Received: 24 May 2023 | Accepted: 10 January 2024

DOI: 10.1002/jeq2.20548

Journal of Environmental Quality

TECHNICAL REPORT

Surface Water Quality

Saturated buffers: Improvements and issues

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Assigned to Associate Editor Katrina Macintosh.

Abstract

Saturated buffers are a newly developed agricultural best management practice used to redirect tile flow away from waterways, thereby mitigating nutrient losses and downstream eutrophication. This study evaluated the potential benefits of a novel saturated buffer design, which included pitchfork-shaped (PF) dispersion lines and a backflow check valve, that was installed alongside a traditional or standard (ST) buffer on a field in Moultrie County, Illinois, in the spring of 2019. Daily flow measurements and routine water samples were used to monitor the movement of water through both buffers and estimate nutrient loads. During observation days in 2020 and 2021, the PF buffer diverted 35% and 1.9% of incoming tile flow, respectively, while the ST buffer increased effluent rates by 116% and 137% over the same period. Both the PF and ST buffers experienced backflow from 30% to 47% of the monitoring period, well above the often reported 5%. Ultimately, the efficacy of saturated buffers could be improved with minimal, low-cost additions to their designs. Check valves are a simple supplement to saturated buffer design that can enhance flow diversion and potential nutrient removal. Added dispersion lines provide more opportunity for diversion of tile flow; however, they require more land to be removed from agricultural production and could increase backflow volumes, so the costs and benefits should be weighed.

Plain Language Summary

Saturated buffers (SBs) can prevent harmful impacts of nutrient losses from artificially drained fields. A typical SB uses one distribution line to divert water into a buffer zone. This study compares a standard SB to a new design, with three distribution lines and a check valve to prevent backflow, installed side-by-side on the same field. We found that SBs have potential to increase the water and nutrients that are drained from a field, but the backflow check valve can prevent excess water loss. Furthermore, the added distribution lines diverted more water into the buffer. These

Abbreviations: BMP, best management practice; DRP, dissolved reactive phosphorus; ML, million liters; NLRS, nutrient loss reduction strategy; PF, pitchfork; ST, standard; UMRB, Upper Mississippi River Basin.

findings are important so farmers can maintain crop production while minimizing damages to water resources.

1 | INTRODUCTION

Organizations and agencies across the Upper Mississippi River Basin (UMRB) are working to reduce nitrogen (N) and phosphorus (P) loads to the Gulf of Mexico in order to reduce hypoxia and eutrophication. Illinois, specifically, has implemented a nutrient loss reduction strategy (NLRS) aimed at reducing total N and P loads by 45%, with interim targets of a 15% reduction in nitrate-nitrogen (NO_3–N) load and a 25% reduction in total P load by 2025 (Illinois EPA, 2021). One of the main targets of nutrient loss abatement is agricultural sources. Implementing agricultural best management practices (BMPs) such as cover crops, reduced or no till, and proper nutrient management has potential to reduce losses of N and P throughout the state of Illinois. However, much of central Illinois is artificially drained, meaning many commonly used BMPs are not as useful because nutrient-rich tile water is quickly conveyed toward waterways (Pavelis, 1987). Jaynes and Isenhart (2014) developed an edge-of-field practice to disperse tile flow into a riparian buffer zone via perforated tile lines to treat nutrients via biogeochemical processes within the buffer, and thereby reduce nutrient loading at the outlets. This BMP, called saturated buffers, promotes denitrification by creating saturated conditions, which further reduces NO_3–N loading alongside reduction of tile outlet flow (Davis et al., 2018; Groh et al., 2019; Streeter & Schilling, 2021). Saturated buffers were added to the suggested practices of the Illinois NLRS in 2021 because of the promising results across the UMRB (Biennial Report, 2021).

Since their inception in 2014, saturated buffers have been implemented in Iowa, Illinois, and Ohio within the Lake Erie Basin. It is estimated that more than 245,000 saturated buffers could be established on over 75,000 km of streambank in the Midwest United States, and doing so could reduce NO_3–N loss in the Midwest by 5%–10% (Chandrasoma et al., 2019). On a smaller scale, six saturated buffers over 17 site-years in Iowa resulted in an observed 8%–84% reduction of NO_3 from the field tile to the stream, or an average of 73 kg NO_3–N year^{-1} (Jaynes & Isenhart, 2019a). A study of saturated buffers in Iowa, Illinois, Indiana, and Minnesota observed 0%–85% NO_3 removal, which corresponded with 0%–99% flow diversion (Utt et al., 2015). In Illinois, three saturated buffers over 10 site-years reduced NO_3 losses by an average of 48% ± 19%, or 3.5–25.2 kg NO_3–N year^{-1} (Chandrasoma et al., 2022). A saturated buffer in Ohio redirected 25% of tile flow and an estimated 15 kg N and 0.025 kg dissolved reactive phosphorus (DRP) into the buffer during a 12-month observation period (Jacquemin et al., 2020).

