# IMPROVING SATURATED BUFFER SYSTEMS PERFORMANCE WITH A NEW DESIGN APPROACH AND MANAGEMENT GUIDELINES FROM AN EVALUATION OF A FIELD EXPERIMENT

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# ABSTRACT

Subsurface drainage is needed for maintaining good crop yields in poorly drained lands, mitigating water stress, ensuring field trafficability, and timely agronomic operations. However, it can lead to water quality issues by providing faster routes for nutrients to leave the field resulting in more nitrate loading. Saturated buffers (SB) are conservation drainage practices aimed at reducing nitrate loss. By redirecting a portion of the drainage discharge through vegetative buffers, nitrate is mainly removed via denitrification. Yet, reported effectiveness varies, necessitating a consistent design approach. Current literature is limited, primarily focusing on Iowa and Illinois. Therefore, there's a need for broader understanding of the SB hydrology and nitrate loading functionality. Better understanding can aid in proposing design and management guidelines to enhance SB performance.

We developed a new SB design approach incorporating site-specific conditions to determine the optimal buffer width. Using process-based modeling, we estimated nitrate load removal iteratively across various buffer widths. Performance comparisons with existing SB design approaches utilized modeling and field data from two Michigan sites. SB parameters (buffer width and distribution pipe length) and field data inputs were used to estimate diverted flow and nitrate load removal for each design. Comparison revealed that designs 2 and 3 were equally effective, yielding higher nitrate load removal (20%) than Design 1. Maximizing diverted flow didn't improve nitrate removal, emphasizing the need to target maximum nitrate load removal directly while considering site-specific characteristics.

We developed a DRAINMOD-based decision-support tool for SBs (DBDSTSB), to incorporate the new design approach and facilitate its use. Moreover, we validated its prediction performance of the flow and nitrate load parameters utilizing published evaluation criteria of standard statistical indicators and measured data from two fields in Iowa. The DBDSTSB showed “good” performance in predicting annual field drainage, diverted flow to buffer, nitrate load in drainage, and nitrate load removal by SB. The DBDSTSB’s predictions of the long-term average annual percentages of diverted flow and nitrate load removal were also reasonable, where their deviations from the corresponding measured values amounted to only 1% and 2%, respectively.

We conducted an SB field study to assess the stacked CD+SB system's performance and component contributions in reducing drainage discharge and nitrate loading from tiled agricultural fields. The study, from Jun 2019 to Feb 2024 in Michigan, employed a paired-field approach. The stacked CD+SB system notably reduced drainage discharge and nitrate load of free drainage (FD) by annual averages of 43.1% and 83.4%, respectively. The CD component played a major role in these reductions (44.1% and 82.5%, respectively). Conversely, the SB only slightly contributed to overall nitrate load reduction (0.9%). Mild management of the stoplogs, with depths greater than 50 cm, caused backflow and additional nitrate load from the SB. Conversely, intense management, with depths around 30 cm, limited the backflow volume.

In conclusion, DBDSTSB facilitates the new design's use and provides credible quantification of SB performance. This can support nitrate trading programs, promoting SB adoption for enhanced nitrate removal. Stacking SB with CD and employing intense management has the potential to improve nitrate removal performance.

To my mom. Words cannot express my love and gratitude to you. Your unconditional love and support, and countless sacrifices will always be the main reason to anything good I accomplish. To my wife and son. You are both blessings to my life motivating me to do better.

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# 1. CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

With the ever-growing increase in population and food demands, agricultural drainage is indispensable to maintain adequate yields, especially in areas that are naturally poorly drained. Agricultural drainage, particularly referring to conventional subsurface drainage, provides adequate conditions for crop growth as it reduces the stress from excess water (Helmers et al., 2012), provides means to flush soil salinity and can ensure field-trafficability for conducting timely agronomic operations (Evans and Fausey, 1999). On the other end, subsurface drainage provides faster routes for nutrients to escape the field and can cause more nitrate loading to receiving water bodies (Ghane et al., 2016; Mrdjen et al., 2018; Kokulan et al., 2019). Excessive leaching of the nutrient-rich water leads to its accumulation in the receiving water streams. Excessively high nutrient levels alter the chemical and biological balances of water bodies leading to water quality deterioration. Eutrophication and dead zones could eventually develop in water bodies with deteriorated water quality, as the case in the Gulf of Mexico (Goolsby, 2000) or at Lake Erie (Gatz, 2017).

Eutrophication of water bodies is a widespread hazard that can become worse over time if not addressed adequately. More than 400 locations around the world with an area exceeding 245 thousand $km^2$ have conditions that are considered a stage of eutrophication or can foster eutrophication (Diaz and Rosenberg, 2008). If not stimulated, eutrophication develops slowly representing the natural aging of water bodies (Greeson, 1969). But the excessive abundance of nutrients inside the water body in the presence of favorable water current and sunlight conditions promotes the growth of algae and phytoplankton speeding up eutrophication (Greeson, 1969; Smith et al., 1999; Anderson et al., 2002). If not addressed, eutrophication of water bodies is a continuous cycle that only gets worse with time. The decay of dead algae and other living organisms release more nutrients in the water which in turn promotes the growth of more algae and causes more depletion of dissolved oxygen and dead zones creation (NOAA, 2017).

Eutrophication and elevated nutrient levels in surface water cause societal, ecological, and economic concerns. The unpleasant smell and greenish color of water bodies suffering from eutrophication can limit the use of water bodies in recreational activities. At high pollution levels, for health safety, shutting down of polluted water bodies will further limit our available water resources. An example of this already occurred in 2014 where a tap water usage ban was issued for Toldeo, OH, as the harmful algae in Lake Erie affected the drinking water utilized by the city (Gatz, 2017). Eutrophication can also result in considerable economic losses. Examples of reported financial losses caused by eutrophication include tourism revenue losses at Ohio lake, exceeding 37 million USD, and fishing harvest losses caused by algal blooms at Maine coast, exceeding 2.5 million USD, (EPA, 2015). Other economic losses that could occur are the reduction in property value that are close to the waterfront of the affected water bodies, and the increased costs for human health treatment that develop from coming in contact with the polluted waters or consuming fish or other species that exist in these waters.

The fish kill incidents at some of the polluted water bodies and deterioration of water quality raised public awareness towards the negative off-site impacts of agricultural drainage. This increased the need to develop new, and enhance existing, conservation practices to reduce the negative water quality impacts of crop production. One category of these conservation practices that proved its effectiveness is the application of edge-of-field drainage management systems (such as controlled drainage, shallow drainage, and saturated buffers).

Controlled drainage (CD) is a conservation drainage practice that manages the drainage discharge leaving the field from the subsurface drainage system. In this system the main collector is connected to a control structure in which stoplog boards are set at a desired depth from the ground surface to limit the drainage discharge outflows. Field soil water that is deeper than the level of the stoplog will remain stored in the field soil. Drainage discharge only occurs for the portion of water that is above the stoplog set inside the control structure. Review studies of CD performance at 20 field sites across the Midwest, Eastern US and Canada showed that CD reduced drainage discharge by 18 to 80% and nitrate loading by 18% to 79 % as compared to the conventional drainage (Skaggs et al., 2012a). A recent meta-analysis study that investigated CD effects using data from multiple modeling studies reported that the average reductions in drainage discharge and nitrate losses under CD practice were 30.5% and 33.6% respectively as compared to conventional drainage (Kęsicka et al., 2022).

Shallow drainage (SD) is a conservation drainage practice that is similar to CD. In this practice the stoplogs in the control structure can be dispensable while having similar benefits to CD. The reason of achieving similar benefits with no management is because in SD the laterals are installed at a shallow depth, and only the water above the laterals depth will leave through the drainage system. Field studies showed that the average reduction in drainage outflows and nitrate losses under shallow drainage were 42% and 27% respectively (R. Burchell II et al., 2005), and can reach up to 58% and 49 %, respectively, (Schott et al., 2017). Modeling showed that shallow drainage can reduce drainage outflows by an average of 40% and the nitrate losses by a range between 35% to 56% depending on the meteorological conditions (Craft et al., 2018).

Unfortunately, despite the efforts made to limit the detrimental effects of eutrophication on natural ecosystems, eutrophication is a major problem that still persists and needs more attention. EPA and NOAA reports for year 2019 show that target levels of nutrient loadings and numerous water quality indicators were not met at many of the polluted waters. This calls for the need to further reduce the nutrient loadings from sources. This can be achieved by maximizing the performance of conservation practices, stacking with other agronomic or conservation drainage practices, and through large-scale application of conservation practices.

There are other edge-of-field conservation drainage systems that can be stacked with conservation drainage practices like CD and SD. Separately, these systems were proven effective in reducing the nutrient loading of field drainage, such as denitrifying bio-reactors (Christianson et al., 2021), drainage water recycling (Reinhart et al., 2019; Hay et al., 2021), and saturated buffers (Jaynes and Isenhart, 2019a). Stacking conservation practices will result in further nutrient loading reduction of the field drainage discharge, better water quality and consequently help alleviate Eutrophication problems.

Saturated buffer (SB) is a conservation drainage practice that is designed to reduce nitrate loss from subsurface-drained farms (NRCS, 2018). In this system, a portion of the drainage discharge is redirected into perforated distribution pipes that run underground along the length of the buffer (Jaynes and Isenhart, 2014). As water moves out of the perforated distribution pipes, it seeps through the soil toward the ditch, and nitrate is removed via denitrification as it moves through the buffer soil (Groh et al., 2019). An investigation on the performance of a SB system in Iowa showed that the nitrate concentration of the field drainage discharge decreased at a rate of 0.11 mg/l/m of the buffer width (Streeter and Schilling, 2021).

Multiple field studies have proven the efficacy of saturated buffers (SBs) to reduce nitrate loads in drainage water. Johnson et al., (2023) reported an average annual nitrate load removal of 46% for a dataset that included 30 site years across multiple SB sites in the Midwest. The average percentage reduction of the yearly nitrate load in drainage discharge across six SB sites in Iowa amounted to about 44% (Jaynes and Isenhart, 2019a), and it amounted to 48% across three sites in Illinois (Chandrasoma et al., 2022).

Despite the relatively high reported average nitrate load reductions of SBs, there is considerable variability between sites and between years at the same sites. Across the published literature, annual nitrate load removal ranged from 7% to 92% (Johnson et al., 2023). Jaynes and Isenhart, (2019a) reported annual nitrate load reductions for a single site ranging from 31% to 56%, and inter-site average nitrate load reductions ranging from 8% to 84% across six sites in Iowa. Chandrasoma et al., (2022) reported the largest inter-annual range of nitrate load reductions within a single SB site in Illinois (19% to 73%), and the largest range of the inter-site nitrate load reductions was 19% to 77% across three sites .

Geospatial analysis have demonstrated the potential for large-scale SB implementation in the Midwest to reduce regional nitrate loading (Chandrasoma et al., 2019; Tomer et al., 2020). The extent of SB-suited sites across multiple watersheds in Iowa were mostly greater than 30% of the streambank length, which can serve about 15% to 40% of the subsurface-drained areas in these watersheds (Tomer et al., 2020). Also, Chandrasoma et al., (2019) reported that about 50% of the total length of streambanks in the Midwest is suitable for SB implementation. The same study estimated a 5% to 10% reduction in nitrate load to the Mississippi River with the large-scale adoption of the practice. This reduction may represent a conservative estimate since the study assumed a nitrate loss percentage reduction from SB of 23% which is lower than the reported average of the practice. The reported performance of the SB system in these different studies shows the great potential of the practice in reducing nitrate loads from croplands, which subsequently helps achieving N-reduction goals at watershed and river basin scales.

Wide ranges in nitrate load removal were reported in an assessment of existing SB systems across multiple sites in Iowa, despite the soil similarity between some of the investigated sites (Jaynes and Isenhart, 2019a). Percentages of annual nitrate load removal ranged from 8% to 84% (Jaynes and Isenhart, 2019a). The absence of a site-specific design approach for SB systems could be the reason behind the variations in the reported nitrate load removal at these sites. Macrae et al., (2021) reported that generally for conservation practices a one-size-fits-all approach may not result in considerable nutrient reduction. This mainly occurs as a result of the differences in climate, soil, topography, and land use which necessitates implementing a site-specific approach for conservation practices (Macrae et al., 2021). Thus, an improvement to SB design criteria is required, so all saturated buffers are designed to have a satisfactory performance.

To the best of our knowledge, there are two available SB design criteria: Illinois Natural Resources Conservation Service (Design 1) and McEachran et al., (2020) (Design 2). Design 1 is based on choosing a distribution pipe length to handle 5% of the drainage capacity from the drainage area providing water to that buffer, which is a one-size-fits-all minimum 5% design criterion. Design 1 depends on a user defined buffer width, and it limits the distribution pipe length calculation only to the diverted flow to buffer without considering the nitrate load removal. As for Design 2, it uses a single equation to calculate the optimum buffer width that would maximize the effectiveness of nitrate load removal of the system, regardless of the distribution pipe length. Both design criteria are only implemented at one point in time that reflects an average flow condition for the SB system. As a result of that, these designs cannot capture the changes in the system's performance as impacted by changes in field flows, weir management, or soil conditions. The development of a new design criterion that would account for the impact of the temporal variability of site conditions on the SB system would help obtain further understanding of the system and choose the design parameters in a way suiting the site-specific conditions and thereby maximizing the nitrate load removal of these systems.

The high potential for widespread SB implementation to reduce nitrate loading across the Midwest and variability in performance demonstrates the need for additional research to improve design and performance. Few modeling studies were conducted to understand the SB functionality or to improve the SB design. Jaynes and Isenhart, (2019b) used the Hydrus2D model to investigate the impact of the distribution pipe configuration on the infiltration characteristics and residence time in the buffer soil using measured data for an SB site in Iowa. McEachran et al., (2023) utilized the MODFLOW model to examine how water moves from the distribution pipe to the ditch in an SB in Iowa. They also formulated a one-dimensional equation to predict the time it takes for water to travel through the buffer soil after diversion. However, the use of such models requires a high level of modeling expertise, estimating the site-specific performance of SB under different designs, soil properties and climatic conditions can be challenging.

A decision-support tool is one convenient method that can aid with the design and evaluation of SBs based on local soil, weather, and drainage design conditions. Multiple user-friendly tools were developed to facilitate the design of drainage systems or as a method to evaluate the performance of other conservation drainage practices. Ghane and Askar, (2021) used empirical regression equations based on DRAINMOD simulations to develop an online tool to estimate the cost-effective drain spacing for subsurface drainage systems that would maximize the annual return on investment for corn-soybean rotation given simple user inputs. Guo et al., (2020) validated the performance of the Nutrient Tracking Tool (NTT) to provide acceptable annual crop yields, water balance, and nutrient loading predictions at the field scale in northwest Ohio using a set of parameters calibrated for this region. These tools can facilitate the design or improve the decision-making process regarding the use of conservation practices such that the benefits are maximized without the need of expertise in running complicated models. However, there is no similar tool for the SB system. Therefore, there is a need for an SB decision-support tool that can provide an acceptable representation of the hydrology and nitrate load removal performance of the practice.

Gaining knowledge and understanding of the functionality of the SB systems would aid in developing better SB design approaches and management guidelines that can improve the effectiveness of the system. Also, stacking conservation drainage practices is expected to result in greater nitrate load removal. Controlled drainage and saturated buffers practices can be stacked together since they are both implemented at an edge-of-field water control structure.

Multiple field studies investigated the hydrology and nitrate load removal performance of CD, but limited studies were conducted for SB. A review by Mitchell et al., (2023) showed that only across the corn belt region in the US, 48 studies investigated multiple aspects related to the performance of CD and 26 out of these studies used field data in their analysis. On the other hand, the same review study showed that only 13 studies were related to SB. Up to our knowledge, there are six of field studies that used measured data to investigate few of the aspects related to the hydrology and nitrate removal performance of SB. Three of these field studies were conducted in Iowa (Jaynes and Isenhart, 2014, 2019b; Streeter and Schilling, 2021), and notably the studies by Jaynes and Isenhart (2014, 2019b) reported the data of the same SB site along the Bear creek in Iowa. Two studies were conducted in Illinois (Bosompemaa et al., 2021; Chandrasoma et al., 2022). Chandrasoma et al., (2022) reported the hydrology and nitrate load removal performance across three SB sites in Illinois, while Bosompemaa et al., (2021) investigated only the impact of the buffer’s vegetation on the nitrate concentration within the vadose zone.  A single study was conducted in Ohio, but the focus of this study was on the reduction of nitrate concentration across the buffer width, so the hydrology and nitrate load removal performances were not reported (Jacquemin et al., 2020). Therefore, there is a need to conduct more field studies that investigate the hydrology and nitrate removal performance of SBs at different locations due to the limited number of publications in this field.

The considerable variations in the reported percentages of diverted flow to edge-of-field buffers and nitrate load removal by SBs (Jaynes and Isenhart, 2019b; Chandrasoma et al., 2022; Johnson et al., 2023; Mitchell et al., 2023) calls for better understanding of the hydrology and the nitrate loading dynamics in SB systems. Additionally, published work on the nitrate load removal performance of SBs reported the combined performance of the CD and SB system and did not study the contribution of each component. Therefore, there was a need to evaluate the drainage discharge and nitrate load reduction performances of a stacked CD and SB system (CD+SB) in Michigan, and the contribution of each of the CD component and the SB component.

This research work has two main objectives that aim to improve the nitrate load removal performance of saturated buffers. The first objective was to propose a new design approach for SBs and facilitate its use, where the specific tasks of the first objective were to 1) propose a new SB design approach that considers site-specific characteristics, 2) compare the performance of the proposed new SB design and the available SB design approaches to identify the optimum approach that would maximize the nitrate load removal, and 3) develop a decision-support tool for SB that uses the optimum design approach and test its prediction performance of the yearly field drainage discharge, nitrate load in drainage water, diverted flow to the buffer and nitrate load removal and the average annual performance metrics of SBs (average annual percentages of the diverted flow to buffer and the nitrate load removal).

The second objective was to gain more knowledge and understanding of the hydrology and nitrate load removal performance of SBs, where the specific task related to this objective was to 4) evaluate the hydrology and nitrate load performance of a stacked SB and controlled drainage system in Michigan, and the contribution of each of its components (the controlled drainage component and the saturated buffer component).

# 2. CHAPTER 2: DEVELOPMENT OF A NEW DESIGN APPROACH FOR SATURATED BUFFERS

## 2.1. Abstract

A saturated buffer (SB) is a conservation drainage practice that removes nitrate from subsurface drainage discharge. The reported wide range of nitrate load removal necessitates improvement in SB design approaches to ensure more consistent performance of the practice. There are two SB design approaches: Illinois Natural Resources Conservation Service (Design 1) and McEachran et al., (2020) (Design 2). We proposed a new design approach (Design 3) that builds on the previous two designs. Design 3 uses a main routine to simulate the hydrology and estimate the nitrate load removal across a range of buffer widths (3 to 30 m with 0.3-m intervals) to determine the optimal buffer width that will result in the maximum long-term nitrate load removal. Design 3 ensures an overall effective performance of the SB under diverse hydrological and buffer soil conditions that characterize a location, instead of limiting the effective performance to a single-point-in-time condition. It assesses the long-term performance of numerous designs under the variations in field drainage discharge, hydraulic head, and the buffer soil nitrate removal coefficient over time. Also, it provides better representation of SB by considering the exit head loss as water leaves the perforated distribution pipe into the buffer soil. Despite the mentioned improvements, Design 3 is based on many assumptions and has many limitations that can be addressed in future research work. The value of this work is that the improved design approach will result in better SB systems with consistent adequate nitrate load removal performance and thereby can lead to better water quality.

## 2.2. Method Description

### 2.2.1. Governing equations of a saturated buffer

The governing equations of a SB system can be classified into hydrological and biogeochemical components. The hydrological component is responsible for water movement from the pipes, to and through the buffer soil, and to the open ditch. The biogeochemical component is responsible for the processes of removing nitrate. In this section, we describe the governing equations.

Flow equation: Based on McEachran et al., (2020), the flow through buffer soil can be represented by the Dupuit equation, that describes water movement through porous media in an unconfined aquifer as expressed in Equation 2.1. In this setting, steady-state flow conditions is assumed to be an applicable representation of water movement through the buffer soil.

$$Q_{DP} = K\frac{(h_1^2 - h_2^2)}{2W} L_{DP} \tag{2.1}$$

where

$Q_{DP}$ = diverted volumetric flow into the buffer soil (cm$^3$/day),

$K$ = saturated hydraulic conductivity of the buffer soil (cm/day),

$h_1$ = hydraulic head at the distribution pipe (cm),

$h_2$ = hydraulic head at the open ditch (cm),

$W$ = width of the buffer (cm), and

$L_{DP}$ = length of the distribution pipe (cm) (Fig. 1).

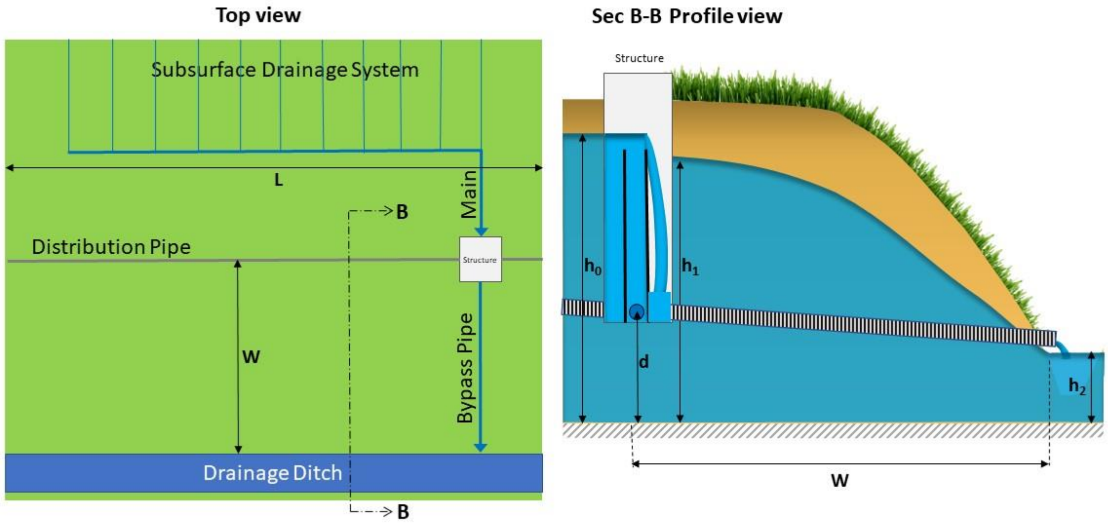


Figure 2.1. Top view and cross section B-B showing the design parameters of saturated buffer and the parameters of the Dupuit and head loss formulas.

Head loss equation: In subsurface drainage, entrance head loss occurs as flowlines converge toward the pipe perforation (Skaggs, 1991). In a SB system, the distribution pipe functions as a subirrigation pipe where exit head loss occurs as water moves out of the pipe and enters the surrounding soil (Skaggs, 1991). The diverted flow to the buffer and the exit head loss can be represented by the effective radius of the distribution pipe (Skaggs, 1991) as

$$Q_{DP} = -2\pi K \frac{(h_1 - h_0)}{\ln\frac{h_1 - d}{R_{ef}}} L_{DP} \tag{2.2}$$

where

$h_0$ = hydraulic head inside the control structure (cm),

$d$ = distance from the distribution pipe center to the impermeable layer (cm), and

$R_{ef}$ = effective radius of the distribution pipe (cm).

Nitrate removal equation: McEachran et al., (2020) assumed that denitrification is the primary mechanism that removes nitrate from the diverted water to buffer soil, and used a first-order kinetics equation (Equation 2.3) to estimate the nitrate concentration of the diverted flow as it moves through the buffer soil

$$C = C_{DD}\, e^{-\lambda T_u} \tag{2.3}$$

where

$C_{DD}$ = initial nitrate concentration of diverted flow (mg/l),

$\lambda$ = nitrate removal coefficient (1/day),

$C$ = final nitrate concentration of diverted flow at the maximum width of buffer (mg/l), and

$T_u$= time of travel for water to move from the distribution pipe through the buffer width (day).

The time of travel ($T_u$) can be calculated using equation 2.4 (McEachran et al., 2020)

$$T_u = \frac{4}{3}\frac{n_e\, W^2}{K}\frac{{h_1}^3 - {h_2}^3}{\left({h_1}^2 - {h_2}^2\right)^2} \tag{2.4}$$

where

$n_e$ = effective porosity (cm$^3$/cm$^3$).

### 2.2.2. Design approaches for saturated buffers

There are two SB design approaches: Illinois Natural Resources Conservation Service (NRCS) design spreadsheet (Design 1) and McEachran et al., (2020) (Design 2). We proposed a new approach (Design 3) that builds on the previous two designs. In this section, we describe these design approaches.

Design 1: The USDA NRCS design spreadsheet determines the length of a SB system that would divert a minimum of 5% of the drainage system capacity into the buffer soil based on a minimum buffer width of 9.1 m, standard code 604, (NRCS, 2018). This design does not have an optimization function to maximize nitrate removal. The NRCS design criterion is based on one set of inputs at one point in time (i.e., peak flow). The set of inputs includes the hydraulic head at the control structure and at the open ditch, and the drainage system capacity.

Design 2: The second SB design criterion was theoretically developed by McEachran et al., (2020) to determine the optimum width for maximum nitrate removal as

$$W^* = 0.97\left(\frac{K\,({h_w}^2 - {h_2}^2)^2}{\lambda\, n_e\,({h_w}^3 - {h_2}^3)}\right)^{0.5} \tag{2.5}$$

where

$W^*$ = optimum width of the buffer (cm).

$h_w$ = weir level inside the control structure referenced to the restrictive layer (cm).

This design criterion is based on one set of inputs at one point in time. The set of inputs include the hydraulic head inside the control structure (approximated as the weir level) and at the open ditch and the removal coefficient $\lambda$ which can be calculated as suggested by McEachran et al., (2020)

$$\lambda = K_d f_T \tag{2.6}$$

where

$K_d$ = first-order denitrification coefficient (1/day), and

$f_T$ = reduction coefficient affected by temperature (unitless) that can be calculated as reviewed by Heinen, (2006)

$$f_T = Q_{10}^{\,(T - T_r)/10} \tag{2.7}$$

where

$T$ = the soil temperature (°C),

$T_r$ = reference temperature (°C), and

$Q_{10}$ = factor with typical value ranging between 2 and 3.

Design 3: This design builds on the previous two design criteria that used the Dupuit equation and first-order nitrate removal kinetics. Similar to the existing designs, Design 3 assumes that steady state can be used to represent water movement through the buffer system. This design includes a new mechanism that considers exit head loss as water leaves the distribution pipe through perforations and flows into the surrounding soil. Design 3 also considers the behavior of the SB system on a daily basis over several years by accounting for variations in the drainage discharge from the field $(Q_{DD})$, and consequently accounting for variations in the hydraulic head at the distribution pipe $(h_1)$, also the variations in the nitrate removal coefficient $(\lambda)$ as affected by variations in soil temperature. This is in contrast to Designs 1 and 2 that only use single values for $h_1$, $Q_{DD}$, and/or $\lambda$ at one point in time.

In Design 3, daily nitrate load removal was simulated using the main routine presented in the following section. The daily nitrate load removal was estimated for all buffer widths ranging from 3 to 30 m in increments of 0.3 m. The buffer width that maximized long-term nitrate load reduction was chosen as the SB design.

### 2.2.3. Main routine for estimating the daily nitrate load removal

The main routine builds on Designs 1 and 2 and it is composed of a hydrological and nitrate removal component. For the main routine, we assumed that drainage water is managed with a three-chamber control structure. The drainage discharge comes into the upstream chamber, and the distribution pipe comes out of the middle chamber. The weir management of the upstream and downstream chambers were identical. The main routine is described as follows.

Hydrology component: The hydrology component of the main routine includes a water balance model (Equations 2.1, 2.2, 2.8, 2.9, and 2.10), in which two water balance equations are defined. The first water balance equation is a conservation of mass inside the control structure

$$Q_{DD} = Q_{DP} + Q_{BY} \tag{2.8}$$

where

$Q_{DD}$ = the field drainage discharge (cm$^3$/day),

$Q_{DP}$ = the diverted flow (cm$^3$/day), and

$Q_{BY}$ = bypass flow (cm3/day).

The bypass flow was calculated using the calibrated weir equation developed by Chun and Cooke, (2008). The authors' equations can be used for any structure size with a rectangular weir. For the purpose of this paper, we used the 250-mm control structure, written as

$$H = (h_0 - H_{weir}) \tag{2.9}$$

$$Q_{BY} = 1.8144 \times 10^6 \times L_{weir} \times H^{1.37} \tag{2.10}$$

where

$H$ = head over the rectangular weir (cm),

$h_0$ = hydraulic head inside the control structure (cm),

$L_{weir}$ = length of the weir in the control structure (cm),

$H_{weir}$ = height of the weir from the bottom of the control structure (cm), and

$Q_{BY}$ = bypass flow (cm$^3$/day), and

The $1.8144 \times 10^6$ is a unit conversion factor.

The second water balance is applied at the interface between the buffer soil and the distribution pipe, and states that the flow exiting the distribution pipe through pipe perforations (Equation 2.2) should be equal to the flow moving through the buffer soil toward the open ditch (Equation 2.1).

Nitrate removal component: The nitrate load removal component of the main routine involved three steps. Based on McEachran et al., (2020), the first step estimated the final nitrate concentration of the diverted water that reached the ditch after passing through the buffer soil using first-order kinetics for nitrate removal (Equation 2.3). The second step calculated the nitrate load as the product of the volumetric flow times its nitrate concentration (Equations 2.11, 2.12, and 2.13). The third step calculated the nitrate load removal of the system as the difference between the nitrate load in the drainage discharge coming from the subsurface-drained field (the case if there was a free drainage system without a SB system) and the nitrate load reaching the ditch (sum of the loads from the diverted and bypass flows) (Equations 2.14 and 2.15).

$$NLDD = Q_{DD} \times C_{DD} \times 10^{-9} \tag{2.11}$$

$$NLRDB = Q_{DP} \times C \times 10^{-9} \tag{2.12}$$

$$NLBY = Q_{BY} \times C_{DD} \times 10^{-9} \tag{2.13}$$

$$NLLD = NLRDB + NLBY \tag{2.14}$$

$$RNLSB = NLDD - NLLD \tag{2.15}$$

where

$NLDD$ = drainage discharge nitrate load coming from the subsurface-drained field (kg/day),

$NLRDB$ = nitrate load reaching ditch after moving through the buffer soil (kg/day),

$NLBY$ = nitrate load reaching the ditch via bypass flow (kg/day),

$NLLD$ = nitrate load reaching the ditch through both buffer and bypass (kg/day),

$RNLSB$ = reduction in nitrate load due to the SB system (kg/day), and

The $10^{-9}$ is a unit conversion factor.

### 2.3. Assumptions and Limitations of the Proposed SB Design Approach

Although the proposed design approach addressed some of the limitations in the existing designs, it should be noted that there are some main underline assumptions that are considered, and limitations that can be addressed in future improvements.

Similar to existing designs, the new approach assumes that steady state condition is maintained for the flow through the buffer soil to the open ditch. The reason for that was to limit the required inputs and facilitate the use of the proposed design approach. This assumption should provide good approximation of the diverted flow to buffer during most of the year, when the drainage discharge in the control structure has low to moderate values, and in the absence of conditions that would abruptly increase the WTD within the buffer area. On the other hand, during extended large rainfall events or the period during which major thawing of snow occurs, overestimations of the diverted flow to the buffer are expected. The overestimations are due to neglecting the backwater flow from buffer to the control structure that is expected to happen because of the higher hydraulic head gradient between the shallower WTD in the buffer over the distribution pipe ($h_1$) and the deeper hydraulic head inside the control structure ($h_0$). Nonetheless, these excessively inundated periods normally extend for a limited number of days that are relatively incomparable to the remaining days of the year and are usually accompanied by large drainage discharge in the control structure. Reported measurements at a SB in Iowa showed that the abrupt increase in the WTD were for only a limited number of days and most of the time the WTD in the buffer was at or deeper than the distribution pipe depth (Jaynes and Isenhart, 2014). It should be noted that SB practice is mainly effective for diverting base flow drainage discharge, since the diverted flow to the buffer is limited by the infiltration capacity of the buffer soil (McEachran et al., 2020). It should also be expected that the overestimation in diverted flows would be greater in very fine texture soils since their storage capacity is higher and abrupt changes in WTD are more noticeable. But normally the very fine soils are not suited as locations for SB implementation, since their extremely low hydraulic conductivity will significantly limit the infiltration capacity which in turn would significantly reduce the diverted flow to the buffer.

Another main assumption is that the diverted flow was distributed uniformly along the distribution pipe. Although this is not the case in real conditions due to the heterogeneity of the buffer soil along the length of the distribution pipe, but the use of a set of effective values representing the soil properties of the buffer area can still provide adequate representation of the buffer hydrology (Jaynes and Isenhart, 2019b).

Another assumption is that the type of the control structure was a three-chamber structure, i.e. the stoplogs controlling the drainage discharge flow in the field are located in the first chamber and are different from the stoplogs maintaining the head over the distribution pipe of the SB in the second chamber. For the three-chamber structure, the water head in the second chamber due to the presence of the stoplogs can only divert water to the distribution pipe. This is different from the case of using two-chamber structure, since both the distribution pipe and the field collector outlet are in the same chamber, and there is only one location for the stoplogs. So, the developed water head in the structure can push the water through both pipes.

