lower than inflow concentrations (Figure 11). The net phosphorus export is likely from erosion losses within the reservoir and outflow stream channel, particularly outflow channel erosion. This location was constructed in late 2021, which required excavation of the reservoir itself, displacing and destabilizing soils within the reservoir. With a new system, there has not been time for the outgoing stream to stabilize. Further observations would be needed once the stream bed and banks have stabilized to determine phosphorus capture efficacy properly.

Furthermore, the outflow stream is open to livestock during parts of the year, which further erodes and degrades the stream, causing more phosphorus losses from erosion. While some erosion losses may be coming from the reservoir near its outlet, the most likely cause of the phosphorus losses is from the outflow stream bed and bank between the reservoir overflow and the sampling location within the stream channel. Outflow flow weighted concentrations (FWC) of phosphorus are significantly higher than inflow or irrigation withdrawal primarily due to the significant rain event from 6/15/2022 to 6/20/2022. Over this event, 54% of total outflow water flux was observed, but the event accounted for 90% of the TRP outflow and 88% of the TP outflow. This amount of phosphorus export is most likely the result of stream incision and widening from the heavy flow period, leading to bed and bank losses. The outflow FWC for this event was 982 µg/L TRP and 1040 µg/L TP, during which time the average pond concentrations were 195 µg/L TRP and 245 µg/L TP. Large flow events, such as this one, are a major cause of erosion (Julian & Torres, 2006) in surface waterways, which is likely the main driver of the phosphorus export from the system.

Phosphorus concentrations were much higher within the reservoir during 2023 than in 2022 (Figure 12). The average concentration of TRP and TP within the reservoir were 522 µg/L and 626 µg/L respectively. Outflow concentrations were similarly high, but with significantly less outflow in 2023, the overall phosphorus load export was lower. The inflow concentrations for phosphorus were marginally higher in 2023. But more notable is the ratio of TRP to TP, changing from 2022 to 2023. In 2022, 71% of incoming TP was TRP, but in 2023, the ratio fell to 57% due to an increase in TP concentrations within inflow; while TRP concentration also increased, the TP increase was larger. The increase in TP could be due to changes in the timing of rainfall or land use changes in the drainage area above the tile outlet that feeds the reservoir (T. Q. Zhang et al., 2015).

Lake City Flow Weighted Concentrations (FWC)

Flow-weighted concentrations (FWC) are a measure of the average concentration within fluxes based on nutrient loads and total flow for each flux from the monitoring period. NO_3-N and TN FWC were higher in inflow waters than outflows from any source for both 2022 and 2023, indicating a reduction in all measured forms of nitrogen within outgoing water relative to when it entered the reservoir (Table 4). Stream outflows had higher FWC than irrigation withdrawal for nitrogen due primarily in part to the significant flow event in mid-July, leading to reduced residence time within the reservoir. Furthermore, most stream outflows occurred in the spring when incoming nitrogen was at higher concentrations, whereas most irrigation occurred later in the season when concentrations would have been reduced. Irrigation FWC was based on the nutrient concentration of reservoir sampling, assuming well-mixing within the reservoir. Despite similar concentrations of nitrogen between the reservoir and outflow stream at any given time, the difference in the timing of irrigation withdrawal and stream outflows led to different FWCs. In 2023, the average concentrations within the reservoir were much lower than the previous year, leading to a lower FWC for irrigation withdrawal. The outflow FWC for NO_3-N and TN follow a similar trend with much lower FWC than the previous year, indicating much of the nitrogen within the reservoir has been converted to forms other than nitrate. Inflow TN was once again composed mostly of nitrate, like in 2022 but with similarly lower FWC for NO_3-N and TN in comparison to the previous year (Table 4).

In 2022, phosphorus FWCs indicated an increase in TRP and TP concentrations as flow moved through the reservoir. Inflow concentrations were similar to or lower on average than irrigation withdrawal or stream channel outflow. The export of phosphorus may be due to the newly constructed nature of this reservoir rather than being indicative of an inability for phosphorus reduction from the reservoir. The freshly disturbed sediment could have led to an initial flush of easily erodible material. Over time, the reservoir and outflow stream channel may stabilize to the amount of flow, decreasing phosphorus losses. Further monitoring as the system changes over time will be needed to draw more informed conclusions. Additional measures could be taken, such as controlled grazing or planting additional vegetation in the riparian zone along the outflow channel, which could also aid in reducing phosphorus export. However, at this time, TRP and TP concentrations were higher in the outflow stream channel than in the reservoir (Table 4), indicating phosphorus was accumulating between the reservoir and the outflow sampler downstream of the reservoir overflow. This was most likely stream bed and bank erosion of the stream outflow channel, as well as scouring of the soil directly below the overflow weir based on how much higher the phosphorus FWCs were for the overflow compared to the reservoir. In 2023, FWC for phosphorus was higher for all flows for both TRP and TP. Stream outflow was still the highest FWC, indicating that additional phosphorus was being accumulated within the outflow stream channel. Irrigation withdrawal had a significantly higher FWC for both TRP and TP in 2023, driven by much higher concentrations of both forms of phosphorus within the reservoir throughout the year when compared to 2022. Inflow FWC for phosphorus was higher than in 2022, but not enough to cause the higher concentrations within the reservoir. At this time, it is unknown where the additional phosphorus is coming from. Further research will be needed, such as monitoring overland flow and sampling of the reservoir bed to determine if there is any release of phosphorus from the soil beneath the reservoir.

Lake City Nutrient Loads

Nutrient loads into and out of the reservoir demonstrated a loss of N within the reservoir and the export of phosphorus at the outflow monitoring location for both years, except for a reduction of TP in 2023 (Table 5, Figure 13 and Figure 14). In 2022, The reservoir received 1917 Kg of nitrate-nitrogen over the 146 days of monitoring flow and nutrient concentrations. The primary nutrient exports from the reservoir were from stream channel outflow and irrigation withdrawal, with additional losses from assumed seepage. The total reduction for the 2022 season was 1326 kg N of NO_3-N, which equates to 69% of the inflow load. Total nitrogen (TN) influx was only marginally higher at 1954 Kg, but the exports of TN were greater, resulting in a lower potential reduction of 1228 kg or 63%. The decrease in loads and concentration for both TN and NO_3-N indicates nitrogen reduction from the system. Differences in nutrient reduction from NO_3-N and TN are more clearly understood when examining the ratio of NO_3-N to TN (Figure 9). Within inflow water, 98% of TN was attributed to NO_3-N, whereas for irrigation pumping, only 79% of TN was from NO_3-N. The change in the percentage of TN that is NO_3-N indicates a change in the chemical state of nitrogen within the reservoir. These changes could be organic forms of nitrogen or other nitrogen compounds, such as nitric acid, due to partial denitrification. The exact nature of the additional TN would require further study. Overall, the reduction of nitrate-nitrogen and total nitrogen in relation to reservoir size was 1205 kg NO_3-N per hectare pool area and 1116 kg TN per hectare pool area, which is under the average rates for nutrient removal wetlands of 1,500 and 1,440 kg N per hectare removal for NO_3-N and TN respectively(Crumpton et al., 2020). However, this reservoir received a third of the average nitrogen influx of wetlands, yet load reduction was 80% of the average of wetlands, indicating a much higher percent reduction. Wetlands average 35% NO_3-N reduction, ranging from 9% to 92%, and 30% TN reduction, ranging from 5% to 83%, while in this year, the percent reduction for the Lake City reservoir was 69% and 63%, respectively(Crumpton et al., 2020).

The 2023 load mass reduction was lower due to reduced flow, but the percent reduction was greater due to very little stream outflow occurring. Without stream channel outflow, the only outgoing flux of nutrients was assumed seepage, causing reduction rates to be much larger than the previous year. In 2023, the reservoir received 834 kg of NO_3-N and 844 kg TN. Like in 2022, the majority of incoming nitrogen was in the form of nitrate. Nitrate concentrations quickly dropped off within the reservoir, leading to very little outgoing NO_3-N in the outflow and seepage losses, resulting in a reduction of 825 kg NO_3-N or 99% of the incoming load. While TN was also reduced, it was not reduced to as low of concentrations as NO_3-N, with a reduction percentage of 92%, which equates to 775 kg of TN (Figure 14). Reduction per hectare was much lower this year primarily due to lower flows bringing nutrients into the reservoir. Nitrate-nitrogen and total nitrogen reductions per hectare pool area were 750 kg and 705 kg, respectively, which again is lower than the average mass reduction per hectare for wetlands, but the percent reduction is much higher, coming in over the range of percent reduction values from Crumpton (2020).

The lost mass of nitrogen was likely converted to harmless N^2 gas via denitrifying bacteria, lost as nitrous oxide, or incorporated into the soil within the reservoir, but denitrification is likely responsible for the majority of nitrogen loss (Scott et al., 2008). Further research would be required to ascertain the exact fate of the lost nitrogen at the studied locations.

Phosphorus loads, while much smaller in total mass than nitrogen loads, can be just as detrimental to stream ecosystems (Correll, 1998), and unlike nitrogen, the system was exporting phosphorus to downstream waterways. The reservoir received 11.5 kg of TRP and 16.3 kg of TP from inflows but exported 26.8 kg of TRP and 29.1 kg of TP via the stream channel outflow. An additional 3.8 kg of TRP and 10.5 kg of TP were exported with the irrigation withdrawal. Additional losses are assumed from seepage, leading to an export of 172% of total incoming TRP and 122% of incoming TP. The export of P could be due to the fact that this system was recently constructed. Without time for channels to stabilize, no conclusions about phosphorus reduction capabilities should be made from this study. Continued monitoring would be needed to gain any insights into these reservoirs' capabilities for phosphorus capture. Without further study, it is unknown if the outgoing phosphorus is the same as the incoming or if it is sourced from the freshly disturbed soil in the reservoir bed in addition to the stream bed and banks of the outflow channel. Additionally, this site is built on a low-lying flood plain, which has been shown to have an increased concentration of phosphorus (Craft et al., 2000). The inherent higher quantities of phosphorus within the soil could lead to more significant losses from erosion, which was likely the primary driver of the phosphorus export from this location.

The 2023 season had lower flows for the majority of the year, resulting in little stream outflow, leading to a reduction of TP loads, but there was still an export of TRP. All fluxes had more mass load except the stream outflow in 2023. The outflow channel only had 4 kg TRP and 4.3 kg TP, which was about 85% less than in 2022, but the flow was 87% less, indicating the primary driver of phosphorus loss in the outflow channel was flow with concentrations remaining similar in both years regardless of flow volume. There was more phosphorus inflow than the previous year, even with less flow, leading to an influx of 11.6 kg TRP and 20.5 kg TP influx. The reservoir had much higher ambient TRP and TP concentration in 2023, resulting in more outgoing phosphorus in assumed seepage and irrigation withdrawal. Even with lower outflow losses, there was still an export of 1.3 kg TRP, but an overall reduction in TP of 6.6 kg TP. There was a reduction in TP primarily due to the reservoir receiving nearly 9 kg more TP than TRP, so even with higher TP losses in seepage and outflow, there was still an overall reduction.

