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TECHNICAL REPORTS

Landscape and Watershed Processes

# Slope stability of streambanks at saturated riparian buffer sites

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**Abstract**

Saturated riparian buffers (SRBs) reduce nitrate export from agricultural tile drainage by infusing drainage water into carbon-rich riparian soils where denitrification and plant uptake occur. The water quality benefits from SRBs are well documented, but uncertainties about their effect on streambank stability have led to design standards that limit the maximum bank height and minimum buffer width, thus reducing the number of suitable candidate sites. In this study, the relationship between SRB design and streambank stability was examined through numerical slope stability modeling and validated using field sites. At the study sites, the addition of SRB flow increased the probability of failure by less than 3% for both simulated dry and rainfall scenarios. Furthermore, the simulations provide no evidence to support excluding potential sites based on bank height alone. Multivariate analysis of dimensionless parameters developed for SRB flow conditions was used to predict the factor of safety as a function of the SRB site and design conditions. The equation presented allows designers to assess the stability of a potential site where bank failure poses a heightened risk. The results of this study alleviate the need for extensive geotechnical evaluations at future SRB sites and could increase SRB implementation by expanding the range of eligible sites.

## 1 | INTRODUCTION

Nitrate-rich water exported via artificial subsurface (tile) drainage in the midwestern United States degrades local water quality and contributes to excessive nutrient loading in downstream waters (Goolsby et al., 2001). Strategies to reduce the nutrient export in tile-drained systems typically focus on combining in-field source management and edge-of-field water quality treatment. A saturated riparian buffer (SRB) is an edge-of-field water quality practice in which tile drainage water is routed through soil adjacent to a stream or drainage ditch. Saturated riparian buffers use a water control structure and perforated distribution pipe to infiltrate drainage water into carbon-rich soil where microbial denitrification, immobilization, and plant uptake occur (Jaynes & Isenhart, 2014). A hydraulic gradient, governed by the water level set at the control structure, is used to induce flow toward the stream. The SRBs remove up to 92% of nitrate, with an average cost of approximately \$3.00 kg$^{-1}$ of nitrate removed (Jaynes & Isenhart, 2019). The SRBs can be incorporated into an existing riparian buffer without removing additional land from production and require little-to-no maintenance. The effectiveness, low cost, and limited maintenance requirements have made SRBs a desirable option to reduce nitrate loading to surface waters.

**Abbreviations:** CEM, Channel Evolution Model; FS, factor of safety; GLM, generalized linear model; SRB, saturated riparian buffer.

Because SRBs function by artificially elevating the groundwater level, they can reduce streambank stability. High groundwater levels can induce excessive pore water pressures and lead to slope failure (Jia et al., 2009). Streambank failures degrade water quality and can disrupt sensitive riparian and aquatic ecosystems (M. Palmer et al., 2000), counteracting potential water quality improvements from the SRB. Streambank erosion is a significant contributor to the total export of suspended sediment from a watershed in many regions (Fox et al., 2016; J. Palmer et al., 2014) and a major source of riverine phosphorus export (Beck et al., 2018; Belmont et al. 2011).

Current SRB design standards reflect these concerns by establishing conservative guidelines. The USDA-NRCS Saturated Buffer Conservation Practice Standard (Code 604) (USDA-NRCS, 2018) requires a minimum 9.1-m setback from the SRB distribution pipe to the streambank and precludes siting SRBs along streams with channels deeper than 2.4 m without an evaluation of slope stability. Such an evaluation would determine whether the factor of safety (FS), typically calculated as the ratio of forces resisting and driving slope failure, exceeds a critical value. Geotechnical slope stability evaluations are expensive and could more than double the installation cost of an SRB. Furthermore, traditional geotechnical slope stability evaluations fail to account for channel instability caused by in-stream processes unrelated to SRB flow. These limitations, though well intentioned, may reduce the implementation of SRBs if otherwise suitable sites are excluded.

The objective of this study was to evaluate the effect of SRBs on streambank stability. Five existing sites in Iowa were examined to gain insight into typical SRB conditions and validate the modeling methods. Seepage conditions generated by the SRB were compared with no-flow conditions without an SRB at varying stream stages to assess the changes in the FS and the probability of slope failure. A range of potential SRB site conditions was considered to evaluate Code 604 design standards and investigate conditions that cause bank instability. A regression equation was created to relate streambank stability to SRB design parameters and increase practical applicability of this study for field practitioners who are unlikely to have access to slope stability modeling software. Finally, limitations due to uncertainty in parameters and streambank instability related to channel morphology are considered. The implications of the results on SRB design are discussed.

**Core Ideas**

- The addition of SRB flow did not cause streambank instability in 97% of simulated cases.
- Stability prior to SRB installation is a good indicator of post-installation stability.
- Bank height is not a significant determinant of streambank stability.
- SRB flow increased the probability of streambank failure by less than 3%.