Other limitations of the proposed design approach, in terms of the SB hydrology, was not considering the effect of evapotranspiration and infiltration on the calculated diverted flow to the buffer. This was to limit the required user input and preserve the simple use of the design approach. Published modeling and field research that studied SB did not report significant impact of ET or infiltration on the overall hydrology or the nitrate load removal of SB (Jaynes and Isenhart, 2014, 2019a; McEachran et al., 2020, 2023). It should be noted that these studies focused their analysis on the spring period because this is the period during which most of the nitrate load export occurred. Possible underestimations of the diverted flow to buffer could occur if ET was ignored during periods of high ET when the drainage discharge values are near the buffer soil infiltration capacity or higher. During this period ET can represent another sink for the diverted water in addition to the water movement through the buffer soil to the ditch. This will increase the capacity to divert water to the buffer from control structure and not limit it only to the hydraulic characteristics of the buffer soil. But it is rare to have relatively high drainage discharge events during summer. As for the impact of infiltration, it was described previously in the paragraph related to the steady flow assumption.

The water-table position and soil temperature within the buffer soil can limit denitrification or affect other processes mediating the nitrogen balance such as organic carbon decomposition or nitrogen mineralization/immobilization (Youssef et al., 2005). The water-table position in the buffer soil defines the available soil-water pore space, the available soil organic carbon content, and the soil organic carbon decomposition (i.e., shallower layers have more labile organic carbon with higher content) (Youssef et al., 2005). Also, the first-order kinetics method does not have a limit for the nitrate substrate that can undergo denitrification, unlike other methods (e.g., Michaelis-Menten model). Therefore, improvements are needed to the nitrogen load removal component of the main routine in Design 3 to have a better representation of the processes impacting the nitrate removal in the buffer soil, although this will limit the use of Design 3 due to the increase in complexity and the additional input data requirements.

## 2.4. Summary

This chapter provided a description of the existing approaches to design the saturated buffer system. The chapter also provided a description of the newly proposed approach that was built on the existing designs. The chapter presented the theoretical formulation of the main routine used to simulate the hydrology and nitrate load removal in a saturated buffer of known characteristics. It also provided a description of the method used to identify the optimum buffer width parameter. Finally, the chapter presented the assumptions and limitations pertaining to the proposed design approach.

# 3. CHAPTER 3: COMPARISON OF NEWLY PROPOSED AND EXISTING DESIGN CRITERIA FOR SATURATED BUFFERS

## 3.1. Abstract

Saturated buffers (SBs) are pivotal in removing nitrate from subsurface drainage discharge. However, the choice of the SB design approach significantly impacts their performance. In this study, we evaluated three design approaches: Illinois Natural Resources Conservation Service (Design 1), McEachran et al.'s method from 2020 (Design 2), and our proposed Design 3. Using daily drainage discharge data from two Michigan field sites, we used each design approach to determine the distribution pipe length and buffer width of the hypothetical SB at each field site. The comparison involved applying a uniform method to estimate nitrate load removal for each hypothetical SB system, incorporating hydrological and nitrate removal components. Our findings revealed that Design 1, with a minimum buffer width of 9.1 m and a 5% SB design capacity, resulted in 25% to 35% diverted flow to the buffer and 14% to 16% nitrate load removal at both field sites, consistently underperforming Designs 2 and 3 (i.e., 0.3% to 3.4% lower nitrate removal). On the other hand, designs 2 and 3 consistently provided maximum nitrate load removal regardless of the site conditions. In conclusion, designs 2 and 3 were equally good and resulted in higher nitrate load removal compared to Design 1, indicating their potential for enhancing the nitrate load mitigation from SB.

## 3.2. Introduction

Although subsurface drainage is essential to increase crop production, it also transports nitrate to surface water (Ghane et al., 2016). Elevated nitrate levels in surface water cause societal, ecological, and economic concerns (USEPA, 2013). The hypoxic zone in the northern Gulf of Mexico is caused by excess nitrate, primarily originating from subsurface-drained farms in the Upper Mississippi River basin (USEPA, 2018). Therefore, there is a critical need to reduce nitrate loss from subsurface-drained farms using conservation practices.

Saturated buffers (SB) are a conservation drainage practice that are designed to reduce nitrate loss from subsurface-drained farms (NRCS standard 604) (Jaynes and Isenhart, 2014; NRCS, 2018). In this system, a portion of the drainage discharge is redirected into perforated distribution pipes that run underground along the length of the buffer (Jaynes and Isenhart, 2014). As water moves out of the perforated distribution pipes, it seeps through the soil toward the ditch, and nitrate is removed via denitrification as it moves through the buffer soil (Groh et al., 2019).

The SB system removed an average of 45% total nitrate load from drainage discharge in Iowa (Jaynes and Isenhart, 2018). Streeter and Schilling, (2021) have also found that the nitrate concentration of the field drainage discharge decreased at a rate of 0.11 mg/l/m of the buffer width in a SB in Iowa. Other studies showed the potential of using SB systems as a strategy to alleviate N loss in the Midwest and help meet N-reduction targets (Chandrasoma et al., 2019, 2022; Jaynes and Isenhart, 2019a; Tomer et al., 2020). Nonetheless, annual percentages of nitrate load removal ranged from 8% to 84% (Jaynes and Isenhart, 2019a). The wide range of nitrate removal necessitates improvement in design approaches, so all saturated buffers are designed to have a satisfactory performance.

The USDA Natural Resources Conservation Service (NRCS) uses the Illinois NRCS design spreadsheet to design SB. That design approach is based on choosing a distribution pipe length to handle 5% of the drainage capacity from the drainage area providing water to that buffer

(Design 1), which is a one-size-fits-all minimum 5% design criterion. Wide ranges in nitrate load removal were reported in an assessment of existing SB systems across multiple sites in Iowa, despite the soil similarity between some of the investigated sites (Jaynes and Isenhart, 2019a). Macrae et al., (2021) reported that a one-size-fits-all approach may not result in considerable nutrient reduction. Thus, it is even harder to predict the performance of the same design at regions that have very different climate, soil, topography, and land use which necessitates implementing a site-specific approach as stated in Macrae et al., (2021).

The second design approach was developed by McEachran et al., (2020), which proposed using a theoretically developed equation for estimating the SB width (Design 2). The authors' equation provides an optimum buffer width that would maximize the nitrate load removal effectiveness without the need for using the drainage capacity as an input.

The third design approach (Design 3) was proposed in the research work presented in Chapter 2. Design 3 systematically assesses nitrate load removal across a range of buffer widths (3 to 30 m with 0.3-m intervals) to determine the optimal buffer width for long-term nitrate reduction. Design 3 considers the variations in the incoming drainage discharge, the weir management over the year, and the nitrate removal coefficient as impacted by seasonal temperature changes.

Although McEachran et al., (2020) did an indirect comparison between Designs 1 and 2 for six existing SB sites in Iowa, in terms of the buffer widths and the effectiveness ratios at the optimal width versus effectiveness at the current widths, a direct comparison between Designs 1 and 2 in terms of saturated buffer performance (i.e., average annual nitrate load removals and diverted flows) using variable field data was not conducted. Moreover, Design 3 was not compared to any of the existing design approaches. Therefore, the objective of this study was to compare the existing and newly proposed SB design approaches to identify the best design approach that would maximize nitrate load removal based on field data. The value of this study is that it will provide decision-makers with recommendations on how to improve SB design.

## 3.3. Materials and Methods

### 3.3.1. Fields location and collected data

We collected drainage discharge from two field sites (CL and BL) in Michigan, Figure 3.1, over three years from January 2019 to the end of December 2021. The data were used to design a hypothetical SB, i.e. determine the distribution pipe length and the buffer width for each design approach at each site. The sites provided real-world field variations in flow and hydraulic head to have a better comparison of the design approaches.

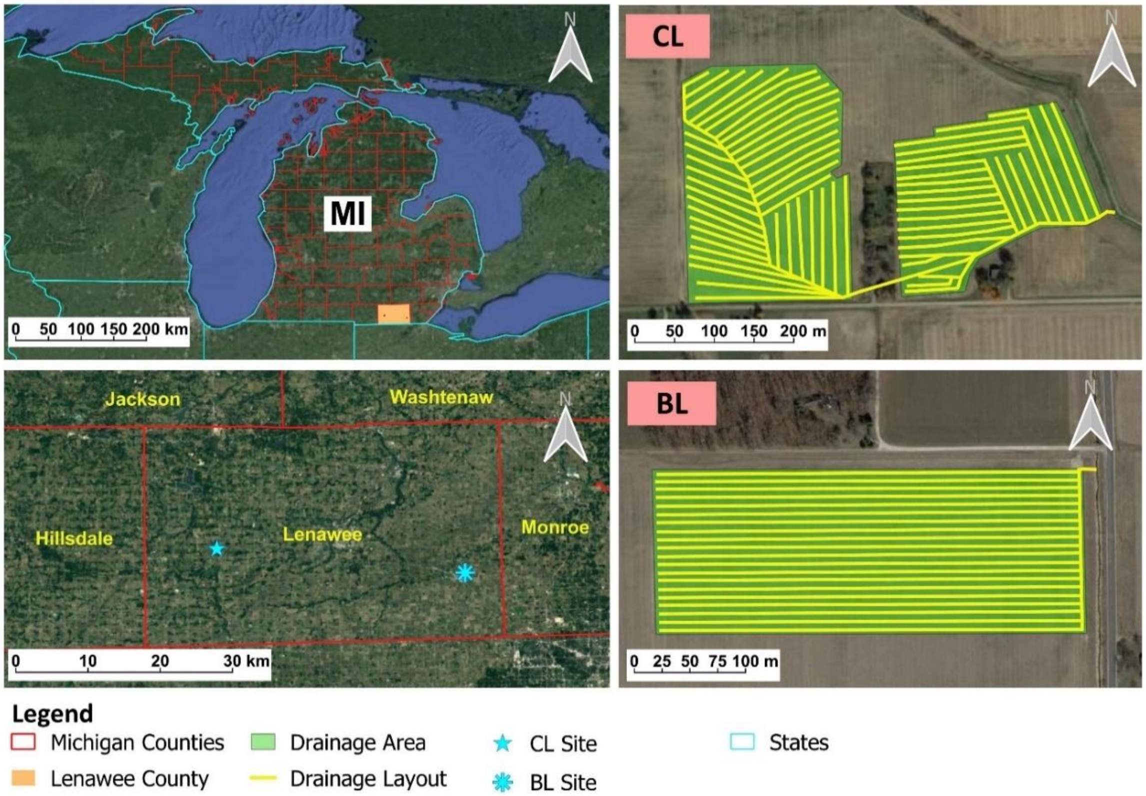


Figure 3.1. The locations, drainage areas and subsurface drainage layouts of CL and BL field sites used in the comparison study.

The area of the CL field was 14.7 ha and the agronomic practices at this site were no-till with manure application. The area of the BL site was 7.6 ha and the agronomic practices at this site were conventional tillage with commercial fertilizer application. Both sites followed a corn-soybean rotation and were under conventional drainage management with lateral spacing of about 15 and 10 m at CL and BL, respectively, and drain depth of about 0.9 and 0.8 m at CL and BL, respectively.

Soil sampling was conducted at the start of the project and the samples were analyzed at the Soil and Plant Nutrients Laboratory (SPNL) in Michigan State University, for the texture and bulk density ($\rho_{bulk}$) from soil surface to 90 cm depth. Other important soil parameters were obtained from the post processing of the extracted data from the Gridded Soil Survey Geographic Database (gSSURGO) soil database (Soil Survey Staff, 2020).

Through Geospatial analysis, the areal extent of each field site was used to identify the dominant Map Unit Key (MUKEY) from gSSURGO and all the soil components linked to this dominant MUKEY. The dominant soils were identified as Blount Loam and Ziegenfuss Clay Loam at CL and BL respectively. After that, the values of the required soil parameters were extracted from the data of the soil component that had the closest matching with the results of the soil texture obtained from the laboratory analysis. The required soil parameters from gSSURGO were the thickness of soil layers, the volumetric water content at third-bar to represent the field capacity $(\theta_{fc})$, and at 15 bar to represent the wilting point $(\theta_{wp})$.

The vertical saturated hydraulic conductivity of the soils $(K_v)$ were identified using Rosetta 3 model (Zhang and Schaap, 2017). The inputs for Rosetta 3 were the GSSURGO extracted values of $\theta_{fc}$ and $\theta_{wp}$, and the laboratory results of the texture and $\rho_{bulk}$. The lateral saturated hydraulic conductivity $(K_{Lat})$ was assumed to be 3 times the value of $K_v$, which is the average of the suggested range (2 to 4) in DRAINMOD model manuals. The average $K_{Lat}$ values were 3.09 and 4.19 cm/h at CL and BL respectively. The soil utility tool in DRAINMOD was used to estimate the drainable porosity $(n_{dr})$ of the different soil layers which were used as the values for the effective porosities $(n_e)$. The used values for effective porosities at CL and BL were 0.042 and 0.056 respectively.

To measure hourly drainage discharge, the control structure at each site was instrumented with a V-notch weir and a water-level logger setup to measure low to moderate unsubmerged flows (Shokrana and Ghane, 2021), and an area-velocity sensor to measure flows during submerged conditions and large flows exceeding the capacity of the V-Notch. Details of these measurements are presented in Dialameh and Ghane, (2022). An automated sampler was used to collect daily composite water samples, which were analyzed for nitrate concentration using the colorimetric nitrate reductase analysis method at the Water Quality Lab of Michigan State University. The average nitrate-N concentrations in drainage discharge were 10.3 and 16.8 mg/l at CL and BL, respectively.

### 3.3.2. Comparison of the three design approaches and their inputs

The three design approaches were compared by applying an identical main routine to estimate the nitrate load removal for each hypothetical SB system, presented in the methods section. To compare the nitrate load removal of the three design approaches, first we had to determine the design parameters (length of distribution pipe and buffer width). Due to the differences in the three design approaches (Table 3.1), a specific sequence was followed to calculate the SB design parameters for each of the three design approaches. The considered design parameter in this study was the buffer width, which was based on the data presented in Table 3.1. The sequence of calculations of the three design criteria started with the use of field data to define the inputs for Design 1. Then, Design 1 was used to determine the length of the distribution pipe. After that, the same input values from Design 1 were used to calculate the optimum buffer width of Design 2. Finally, the calculated length of the distribution pipe from Design 1 and the daily field values of drainage discharge and soil temperatures were used to determine the optimum width of the buffer of Design 3.

Table 3.1. Main differences between the three design approaches of a saturated buffer system.

| | **Design 1** | **Design 2** | **Design 3** |
|---|---|---|---|
| **Considered time span** | One point in time. (Variations over time are not considered). | One point in time. (Variations over time are not considered). | Any Period. (Variations over time are considered). |
| **Buffer width** | Input: Minimum of 9.1 m | Output | Output |
| **Distribution pipe length** | Output | Does not require a length input | Input |
| **Optimization function** | None | Maximize effectiveness of nitrate removal | Maximize effectiveness of nitrate removal |
| **Processes considered** | Flow through buffer soil. | Flow through buffer soil.<br>First-order kinetics for nitrate removal. | Flow through buffer soil.<br>First-order kinetics for nitrate removal.<br>Exit head loss of water moving out of the distribution pipe. |

In Design 1, the drainage system capacity input was calculated as the maximum drainage discharge that occurred over the three-year period. The maximum values of the measured daily flows were 2596 and 1267 $m^3$/day at CL and BL, respectively. The input value for the water control weir elevation was set so that it would be 30.5 cm from the soil surface (NRCS code 604) (NRCS, 2018). The depth to the restrictive layer, top of the clay pan, at each site was determined using a combination of field investigation and the reported data in gSSURGO database; these values were 305 and 170 cm at CL and BL respectively. This resulted in $h_1$ values of 274 and 149 cm at CL and BL, respectively. The input value for baseflow water elevation in the ditch was taken as the geometrical mean value of the ditch water level across the three-year period at the CL site, which resulted in an $h_2$ value of 38.4 cm, assuming that the bed of the ditch was 30 cm above the impervious layer. The $h_2$ value at the BL site was assumed to be the same because the water elevation was not monitored at BL. The inputs discussed in this paragraph were used in the NRCS Illinois spreadsheet to determine the length of the distribution pipe.

In Design 2, the head difference ($\Delta h$) was calculated as the difference between the values of $h_1$ and $h_2$ that were used in Design 1. The coefficient of nitrate removal was calculated using Equations 2.6 and 2.7, and the literature-reported values in McEachran et al., (2020) for $Q_{10}$ (2.5), T (7˚C), $T_r$ (20˚C), and $K_d$ (0.55 day-1). The coefficient of nitrate removal ($\lambda$) was calculated to be 0.165 day$^{-1}$. The input values were used in Equation 2.5 to calculate the optimum width of the buffer for Design 2, which does not require a distribution pipe length as an input.

In Design 3, multiple simulations were conducted using multiple values of the buffer width that were coupled with other fixed inputs. The fixed inputs were the $h_2$ value and length of distribution pipe from Design 1, the distribution pipe properties and depth, the daily values of the drainage discharge, the long-term average daily values of the soil temperature, the whole-period average of the nitrate concentration of the drainage discharge, and the weir levels. The distribution pipe properties were identified for an 8-row, 100-mm diameter perforated pipe, so the effective radius was 1.6 cm (Ghane, 2022). The distribution pipe depth in the buffer soil was taken as the commonly used value of 80 cm. The weir level was set to be 100 cm from the soil surface during the periods of April 1 to May 15 and October 1 to November 1, 45 cm from the soil surface during the growing season (May 16 to end of September), and 30 cm from the soil surface during the rest of the year. The long-term average daily values of soil temperature were calculated using historical measured daily values at Kellogg Station Michigan at a depth of 100 cm (this depth was chosen because it was the closest to the distribution pipe depth).

The buffer width value from each design criterion was coupled with the constant value of the length of distribution pipe from Design 1 to represent a hypothetical SB system. This resulted in a total of six hypothetical SB systems (three designs and two sites).

To conduct a fair comparison between the three design criteria, we used the same method to estimate the nitrate load reduction for each of the hypothetical SB systems representing the three design criteria. At each field site, the main routine (presented in the methods section) was applied to the daily measured field data to calculate the amount of nitrate load removal for each of the hypothetical SB systems. Finally, the best design criterion was chosen as the design criterion that resulted in the largest nitrate load removal.

## 3.4. Results and Discussion

### 3.4.1. Distribution pipe length and buffer width of Design 1

Using the minimum buffer width of 9.1 m, the distribution pipe length was calculated so that it would divert 5% of the maximum drainage discharge to the buffer at each field site (NRCS Standard Code 604) (NRCS, 2018). The calculated distribution pipe lengths were 433 m at the CL site and 643 m at the BL site. The required distribution pipe length decreased as the maximum drainage discharge decreased and as the hydraulic gradient across the buffer width increased.

### 3.4.2. Optimum width of Design 2

For Design 2, the calculated optimum buffer widths were 16.3 m at the CL site and 11.1 m at the BL site. These optimum widths were greater than the 9.1-m minimum width of the NRCS standard code 604. McEachran et al., (2020) estimated the optimum widths for six sites in Iowa, and they found four optimum widths greater than the minimum width and two smaller than the minimum width recommended by NRCS. This shows that having a one-size-fits-all 9.1-m minimum width may not result in optimum performance.

The calculated optimum buffer width increased as the hydraulic head difference between the control structure and the open ditch increased. The faster flow velocity through the buffer soil at the CL site, as calculated by equation 2.4, required a wider buffer as compared to the BL site to effectively reduce the nitrate concentration of the diverted flow before it exited the buffer soil into the open ditch. This was the case as the nitrate removal in Design 2 was represented through a function that used a fixed value for the removal coefficient, and the width was the only parameter that affected the final nitrate concentration for the same site.

### 3.4.3. Optimum width of Design 3

For Design 3, the calculated optimum buffer widths were 17.1 m at the CL site and 11.0 m at the BL site. These optimum widths were greater than the 9.1-m minimum width of the NRCS standard code 604. For a fixed distribution pipe length, the maximum value of the diverted flow was at the minimum buffer width, and it decreased as the width increased (Figure 3.2). Consequently, the bypass flow increased as the buffer width increased because of the conservation of mass at the control structure.

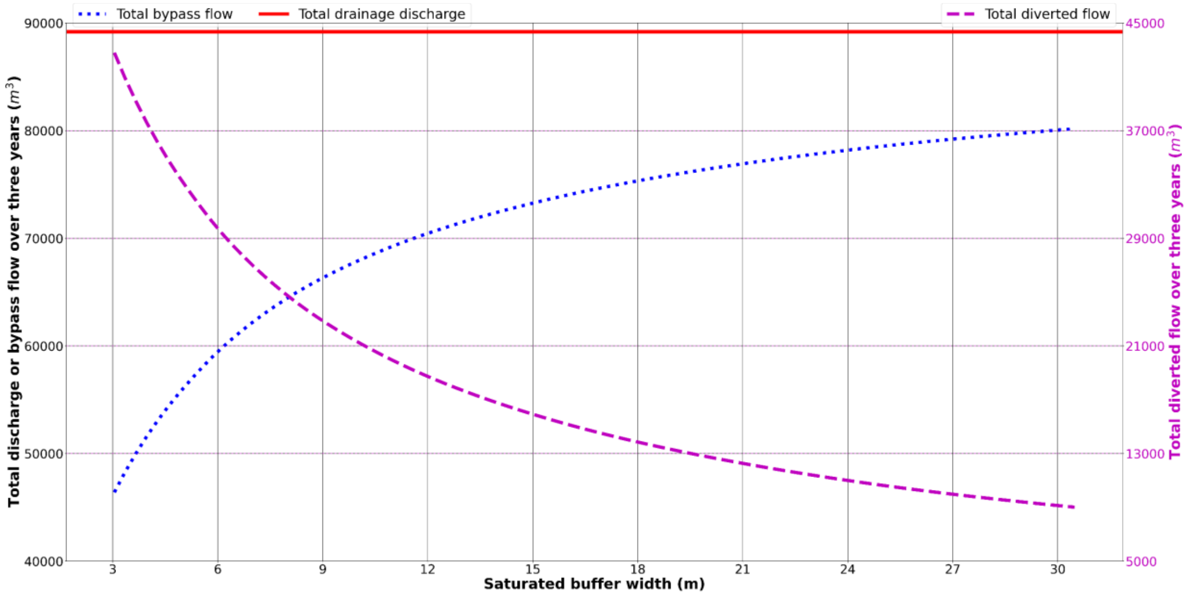


Figure 3.2. Flow dynamics in the saturated buffer with varying buffer widths based on the long-term daily simulations at the BL site.

Design 3 showed that increasing the buffer width resulted in a reduction in the nitrate load of the diverted flow and an increase in the nitrate load of the bypass flow (figure 3.3). The reduction in the nitrate load of the diverted flow was not linear, where the intensity of reduction (slope of the curve) was steep at low buffer widths and reached an asymptote close to zero at large buffer widths. Large buffer widths essentially eliminated nitrate load in the diverted flow, and these widths were approximately 19 m at the BL site and 24.4 m at the CL site. At small widths, the travel time was too small for considerable nitrate removal to occur. At large widths, the bypass was too large, thereby decreasing the diverted flow, which resulted in a small nitrate removal.

The chosen optimum buffer widths for Design 3 that resulted in the largest total nitrate load removal were at smaller buffer width (11.0 m at BL and 17.1 m at CL) than the widths where the nitrate load in diverted flow was essentially eliminated. These chosen widths had higher total nitrate load removal since it also considered the increase in nitrate load from bypass flow that resulted from the increase in buffer width.

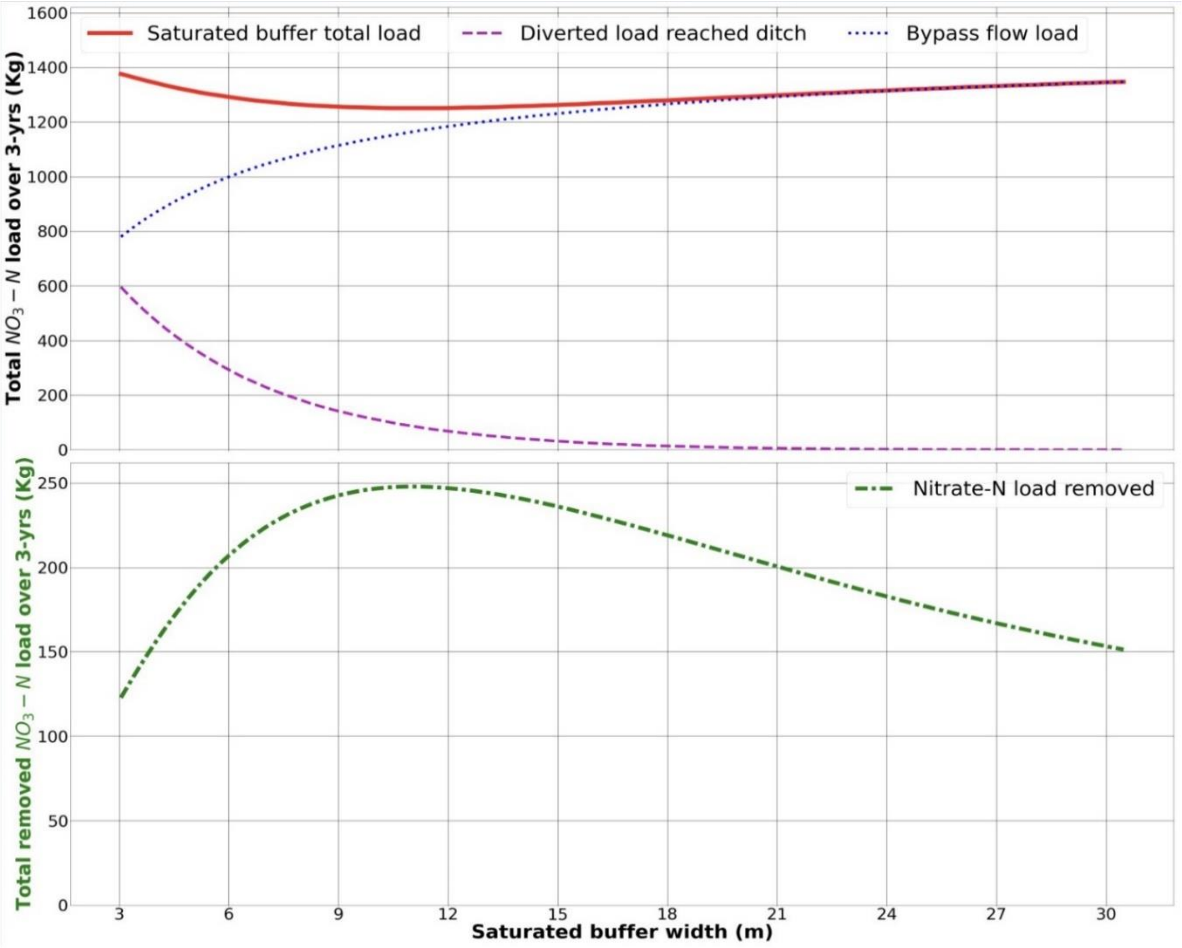


Figure 3.3. Nitrate load dynamics of the saturated buffer with varying buffer widths based on long-term daily simulations at the BL site.

### 3.4.4. Comparison of the design approaches

The comparisons among the three design criteria across the two field sites showed that Designs 2 and 3 yielded the best designs (table 4.2). Design 1 resulted in the largest percentage of diverted flow to the buffer and the least nitrate removal at both field sites. Design 1 had the largest diverted flow because it had the smallest width, and the Dupuit equation indicates that smaller buffer widths will have larger diverted flows. The smaller buffer widths of Design 1 did not provide enough time for the buffer soil to remove larger amounts of nitrate from the diverted water as it passed through the buffer soil when compared to the case of Design 2 or Design 3.

Design 1 removed the least nitrate load because it did not include an optimization for nitrate removal and used the minimum allowable buffer width (9.1 m). Therefore, choosing a smaller buffer width that diverts more flow into the buffer may not always result in larger nitrate load removal.

As shown in table 3.2, Designs 2 and 3 consistently provided maximum nitrate load removal at two distinct sites. These two sites had different soil properties and drainage design (drain depth and spacing). However, Design 1 removed 20% ((352.9-282.1)/352.9) and 2% ((247.8-243.4)/247.8) less nitrate load compared to Design 3 at the CL and BL sites, respectively. As evident, Design 1 performed well at the BL site, but performed poorly at the CL site. This shows that Design 1 did not have consistency in nitrate load removal from one site to another. Therefore, designs 2 and 3 consistently provided maximum nitrate load removal regardless of the site conditions, whereas the performance of Design 1 was inconsistent.

Table 3.2. Comparison between saturated buffer parameters, and the hydrology and nitrate removal performances of three design approaches, using minimum width (9.1 m) in Design 1.

| **Design criterion** | **CL Site** | | | **BL Site** | | |
|---|---|---|---|---|---|---|
| | *Design 1* | *Design 2* | *Design 3* | *Design 1* | *Design 2* | *Design 3* |
| **Buffer length (m)** | | 433 | | | 643 | |
| **Buffer width (m)** | 9.1 | 16.3 | 17.1 | 9.1 | 11.1 | 11.0 |
| **Total drainage discharge over three years (m$^3$)** | | 197573 | | | 89196 | |
| **Total nitrate-N load from field over three years (kg)** | | 2035 | | | 1498 | |
| **Total diverted flow over three years (m$^3$)** | 68776 | 46686 | 45125 | 22625 | 19750 | 19963 |
| **Total diverted flow over three years percentage (%)** [a] | 34.8% | 23.6% | 22.8% | 25.4% | 22.1% | 22.4% |
| **Nitrate-N load removed over three years (kg)** | 282.1 | 352.5 | 352.9 | 243.4 | 247.8 | 247.8 |
| **Nitrate-N load removed percentage (%)** [b] | 13.9% | 17.3% | 17.3% | 16.2% | 16.5% | 16.5% |
| **Average annual field drainage (m3/yr)** | 65858 | | | 29732 | | |
| **Average annual diverted flow (m$^3$/yr)** | 22926 | 15562 | 15042 | 7542 | 6583 | 6654 |

Table 3.2 (cont'd)

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **Average annual nitrate-N removed (kg/yr)** | **94.0** | **117.5** | **117.6** | **81.1** | **82.6** | **82.6** |

[a] Percentages are out of the total drainage discharge.
[b] Percentages are out of the total nitrate-N load from field.

Designs 2 and 3 resulted in similar nitrate load removal, mainly because both used the first-order removal kinetics. The first-order removal kinetics in Designs 2 and 3 assumed that denitrification was the primary mechanism affecting the nitrate balance within the buffer soil and did not account for other mechanisms (such as plant uptake, mineralization, and immobilization), which can be affected by the hydrology changes that may arise from using different buffer widths. The water-table position and soil temperature within the buffer soil can limit denitrification or affect other processes mediating the nitrogen balance such as organic carbon decomposition or nitrogen mineralization/immobilization (Youssef et al., 2005). The water-table position in the buffer soil defines the available soil-water pore space, the available soil organic carbon content, and the soil organic carbon decomposition (i.e., shallower layers have more labile organic carbon with higher content) (Youssef et al., 2005). Also, the first-order kinetics method does not have a limit for the amount of nitrate substrate that can undergo denitrification, unlike other methods (e.g., Michaelis-Menten model). Therefore, we recommend an improvement of the method used to represent nitrate removal in Designs 2 and 3.

### 3.4.5. Importance of accounting for exit head loss

Exit head loss occurs as water moves out of the distribution pipe perforations and enters the surrounding soil (Skaggs, 1991). To demonstrate the importance of exit head loss in SB design, the percentage of diverted flow and total nitrate load removal were compared for the two cases of considering or not considering exit head loss for Design 1. The results at the CL site showed that the designed SB system (9.1-m width and 433-m length) diverted 5% of flow when exit head loss was not considered, whereas the same design diverted 4.4% of flow when exit loss was considered (table 3.3). Therefore, not accounting for exit head loss in Design 1 resulted in an undersizing of the buffer length for a given width.

Table 3.3. Effect of ignoring exit head loss on Design 1 at CL and BL sites. The analysis was conducted using NRCS Illinois spread sheet for SB Design. The calculation is for one point in time for the maximum observed field drainage discharge.

| Parameter | CL site | BL site |
|---|---|---|
| **Buffer length (m)** | 433 | 643 |
| **Buffer width (m)** | 9.1 | 9.1 |
| **Max drainage discharge (m3/day)** | 2596 | 1267 |
| **Hydraulic head at control structure (cm)** | 274.5 | 139.5 |
| **Hydraulic head in buffer soil without exit head loss (cm)** | 274.5 | 139.5 |
| **Hydraulic head in buffer soil with exit head loss (cm)** | 258.4 | 134.9 |
| **Diverted flow without exit head loss (m3/day)** | 129.8 | 63.4 |
| **Diverted flow with exit head loss (m3/day)** | 114.7 | 59.1 |

Simulations using the main routine and neglecting exit head loss showed that the total diverted volume at the CL site over three years increased by about 4400 $m^3$ (2.2% difference), and total nitrate-N removal increased by 7.7 kg (0.3% difference) compared to the scenario of considering exist head loss. Similar results for Designs 2 and 3 are presented in tables 3.4 to 3.6. Regardless of the buffer dimensions, the amount of diverted flow to the buffer and the amount of nitrate load removed were overestimated when exit head loss was neglected. The impact of the exit losses was also more evident at the field site (CL site) that was characterized by higher flow rates.