Story City

Given that Story City has no outflow, the only nutrient losses were from assumed seepage losses. As a result, Story City had a higher maximum potential reduction. Without a consistent influx of water and nutrients, the overall concentration of the reservoir remained low throughout the season (Figure 15). An increase in nitrate-nitrogen and total nitrogen concentrations was observed following the inflow initial pumping from the stream, during which 70% of all nitrogen inflows occurred. As a result of the influx of both nitrate and TN, the ambient concentrations within the reservoir rose by 2 mg/L and 2.5 mg/L, respectively. After the initial influx, the concentrations within the reservoir returned to baseline concentrations of less than 1mg/L for NO_3-N and less than 2mg/L for TN after 45 days. TN concentrations had more variability throughout the year compared to NO_3-N but remained lower than the post-filling rise in concentration for most of the year. Pre-filling concentrations were marginally higher than post-fill, likely due to an influx of nitrogen from the unmonitored tile outlet within the reservoir. Tile flow is also the most likely cause of the increase in concentration at the end of the season before monitoring ceased for the winter.

Phosphorus concentrations varied greatly throughout the season (Figure 16). Concentrations for either form of P were never greater than 400 µg/L in the reservoir but were up to 600 µg/L at the maximum within inflow water. Unlike nitrogen, there was no increase in reservoir concentrations following inflow pumping; however, inflow concentrations for phosphorus were not initially above ambient pond concentrations when the rise in nitrogen concentrations was observed. The initial inflow pumping period only accounted for 15% of the total phosphorus influx. Unlike nitrogen, the bulk of phosphorus inflow came during the latter portion of inflow pumping. The lower concentrations of phosphorus in the inflow relative to the ambient pond concentration led to no noticeable rise in pond concentrations throughout the season. The remaining phosphorus input came over the course of 31 days of pumping, which had little effect on overall pond concentrations despite amounting to 2.4 kg of TRP and 2.5kg of TP.

While Story City nutrient loads were lower than that of Lake City, the overall percentage reduction was higher due to differences in reservoir structure. The only major export was irrigation withdrawal, which was not factored against the reduction, meaning the only nutrient export was from assumed seepage. Without stream overflow, nutrient loads were captured and contained until irrigation withdrawal, giving time for nutrient losses to occur from the reservoir. While the inflow is not directly from subsurface drainage, the stream used for supplemental pumping has numerous subsurface outlets leading to high nutrient concentrations, particularly for nitrogen, during initial pumping in July. Inflow pumping lasted 48 days from Mid-July to the end of August, accounting for all monitored nutrient influxes (Table 6 and Figure 17). During filling, the reservoir received 213 Kg TN, 203 Kg NO_3-N, 2.8 kg TRP, and 3 Kg TP. The only major export of nutrients from this reservoir was from irrigation withdrawal. Given that these nutrients were not factored against reduction potential, overall phosphorus reduction for this location was higher than that of Lake City. A total of 33 Kg NO_3-N and 52 Kg TN were exported from the reservoir via irrigation withdrawal with FWC of 1.7 mg/L and 2.6 mg/L for NO_3-N and TN, respectively. However, much of this load was likely further reduced in the field or absorbed by plant roots. Additional FWC for Story City can be seen in Table *7*.

Losses for this reservoir come only from assumed seepage of 48 cubic meters per day based on the drop in reservoir level after accounting for evaporative losses. Using daily ambient reservoir concentrations, 8 Kg NO_3-N and 22 Kg TN were lost throughout the year from assumed seepage, as well as 0.7 kg TRP and 1.9 Kg TP. The Story City reservoir reduced NO_3-N and TN loads to downstream waterways by 96% and 90%, respectively. Downstream phosphorus loads were also reduced by 82% and 66% for TRP and TP, respectively. While the total mass was much smaller, phosphorus loads also contribute to downstream nutrient pollution and eutrophication (Correll, 1998). Considering the only outflows are from irrigation withdrawal and assumed seepage and only seepage losses affect potential reduction, the actual reduction for this reservoir was potentially greater than reported. The fate of nutrients exiting the reservoir from these fluxes is unknown. Still, there was likely additional nutrient loss during transport of this seepage to the stream, resulting in further reduction before reaching surface waters. More research would be needed to determine the actual outgoing load from seepage and leaching from irrigation to find the proper reduction percentages.

During the 2023 season there was no inflow pumping which was the only monitored inflow source for this reservoir. There would have been some inflow from overland flow and the small drainage tile, but conclusions about the reduction can't be made because those influxes were not monitored. There were increases in concentration for all nutrients at different points throughout the monitoring period and a subsequent fall in those concentrations over time. NO_3-N remained less than 1 mg/L throughout much of the year, while TN concentrations were again over double that of NO_3-N; the average concentration for both TN and NO_3-N were less than the previous year (Figure 18). The concentrations remained relatively low throughout the year without the influx of nitrogen from the supplemental pumping. TN concentrations fluctuate more than NO_3-N but are still comparable to the previous year. Phosphorus concentrations were also similar to the previous year outside of some samples that were much higher than average late in the season (Figure 19). The increase in phosphorus concentrations in late July and late August corresponded with irrigation withdrawal events, which may have stirred up sediments, adding phosphorus to the reservoir. Following the late July event, the concentration did begin to drop afterward, indicating the sediments and phosphorus began to settle out. Due to an equipment error, linear interpolation was used to fill in data gaps in August.

While there was no inflow, irrigation withdrawal and assumed seepage losses were still monitored throughout the season. Seepage losses were similar to the previous year, but irrigation withdrawal differed in phosphorus loads from 2022. Due to much higher concentrations during withdrawal periods, the TRP and TP loads in irrigation withdrawal were 3.5 kg TRP and 9.9 kg TP, which were five times the amount in 2022 for TRP and nearly seven times the amount for TP. Like Lake City, ambient pond concentrations at Story City for TRP and TP were higher in 2023 than in 2022, leading to more losses in assumed seepage (Table 6). It is unclear why phosphorus levels were higher in 2023 than in 2022. It could be from higher rainfall over winter and early spring months, leading to increased surface erosion deposited in the reservoir. Still, without further research, the source of the additional phosphorus is unknown.

Dayton

The Dayton reservoir receives all its inflow from an underground drainage main fed entirely from tile drainage. This leads to high nitrate-nitrogen and total nitrogen concentrations while concentrations of TRP and TP are less(Johnston et al., 1965). This reservoir began and ended the 2023 season at near empty, making it an ideal year for nutrient reduction. Due to completely filling the reservoir during springtime, when nutrient concentrations are highest, the maximum total load was prevented from continuing downstream. The reservoir received 444 kg of NO_3-N and 459 kg of TN, indicating a large proportion of nitrogen within the drainage main was in the form of nitrate (Table 8). Furthermore, FWC of NO_3-N and TN were 11.6 mg/L and 12 mg/L, respectively, meaning 97% of inflow nitrogen was in the form of nitrate (Table 9). In addition to the nitrogen influxes, 2.3 kg of TRP and 2.3 kg of TP were received from the spring pumping (Table 8). Almost 100% of TP inflows were TRP, which is clear from the difference in FWC (Table 9) of 59.5 µg/L for TRP and 60 µg/L for TP, as well as the loads differing by only 30 grams.

The inflow pumping ended in early May, and irrigation withdrawal began in August, leaving three months for nutrient reduction to take place within the pond. As a result, the irrigation withdrawal FWCs were much lower than the inflow at 2.7 mg/L for NO_3-N, 3.1 mg/L for TN, 15.1 µg/L for TRP, and 45.3 µg/L for TP. Irrigation withdrawal completely emptied the reservoir, amounting to loads of 83.5 kg NO_3-N, 95.8 kg TN, 0.47 Kg TRP, and 1.4 kg TP being applied over the 42.5 hectares of irrigated area.

Assumed seepage losses are the only other nutrient outflux from the reservoir which are estimated to be 31.1 kg of NO_3-N, 36.8 kg of TN, 0.1 Kg of TRP, and 0.2 kg of TP. Seepage was assumed to be a constant rate throughout the year at ambient pond concentrations to find the load lost and FWC of 5.8 mg/L for NO_3-N, 6.3 mg/L for TN, 16.9 µg/L for TRP and 37.1 µg/L for TP. Daily nitrogen and phosphorus concentrations for inflow and ambient pond concentrations can be seen in Figure 20 and Figure 21, respectively.

Given that the only negative nutrient outflow is assumed seepage, reservoirs like Dayton and Story City had much higher percent reductions when compared to Lake City because Lake City loses nutrients within the stream channel outflow before concentrations can be reduced as much as the reduction from an enclosed reservoir where the concentrations have months to decrease. However, Lake City had more mass reduction due to intercepting larger flow volumes than the other reservoirs. Dayton showed a reduction for NO_3-N and TN of 413 kg (93%) and 423 kg (92%), respectively (Figure 22). During the initial filling inflow, concentrations were above 13 mg/L NO3-N. At the end of the season, what water was left to be sampled in the near empty reservoir had a concentration of less than 1 mg/L NO^3-N indicating a significant drop in concentrations throughout the year. Phosphorus was significantly more variable in concentration; however, the reservoir reduced inflow loads by 2.2 kg (96%) and 2.1 kg (90%) for TRP and TP, respectively. Concentrations of TRP and TP increased near the end of irrigation withdrawal, likely from the water sampler intake getting too close to the bottom of the reservoir, causing extra sediment to be taken in with the sample.

General Discussion

Weather and climate play an important role in the efficiency of many conservation practices, particularly the difference between wet and dry years, which can lead to varying results. A drier-than-average 2022, combined with below-average precipitation in 2020 and

2021, likely led to reduced drainage volume in 2022. The reduction in drainage volume and lower-than-average rainfall would lead to a reduction in overall inflows, especially from tile drainage, which would be a large source of nutrients entering the reservoirs. However, a larger drainage volume would lead to a reduced residence time within the reservoir, leading to a potentially lower percent reduction (Fisher & Acreman, 2004; Pavlineri et al., 2017). Continual monitoring would be needed to determine nutrient reduction efficiency under different climate conditions, particularly in wet years or a series of consecutive wet years where less supplemental irrigation is needed. Without irrigation withdrawal to lower the reservoir depth, sites like Story City and Dayton will not be as effective at nutrient reduction because if the reservoir is too full to pump into, no additional nutrients can be captured and reduced by the reservoir. However, these more contained systems like Dayton and Story City could potentially be emptied and refilled for further nutrient reduction in wet years. Still, if these systems are not designed with this in mind, it may be costly to implement that amount of additional pumping, decreasing the financial incentives of DWR. Sites like Lake City, with continual inflow and outflow designed into the system, may still be useful for nutrient reduction in wet years. However, further monitoring would be required to properly determine the capability of DWR nutrient reduction under different climate variables.