## 2 | MATERIALS AND METHODS

### 2.1 | Field sites

Five existing SRB sites in central Iowa—which Jaynes and Isenhart (2019) label BC-1, BC-2, B-T, IA-1, and SH—were studied to inform and validate a conceptual model of SRB slope stability. The sites represent a range of slope geometries and seepage conditions (Table 1), but they are similar in design and function. Each SRB includes a control structure that intercepts the tile drainage main and routes water to a 10-cm-diameter distribution pipe installed approximately 75 cm below the soil surface, running parallel to the stream. The hydraulic head in the distribution pipe is set by the control structure to ensure water encounters carbon-rich soils near the ground surface. Soils at the sites are poorly drained, free from extensive sand layers, and predominantly composed of clay loams as classified under the USDA-NRCS soil taxonomy system. The geology of all sites indicates glacial till as the underlying soil parent material. All sites were vegetated with perennial vegetation in accordance with applicable conservation practice standards.

Site characteristics were determined through field measurements, monitoring, and review of past research. Topographic surveys were used to assess SRB width, bank height, and slope angle associated with the maximum section of the streambank. Groundwater levels were monitored with pressure transducers (Levelogger 3001, Solinst-Canada Ltd.) installed in wells located throughout the SRB. The wells were also used for slug testing to determine the saturated hydraulic conductivity of the soil, as detailed by McEachran et al. (2020). Soil strength parameters were first estimated from a range of published values corresponding to Iowa glacial tills (Lohnes et al., 2001) and refined through a back analysis of a slope failure that occurred at site BC-2. The back analysis was conducted by incrementally adjusting the parameters until an FS of 1 was achieved in the model. The final parameter values used to model the field sites were an average unit weight of 19 kN $m^{-3}$, an effective cohesion of 4 kPa, and a friction angle of 28°.

### 2.2 | Quantifying slope stability

Slope stability depends on three primary elements: soil properties, slope geometry, and seepage conditions. Soil properties

**TABLE 1** Saturated riparian buffer site characteristics

| Site | θ | $h_b$ | $h_0$ | $h_w$ | $L_b$ | USDA soil series |
|---|---|---|---|---|---|---|
| | degrees | m | | | | |
| BC-1 | 25 | 2.10 | 1.80 | 0.42 | 21 | Coland clay loam |
| BC-2 | 69 | 2.60 | 1.79 | 0.22 | 22 | Spillville-Coland complex |
| B-T | 53 | 0.95 | 1.66 | 0.47 | 10 | Colo silty clay loam |
| IA-1 | 47 | 2.30 | 2.03 | 0.23 | 24 | Coland-Terril complex |
| SH | 13 | 2.00 | 1.70 | 0.11 | 21 | Coland-Spillville complex |

*Note*. θ, slope angle; $h_0$, control structure water level; $h_b$, bank height; $h_w$, stream water level; $L_b$, width of the buffer.

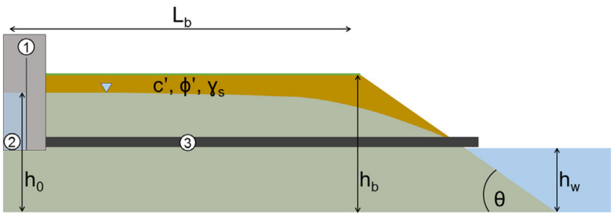


**FIGURE 1** A simplified profile view of a saturated riparian buffer where the bottom of the stream channel is taken as the datum. The control structure (1) is shown at the left edge, the distribution pipe (2) extends into the page, and the overflow outlet pipe (3) connects the control structure to the stream. Groundwater flow is from left to right. The blue triangle indicates saturated soil, and unsaturated soil is shown in brown. The tile drainage main and field are not shown. $γ_s$, unit weight; θ, slope angle; ϕ', friction angle; $c'$, effective cohesion; $h_0$, control structure water level; $h_b$, bank height; $h_w$, stream water level; $L_b$, width of the buffer

include the unit weight $γ_s$ and the shear strength parameters of effective cohesion $c'$ and friction angle φ'. Slope geometry is determined by the bank height $h_b$, and the slope angle θ. Seepage conditions are governed by the water level $h_0$ set in the control structure, the width $L_b$ of the buffer defined as the linear distance from the distribution pipe to the streambank, and the stream water level $h_w$ (Figure 1). The limit equilibrium method is most commonly used to determine the FS by calculating the ratio of resisting to driving forces acting on a two-dimensional failure surface (Abramson et al., 2002). Resisting forces at a given streambank include soil shear strength, confining water pressure exerted by the stream, and any reinforcements such as plant roots or structural elements. Forces driving streambank failure include weight of the soil, weight of the groundwater within the soil, and external loadings applied to the slope. Although bank height is germane to slope stability, the determination of the FS depends on the combination of all elements at a given site and cannot be deduced from a singular characteristic.