Table 3.4. Effect of ignoring exit head loss on the performance of the hypothetical SB systems obtained from Design 1 at CL and BL sites. The main routine of Design 3 was used to estimate the diverted flow and nitrate load removal using data for a three-years period.

| | **CL Site** | | **BL Site** | |
|---|---|---|---|---|
| **Exit head loss condition** | Exit loss | No exit loss | Exit loss | No exit loss |
| **Buffer length (m)** | 433 | | 643 | |
| **Buffer width (m)** | 9.1 | | 9.1 | |
| **Total drainage discharge over three years ($m^3$)** | 197573 | | 89196 | |
| **Total nitrate-N load from field over three years (kg)** | 2035 | | 1498 | |
| **Total diverted flow over three years ($m^3$)** | 68776 | 73170 | 22625 | 26205 |
| **Total diverted flow over three years percentage (%) [a]** | 34.8 % | 37.0 % | 25.4 % | 29.4 % |
| **Nitrate-N load removed over three years (kg)** | 282.1 | 289.8 | 243.4 | 275.4 |
| **Nitrate-N load removed percentage (%) [b]** | 13.9 % | 14.2 % | 16.2 % | 18.4 % |
| **Average annual field drainage (m3/yr)** | 65858 | | 29732 | |
| **Average annual diverted flow ($m^3$/yr)** | 22926 | 24390 | 7542 | 8735 |
| **Average annual nitrate-N removed (kg/yr)** | 94.0 | 96.6 | 81.1 | 91.8 |

[a] Percentages are out of the total drainage discharge.

[b] Percentages are out of the total nitrate-N load from field.

Table 3.5. Effect of ignoring exit head loss on the performance of the hypothetical SB systems obtained from Design 2 at CL and BL sites. The main routine of Design 3 was used to estimate the diverted flow and nitrate load removal using data for a three-years period.

| | **CL Site** | | **BL Site** | |
|---|---|---|---|---|
| **Exit head loss condition** | Exit loss | No exit loss | Exit loss | No exit loss |
| **Buffer length (m)** | 433 | | 643 | |
| **Buffer width (m)** | 16.3 | 15.8 | 11.1 | 11.1 |
| **Total drainage discharge over three years ($m^3$)** | 197573 | | 89196 | |
| **Total nitrate-N load from field over three years (kg)** | 2035 | | 1498 | |
| **Total diverted flow over three years ($m^3$)** | 46686 | 50178 | 21893 | 20522 |
| **Total diverted flow over three years percentage (%) [a]** | 23.6 % | 25.4 % | 22.1 % | 23.0 % |
| **Nitrate-N load removed over three years (kg)** | 352.5 | 362.4 | 247.8 | 253.9 |
| **Nitrate-N load removed percentage (%) [b]** | 17.3 % | 17.8 % | 16.5 % | 16.9 % |
| **Average annual field drainage (m3/yr)** | 65858 | | 29732 | |
| **Average annual diverted flow ($m^3$/yr)** | 15562 | 16726 | 6583 | 6841 |
| **Average annual nitrate-N removed (kg/yr)** | 117.5 | 120.8 | 82.6 | 84.6 |

[a] Percentages are out of the total drainage discharge.

[b] Percentages are out of the total nitrate-N load from field.

Table 3.6. Effect of ignoring exit head loss on the performance of the hypothetical SB systems obtained from Design 3 at CL and BL sites. The main routine of Design 3 was used to estimate the diverted flow and nitrate load removal using data for a three-years period.

| | **CL Site** | | **BL Site** | |
|---|---|---|---|---|
| **Exit head loss condition** | Exit loss | No exit loss | Exit loss | No exit loss |
| **Buffer length (m)** | 433 | | 643 | |
| **Buffer width (m)** | 17.1 | 17.1 | 9.1 | |
| **Total drainage discharge over three years ($m^3$)** | 197573 | | 89196 | |
| **Total nitrate-N load from field over three years (kg)** | 2035 | | 1498 | |
| **Total diverted flow over three years ($m^3$)** | 45125 | 47234 | 19963 | 20334 |
| **Total diverted flow over three years percentage (%) [a]** | 22.8 % | 23.9 % | 22.4 % | 22.8 % |
| **Nitrate-N load removed over three years (kg)** | 352.9 | 364.0 | 247.8 | 253.9 |
| **Nitrate-N load removed percentage (%) [b]** | 17.3 % | 17.9 % | 16.5 % | 16.9 % |
| **Average annual field drainage (m3/yr)** | 65858 | | 29732 | |
| **Average annual diverted flow ($m^3$/yr)** | 15042 | 15745 | 6654 | 6778 |
| **Average annual nitrate-N removed (kg/yr)** | 117.6 | 121.3 | 82.6 | 91.8 |

[a] Percentages are out of the total drainage discharge.
[b] Percentages are out of the total nitrate-N load from field.

The saturated buffer is not the only system that is affected by exit head loss. Simulations showed that subirrigation can have significant exit head loss over the drainage pipes, specifically right after the start of the subirrigation. The head loss can reach more than 13 cm even after a whole day of steady subirrigation (Skaggs, 1991). Like the saturated buffer, woodchip bioreactors will be undersized if exit head loss of the water forced out of the distribution pipe and entrance head loss of the water entering the collection pipe are not considered. This is because the hydraulic head in the inlet control structure will be higher than the hydraulic head in the upstream end of the bioreactor due to exit head loss, and the hydraulic head in the outlet control structure will be lower than the hydraulic head in the downstream end of the bioreactor due to entrance head loss. The same concept applies to phosphorus removal structures where water is forced out of a perforated pipe into a porous media. Therefore, exit and entrance head losses should be incorporated in the designs of conservation drainage practices that involve water movement into and out of a perforated pipe surrounded by a porous media.

### 3.4.6. Practical application of Design 3

Climate, soil, and drainage design varies from one location to the other, thereby this can result in distinct hydrologic response from the subsurface-drained at different farms. As shown in table 3.2, the optimum width of the buffer for Design 3 were 17.1 and 11.0 m at the CL and BL sites, respectively. This difference between the optimum widths at the two sites was because of the differences in the hydrologic response of the two farms. Therefore, SB design requires site-specific determination of length and width. Design 3 accounts for site-specific conditions to estimate the annual nitrate load removal of the SB system. Designs 1 and 2 use only one point in time, so they cannot calculate the annual nitrate load removal. Consequently, Design 3 is more suitable for incorporation into decision-support tools because it shows the value of this practice by quantifying the nitrate load removal compared to Designs 1 and 2. Decision-support tools can accelerate the adoption of saturated buffers by increasing knowledge of the value of this practice. This approach informs state and federal efforts to support nutrient-trading programs. In a nutrient-trading program, the farmer receives a payment for the nitrate load removed based on their site-specific conditions. Overall, Design 3 has potential for application in decision-support tools to increase adoption of SB.

Design 3 offers versatile applications, allowing users to simulate multiple SB designs and use the data in user-defined objective functions. For instance, one objective function might aim to balance nitrate load removal and crop production profits. Figure 3.4 shows that the range of buffer width values around the optimum width have very small variations from the maximum annual nitrate load removal. So, a smaller buffer width instead of the optimum width can increase the cultivated area and cause a consequent increase in the crop production profits without significantly impacting the SB nitrate load removal performance. The CL data in figure 3.4 and table 3.2, showed that the maximum annual nitrate load removal was 117.6 kg with an optimum buffer width of 17.1 m, if a buffer width of 14.3 m was used instead of the optimum width, the annual nitrate load removal would decrease by only 2.35 kg but an increase in the cultivated area of about 1210 $m^2$ would occur, which is the area that otherwise would have been taken out of cultivation if the optimum width was used. This increase in the cultivated area would increase yearly profits from crop production by about 200 USD for the years that had corn planted and 139 USD for the years that had soybean planted, considering a hypothetical scenario in which the average annual yields are 10670 Kg/ha (170 bu/ac) for corn and 3362 Kg/ha (50 bu/ac) for soybean, with prices of 0.15 USD/Kg (3.93 USD/bu) for corn and 0.34 USD/Kg (9.25 USD/bu) for soybean (MSU Crop Budget Estimator Tool for Grains). Overall, other objective functions can be coupled with Design 3 to achieve multiple desired goals.

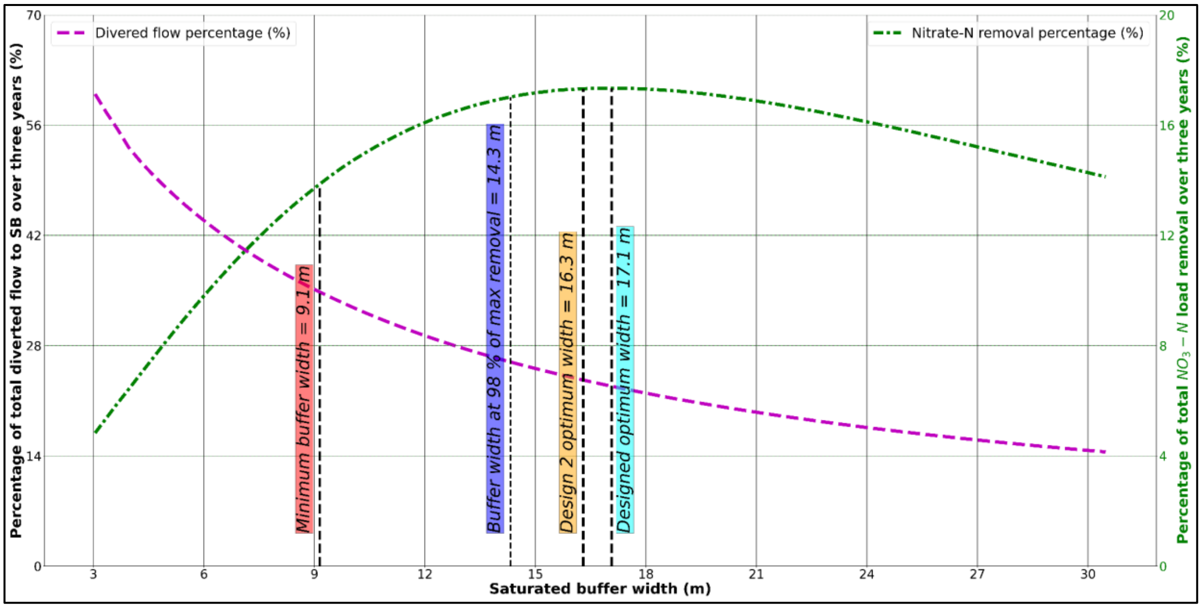


Figure 3.4. Diverted flow and nitrate load removal percentages of the design criteria of saturated buffers at the CL site using the maximum available buffer length suitable for distribution pipe installation.

### 3.4.7. Impact of the distribution pipe length on SB performance and the design approaches

The distribution pipe length could be limited by the field dimensions or the slope of the buffer in the direction parallel to the ditch. The NRCS Code 604 recommends that the distribution pipe should be level or slope downward away from the control structure. The buffer slope in the direction parallel to the ditch should have the minimum soil cover over the distribution pipe, and the pipe depth should not exceed the maximum possible operation depth of the installation machine.

The maximum allowable lengths of the distribution pipes for the SB were identified at CL and BL sites using the measure and the elevation profile plot tools within Google earth pro software. Since the available length of the buffer was only limited at CL (smaller than the calculated length from design 1), the assessment of the design criteria at CL site was reconducted using the maximum allowable length of 366 m instead of 433 m. The use of smaller length at CL reduced the diverted flow to the distribution pipe by 17% for Design 1, 13.3% for Design 2, and 12.5% for Design 3, as compared to the results when the calculated length of distribution pipe from design 1 was used. Also, the nitrate removal decreased by 7.9% for Design 1, 9.6% for Design 2, and 9.7% for Design 3. Our results showed that when the distribution pipe length was smaller than the calculated design length from Design 1, the average reduction in the percentage of total diverted flow of the three designs was 14.3%, and the average reduction in the percentage of total nitrate removal was 9.1%. Moreover, the results of this analysis showed that regardless of the length of distribution pipe, the outcome of designs 2 and 3 being equally good is still valid and both designs removed more nitrate compared to that of Design 1.

Because of the way the comparison was conducted in this study, the defined buffer width value in Design 1 affected the calculated length of the distribution pipe and consequently the performance of all the design approaches, because the length of distribution pipe was kept constant. Therefore, we conducted a follow-up investigation on the impact of the length of distribution pipe on the SB system performance and the implications for the design approaches comparison. The comparison was reconducted using two larger buffer widths in Design 1. Tables 3.7 and 3.8 show the SB design parameters, and the hydrology and nitrate removal performances of the three design approaches when Design 1 was reused with buffer width values (12.2 m and 18.3 m) larger than the NRCS minimum (9.1 m). It's noteworthy that opting for a wider width in Design 1 required a longer distribution pipe to ensure the treatment of the recommended 5% of the drainage system capacity, as opposed to the case when the minimum width was employed.

Table 3.7. SB parameters and performances of the three design approaches using 12.2 m buffer width and 5% diverted flow criterion in Design 1.

| Design criterion | CL Site | | | BL Site | | |
|---|---|---|---|---|---|---|
| | *Design 1* | *Design 2* | *Design 3* | *Design 1* | *Design 2* | *Design 3* |
| **Buffer length (m)** | 578 | | | 853 | | |
| **Buffer width (m)** | 12.2 | 17.9 | 18.9 | 12.2 | 11.8 | 11.9 |
| **Total drainage discharge over three years ($m^3$)** | 197573 | | | 89196 | | |
| **Total nitrate-N load from field over three years (kg)** | 2035 | | | 1498 | | |
| **Total diverted flow over three years ($m^3$)** | 72212 | 56476 | 54182 | 25388 | 26007 | 25837 |
| **Total diverted flow over three years percentage (%) [a]** | 36.6 % | 28.6 % | 27.4 % | 28.5 % | 29.2 % | 29.0 % |
| **Nitrate-N load removed over three years (kg)** | 378.3 | 426.7 | 426.9 | 330.9 | 331.0 | 331.2 |
| **Nitrate-N load removed percentage (%) [b]** | 18.6 % | 21.0 % | 21.0 % | 22.1 % | 22.1 % | 22.1 % |
| **Average annual field drainage (m3/yr)** | 65858 | | | 29732 | | |
| **Average annual diverted flow ($m^3$/yr)** | 24071 | 18826 | 18061 | 8463 | 8669 | 8612 |
| **Average annual nitrate-N removed (kg/yr)** | 126.1 | 142.2 | 142.3 | 110.3 | 110.3 | 110.4 |

[a] Percentages are out of the total drainage discharge.

[b] Percentages are out of the total nitrate-N load from field.

Table 3.8. SB parameters and performances of the three design approaches using 18.3 m buffer width and 5% diverted flow criterion in Design 1.

| Design criterion | CL Site | | | BL Site | | |
|---|---|---|---|---|---|---|
| | *Design 1* | *Design 2* | *Design 3* | *Design 1* | *Design 2* | *Design 3* |
| **Buffer length (m)** | 433 | | | 643 | | |
| **Buffer width (m)** | 18.3 | 17.9 | 20.1 | 18.3 | 11.8 | 12.2 |
| **Total drainage discharge over three years ($m^3$)** | 197573 | | | 89196 | | |
| **Total nitrate-N load from field over three years (kg)** | 2035 | | | 1498 | | |
| **Total diverted flow over three years ($m^3$)** | 73261 | 74284 | 69180 | 25606 | 34331 | 33573 |
| **Total diverted flow over three years percentage (%) [a]** | 37.1 % | 37.6 % | 35.0 % | 28.7 % | 38.5 % | 37.6 % |
| **Nitrate-N load removed over three years (kg)** | 569.6 | 567.7 | 573.5 | 404.7 | 444.0 | 444.1 |
| **Nitrate-N load removed percentage (%) [b]** | 28.0 % | 27.9 % | 28.2 % | 27.0 % | 29.6 % | 29.6 % |
| **Average annual field drainage (m3/yr)** | 65858 | | | 29732 | | |
| **Average annual diverted flow ($m^3$/yr)** | 24420 | 24761 | 23060 | 8535 | 11444 | 11191 |

Table 3.8 (cont'd)

| | | | | | | |
|---|---|---|---|---|---|---|
| **Average annual nitrate-N removed (kg/yr)** | **189.9** | **189.2** | **191.2** | **134.9** | **148.0** | **148.0** |

[a] Percentages are out of the total drainage discharge.

[b] Percentages are out of the total nitrate-N load from field.

Results presented in Tables 3.2 (for 9.1 m width), 3.7 (for 12.2 m width), and 3.8 (for 18.3 m width) show that the larger length of distribution pipe slightly increased the total diverted flow to the buffer for Design 1 with a maximum percentage increase of 0.6 % at CL and 0.4% at BL, when the buffer width was increased from 9.1 m to 18.3 m. For Design 1, the wider width values reduced the magnitude of the diverted flow per unit length of the distribution pipe, but the longer distribution pipe length resulted in total volumetric diverted flow that compensated this reduction and was slightly larger than the case when the minimum buffer width was used.

On the other hand, the larger length of distribution pipe for Designs 2 and 3 caused a more evident increase in the total diverted flow to the buffer. The maximum percentage increase in diverted flow was 14.6% at CL and 14.8% at BL for Design 2, and 12.7% at CL and 13.6% at BL for Design 3. This was because the changes in the values of the optimum width for Designs 2 and 3 as a result of the having longer distribution pipe length were minor. So, the new calculated optimum width values of designs 2 and 3 did not cause significant reduction in the magnitude of the flow per unit length of the distribution pipe, and at the same time the longer distribution pipe length increased the total volumetric diverted flow to the buffer as compared to the case when the minimum buffer width was used.

The resulting larger length of distribution pipe significantly increased the total nitrate load removal of the three designs, when the buffer width was increased from 9.1 m to 18.3 m in Design 1. For Design 1, the percentage increase in total nitrate load removal was 15.3% at CL and 9.8%

at BL. For Design 2, the percentage increase in total nitrate load removal was 11.1% at CL and 11.8% at BL. For Design 3, the percentage increase in total nitrate load removal was 11.4% at CL and 11.8% at BL. Having a longer distribution pipe length while having a buffer width that is close to the optimum buffer width value increased both the diverted flow to the buffer and the nitrate load removal. At BL site, the nitrate load removal decreased slightly when the buffer width (18.3 m) exceeded the optimum buffer width (12.2 m). Therefore, the saturated buffer design that would result in the largest nitrate load removal should have the maximum allowable length of the distribution pipe based on site conditions while having a wide enough buffer width that is close to the optimum value. The maximum allowable length of the distribution pipe length will maximize the diverted flow to the buffer, and the optimum buffer width will not shortcut the diverted flow without treatment but instead it would ensure adequate reduction in the nitrate concentration of the diverted water as it moves through the buffer soil to the open ditch.

The increase in total nitrate removal was more evident for Design 1 as compared to Designs 2 and 3. In comparison to the case of using the minimum width (9.1 m), the wider buffer width for Design 1 resulted in more nitrate concentration reduction of the diverted flow as it passes through the buffer soil. Also at the same time, the larger distribution pipe length ensured that the total amount of diverted flow to the buffer did not decrease as a result of using larger buffer width than the minimum.

We believe that the best SB design criterion should first determine the maximum allowable length of distribution pipe that can be used in the buffer as an input, then estimate the buffer width to maximize the nitrate load removal or to achieve the target nitrate load removal and financial demands of the user. This is because the length of the distribution pipe considerably impacts the total diverted flow to the buffer, and in turns the total nitrate load removal. The longer the length of the distribution pipe, the larger diverted flow and nitrate load removal.

## 3.5. Conclusions

We conducted a comparison between three saturated buffer design criteria to determine the best design. Our study resulted in the following key conclusions.

- Using Design 1 with the minimum width stated in NRCS Code 604 and the minimum recommended treatment capacity of 5% of the drainage system capacity resulted in a system with the maximum diverted flow to the buffer and the lowest nitrate removal. The main reason for the low nitrate removal was that the current version of Design 1 did not optimize for nitrate removal and only targeted the amount of diverted flow to the buffer.
- Choosing a smaller buffer width that diverts more flow into the buffer may not always result in larger nitrate removal.
- For a fixed buffer length, increasing the buffer width reduced the diverted flow to the buffer and increased the bypass flow. Increasing the buffer width reduced the nitrate load of the diverted flow and increased the nitrate load of the bypass flow.
- Assuming that the nitrate removal within the buffer soil followed first-order removal kinetics, Designs 2 and 3 resulted in saturated buffer widths with comparable nitrate load removal that were better than those obtained with Design 1.
- Designs 2 and 3 consistently provided maximum nitrate load removal regardless of the site conditions. Design 1 did not provide consistent nitrate load removal from one site to another.

- The first step in SB design should be the determination of the maximum allowable distribution pipe length to be used in the buffer, followed by estimation of the buffer width that would maximize the nitrate removal. The longer the length of the buffer, the larger diverted flow and nitrate load removal.
- Neglecting exit head loss (when water exited the distribution pipe) resulted in overestimation of the diverted flow into the distribution pipe and overestimation of nitrate load removal by the saturated buffer.

In conclusion, the results indicated that Designs 2 and 3 were both good, and they were both better than Design 1 in terms of maximizing nitrate load removal. Design 3 follows a process-based approach to estimate the annual nitrate removal for site-specific conditions. The benefit of Design 3 is that it can be used in decision-support tools for accelerating the adoption of saturated buffers by increasing knowledge of the value of this conservation drainage practice. This approach informs state and federal efforts to support nutrient-trading programs. To further improve Design 3, we recommend including more sophisticated nitrate removal and hydrology components that can capture other processes that affect nitrogen dynamics in soil and its interaction with hydrology.

# 4. CHAPTER 4: DEVELOPMENT AND APPLICATION OF A SATURATED BUFFER DECISION-SUPPORT TOOL

## 4.1. Abstract

A more effective design and evaluation approach for saturated buffers (SB) is essential to maximize nitrate load removal. Currently, there are no tools specifically tailored for SB design and evaluation. This study aimed to develop a DRAINMOD-based decision-support tool for SB and assess its performance in predicting hydrology and nitrate load. The assessment utilized published evaluation criteria of standard statistical indicators and measured data from two fields in the state of Iowa, U.S. Results showed that the tool reasonably estimates yearly and long-term average hydrology and nitrate removal. The differences between predicted average annual diverted flow and SB nitrate load removal from measured values were minimal (1% and 2%, respectively), at the site with higher data availability, and relatively reasonable (-20% and -16%, respectively), at the site with limited years of data. In conclusion, the tool offers valuable support for SB design and evaluation based on local conditions, including soil, weather, and drainage system characteristics.

## 4.2. Introduction

Subsurface drainage is necessary in naturally poorly drained soils for good crop yields, but it can result in excessive nutrient losses that can deteriorate surface water quality (Ghane et al., 2016). The saturated buffer (SB) system is an edge-of-field conservation drainage practice designed to reduce the nitrate load in drainage discharge from subsurface-drained lands (NRCS standard 604) (NRCS, 2018). This system uses a control structure and a distribution pipe to reroute a portion of the drainage discharge to an edge-of-field buffer before releasing into a receiving stream or ditch (Jaynes and Isenhart, 2014). Diverted water leads to shallow water table in the buffer soil, with sufficient soil carbon levels, the nitrate concentration in the diverted water decreases as it moves from the distribution pipe toward the ditch (Jaynes and Isenhart, 2014, 2019a). The reduction in nitrate concentration is mainly a result of denitrification (Groh et al., 2019).

Multiple field studies have proven the efficacy of saturated buffers (SBs) to reduce nitrate loads in drainage water. Johnson et al., (2023) reported an average annual nitrate load removal of 46% for a dataset that included 30 site years across multiple SB sites in the Midwest. The average percentage reduction of the yearly nitrate load in drainage discharge across six SB sites in Iowa amounted to about 44% (Jaynes and Isenhart, 2019a), and it amounted to 48% across three sites in Illinois (Chandrasoma et al., 2022).

Despite the relatively high reported average nitrate load reductions of SBs, there is considerable variability between sites and between years at the same sites. Across the published literature, annual nitrate load removal ranged from 7% to 92% (Johnson et al., 2023). Jaynes and Isenhart, (2019a) reported annual nitrate load reductions for a single site ranging from 31% to 56%, and inter-site average nitrate load reductions ranging from 8% to 84% across six sites in Iowa. Chandrasoma et al., (2022) reported the largest inter-annual range of nitrate load reductions within a single SB site in Illinois (19% to 73%), and the largest range of the inter-site nitrate load reductions was 19% to 77% across three sites .

Geospatial analysis have demonstrated the potential for large-scale SB implementation in the Midwest to reduce regional nitrate loading (Chandrasoma et al., 2019; Tomer et al., 2020). The extent of SB-suited sites across multiple watersheds in Iowa were mostly greater than 30%

of the streambank length, which can serve about 15% to 40% of the subsurface-drained areas in these watersheds (Tomer et al., 2020). Also, Chandrasoma et al., (2019)) reported that about 50% of the total length of streambanks in the Midwest is suitable for SB implementation. The same study estimated a 5% to 10% reduction in nitrate load to the Mississippi River with the large-scale adoption of the practice. This reduction may represent a conservative estimate since the study assumed a nitrate loss percentage reduction from SB of 23% which is lower than the reported average of the practice. The reported performance of the SB system in these different studies shows the great potential of the practice in reducing nitrate loads from croplands, which subsequently helps achieving N-reduction goals at watershed and river basin scales.

The high potential for widespread SB implementation to reduce nitrate loading across the Midwest and variability in performance demonstrates the need for additional research to improve design and performance. Few modeling studies were conducted to understand the SB functionality or to improve the SB design. Jaynes and Isenhart, (2019b) used the Hydrus2D model to investigate the impact of the distribution pipe configuration on the infiltration characteristics and residence time in the buffer soil using measured data for an SB site in Iowa. McEachran et al., (2023) utilized the MODFLOW model to examine how water moves from the distribution pipe to the ditch in an SB in Iowa. They also formulated a one-dimensional equation to predict the time it takes for water to travel through the buffer soil after diversion. However, the use of such models requires high level of modeling expertise, and estimating the site-specific performance of SB under different designs, soil properties and climatic conditions can be challenging.

A decision-support tool is one convenient method that can aid with the design and evaluation of SBs based on local soil, weather, and drainage design conditions. Multiple user-friendly tools were developed to facilitate the design of drainage systems or as a method to evaluate the performance of other conservation drainage practices. Ghane and Askar, (2021) used empirical regression equations based on DRAINMOD simulations to develop an online tool to estimate the cost-effective drain spacing for subsurface drainage systems that would maximize the annual return on investment for corn-soybean rotation given simple user inputs. Guo et al., (2020) validated the performance of the Nutrient Tracking Tool (NTT) to provide acceptable annual crop yields, water balance, and nutrient loading predictions at the field scale in northwest Ohio using a set of parameters calibrated for this region. These tools can facilitate the design or improve the decision-making process regarding the use of conservation practices such that the benefits are maximized without the need of expertise in running complicated models. However, there is no similar tool for the SB system. Therefore, there is a need for an SB decision-support tool that can provide an acceptable representation of the hydrology and nitrate load removal performance of the practice.

The main objectives of this study were to develop a decision-support tool for SB, and evaluate its prediction performance of the hydrology and nitrate loading parameters of SB. The SB tool's value is that it can inform decision-makers on the benefits of the SB practice, facilitate and improve SB design, and provide a credible quantification method of diverted flow and nitrate load removal. The quantification of flow and nitrate load can help support emerging and future nitrate trading programs, thereby leading to increased adoption of the practice.

## 4.3. Materials and Methods

### 4.3.1. Development of a DRAINMOD-based saturated buffer decision-support tool

The development of a decision-support tool for SBs requires the quantification of the diverted and bypass flows, their respective nitrate loads, and the nitrate load removal of an SB system. The modeling routine presented in the study by Abdalaal and Ghane, (2023), here onwards referred to as the SB model, could estimate these parameters for an SB system with known design configuration and buffer soil properties but it requires the subsurface drainage discharge and its nitrate load as inputs. The subsurface drainage input requirement limits the direct use of the SB model as a decision-support tool for SBs. To address this limitation DRAINMOD was used to predict the subsurface drainage discharge based on the soil, weather, and subsurface drainage system characteristics at a field of interest (Skaggs et al., 2012b).

The DRAINMOD-based saturated buffer decision-support tool (DBSDTSB) is mainly composed of four components: (1) a component for obtaining user input, preparing input data required by the tool and presenting tool outputs, (2) a component for estimating the subsurface drainage discharge from a field of interest, currently utilizing DRAINMOD model, (3) a component for estimating the diverted and bypass flows, their respective nitrate loads, and the nitrate load removal of an SB system of known design configuration, currently utilizing the SB model, and (4) a component with defined objective functions used for implementing design approaches and predicting essential hydrology and nitrate load parameters that describe the performance of SBs. The general framework of the DBSDTSB is presented in Figure 4.1.

Notably, the DBSDTSB's component structure enables future enhancements, as it can accommodate the integration of alternative models or updated versions in place of the current ones utilized in the second and third components. Moreover, other objective functions or design approaches can be implemented in the fourth component of the DBSDTSB.

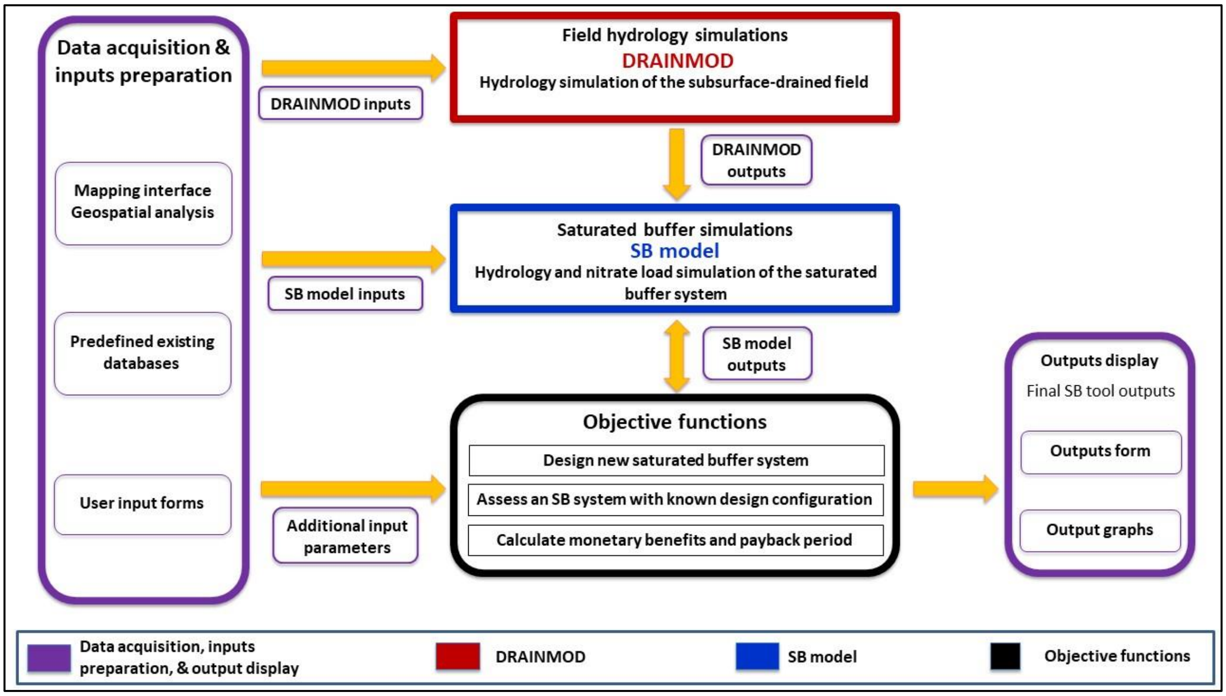


Figure 4.1. Components of the DRAINMOD-based decision-support saturated buffer tool.

### 4.3.2. Geospatial analysis

Geospatial analysis is a part of the first component responsible for obtaining and preparing the user input data. Geospatial analysis was implemented using python scripting with relevant publicly available python libraries and is performed twice when the SB tool is run. The first geospatial analysis is performed after the user specifies the field of interest to obtain the soil, weather, and soil temperature data. Based on the field location, the soil data is extracted from the gSSURGO database (Soil Survey Staff, 2020). The coverage percentages of the different soil units within the field are defined. Only the top three soil map units with coverage greater than 10% are considered. The extracted soil parameters are the texture percentages (sand, silt, and clay percentages), bulk density ($\rho_b$), vertical saturated hydraulic conductivity ($K_v$), depth to restrictive layer (D), and the water content at saturation ($\theta_s$), field capacity ($\theta_{fc}$), and wilting point ($\theta_{wp}$). The field location is also used to determine the input weather data from the predefined datasets. The parameters included in the predefined datasets are the daily precipitation and the maximum and minimum daily temperature data from the Daymet database (Thornton et al., 2021). The field location is also used to define the long-term average daily soil temperature data file from existing precompiled files of the data obtained from the Soil Climate Analysis Network, SCAN, (Schaefer et al., 2007).