While these saturated buffers have demonstrated success, the functionality of saturated buffers is heavily dependent on site conditions. The NRCS developed a standard (ST) for saturated buffers (Code 604) that includes presence of restricted layers to induce saturated conditions, consistent hydraulic conductivity throughout the buffer, 1.2% organic matter (or 0.75% organic carbon), sufficient width to establish a vegetated buffer, and stream channels with banks less than 2.4 m above the streambed to prevent bank failure (USDA-NRCS, 2020). Those criteria were later expanded to include subsoils consisting of less than 50% sand at 0.75- to 1.2-m depth and water tables less than 1.0 m from the surface from April to June to enhance denitrification (Tomer et al., 2017). Additionally, McEachran et al. (2019) monitored six sites with existing saturated buffers and developed an equation to determine the ideal width of a saturated buffer to maximize nitrate removal, which was consistently narrower than the current widths of the buffers. Tomer et al. (2017) further emphasized the importance of stable streambanks to prevent sediment loss and other unintended consequences (2017), although Dickey et al. (2021) determined that saturated buffers only resulted in bank instability in less than 3% of simulated examples, potentially increasing the applicability of saturated buffers in the Midwest. Nevertheless, there is a dearth of literature on the usefulness of saturated buffers in the assorted soil and topographical conditions of the UMRB.

While saturated buffers are effective in redirecting tile volumes to remove nutrients before entering a stream and are widely used, they are not without problems. The issues with backflow, defined as flow from shallow groundwater in and around the buffer into the control structure (Chandrasoman et al., 2022; Jacquemin et al., 2020), leave room for improvement in design and implementation. Furthermore, flow that bypasses a saturated buffer lowers the amount of NO_3 that is treated by the buffer (Chandrasoma et al., 2022; Jaynes & Isenhart, 2019a). Models indicate that adding a second distribution line could increase infiltration by 15% under practical, variable flow conditions, and therefore reduce bypass flow volumes, but no in-field studies have been conducted (Jaynes & Isenhart, 2019b). In 2019, an experimental saturated buffer equipped with a one-way check valve to prevent backflow and three dispersion lines in a pitchfork (PF) shape was installed alongside an ST design saturated buffer on a privately owned farm in Moultrie County, Illinois (Images S1–S3). The objectives of the study were to determine if the check valve and added dispersion lines from the experimental design increased dispersal volumes, and therefore diverted nutrients from the nearby stream. Not only could this design improve the performance of saturated buffers across the UMRB, but it is also a simple, financially prudent addition to an already low-cost BMP.

Core Ideas

- Saturated buffers can increase total discharge and nutrient loads to a waterway as a result of backflow.
- Additional distribution lines increased dispersion, but they also carried the risk of greater backflow volumes.
- A one-way check valve prevented backflow within the pitchfork buffer.
- The standard buffer design contributed excess effluent via backflow in 2021 and 2022.
- The pitchfork buffer design decreased effluent discharge in 2020 and 2021.

2 | MATERIALS AND METHODS

2.1 | Site description

This study was conducted during 2020 and 2021 at a privately owned farm located in Moultrie County in central Illinois. The crop field follows a corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation, with soybeans in even years and corn in odd years. In fall of 2020, 196 kg ha^{-1} of 12-40-75-10 S-2.5 Zn and 84 kg ha^{-1} of pellet gypsum were applied following soybean harvest. In 2021, 78 kg ha^{-1} of N was applied at the time of corn planting (April 27), and then 157 kg ha^{-1} of N was applied via Y-drop side dress about 1 month later. Soils at the site are primarily Xenia silt loam (a fine-loamy, mixed, superactive, mesic, and Aquic Hapludalf) with small portions of Drummer-Milford silty clay loam (a fine, mixed, superacitve, and mesic Typic Endoqualf) on the east side of the field (Soil Survey Staff, 2023). Soil pH (1 water: 1 soil) ranged from 5.8 to 7.7 throughout the drained portion of the field and the buffers, and active C within the buffers ranged from <1.0 to 1100 mg C kg^{-1} soil, determined through analysis from a method adapted from Weil et al. (2003). In 2019, two saturated buffers were installed side-by-side on the edge of this field. ST saturated buffer that drains 2.59 ha of the west side of the field was installed, and an experimental PF buffer design that drains 7.81 ha of the east side of the field was installed adjacent to the ST buffer (Figure S1). Both buffers drained to the same nearby stream. To examine water tables and nutrients within the buffers, two transects of monitoring wells were installed (Figure S1). Each buffer had a three-chambered control structure (CS) with v-notch weirs to measure inflow and outflow, and dispersed flow (Agri Drain Corp.). Control structures were 1.83-m tall, with 0.30 m above ground. The experimental PF design includes three dispersion lines in the shape of a PF, a shut-off valve for the portion of the buffer within the crop field, and a one-way check valve to prevent water from entering the middle chamber of the control structure (Figure 1). The installation of both buffers was overseen by the NRCS to ensure proper site conditions and buffer attributes. After installation, an Illinois Forage and Pollinator Mix from Pennington, composed of 13 native flowers and grasses, was established on both buffer areas. A summary of site characteristics is presented in Table S1.