In 2022, Lake City and Story City reservoirs displayed the capacity for nitrogen loss. Nitrate-nitrogen varied from 49% to 96% reduction, while total nitrogen reduction varied from 63% to 90%. Phosphorus results varied greatly from net phosphorus export for both TRP and TP and a reduction of 82% to 66%, respectively. The combined total from the Story City and Lake City locations amounted to 1419 kg of total nitrogen prevented from entering downstream waterways. Total nitrate-nitrogen reduction was marginally more, amounting to 1521 kg removed. There was more nitrate-nitrogen reduction than total nitrogen even though nitrate-nitrogen is part of total nitrogen because of the way concentrations of the two changed within the reservoirs. Nitrate-nitrogen concentrations fell much lower than total nitrogen within reservoirs due to changing in the nitrogen compounds leading to more nitrate-nitrogen loss than total nitrogen. Phosphorus was not reduced at both locations like nitrogen, but Story City prevented 2 kg of total phosphorus from continuing downstream while Lake City exported 20 kg of total phosphorus. In 2023, total load reduction from all locations was less for nitrate-nitrogen and TN at 1238 kg and 1197 kg, respectively, The percent reductions were much higher than in 2022, varying between 93% and 99% for NO_3-N and 92% at both locations for TN. There was a reduction in TRP and TP in 2023 of 0.9 kg and 8.7 kg from all sites, respectively. The reduction of phosphorus loads can mainly be attributed to the low flow conditions at Lake City, leading to very little stream outflow, which was the main loss of phosphorus in 2022 (Table 10).

This study indicates DWR reservoirs are an effective nitrate-nitrogen and total nitrogen reduction practice, but more research will be needed as to the efficacy of phosphorus reduction potential.

2.5 Conclusion

The results of this study indicate that DWR reservoirs can serve as an effective nutrient capture and removal practice, especially for nitrogen. Nitrogen and phosphorus have been shown to have adverse effects on downstream waterways, leading to harmful algal blooms and hypoxia. DWR can serve as a valuable tool to prevent nitrogen and potentially phosphorus movement downstream by capturing and storing nutrient-rich subsurface drainage water. In

2022, these reservoirs displayed the capacity to reduce nutrient concentrations of NO_3-N and TN by 69 – 96% and 63- 90%, respectively, resulting in 1521 kg of nitrate-nitrogen and 1419 kg of total nitrogen being prevented from entering downstream waterways via subsurface drainage. This reduction was roughly equivalent to 5.5 nutrient removal bioreactors, each capturing flow from 20 hectares (50 acres) (Christianson et al., 2021). Phosphorus was less consistent between locations, with a net export of phosphorus from Lake City of 20 kg. Still, Story City captured 2 kg of phosphorus, reducing nutrient loads by 82% and 66% for TRP and TP, respectively (Table 10). In 2023, the Lake City and Dayton reservoirs reduced downstream loads for NO_3-N and TN of 1238 kg and 1197 kg, respectively, resulting in a percent reduction range of 93% to 99% for NO_3-N and 92% at both locations for TN. While the total reduction was lower than the previous year, it still equated to roughly 4.7 bioreactors (Christianson et al., 2021). Unlike 2022, 2023 had an overall reduction for both types of phosphorus, resulting in 0.9 kg TRP and 8.7 kg TP being prevented from continuing downstream (Table 10). The reduction instead of loss was primarily due to dry conditions reducing the stream outflow volume at Lake City, which was the primary phosphorus export in 2022.

Further research should continue to monitor these systems to improve our understanding of the nutrient reduction capacity over time. This study was conducted during a span of lower than average to average rainfall with the study years in 2022 and 2023, as well as lower than average rainfall in the years preceding the study. To determine reduction efficacy in all years, more monitoring of these systems is needed under varying climate conditions, especially in years with greater than average precipitation. As the practice continues to grow in usage, so should the research effort to examine how variations in design and implementation can influence nutrient reduction capabilities.

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Tables and Figures

Table 1: Site Characteristics

Location	Lake City	Dayton	Story City
Pump Monitoring Equipment	Inline electromagnetic flow meter (MaCrometer)	Clamp-on ultrasonic flow meter (Keyence)	Inline electromagnetic flow meter (MaCrometer)
Inflow	Tile outlet Surface flow from a cattle lot	Pumping from underground drainage main	Pumping from creek Small unmonitored inflow tile
Outflow	Stream Channel outflow	Overflow cement culvert	No outflow
Sampling Locations	Inflow Reservoir Outflow	Inflow Reservoir	Inflow Reservoir
Reservoir area (ha)	1.1	1.3	1
Irrigated area (ha)	21.5	42.5	23.5

Table 2: Precipitation (cm)

Precipitation (cm)	**March**	**April**	**May**	**June**	**July**	**August**	**Sept.**	**Oct.**	**Annual**
Story City Average (1993-2023)	5.3	9.17	13.7	13.5	11.1	11.7	9.6	7.1	94.7
Story City 2022	10.1	14.1	14.8	21.3	7.7	7.3	5.6	2.3	97.4
Story City 2023	7.1	5.4	7.0	15.1	5.9	11.6	4.2	7.0	
Lake City Average (1993-2023)	4.4	8.7	12.3	12.4	8.9	11.4	7.2	6.2	82.2
Lake City 2022	3.6	5.9	11.1	9.8	5.9	4.6	4.8	2.4	57
Lake City 2023	3.2	6.4	6.0	6.2	8.4	6.6	5.6	7.7	
Dayton Average (1993-2023)	5.3	9.6	12.6	15.2	11.0	14.2	8.2	7.5	98.2
Dayton 2022	6.3	7.8	10.5	6.2	8.3	10.2	4.1	2.8	66.9
Dayton 2023	5.5	5.6	8.1	8.7	5.8	6.6	5.7	8.4	

Table 3: Yearly Total Water Flux m3

Site	**Inflow (m^3)**	**Irrigation Withdrawal (m^3)**	**Seepage (m^3)**	**Outflow (m^3)**
Lake City 2022	121,571	45,697	22,236	45,206
Story City 2022	17,364	19,595	7,675	NA
Dayton 2023	38,209	31,078	5,888	NA
Lake City 2023	79,901	38,969	22,084	6,029
Story City 2023	0	15,702	6,535	NA

Table 4: Lake City Flow Weighted Concentrations (FWC)

2022 Flow Weighted Concentrations	**NO_3-N** (mg/L)	**TN** (mg/L)	**TRP** (µg/L)	**TP** (µg/L)
Inflow	15.8	16.1	95	135
Stream Channel Outflow	11	13	593	644
Irrigation Withdraw	8.4	10.6	83	230
Assumed Seepage	4.3	6.1	193	321

2023 Flow Weighted Concentrations	**NO_3-N** (mg/L)	**TN** (mg/L)	**TRP** (µg/L)	**TP** (µg/L)
Inflow	12	12.5	145	257
Stream Channel Outflow	0.3	4.4	673	713
Irrigation Withdraw	0.7	2.3	427	473
Assumed Seepage	0.4	1.7	327	438

Table 5: Lake City Nutrient loads (kg)

2022 Nutrient loads by flux (kg)	**NO_3-N (kg)**	**TN (kg)**	**TRP (kg)**	**TP (kg)**
Inflow	1917	1954	11.5	16.3
Outflow	496	590	26.8	29.1
Irrigation Withdraw	384	486	3.8	10.5
Assumed Seepage	95	135	4.4	7.1
Potential Reduction	1326	1228	-19.7	-19.9
Percent reduction	69%	63%	-171%	-122%

2023 Nutrient loads by flux (kg)	**NO_3-N (kg)**	**TN (kg)**	**TRP (kg)**	**TP (kg)**
Inflow	834	844	11.6	20.5
Outflow	1.7	27	4.0	4.3
Irrigation Withdraw	27	79	16.6	18.4
Assumed Seepage	8.5	43	8.9	9.7
Potential Reduction	825	775	-1.3	6.6
Percent reduction	99%	92%	-11%	32%

Table 6: Story City Nutrient Loads (kg)

2022 Nutrient loads by flux (kg)	NO_3-N (kg)	TN (kg)	TRP (kg)	TP (kg)
Inflow	203	213	2.8	3
Irrigation Withdraw	33	52	0.7	1.5
Assumed Seepage	8	22	0.5	1.0
Potential Reduction	195	191	2.3	1.9
Percent Reduction	96%	90%	82%	63%
2023 Nutrient loads by flux (kg)	**NO_3-N (kg)**	**TN (kg)**	**TRP (kg)**	**TP (kg)**
Inflow	NA	NA	NA	NA
Irrigation Withdraw	3.3	44.1	3.5	9.9
Assumed Seepage	2.4	15	0.6	1.6
Potential Reduction	NA	NA	NA	NA
Percent Reduction	NA	NA	NA	NA

Table 7: Story City Flow Weighted Concentrations (FWC)

2022 Flow weighted concentration	NO_3-N (mg/L)	TN (mg/L)	TRP (µg/L)	TP (µg/L)
Inflow	11.7	12.2	160.4	170.3
Irrigation Withdraw	1.7	2.6	34.6	77.5
Assumed Seepage	1.0	2.8	66.6	132.3
2023 Flow weighted concentration	**NO_3-N (mg/L)**	**TN (mg/L)**	**TRP (µg/L)**	**TP (µg/L)**
Inflow	NA	NA	NA	NA
Irrigation Withdraw	0.2	2.8	225.6	630.6
Assumed Seepage	0.4	2.3	93.4	242.6

Table 8: Dayton Nutrient Loads (kg)

2023 Nutrient loads by flux (kg)	NO_3-N (kg)	TN (kg)	TRP (kg)	TP (kg)
Inflow	444	459	2.3	2.3
Irrigation Withdraw	84	96	0.5	1.4
Assumed Seepage	31	37	0.1	0.2
Potential Reduction	413	422	2.2	2.1
Percent Reduction	93%	92%	96%	90%

Table 9: Dayton Flow Weighted Concentrations

Flow weighted concentration	NO_3-N (mg/L)	TN (mg/L)	TRP (µg/L)	TP (µg/L)
Inflow	11.6	12	59.5	60.1
Irrigation Withdraw	2.7	3.1	15.1	45.3
Assumed Seepage	5.3	6.3	16.9	37.1

Table 10: Total Load Reduction from all sites

Total Load Reduced	NO_3-N (kg)	TN (kg)	TRP (kg)	TP (kg)
2022	1521	1419	-17.4	-18
2023	1238	1197	0.9	8.7

