Sectional model of a prairie buffer strip in a laboratory flume for water quality research

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Sectional model of a prairie buffer strip in a laboratory flume for water quality research

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Abstract
Vegetative buffers have shown promising results in reducing runoff volume, sediment, nutrients, and manure-borne contaminants in runoff from agricultural fields. Although these vegetative buffer systems have been extensively tested in field and plot-scale studies that utilize either natural or simulated rainfall, studies of such systems under highly controlled conditions in the laboratory have been limited. Here, we present the development of a new system for laboratory testing of a full-scale, sectional, physical model of a new practice under the Continuous Conservation Reserve Program (CRP) Clean Lakes, Estuaries, and Rivers (CLEAR) Initiative, CP-43 Prairie Strips. This work includes the extraction of prairie strip sections from the field and their integration into an existing laboratory flume facility with specific auxiliary features to facilitate overland flow experimentation. As a proof of concept run, a potassium chloride (KCl) tracer study was conducted to verify system functionality and inform future work. The tracer pulse was injected under saturated conditions and the response was monitored through surface water (upstream and downstream of the prairie strip model) and subsurface water (infiltrated) sampling with continuous flow rate monitoring at the sampling locations. The tracer test provided highly resolved breakthrough curves (BTCs) with 93.5% of the injected tracer mass recovered, and provided useful information on flow partitioning, velocities, and dispersion characteristics along the surface and through the subsurface profile of the model. This model prairie strip system is expected to be useful in optimizing the performance of prairie strips under highly controlled flow and contaminant source conditions.

1 | INTRODUCTION

Vegetative filter strips (VFS) have been integrated with agricultural cropping systems for many years and are a broadly accepted practice for reducing runoff volume (Arora, Mickelson, Helmers, & Baker, 2010; Schulte et al., 2017), sediment (Dabney, Moore, & Locke, 2006, Mickelson, Baker, & Ahmed, 2003, Webber et al., 2010), and nutrients such as nitrogen and phosphorus (Lin, Lerch, Garrett, Jordan, & George, 2007; Yamada, Logsdon, Tomer, & Burkart, 2007; Zhou, Helmers, Asbjornsen, Kolka, & Tomer, 2010) in runoff from agricultural fields. Vegetative filter strips have also shown promise in mitigating the downstream
dissemination of manure-borne contaminants in runoff from manure-amended crop fields (Durso, Miller, & Henry, 2018; Soni et al., 2015). For example, the treatment of feedlot runoff with VFS reduces concentrations of fecal indicator bacteria (FIB) by 80% (Mankin, Barnes, Harner, Kalita, & Boyer, 2006). In addition to the water quality benefits of VFS, a recently adopted Continuous Conservation Reserve Program (CRP) practice called CP-43 Prairie Strips, which was developed by the STRIPS (Science-based Trials of Rowcrops Integrated with Prairie Strips) team at Iowa State University (ISU), has demonstrated that integrating strips of prairie within and at the edge of crop fields can yield benefits for soil, water, and biodiversity at levels disproportionately greater than the area diverted from annual crop production. (Schulte et al., 2017).

Much of the research on the pollutant-trapping capability of buffers has been performed on plot-scale buffer systems, normally incorporating the use of rainfall simulators (Humphry, Daniel, Edwards, & Sharpley, 2002; Miller, 1987; NPRP, 2001). Rainfall simulator systems can vary from small, portable systems, to larger, semi-permanent systems. In any case, simulated rainfall that mimics natural rainfall (natural raindrop size, distribution, impact velocity, and energy) is applied to the test area. After a period of time, runoff is generated and runoff samples are collected downstream of the test area. In most plot-scale studies, runoff is confined by sidewall borders, which may increase the uniformity of flow and the associated effectiveness of the filter strip. Although most studies have been conducted on plot-sized buffers, some studies have investigated unbordered, field-scale buffers. Field-scale studies typically evaluate contaminant reductions by monitoring water input and surface and subsurface outputs through large VFS with automated samplers at strip inlets and outlets. Samples are often generated from natural runoff events over time and evaluated via direct comparison of inlet and outlet concentrations (Shellinger & Clausen, 1992). In other cases, runoff is manually applied for comparison to treatment and control areas through pumped manifolds or irrigation pipe (Durso et al., 2018). Field and plot-scale studies are of great importance to agricultural water quality research, but there are some limitations. For example, it can be difficult to develop realistic runoff in the rainfall simulator derived systems due to the lack of upslope rainfall contribution to the study plot.

A higher level of control may be achieved through a physical modeling approach. Physical hydraulic modeling is a practical approach to developing effective engineering designs and conducting applied research associated with complex flow systems. Physical hydraulic models are commonly used during design stages to optimize a design, ensure safe operation, and facilitate the decision-making process (Chanson, 1999). The models are typically constructed in laboratories where a high level of control can be applied to the hydraulic and hydrologic conditions. Some examples of physical modeling applications in water resources and hydraulic engineering include dams and reservoirs, power generation, water treatment and supply, sewer and stormwater conveyance, sediment transport and river engineering processes, fish passage, and coastal engineering (Briggs, 2013, Muste et al., 2017). The models are used to develop relationships and equations to predict the specific characteristics and behavior of a system. However, the physical modeling approach has been underutilized in agricultural landscape studies.