Pore water pressures induced near the streambank at an SRB site depend on the groundwater elevation, which is governed by the head difference between the level set by the control structure, the stream water level, and the distance between the distribution pipe and the stream. Positive pore water pressure reduces resisting forces by decreasing frictional resistance, thereby lowering the effective shear strength (Duncan et al., 2014), while negative pore water pressure increases shear strength because of matric suction (Simon et al., 2001). Flow in SRBs follows Darcy's law and primarily travels horizontally toward the stream; therefore, the groundwater level near the slope can be determined using equations for steady one-dimensional flow (McEachran et al., 2020).

Because FS represents a margin of safety against slope failure, additional context is needed to interpret streambank stability at SRB sites. An FS less than 1 indicates instability, predicts imminent failure, and implies a need for remediation (Duncan et al., 2014). For FS above 1, stability determinations depend on the application (USACE, 2003). In situations where slope failures could lead to loss of life and property, a higher FS is required, while low-risk situations may warrant the use of a lower FS. The risk to life and property at a typical SRB site is low; SRBs are located in agricultural fields devoid of structures and away from populated areas. The low risk combined with USDA-NRCS technical guidance for stream stabilization suggests that an FS of 1.3 is adequate at SRB sites (USDA-NRCS, 2007).

## 2.3 | Slope stability modeling

Numerical analyses of groundwater seepage and slope stability were undertaken using Geo-Studio SEEP/W and SLOPE/W software (Geo-Slope International Ltd). In SEEP/W, Darcy's law is applied to flow through the soil medium to calculate pore water pressures in the soil (Krahn, 2004). In SLOPE/W, static equilibrium equations are applied to segments of soil along potential slip surfaces near the slope to compute FS for both force and moment equilibrium (Krahn, 2004). Additionally, probabilistic analyses performed in SLOPE/W can account for uncertainty in input parameters by calculating the probability of slope failure through Monte Carlo simulation. Input requirements for the simulations include soil characteristics, slope geometry, and groundwater and stream boundary conditions. Simplified, two-dimensional representations of SRBs were used in the seepage and stability analyses. Site topography was abstracted to a flat portion of ground representing the SRB and an idealized slope delineating the streambank. Soil properties for the seepage and stability analyses were assumed to be homogeneous in the analysis and trees and plants were ignored, though they could increase the soil strength along the slope.

In the seepage analysis, steady-state SRB flow was simulated by incorporating model elements to represent operating conditions. Pore water pressure depends on the water level in the soil as determined from boundary conditions independent of the saturated hydraulic conductivity; therefore, a constant value of 1 m $d^{-1}$ was used for analysis. The ratio of the vertical and horizontal saturated hydraulic conductivities was taken to be 0.1 (Domenico & Schwartz, 1998). Constant head boundaries were applied to represent the water level at the distribution pipe and water level in the stream. A potential seepage face boundary condition was used along the unsaturated portion of the streambank. Negative pore water pressures induced by matric suction were not considered in the analysis.

Boundary conditions were chosen to obtain conservative FS and slope failure probability values while accurately representing SRB function. Although the groundwater level in the SRB can exceed the level set at the control structure, monitoring data from the field sites indicate that this condition rarely occurs and is not sustained for long periods because the overflow outlet allows the distribution pipe to function as a drain. During low flow periods, the water level in the SRB can be lower than the level set in the control box. The worst case for stability occurs when the groundwater level is high; therefore, the SRB boundary condition was set to reflect the higher groundwater level set by the structure. Additionally, the baseflow stream level was used as the boundary condition because it corresponds to the worst case when the water level is high in the soil and low in the stream. Stream stage and SRB flow depend on precipitation at the site; thus, if the stream went completely dry, little-to-no flow would be expected in the SRB.

Slope stability was evaluated with the Morgenstern–Price general limit equilibrium method to determine the FS against failure and slope failure probability. In this method, a potential sliding mass is divided into discrete slices, and equations of static equilibrium are applied from left to right across the sliding mass (Krahn, 2004). Interslice forces were calculated with the half-sine function in SLOPE/W. Pore water pressures were determined from the results of the seepage analysis, and the Mohr–Coulomb function for effective strength represented the soil strength. In the deterministic analysis, the failure surface corresponding to the lowest FS was identified through an iterative routine where an entry and exit range along the slope was specified, and thousands of potential slip surfaces were generated. A minimum slip surface depth of 10 cm was specified to exclude very shallow failures from the analysis. Slope failure probability was calculated using Monte Carlo simulations along critical slip surfaces identified in the deterministic analysis.