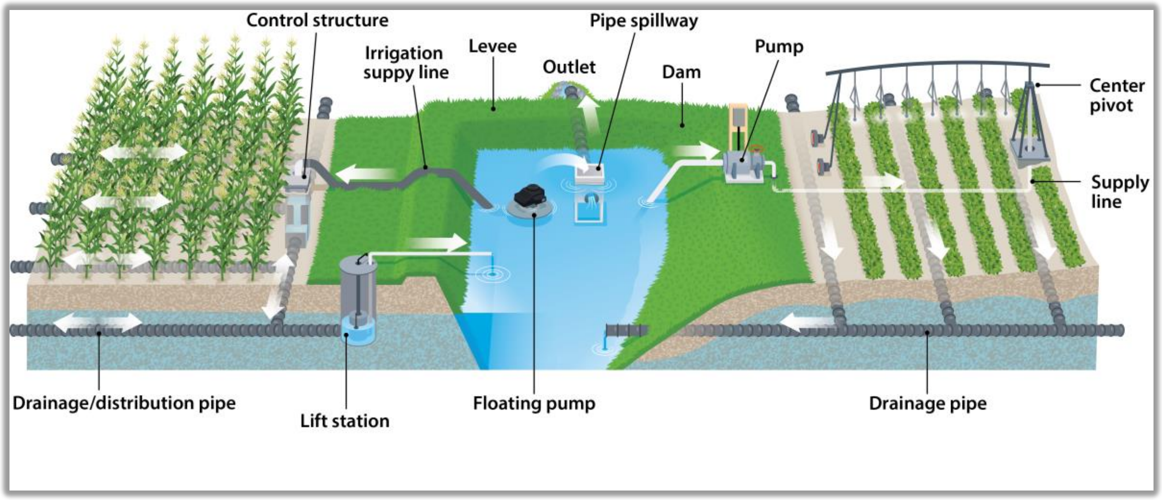

Figure 1: DWR System Design

Figure 2: Lake City Site Map

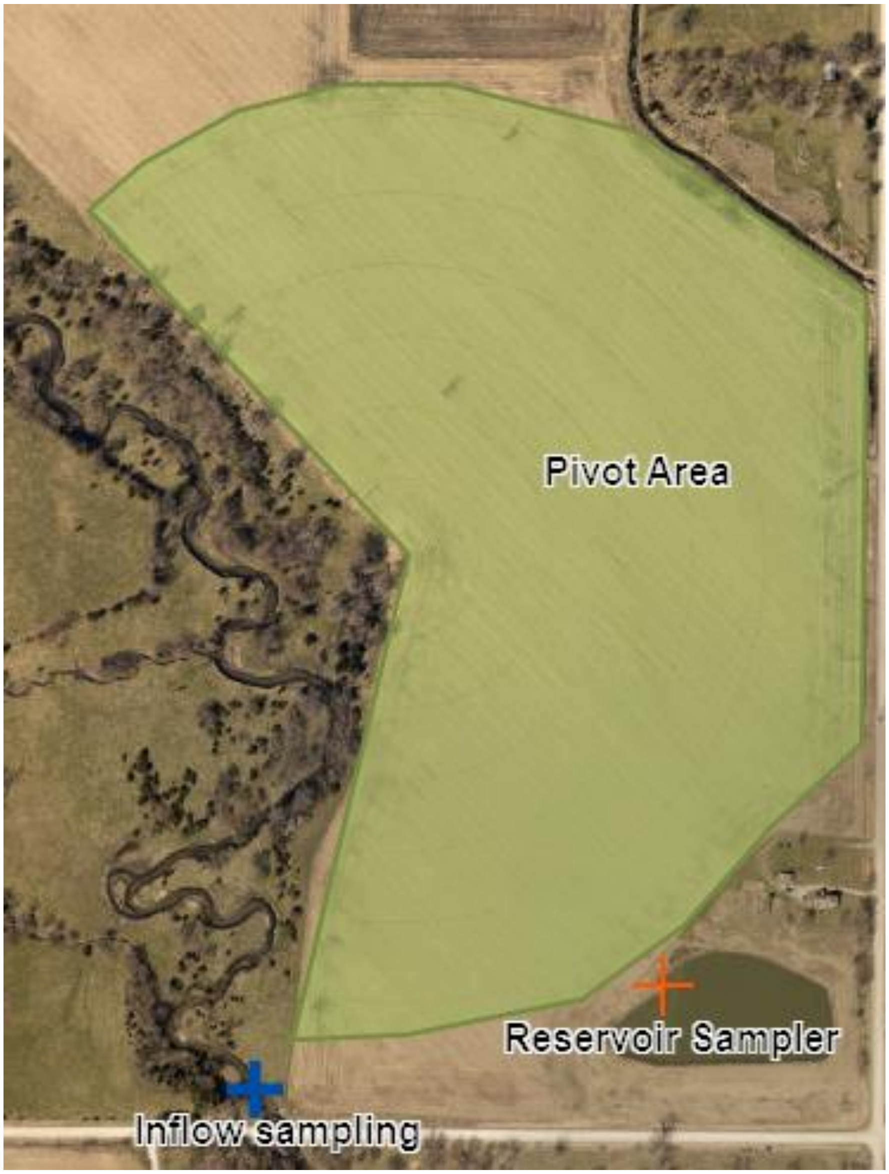

Figure 3: Story City Site Map

Figure 4: Dayton Site Map

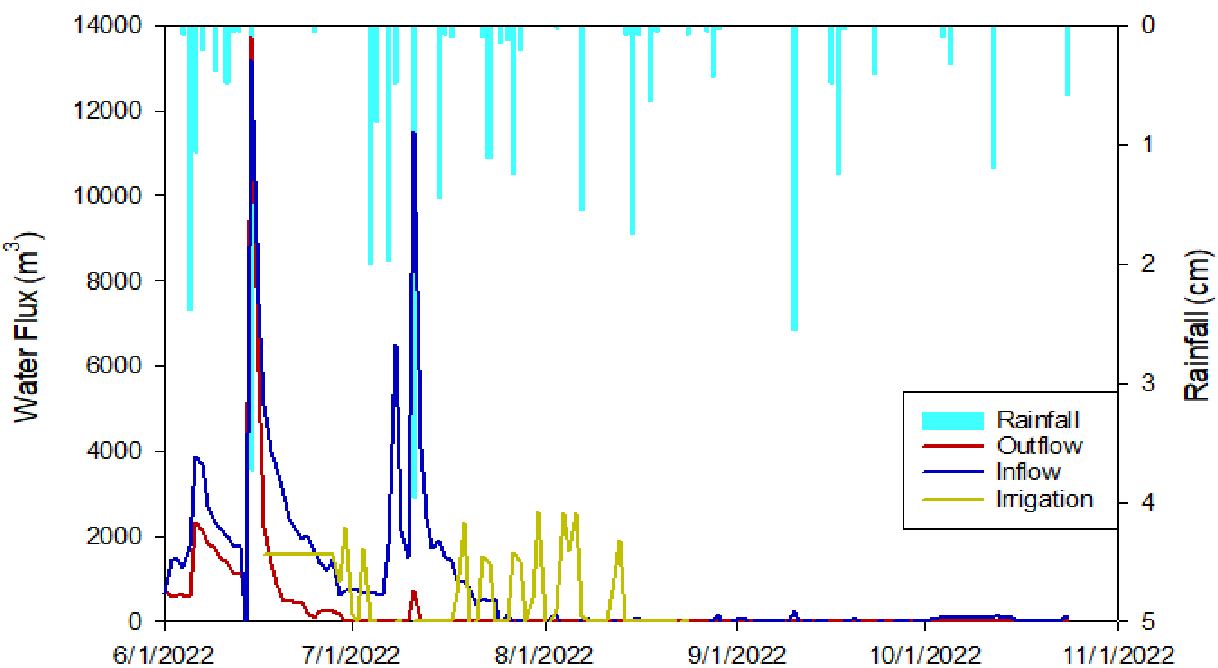

Figure 5: 2022 Lake City Daily Water Flux (m^3)

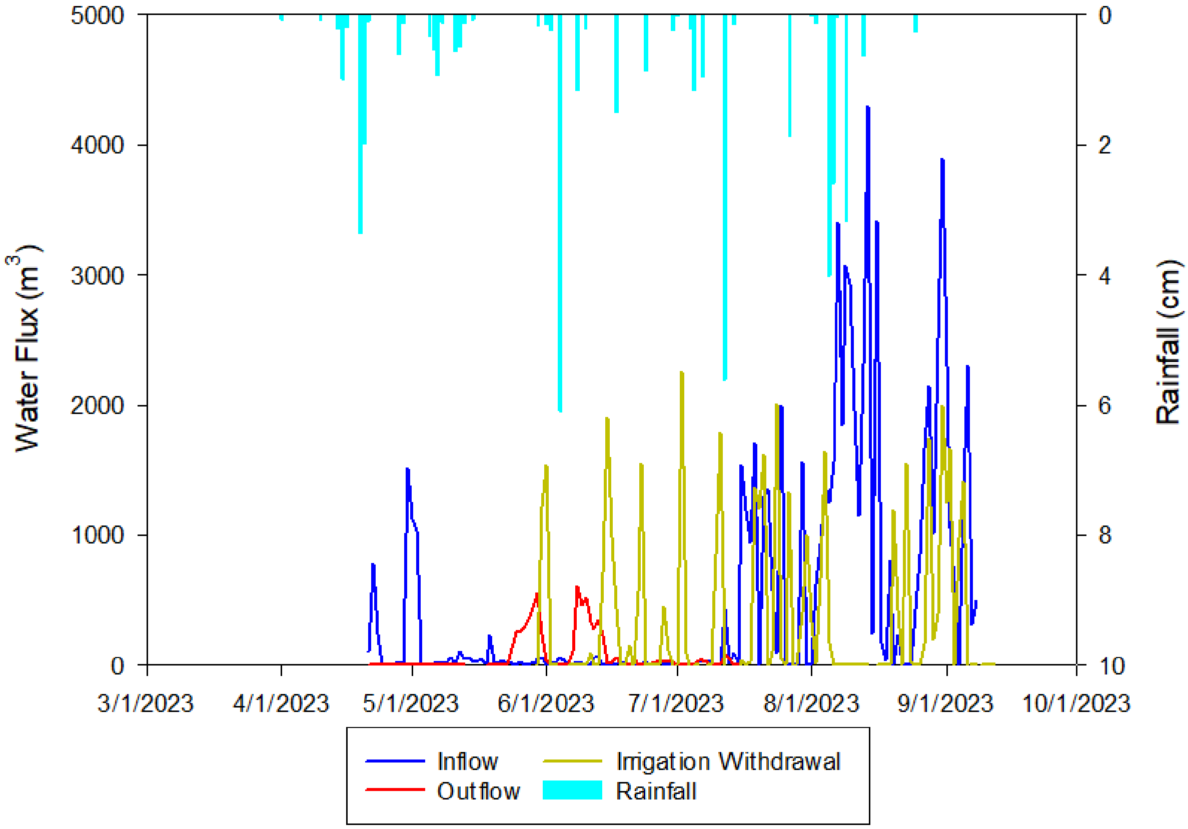

Figure 6: 2023 Lake City Daily Water Flux (m^3)