Laboratory experiments have an important role to play in providing ground-truthing for the development of reliable and user-friendly numerical applications. Numerical simulations in agricultural water resources applications have evolved to the point that they can resolve the mechanics of many practical flows (e.g., Soil and Water Assessment Tool [SWAT], Agricultural Non-Point Source Pollution Model [AGNPS], Hydrological Simulation Program–FORTRAN [HSPF]). However, their ability to include many of the micro-scale pollutant transport processes, such as straining, attachment, entrapment, and adsorption, involved in contaminant mitigation via VFS or prairie strips relies on detailed studies of these processes. For example, Pandey, Soupir, Ikenberry, and Rehmann (2016) developed a sub-model for SWAT to predict *Escherichia coli* levels in streambed sediment and in the water column while utilizing extensive concentration monitoring data used to verify model predictions. Coupling our knowledge of field-scale and plot-scale based experimentation with a complementary physical modeling approach in the laboratory will aid in resolving some of the known complexities and challenges.

Here, we developed a system for testing a full-scale, sectional, physical model of prairie strips in the laboratory. This work involved developing a method for extracting a section of prairie strip from the field, integrating it into an existing laboratory flume facility, and assessing its hydraulic and hydrologic characteristics to inform future experimental work. The system will be useful to optimize the performance of prairie strips under highly controlled flow and contaminant source conditions.

**Core Ideas**

- A physical hydraulic modeling approach is utilized to study water quality in prairie strips.
- The approach allows better control and flexibility than standard rainfall simulation studies.
- A tracer test was conducted in which 93.5% of the injected mass was recovered.
2 MATERIALS AND METHODS

2.1 Prairie strip extraction site description

Prairie strips samples were extracted from ISU’s STRIPS/WOR Research Farm west of Ames, IA (42°00′02″ N, 93°41′38″ W), which is in continuous corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) cropping rotation and consists mainly of Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls) and Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soils. In-field prairie strips of Statewide Mesic 10-30, Iowa Pollinator Mix were established 1 Apr. 2015. Extraction of samples occurred on 25 Oct. 2019.

2.2 Field extraction of prairie strip

Prior to the laboratory testing, it was necessary to develop a reliable method of extracting an intact section of prairie strip from the field, transporting it to the laboratory undisturbed, and offloading and installing the strip section into the flume facility. To achieve these steps, custom equipment was designed and fabricated. The equipment consisted of the following major components: guide frame used to encapsulate the targeted prairie strip section and control the excavated thickness (0.089 m) of the strip; heavy gauge steel cutting box with open front and knife edge that is used to undercut the guide frame and sever the strip sample from the earth (Figure 1a); a perforated stainless steel sheet cut to strip dimensions that serves as a temporary structural base for the extracted strip; the final extraction tray/flume test section insert constructed of stainless steel with a 325-mesh woven stainless steel cloth floor to retain soil while allowing water infiltration during subsequent experiments (Figure 1b); a structural lifting frame that is temporarily fastened to the flume insert trays and aids in lifting and installation of the inserts with an existing jib crane and hoist assembly in the laboratory (Figure 1c).

The following method, which refers to the equipment described above, and the process depicted in Figure 2, was adopted for extracting sections of prairie strips from the field: A target prairie strip area was identified (Figure 2a). The guide frame was pressed into the soil with the aid of an excavator bucket until the top of the guide frame was flush with the adjacent soil surface. The immediate area surrounding the guide frame was then scraped away with the excavator to expose the guide frame (Figure 2b). The cutter box was driven into the sample prairie strip with a sledge hammer, effectively severing the targeted strip from the earth below (Figure 2c). The prairie strip sample was moved onto the perforated stainless steel plate, eye hooks were attached to threaded inserts welded into the floor of the plate, and the sample was lifted by ropes with the aid of the excavator bucket (Figure 2d and Figure 2e); The excavated sample was placed into the final extraction tray/flume insert tray and transported to the laboratory (Figure 2f).

2.3 Flume facility

Experiments were conducted in a state of the art experimental flume facility in the Agricultural and Biosystems Engineering (ABE) Hydrology laboratory at ISU. A schematic of the ABE flume is shown in Figure 3. A detailed description of the ABE flume design, construction, and operations is available in Craig, Wilson, Niemeier, and McCarville (2016). The flume channel is 0.61 m high by 1.2 m wide by 11.5 m long with an open channel and uniform cross-section. The flume has an adjustable tailgate weir to control flow depth, and its slope can be adjusted from 0 to 5%. The flume is equipped with a Hydroflo two-stage mixed flow vertical turbine pump and a 60 horsepower motor that draws water from a 37.5 cubic meter below-grade sump with a peak flow of about 0.25 m$^3$ s$^{-1}$ through a 0.3-m PVC inflow line to the flume’s head tank. The flume flow rate is measured with an electromagnetic flow meter (magflow meter, Badger M2000) and additional manual flow rate control is provided by a variable frequency drive and
electronically actuated butterfly valves. The magflow meter also provides electronic feedback between the variable frequency drive and a custom proportional controller in LabVIEW that allows flow rates to be specified and maintained in the case where water is drawn from the supply sump and discharged into the secondary sump. The proportional controller provides a way for the pump to compensate for the falling head in the supply sump and maintain the desired input flow rate during experiments. A critical component of this flume system is the recessed test section, 1.16 m long by 0.99 m wide by 0.15 m deep, where rectangular samples of prairie buffer strips extracted from the field can be installed, tested, and interchanged.