The second geospatial analysis is conducted after the user draws a polyline to identify the extent of the distribution pipe length. This polyline is used to determine an initial value of the maximum length of the distribution pipe ($L_{DP}$). This value can be overridden by the users with a more practical value that considers the impact of the elevation, slope, and the presence of neighboring tile outlets along the buffer or other reasons that can limit this length. The polyline specified by the user serves the dual purpose of identifying the primary soil map units along its path and calculating the percentage of the distribution pipe's total length represented by each soil map unit. Subsequently, soil properties such as $\rho_b$, $K_v$, D, and $\theta_{fc}$ are extracted from the gSSURGO database for each of the defined soil map units. After that, a final value for each required parameter is calculated as a length-weighted average of the values representing the different soil map units along the user-specified distribution pipe extent.

### 4.3.3. DRAINMOD model

The DBSDTSB uses DRAINMOD model ( Skaggs et al., 2012) in the second component to predict the daily drainage discharge from user-defined fields of interest under conventional and controlled drainage modes. DRAINMOD is a 1-dimensional process-based model that simulates the hydrology of naturally poorly drained soils with shallow water table and artificial drainage systems, and predict key water balance components including subsurface drainage discharge as affected by site-specific conditions (i.e., weather, soil, , crop, and drainage system). DRAINMOD was used since it was widely tested and validated in numerous studies across the U.S. (Skaggs et al., 2012b; Shedekar, 2016; Askar et al., 2020) and other locations around the world (Cox et al., 1994; Shukla et al., 1994; Bechtold et al., 2007; Salazar et al., 2009). DRAINMOD is highly versatile since it can be used for evaluating the hydrologic performance of key conservation drainage practices including controlled drainage (Youssef et al., 2018; Youssef et al., 2021) and drainage water recycling (Moursi et al., 2022). Having credible estimates of the daily drainage discharge from DRAINMOD is essential to the DBSDTSB to estimate the diverted flow to the buffer and consequently the nitrate load removal by the buffer..

### 4.3.4. Saturated buffer model

The DBSDTSB uses the modeling routine (SB model) described in Abdalaal and Ghane, (2023) in the third component to predict the diverted and bypass flows, their respective nitrate loads, and the nitrate load removal of an SB system. The SB model uses the daily drainage discharge output from DRAINMOD model, a user-defined input of the average value for nitrate concentration of drainage water, the design configuration of the SB system (distribution pipe length, depth and diameter, and buffer width), the management of the stoplogs in the control structure, and the buffer characteristics (lateral hydraulic conductivity, effective porosity, depth to restrictive layer, nitrate removal coefficient, and water stage in the adjacent stream) to predict the required parameters. The SB model was developed using python scripting, and it builds on the hydrology representation of the NRCS SB design spreadsheet and the work by McEachran et al., (2020).

For hydrology, the SB model assumes steady-state conditions and conducts daily mass balance at two locations: inside the control structure and at the interface between the distribution pipe and the buffer soil, to estimate the diverted flow to the distribution pipe ($Q_{DP}$) and the bypass flow ($Q_{BY}$). The mass balance ensures that the incoming drainage discharge ($Q_{DD}$) to the control structure is equal to the summation $Q_{DP}$ and $Q_{BY}$. Moreover, the magnitude of the $Q_{DP}$ will be limited by the buffer's capacity to transmit water through the soil matrix, as represented by Equation (4.1), the Dupuit formula (McEachran et al., 2020). The magnitude of the $Q_{DP}$ will also be impacted by the exit head loss, as represented by Equation (4.2), the subirrigation equation suggested by Skaggs, (1991).

For simulating the nitrate load removal by SB, the model calculates the nitrate load from each flow component ($Q_{DD}$, $Q_{BY}$, and $Q_{DP}$) as the product of the user-defined average nitrate concentration of the drainage water and the corresponding volumetric flow. After that, the model assumes that the nitrate removal in the buffer follows first-order removal kinetics controlled by the width of the buffer, the time of travel through buffer soil, and the nitrate removal coefficient, as suggested by McEachran et al., (2020) and represented in equations 4.3 to 4.6. The SB model calculates the nitrate load reaching the ditch from the diverted water (NLRDDP) as the product of $Q_{DP}$ and the nitrate concentration of the buffer soil water at the maximum buffer width ($C$). The total nitrate load reaching the ditch from the SB system (NLSB) is calculated as the summation of the nitrate load from bypass flow (NLBY) and the NLRDDP.

Finally, the nitrate load removal is calculated as the difference between the nitrate load of drainage water (NLDD) and the NLSB.

$$Q_{DP} = K_{sat} \frac{\left(h_1^2 - h_2^2\right)}{2W} L_{DP} \tag{4.1}$$

$$Q_{DP} = -2\pi K_{sat} \frac{\left(h_1 - h_0\right)}{\ln \frac{h_1 - d}{R_{ef}}} L_{DP} \tag{4.2}$$

$$C = C_{DD}\, e^{-\lambda T_u} \tag{4.3}$$

$$T_u = \frac{4}{3} \frac{n_e W^2}{K} \frac{{h_1}^3 - {h_2}^3}{\left({h_1}^2 - {h_2}^2\right)^2} \tag{4.4}$$

$$\lambda = K_d f_T \tag{4.5}$$

$$f_T = Q_{10}^{(T - T_r)/10} \tag{4.6}$$

where

$K_{sat}$ = equivalent lateral saturated hydraulic conductivity of the buffer soil,

$h_0$ = hydraulic head inside the control structure,

$h_1$ = hydraulic head in the buffer soil just outside the distribution pipe,

$h_2$ = hydraulic head in the stream or ditch,

$W$ = buffer width,

$L_{DP}$ = length of distribution pipe,

$d$ = distance from center line of the distribution pipe to impermeable layer,

$R_{ef}$ = effective radius of distribution pipe,

$C$ = nitrate concentration in the buffer soil water at the maximum buffer width,

$C_{DD}$ = nitrate concentration in drainage water,

$\lambda$ = nitrate removal coefficient,

$T_u$ = time of travel for water to move from the distribution pipe to the maximum buffer width,

$K_d$ = first-order denitrification coefficient,

$f_T$ = reduction coefficient by temperature, calculated as reviewed by Heinen (2006),

$T$ = soil temperature,

$T_r$ = reference temperature, and

$Q_{10}$ = factor with typical value ranging between 2 and 3.

### 4.3.5. Objective functions

Currently, there are three objective functions that are defined in the fourth component of the DBSDTSB. The first is the proposed design approach described in Abdalaal and Ghane, (2023), which is used to calculate the design buffer width. The second is used to assess the performance of an existing SB with known design parameters (buffer width, length of distribution pipe, and weir management) using the SB model described in section 4.3.3. The third is used to estimate the monetary benefits and payback periods as impacted by assumed gain in crop yield as a result of implementing the stacked CD and SB system and incentives from Environmental Quality Incentives (EQIP) programs. Notably, more objective functions can be added to this component to investigate the needs at different watersheds or districts, making the DBSDTSB more versatile for decision-making process.

### 4.3.6. Evaluation of the prediction performance of the DBSDTSB

This study aimed at evaluating the ability of the DBSDTSB to predict the hydrology and nitrate load parameters that are essential for quantifying the performance of an SB system. The DBSDTSB's predictions of the subsurface drainage discharge, diverted flow to buffer, nitrate load in drainage water, nitrate load removal by SB were compared against their corresponding measured values at two field sites (BC1 and IA1) in Iowa.

Since the DBSDTSB is more oriented for decision-makers, the evaluation of the prediction performance at the yearly scale seemed more relevant than at the finer timescales. Evaluations of similar tools, such as NTT or DRAINMOD-based regression tools were also conducted on a yearly scale (Negm et al., 2016; Guo et al., 2020). The daily predictions of the considered parameters were aggregated to yearly values after dropping the days with missing measurements, before conducting the evaluation methodology.

Four widely used statistical indicators in hydrological and water quality modeling studies were used to report the prediction performance of the DBSDTSB. Three of them were used as a measure of the goodness-of-fit between the measured values and their corresponding predictions from the DBSDTSB, which are the Nash-Sutcliffe efficiency (NSE), the Kling–Gupta efficiency (KGE), and the index of agreement (IoA) (Nash and Sutcliffe, 1970; Willmott, 1981; Gupta et al., 2009; Moriasi et al., 2015). The fourth statistical indicator was the percent bias (PBIAS), which was used to measure the tendency to have overestimated or underestimated predictions (Gupta et al., 1999; Moriasi et al., 2015). The equations of the used statistical indicators are presented in equations 7 to 10, and the evaluation criteria to judge the prediction performance of the DBSDTSB is listed in Table 4.1.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(X_{obs,i} - \bar{X}_{obs}\right)^2} \tag{7}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{sim,i}\right)}{\sum_{i=1}^{n}\left(X_{obs,i}\right)} \times 100 \tag{8}$$

$$\mathrm{KGE} = \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\bar{X}_{sim}}{\bar{X}_{obs}} - 1\right)^2} \tag{9}$$

$$\mathrm{IoA} = 1 - \frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{sim,i}\right)^{2}}{\sum_{i=1}^{n}\left(\left|X_{obs,i} - \bar{X}_{obs}\right| + \left|X_{sim,i} - \bar{X}_{obs}\right|\right)^{2}} \tag{10}$$

where

$X_{obs,i}$ = Observed value number “I”.

$X_{sim,i}$ = Simulated value number “I”.

$\bar{X}_{obs}$ = Mean observed value.

$n$ = Total number of records.

$r$ = Pearson correlation coefficient.

$\sigma_{sim}$ = Standard deviation of the simulated records.

$\sigma_{obs}$ = Standard deviation of the observed records.

Table 4.1. The evaluation criteria of the statistical indicator metrics considered in the assessment of the prediction performance of the DRAINMOD-based decision-support tool for saturated buffers.

| Properties | Range | Parameter | Categorical range | classification | Source |
|---|---|---|---|---|---|
| **Nash Sutcliffe Efficiency (NSE)** | $-\infty$ *to* 1 | Flow | $(\mathrm{NSE} > 0.75)$ | Very Good | Moriasi et al., (2015) |
| | | | $(0.60 \le \mathrm{NSE} \le 0.75)$ | Good | |
| | | | $(0.50 < \mathrm{NSE} < 0.60)$ | Satisfactory | |
| | | | $(\mathrm{NSE} \le 0.50)$ | Unsatisfactory | |
| | | Nutrients | $(\mathrm{NSE} > 0.70)$ | Very Good | |
| | | | $(0.60 \le \mathrm{NSE} \le 0.70)$ | Good | |
| | | | $(0.35 < \mathrm{NSE} < 0.60)$ | Satisfactory | |
| | | | $(\mathrm{NSE} \le 0.35)$ | Unsatisfactory | |
| **Kling-Gupta Efficiency (KGE)** | $-\infty$ *to* 1 | General | $(\mathrm{KGE} \ge 0.70)$ | Very Good | Jeantet et al., (2021) |
| | | | $(0.60 \le \mathrm{KGE} < 0.70)$ | Good | |
| | | | $(0.50 \le \mathrm{KGE} < 0.60)$ | Satisfactory | |
| | | | $(\mathrm{KGE} < 0.50)$ | Unsatisfactory | |
| **Index of Agreement (IoA)** | 0 to 1 | General | $(\mathrm{IoA} > 0.90)$ | Very Good | (Ma et al., 2011, 2012) |
| | | | $(0.80 < \mathrm{IoA} \le 0.90)$ | Good | |
| | | | $(0.70 < \mathrm{IoA} \le 0.80)$ | Satisfactory | |
| | | | $(\mathrm{IoA} \le 0.70)$ | Unsatisfactory | |
| **Percent Bias (PBIAS)** | $-\infty$ *to* $\infty$ | Flow | $(\lvert\mathrm{PBIAS}\rvert \le 2.5)$ | Very Good | Moriasi et al., (2015) |
| | | | $(2.5 < \lvert\mathrm{PBIAS}\rvert < 15)$ | Good | |
| | | | $(15 \le \lvert\mathrm{PBIAS}\rvert \le 35)$ | Satisfactory | |
| | | | $(\lvert\mathrm{PBIAS}\rvert > 35)$ | Unsatisfactory | |
| | | Nutrients | $(\lvert\mathrm{PBIAS}\rvert \le 10)$ | Very Good | |
| | | | $(10 < \lvert\mathrm{PBIAS}\rvert < 15)$ | Good | |
| | | | $(15 \le \lvert\mathrm{PBIAS}\rvert \le 30)$ | Satisfactory | |
| | | | $(\lvert\mathrm{PBIAS}\rvert > 30)$ | Unsatisfactory | |

### 4.3.7. Sites descriptions for evaluating the tool

Two fields, Hamilton1 (BC1) and Hamilton3 (IA1), were considered in evaluating the prediction performance of the DBSDTSB. The data defining each site were obtained from published data in the Transforming Drainage Database (TDD) (Chighladze et al., 2021). Additional data were obtained through direct communication with the Iowa State University research (ISU) team. The additional data included more site years at BC1 (2019 to 2022), information about the lateral drain spacing at BC1, and the weir management records for BC1 and IA1. The data collected comprised a total number of 14 site years across both sites. The fields' locations are shown in Figure 4.2. The general properties of the two fields are presented in Table 4.2 and additional information on the SB and subsurface drainage systems at each site is presented in Section 4.3.4.

Table 4.2. General properties of the BC1 and IA1 sites considered in the field evaluation study of the DRAINMOD-based decision-support tool for saturated buffers.

| Properties | BC1 Site | IA1 Site |
|---|---|---|
| **Available site years data** | 2014-2022 | 2014-2018 |
| **Subsurface-drained area (ha)** | 5.95 | 4.7 |
| **Dominant soil (subsurface-drained area)** | Clarion loam - Storden loam - Coland clay loam | Webster clay loam – Nicollet clay loam - Clarion loam |
| **Dominant soil (buffer zone)** | Coland clay loam | Coland-Terril complex |

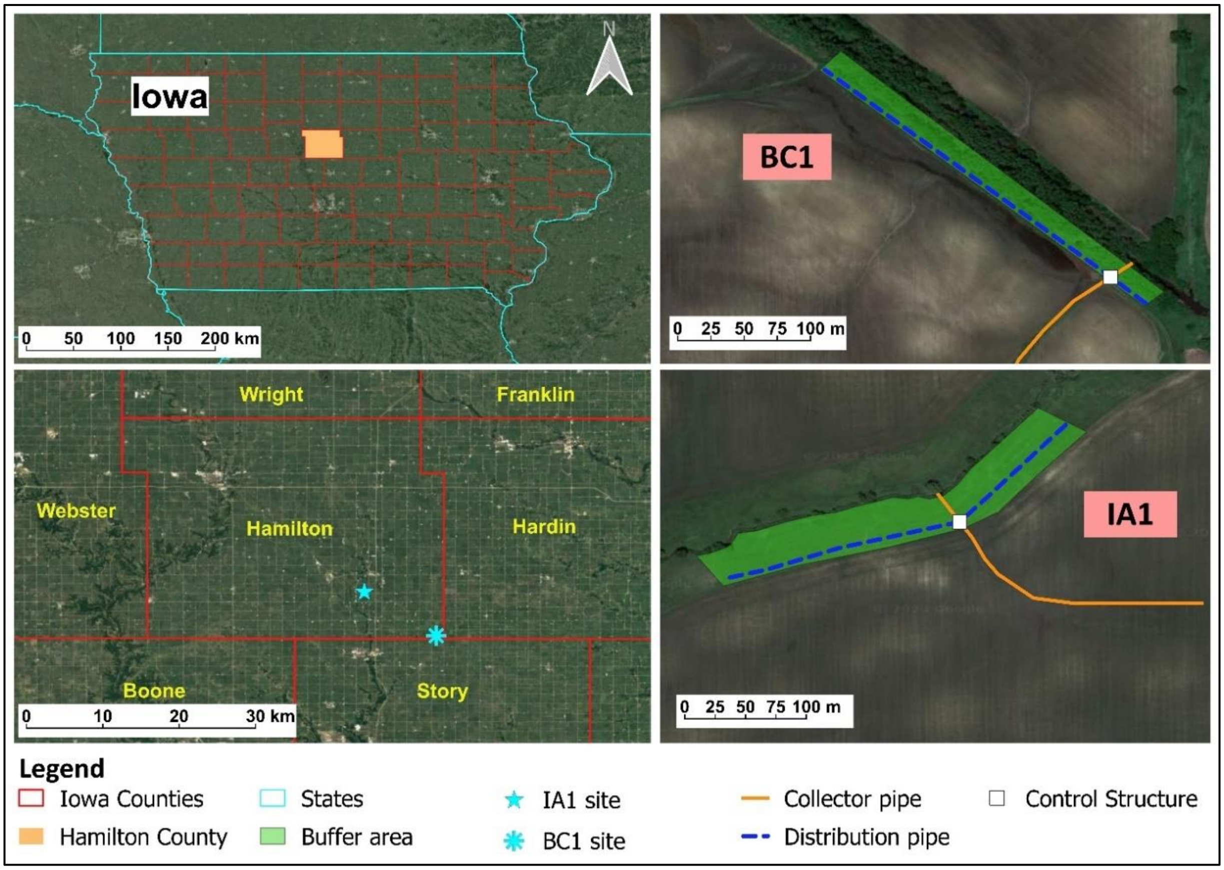


Figure 4.2. BC1 and IA1 sites are considered in evaluating the DRAINMOD-based decision-support tool for saturated buffers. The shape buffer areas and the locations of the control structure, main collectors, and distribution pipes are roughly represented based on the information provided in the site summaries of the Transforming Drainage Database.

### 4.3.8. Parameterization of the DRAINMOD-based saturated buffer tool

Adequate parameterization of decision-support tools facilitates its use and enhances its performance. Also, tailoring the parameterization to a specific region can further improve the performance of decision-support tools. Guo et al., (2020) identified a set of calibrated parameters for the NTT that are suited for the fields in the Western Lake Erie Basin, where their study showed that the NTT provided a good representation of the annual average crop yields, flows, and nutrient losses across 12 paired sites in northwest Ohio. The parameterization of some of the inputs required by the core models of the DBSDTSB was conducted for Iowa since the sites used in the current study were limited to this region. The proposed default values were obtained from literature or through calibration (Table 4.3). Detailed elaboration on the parameterization process is presented in the supplementary Appendix A.2.

Table 4.3. The default values and the parameterization scheme for Iowa for the main inputs needed by the core models (DRAINMOD and SB model) of the DRAINMOD-based decision-support tool for saturated buffers.

| Parameter | Value |
|---|---|
| **Soil temperature parameters (DRAINMOD)** | |
| Snow temperature | -2.0 °C |
| Melting temperature | -1.0 °C |
| Thawing rate | 1.0 mm/dd. °C |
| **Subsurface drainage system property (DRAINMOD)** | |
| The effective radius of lateral pipe [a] | 1.9 cm |
| Drainage coefficient | 1.9 cm/day |
| Maximum surface storage | 2.0 cm |
| Kirkham's depth | 1.0 cm |
| **Soil properties of the tiled-field (DRAINMOD)** | |
| DRAINMOD soil files [b] | gSSURGO, Module 5 Rosetta3, and DRAINMOD soil utility program |
| Lateral Ksat of each soil layer [a] [c] | Twice the extracted Ksat value from gSSURGO |
| Depth to the restrictive layer | 305 cm (10 ft) |
| **Weather parameter (DRAINMOD)** | |
| Daily rainfall and temperature | Daymet database using the nearest airport location |
| Monthly PET correction factors | From Jan to Dec: 2.8, 2.9, 2.5, 1.8, 1.0, 0.8, 1.0, 1.0, 0.8, 1.0, 1.5, 2.5 |
| **Cropping system info (DRAINMOD)** | |
| Corn planting date [a] | 5-May |
| Soybean planting date [a] | 21-May |
| Corn growing days [a] | 168 days |
| Soybean growing days [a] | 143 days |
| **Buffer properties (SB Model)** | |
| Effective Lateral Ksat [a] [d] | Effective value using gSSURGO |
| Depth to the restrictive layer [a] | 427 cm (14 ft) |
| First-order denitrification coefficient [a] | 0.45 day$^{-1}$ |
| Distance between stream water stage and restrictive layer [a] | 30.5 cm (1 ft) |

[a] Value can be overridden by the user.

[b] Extracted soil data (soil texture percentages, bulk density, and water content values at field capacity) from gSSURGO database were used in Rosetta3 model (Zhang and Schaap, 2017), then the output from Rosetta3 was used in the DRAINMOD soil utility program to create soil files.

[c] Ksat is the saturated hydraulic conductivity. The lateral Ksat at each soil layer was calculated as twice the vertical hydraulic conductivity extracted from the gSSURGO database.

[d] Four-times, the depth-weighted effective value of extracted vertical hydraulic conductivity values of existing soil mapunits in the buffer.

The values of other site-specific parameters used in the current study are listed in Table 4.4. It should be noted that the DBSDTSB allows for modifying the default values of many of the parameters, which can allow a better representation of the field of interest and a possible improvement to predictions.

Table 4.4. The defined site-specific values of the DRAINMOD-based decision-support tool for saturated buffers input parameters in the simulations at BC1 and IA1 sites.

| **Parameter** | **Value at BC1** | **Value at IA1** |
|---|---|---|
| **Subsurface drainage system property** | | |
| Lateral spacing [a] | 30.0 m | 29.0 m |
| Lateral depth [a] | 1.2 m | 1.2 m |
| **Weather records** | | |
| Weather data [a] | Daymet at Ames airport | Daymet at Webster City airport |
| **Cropping system info** | | |
| Crop rotation [a] | Corn (even years)<br>Soybean (odd years) | Corn (even years)<br>Soybean (odd years) |
| **Outlet management settings** | | |
| Corn management [a] | Constant 17 cm from ground surface | Constant 17 cm from ground surface |
| Soybean management [a] [b] | Dates: 1/1 - 5/31 - 6/9 -<br>Depths (cm) : 17 - 100 - 17 | Constant 17 cm from the ground surface |
| **Nitrate concentration in drainage discharge** | | |
| Avgerage annual NO3 concentration [a] | 9.6 mg/l [c] | 9.8 mg/l [d] |
| **Saturated buffer system property** | | |
| Distribution pipe length [a] | 335 m (1101 ft) | 308 m (1010 ft) |
| Buffer width [a] | 21 m (70 ft) | 24 m (80 ft) |
| Distribution pipe depth [a] | 0.76 m (2.5 ft) | 0.76 m (2.5 ft) |
| Distribution pipe diameter [a] | 10 cm (4 in) | 10 cm (4 in) |
| Distribution pipe effective radius [a] | 5.8 cm | 5.8 cm |
| **Buffer properties** | | |
| Effective Lateral saturated hydraulic conductivity [a] | 8.1 cm/h | 9.8 cm/h |
| Distance between stream water stage and restrictive layer [a] | 259 cm | 220 cm |

[a] Value can be set in the user interface of the tool.

[b] The outlet level is set to the specified depth from ground surface at its corresponding date.

[c] Calculated as the arithmetic mean of the available records of the grab samples at BC1 site between the years of 2014 to 2022.

[d] Calculated as the arithmetic mean of the available records of the grab samples at IA1 site between the years of 2014 to 2018.

## 4.4. Results and Discussions

### 4.4.1. Model performance to predict subsurface drainage discharge predictions

When all of the data was considered in the evaluation the predicted drainage discharge had better agreement with the corresponding measured records as compared to the calibration or validation periods, as reflected by the better statistical indicators reported in Table 4.5. Over all years, the performance of the DBSDTSB to predict the drainage discharge was classified as "Good" for the yearly timescale and "Satisfactory" for the monthly timescale based on the NSE values, "Good" for both time scales based on the PBIAS values, "Very Good" for both time scales based on KGE values, and "Very good" for yearly timescale and "Good" for monthly timescale based on IoA values. Notably, the smaller sample size used in the calculation of the calibration and validation yearly metrics might have resulted in the lower values and classification.

Table 4.5. Calculated statistical performance metrics for the predictions from the DRAINMOD-based decision-support tool for saturated buffers.

| **Parameter** | | **Time period** | **Nash-Sutcliffe Efficiency (NSE)** | **Kling-Gupta Efficiency (KGE)** | **Percent bias (PBIAS)** | **Index of Agreement (IoA)** |
|---|---|---|---|---|---|---|
| **Normalized drainage discharge (drainage depth)** | *Calibration* [a] | Yearly | 0.60 | 0.57 | -14.5 % | 0.85 |
| | | Monthly | 0.55 | 0.73 | -14.5 % | 0.88 |
| | *Validation* [b] | Yearly | 0.73 | 0.86 | 1.5 % | 0.93 |
| | | Monthly | 0.60 | 0.72 | 1.5 % | 0.87 |
| | *All years* [c] | Yearly | 0.69 | 0.83 | -4.4 % | 0.91 |
| | | Monthly | 0.58 | 0.74 | -4.4 % | 0.87 |
| **Normalized diverted flow (diverted depth)** | *All years* [c] | Yearly | 0.68 | 0.68 | -0.03 % | 0.89 |
| | | Monthly | 0.41 | 0.58 | -0.03 % | 0.79 |
| **Normalized nitrate load of drainage discharge** | *All years* [c] | Yearly | 0.45 | 0.69 | -3.0 % | 0.83 |
| | | Monthly | 0.49 | 0.61 | -3.0 % | 0.82 |
| **Normalized nitrate load removal by SB** | *All years* [c] | Yearly | 0.62 | 0.80 | -9.0 % | 0.91 |
| | | Monthly | 0.36 | 0.58 | -9.0 % | 0.78 |

[a] Calibration period analysis included the years (2015, 2016, and 2022) at BC1 and (2015 and 2016) at IA1.

[b] Validation period analysis included the years (2014, and 2017 to 2019) at BC1 and (2014, 2017 and 2018) at IA1.

[c] All years analysis included the years (2014 to 2022) at BC1 and (2014 to 2018) at IA1.

Visual inspection of the predicted drainage discharge values against the measured data showed that the DBSDTSB could adequately represent the yearly and monthly drainage discharge. As shown in Figures 4.3 and A.2, the drainage discharge predictions followed the same patterns of the measured records. Moreover, the difference between the predicted and measured values was generally acceptable and only differed considerably in a few circumstances.

The absolute deviations between predicted and measured yearly values were relatively small (Range = 3 to 149 mm, Mean = 55 ± 39 mm), and the average annual deviation was only 10 ± 66 mm. Therefore, the performance of the DBSDTSB to predict the yearly drainage discharge can be considered good.

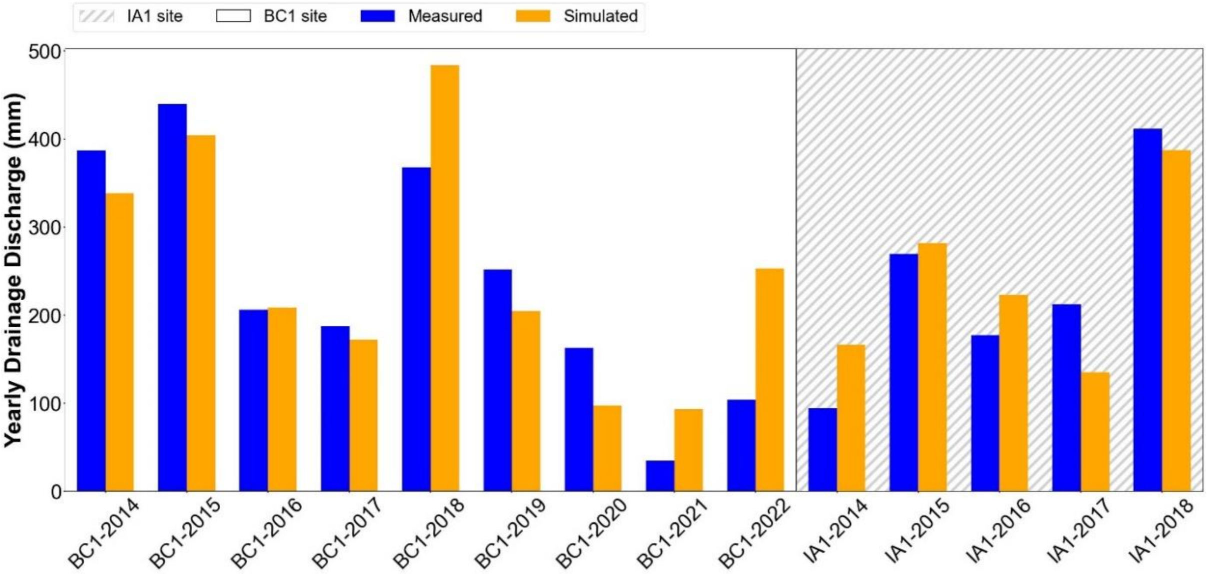


Figure 4.3. Comparison between the predicted yearly drainage discharge from the SB tool and the measured records at BC1 and IA1 in Iowa for all years.

The PBIAS value indicated that the tool slightly overpredicted the drainage discharge. The estimated drainage discharge data inspection showed that the DBSDTSB overpredicted the drainage discharge during the late winter and early spring. The overpredictions occurred due to multiple reasons. Firstly, it may have occurred because of the uncertainties in the precipitation data obtained from the Daymet database. Secondly, the overpredictions in late winter may be attributed to inaccuracies in representing snow-thawing dynamics. Meanwhile, overpredictions in early spring were possibly due to the misrepresentation of the free drainage period. This resulted from the limitation in defining the actual weir management setup, which led to the misrepresentation of the weir management in terms of the managed periods or intensity and resulted in overestimating the drainage discharge. The limitation in defining the actual weir settings was that the DBSDTSB allows the definition of only two management settings (one for even years and one for odd) for the simplicity of the tool's usage. Additionally, due to its variable nature, active weir management is not accounted for in DRAINMOD. The drainage discharge overpredictions were more pronounced during extremely wet years, particularly in 2018. In dry years of 2021 and 2022, the overpredictions were obvious since the total drainage discharge during these years was low, so the ratio of overpredictions to total flows was high. Other modeling studies also showed that underperformance in predictions is expected during extreme deviations from normal (Negm et al., 2016). Notably, in years with average precipitation, deviations from measured values remained relatively mild, and the general overpredictions were within the "Good" range for the PBIAS evaluation criterion of hydrological models (Moriasi et al., 2015). Moreover, other similar tools reported good simulation performance of tile drainage with a PBIAS of 4% (Guo et al., 2020).

### 4.4.2. Performance to predict diverted flow to buffer

The predicted diverted flow to the buffer had relatively good agreement with the measured records despite the varying performance classification of a single statistical indicator listed in Table 4.5. The prediction performance of the yearly diverted flow to the buffer was classified as "Good" based on NSE, KGE, and IoA scores and "Very Good" based on PBIAS score . On the other hand, the predictions on the monthly timescale had an "Unsatisfactory" classification only for NSE, while other classifications were "Good" for KGE and IoA and "Very Good" for PBIAS. Considering the scores of the different statistical indicator metrics, it can be concluded that the performance of the DBSDTSB to predict the diverted flow to the buffer was deemed good at both timescales.

Visual inspection of the predicted diverted flow against the measured showed that the DBSDTSB can generally provide adequate representation of the yearly diverted flow to buffer. Generally, the diverted flow predictions followed the same trends as the measured records, as shown in Figures 4.4 and A.3. Only a few years at IA1 had major discrepancies between the predicted and measured yearly values. The prediction performance of the diverted flow to the buffer was expected to have lower efficiency than that of the drainage discharge since the DBSDTSB used the predicted drainage discharge as input to the SB model, which propagated the prediction errors to the diverted flow predictions. Nonetheless, the absolute deviations between predicted and measured yearly values were relatively small (Range = 7 to 115 mm, Mean = 42 ± 31 mm), and the average annual deviation was only 0.04 ± 52 mm. Therefore, the performance of the DBSDTSB to predict the yearly diverted flow was deemed good.

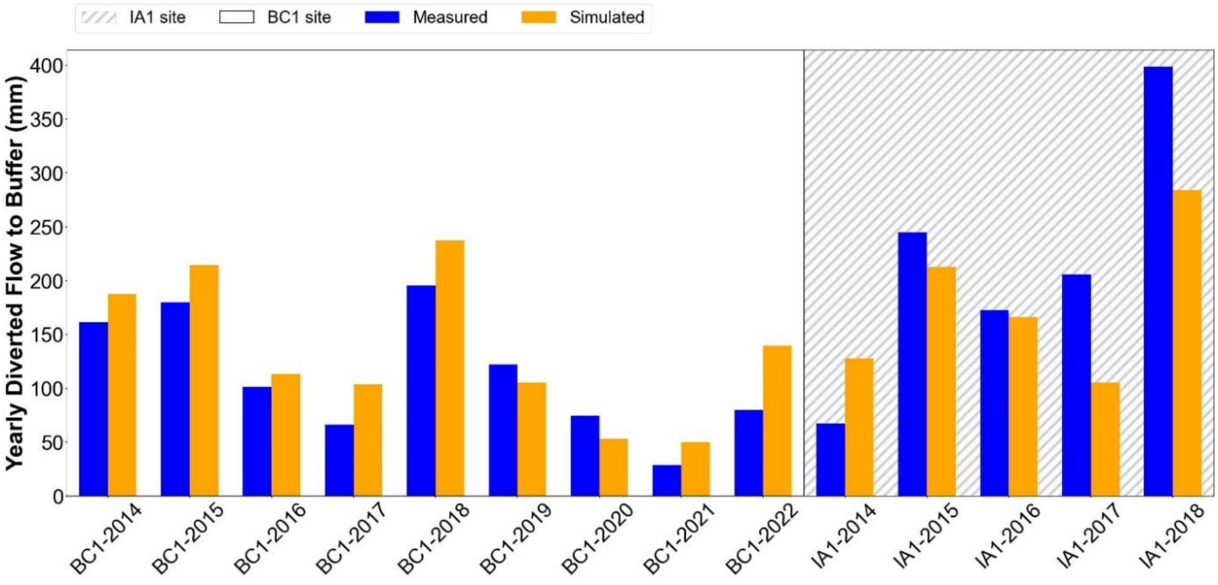


Figure 4.4. Comparison between the predicted yearly normalized diverted flow to the buffer from the SB tool and the measured records at BC1 and IA1 in Iowa for all years.