2.2 | Field data collection

2.2.1 | Buffer monitoring

Each control structure was equipped with two automatic groundwater samplers (ISCO 6712 Automated Stream Sampler, Teledyne) outfitted with data-logging pressure transducers (ISCO 720p, Teledyne). Pressure transducers were placed in the first (upstream) and second chambers and logged the depth every 15 min to measure flow from the field and to the outlet, respectively, which can vary in nutrient concentrations during low flow or backflow events. Depths were aggregated to daily means for analysis. The v-notches on the first and second chamber of the ST buffer were 92.1 and 74.4 cm from the bottom of the structure (60.3 and 78.0 cm from soil surface), respectively. For the PF buffer, the first v-notch was set to 113.0 cm and the second was set to 92.1 cm (39.4 and 60.3 cm from soil surface). Both buffers were designed in adherence with the NRCS ST conservation practice for saturated buffers, Code 604 (USDA-NRCS, 2020). The differences in stoplog height between the buffers were to account for the differences in field drainage area, and therefore tile volumes.

2.2.2 | Sampling

Samples were collected routinely each month and on a roughly biweekly basis when visiting for maintenance. Routine sampling included 250 mL from control structure chambers, monitoring wells, and outlets. Grab samples were collected from all three chambers of both control structures. To sample the monitoring wells, contents of the wells were bailed via a pump and then allowed to refill before collecting a sample. When tile outlets were flowing, a sample was gathered in a Nalgene bottle. On biweekly maintenance visits samples were collected from control structures and outlets. All

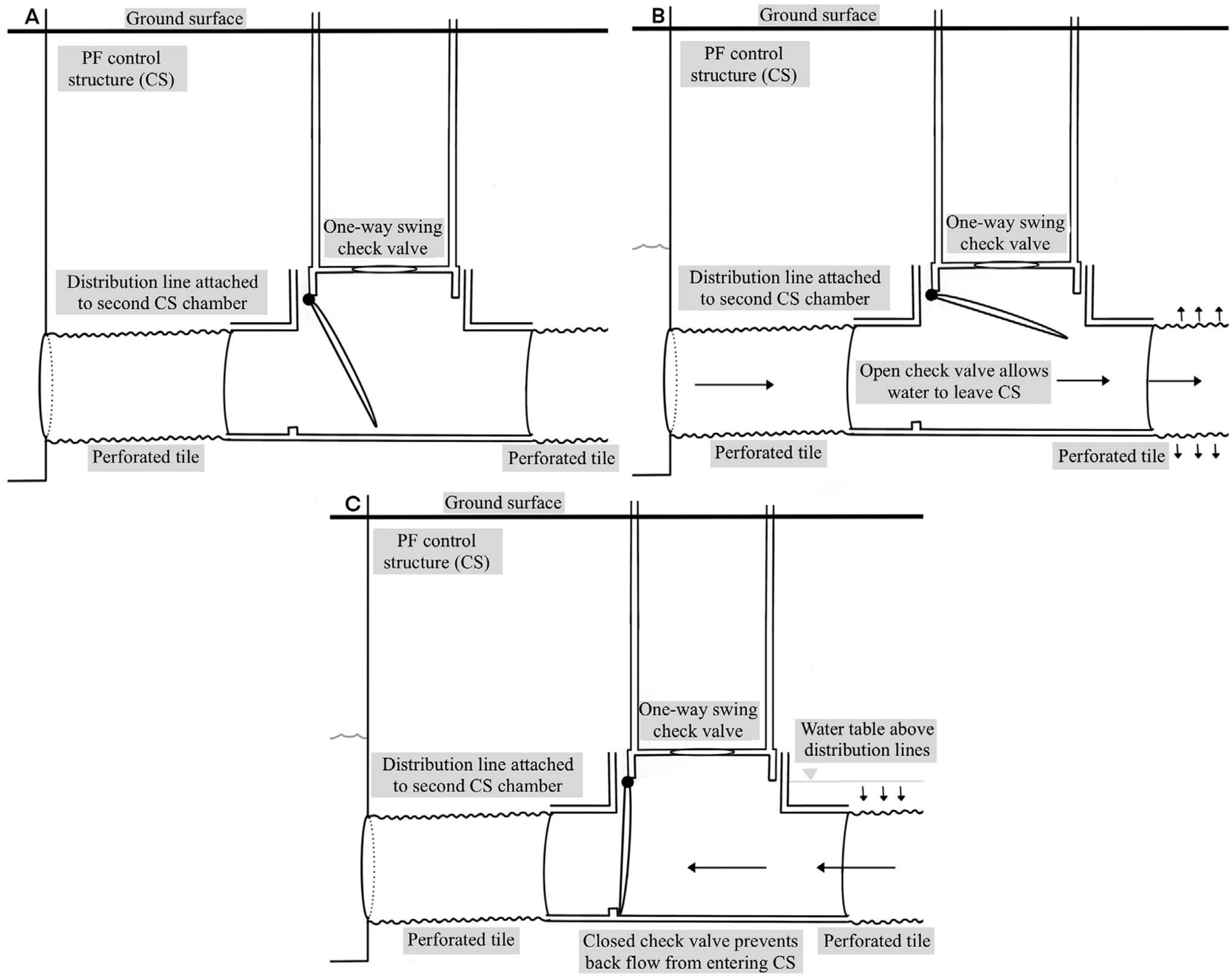

FIGURE 1 Diagram of the pitchfork (PF) buffer check valve when there is no flow (A), in the open position (B), and the closed position (C).

samples were stored in a cooler on ice for transportation, and then kept at −3˚C until laboratory analysis.