TABLE 2 Range of conditions used in simulations

| Parameter | Range simulated |
|---|---|
| **Soil** | |
| Effective cohesion, $c'$, kPa | 0.5–10 |
| Friction angle, $\phi'$, degrees | 22–38 |
| Unit weight, $\gamma_s$, kN $m^{-3}$ | 10–25 |
| **Geometry** | |
| Bank height, $h_b$,m | 0.9–5 |
| Slope angle, $\theta$, degrees | 10–75 |
| Buffer width, $L_b$,m | 0–24 |
| **Seepage** | |
| Water level at control structure, $h_0$,m | 0.2–5 |
| Water level at stream, $h_w$, m | 0–4 |

## 2.4 | Simulated model conditions

The methods described previously were used to determine FS against failure for the five field sites and a range of additional potential SRB conditions. Because SRBs are relatively new, a diverse range of site conditions was not available for study, thereby limiting the ability to examine their effect on stability. To overcome this limitation, models representing hypothetical SRBs ($N$ = 560) were created by varying soil conditions, slope geometry, buffer width, and water levels (Table 2). The ranges chosen for the hypothetical conditions were informed by knowledge of SRB siting requirements, review of published literature, and physical constraints. Because SRBs treat agricultural tile drainage water, they are located in regions with primarily poorly drained soils composed of clays and silts, limiting the range of soil properties and excluding consideration of sands. A range of soil strength combinations determined by Lohnes et al. (2001) was used in the analysis. Bank height is of particular interest in this study; thus, the range of bank heights was determined by focusing on typical SRB installations that occur along drainage ditches or small streams rather than large rivers. The stream water level was varied by incrementally increasing the level from zero up to the corresponding bank height. The SRB water level was varied by depth, starting from the ground surface down to just above the stream water level to maintain a flow gradient in the direction of the stream.

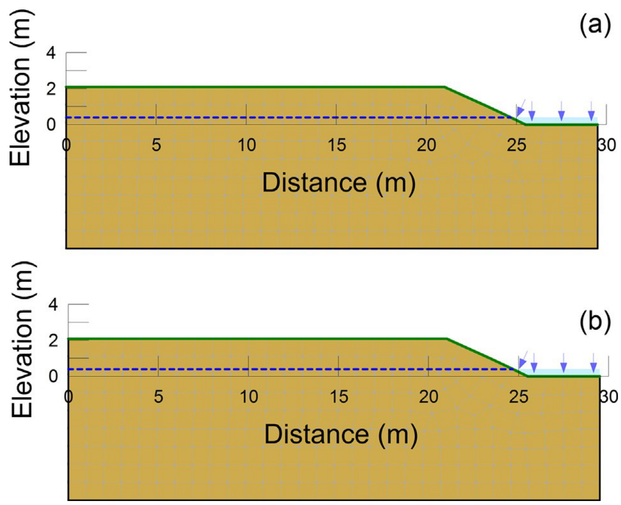


**FIGURE 2** Example of (a) no-flow and (b) saturated riparian buffer flow conditions at site BC-1. The blue line indicates the groundwater level used to calculate pore water pressures in the slope stability analysis

Because seepage conditions near the streambank depend on the hydraulic gradient, buffer width was also varied in the simulations.

In addition to determining FS for an existing or potential SRB site, the effect of SRB installation on the stability of the streambank was evaluated. Because slope stability depends largely on soil conditions and slope geometry, sites may be unstable prior to and regardless of SRB installation, which alters only groundwater flow conditions. To understand the change in FS caused by SRBs, two conditions were simulated: a "no-flow" antecedent of SRB installation in which the constant head boundary at the edge of the buffer was equivalent to the water in the stream and "SRB flow" where the constant head boundary at the edge of the buffer was set at the level in the control structure representing sites after SRB installation (Figure 2a and b). Comparing FS from the two conditions allows the reduction in stability caused by the SRB to be assessed.

Finally, probabilistic analyses were performed to account for uncertainty in soil strength parameter values at the five study sites. Again, values determined by Lohnes et al. (2001, Table 6.1) were used to represent the range of soil strength parameters for Iowa glacial till. The probabilities of failure in the no-flow (no SRB) vs. the SRB flow (after SRB installation) scenarios were calculated under a simulated dry and rainfall condition for each study site. Rainfall was simulated through a conservative representation assuming 100% infiltration along the riparian buffer of a precipitation event with rainfall intensity of 1.27 m $s^{-1}$, corresponding to a 10-yr 24-h precipitation event in the region (Perica et al., 2013).

## 2.5 | Multivariate analysis

Streambank stability was related to site conditions to inform decisions related to the siting and design of future SRBs. To reduce complexity, dimensional analysis of the parameters was undertaken. The dependence of FS on the parameters can be expressed as follows:

$$\mathrm{FS} = f_1\left(c', \phi', \gamma_s, \gamma_w, \theta, L_b, h_b, h_0, h_w\right) \quad (1)$$

where $\gamma_w$ is the unit weight of water. Equations for flow in an unconfined aquifer can be used to estimate the height of the groundwater in the soil at the beginning of the slope $h_g$:

$$h_g = \left[h_0^2 - \left(h_0^2 - h_w^2\right)\frac{L_b}{L_x}\right]^{\frac{1}{2}} \quad (2)$$

where $L_x$ is the linear distance between $h_0$ and $h_w$ determined from the slope geometry:

$$L_x = L_b + \frac{h_b - h_w}{\tan\theta} \quad (3)$$

Substituting $h_g$ and adding $L_x$ gives the following:

$$\mathrm{FS} = f_2\left(c', \phi', \gamma_s, \gamma_w, \theta, L_b, h_b, h_g, L_x\right) \quad (4)$$

which can be further simplified by inspecting the FS equation from a simple limit equilibrium analysis such as the method of ordinary slices (Fellenius, 1936) and grouping terms accordingly. Four dimensionless parameters were identified:

$$\mathrm{FS} = f\left[\frac{\tan\phi'}{\tan\theta}, \frac{c'}{\gamma_s h_b \sin\theta}, \frac{\gamma_w\left(h_g - h_w\right)\tan\phi'}{\left(\gamma_s - \gamma_w\right) h_b \sin\theta}, \frac{L_b}{L_x}\right] = f\left(\pi_1, \pi_2, \pi_3, \pi_4\right) \quad (5)$$

The first term involves the stability of dry cohesionless soil; the second term relates effective cohesion to slope geometry and soil mass; the third accounts for pore water pressure near the slope; and the final term incorporates SRB design.

Statistical analysis was performed to gain insight into the relationship between SRB site conditions and the stability of the streambank. Regression analysis was conducted using the generalized linear model (GLM) procedure with Python Stats Model API (Hastie et al., 2006). The GLM was set to regress through the origin to increase model interpretability and reflect the lack of a physical basis for an intercept term. The relationship between individual parameters and FS was evaluated with Pearson's correlation coefficient $r$, ranging from −1 to +1, where perfect correlation corresponds to −1 or +1.

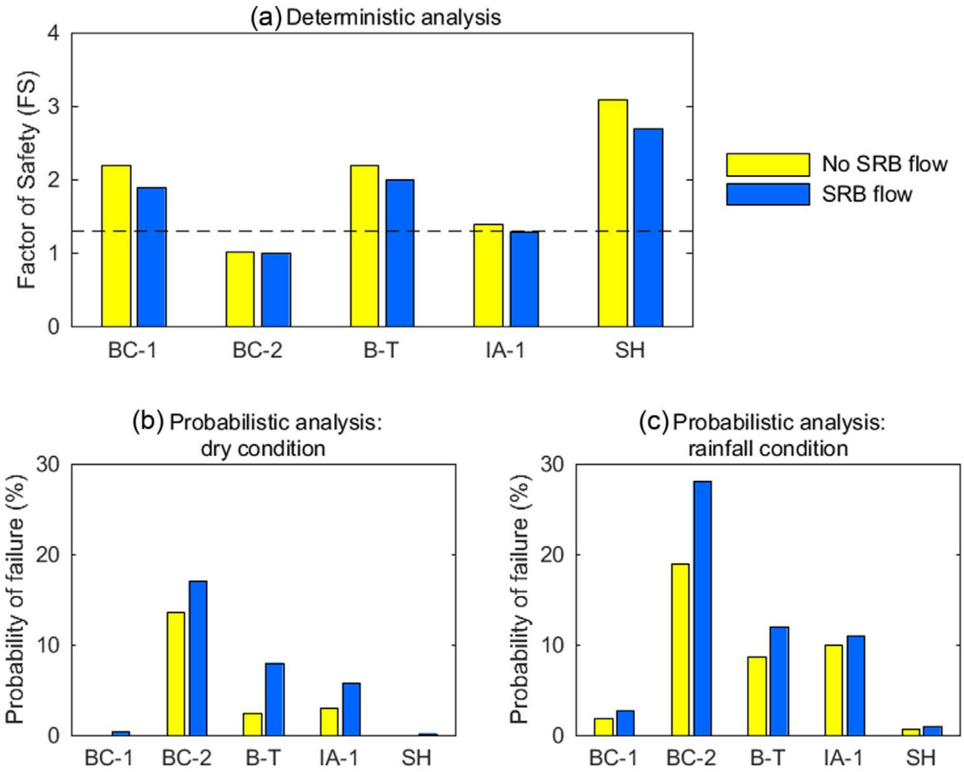


FIGURE 3 (a) Factors of safety (FSs) for study sites with and without flow, where the FS threshold of 1.3 is represented by the black dotted line. Results of the probabilistic analysis for (b) the dry condition and (c) the rainfall condition are shown for each study site with no-flow and saturated riparian buffer (SRB) flow

An equation to predict FS as a function of the dimensionless parameters (Equation 5) was developed with the GLM procedure. A sample ($N = 365$) of data corresponding to simulations resulting in an FS less than 3.5 was used to bias the model toward more critical values, and the study sites were excluded. Train and test splitting and cross-validation were conducted to obtain robust performance measures. Model fit was assessed with the coefficient of determination $R^2$, where a value of 1.0 corresponds to an ideal fit and a significance level (alpha) of .01 was used in statistical analysis.