The major discrepancies between the predicted and the observed diverted flows varied between underpredictions and overpredictions. Underpredictions were more obvious during periods that had relatively high drainage discharge measurements. Examples of these periods were during some months in 2018 and 2017 at IA1 or September 2018 at BC1. The underestimation probably occurred due to the combination of two reasons. Firstly, the underestimation of the predicted drainage discharge directly led to the underestimation in the predicted diverted flow because the magnitude of the diverted flow cannot exceed the drainage discharge. The underestimation in the diverted flow predictions was further increased by the defined modeling approach in the SB model to predict the diverted flow since the current modeling approach limits the maximum value to the capacity of the buffer soil to transmit water (McEachran et al., 2020; Abdalaal and Ghane, 2023).

On the other hand, the overprediction in diverted flows occurred mainly during late winter and early spring. This can be attributed to the overprediction in the drainage discharge resulting from the poor representation of the snow and thawing mechanics at the fields. Further improvement to the representation of the diverted flow capacity and the method to estimate the drainage discharge will further improve the diverted flow prediction performance of the DBSDTSB. Notably, the hydrology of SB systems is complex (McEachran et al., 2023), and even for the same SB system, the magnitude of the measured annual diverted flow had wide ranges, 29 to 196 cm at BC1 and 173 to 399 mm at IA1. Therefore, the DBSDTSB's prediction performance of the annual diverted flow was good, as shown by visual inspection and the scores of the statistical indicators.

### 4.4.3. Performance to predict nitrate loading of drainage discharge

The predicted nitrate load in drainage discharge (NLDD) was in good agreement with the measured data, as reflected by the statistical indicators reported in Table 4.5. The performance of the DBSDTSB to predict NLDD was classified as “Satisfactory” for both timescales only for the NSE metric, while the classifications of other metrics for both time scales were “very good” for PBIAS, and “Good” for both KGE, and IoA. Overall, the prediction performance of the DBSDTSB to estimate the nitrate load in drainage discharge under controlled drainage management was good.

Visual inspection of the predicted NLDD values against the measured records showed that the DBSDTSB can provide an adequate representation of the NLDD on the yearly timescale. Generally, the predictions followed the same trends of the measured records (Figures 4.5 and A.4). The lower prediction performance on the monthly timescale can be partly accredited to the propagated error from the drainage discharge predictions and partly to not accounting for the seasonal change in the actual nitrate load concentration. Notably, the maximum deviation of the NLDD predictions from the measured at the yearly timescale, a maximum of 18.3 Kg-N/ha, was within the range reported by other nutrient loading accounting tools with acceptable performance. For example, the DRAINMOD-based regression tool reported annual deviations from measurements that were lower than about 32 Kg-N/ha for the corn-winter wheat-soybean rotation under drainage water management (Negm et al., 2016). Also, the absolute deviations between predicted and measured yearly values were reasonable (Range = 1.2 to 18.3 kg-N/ha, Mean = 7.7 ± 4.6 kg-N/ha) with average annual deviation of only 0.7 ± 8.9 kg-N/ha. Therefore, the DBSDTSB's performance in predicting the annual NLDD under CD management was acceptable.

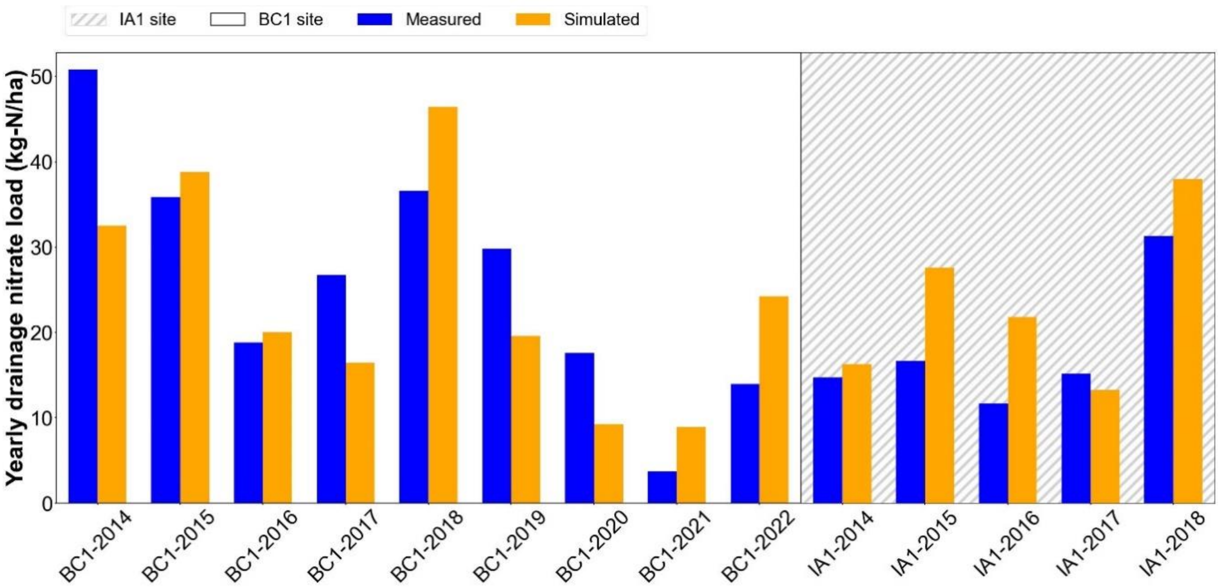


Figure 4.5. Comparison between the predicated yearly normalized nitrate loading from drainage discharge and the measured records at BC1 and IA1 in Iowa for all years.

### 4.4.4. Performance to predict nitrate load removal by saturated buffer

The predicted nitrate load removal by the saturated buffer (NLRSB) was in good agreement with the measured data, as reflected by the statistical indicators reported in Table 4.5. For the yearly timescale, the prediction performance of the DBSDTSB was classified as “Good” based on NSE and KGE metrics, and “Very Good” based on IoA and PBIAS metrics. While for the monthly timescale, the classification was “Satisfactory” based on NSE, KGE and IoA, and “Very Good” for PBIAS. In general, the prediction performance of the nitrate load removal by SB was acceptable.

Visual inspection of the predicted NLRSB against the measured data shows that, in general, the DBSDTSB can provide an acceptable representation of the yearly and monthly NLRSB. As shown in Figures 4.6 and A.5, the NLRSB predictions followed the same trends of the measured records, and the differences between the predicted and measured values were generally acceptable except for a few times. The absolute deviations between predicted and measured yearly values were reasonable (Range = 0.8 to 7.2 kg-N/ha, Mean = 3.2 ± 1.9 kg-N/ha) and the average annual deviation was only 1.2 ± 3.5 kg-N/ha. Owing to the complexity of SB system nitrate removal mechanisms (Johnson et al., 2023), and to the wide range of interannual and across-sites nitrate load removal performance reported in many of the review studies (Jaynes and Isenhart, 2019a; Johnson et al., 2023), the performance of the DBSDTSB to predict the yearly nitrate load removal by the saturated buffer was deemed acceptable.

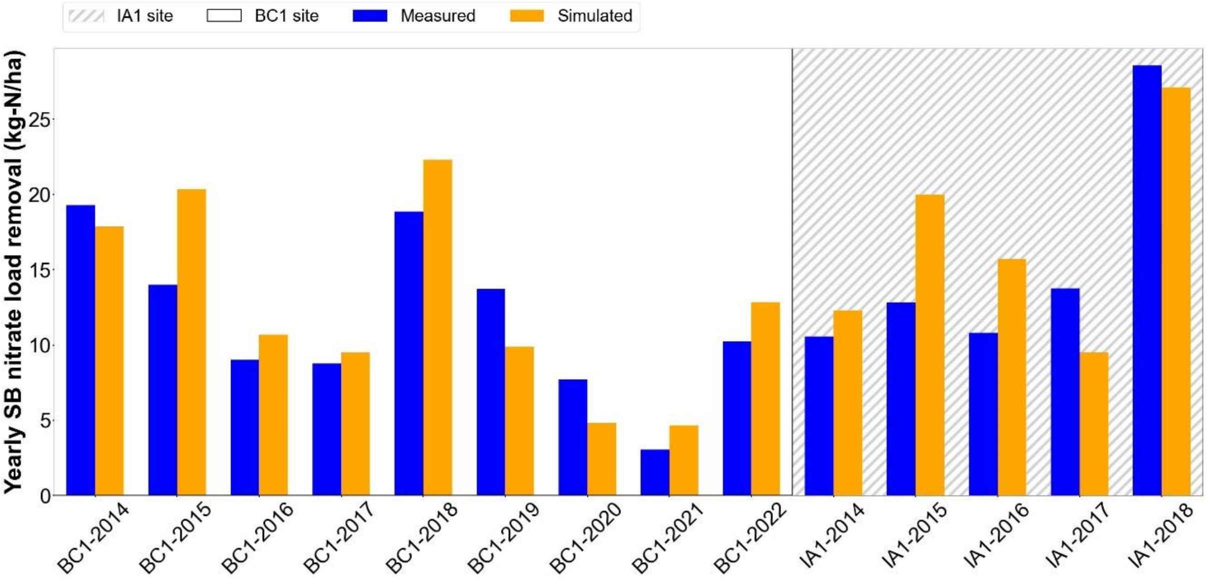


Figure 4.6. Comparison between the predicted yearly normalized nitrate load removal by the saturated buffer and the measured records at BC1 and IA1 in Iowa for all years.

The largest deviations between the measured and predicted NLRSB were due to overpredictions. Analysis of the data showed significant overprediction in NLRSB occurred during relatively wet periods. In these periods, the overprediction of drainage discharge led to overprediction in diverted flow, which in turn led to overprediction in nitrate load removal by SB. On the other hand, the underpredictions were a result of the underprediction in the predicted diverted flow to the buffer, where the reasons for underpredictions in the diverted flow area were discussed previously in section 4.4.2.

### 4.4.5. Performance to predict the average annual performance metrics of the saturated buffer

Evaluating the DBSDTSB's ability to predict the average annual performance metrics of the saturated buffer was necessary since these parameters are crucial in the decision-making process. The DBSDTSB's average annual estimates of the parameters describing the SB performance were calculated for each site and presented in Table 4.6.

Table 4.6. Calculated average annual performance metrics of the saturated buffers from field measurement records and the DRAINMOD-based decision-support tool for saturated buffers predictions for the years with complete data at BC1 and IA1 in Iowa.

| **Parameter** | **BC1 site** | | **IA1 site** | |
|---|---|---|---|---|
| | *Measured* | *Predicted* | *Measured* | *Predicted* |
| Average annual normalized drainage discharge (mm) [a] | 238 | 251 | 268 | 257 |
| Average annual normalized diverted flow to buffer (mm) [a] | 112 | 134 | 256 | 192 |
| Average annual percentage diverted flow to buffer (%) [a], [b] | 52.8 | 54.2 | 95.6 | 75.3 |
| Average annual normalized nitrate load of drainage discharge (Kg-N/ha) [a] | 26.0 | 24.1 | 18.7 | 25.2 |
| Average annual normalized nitrate load removal by buffer (Kg-N/ha) [c] | 11.6 | 12.6 | 16.5 | 18.1 |
| Average annual percentage reduction of nitrate load by buffer (%) [c], [d] | 50.4 | 52.7 | 87.9 | 71.9 |

[a] Calculated values were for years 2014 to 2022 at BC1 and 2015 to 2018 at IA1.

[b] Percentage reduction is calculated as the average of all yearly percentage reduction values, where each yearly value was referenced to the corresponding annual normalized drainage discharge.

[c] Calculated values were for years 2015 to 2018 at BC1 and IA1.

[d] Percentage reduction is calculated as the average of all yearly percentage reduction values, where each yearly value was referenced to the corresponding annual normalized nitrate load of drainage discharge.

The average annual SB performance metrics calculated using the DBSDTSB predictions had reasonable values and did not vary considerably from those calculated using the measurement records. This was expected given the DBSDTSB's relatively good performance in predicting the yearly drainage discharge, diverted flows, NLDD, and NLRSB used in calculating these SB performance metrics. The deviations of the predicted average annual performance metrics from their corresponding measured values followed the same deviation pattern of the yearly values used in their calculations. For example, the underestimation of the yearly diverted flow at IA1 led consequently to an underestimation in the average diverted flow.

The maximum percentage difference between the predicted and measured average annual diverted flow to a buffer was at the IA1 site and amounted to about -20%. Also, the maximum percentage difference between the predicted and measured average annual nitrate load reduction by the SB was again at the IA1 site and amounted to about -16%. Notably, only four years had complete measurement records at IA1, which were utilized to calculate the measured and predicted average annual values. The restricted number of years likely influenced the performance evaluation of the DBSDTSB in estimating the average annual values at IA1. On the other hand, more years were used in calculating the average annual values at BC1 (nine years), and the higher certainty in BC1 data, in general, resulted in fewer differences between the measured and predicted average annual flow and load values. The deviations of SB's predicted percentages of diverted flow and nitrate load reduction from the measured values were considerably smaller and amounted to only 1% and 2%, respectively.

Notably, the predicted diverted flow and nitrate load removal were within the reported ranges in review studies by Jaynes and Isenhart, (2019a) and Johnson et al., (2023). In addition, at the site that had more data years (BC1), the long-term average nitrate load removal by SB was close to the mean value of nitrate load removal by SB in the US (46%) reported by Johnson et al., (2023). Therefore, the performance of the DBSDTSB to predict the average annual SB hydrology, nitrate loading, and nitrate load removal performance metrics can be considered acceptable.

### 4.4.6. Potential applications of the DBSDTSB

The average annual estimates from the DBSDTSB can enhance the decision-making process related to the SB system. The average annual diverted flow to the buffer can give an initial understanding of the potential of using the SB practice at a field site, even with the lack of data necessary to calculate nitrate load removal performance. This is because the SB nitrate load removal from drainage discharge is highly correlated with the amount of diverted water that eventually gets treated (Jaynes and Isenhart, 2019a). With the presence of nitrate-related data, adequate estimates of the average annual nitrate load removal by the SB can further enhance the decision-making process.

The benefits to the decision-making process can further be leveraged by incorporating the DBSDTSB with larger scale geospatial analysis that can identify potential locations for SB implementation. The ability of the tool to reasonably estimate the nitrate load removal by SB at the identified potential locations while considering local soil, water, and drainage systems conditions can be used to set up plans and implementation priority lists, and estimate the potential nitrate loading reductions at the different watersheds or districts.

Having a credible tool that can serve as an accounting method for nitrate loading reductions is a necessary element for planning and setting nitrate trading programs that can promote the use of the practice and consequently result in more nitrate load removal. Moreover, the DBSDTSB has an objective function that can facilitate the SB's designing process. Thereby, the DBSDTSB has the potential to improve the decision-making process, promote the use of the SB practice, and enhance the SB nitrate load removal performance, consequently resulting in more nitrate load reductions and better water quality.

### 4.4.7. Limitations of the study and future considerations

The current study had some limitations because of the assumptions defined while developing the DBSDTSB. A comprehensive understanding of the DBSDTSB's limitations and potential areas for improvement is crucial for enhancing the DBSDTSB's prediction performance which subsequently can lead to better evaluation and design of SB systems. The main limitations are listed in this section, further elaboration on the limitations is listed in Appendix A.4.

The methods used for defining the drainage area of the subsurface-drained field and modeling its hydrology can influence predicted drainage discharge and SB nitrate load removal. Firstly, the DBSDTSB overlooks the impact of field slope on drainage discharge. The CD hydrology simulation of the DRAINMOD component is limited to fields with slopes up to about 1.5 to 2%, potentially introducing uncertainty for steeper slopes without additional water control structures. Secondly, the geospatial analysis outlined in section 4.3.1 may overestimate the drainage area, assuming subsurface drainage water is collected from the entire delineated area and discharged through a single edge-of-field water control structure connected to the SB system. Using the DBSDTSB in sloped fields with a single edge-of-field water control structure could overestimate the drainage area under CD, as CD-affected areas might not align with field boundaries in sloped terrain. These limitations may lead to overestimations in subsurface drainage discharge and nitrate loading, developing uncertainty in the quantification of SB effectiveness that varies differently based on buffer soil hydraulic properties and drainage discharge characteristics. Overestimation of SB effectiveness is expected in buffers with highly transmissive soils and moderate drainage discharge rates, because of the likely overestimation of diverted water to the buffer and subsequent nitrate load removal. Conversely, underestimation of SB effectiveness is anticipated in poorly drained buffers with high drainage discharge rates, because the overestimation of bypass flow is expected to exceed that of diverted flow.

The SB model component assumes steady state flow through the buffer, uses single equivalent value for the later Ksat of the buffer soil, and assumes no other water sinks in the buffer beside the seepage of diverted water to the adjacent stream(Abdalaal and Ghane, 2023). This limits diverted flow to the buffer's soil capacity to transmit water (McEachran et al., 2020). This concept confines diverted flow solely to the hydraulic gradient between the distribution pipe's water head and the drain ditch's water head. This resulted in underestimating the diverted flow to the buffer, especially with high subsurface drainage discharge. For instance, the maximum predicted diverted flow to the buffer did not exceed 156 and 172 $m^3$/day at BC1 and IA1 sites, respectively. In contrast, the maximum reported value in the data was approximately 324 at BC1 $m^3$/day and 776 $m^3$/day at IA1 sites.

The SB model assumes denitrification as the primary mechanism of the nitrate load removal by SB and uses first-order removal kinetics to represent it (Abdalaal and Ghane, 2023). This may have resulted in overestimating denitrification and nitrate load removal by the SB since this assumption considers that the retention time in buffer soil alone governs nitrate removal. This approach neglects potential variations in denitrification rates due to environmental factors like soil saturation, and organic carbon availability, and fails to capture the nitrogen dynamics influenced by nitrogen pools in the soil (Youssef et al., 2005). These environmental factors might differ by the changes in water table position, weather, or site management. Moreover, Jaynes and Isenhart, (2019a) observed higher nitrate removal in sites with established perennial vegetation compared to those without; however, plant uptake is not considered as a nitrate sink in the SB model. While the effect of rainfall dilution on reducing nitrate concentration in buffer soil water has not been investigated, it is a possible sink that is not considered. The relatively long retention time in buffer soil can extend for weeks or months (Jaynes and Isenhart, 2019b; McEachran et al., 2023), which can potentially experience multiple rainfall events with negligible nitrate concentration. The nitrate-free rainfall volume can reduce the nitrate concentration in the diverted water to buffer. Despite these limitations, estimates of SB nitrate load removal using first-order kinetics were reasonable, and it facilitates the use of the DBSDTSB, since the coefficient of nitrate load removal provides an average value accounting for all removal forms.

### 4.4.8. Limitations of the study and future considerations

Future improvements to the DBSDTSB can be realized by enhancing its modeling approach and adopting a more effective parameterization scheme. Expanding the water balance in the buffer by incorporating other major water sinks may enhance the DBSDTSB's ability to predict diverted flow. For instance, accounting for ET can increase the buffer's capacity to receive diverted water, thus reducing underprediction. Additionally, considering transient conditions rather than relying solely on steady-state assumptions can lead to a more accurate representation of SB hydrology (McEachran et al., 2023). This includes accounting for variations in the water stage of the adjacent stream, its impact on hydraulic gradient, and changes in antecedent soil water conditions near the distribution pipe. For example, less diverted water is likely to happen when water head over the distribution pipe is high, or for extreme cases, backwater to control structure from the buffer could occur when it exceeds the water head inside the control structure. This might not be the case when the water table depth near the distribution pipe is below the pipe's depth.

Furthermore, having a better representation of the freezing and thawing phenomenon can limit the overprediction of drainage discharge by the tool. This can be achieved by enhancing the module representing these processes in DRAINMOD. The DBSDTSB could also improve performance by defining a better parameterization scheme through rigorous testing with a larger, more diverse, and complete set of good-quality data.

Finally, it should be noted that having a more sophisticated approach to represent the hydrology or the nitrate load removal within the buffer zone may improve the DBSDTSB's ability to predict the performance indicators of the SB system, but this will require more input data and knowledge from the users which can contradict the purpose of having an easy-to-use tool with relatively low data and modeling expertise requirements.

## 4.5. Conclusions

We developed a DRAINMOD-based decision-support tool for saturated buffer systems and evaluated the DBSDTSB's performance to predict the hydrology and nitrate load performance of two SB systems in Iowa, by comparing field measurements with predictions and based on published evaluation criteria of widely used statistical performance indicator metrics. Our study concluded the following about using the DBSDTSB in Iowa.

- The DBSDTSB can provide good predictions of the area-normalized yearly drainage discharge and its nitrate load, diverted flow to buffer, and SB nitrate load removal, where across a total of 14 site years, the average annual deviations from the respective measured values were 10 mm, 0.7 kg-N/ha, 0.04 mm, and 1.2 kg-N/ha, respectively, and the average annual absolute deviations were 55 mm, 7.7 kg-N/ha, 42 mm, and 3.2 kg-N/ha, respectively.

- The DBSDTSB can provide good predictions of the performance metrics of an SB system (average annual percentage diverted flow to buffer, and average annual SB percentage nitrate load removal), where average annual deviations from measured values at the site with higher data availability were only 1% and 2%, respectively.
- The DBSDTSB overpredicts drainage discharge during thawing and wet periods and underpredicts diverted flow during periods with high drainage discharge. This affects the prediction accuracy of the nitrate load parameters.
- Improvements in the DBSDTSB's performance can be achieved by enhancing its core models and through better parameterization, though a balance should be made to maintain the ease of use and low knowledge requirements and ensure data availability.

In summary, the DBSDTSB demonstrated acceptable performance in Iowa for predicting yearly and average annual hydrology, nitrate load parameters, and performance indicators of saturated buffer systems under the proposed parameterization scheme. Because this study evaluated a decision-support tool and not a rigorous calibration-validation modeling project, we do not expect very good to excellent performance indices. Proposed enhancements can address current limitations and improve prediction performance. Further testing across diverse locations and conditions is necessary to reduce uncertainty and enhance performance. A tool that quantifies SB performance is crucial for better design and evaluation of the system, thereby supporting wider adoption of this practice through emerging and future nutrient trading programs.

# 5. CHAPTER 5: FIELD EVALUATION OF A STACKED CONTROLLED DRAINAGE AND SATURATED BUFFER SYSTEM IN MICHIGAN

## 5.1. Abstract

Understanding the hydrological dynamics and nitrate loading mechanisms of saturated buffers (SBs) is crucial for enhancing their effectiveness in reducing nitrate losses from subsurface drainage. While saturated buffer systems operate through a combination of controlled drainage (CD) and SB components, prior studies have often treated them as a singular unit, with field research predominantly limited to the States of Iowa and Illinois in the US. This study addresses these gaps by evaluating the hydrology and nitrate load removal performance of a stacked controlled drainage and saturated buffer (CD+SB) system in Michigan, and assessing the individual contributions of the CD and SB components. Conducted from Jun 2019 to Feb 2024 using a paired-field approach, the evaluation reveals significant reductions in drainage discharge (43.1% annually) and nitrate load (83.4% annually) compared to free drainage (FD). Notably, the CD component emerges as the primary contributor to these reductions, with average annual percentages of 44.1% for drainage discharge and 82.6% for nitrate load. Conversely, the SB component's contribution to nitrate load reduction under FD was minimal (0.9% annually), attributed to backflow generated due to mild management of SB weir stoplogs. However, intensive management (30 cm from ground surface) effectively eliminated backflow, emphasizing the importance of precise management strategies. This study underscores the need for improved understanding of SB performance to inform design and management practices, ultimately enhancing nitrate load removal efficacy.

## 5.2. Introduction

Subsurface drainage can increase crop yields in naturally poorly drained croplands (Acharya et al., 2019; Kaur et al., 2021). Subsurface drainage lowers the water table, generating subsurface drainage outflows (Helmers et al., 2012). Deeper water tables can limit excessive water stresses and provide trafficability to ensure timely planting operations (Evans and Fausey, 1999). However, nitrate losses from subsurface-drained farms increase as the drainage outflows increase (Kladivko and Bowling, 2021). Saturated buffers (SB) and controlled drainage (CD) are edge-of-field drainage management practices capable of reducing nitrate losses of drainage outflows from subsurface-drained farms (Mitchell et al., 2023). In these practices a control structure is used at the edge of the field to manage drainage outflows and limit its direct release to the drain ditch under the case of conventional drainage (FD), using stoplogs that are set to shallow depths from the ground surface (NRCS standards 604 and 554) (NRCS, 2018, 2023).

For CD, the stoplogs at the control structure hold the drainage water in the soil profile leading to shallower water table depth in the field as compared to the FD case which can promote denitrification (Liu et al., 2019; Skaggs et al., 2010). Controlled drainage also promotes higher evapotranspiration, runoff, and seepage losses, which results in lower subsurface drainage outflows (Skaggs et al., 2010).The reduction in nitrate loading from CD is mainly attributed to the reduction in subsurface drainage outflows rather than to the reduction in nitrate concentration (Helmers et al., 2022).

For SB, a perforated distribution pipe is used with the stoplogs in the control structure to divert a portion of the drainage discharge to an edge-of-field vegetative buffer (Jaynes and Isenhart, 2014). A reduction in the nitrate concentration of the diverted water occurs as the water moves from the vicinity of the distribution pipe toward the ditch through the buffer soil (Jaynes and Isenhart, 2019a; Streeter and Schilling, 2021), primarily through denitrification (Groh et al., 2019).

Multiple field studies investigated the hydrology and nitrate load removal performance of CD, but limited studies were conducted for SB. A review by Mitchell et al., (2023) showed that only across the corn belt region in the US, 48 studies investigated multiple aspects related to the performance of CD and 26 out of these studies used field data in their analysis. On the other hand, the same review study showed that only 13 studies were related to SB. Up to our knowledge, there are six of field studies that used measured data to investigate few of the aspects related to the hydrology and nitrate removal performance of SB. Three of these field studies were conducted in Iowa (Jaynes and Isenhart, 2014, 2019a; Streeter and Schilling, 2021), and notably the studies by (Jaynes and Isenhart, 2014, 2019a) reported the data of the same SB site along the Bear creek in Iowa. Two studies were conducted in Illinois (Bosompemaa et al., 2021; Chandrasoma et al., 2022). Chandrasoma et al., (2022) reported the hydrology and nitrate load removal performance across three SB sites in Illinois, while Bosompemaa et al., (2021) investigated only the impact of the buffer’s vegetation on the nitrate concentration within the vadose zone.  A single study was conducted in Ohio, but the focus of this study was on the reduction of nitrate concentration across the buffer width, so the hydrology and nitrate load removal performances were not reported (Jacquemin et al., 2020). Therefore, there is a need to conduct more field studies that investigate the hydrology and nitrate removal performance of SBs at different locations due to the limited number of publications in this field.

The considerable variations in the reported percentages of diverted flow to edge-of-field buffers and nitrate load removal by SBs (Jaynes and Isenhart, 2019a; Chandrasoma et al., 2022; Johnson et al., 2023; Mitchell et al., 2023) calls for better understanding of the hydrology and the nitrate loading dynamics in SB systems. Additionally, published work on the nitrate load removal performance of SBs reported the combined performance of the CD and SB system and did not study the contribution of each component. Therefore, the main objectives of this study were to 1) evaluate the drainage discharge and nitrate load reduction performances of a stacked CD and SB system (CD+SB) in Michigan, and 2) evaluate the contribution of each of the CD component and the SB component. The value of this study is that it will provide better understanding of the hydrology and nitrate load dynamics in a stacked CD+SB system. Better understanding of the SB system can lead to better design approaches for SBs or management guidelines that can enhance the nitrate load removal effectiveness of the practice.

## 5.3. Materials and Methods

### 5.3.1. Site description

The evaluation study was conducted at a field site in Lenawee County, Michigan (Figure 5.1). The site is composed of two zones, the east zone (CFD) with an area of 14.7 ha under free drainage, which represents the control zone, and the west zone (CSB) with an area of 22.5 ha with the stacked CD+SB system, which represents the impact zone. Both zones are drained through a subsurface drainage system with lateral depths of about 0.91 m (3 ft) at CFD and 0.76 m (2.5 ft) at CSB. The lateral spacing is about 15 m (50 ft) at both zones, as estimated from the Google Earth satellite imagery. The major soil series at the two zones are Blount loam (somewhat poorly drained), Glynwood loam (moderately well drained) and Pewamo clay loam (very poorly drained). The Blount loam soil comprised most of the area at each zone, almost two-thirds. The next major soil is the Glynwood loam at the CFD zone, about 27%, and the Pewamo clay loam at the CSB zone, about 16%. The followed agronomic management at both zones were: A corn-soybean rotation with cereal rye as cover crop, no-till management, and the fertilizer application was mainly surface broadcast of dairy manure and during some years commercial fertilizer was also used.

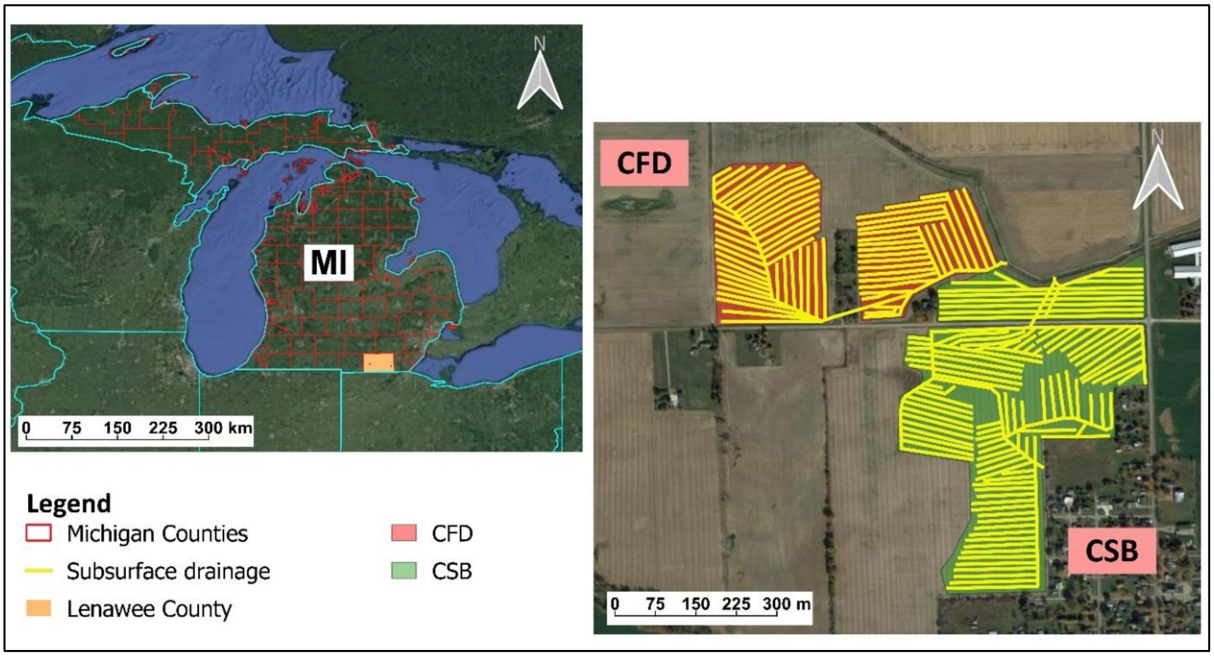


Figure 5.1. The locations, drainage areas and subsurface drainage layouts of CFD and CSB zones.

The SB system was installed at the CSB zone in the fall of 2017, and the control structure was retrofitted with a three-chamber 10-inch control structure in April 2018. The SB distribution pipe is a 4-inch staggered slot, with a slope of 0.05% going uphill away from control structure. The distribution pipe extended for a length of about 160 and 97 m in the east and west directions, respectively, and its depth ranged between 90 to 100 cm from the ground surface. The buffer width is approximately 13.7 m. The buffer was planted to a mixed-species of a perennial grass, which is round bailed in the spring and fed to the cows.

### 5.3.2. Field data

Multiple parameters were monitored at both zones over the period from 2019 to 2023. The parameters included the flow rates and the water levels inside the control structure of each zone, the water depth in the buffer zone, and the nitrate concentration of the flowing water in the control structure of each zone and of the soil water in the buffer soil along the buffer width. A two-chamber control structure was used at the CFD zone, while a three-chamber control structure was used at the CSB zone to monitor diverted flow to buffer. The measurement setup and instrumentation used at each zone were the same, except for not having the middle chamber and its components in the control structure at the CFD zone (Figure 5.2).