2.3 | Laboratory analysis

A 125 mL volume of all samples was filtered through a 0.45 μm pore nylon membrane filter, and the filtrate was saved for analysis of NO_3–N and DRP. Analyses of NO_3–N were performed using an ion chromatograph (Dionex ICS-2000), and DRP was analyzed via colorimetric determination using the ascorbic acid method and a spectrophotometer (Perkin Elmer Lambda 25 UV/VIS).

2.4 | Calculations and statistics

AgriDrain, the control box manufacturer, provided equations for accurate calculations of discharge as a function of water depth in the box. Flow into the upstream and downstream chambers of each control structure were used to calculate diverted flow and bypass flow according to Jaynes and Isenhart (2014). Diverted or dispersed flow was defined as the difference between the volume of water entering the control structure and the volume of water discharging to the stream. Bypass flow is equivalent to the discharge into the stream, as that water has bypassed the buffer. Backflow was defined as occurrences in which the outlet flow exceeded the inlet flow. To calculate annual nutrient loads, daily flow volumes were multiplied by nutrient concentrations to obtain mass of nutrients (per ha), which was summed for each year. Samples collected from the control structures were used to estimate loads.

Daily flow rates and nutrient loads were not normally distributed; however, the data were independent and continuous, thus, a Wilcoxon rank sum test was used to compare discharge and nutrients between the ST and PF buffers in 2020 and 2021 (Hollander et al., 2014) (R Studio version 4.0.2, R

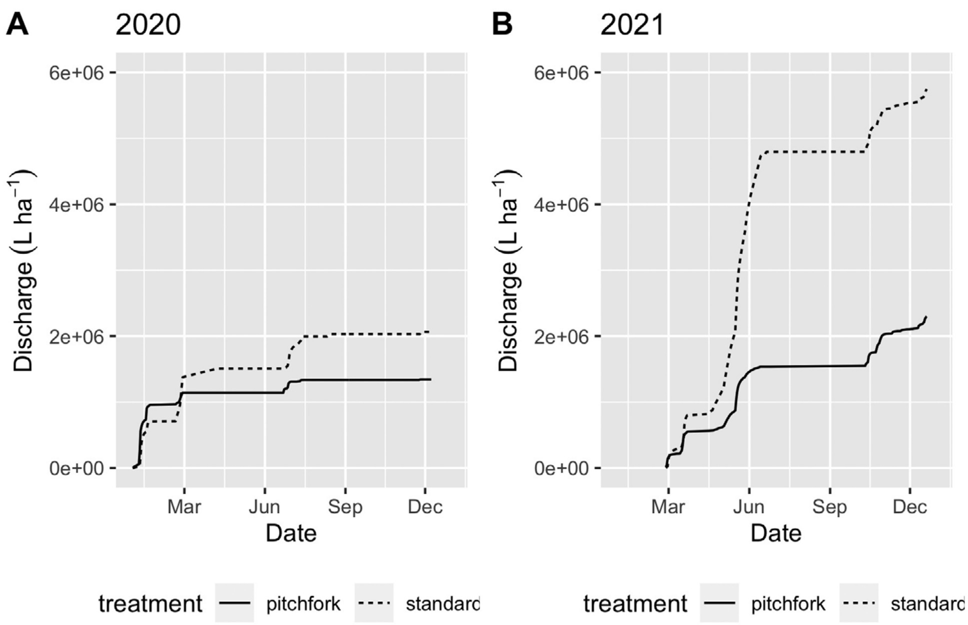

FIGURE 2 Cumulative outlet discharge for the standard (ST) and pitchfork (PF) buffers in 2020 (A) and 2021 (B).

Core Team). Days of dispersion and days of backflow were used as measures of efficacy to analyze differences due to the PF-shaped tile and the check valve, respectively. A chi-square analysis was used to compare days of flow and dispersion between the ST and PF buffers. A significance level of $\alpha \leq 0.05$ was used.

3 | RESULTS AND DISCUSSION

3.1 | Effluent, dispersion, and backflow

Bypass flow to the stream is the main concern for a BMP like saturated buffers. In 2020, a measured 1.91 ML ha^{-1} (4.95 ML) discharged at the ST tile outlet and 1.32 ML ha^{-1} (10.3 ML) from the PF outlet (W = 17,814, p = 0.2457). During the first 3 months of 2020, the PF buffer was discharging at a greater rate than the ST, due to seasonal precipitation and lack of evapotranspiration causing saturated soil conditions, but in March the ST buffer surpassed the PF in cumulative discharge and remained that way the rest of the year (Figure 2A). During the 2021 sampling period, the ST buffer discharged 5.33 million liters (ML) ha^{-1} (13.8 ML), and the same year 2.22 ML ha^{-1} (17.3 ML) discharged at the PF outlet (Figure 2A) (W = 22,564, p < 0.001). At the beginning of the year, the bypass flow volumes for both buffers were similar. However, starting in mid-May, the ST bypass flow volume increased from about 1.5 ML ha^{-1} to nearly 5.0 ML ha^{-1} throughout the summer (Figure 2B).