# 3 | RESULTS

## 3.1 | Effect of SRB flow

At the five study sites, FS decreased with the addition of SRB flow, but the effect was not enough to induce failure at a previously stable site (Figure 3a). Site SH experienced the greatest reduction in FS, though both SRB flow and no-flow conditions are highly stable. Site BC-2 experienced the smallest reduction in FS (−0.002%); however, both conditions were unstable, with FS values indicating imminent failure. Furthermore, the probability of failure at the study sites displays a similar trend: higher probabilities of failure occur at a site for both the no-flow and the SRB flow scenarios (Figure 3b and c). Sites BC-2 and B-T experienced the greatest increase in failure probability with 3.4% (dry), 9.0% (rainfall) and 5.5% (dry), 3.4% (rainfall), respectively. Overall, the average increases in the probability of failure due to the addition of SRB flow were relatively small, with a 2.5% increase under the dry condition and a 2.9% increase under the rainfall condition.

Stability at an SRB site is strongly correlated to the stability of the existing streambank prior to installation (Figure 4). Under most (97%) simulated conditions, SRB flow does not cause a stable streambank to fail. In 3% of cases, a previously stable streambank became unstable when SRB flow was added. Two conditions were associated with cases in which the stability condition changed: soils with effective cohesion less than 2 kPa or sites with buffer widths less than 2 m. Under all simulated conditions, the magnitude of the reduction in FS was most strongly correlated to the groundwater level near the slope estimated by Equation 2 ($r = .62$), where reduction in stability increased with water level.

## 3.2 | Bank height

Sites with streambanks higher than Code 604's limit of 2.4 m can be stable with SRB flow. The only study site with a bank height that exceeded the limit was BC-2, which had a low FS

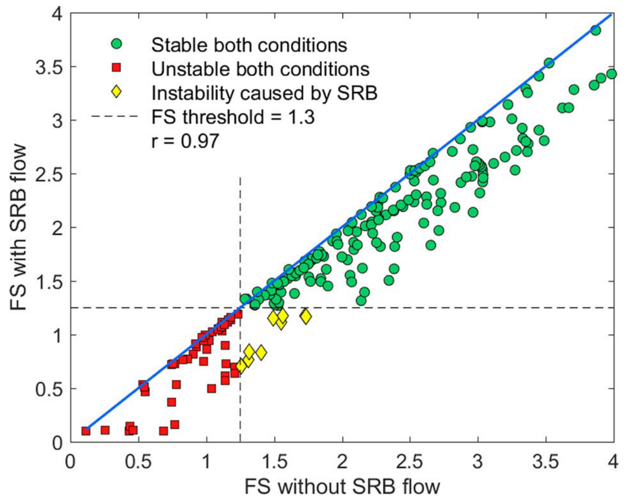


**FIGURE 4** The factor of safety (FS) with and without saturated riparian buffer (SRB) flow for all simulated cases grouped by stability condition. The line of equality is shown in blue

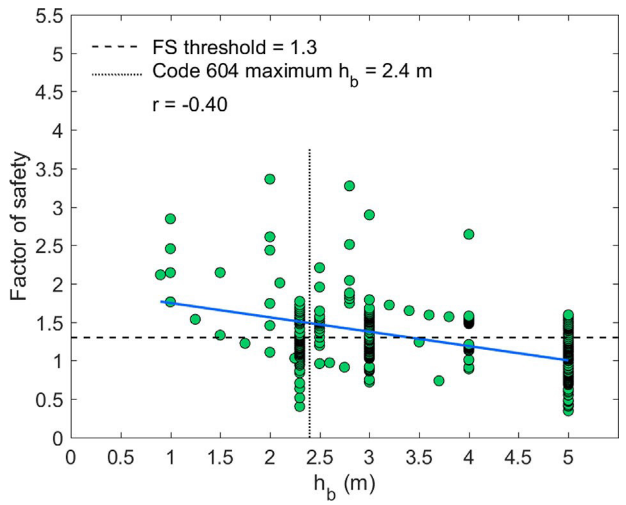


**FIGURE 5** Saturated riparian buffer factor of safety (FS) as a function of bank height ($h_b$). The linear fit is shown in blue

indicating streambank instability. In simulated cases with a streambank higher than 2.4 m ($N = 288$), 39% were stable, while 61% were unstable. The SRB simulations with bank heights below the Code 604 limit also exhibited instability in 47% of cases. An increase in bank height reduced stability if all other factors remained constant (Figure 5). However, bank height did not have a statistically significant effect ($P = .864$) on FS when all parameters given in Equation 4 were included.

## 3.3 | Relating site conditions to FS

Inherent site conditions of slope geometry and soil properties had a stronger influence on the FS than those related solely to SRB flow. The second dimensionless term in Equation 5, which related soil cohesion to the bank height and slope angle, had a much stronger correlation with the FS ($r = .92$ and $P < .0001$) than bank height alone, indicating the overall geometry of the slope was more critical to streambank stability. Additionally, of the dimensionless terms from Equation 5, the first and second terms—which are inherent to a site with or without SRB flow—had the strongest correlation with the FS ($r = .39$ and $r = .92$, respectively). The two remaining terms representing the addition of SRB flow and SRB design choices had much weaker correlations with the FS ($r = .12$ and $r = .05$, respectively).