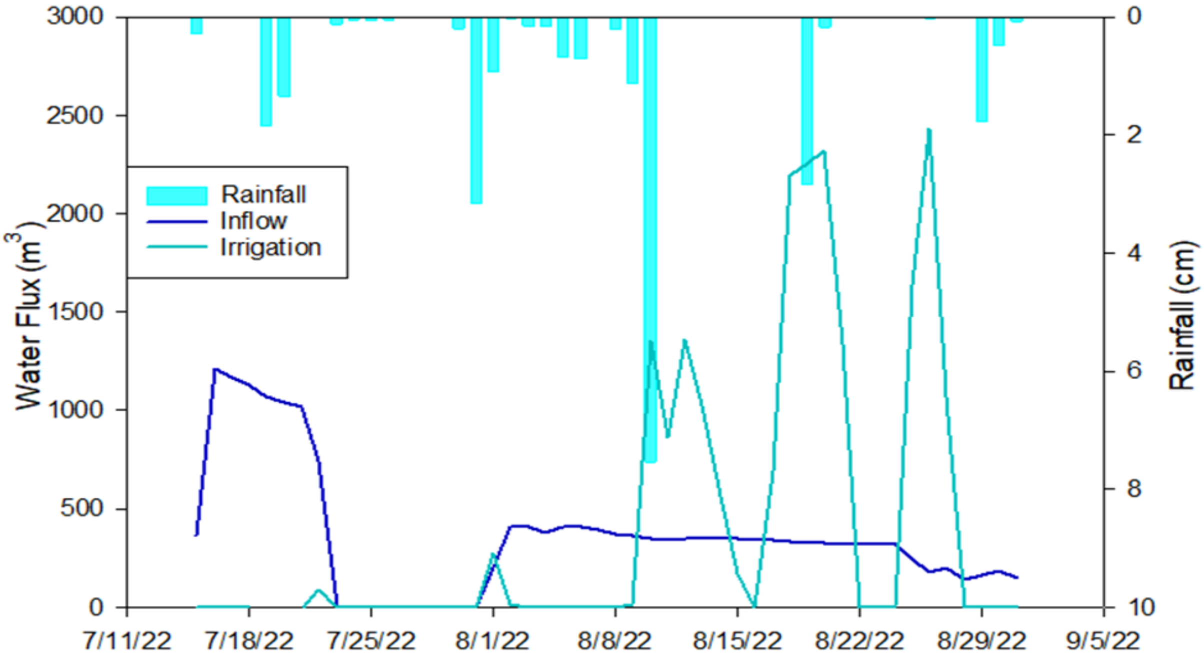

Figure 7: 2022 Story City Water Flux (m^3)

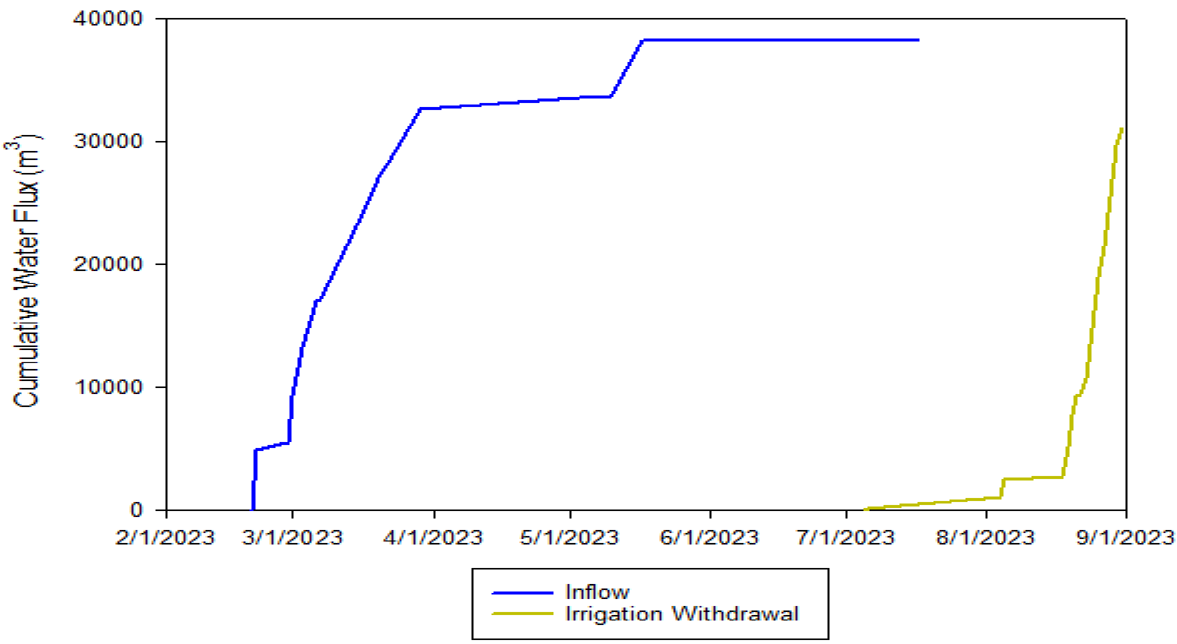

Figure 8: 2023 Dayton Cumulative Water Flux (m^3)

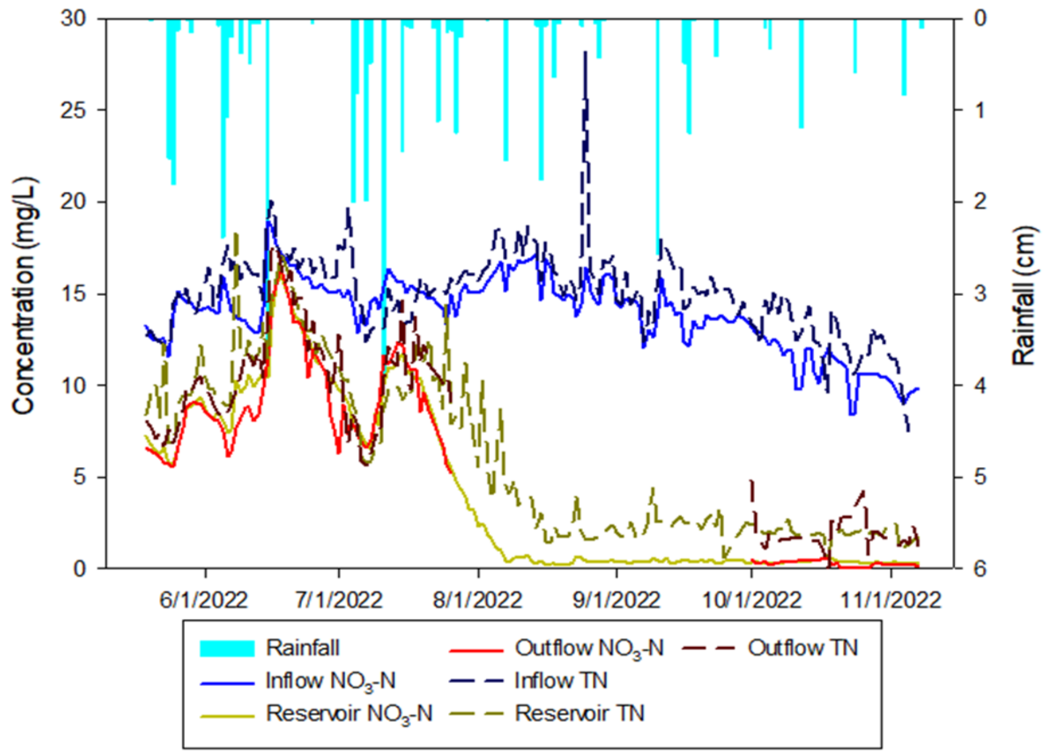

Figure 9: 2022 Lake City Daily Nitrogen Concentrations (mg/L)

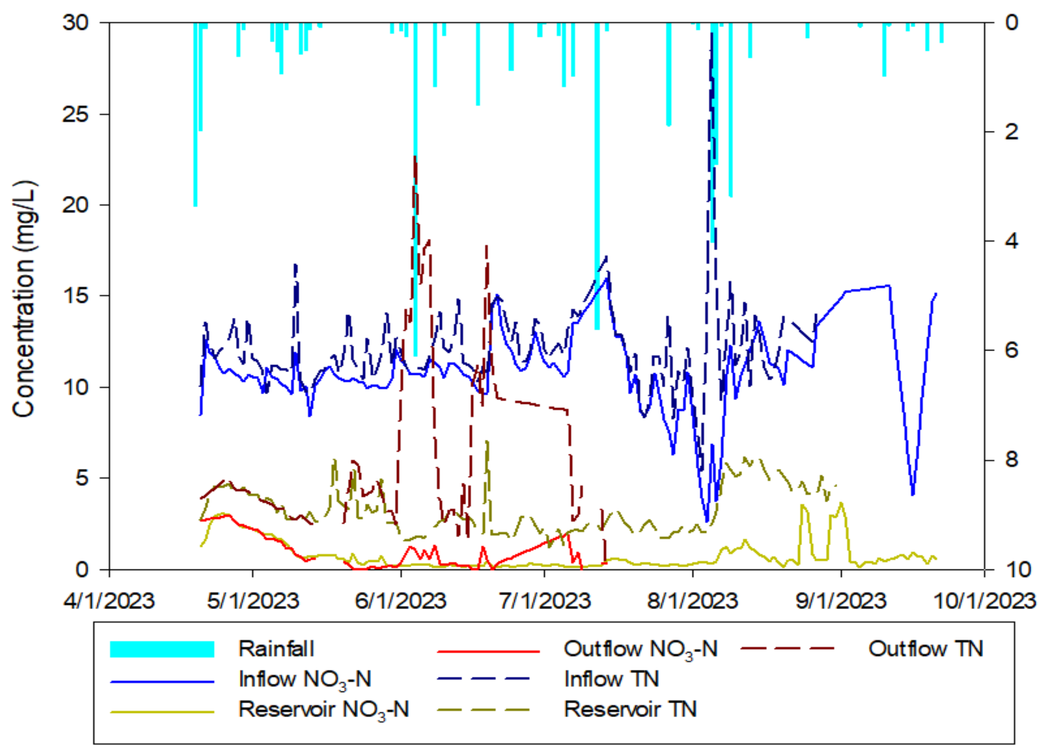

Figure 10: 2023 Lake City Daily Nitrogen Concentrations (mg/L)

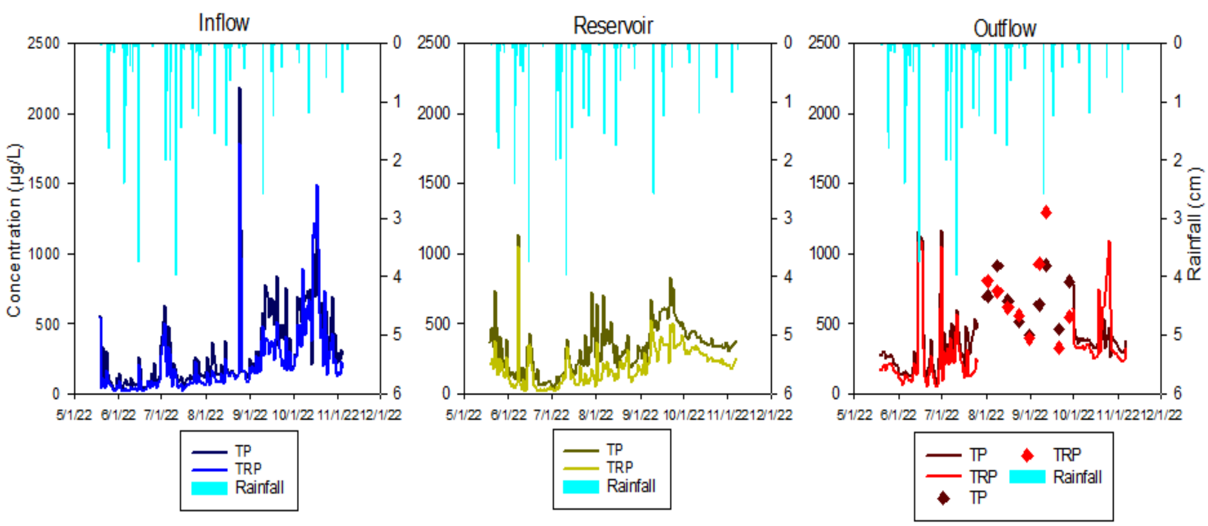

Figure 11: 2022 Lake City Daily Phosphorus Concentrations (mg/L)