In 2020, more water left the ST control structure than entered from the crop field. An excess 0.91 ML ha^{-1} (2.36 ML) entered the control structure via the buffer distribution lines, which is termed backflow. Backflow occurs when water tables within the buffer rise above the distribution lines, at which point the distribution lines serve as tiles, draining the extra water stored in the buffer. During the same sampling period, the PF buffer discharged less water to the stream than entered from the field. The PF buffer dispersed 0.72 ML ha^{-1} into the buffer via distribution pipes (5.56 ML). The PF buffer outperformed the ST buffer in terms of volume dispersed (W = 22,564 p < 0.001). Although the PF buffer did disperse tile water overall, there was still some backflow at peak flows. The intention of the check-valve was to prevent all backflow in the PF buffer, but it became clear during the study that some backflow was to be expected, especially during periods of extended or intense precipitation. One potential reason the valve does not prevent all backflow is that when the water level changes rapidly the flap gets stuck in the wrong position, allowing water to pass when it should not. It does not appear that backflow occurs at one threshold, such as water level, discharge, or precipitation, for either buffer.

Similarly, in 2021 there was notable backflow for the ST buffer, likely due to increased precipitation (Table S2). A measured 3.1 ML ha^{-1} (7.98 ML) entered the second chamber of the control structure via backflow during the observation period, nearly three times greater than backflow volumes in 2020. Concurrently, the PF buffer continued to disperse tile flow overall in 2021, but at much lower volumes. Only 4.29 kL ha^{-1} (3.39 kL) was retained in the PF buffer during the 2021 study period, substantially less than in 2020, but still more than was retained in the ST buffer in 2021 (W = 20,406, p < 0.001). Similar to 2020, there were occurrences of backflow in the PF buffer during the observation period in 2021. However, the volumes of dispersed tile flow were greater than the volumes of backflow.

The excessive influx of water from the ST buffer was an unexpected result of this study. Some publications have reported instances of backflow in a saturated buffer, but none to the extent of the ST buffer. Where Chandrasoma et al. (2022) observed backflow during less than 5% of the study period, the ST and PF buffers experienced backflow during 30%–47% of the observation period, which is a remarkably longer timeframe. Furthermore, backflow is often excluded from analysis due to the definition of the buffer's treatment area (Chandrasoma et al., 2022). While technically the backflow volume does originate from outside the treatment area (outside the tile-drained portion of the field), additional volume to waterways, especially when sourced in agricultural lands, cannot be neglected in the considerations of efficacy of the practice.

For the sake of comparison to the literature, annual flow volumes were also calculated negating days with greater effluent than influent, or backflow. In this analysis, the PF buffer diverted 79% of incoming flow from the stream in 2020, just slightly more than the 71% the ST buffer diverted the same year. In 2021, the PF buffer diverted 71% of tile flow to the buffer while the ST buffer only diverted 40%. Notably, the PF buffer only diverted substantially more influent in 2021, when there was more precipitation and greater overall tile volumes, indicating the increased dispersion lines had a greater impact at high flows (Table S2). Including backflow in the calculations, only the 35% flow reduction by the PF buffer in 2020 lies within the reported rates, which ranged from 19% to 100% (Jacquemin et al., 2020; Jaynes & Isenhart, 2019a). However, when calculated without backflow, the ST and PF buffers both diverted flow at comparable rates to other saturated riparian buffers in 2020 and 2021. While neither the ST or PF buffer diverted 100% of tile flow (calculated without backflow), the dispersal of over 70% of tile flow to the PF buffer and 40%–71% of tile flow to the ST buffer is on the higher end of other published dispersal rates (Jacquemin et al., 2020; Jaynes & Isenhart, 2019a).

3.2 | Design efficacy

Evaluating the efficacy of tile water distribution of the PF shape and the one-way check valve was difficult, as both additions to the design were only on the PF buffer. To parse out the influence of both components, days of dispersion and days of backflow were used as a measure of efficacy for the dispersion lines and the valve, respectively. Days of complete dispersion were defined as days where inflow was measured at the first control structure chamber and no outflow was measured, and days of backflow were defined as days when flow was measured in the second chamber but not the first. Another measure of efficacy of tile water distribution used was percent reduction or increase of outlet discharge.

Results for the 2 years vary due to differences in precipitation during the sampling periods (Table S2). In 2020, the check valve and dispersion lines worked as intended by increasing dispersion and decreasing backflow (Table 1). However, in 2021, the PF design did not result in more days of complete dispersion due to the increased precipitation that year (Table 1). When the water table in the buffers is above the dispersion lines, the dispersion lines will act as tile drains. This further emphasizes the importance of a check valve in saturated buffer designs. The rainfall in 2021 (Table S2) resulted in increased occurrences of backflow for both buffers, with the ST buffer experiencing over three times the number of backflow days compared to 2020, and the PF buffer more than doubling its number of backflow days (Table 1). Although there was more backflow in 2021, the check valve still worked to prevent some backflow in the PF buffer (Table 1). The addition of a one-way check valve to saturated buffer designs would be a simple and cost-efficient approach to reducing backflow.