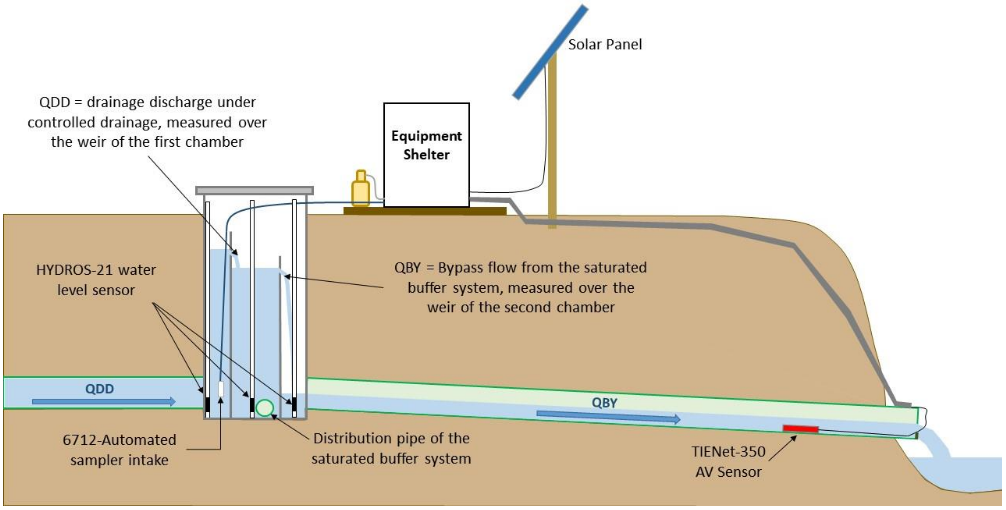


Figure 5.2. Diagram of equipment setup at the CSB zone.

#### *5.3.2.1. Flow rates data*

Flow measurements were conducted to obtain the field records of three types of flow rates: the drainage discharge from the subsurface-drained field at the control zone (QFD), the drainage discharge from the subsurface-drained field at the impact zone (QCD), and the bypass flow rate from the stacked CD+SB system at the impact zone (QBY). Afterwards, the QCD and QBY measurements were used to calculate the diverted flow to the buffer (QDP) using Equation 5.1.

$$QDP = \mathrm{QCD} - \mathrm{QBY} \tag{5.1}$$

where

QDP = daily diverted flow to the buffer at the impact zone ($m^3$/day), QCD = daily drainage discharge from the subsurface-drained field at the impact zone ($m^3$/day), and QBY = daily bypass flow to the ditch at the impact zone($m^3$/day).

Two measurement setups were implemented to monitor the flow rates, to ensure the good quality of the measurements and address the limitations of each setup. The first setup was a customized V-notch weir with a Hydrus-21 water level sensor installed inside the control structure. The second setup was an area-velocity sensor installed near the outlet of the main collector on the drain ditch. Both measurement setups provided hourly flow measurement records that were registered to a data logger and uploaded to a cloud storage service.

The first setup was installed inside the first chamber of the control structure at the CFD zone to monitor QFD, the first chamber of the control structure at CSB zone to monitor QCD, and the second chamber of the control structure at the CSB zone to monitor QBY. An additional Hydrus-21 water level sensor was installed in the chamber just downstream each V-notch weir to ensure that the conditions required to use the V-notch method were not violated. The flow rates from the first setup were calculated using the records of the water head over the V-notch weir, measured by the Hydrus-21 sensor, based on the work by Shokrana and Ghane (2021). The flow measurements from the first setup were generally used as the default source for the flow rate records except for the periods of relatively high flows or when free flow condition over the V-notch was violated. During submergence of the V-notch weir, i.e. when the water level in the downstream chamber was above the apex of the V-notch weir, or when the head over the V-notch weir exceeded the maximum height of the V-notch (21 cm), the second setup was used as the source for the measurements of the flow reaching the ditch.

### *5.3.2.2. Concentrations and load data*

The nitrate concentration data were identified for the water flowing inside the control structure at each zone ($C_{CS}$) and the soil water at the maximum width of the edge-of-field buffer at the CSB zone ($C_{SB}$). The nitrate concentration data were determined using laboratory analysis of field collected samples. For the flowing water inside the control structure, an automated water-sampler was used at each zone to collect daily composite samples through an intake installed in the first chamber (Figure 5.2). For the soil water at the CSB buffer, weekly grab samples were collected, if available, from three monitoring wells installed at three different locations along the length of the buffer. Each well was installed at the maximum width of the edge-of-field buffer in the CSB zone, close to the ditch. This was done to have better representation of the nitrate concentration of the soil water in the buffer at the maximum buffer width. All collected water samples were analyzed in the laboratory using the colorimetric nitrate reductase analysis method (NECi Method N07-0003) (Campbell et al., 2006).

Post processing of the laboratory analysis data was conducted to obtain the complete dataset for $C_{CS}$ and $C_{SB}$ that were used in the nitrate load calculations. Linear interpolation was used to fill missing daily $C_{CS}$ data at each zone. Since weekly grab samples were collected from three observation wells in the buffer of the CSB zone, the final weekly $C_{SB}$ values were calculated as the arithmetic average of the available weekly $C_{SB}$ values of the different observation wells. After that, linear interpolation was used to obtain the daily $C_{SB}$ data from available weekly values.

The nitrate load reaching the ditch from the CFD zone (NLQFD), the stacked CD+SB system at the CSB zone (NLCDSB), and the CD component only at the CSB zone (NLQCD) were calculated using Equations 5.2, 5.3, and 5.4, respectively.

$$\mathrm{NLQFD} = \mathrm{QFD} \times \mathrm{C}_{CS\ CFD} \times 10^{-3} \tag{5.2}$$

$$\mathrm{NLQCD} = \mathrm{QCD} \times \mathrm{C}_{CS\ CSB} \times 10^{-3} \tag{5.3}$$

$$\mathrm{NLCDSB} = (\mathrm{QCD} \times \mathrm{C}_{CS\ CSB} + QDP \times \mathrm{C}_{SB\ CSB}) \times 10^{-3} \tag{5.4}$$

where

NLQFD = daily nitrate load reaching ditch from the CFD zone (kg-N/day), $\mathrm{C}_{CS\ CFD}$ = daily nitrate concentration of the composite water sample from the control structure at the CFD zone (mg/l), NLQCD = daily nitrate load reaching ditch from the CD component only at the CSB zone (kg-N/day), $\mathrm{C}_{CS\ CSB}$ = daily nitrate concentration of the collected water sample from the control structure at the CSB zone (mg/l), NLCDSB = daily nitrate load reaching ditch from the stacked CD+SB system at the CSB zone (kg-N/day), $\mathrm{C}_{SB\ CSB}$ = daily nitrate concentration of the soil water near the drain ditch in the buffer at the CSB zone (mg/l), and $10^{-3}$ factor for unit transformation.

Similar procedure to the calculations of the nitrate loads under FD, CD and CD+SB were conducted to identify the impact of the stacked system (CD+SB), CD component and SB component on the loads of the dissolved reactive phosphorus (DRP), and the total phosphorus (TP). Laboratory colorimetric analysis was conducted to identify the concentrations of the DRP and TP of the same water samples collected using the gallery analyzer. The results regarding DRP and TP loads were reported briefly since the objective of the dissertation was mainly focused on the impact of the stacked system and its component on the nitrate load.

### 5.3.3. Zones management

Free drainage was maintained at the CFD zone for the whole study period. The management at the CSB zone was implemented by adjusting the level of the V-notch weirs in the first and the second chambers of the three-chamber control structure using stoplogs. The management setting of the CD+SB system comprises the different levels set for the V-notch weir and the corresponding periods used for each level. The management setting of the system becomes more intensive as the V-notch weir levels are set shallower to the ground surface and for longer periods. The management settings in the first chamber controlled the CD system, while the settings in the second chamber controlled the SB system. The management settings of CD and SB during the treatment period are shown in Figure 5.3.

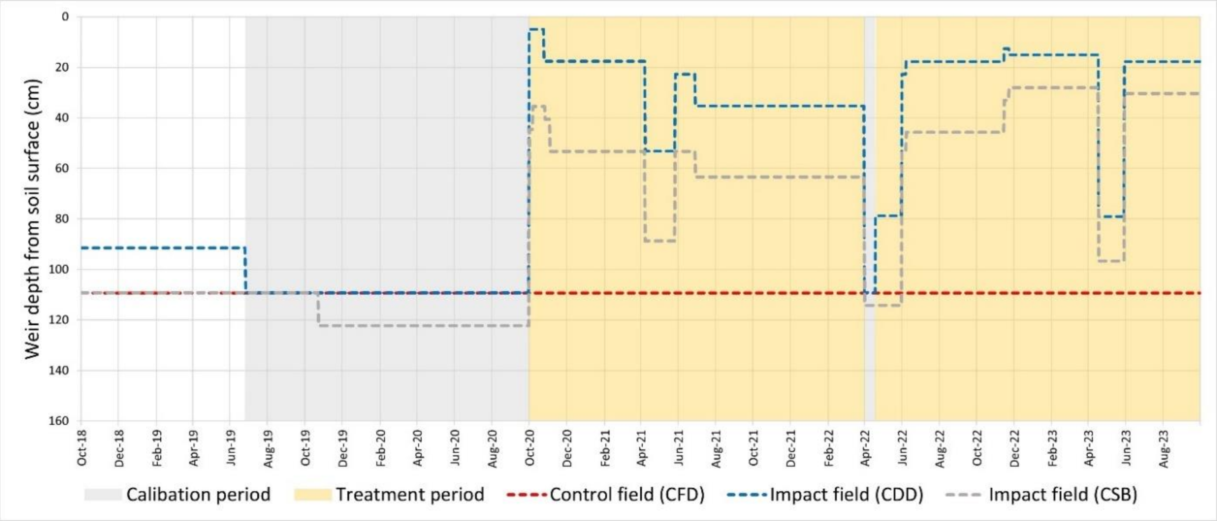


Figure 5.3. The weir management setting of the V-notch weirs implemented for the stacked saturated buffer and controlled drainage system at the CL site. CDD represents the management setting for the controlled drainage system (implemented at the first chamber in the control structure). The CSB represents the management setting for the saturated buffer system (implemented at the second chamber in the control structure).

### 5.3.4. Paired-field evaluation

A paired-field approach was implemented following the procedures described by Clausen and Spooner (1993) to evaluate the hydrology and nitrate load removal performances of the stacked SB and CD system. This method tests the significance of the impact of a management on a parameter of interest. The method conducts an analysis using the values of a parameter of interest at two fields: the control field and the impact field. It also considers two monitoring periods while conducting the analysis: the calibration period and the treatment period. During the calibration period, the same control management is implemented at both fields. During the treatment period, the new management is applied only to the impact field. A linear-regression relationship (pre-treatment regression) is established between the two fields using the measured records of the parameter of interest during the calibration period. Similarly, another linear-regression relationship (after-treatment regression) is established between the two fields using the measured records of the parameter of interest during the treatment period. The analysis of the variance (ANOVA) is used to check the significance of each established linear regression of the calibration or the treatment period. The analysis of covariance (ANCOVA) is used to check the significance of the difference between the slope coefficients or the intercepts of the established linear regressions of the calibration and the treatment periods. The impact of the treatment is considered significant if the ANCOVA test showed that the slopes of the pre-treatment and the after-treatment regressions were statistically significant. Moreover, the difference can be quantified using the established linear regressions.

In the current study, the calibration period was set as the days during which both zones were under free drainage management. The calibration period included days from 26 June 2019 to 30 September 2020 and from 4 to 19 April 2022. A total number of 466 and 457 days were included in the calibration period of drainage discharge and nitrate load, respectively. To determine if the calibration duration was sufficient to detect a predefined smallest detectable difference in response between the two zones of 10%, we used Equation 5.5 to check that the right-hand side of the equation was greater than the left-hand side as described by Clausen and Spooner (1993).

$$\frac{{S_{xy}}^2}{d^2} = \frac{n_1 \times n_2}{n_1 + n_2} \frac{1}{F\left(1 + \frac{F}{n_1 + n_2 - 2}\right)} \tag{5.5}$$

where

${S_{xy}}^2$ = estimated residual variance of the linear regression,

$d$ = smallest detectable difference (10% of the mean),

$n_1$ = the sample size for the calibration period,

$n_2$ = the sample size for the treatments period, and

$F$ = table value at significance level 0.10 for the variance ratio at 1 and $n_1 + n_2 - 3$ degrees of freedom ($df_1 = 1$ and $df_2 = n_1 + n_2 - 3$).

The treatment period included the days during which the CD+SB system was activated at the CSB zone during the water years (WYs) of 2021, 2022 and 2023. These days in all WYs were used in the analysis pertaining to drainage discharge. Whereas the nutrient load analysis only included the days of WY 2021. The WYs of 2022 and 2023 were excluded from the nutrient load analysis because the fertilizer application at the two zones in each of these WYs was not identical. The days that had zero flows in both zones were excluded from the treatment period data. Moreover, the days during which the SB or CD component was not under management were excluded from the treatment period data. Additionally, the days that had missing nitrate concentration records were excluded from the treatment period nitrate loading data. A total number of 337, and 337 were included in the treatment period of drainage discharge and nitrate load, respectively.

There were two main parameters considered in the analysis of this study: the flow reaching the drain ditch, here onwards referred to as (drainage discharge), and its corresponding nitrate load. For the calibration period, the drainage discharge at the CFD and CSB zones were taken as the QFD and the QCD, respectively. While the corresponding nitrate load at CFD and CSB zones were taken as the NLQFD and NLQCD, respectively. For the treatment period, the drainage discharge and its corresponding nitrate load at the CFD zone had the same definition as the one used during the calibration period. While for the CD+SB system at the CSB zone they were taken as the QBY and the NLCDSB, respectively, and for the CD component only at the CSB they were taken as the QCD and the NLQCD, respectively.

This study checked the statistical significance of the impact of the CD+SB system as a whole and of the CD component only on the hydrology and nitrate loading from subsurface-drained fields. The statistical analysis was conducted using the platform of SAS OnDemand for Academics. The pre-treatment regression for each parameter was established between the CFD and CSB zones using the measured records during the calibration period. After that, the after-treatment regression for each parameter was established using the measured records during the treatment period. Finally, the ANCOVA was used to check for significant statistical difference between the slopes of the established pre-treatment and after-treatment linear regressions of each parameter.

Moreover, the study quantified the impact of the CD+SB system as a whole and the contribution of each of its components (CD and SB) on the hydrology and nitrate loading over the treatment period. The impact on hydrology was quantified by calculating the reduction in the drainage discharge over the treatment period for two cases: the CD+SB system as a whole, and the CD component only. While the impact on the nitrate load was quantified by calculating the reduction in the nitrate loading over the treatment period for three cases: the CD+SB system as a whole, CD component only, and SB component only.

The reductions in the drainage discharge and the nitrate load caused by the whole system and its different components were calculated using the pre-treatment regressions from the calibration period and the measured records of the treatment period. The pre-treatment regression equations were used to estimate the pre-treatment drainage discharge and its nitrate loading at the CSB zone during the treatment period. The reductions in drainage discharge were calculated by subtracting the measured drainage discharge at CSB zone during the treatment period from the estimated pre-treatment drainage discharge. Similarly, the records of the daily nitrate loading were used to calculate the daily reductions in nitrate loading. Finally, the yearly and total reductions values were calculated by summing their respective daily reduction values. The percentage reduction of the drainage discharge and nitrate load reaching the drain ditch were calculated with respect to the estimated pre-treatment drainage discharge and its corresponding nitrate load, respectively.

## 5.4. Results and Discussion

### 5.4.1. Pre-treatment regressions of drainage discharge and nitrate load

The results of the pre-treatment regressions showed that the paired-field approach could be utilized in the evaluation of the CD+SB system at the CFD and CSB zones used in this study. Quantifiable regression relationships between the two zones for each of the drainage discharge and nitrate load were established (Figure 5.4), which is mandatory for conducting the paired field approach analysis (Clausen and Spooner, 1993).

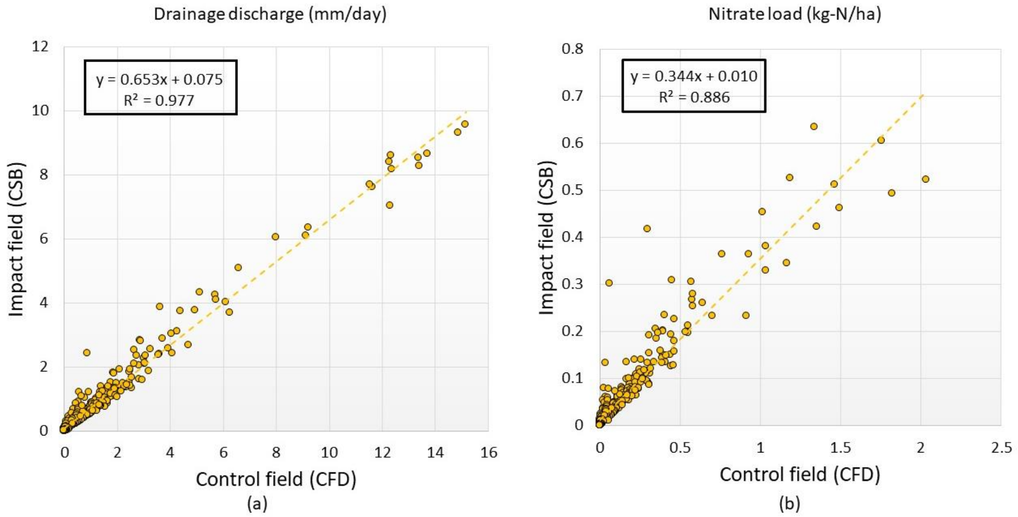


Figure 5.4. Pre-treatment linear regressions between the CFD and CSB zones for a) the drainage discharge and (b) the nitrate load from drainage discharge (calibration period).

The ANOVA showed that the pre-treatment linear regressions between the CFD and CSB zones for both the drainage discharge and nitrate load were statistically significant (p-value < 0.001). The pre-treatment regression of the drainage discharge showed less variability than that of the nitrate load as shown by the higher coefficient of determination ($R^2$) value (Figure 5.4).

### 5.4.2. Impacts on drainage discharge

The after-treatment regression between the two zones for the drainage discharge was statistically significant for the stacked system CD+SB as a whole and the CD component only with good correlation as indicated by the high $R^2$ scores of either regression (Figure 5.5). The ANOVA of the after-treatment regressions of the drainage discharge for the system as a whole or the CD component only had a p-value < 0.001.

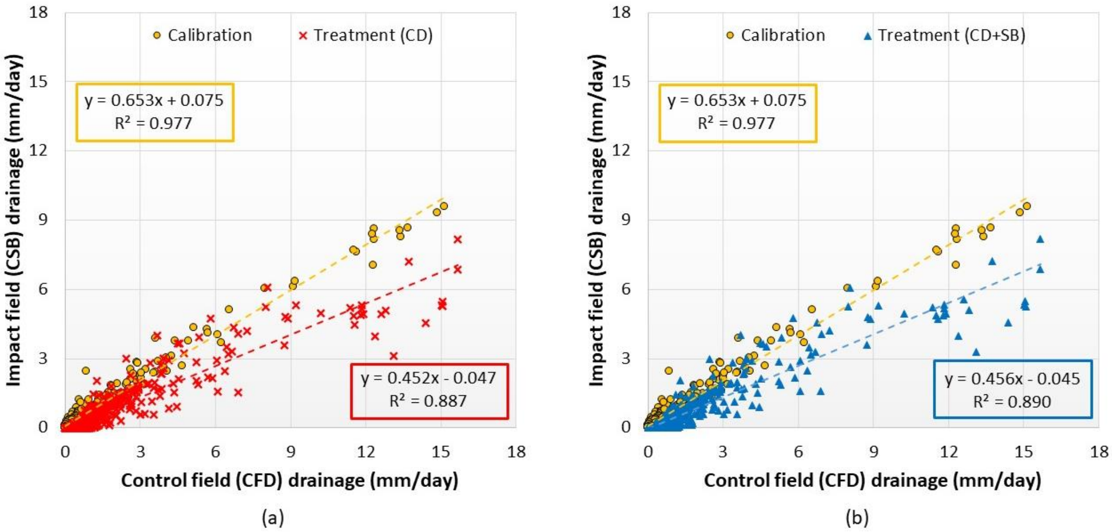


Figure 5.5. After-treatment linear regressions between the CFD and CSB zones for the drainage discharge as impacted by the controlled drainage only (CD effect) and (b) the stacked controlled drainage and saturated buffer system ( CD+SB effect).

The slopes of both drainage discharge after-treatment regression of the CD and CD+SB were smaller than the slope of the drainage discharge pre-treatment regression. The results from the ANCOVA test for the comparisons between the slopes of the after-treatment regression and pre-treatment regression for the CD component was (F=558, p-value < 0.0001) , and for the stacked system (CD+SB) was (F=542, p-value < 0.0001). This indicated that both treatments resulted in lower drainage discharge compared to the case under FD mode. The drainage discharge reduction under CD is well established (Mitchell et al., 2023; Skaggs et al., 2010, 2012). As for SB systems, a common conception is that SBs do not result in additional drainage discharge reduction, since it is assumed that there are no losses to the diverted water as it moves through the buffer soil and that all diverted water to the buffer reaches the drain ditch eventually (Jaynes and Isenhart, 2019b; McEachran et al., 2023).

It was expected that the slopes of both after-treatment drainage discharge regressions of the stacked CD+SB system and CD component would be the same. But the slightly larger slope value of the after-treatment regression of the stacked CD+SB system proposed a possible lower drainage discharge reduction from the stacked CD+SB system compared to the that from the CD component only. However, ANCOVA analysis showed that the difference between the slopes of the drainage discharge after-treatment regressions of CD and the stacked CD+SB was not significant (F=0.28, p-value=0.6).

### 5.4.3. Impacts on nitrate load

The after-treatment regression between the two zones for the nitrate load was statistically significant for the stacked system CD+SB as a whole or the CD component only. The ANOVA of each after-treatment regression of the nitrate load for the stacked CD+SB system or the CD component had a p-value < 0.001, indicating good regressions. For either the CD+SB system or the CD component, the correlation between the nitrate load at the two zones during the treatment period was smaller than their respective correlation during the calibration period (Figure 5.6). This indicates higher variability in the nitrate load between the two zones during the treatment period.

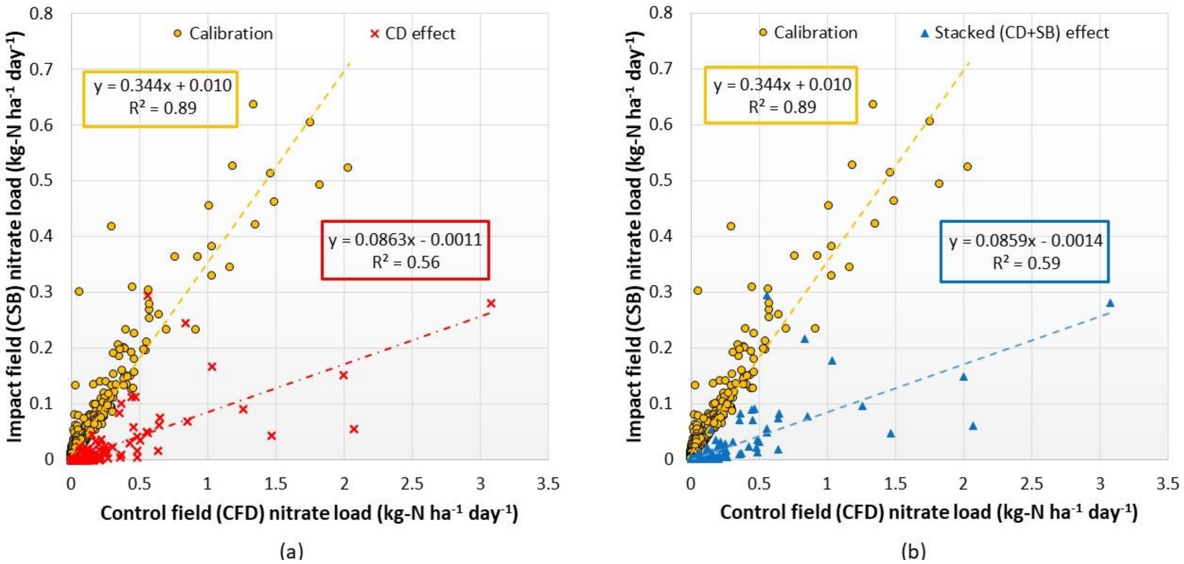


Figure 5.6. After-treatment linear regressions between the CFD and CSB zones for the nitrate load as impacted by the controlled drainage only (CD effect) and (b) the stacked controlled drainage and saturated buffer system ( CD+SB effect).

The slopes of both nitrate load after-treatment regressions of the CD and CD+SB were statistically smaller than the slope of the nitrate load pre-treatment regression. The result from the ANCOVA test for the comparison between the slopes of the after-treatment regression and pre-treatment regression for the CD component was (F=1188, p-value < 0.0001) , and for the stacked system (CD+SB) was (F=1227, p-value < 0.0001). This indicated that both treatments resulted in lower nitrate load compared to the case under the FD mode. The effectiveness of CD in reducing nitrate load from drained fields is well-documented in literature (Skaggs et al., 2010, 2012a; Mitchell et al., 2023). Also, the effectiveness of SB in reducing nitrate load from drained fields is well-documented in literature (Jaynes and Isenhart, 2019a; Johnson et al., 2023; Mitchell et al., 2023).

The slope of the nitrate load after-treatment regression of the stacked CD+SB system was slightly smaller than that of the CD component, but the difference between them was not statistically significant (F=0.01, p-value=0.94). Therefore, this shows that the SB component did not contribute with additional nitrate load reductions over those made by the CD component.

Notably, it was expected that the difference between the slopes of the nitrate load after-treatment regressions would be considerably greater than what the results showed in this study. The SBs can significantly contribute to nitrate load reduction, where reported average annual nitrate load removal percentage from the diverted flow to buffer amounted to 82% and could even reach up to 100% (Johnson et al., 2023). We believe that the slight difference between the after-treatment slopes of the stacked CD+SB system and the CD component was a result of the underperformance of the SB component.

### 5.4.4. Drainage discharge and nitrate load removal reductions quantification

The stacked CD+SB treatment reduced the drainage discharge of the CSB zone by about 42% over the days considered in the paired field analysis from 1 Oct 2020 to 15 Feb 2024. The stacked CD+SB reduced the pre-treatment drainage discharge from 667 mm (150016 m$^3$) to 381 mm (87064 m$^3$) with a total reduction of 280 mm (62952 m$^3$). The reduction under the CD component amounted to 42.8%, where it reduced the drainage discharge to 381 mm (85741 m$^3$) with total reduction of 286 mm (64274 m$^3$). Over the treatment period, the SB component of the CSB zone contributed an additional drainage discharge that amounted to about 6mm which negatively impacted the performance of the stacked CD+SB system (Table 5.1).

Table 5.1. Hydrology performance of the stacked controlled drainage and saturated buffer (CD+SB) system and the controlled drainage (CD) component only at the CSB zone over the different water years (WY) for the considered days in the paired field analysis for the period between 1 Oct 2020 to 30 Sep 2023.

| Treatment | Parameter | WY 2021 | WY 2022 | WY 2023 | Average [a] |
|---|---|---|---|---|---|
| **Free drainage** | Pre-treatment drainage discharge | 201.2 mm (45273 m$^3$) | 232.8 mm (52372 m$^3$) | 164.5 mm (37021 m$^3$) | 199.5 mm (44889 m$^3$) |

Table 5.1 (cont’d)

| | | | | | |
|---|---|---|---|---|---|
| **Stacked CD+SB** | Measured drainage discharge | 78.6 mm (17692 $m^3$) | 181.7 mm (40875 $m^3$) | 88.1 mm (19817 $m^3$) | 116.1 mm (26128 $m^3$) |
| | Drainage discharge reduction [b] | 122.6 mm (60.9%) | 51.1 mm (22.0 %) | 76.5 mm (46.5%) | 83.4 mm (43.1%) |
| **CD** | Measured drainage discharge | 72.9 mm (16399 $m^3$) | 181.5 mm (40846 $m^3$) | 88.1 mm (19817 $m^3$) | 114.2 mm (25687 $m^3$) |
| | Drainage discharge reduction [b] | 128.3 mm (63.8%) | 51.2 mm (22.0%) | 76.5 mm (46.5%) | 85.3 mm (44.1%) |
| **SB** | Diverted flow to buffer | 6.66 mm<br>(3.3%) [b]<br>(9.1%) [c] | 39.75 mm<br>(17.1%) [b]<br>(21.9%) [c] | 32.02 mm<br>(19.5%) [b]<br>(36.4%) [c] | 26..14 mm<br>(13.3%) [b]<br>(22.5%) [c] |
| | Backflow generated | 5.75 mm<br>(2.9%)[b]<br>(7.9%) [c] | 0.24 mm<br>(0.1%)[b]<br>(0.13%) [c] | No backflow | 3.0 mm<br>(1.0%) [b]<br>(2.6%) [c] |
| | Net diverted flow to buffer | 0.91 mm<br>(0.5%) [b]<br>(1.3%) [c] | 39.51 mm<br>(17.0%) [b]<br>(21.8%) [c] | 32.02 mm<br>(19.5%) [b]<br>(36.4%) [c] | 24.15 mm<br>(12.3%) [b]<br>(19.8%) [c] |

[a] Average value was calculated as the arithmetic mean of respective water year values.

[b] Values are referenced to the calculated pre-treatment drainage discharge using the paired field approach after (Clausen and Spooner, 1993). The pre-treatment drainage discharge represents the free drainage conditions at CSB zone.

[c] Values are referenced to the measured drainage discharge under controlled drainage at CSB zone.

The annual drainage reduction of the CD component was slightly greater than that of the stacked CD+SB system in two out of the three water years (Table 5.1). The average annual percentage drainage discharge reduction of the CD component (44.1%) was close to the reported average annual percentage reduction (46%) (Ross et al., 2016; Mitchell et al., 2023). While the average annual drainage reduction of the stacked system was slightly lower (43.1%).

The mild management of the weir stoplogs controlling the SB and the wetter conditions, especially during WY 2021, resulted in backflow from the buffer to the control structure. In WY 2021, the weir controlling the SB was set to an average depth of about 74 cm from soil surface during 116 out of the 338 days considered in the paired field analysis (34% of the period). This weir depth was close to the depth of the distribution pipe in the buffer (90 to 100 cm). Moreover, WY 2021 experienced more days with wetter weather conditions, which together with the mild management of the SB weir stoplogs resulted in more backflow events (Table 5.2). The largest backflow event occurred on July 25, 2021, and amounted to 143 $m^3$/day. Four consecutive precipitation events, with a total rainfall volume of 109 mm over the days of 13, 16, 23 and 24 July, contributed to the wet conditions in the buffer zone and eventually to the generation of the maximum backflow volume.

Table 5.2. Flowing days and backflow occurrence at the CSB zone for the considered days in the paired field analysis for the period between 1 Oct 2020 to 30 Sep 2023.

| | **WY 2021** | **WY 2022** | **WY 2023** |
|---|---|---|---|
| Total number of days considered in the paired field analysis | 338 | 244 | 174 |
| Total number of days with backflow | 37 (10.9%) [a] | 4 (1.6%) [a] | 0 (0.0%) [a] |
| Average backflow | 0.155 mm (35 $m^3$/day) | 0.059 mm (13.2 $m^3$/day) | No backflow occurred |
| Number of flowing days considered in the paired field analysis | 84 | 152 | 62 |
| Number of days with backflow out of the flowing days | 28 (33.3%) [b] | 3 (2.0%) [b] | 0 (0.0%) [b] |

[a] Percentage was referenced to the total number of days considered in the paired field analysis.
[b] Percentage was referenced to the number of flowing days considered in the paired field analysis.

Interestingly, WY 2023 did not generate any backflow (Tables 5.1 and 5.2). A possible reason for that was the intense management of the weir stoplogs of both the CD and SB components, where the average depths of the CD weirs and the SB weirs were 16 and 29 cm from the ground surface, respectively. Another possible reason was the relatively drier weather conditions and scattered rainfall events as compared to other water years, which was reflected by the greater number of days with zero flows. In conclusion, limiting backflow from the buffer zone into the control structure can be accomplished via intense management of the stoplogs controlling the SB.

The annual nitrate load removal caused by the stacked CD+SB system was majorly from the CD component (Table 5.3). The annual percentage nitrate load reduction of the CD component (82.6%) in WY 2021 was considerably higher than the reported average annual value in the Midwestern US (45%) but fell within the range of reported value (Mitchell et al., 2023). The calculated annual reduction of the SB component was only about 0.8% of the pre-treatment nitrate load representing the FD mode. On the other hand, it was about 5.1% when it was referenced to the measured nitrate load under CD. The average annual nitrate load reduction referenced to the CD load was not close to the average annual reduction from reported SBs in Iowa and Illinois (41%) (Jaynes and Isenhart, 2019a; Chandrasoma et al., 2022), and did not fall within the ranges of the SB annual percentage nitrate load reduction in Midwestern US (Johnson et al., 2023; Mitchell et al., 2023).