## 3.4 | FS prediction at SRB sites

The predicted FS calculated from the GLM fit FS observed in the numerical simulations ($N = 365$) well (Figure 6a). The FS can be estimated as follows (Table 3):

$$FS = 0.497\pi_1 + 6.459\pi_2 - 0.454\pi_3 + 0.326\pi_4 \qquad (6)$$

In 98% of cases, the stability determination from the GLM agreed with the result of the numerical simulation; however, in 1% of cases, the GLM overpredicted FS—that is, it predicted a stable condition at an unstable site. Comparison of FS found in simulations of the study sites vs. the GLM prediction shows a weaker fit (Figure 6b), with the GLM results often overpredicting FS at highly stable sites. The mismatch between the fit of the simulated cases vs. the study sites is likely due to the small sample size ($N = 5$) and the choice to bias the analysis toward critical FSs near the stability threshold and exclude highly stable sites. Although the GLM had a less robust fit to the study sites, the stability condition predicted for all sites matched the stability condition determined in the numerical analysis.

## 4 | DISCUSSION

In most simulated cases, the SRB flow did not decrease streambank stability from the no-flow condition enough to induce failure. Results of the probabilistic analysis of the study sites reinforce this finding: on average, the probability of failure increased so minimally (less than 3% for both dry and rainfall conditions) that a stable site is unlikely to become unstable from the addition of SRB flow alone. Of the few simulated cases where SRB flow did induce failure, soil cohesion was very low (less than 2 kPa), or the buffer width was very small (less than 2 m). Neither of these conditions is likely to occur in practice; Code 604 states SRBs should not be sited in highly conductive soils such as sands or gravels that have little soil cohesion, and SRB function relies on maintaining an adequate hydraulic residence time for nitrate removal

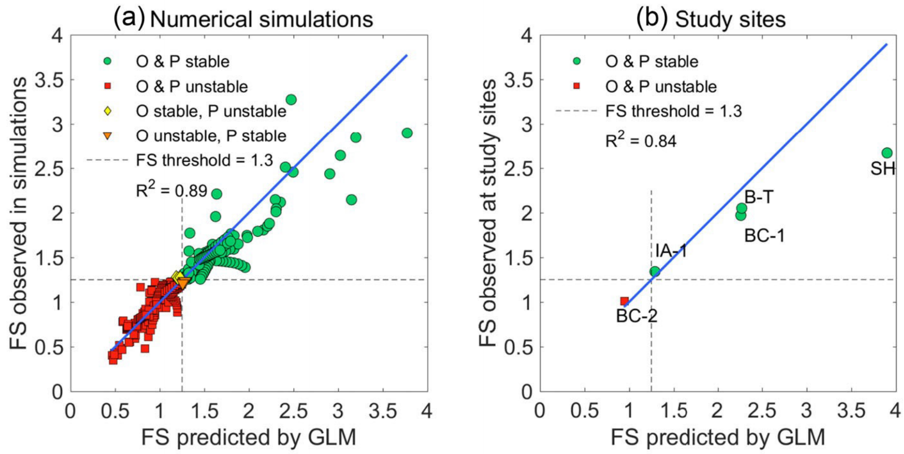


**FIGURE 6** Evaluation of the generalized linear model (GLM) performance corresponding to (a) the numerical simulations and (b) the study sites. Stability conditions correspond to the factor of safety (FS) predicted by the GLM (P) and the FS found in numerical simulations (O). The line of equality is shown in blue

**TABLE 3** Result of generalized linear model giving the estimated factor of safety as a function of the dimensionless terms

| Term | Definition | Coefficient | Standard error | z score | *P* | 95% confidence interval | |
|---|---|---|---|---|---|---|---|
| $\pi_1$ | $\frac{\tan\phi'}{\tan\theta}$ | 0.497 | .040 | 12.5 | <.0001 | 0.420 | 0.574 |
| $\pi$ | $\frac{c'}{\ }$ | 6.459 | .153 | 41.6 | <.0001 | 6.164 | 6.754 |
| $\pi_3$ | $\frac{\gamma_w(h_g-h_w)\tan\phi'}{(\gamma_s-\gamma_w)h_b\sin\theta}$ | 0.454 | .066 | −7.6 | <.0001 | −0.581 | −0.327 |
| $\pi$ | $\frac{L_b}{\ }$ | 0.326 | .017 | 20.6 | <.0001 | 0.293 | 0.359 |

*Note*. φ', friction angle; θ, slope angle; *c*', effective cohesion; $\gamma_s$, unit weight; $h_b$, bank height; $\gamma_w$, weight of water; $h_g$, height of groundwater in soil; $h_w$, stream water level; $L_b$, width of the buffer; $L_x$, linear distance between $h_0$ and $h_w$.

that is largely controlled by buffer width. In a study of the same sites by McEachran et al. (2020), the optimal widths for maximizing nitrate removal were all well above the 2-m width associated with failure induced by SRB flow.