Interestingly, even with the design additions, the ST and PF buffers performed similarly to other saturated buffers in central Illinois and other states in the UMRB. Outflow was reduced by 1.9%–35% in the PF buffer in 2020 and 2021, while Chandrasoma et al. (2022) reported 48 ± 19% flow reduction from five saturated buffer sites in central Illinois (Illinois EPA, 2021). Other authors have reported flow reduction varying from 19% up to 100%, at multiple sites in Iowa and one in Ohio (Jaynes & Isenhart, 2019a; Jacquemin et al., 2020). However, it is important to note that saturated buffer performance is influenced by many environmental and design factors, making for an incomplete comparison. Although the flow reduction from the PF buffer was within a similar range to some other saturated buffers, the inclusion of backflow volumes in the flow calculations of the PF and ST buffers makes a comparison difficult. Despite that, these results are promising for the PF buffer, as it had greater flow reduction with all instances of backflow incorporated than some of those with no backflow included. The ST buffer, however, had more effluent than influent in 2020 and 2021, resulting in flow reductions of −116% and −97% (or contributions of 116% and 97% of influent to the stream). While, presumably, the ST buffer performed worse than other published saturated buffers, it cannot be confidently determined unless calculations for all saturated buffers included backflow volumes.

3.3 | Nutrient loading and dispersion

The key function of a saturated buffer is to divert nutrient loads from waterbodies by diverting tile flow. Not only does

TABLE 1 Measures of efficacy in terms of number of days flowing in 2020, including χ^2-values and p-values.

	Days of data		Days of flow		Days of complete dispersion		Days of backflow	
Treatment	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
Standard	194	164	56	151	3	3	46	1122
Pitchfork	194	164	49	148	18	5	30	80
χ^2			0.6398	0.3404	11.3	0.5125	4.189	22.73
p-value			0.4238	0.5596	<0.001***	0.4741	0.0407*	<0.001***

Note: Days of data include days of no flow in either chamber as well as bypass flow, which are not included in the table. Days of flow includes days of dispersion and days of backflow, as the buffers are flowing.

*Significant at the 0.05 probability level; ***significant at the 0.001 probability level.

the buffer zone slow water, but the elevated water tables from the extra water also promote denitrification, which reduces NO_3–N to inert forms. Despite those agreed upon functions, and no other similar results published, the ST buffer discharged an additional 3.32 kg NO_3–N ha^{-1} (8.60 kg NO_3–N) to the stream than came into the first chamber from the field in 2020, a 94% increase in NO_3–N, which was attributed to backflow; the same year, the PF buffer diverted 1.16 kg NO_3–N ha^{-1} (9.06 kg NO_3–N) from the stream, an 18% reduction in NO_3–N loading directly to the stream (W = 23,362, $p < 0.001$). Monitoring well data showed NO_3-N concentrations were reduced across the width of both buffers, supporting the idea that NO_3-N was removed via denitrification or plant assimilation (Figures S2A and S3A; Tables S3 and S4). Since there is no analogous biogeochemical process for P, saturated buffers are not considered for P loss abatement; however, there is some evidence for DRP removal by saturated buffers (Carstensen et al., 2020; Jacquemin et al., 2020). Similar to NO_3–N movement in 2020, the ST buffer contributed an excess 0.0930 kg DRP ha^{-1} (2.13 kg DRP) to the stream, or a 97% increase from the inlet, while the PF buffer diverted 0.141 kg DRP ha^{-1} (1.10 kg DRP), or 52% of incoming DRP, from the stream (W = 22,673, $p < 0.001$). While DRP was diverted from the stream, monitoring well data did not show reduction of DRP across the widths of the buffers (Figures S2C and S3C). Results for diversion were consistent for both nutrients in 2020, with the ST buffer contributing to loading and the PF buffer reducing loading.

As a result of higher than average precipitation and, therefore, greater tile volumes in 2021, there were extra losses of nutrients due to backflow. In the duration of the year, the ST buffer contributed an excess 25.2. kg NO_3–N ha^{-1} (65.0 kg NO_3–N) to the stream, increasing loads by 151%, and while the PF buffer also contributed excess to the stream, it was at a much lower rate of 2.20 kg NO_3–N ha^{-1} (17.2 kg NO_3–N), still NO_3–N loading increased in the PF buffer by 180% (W = 22,623, $p < 0.001$). Even though both buffers contributed excess NO_3-N to the stream, there was still reduction of NO_3-N concentrations across the width of the ST buffer and between distribution lines in the PF buffer (Figures S2B and S3B). DRP load diverted displayed a dissimilar pattern in 2021. The ST buffer, again, contributed an extra 0.120 kg DRP ha^{-1} (0.311 kg DRP), a 126% increase in loading, while the PF buffer diverted 0.121 kg DRP ha^{-1} (0.945 kg DRP) from the stream (W = 2675, $p < 0.001$). Like the previous year, there was no changes in DRP concentrations across the width of the ST or PF buffers (Figures S2D and S3D).