Table 5.3. Nitrate load reduction performance of the stacked controlled drainage and saturated buffer (CD+SB) system and the controlled drainage component (CD) at the CSB zone in water year 2021 during the days considered in the paired field analysis.

| **Treatment** | **Parameter** | **Values** |
|---|---|---|
| **Free drainage** | Pre-treatment nitrate load | 16.12 kg-N/ha<br>(362.7 kg-N) |
| **Stacked CD+SB** | Nitrate load | 2.67 kg-N/ha<br>(60.1 kg-N) |
| | Nitrate load reduction [a] | 13.45 kg-N/ha<br>(83.4%) |
| **CD** | Nitrate load | 2.81 kg-N/ha<br>(63.3 kg-N) |
| | Nitrate load reduction [a] | 13.31 kg-N/ha<br>(82.6%) |
| **SB** | Nitrate load reduction of diverted load to buffer [b] | 0.26 kg-N/ha<br>(1.6%)[a]<br>(9.3%)[c] |
| | Nitrate load generated from backflow | 0.12 kg-N/ha<br>(0.7%)[a]<br>(4.2%)[c] |
| | Net nitrate load reduction by SB | 0.14 kg-N/ha<br>(0.9%)[a]<br>(5.1%)[c] |

[a] Values are referenced to the pre-treatment nitrate load calculated using the pre-treatment regression equation of the nitrate load between the CFD and the CSB zones when both zones where under free drainage.

[b] Values were calculated using records that did not have backflow.

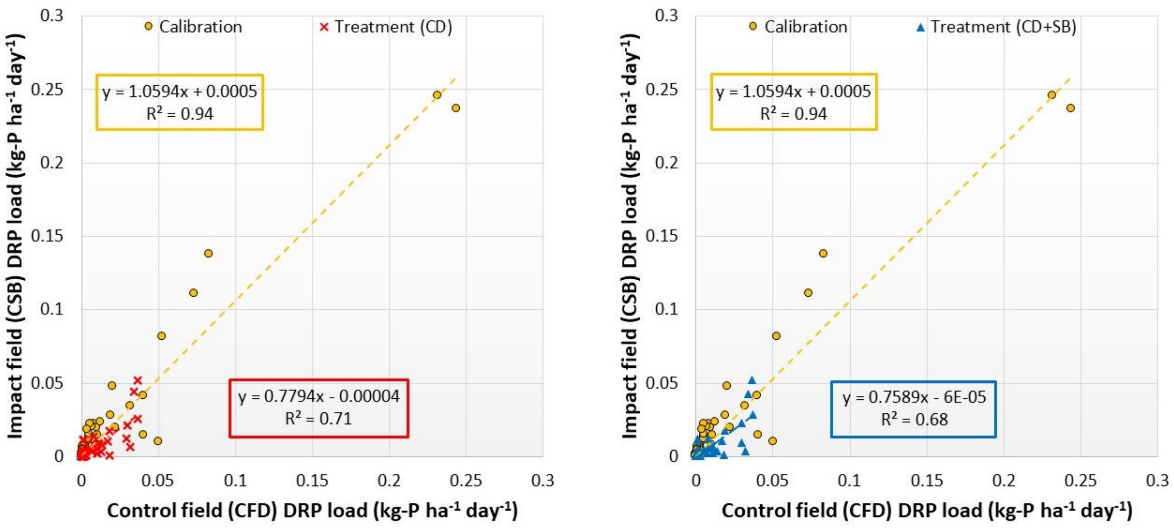
[c] Values are referenced to the measured nitrate load from controlled drainage (CD) at the CSB zone.

The nitrate load removal performance of the stacked CD+SB system was only slightly greater than that of the CD component (Table 5.3). The mild management of SB weir stoplogs generated backflow during extremely wet periods which reduced the net diverted flow to the buffer (Table 5.1) and generated additional nitrate load (Table 5.3). Therefore, the contribution of the SB component to the nitrate load removal of the stacked system was minimal during WY 2021.

Interestingly, the generated backflow from the SB system at CSB in WY 2021 was not huge. If considerable volume of backflow had been generated, this could have drastically impacted the performance of the stacked CD+SB system to reduce nitrate load. Eldridge et al., (2024) reported increased nitrate loading from an SB in Illinois when backflow from the buffer was considered in the nitrate load calculation. Thereby, backflow from SBs should be reduced to improve the nitrate load removal effectiveness of the stacked CD+SB system.

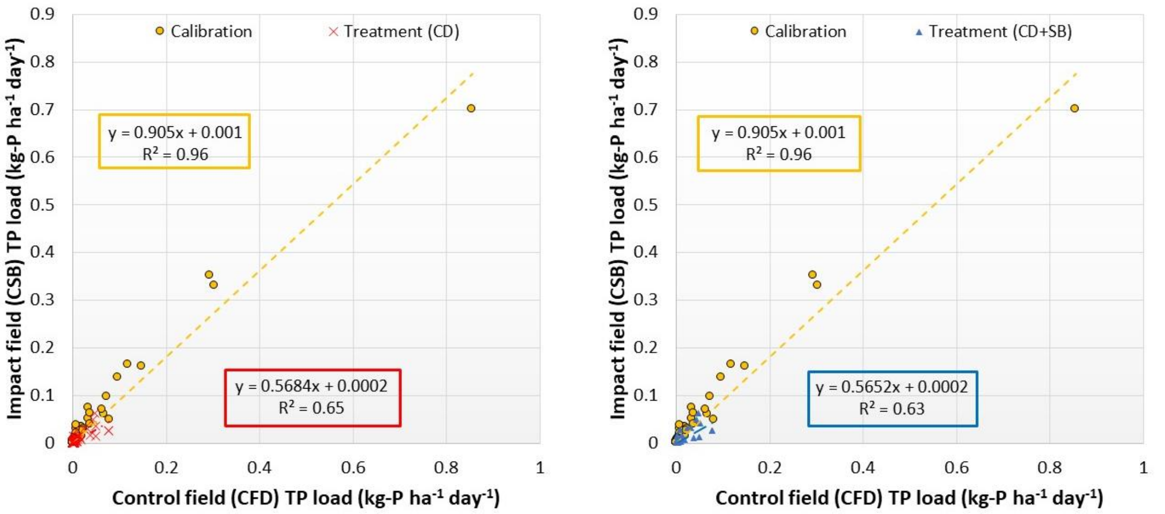
### 5.4.5. Impacts on phosphorus load

The slope of the after-treatment regression between the two zones for the DRP was statistically different from pre-treatment regression slope for the stacked system CD+SB as a whole (F=613, p-value < 0.0001). This was also the case for the CD component only (F=610, p-value < 0.0001). The same was also true for the TP load, where the results from the ANCOVA test in regard to the stacked (CD+SB) system were (F=792, p-value < 0.0001) and in regard to CD component only were (F=58, p-value < 0.0001). For either the CD+SB system or the CD component, the correlation between the DRP or the TP load at the two zones during the treatment period was considerably smaller than their respective correlation during the calibration period, as shown in Figures 5.7 and 5.8, respectively. This indicates higher variability in the DRP and TP loads between the two zones during the treatment period.



(a) (b)

Figure 5.7. After-treatment linear regressions between the CFD and CSB zones for the dissolved reactive phosphorus (DRP) load as impacted by the controlled drainage only (CD) treatment and (b) the stacked controlled drainage and saturated buffer system (CD+SB) treatment.



(a) (b)

Figure 5.8. After-treatment linear regressions between the CFD and CSB zones for the total phosphorus (TP) load as impacted by the controlled drainage only (CD) treatment and (b) the stacked controlled drainage and saturated buffer system (CD+SB) treatment.

The slope of the DRP load after-treatment regression of the stacked CD+SB system was smaller than that of the CD component, but the difference between them was not statistically significant (F=0.27, p-value = 0.6). This was the same for the TP load, as reflected by the ANCOVA analysis results (F=0.01, p-value = 0.92). Therefore, the SB component did not make a significant contribution in the DRP and TP load reductions.

The generated load and reductions from the stacked (CD+SB) system and each of its components are presented in Table 5.4. It should be noted that the average reductions from the stacked system and the SB component were affected by the management of weirs. The mild management of the SB weir stoplogs in WY 2021 resulted in low DRP load reduction and additional generated TP load.

Table 5.4. Phosphorus load reductions by the stacked controlled drainage and saturated buffer (CD+SB) and the controlled drainage component (CD) at the CSB zone as compared to the pre-treatment loads under free drainage (FD) in water year 2021 during the days considered in the paired field analysis. [a]

| **Treatment** | **Parameter** | **DRP** | **TP** |
|---|---|---|---|
| **FD** | Load | 0.655 | 0.880 |
| **Stacked CD+SB** | Load | 0.282 | 0.417 |
|  | Reduction[b] | 0.373<br>(57.0%) | 0.435<br>(49.5%) |
| **CD** | Load | 0.297 | 0.415 |
|  | Reduction[b] | 0.358<br>(54.7%) | 0.438<br>(49.7%) |
| **SB** | Reduction | 0.015<br>(2.3%)[b]<br>(5.0%)[c] | -0.002<br>(-0.3%)[b]<br>(-0.6%)[c] |

[a] non-percentage values represent loads or load reductions and are in units of kg-P/ha.

[b] Values are referenced to the respective DRP or TP pre-treatment load calculated using the pre-treatment regression equation of the DRP or TP loads between the CFD and the CSB zones when both zones where under FD.

[c] Values are referenced to the measured respective DRP or TP load from controlled drainage (CD) at the CSB zone.

### 5.4.6. Implications on saturated buffer performance and recommendations

Improper design and management of the saturated buffer system can negatively impact the nitrate removal performance of the stacked CD+SB system. The generation of backflow from the buffer to the control structure can reduce the drainage discharge reduction of the stacked system and limit its capacity to reduce the nitrate load as presented in the results of the current study and the study by Eldridge et al., (2024). Also, the loose management of the weirs controlling the SB system can limit the potential of diverting more water to the buffer to undergo treatment. This was reflected by the higher net diverted flow in WY 2023 with the intense management as compared to that of WY 2021 with the mild management (Table 5.1). This is partly because of the smaller hydraulic gradient between the water head in the control structure and the buffer soil under mild management as compared to that under intense management. Additionally, the lower positioning of the weir boards compared to the intense management settings can generate more backflow to the control structure (Table 5.1).

The impact of the design and management of the SB system on the hydrology and nitrate load removal performance of the system is influenced by the site and SB system characteristics. The site characteristics are reflected by the buffer soil hydraulic properties, ditch hydraulic characteristics and weather conditions. Buffer soils with finer particles and slower hydraulic conductivities, i.e. poorer drainage conditions, will more likely have less diverted water and more backflow generation. This may be exacerbated for sites that experience more frequent precipitation with relatively high rainfall volume, since this will increase the occurrence of shallow water tables in the buffer soil. This effect may also be exacerbated for sites characterized by relatively consistent high-water-stage drain ditches. Since the hydraulic head driving the diverted water through the buffer soil decreases as the water stage in the ditch increases. This results in more retention time of the water in the buffer soil and more possibility of having saturated profiles that can generate backflow. Further elaboration of the general viability of the SB system is discussed in Appendix B.1.

As for the SB system characteristics, the depth of the distribution pipe with respect to the weir level in the control structure can impact the amount of generated backflow. Deeper distribution pipes with mild weir management settings will more likely generate more backflow to the control structure. This is because of the greater water head over the distribution pipe and the low positioning of the weir boards in the control structure. Thereby limiting backflow should be taken into account when designing, managing or installing SB systems.

Limiting backflow could be done through better design of the saturated buffers. Smaller buffer width can increase diverted flow to buffer and reduce the retention time of water in the buffer soil (Jaynes and Isenhart, 2019b; McEachran et al., 2020; Abdalaal and Ghane, 2023). Lower retention time in the buffer soil can reduce the occurrence of extremely shallow water table in the buffer which can reduce the backflow generation. More net diverted water to the buffer as a result of less backflow generation can increase the SB effectiveness to reduce nitrate load. Nonetheless, proper choice of the buffer width should be done to maximize both diverted flow and nitrate load removal based on the site characteristics (Abdalaal and Ghane, 2023).

Proper management of the CD and SB systems can also limit the backwater to the control structure. Control structure weir boards for the CD and SB systems should be managed intensively without impacting the crop yield to maximize the nitrate load removal from the stacked CD+SB system without causing economic losses to landowners. Modeling tools can be utilized to determine the management depth of the weir boards based on the flow and weather characteristics at the sites of interest.

Additionally limiting backflow to control structure could be done by enhancing the components of the saturated buffer system. The backflow to the control structure could be reduced by installing a check valve at the connection between the control structure and the distribution pipe (Eldridge et al., 2024). Also, careful selection of the distribution pipe depth in accordance with the planned weir management settings can limit the backflow generation.

## 5.5. Conclusions

We conducted a field study and evaluated the performance of a stacked saturated buffer and controlled drainage system in Lenawee County, MI, using paired-field approach over the periods of June 2019 to 31 Sep 2021 and 1 Oct 2022 to 15 February 2024. The evaluation quantified and checked the significance of the impact of the stacked CD+SB system, and the CD component on the drainage discharge reduction. The evaluation also quantified and checked the significance of the impact of the stacked CD+SB system, and the contribution of each of the CD component and the SB component on nitrate load removal. Our study concluded the following:

- The stacked CD+SB system significantly reduced the annual drainage discharge of FD by about 43.1%.
- The CD component significantly reduced the annual drainage discharge from FD by about 44.1%, and it was the sole contributor to the reduction caused by the stacked CD+SB system.
- The stacked CD+SB system resulted in an annual nitrate load percentage reduction of the field drainage under FD of about 83.4%.
- The CD component significantly reduced the annual nitrate load from field drainage under FD by about 82.6%, and it was the main contributor to the reduction caused by the stacked CD+SB system.
- The SB component resulted in an annual nitrate load reduction from field drainage under FD of about 0.9% and reduced the annual CD nitrate load by about 5.1%.

- The mild management of the SB weir stoplogs generated backflow from the buffer into the control structure resulting in additional bypass load which was overcome by the reductions in the diverted nitrate load to the buffer leading to a slight net increase in nitrate load removal.
- Intense management of the SB weir stoplogs limited the backflow generation.
- The stacked CD+SB system resulted in an annual nitrate load percentage reduction of the field drainage under FD of about 49.5%.
- The CD component significantly reduced the annual nitrate load from field drainage under FD by about 49.7%, and it was the main contributor to the reduction caused by the stacked CD+SB system.
- The SB component caused slight reduction of the DRP load and a slight increase in the TP loads from field drainage under FD with annual percentage contributions of about 2.3% and -0.3%, respectively, and it slightly reduced the CD DRP load and increased TP loads by average annual percentages of 5.0% and -0.6%, respectively.
- Improving SB design and careful selection of weir management settings and depth of the distribution pipe can limit backflow from the buffer to the control structure and improve the effectiveness of the stacked CD+SB system to remove nitrate load.

# BIBLIOGRAPHY

Abdalaal, Y., and E. Ghane. 2023. Comparison of newly proposed and existing design criteria for saturated buffers. Journal of the ASABE: 0.

Acharya, U., A. Chatterjee, and A.L.M. Daigh. 2019. Effect of Subsurface Drainage Spacing and Depth on Crop Yield. Agron J 111(4): 1675–1681. doi: https://doi.org/10.2134/agronj2018.11.0738.

Anderson, D.M., P.M. Glibert, and J.M. Burkholder. 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries 25: 704–726.

Askar, M.H., M.A. Youssef, G.M. Chescheir, L.M. Negm, K.W. King, et al. 2020. DRAINMOD Simulation of macropore flow at subsurface drained agricultural fields: Model modification and field testing. Agric Water Manag 242: 106401.

Bechtold, I., S. Köhne, M.A. Youssef, B. Lennartz, and R.W. Skaggs. 2007. Simulating nitrogen leaching and turnover in a subsurface-drained grassland receiving animal manure in Northern Germany using DRAINMOD-N II. Agric Water Manag 93(1–2): 30–44.

Bosompemaa, P., E.W. Peterson, W. Perry, and W.M. Seyoum. 2021. Recycling of Nitrate and Organic Matter by Plants in the Vadose Zone of a Saturated Riparian Buffer. Water Air Soil Pollut 232(6). doi: 10.1007/s11270-021-05202-3.

Campbell, W.H., P. Song, and G.G. Barbier. 2006. Nitrate reductase for nitrate analysis in water. Environ Chem Lett 4: 69–73.

Chandrasoma, J.M., R.D. Christianson, and L.E. Christianson. 2019. Saturated Buffers: What Is Their Potential Impact across the US Midwest? Agricultural & Environmental Letters 4(1): 180059. doi: 10.2134/ael2018.11.0059.

Chandrasoma, J., R. Christianson, R.A. Cooke, P.C. Davidson, D. Lee, et al. 2022. Saturated buffer design flow and performance in Illinois. J Environ Qual. doi: 10.1002/jeq2.20344.

Chen, S., F. Wang, Y. Zhang, S. Qin, S. Wei, et al. 2018. Organic carbon availability limiting microbial denitrification in the deep vadose zone. Environ Microbiol 20(3): 980–992. doi: https://doi.org/10.1111/1462-2920.14027.

Chighladze, G., L.J. Abendroth, D. Herzmann, M.J. Helmers, L. Ahiablame, et al. 2021. Transforming Drainage Research Data (USDA-NIFA Award No. 2015-68007-23193). Ag Data Commons.

Christianson, L.E., R.A. Cooke, C.H. Hay, M.J. Helmers, G.W. Feyereisen, et al. 2021. Effectiveness of Denitrifying Bioreactors on Water Pollutant Reduction from Agricultural Areas. Trans ASABE 64(2): 641–658. doi: https://doi.org/10.13031/trans.14011.

Chun, J.A., and R.A. Cooke. 2008. Calibrating Agridrain water level control structures using generalized weir and orifice equations. Appl Eng Agric 24(5): 595–602.

Clausen, J.C., and J. Spooner. 1993. Paired watershed study design. United States.

Cox, J.W., D.J. McFarlane, and R.W. Skaggs. 1994. Field-evaluation of DRAINMOD for predicting waterlogging intensity and drain performance in South-Western Australia. Soil Research 32(4): 653–671.

Craft, K.J., M.J. Helmers, R.W. Malone, C.H. Pederson, and L.R. Schott. 2018. Effects of Subsurface Drainage Systems on Water and Nitrogen Footprints Simulated with RZWQM2. Trans ASABE 61(1): 245–261. doi: https://doi.org/10.13031/trans.12300.

Dialameh, B., and E. Ghane. 2022. Effect of water sampling strategies on the uncertainty of phosphorus load estimation in subsurface drainage discharge. J Environ Qual. doi: 10.1002/jeq2.20339.

Diaz, R.J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science (1979) 321(5891): 926–929.

Eldridge, E.E., J.E. Schoonover, K.W.J. Williard, A. Sadeghpour, and J.C. Gillespie. 2024. Saturated buffers: Improvements and issues. J Environ Qual n/a(n/a). doi: https://doi.org/10.1002/jeq2.20548.

Evans, R.O., and N.R. Fausey. 1999. Effects of inadequate drainage on crop growth and yield. Agricultural drainage 38: 13–54.

Gatz, L. 2017. Freshwater harmful algal blooms: causes, challenges, and policy considerations.

Ghane, E. 2022. Choice of pipe material influences drain spacing and system cost in subsurface drainage design. Appl Eng Agric 38(4): 685–695.

Ghane, E., and M.H. Askar. 2021. Predicting the effect of drain depth on profitability and hydrology of subsurface drainage systems across the eastern USA. Agric Water Manag 258: 107072.

Ghane, E., N.R. Fausey, and L.C. Brown. 2014. Non-Darcy flow of water through woodchip media. J Hydrol (Amst) 519: 3400–3409.

Ghane, E., A.Z. Ranaivoson, G.W. Feyereisen, C.J. Rosen, and J.F. Moncrief. 2016. Comparison of contaminant transport in agricultural drainage water and urban stormwater runoff. PLoS One 11(12). doi: 10.1371/journal.pone.0167834.

Goolsby, D.A. 2000. Mississippi basin nitrogen flux believed to cause Gulf hypoxia. Eos, Transactions American Geophysical Union 81(29): 321–327.

Greeson, P.E. 1969. LAKE EUTROPHICATION–A NATURAL PROCESS 1. JAWRA Journal of the American Water Resources Association 5(4): 16–30.

Groh, T.A., M.P. Davis, T.M. Isenhart, D.B. Jaynes, and T.B. Parkin. 2019. In Situ Denitrification in Saturated Riparian Buffers. J Environ Qual 48(2): 376–384. doi: 10.2134/jeq2018.03.0125.

Guo, T., R. Confesor Jr, A. Saleh, and K. King. 2020. Crop growth, hydrology, and water quality dynamics in agricultural fields across the Western Lake Erie Basin: Multi-site verification of the Nutrient Tracking Tool (NTT). Science of the Total Environment 726: 138485.

Gupta, H. V, H. Kling, K.K. Yilmaz, and G.F. Martinez. 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. J Hydrol (Amst) 377(1–2): 80–91.

Gupta, H.V., S. Sorooshian, and P.O. Yapo. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J Hydrol Eng 4(2): 135–143.

Hay, C.H., B.D. Reinhart, J.R. Frankenberger, M.J. Helmers, X. Jia, et al. 2021. Frontier: Drainage Water Recycling in the Humid Regions of the U.S.: Challenges and Opportunities. Trans ASABE 64(3): 1095–1102. doi: https://doi.org/10.13031/trans.14207.

Heinen, M. 2006. Simplified denitrification models: Overview and properties. Geoderma 133(3–4): 444–463. doi: 10.1016/j.geoderma.2005.06.010.

Helmers, M.J., L. Abendroth, B. Reinhart, G. Chighladze, L. Pease, et al. 2022. Impact of controlled drainage on subsurface drain flow and nitrate load: A synthesis of studies across the US Midwest and Southeast. Agric Water Manag 259: 107265.

Helmers, M., R. Christianson, G. Brenneman, D. Lockett, and C. Pederson. 2012. Water table, drainage, and yield response to drainage water management in southeast Iowa. J Soil Water Conserv 67(6): 495. doi: 10.2489/jswc.67.6.495.

Jacquemin, S.J., G. McGlinch, T. Dirksen, and A. Clayton. 2020. On the potential for saturated buffers in northwest Ohio to remediate nutrients from agricultural runoff. PeerJ 8: e9007.

Jaynes, D.B., and T.M. Isenhart. 2014. Reconnecting Tile Drainage to Riparian Buffer Hydrology for Enhanced Nitrate Removal. J Environ Qual 43(2): 631–638. doi: 10.2134/jeq2013.08.0331.

Jaynes, D.B., and T.M. Isenhart. 2019a. Performance of Saturated Riparian Buffers in Iowa, USA. J Environ Qual 48(2): 289–296. doi: 10.2134/jeq2018.03.0115.

Jaynes, D.B., and T.M. Isenhart. 2019b. Increasing infiltration into saturated riparian buffers by adding additional distribution pipes. J Soil Water Conserv 74(6): 545–553. doi: 10.2489/JSWC.74.6.545.

Jeantet, A., H. Henine, C. Chaumont, L. Collet, G. Thirel, et al. 2021. Robustness of a parsimonious subsurface drainage model at the French national scale. Hydrol Earth Syst Sci 25(10): 5447–5471. doi: 10.5194/hess-25-5447-2021.

Johnson, G., L. Christianson, R. Christianson, M. Davis, C. Díaz-García, et al. 2023. Effectiveness of Saturated Buffers on Water Pollutant Reduction from Agricultural Drainage. Journal of the ASABE 0(0): 0. doi: https://doi.org/10.13031/ja.15516.

Kaur, H., K.A. Nelson, and G. Singh. 2021. Subsurface drainage and subirrigation for increased corn production in riverbottom soils. Agron J 113(6): 4865–4874.

Kęsicka, B., R. Stasik, and M. Kozłowski. 2022. Effects of modelling studies on controlled drainage in agricultural land on reduction of outflow and nitrate losses–a meta-analysis. PLoS One 17(4): e0267736-. https://doi.org/10.1371/journal.pone.0267736.

Kladivko, E.J., and L.C. Bowling. 2021. Long-term impacts of drain spacing, crop management, and weather on nitrate leaching to subsurface drains.

Kokulan, V., M.L. Macrae, D.A. Lobb, and G.A. Ali. 2019. Contribution of Overland and Tile Flow to Runoff and Nutrient Losses from Vertisols in Manitoba, Canada. J Environ Qual 48(4): 959–965. doi: https://doi.org/10.2134/jeq2019.03.0103.

Liu, Y., M.A. Youssef, G.M. Chescheir, T.W. Appelboom, C.A. Poole, et al. 2019. Effect of controlled drainage on nitrogen fate and transport for a subsurface drained grass field receiving liquid swine lagoon effluent. Agric Water Manag 217: 440–451.

Luo, W., R.W. Skaggs, and G.M. Chescheir. 2000. DRAINMOD modifications for cold conditions. Transactions of the ASAE 43(6): 1569–1582.

Ma, L., L.R. Ahuja, B.T. Nolan, R.W. Malone, T.J. Trout, et al. 2012. Root zone water quality model (RZWQM2): Model use, calibration, and validation. Trans ASABE 55(4): 1425–1446.

Ma, L., L.R. Ahuja, S.A. Saseendran, R.W. Malone, T.R. Green, et al. 2011. A Protocol for Parameterization and Calibration of RZWQM2 in Field Research. Methods of Introducing System Models into Agricultural Research. John Wiley & Sons, Ltd. p. 1–64

Macrae, M., H. Jarvie, R. Brouwer, G. Gunn, K. Reid, et al. 2021. One size does not fit all: Toward regional conservation practice guidance to reduce phosphorus loss risk in the Lake Erie watershed. J Environ Qual 50(3): 529–546. doi: 10.1002/jeq2.20218.

McEachran, A.R., L.C. Dickey, C.R. Rehmann, T.A. Groh, T.M. Isenhart, et al. 2020. Improving the effectiveness of saturated riparian buffers for removing nitrate from subsurface drainage. J Environ Qual 49(6): 1624–1632. doi: 10.1002/jeq2.20160.

McEachran, A.R., L.C. Dickey, C.R. Rehmann, T.M. Isenhart, T.A. Groh, et al. 2023. Groundwater flow in saturated riparian buffers and implications for nitrate removal. Wiley Online Library.

Mitchell, M.E., T. Newcomer-Johnson, J. Christensen, W. Crumpton, B. Dyson, et al. 2023. A review of ecosystem services from edge-of-field practices in tile-drained agricultural systems in the United States Corn Belt Region. J Environ Manage 348: 119220.

Moriasi, D., M. Gitau, N. Pai, and P. Daggupati. 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. Trans ASABE 58(6): 1763–1785. doi: https://doi.org/10.13031/trans.58.10715.

Mrdjen, I., S. Fennessy, A. Schaal, R. Dennis, J.L. Slonczewski, et al. 2018. Tile Drainage and Anthropogenic Land Use Contribute to Harmful Algal Blooms and Microbiota Shifts in Inland Water Bodies. Environ Sci Technol 52(15): 8215–8223. doi: 10.1021/acs.est.8b03269.

Nash, J.E., and J. V Sutcliffe. 1970. River flow forecasting through conceptual models part I—A discussion of principles. J Hydrol (Amst) 10(3): 282–290.

Negm, L.M., M.A. Youssef, G.M. Chescheir, and R.W. Skaggs. 2016. DRAINMOD-based tools for quantifying reductions in annual drainage flow and nitrate losses resulting from drainage water management on croplands in eastern North Carolina. Agric Water Manag 166: 86–100. doi: https://doi.org/10.1016/j.agwat.2015.12.014.

Negm, L.M., M.A. Youssef, and D.B. Jaynes. 2017. Evaluation of DRAINMOD-DSSAT simulated effects of controlled drainage on crop yield, water balance, and water quality for a corn-soybean cropping system in central Iowa. Agric Water Manag 187: 57–68.

Negm, L.M., M.A. Youssef, R.W. Skaggs, G.M. Chescheir, and E.J. Kladivko. 2014. DRAINMOD-DSSAT simulation of the hydrology, nitrogen dynamics, and plant growth of a drained corn field in Indiana. Journal of Irrigation and Drainage Engineering 140(8): 4014026.

NOAA. 2017. What is eutrophication?

NRCS, U. 2018. Conservation Practice Standard, Saturated Buffer, Code 604. USDA-NRCS Field Office Technical Guide. Bismarck, ND: USDA Natural Resources Conservation Service, North Dakota Office.

NRCS. 2022. Saturated Buffer Design and Supporting Information.

NRCS. 2023. Controlled Drainage Conservation Practice Standard, Code 554.

Pease, L.A., N.R. Fausey, J.F. Martin, and L.C. Brown. 2017. Projected climate change effects on subsurface drainage and the performance of controlled drainage in the Western Lake Erie Basin. J Soil Water Conserv 72(3): 240–250.

R. Burchell II, M., R. W. Skaggs, G. M. Chescheir, J. W. Gilliam, and L. A. Arnold. 2005. SHALLOW SUBSURFACE DRAINS TO REDUCE NITRATE LOSSES FROM DRAINED AGRICULTURAL LANDS. Transactions of the ASAE 48(3): 1079–1089. doi: https://doi.org/10.13031/2013.18518.

Reinhart, B.D., J.R. Frankenberger, C.H. Hay, and M.J. Helmers. 2019. Simulated water quality and irrigation benefits from drainage water recycling at two tile-drained sites in the U.S. Midwest. Agric Water Manag 223: 105699. doi: https://doi.org/10.1016/j.agwat.2019.105699.

Ross, J.A., M.E. Herbert, S.P. Sowa, J.R. Frankenberger, K.W. King, et al. 2016. A synthesis and comparative evaluation of factors influencing the effectiveness of drainage water management. Agric Water Manag 178: 366–376.

Salazar, O., I. Wesström, M.A. Youssef, R.W. Skaggs, and A. Joel. 2009. Evaluation of the DRAINMOD–N II model for predicting nitrogen losses in a loamy sand under cultivation in south-east Sweden. Agric Water Manag 96(2): 267–281.

Schaefer, G.L., M.H. Cosh, and T.J. Jackson. 2007. The USDA natural resources conservation service soil climate analysis network (SCAN). J Atmos Ocean Technol 24(12): 2073–2077.

Schott, L., A. Lagzdins, A.L.M. Daigh, K. Craft, C. Pederson, et al. 2017. Drainage water management effects over five years on water tables, drainage, and yields in southeast Iowa. J Soil Water Conserv 72(3): 251. doi: 10.2489/jswc.72.3.251.

Shedekar, V.S. 2016. Developing an integrated, multi-scale modeling system for assessing conservation benefits in subsurface drained watersheds.

Shokrana, M.S. Bin, and E. Ghane. 2021. AN EMPIRICAL V-NOTCH WEIR EQUATION AND STANDARD PROCEDURE TO ACCURATELY ESTIMATE DRAINAGE DISCHARGE. Appl Eng Agric 37(6): 1097–1105. doi: 10.13031/aea.14617.

Shokrana, M.S. Bin, E. Ghane, Y. Abdalaal, and A.P. Nejadhashemi. 2023. Predicting the effect of weir management on the discharge of a controlled drainage system in a changing climate. Agric Water Manag 289: 108534. doi: https://doi.org/10.1016/j.agwat.2023.108534.

Shukla, M.B., S.O. Prasher, A. Madani, and G.P. Gupta. 1994. Field validation of DRAINMOD in Atlantic. Canadian Agricultural Engineering 36(4): 205.

Singh, S., R. Bhattarai, L.M. Negm, M.A. Youssef, and C.M. Pittelkow. 2020. Evaluation of nitrogen loss reduction strategies using DRAINMOD-DSSAT in east-central Illinois. Agric Water Manag 240: 106322.

Skaggs, R.W. 1991. Modeling water table response to subirrigation and drainage. Transactions of the ASAE 34(1): 169–175.

Skaggs, R.W., N.R. Fausey, and R.O. Evans. 2012a. Drainage water management. J Soil Water Conserv 67(6): 167A. doi: 10.2489/jswc.67.6.167A.

Skaggs, R., M. Youssef, and G. Chescheir. 2012b. DRAINMOD: Model Use, Calibration, and Validation. Trans ASABE 55(4): 1509–1522. doi: https://doi.org/10.13031/2013.42259.

Skaggs, R.W., M.A. Youssef, J.W. Gilliam, and R.O. Evans. 2010. Effect of controlled drainage on water and nitrogen balances in drained lands. Trans ASABE 53(6): 1843–1850.

Smith, V.H., G.D. Tilman, and J.C. Nekola. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental pollution 100(1–3): 179–196.

Soil Survey Staff. 2020. The Gridded Soil Survey Geographic (gSSURGO) Database for Iowa.

Streeter, M.T., and K.E. Schilling. 2021. Quantifying the effectiveness of a saturated buffer to reduce tile NO3-N concentrations in eastern Iowa. Environ Monit Assess 193(8). doi: 10.1007/s10661-021-09297-3.

Thornton, P.E., R. Shrestha, M. Thornton, S.-C. Kao, Y. Wei, et al. 2021. Gridded daily weather data for North America with comprehensive uncertainty quantification. Sci Data 8(1): 190.

Thorp, K.R., M.A. Youssef, D.B. Jaynes, R.W. Malone, and L. Ma. 2009. DRAINMOD-N II: Evaluated for an agricultural system in Iowa and compared to RZWQM-DSSAT. Trans ASABE 52(5): 1557–1573.

Tomer, M.D., S.A. Porter, D.E. James, and J.D. Van Horn. 2020. Potential for saturated riparian buffers to treat tile drainage among 32 watersheds representing Iowa landscapes. J Soil Water Conserv 75(4): 453–459. doi: 10.2489/jswc.2020.00129.