Although bank height does affect the stability at a site, there is not enough evidence to support restricting SRB installation at sites with banks higher than the 2.4 m given in Code 604. Bank height was not a significant determinant of stability for the range of conditions simulated; however, the significance of the second dimensionless term in Equation 5 shows that overall slope geometry is an important factor. The influence of slope geometry, typically expressed as the vertical/horizontal ratio corresponding to slope steepness, on stability is well understood—steeper slopes are less stable. Design standards for simple slope applications often specify a slope inclination based on soil type or fill material without the need for extensive geotechnical stability analysis. Because SRBs increase the complexity by adding groundwater flow, the GLM equation found in this analysis (Equation 6) givesa practical method to estimate slope stability at potential SRB sites. Saturated riparian buffer flow generally does not cause instability; therefore, the GLM estimation method should be reserved for cases where there is significant concern regarding streambank stability, such as a site exhibiting failure prior to installation or in a location where failure poses a heightened risk.

Uncertainty in the FS determined for the study sites arises from uncertainty in the soil properties used in the analysis. Because deep soil boring could not be conducted, the shear strength parameters for the deterministic analysis were calibrated from a back analysis of a failure that occurred during the study period at site BC-2. The back analysis method provides some validation of the parameter choices used in the simulations. However, the probabilistic analysis further accounts for uncertainty in soil properties at the study sites and provides evidence to bolster findings from the deterministic analysis. Soils at the study sites were also assumed to be homogeneous without substantial layering, which may be an adequate approximation because the largest component of the slip surface is in a relatively narrow band of soil near the bottom of the slope. If information about layering is available, it is most conservative to use soil characteristics corresponding to the weakest soil layer. When considering a potential SRB site, practitioners may use local engineering studies to estimate soil strength parameters as done in this analysis. Or, if no such resource is available, parameter values can be estimated for a given soil type using generalized guidance available from the USDA-NRCS or the National Forest Service.

In this study, the effect of SRBs on mechanical slope stability was evaluated; however, the overall stability of the streambank also depends on fluvial processes in the stream. Erosion of bank material by streamflow can create high and steep cut banks, thereby inducing subsequent mechanical failure and creating a destructive feedback loop (Simon et al., 2000; Springer et al., 1985; Turner et al., 2010). A geomorphological assessment of the stream reach can give insight into the overall stability at an SRB site. One such assessment, the Channel Evolution Model (CEM), as described by Simon and Hupp (1986), classifies six stages of channel morphology corresponding to states of channel degradation, widening, aggradation, or equilibrium. The CEM is particularly useful because it allows for the prediction of future changes to stream form, which could inform decisions related to SRB design. For example, if a site is found to be in Stage IV of the CEM (degradation and widening), slope failure is likely to occur regardless of the addition of an SRB. The importance of the CEM stage was observed at site BC-2, where FS indicated failure for conditions with and without SRB flow. Because natural streams are not static, and bank failures can contribute to channel equilibrium, the question arises of whether to exclude degraded channels as potential SRB sites. However, that determination was not made in this study; rather, it may be considered in future work.

Expanding eligible SRB sites will increase implementation and facilitate water quality improvement. In Iowa, where agricultural tile drainage is common, streambank heights range from 0.2 to 5.2 m (Eash, 1993), which indicates many potential SRB sites could be identified if Code 604's stability evaluation requirements based on bank height are lifted. Although the addition of flow from SRB installation was not found to cause failure at a previously stable site, without numerical modeling, it may be difficult for designers to assess the existing stability condition at some potential sites. In cases where stability is uncertain, the GLM equation (Table 3) can be used to relate site conditions and SRB design options to FS. At sites where bank failure has occurred or appears to be likely, a geomorphological assessment such as the CEM can further assist understanding the interaction between streambank stability and channel processes.

We assessed the relationship between streambank stability and SRB design conditions and described a method to determine the stability at a potential site. Although the bank height is involved in calculating FS, the effect on stability was not significant when all other factors were considered. The proposed changes to Code 604 and the method we outline will allow more SRBs to be implemented while reducing the risk of streambank failure. Challenges remain in balancing the water quality improvements of SRBs with the risk of bank failure at sites where in-stream processes cause instability.

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## AUTHOR CONTRIBUTIONS

Loulou C. Dickey: Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Writing-original draft; Writing-review & editing. Andrea R. McEachran: Data curation; Investigation; Writing-original draft; Writing-review & editing. Cassandra J. Rutherford: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing-review & editing. Chris R. Rehmann: Conceptualization; Formal analysis; Funding acquisition; Methodology; Project administration; Supervision; Writing-original draft; Writing-review & editing. Michael A. Perez: Conceptualization; Funding acquisition; Investigation; Project administration; Resources; Supervision; Writing-review & editing. Tyler A. Groh: Investigation; Resources; Writing-review & editing. Thomas M. Isenhart: Conceptualization; Data curation; Project administration; Resources; Supervision; Writing-review & editing.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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