To compare the ST and PF buffers to the literature, the percentages of NO_3–N and DRP diverted were also calculated without days containing backflow. With these conditions, in 2020 the ST buffer diverted 25% of NO_3–N and 42% of DRP from the stream while the PF buffer diverted 71% and 85%, respectively. In 2021, the ST buffer diverted 26% of incoming NO_3–N and 11% of incoming DRP, and the PF buffer diverted 23% and 73% of incoming NO_3–N and DRP, respectively. Comparatively, Jaynes and Isenhart (2019a) stated saturated buffers in Iowa diverted 18%–98% of NO_3–N loads, and Chandrasoma et al. (2022) reported 21%–80% of NO_3–N was diverted over 10 site-years in Illinois. The proportion of NO_3–N reduction in the ST and PF buffers performed similarly to other saturated buffers when backflow was disregarded. However, only one other study on saturated buffers has monitored DRP loss. Jacquemin et al. (2020) stated 0.25 kg of DRP was diverted into a saturated buffer in Ohio over a 12-month period, which was considerably less than the total mass of DRP removed by the PF buffer in 2020 and 2021, when 1.1 and 0.94 kg of DRP were diverted by the PF buffer (still including backflow), respectively.

3.4 | Management implications

Early research on saturated buffers showed very promising results for tile flow and nutrient loss reduction. Not only did our study attempt to analyze nutrient and flow diversion as a result of saturated buffers in central Illinois, as there is a dearth of peer-reviewed publications, but it also implemented a novel site configuration to directly compare two buffers and two low-cost design additions to improve flow diversion. The two design additions, PF-shaped dispersion lines and a one-way check valve, were put into practice to treat a greater volume of tile water and reduce instances of backflow, which had been anecdotally observed in previous research (Chandrasoma et al., 2022; Jacquemin et al., 2020). Results from 2 years of sampling, in 2020 and 2021, showed that the addition of the check valve had a significant impact on days of backflow in the PF buffer. While Chandrasoma et al. (2022) observed backflow events during less than 5% of the study period, the PF and ST buffers recorded backflow instances during approximately 30%–47% of the study period, respectively; as backflow represented such a significant portion of the observation period, it was determined that in order to see the "bigger picture" of saturated buffer efficacy it was necessary to keep backflow data in all analyses. Fortunately, however, the increased dispersion lines in the PF buffer also allowed for higher rates of diversion, especially at base flow. Both design additions were successful for their intended purposes and should be considered in future saturated buffer design criteria.

Even with the success, there are some factors to assess before adding either practice to a saturated buffer. First, additional dispersion lines require a larger area to be designated as a riparian buffer zone, which may not be possible or desirable to all landowners. Furthermore, extra dispersion lines lead to the potential for greater volumes of backflow. For that reason, a one-way check valve should be included in any saturated buffer design using more length of tile than listed in the ST NRCS design. Still, a check valve is a useful and worthwhile supplement to any saturated buffer design—low risk and high reward in terms of flow and potential nutrient loss reduction.

While not necessary to the function of the saturated buffer, regular maintenance to the check valve is an additional means to further minimize losses due to backflow. Removing the valve from the system and inspecting the flap for any wear-and-tear or sediment blockages at harvest and planting is a simple and infrequent approach to ensure proper functioning of the valve. During these assessments the flap should be replaced if it appears to have any damage and sediment and debris should be cleared from all visible surfaces. These visits can coincide with routine trips to the field to prevent unnecessary travel and upkeep. By using a check valve, the amounts of backflow can be reduced, and the excess water that may drain from the buffer can reside in the soil longer—allowing more opportunity for nutrient uptake, transformation, or immobilization—before it is routed to the stream.

4 | CONCLUSION

Saturated buffers, while a relatively new BMP, are touted as a useful treatment for nutrient losses on tile-drained fields. Although there is evidence that saturated buffers are beneficial and can move Illinois, and the rest of the UMRB, closer to its NLRS goals, more research is needed. Continuous observation of flow at the ST and PF buffers over the course of 2 years showed that backflow and bypass flow are a common occurrence. Not only that, but also both buffers discharged more NO_3–N than came in from the field during those occurrences, which is counterintuitive to the purpose of a saturated buffer. Only two other studies to date have mentioned backflow in the case of saturated buffers, and in these studies, backflow is not included in calculations. Saturated buffers have potential to reduce nutrient loading across the UMRB, and particularly in some of the most productive and most polluting areas, but further research should be conducted to obtain a more complete perspective of the impacts of saturated buffers and the potential design improvements.