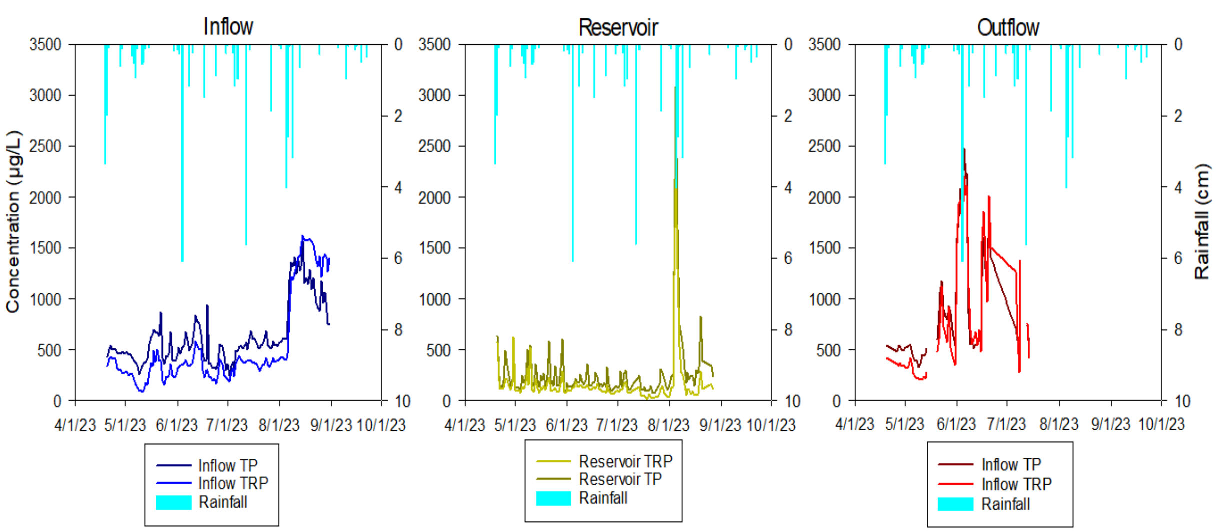

Figure 12: 2023 Lake City Daily Phosphorus Concentrations (µg/L)

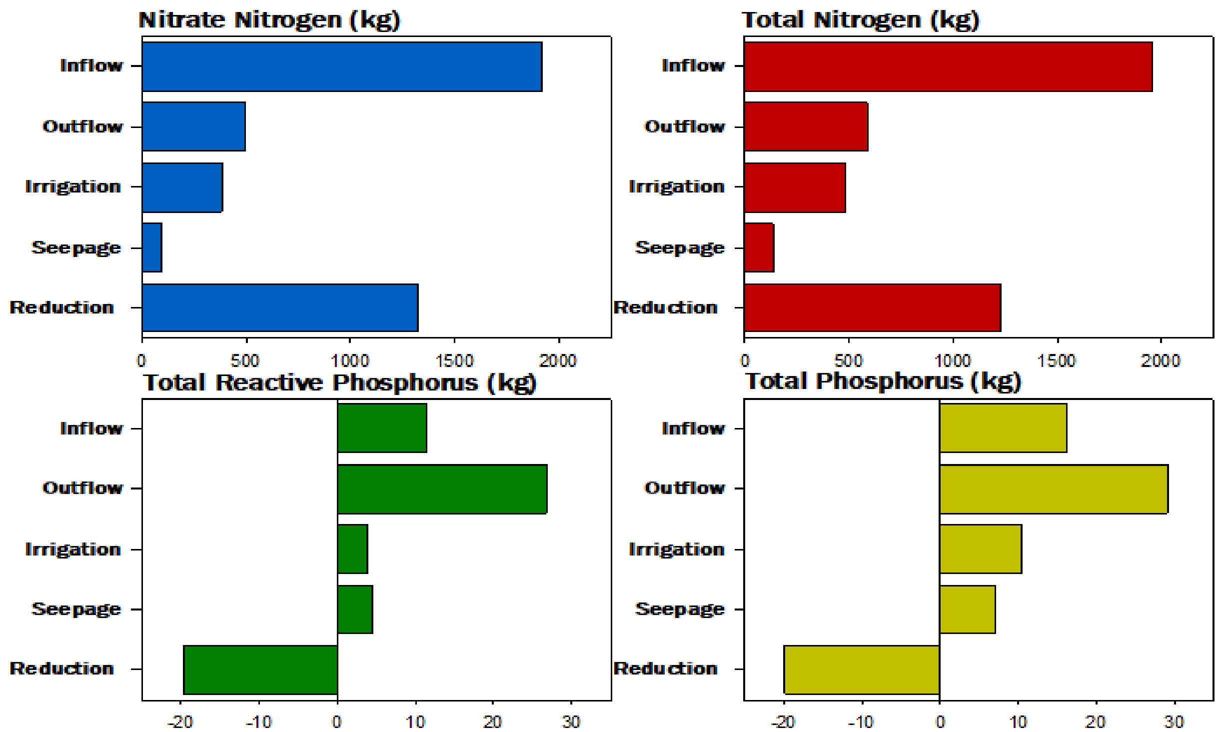

Figure 13: 2022 Lake City Nutrient Loads (kg)

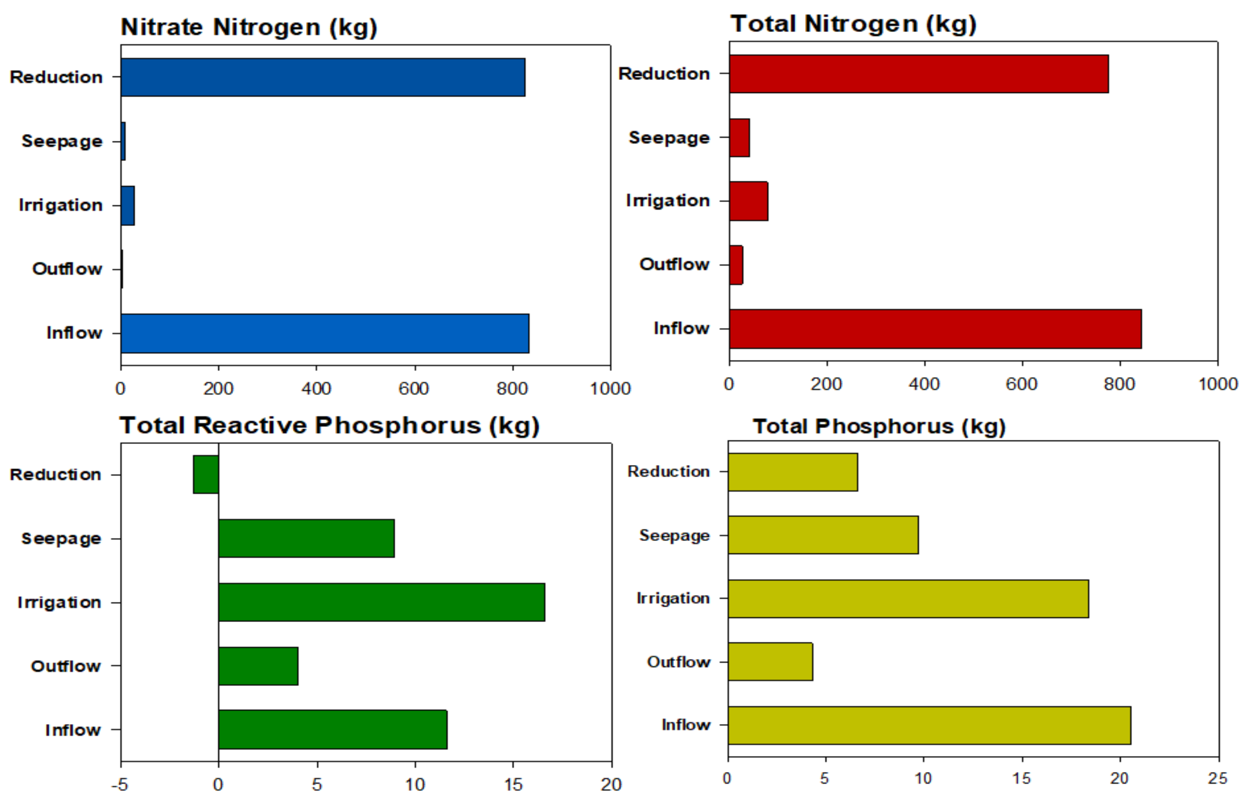

Figure 14: 2023 Lake City Nutrient Loads (kg)

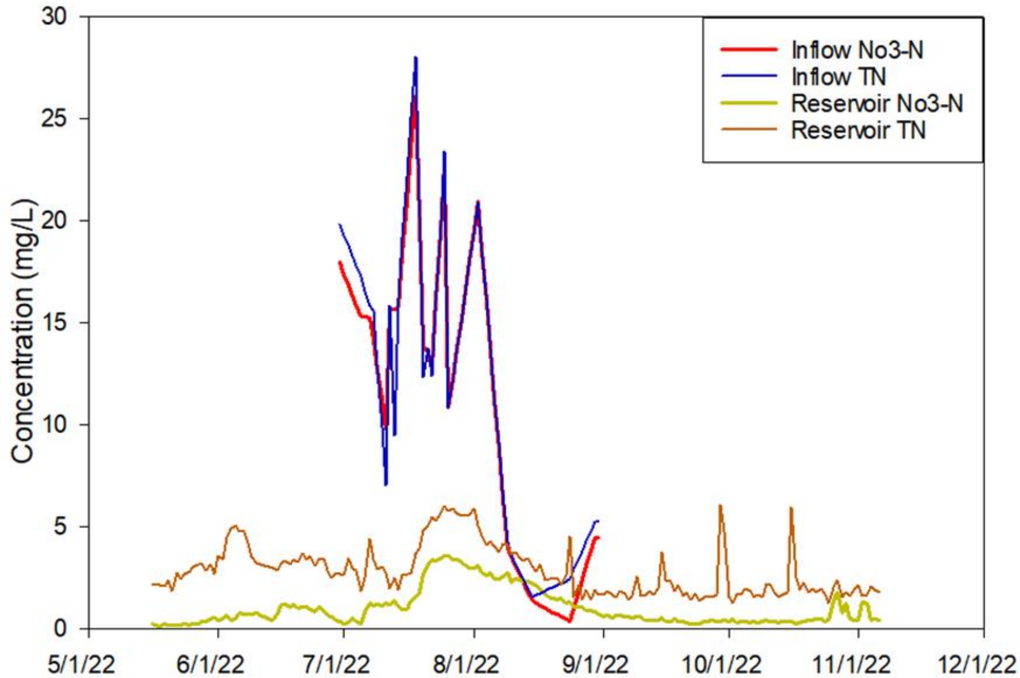

Figure 15: 2022 Story City Daily Nitrogen Concentrations (mg/L)