Wang, X., C.T. Mosley, J.R. Frankenberger, and E.J. Kladivko. 2006. Subsurface drain flow and crop yield predictions for different drain spacings using DRAINMOD. Agric Water Manag 79(2): 113–136.

Willmott, C.J. 1981. On the validation of models. Phys Geogr 2(2): 184–194.

Youssef, M.A., R.W. Skaggs, G.M. Chescheir, and J.W. Gilliam. 2005. The nitrogen simulation model, DRAINMOD-N II. Transactions of the ASAE 48(2): 611–626.

Zhang, Y., and M.G. Schaap. 2017. Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3). J Hydrol (Amst) 547: 39–53. doi: https://doi.org/10.1016/j.jhydrol.2017.01.004.

# APPENDIX A : CHAPTER 4

## A.1. Workflow of the SB tool

The workflow of the SB tool can be described in six steps, as presented in Figure A.1. The first step is to obtain the user inputs (specified areas of interest and form inputs) of the field of interest and the buffer zone. The second step is to conduct a geospatial analysis using the specified area polygon of the field of interest, as described in Section 4.2.2, 1) identify the major soils in the field of interest based on their coverage percentages and up to three major soils, 2) extract the soil properties of each major soil from the gSSURGO database, and 3) identify the daily rainfall, temperature, and soil temperature records based on the location of the field of interest. In the third step, the extracted soil properties, weather daily records, and user inputs related to the field of interest are used to prepare DRAINMOD input files and run the hydrology module. DRAINMOD input files are created for each major soil of the identified major soils in the field of interest.

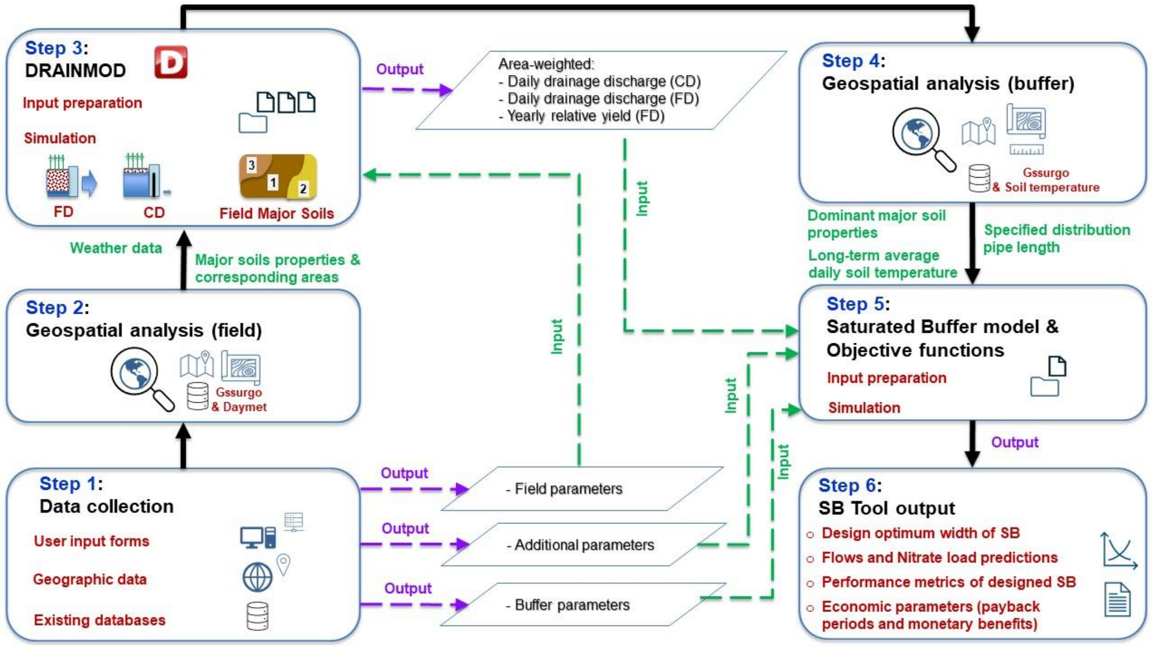


Figure A.1. General workflow followed in the saturated buffer tool.

Two DRAINMOD hydrology simulations are conducted for each major soil in the field of interest, one for free drainage and one for controlled drainage management. At the end of the third step, the final values of the daily drainage discharge under each management are calculated as area-weighted averages of the DRAINMOD output daily drainage discharge values of all major soils. In the fourth step, another geospatial analysis is conducted using the user-defined polyline of the distribution pipe in the buffer zone, as described in Section 4.2.2. In this geospatial analysis, the maximum length of the distribution pipe is identified, and the soil properties of up to three major soils in the buffer zone are extracted from gSSURGO. In the fifth step, depth-weighted values of the buffer soil properties are calculated for each major soil, then area-weighted average values are defined for the whole buffer zone area. Subsequently, the final daily drainage discharge values obtained from the field of interest under controlled drainage management, along with the area-weighted average values of the buffer soil properties, the maximum dimensions of the buffer zone, and other user-defined buffer properties, serve as inputs to the fourth component of the SB tool, known as the objective functions component. Depending on the selected objective function defined, the SB tool utilizes the third component (i.e., the SB model), described in section 4.2.3, to conduct the required SB simulations needed by the objective functions described in section 4.2.4. Finally, in the sixth step, the tool presents the main outputs in the outputs tab depending on the objective functions defined and chosen to run in the tool.

## A.2. Detailed SB tool parameterization

### A.2.1. DRAINMOD parameterization

DRAINMOD requires inputs that describe the soil, weather, subsurface drainage system characteristics, and agronomic practices performed in the field of interest. These inputs are supplied to DRAINMOD in specific formats. The tool has a module that gets the user input and creates the DRAINMOD formatted input files.

DRAINMOD uses the soil input files to describe the hydraulic properties of the different layers in the profile. The soil texture percentages, bulk density, and water content values at field capacity and wilting point were obtained from the geospatial analysis step described in section 4.2.2. These extracted values were used as input to the Rosetta3 model (Zhang and Schaap, 2017) to estimate the van Genuchten water retention parameters and saturated hydraulic conductivity of the layers of each soil map unit. The output from Rosetta3 was used as input to the DRAINMOD soil utility program to create the DRAINMOD soil files (*.SIN and *.MIS). In the SIN file, the values of upflux in the water-table depth and upflux relationship were set to zero for water-table depths deeper than 90 cm. As discussed in section A.1, one set of soil files was created for each major soil map unit of the defined map units in the field of interest. This set of soil input files is then used to perform two hydrology simulations, one for FD and one for CD, representing the hydrology of the field under each management for only a single major soil.

DRAINMOD receives the weather files to describe the temporal variation in precipitation and temperature at the field. The SB tool uses the location of the field of interest to determine the set of daily precipitation and maximum and minimum daily temperature data to use out of predefined datasets. The predefined weather records datasets were obtained by extracting the required weather parameters from the Daymet database (Thornton et al., 2021), at airport locations in Hamilton, Story, Webster, Boone, Hardin, and Marshall counties in Iowa. The daily weather records from Daymet were used as input to the DRAINMOD weather utility program to create DRAINMOD weather input files (*.RAI and *.TEM) at each site.

The general input file of DRAINMOD for each field was edited on the fly with relevant user-defined inputs. The considered simulation period was set for 31 years, from 1992 to 2022. Each soil layer’s lateral saturated hydraulic conductivity was assumed to be twice the extracted vertical saturated hydraulic conductivity value from the gSSURGO database for DRAINMOD simulations (Askar et al. 2024, in press). The depth to restrictive layer parameter was set as the extracted value of the distance from the soil surface to the upper boundary of the restrictive layer from the gSSURGO database if existent or a value of 305 cm (10 ft) if not listed (Askar et al. 2024). All parameters’ values related to soil temperature, freezing, and thawing were adapted from Luo et al., (2000) and Negm et al., (2014), except for the soil temperature at the bottom of the profile, snow temperature, melting temperature, and thawing rate. The soil temperature at the bottom of the profile was calculated as the long-term average daily temperature from the data obtained from Daymet. The Daymet temperature data were also used to calculate the heat index of the Thornthwaite method. The monthly potential evapotranspiration (PET) correction factors used in the tool were adapted from published values of DRAINMOD modeling studies conducted in the Midwest region (Wang et al., 2006; Thorp et al., 2009; Negm et al., 2014, 2017; Shedekar, 2016; Askar et al., 2020; Singh et al., 2020).

The DRAINMOD general input file also includes the parameters describing the subsurface drainage system. The lateral drain depth value used at each field was taken from the published values in the TDD (Chighladze et al., 2021). Lateral spacing values were defined at each site based on the information received through personal communication with the research team at Iowa State University. The type of lateral pipe reported in the TDD was used to determine the effective radius value at each field based on the work (Ghane, 2022). The values of the maximum surface storage and Kirkham's depth for flow to drains were 2 and 1 cm, respectively, and were obtained from calibration (Pease et al., 2017). The drainage coefficient was set to 1.9 cm/day, which is a commonly used value in the design of main collectors of subsurface-drained fields. The tool offers the option to define two weir management settings: One for even years and one for odd years to capture the difference in management of corn and soybean. The weir management setting allows inputs for depth from the ground surface and corresponding dates.

It should be noted that the weir management settings for each crop should be defined by the user based on the commonly practiced management at the field of interest since this parameter can significantly affect the predicted drainage discharge volume of the system, which consequently affects all other outputs from the SB tool. For this current study, the weir management settings for each site were set based on the information collected through direct communication with the ISU research team. The parameters describing the cross-section of the pseudo ditch that controls the water storage at the outlet during CD simulations were set to low values, where the width of the pseudo ditch was set to 0.01 cm and the side slopes were set to 1:1. This was done to limit the water movement from the control structure to the field. Both lateral and deep seepage components were set to zero since the SB tool assumes no seepage in the fields to maintain the tool's low data requirements and limit its use's complexity.

The DRAINMOD crop input file is used to define parameters describing some of the crop phenology, agronomic practices, and susceptibility parameters for the excess, drought, and delayed planting stresses. The current version of the SB tool only considers corn-soybean rotation. The user can specify the first crop planted in the first year of the simulation, the planting dates, and the growing days for corn and soybeans. The default planting dates and growing days were calculated as the long-term average values of the relevant data acquired from the National Agricultural Statistics Services (NASS) for Iowa. The susceptibility factors were based on the reported values in the DRAINMOD manuals and the default values in the crop files created with the installation of DRAINMOD. The lower limit parameter, the soil water content below which the supply of the additional evapotranspiration to get to the potential value is stopped, was calculated based on the approximation shown in Equation A.1 using the extracted values from gSSURGO database. The parameter of the minimum air volume required to work the land was calculated as the value of the free pore space above a ground water table depth drained to equilibrium to 75 cm using the DRAINMOD calculated data of the water table depth and drained volume as suggested in DRAINMOD manuals.

$$\theta_{LL} = \theta_{WP} + 0.25 \times \ (\theta_{FC} - \ \theta_{WP}) \tag{A.1}$$

where

$\theta_{LL}$ = soil water content at the lower limit (cm$^3$/ cm$^3$),

$\theta_{WP}$ = soil water content at the permanent wilting point (cm$^3$/ cm$^3$), and

$\theta_{FC}$ = soil water content at the field capacity (cm$^3$/ cm$^3$).

A limited calibration/validation exercise was conducted to determine the default values of some of the DRAINMOD parameters using the measured drainage discharge records (Table A.1). These DRAINMOD parameters control surface runoff and snow/thawing during the winter period. A calibration period was defined by randomly choosing three years at BC1 (2015, 2016, and 2022) and two years at IA1 (2015 and 2016) from the available years. The validation was conducted using the years that were not included in the calibration period.

Table A.1. Calibrated DRAINMOD parameters used in the saturated buffer tool simulations at BC1 and IA1.

| Parameters | Calibrated Value | Calibration range |
|---|---|---|
| **Soil temperature parameters** | | |
| Snow temperature (°C) | -2.0 | -2, -1, -0.5, and 0 |
| Melting temperature (°C) | -1.0 | -1, 0, 0.5, 1, 1.5, and 3 |
| Thawing rate (mm/dd. °C) | 1.0 | 1, 3, and 5 |
| **Surface runoff parameters** | | |
| Max. surface storage (cm) | 2.0 | 2 and 1 |
| Kirkham's depth (cm) | 1.0 | 1 and 0.5 |

### A.2.2. Saturated buffer model parameterization

To assess the performance of an existing SB system, the SB model requires information related to the SB system and the buffer zone. For the first set of information, the buffer width and length and the distribution pipe depth, diameter, and type at each site were obtained from the published data in TDD (Chighladze et al., 2021). The effective radius of the distribution pipe was defined using the pipe's diameter and type based on the work by Ghane, (2022). The water head in the ditch was assumed to be constant, and the value at each field was calculated using the depth to stream surface reported in Jaynes and Isenhart, (2019a). The default value of the depth to a restrictive layer of the buffer soil was determined from the calibration. The weir management settings in the second chamber that controls the hydraulic head over the distribution pipe were assumed to be identical to those in the first chamber of the three-chamber control structure (i.e., the CD weir setting in the first chamber). The gSSURGO-extracted values of the layers of the dominant buffer soil properties were used to calculate depth-weighted effective values that represent the entire buffer zone. The depth-weighted effective values were calculated for the bulk density, vertical saturated hydraulic conductivity, and volumetric water content at field capacity. The effective porosity of the buffer soil was assumed to be equal to the drainable porosity, taken as the difference between the total porosity and the field capacity (Ghane et al., 2014). The buffer soil's effective porosity was calculated using Equation A.2, incorporating depth-weighted effective values. The first-order denitrification coefficient was assumed as the average value of the reported range of Iowa sites in literature with a value of about 0.45 day$^{-1}$ (McEachran et al., 2020). It should be noted that a user-defined value for the first-order denitrification coefficient is advised since it can significantly impact the predictions of nitrate load removal by the buffer (McEachran et al., 2020).

$$n_e = \left(1 - \frac{\rho_b}{\rho_s}\right) - \theta_{FC} \tag{A.2}$$

where

$n_e$ = effective porosity (cm$^3$/cm$^3$),

$\rho_b$ = bulk density (g/cm$^3$), and

$\rho_s$ = density of solids (g/cm$^3$), assumed as 2.65 g/cm$^3$.

A limited calibration/validation exercise was conducted to determine the default values of two input parameters to the SB model of the tool (Table A.2). The parameters were the multiplier coefficient to the extracted gSSURGO saturated hydraulic conductivity (this is needed to estimate the lateral saturated hydraulic conductivity) and the depth to the restrictive layer in the buffer. The calibration and validation were conducted using the measured daily diverted flow to the buffer of the same years used in the calibration/validation exercise of some of the DRAINMOD parameters.

The other required input to the SB model was calculated using the estimated subsurface drainage discharge from DRAINMOD and a user input value for the average nitrate concentration of drainage water.

Table A.2. Calibrated parameters of the saturated buffer tool used in the simulations at BC1 and IA1.

| **Parameters** | **Calibrated Value** | **Calibration range** |
|---|---|---|
| Multiplier of vertical Ksat [a] [b] | 4 | [ 2 — 12 ] |
| Depth to restrictive layer (cm) [a] | 427 | [ 244— 610] every 33 [c] |

[a] Calibrated value is used at both sites BC1 and IA1.

[b] Multiplier coefficient to estimate lateral saturated hydraulic conductivity from gSSURGO vertical saturated hydraulic conductivity.

[c] Calibration range corresponds to a range from 8 ft to 20 ft with 1-ft intervals.

### A.3. Plots of the SB tool’s monthly predictions against measured monthly records

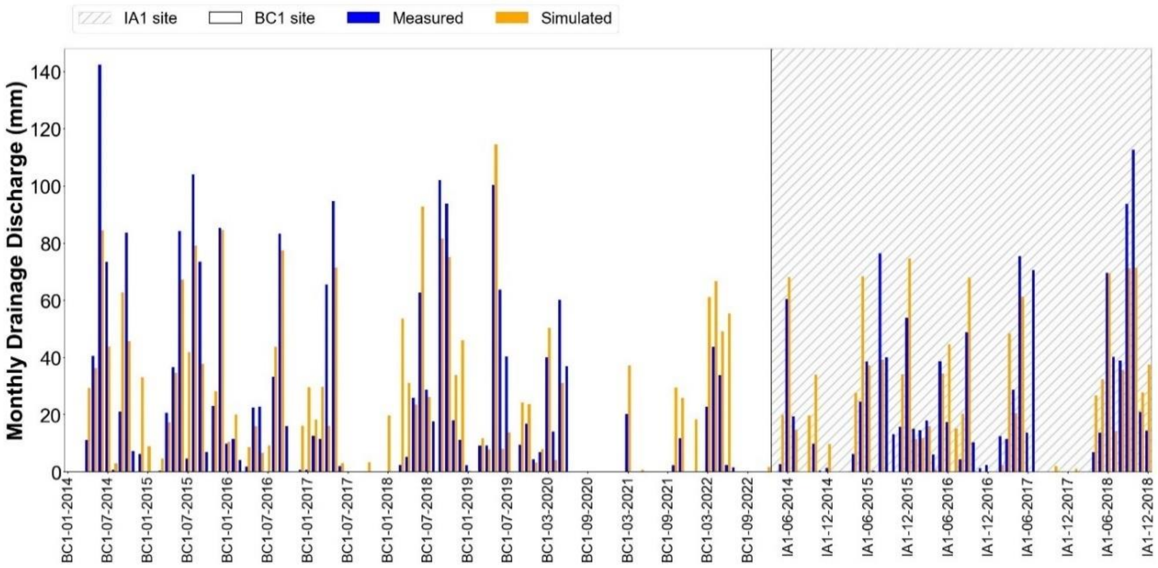


Figure A.2. Comparison between the predicted monthly drainage discharge from the SB tool and the measured records at BC1 and IA1 in Iowa for all years.

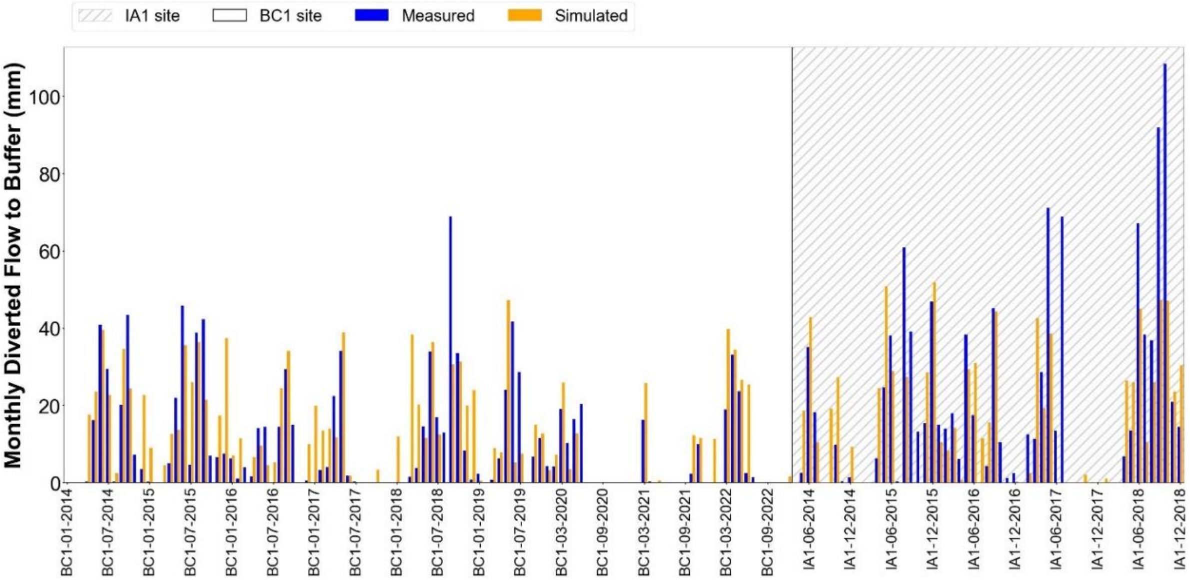


Figure A.3. Comparison between the predicted monthly normalized diverted flow to the buffer from the SB tool and the measured records at BC1 and IA1 in Iowa for all years.

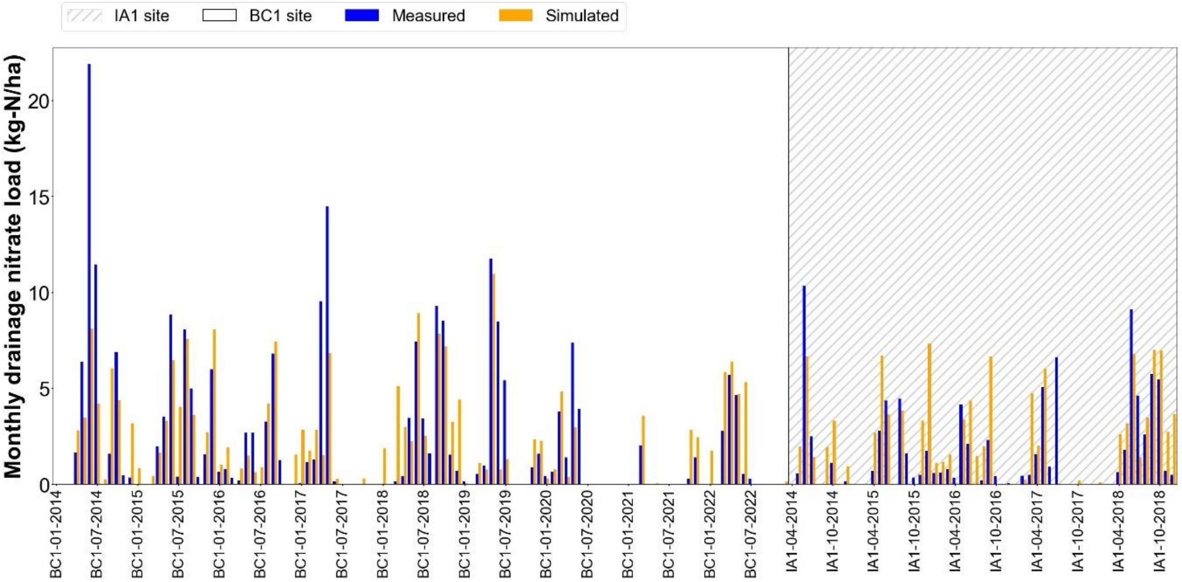


Figure A.4. Comparison between the precited monthly normalized nitrate loading from drainage discharge and the measured records at BC1 and IA1 in Iowa for all years.

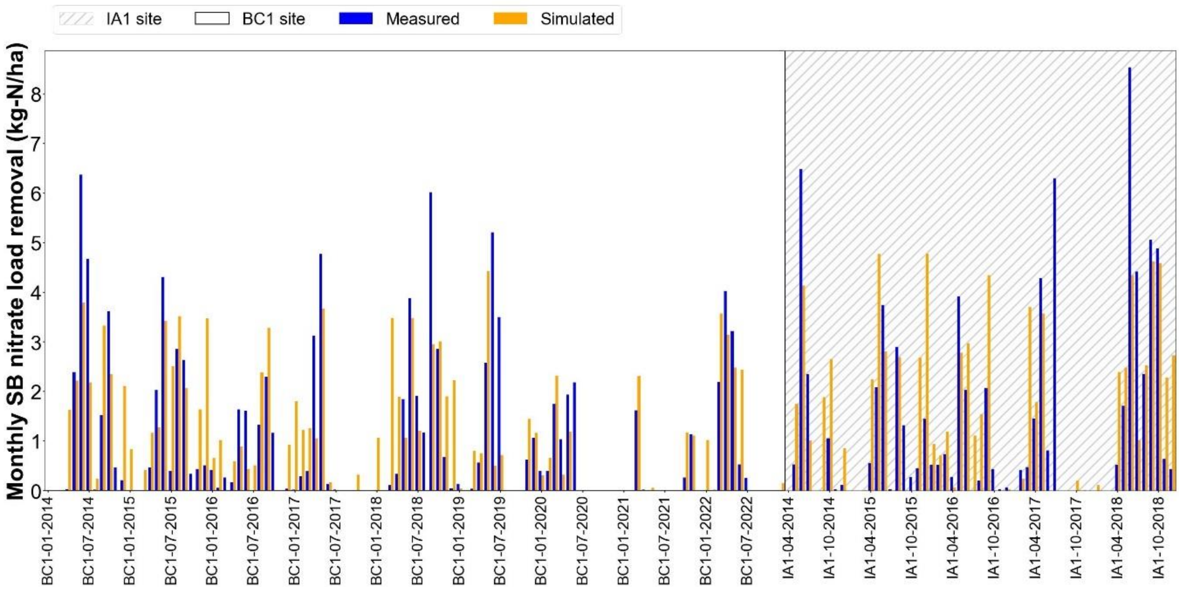


Figure A.5. Comparison between the predicted monthly normalized nitrate load removal by the saturated buffer and the measured records at BC1 and IA1 in Iowa for all years.

## A.4. Additional limitations

The SB model component assumes that SBs are controlled via a three-chamber structure, which might result in an underestimation of the predicted SB effectiveness if used to represent an SB controlled via a two-chamber structure. In a three-chambers setup, the predicted diverted flow is zero when there is no drainage discharge from CD, as flow does not reach the second chamber with the distribution pipe. Conversely, in a two-chamber setup, if the water head in the first chamber is high enough, diverted flow to the buffer can occur even when there is no flow over the weirs, since the distribution pipe is in the first chamber. Additionally, the water head in the first chamber of a two-chamber setup is influenced by the hydrology at the subsurface-drained field (ET, rainfall, thawing, seepage) as well as by that of the SB system (diverted flow, bypass during high drainage discharge, or backflow when buffer soil profile is saturated). Unlike the water head in the second chamber of a three-chamber structure, where it is solely influenced by the hydrology of the SB system.

A general limitation of the tool validation was the lack of a larger set of complete data with high certainty. Despite the availability of measurement records of more sites in the TDD (Chighladze et al., 2021), a few important parameters were either missing or had high uncertainty. There was a lack of data regarding the lateral spacings and the weir management of the subsurface drainage systems. Also, conducting a water balance analysis of the reported measurements and area served by the collector main connected to the SB system showed high uncertainties of the reported area served by some of the TDD sites. Where the water balance analysis showed considerably low amounts of losses through water sinks other than drainage (i.e., summation of ET, runoff, and seepage) during the growing season (from April to the end of October) when the ET alone is expected to have much more than the calculated values. Therefore, multiple sites were excluded from the evaluation, limiting the SB tool's testing. Furthermore, the absence of data characterizing the hydrological properties in the fields constrained the tool's evaluation. For example, having measured values of saturated hydraulic conductivity for the soil in the subsurface-drained fields, along with high-quality data on weather, runoff, seepage, water stage in ditches, or other factors influencing field hydrology, could have facilitated a more rigorous assessment of the tool. Having a complete representation of the elements influencing the SB can improve our understanding of the hydrology in the SB, which in turn can enhance our understanding of the nitrate removal performance and consequently lead to better SB designs. Thereby, the authors recommend that future studies related to saturated buffers should report the hydrological characteristics and main soil hydraulic properties of the cultivated field, the design parameters of the subsurface drainage system connected to the SB, and the management settings used for both the subsurface drainage system and SB.

# APPENDIX B :VIABILITY OF SATURATED BUFFER SYSTEM

## B.1. Discussion about viability of saturated buffers as a conservation drainage practice

The saturated buffer system is a relatively new conservation drainage practice that aims to reduce nitrate loading from tile-drained agricultural lands (Jaynes and Isenhart, 2014). Literature review by Mitchell et al., (2023) showed that there are limited number of studies that investigated the nitrate loading removal performance of saturated buffer. So, our reporting on the viability of SB as a conservation drainage practice to reduce nitrate loading from tiled-drained fields was based on our reasoning as related to the findings from the limited studies found in the literature and from the work done in this dissertation.

Without any doubt, SBs are effective in reducing nitrate loading from tiled-drained lands as shown by the results from our field evaluation study in Michigan (Chapter 5), as well as the published field evaluation results across multiple sites in Iowa and Illinois (Jaynes and Isenhart, 2019a; Chandrasoma et al., 2022). Our field results showed that the SB component only is capable of causing a significant contribution in the nitrate load reduction from tile-drained lands ($p\text{-value}<0.0001$). The SB contribution resulted in an additional reduction of the FD nitrate load of about 0.9% and reduced the CD nitrate load by about 5.1% (Chapter 5). It should be noted that this value could have been better without the periods that had mild management of the weirs. Published studies also reported an average annual reduction in nitrate load by SBs amounting to about 45% of the controlled drainage nitrate load. GIS analysis also showed the suitability of SB implementation in about 50% of the total length of streambanks in the Midwest (Chandrasoma et al., 2019). This estimation was conservative since it only considered perennial water streams and were limited to streams adjacent to corn/soybean planted areas with relatively poor drainage classification (somewhat poorly or worse only).

Although the reduction in nitrate losses is more required in areas that eventually drain to salt water bodies (e.g. oceans, seas, gulfs, ..etc) than those draining to fresh water bodies (e.g. lakes), since nitrogen is the limiting nutrient for algae bloom formation in salt water bodies. The nutrient reduction effectiveness of SBs is not limited to nitrate. Our field study in Michigan showed that the SB component slightly resulted in additional reductions of the DRP loads from tile drainage during the treatment period when management was implemented, even when mild management was implemented. The SB contribution resulted in an additional reduction of the FD DRP load of about 2% and reduced the CD DRP load by about 5% (Chapter 5). With intense management of the SB weir stoplogs, the contribution of the SB component to the reductions in the nitrate and phosphorus losses will more likely increase.

The above-mentioned discussion shows the potential of using SBs as a conservation drainage practice to reduce nitrate loading across multiple locations and US states. However, there are some constraints and conditions that may limit the effectiveness of SBs or in some circumstances even deem them unsuitable for implementation, as listed in Table B.1.

Table B.1. Constraints and conditions negatively impacting saturated buffer performance and their implications.

| **Constraints** | **Implications** |
|---|---|
| **Saturated hydraulic conductivity of soil ($K_{sat}$)** | |
| **Extremely low $K_{sat}$** | - Very poorly drained buffer soils will more likely result in limited diverted flow to buffer and subsequently limited nitrate removal (e.g. very fine soils as clay and silt soils with very low $K_{sat}$values) |
| **Extremely high $K_{sat}$** | - Well drained soils that have extremely high $K_{sat}$ values will more likely result in relatively short retention time for diverted water to buffer, shortcutting the water movement along the buffer width. The short retention time may limit the nitrate load removal via denitrification. These soils could be very coarse soils (e.g. sandy soils) or profiles that have sub-layers with extremely high $K_{sat}$ values. |

Table B.1 (cont'd)

| | |
|---|---|
| **Low soil organic carbon** | Buffer soils that have extremely low soil organic carbon levels will more likely result in extremely low denitrification and subsequently nitrate load removal (Chen et al., 2018). |
| **High water stage in adjacent streams** | - Buffer zones with adjacent streams with water stage levels close to ground surface for extended time period may limit the diverted flow to the buffer. This is because of the smaller hydraulic gradient between the control structure and the stream. Subsequently this will more likely limit the nitrate load reduction. |
| **Depth of restrictive layer ($\boldsymbol{D_{res}}$)** | |
| **Extremely shallow $\boldsymbol{D_{res}}$** | - Extremely shallow restrictive layer depth (close to the depth of the distribution pipe) will increase the likelihood of having saturated soil profile. This will more likely limit the diverted flow to buffer, generate backflow from the buffer into the control structure and subsequently limit the nitrate load reduction, especially in very poorly drained soils. |
| **Extremely deep $\boldsymbol{D_{res}}$** | - Extremely deep restrictive layer depth will more likely result in deep water table in the buffer zone away from the soil layers with minimum soil organic carbon levels required for the denitrification. |
| **Topography and area** | |
| **Length of buffer zone** | - Buffer zones with limited length because of small land-area ownership or presence of neighboring fields will more likely result in the installation of shorter distribution pipe length. This will limit the diverted flow to buffer and subsequently the nitrate load removal. |
| **Large drainage areas** | - SBs installed at tile-drained fields with extremely large drainage areas and limited length of distribution pipe, will more likely result in higher bypass flows to the adjacent streams and less diverted water to buffer and nitrate load removal, especially during high peak flows. |
| **Precipitation** | |
| **High intensity short duration rainfall** | - SBs and similar conservation drainage practices are not well-suited for locations experiencing frequent high intensity short-duration rainfalls. This type of precipitation pattern will more likely result in saturated buffer profiles, higher bypass flows, less diverted flows and subsequent lower nitrate load reduction. |

The implications of the changing climate on SB performance will depend on the type and number of constraints listed in Table B.1 that are present at an SB location. In general, for the Midwest region in the US, future climate predictions expect a shift in the rainfall pattern with wetter non-growing season and drier growing season, relative to current pattern (Shokrana et al., 2023). Under such conditions, studies showed an improvement in the CD performance reflected by greater drainage discharge reductions (Shokrana et al., 2023). Midwest locations that do not experience extreme cases of the conditions listed in Table B.1 will more likely have better SB performance because of the improved performance of CD which represents a major component of the SB system. Higher drainage discharge reduction from CD will result in lower bypass flows and higher diverted flows to buffer which subsequently can lead to more treated volume of water and nitrate load reduction.