AUTHOR CONTRIBUTIONS

Emma E. Eldridge: Data curation; formal analysis; investigation; project administration; resources; software; visualization; writing—original draft. **Jon E. Schoonover**: Conceptualization; funding acquisition; resources; supervision; validation; writing—review and editing. **Karl W. J. Williard**: Funding acquisition; resources; validation; writing—review and editing. **Amir Sadeghpour**: Resources; validation; writing—review and editing. **Jackie C. Gillespie**: Investigation; resources; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Carstensen, M. V., Hashemi, F., Hoffmann, C. C., Zak, D., Audet, J., & Kronvang, B. (2020). Efficiency of mitigation measures targeting nutrient losses from agricultural drainage systems: A review. *Ambio*, *49*(11), 1820–1837. https://doi.org/10.1007/s13280-020-01345-5

Chandrasoma, J. M., Christianson, R. D., & Christianson, L. E. (2019). Saturated buffers: What is their potential impact across the US Midwest? *Agricultural & Environmental Letters*, *4*(1), 180059. https://doi.org/10.2134/ael2018.11.0059

Chandrasoma, J. M., Christianson, R. D., Cooke, R. A. C., Davidson, P. C., Lee, D., & Christianson, L. E. (2022). Saturated buffer design flow and performance in Illinois. *Journal of Environmental Quality*, *51*, 389–398. https://doi.org/10.1002/jeq2.20344

Davis, M. P., Groh, T. A., Jaynes, D. B., Parkin, T. B., & Isenhart, T. M. (2018). Nitrous oxide emissions from saturated riparian buffers: Are we trading a water quality problem for an air quality problem? *Journal of Environmental Quality*, *48*, 261–269. https://doi.org/10.2134/jeq2018.03.0127

Dickey, L. C., McEachran, A. R., Rutherford, C. J., Rehmann, C. R., Perez, M. A., Groh, T. A., & Isenhart, T. M. (2021). Slope stability of streambanks at saturated riparian buffer sites. *Journal of*

Environmental Quality, *50*, 1430–1439. https://doi.org/10.1002/jeq2.20281

Groh, T. A., Davis, M. P., Isenhart, T. M., Jaynes, D. B., & Parkin, T. B. (2019). In situ denitrification in saturated riparian buffers. *Journal of Environmental Quality*, *48*, 376–384. https://doi.org/10.2134/jeq2018.0.0125

Hollander, M., Wolfe, D. A., & Chicken, E. (2014). *Nonparametric statistical methods* (3rd ed.). John Wiley & Sons, Inc.

Illinois EPA. (2021). *Illinois nutrient loss reduction strategy (NLRS) biennial report 2021*. Illinois EPA. https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/water-quality/watershed-management/excess-nutrients/documents/nlrs-biennial-report-2021_FINAL.pdf

Jacquemin, S. J., McGlinch, G., Dirksen, T., & Clayton, A. (2020). On the potential for saturated buffers in northwest Ohio to remediate nutrients from agricultural runoff. *PeerJ*, *2020*(4), e9007. https://doi.org/10.7717/peerj.9007

Jaynes, D. B., & Isenhart, T. M. (2014). Reconnecting tile drainage to riparian buffer hydrology for enhanced nitrate removal. *Journal of Environmental Quality*, *43*(2), 631–638. https://doi.org/10.2134/jeq2013.08.0331

Jaynes, D. B., & Isenhart, T. M. (2019a). Performance of saturated riparian buffers in Iowa, USA. *Journal of Environmental Quality*, *48*(2), 289–296. https://doi.org/10.2134/jeq2018.03.0115

Jaynes, D. B., & Isenhart, T. M. (2019b). Increasing infiltration into saturated riparian buffers by adding additional distribution pipes. *Journal of Soil and Water Conservation*, *74*(6), 545–553. https://doi.org/10.2489/jswc.74.6.545

McEachran, A. R., Dicky, L. C., Rehmann, C. R., Groh, T. A., Isenhart, T. M., Perez, M. A., & Rutherford, C. J. (2019). Improving the effectiveness of saturated riparian buffers for removing nitrate from subsurface drainage. *Journal of Environmental Quality*, *49*, 1624–1632. https://doi.org/10.1002/jeq2.20160

Pavelis, G. A. (1987). *Farm drainage in the United States: History, status, and prospects* (No. 1455). US Department of Agriculture, Economic Research Service.

Soil Survey Staff. (2023). *Natural resources conservation service*. Web Soil Survey, United States Department of Agriculture. https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

Streeter, M. T., & Schilling, K. E. (2021). Quantifying the effectiveness of a saturated buffer to reduce tile NO_3-N concentrations in eastern Iowa. *Environmental Monitoring and Assessment*, *193*, 500. https://doi.org/10.1007/s10661-021-09297-3

Tomer, M. D., Porter, S. E., James, D. E., & VanHorn, J. D. (2017). Potential for saturated buffers to treat tile drainage among 32 watersheds representing Iowa landscapes. *Journal of Soil and Water Conservation*, *75*(4), 453–459. https://doi.org/10.2489/jswc.2020.00129

USDA-Natural Resources Conservation Service. (2020). Conservation practice standard for saturated buffers (Code 604). USDA-NRCS. https://www.nrcs.usda.gov/

Utt, N., Jaynes, D., & Albertsen, J. (2015). *Demonstrate and evaluate saturated buffers at field scale to reduce nitrates and phosphorus from subsurface field drainage systems*. http://www.saturatedbufferstrips.com/images/final_report.pdf

Weil, R. R., Islam, K. R., Stine, M. A., Gruver, J. B., & Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, *18*, 3–17.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Eldridge, E. E., Schoonover, J. E., Williard, K. W. J., Sadeghpour, A., & Gillespie, J. C. (2024). Saturated buffers: Improvements and issues. *Journal of Environmental Quality*, 1–9. https://doi.org/10.1002/jeq2.20548