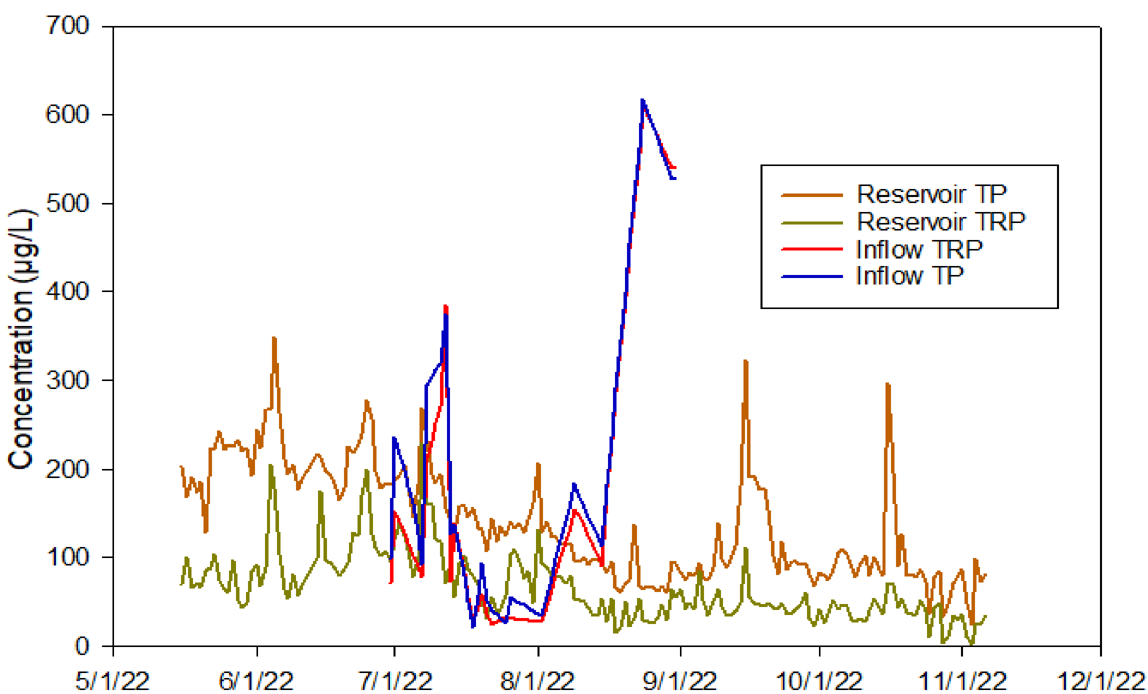

Figure 16: 2022 Story City Daily Phosphorus Concentrations (µg/L)

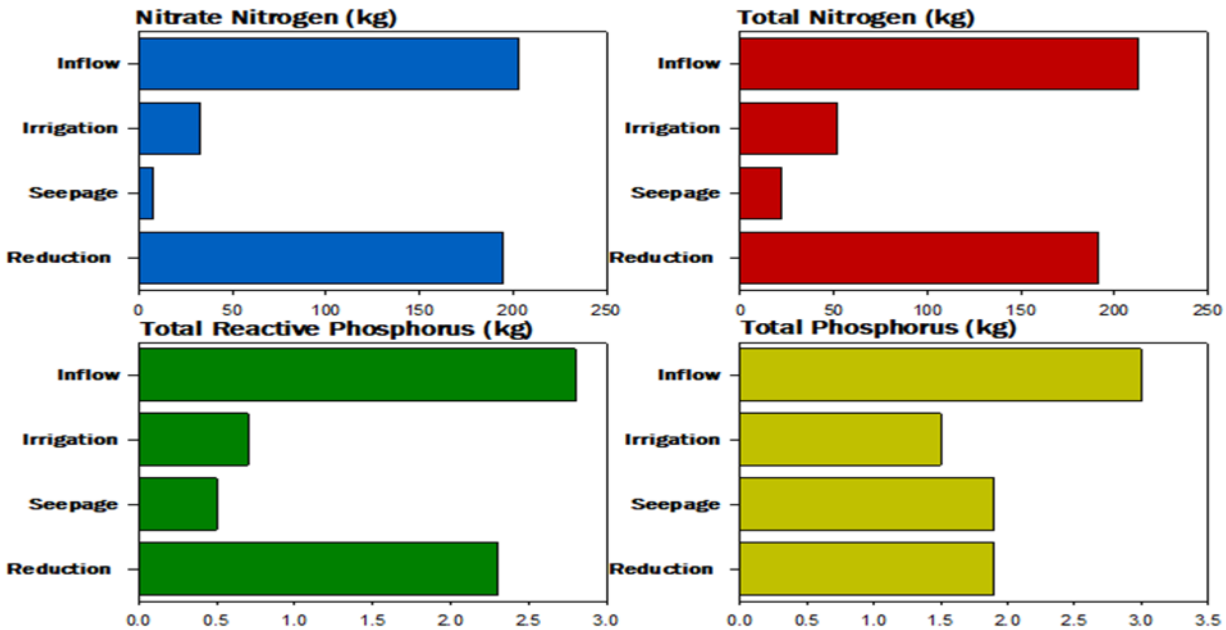

Figure 17: 2022 Story City Nutrient Loads (kg)

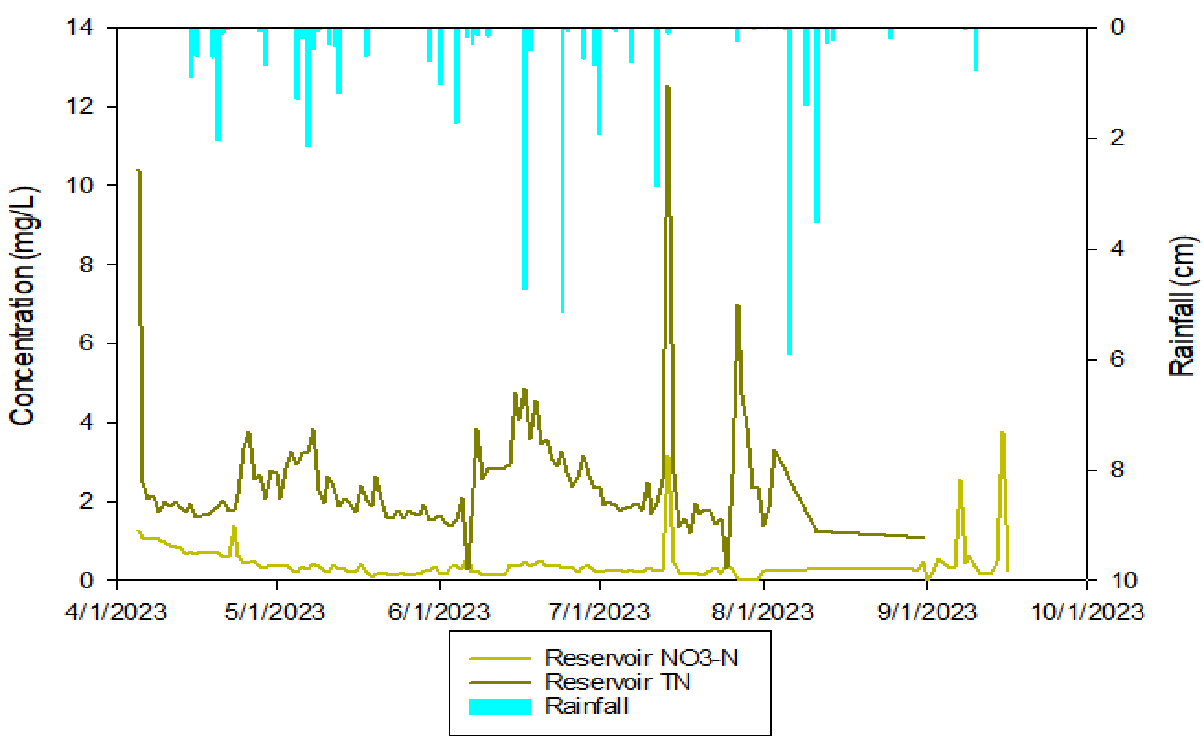

Figure 18: 2023 Story City Daily Nitrogen Concentrations (mg/L)

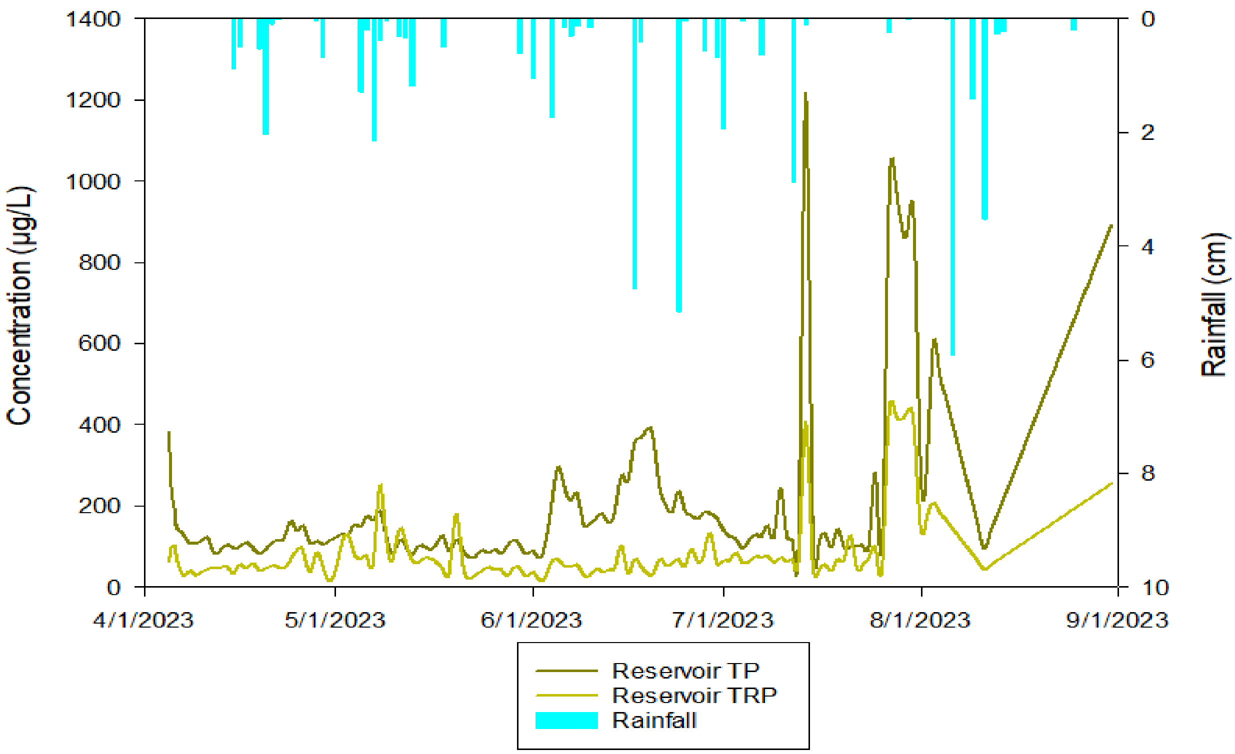

Figure 19: 2023 Story City Daily Phosphorus Concentrations (µg/L)

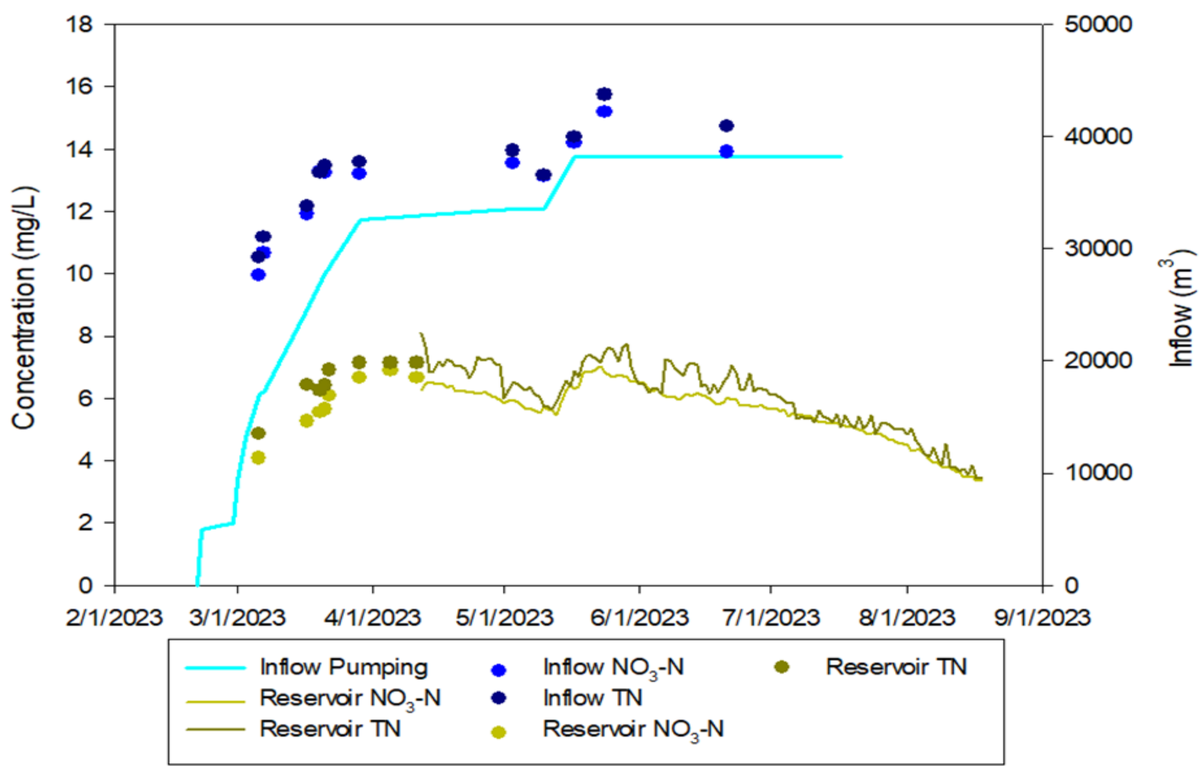

Figure 20: 2023 Dayton Daily Nitrogen Concentrations (mg/L)

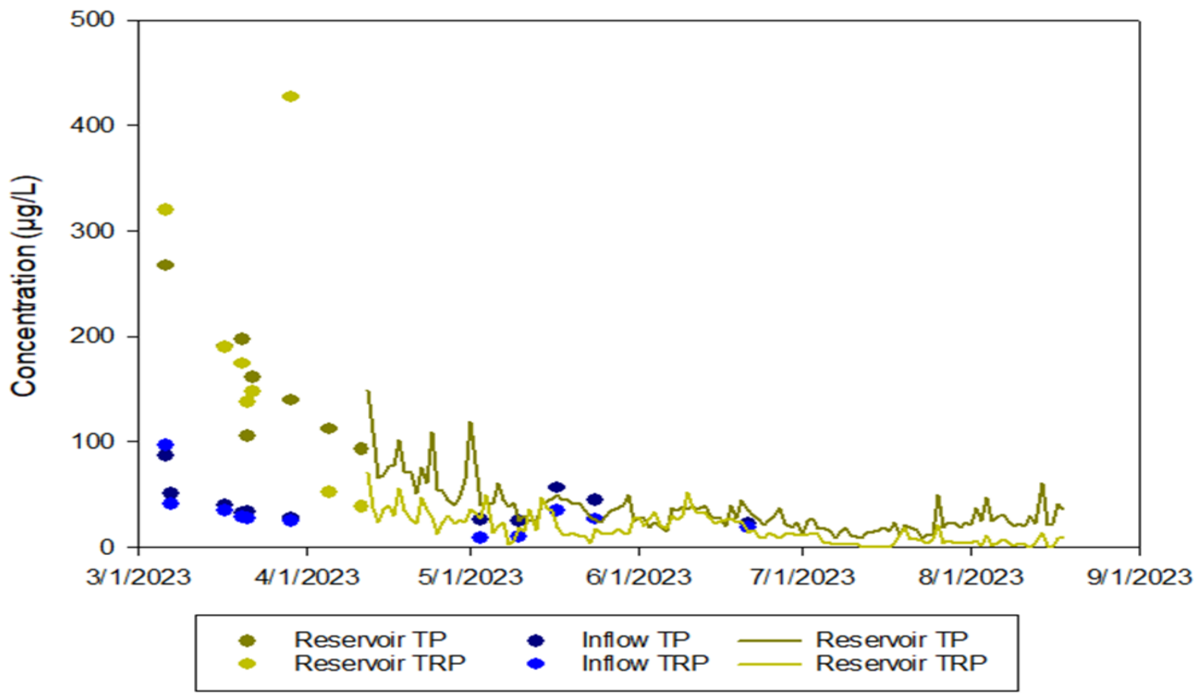

Figure 21: 2023 Dayton Daily Phosphorus Concentrations (µg/L)

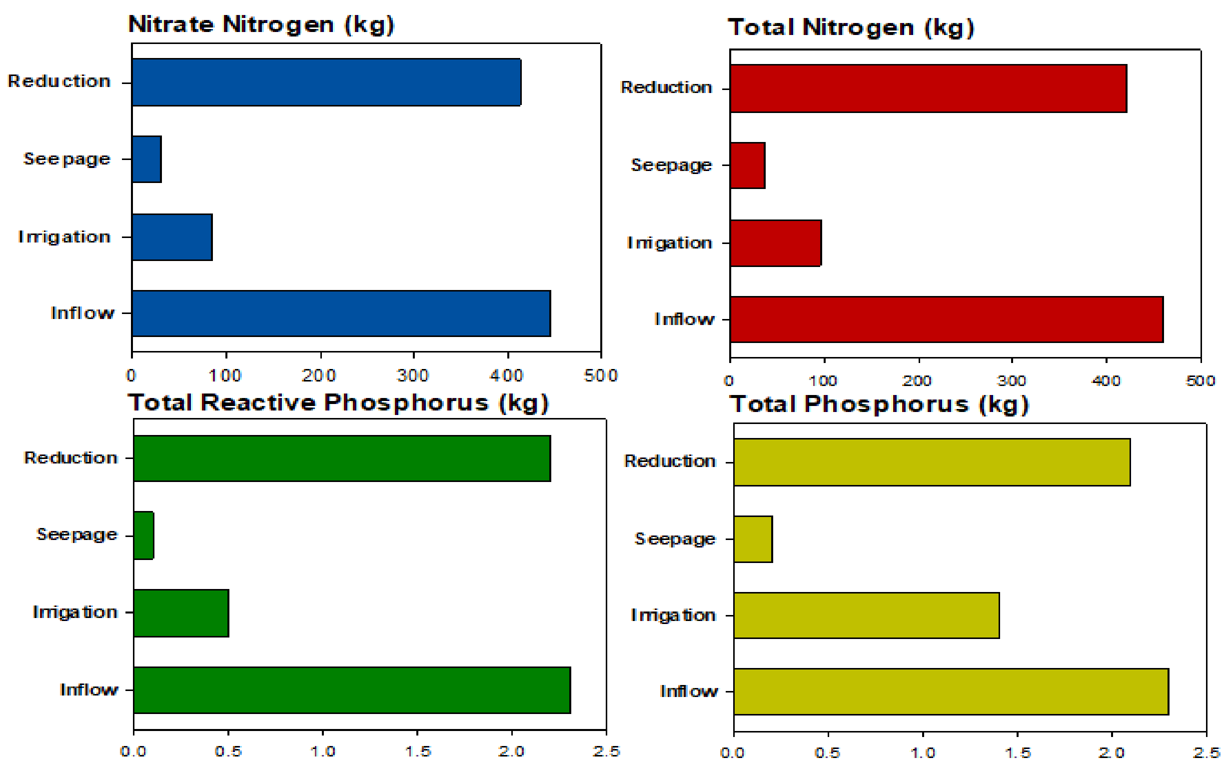

Figure 22: 2023 Dayton Nutrient Loads (kg)

CHAPTER 3. GENERAL CONCLUSIONS

While DWR is a new and understudied practice, understanding its capability to aid farmers as a management tool and aid conservation via nutrient reduction is essential to help continue its growth in usage. This thesis examines the nutrient reduction capability of three different DWR systems, each with varying aspects of design that may impact the nutrient reduction of the system. Chapter 2 indicates that all sites have shown the capacity to reduce nitrogen levels within stored water by 63% to 96%, but phosphorus reduction remains to be fully understood. While some locations reduce phosphorus by up to 82%, the export of phosphorus from Lake City is not fully understood and requires further investigation. There are questions yet to be answered regarding DWR nutrient reduction as well as other facets of the practice. What is driving the phosphorus export at Lake City, and can the DWR system design change to help prevent phosphorus export in future locations? Will the nutrient dynamics change over time as the systems age? Will the systems be as effective under different climate conditions? Could different structure designs of DWR reservoirs be more conducive to nutrient reduction? These are important questions to consider for future research efforts in addition to expanding the practice and finding new locations and designs to monitor.

While this thesis explored the water quality benefits of DWR, many more aspects of the practice need further investigation. Potential research topics for future work include, yield benefits of DWR supplemental irrigation, irrigation scheduling for wetter climates, in-field reduction of nutrient-rich irrigation water within the soil, greenhouse gas emissions (primarily nitrous oxide) from DWR storage reservoirs, additional work as to the economic viability of the practice, and how DWR can serve to increase climate change resilience. With any conservation practice, more implementation will lead to greater results in reducing downstream pollutants but bring about more questions and research opportunities. What are the watershed scale impacts of more widespread DWR implementation? Increasing the knowledge base of the practice by researching these many questions will be crucial for aiding farmers in the potential adoption of DWR.