2.4 Auxiliary components

Additional components including a mixing tank, injection flow meter, and manifolds for injection and sampling were assembled and added to the flume facility to accommodate specific experimental needs for overland flow experiments (Figures 4 and 5). Contaminants were combined with storm reuse water in a 530-L roto-molded horizontal leg tank (Ace Roto-Mold, Figure 5a). The diluted contaminant mixture was vigorously mixed to achieve uniform consistency with a custom-made propeller mixer consisting of a 250-W/1,725 rpm electric motor (Baldor-Reliance, Figure 5a), 1.9 cm stainless steel shaft and 10.2-cm diameter,
10.2-cm pitch stainless steel mixing propeller. Diluted contaminants were injected into the flume channel with a 0–45 L min\(^{-1}\) centrifugal pump (Little Giant Pump Co., Figure 5a). Injected flows are monitored with a 1.9-cm, 9–416 L min\(^{-1}\) electromagnetic flow meter (Banjo model MFM 100, Figure 5b). A custom-built injection manifold consisting of a 1.22-m segment of 2.54-cm diameter PVC pipe with 30, 0.24-cm diameter, equally spaced holes, is mounted in the flume channel upstream of the test section to uniformly distribute/inject contaminant across the width of the flume (Figure 5c). Surface water sampling is facilitated by continuous low flow rate pumping from manifolds assembled with 0.64-cm diameter clear PVC flexible tubing, tees, and elbows (Figure 5d). Each of the sampling manifolds have five ports equally spaced across the width of the flume and are fixed to the flume bed with epoxy directly upstream and downstream of the test section, slightly recessed from the approach bed by 0.64 cm. Water that infiltrates through the prairie strip test section flows through two 1.9-cm outlets in the test section floor and into a tubing and PVC pipe assembly that facilitates intermittent sampling and manual flow rate monitoring. The runoff flow rate was calculated by subtracting the infiltration flow rate from the run-on flow rate.

2.5 Prairie strip installation into flume

The installation of prairie strip extractions into the ABE flume is sequentially outlined below with reference to the equipment described previously and the process depicted in Figure 6: Following sample offloading in the laboratory, the lifting beam is attached to built-in threaded posts on the insert tray (Figure 6a); the sample insert is lifted with a jib crane and hoist system and positioned above the ABE flume test section (Figure 6b); the sample insert is lowered into the flume test section (Figure 6c); the process is repeated for the second insert (Figure 6d); the inserts are sealed in place with silicone sealant and guide walls with a flared entrance are installed to prevent short-circuiting of flow around the prairie strip test section (Figure 6e, 6f).

2.6 Conservative tracer experiment

As a proof of concept for the functionality of the flume and prairie strip model system and to inform future water quality experimentation and sampling design, a test was conducted using the conservative tracer potassium chloride (KCl). The tracer test data were utilized to evaluate the partitioning of flow between run-on, infiltration, and runoff, and to examine dispersion characteristics and the ability of the sampling system to recover the injected mass of tracer through breakthrough curve (BTC) analysis. This experiment was conducted under saturated conditions by initially running clean water (storm reuse water) without KCl tracer at a constant run-on rate of 0.35 L s\(^{-1}\) until constant infiltration and runoff rates of 0.14 and 0.21 L s\(^{-1}\) were established, respectively. The chosen run-on rate into the model prairie strip approximately
**FIGURE 4** Schematic of experimental setup for overland flow experiments

**FIGURE 5** Selected components of the experimental setup in ABE flume: (a) mixing tank; (b) injection flow meter; (c) injection manifold; (d) downstream view
FIGURE 6 Installation of extracted prairie strip sample in ABE flume: (a) attaching the lifting beam; (b) lifting the insert with jib crane and hoist; (c) placing the insert in the flume test section; (d) installing second insert; (e and f) inserts sealed in test section with silicone and flared entrance guide walls installed.
represents runoff at the field extraction site from a 1-yr, 2-h storm based on the rational method (Kuichling, 1889). At the onset of the experiment (time \( t = 0 \)), the injection source was switched to the tracer solution by operating valves upstream of the injection pump connected to separate vessels containing clean water and tracer solution. The tracer solution was injected for 30 s and then switched back to clean water to follow the tracer pulse. The tracer solution consisted of 1.0 kg of KCl in 54.5 L of water resulting in a solution concentration of 18.35 g L\(^{-1}\) and a total injected KCl mass of approximately 192.7 g.

Surface water samples upstream and downstream of the test section were collected in 125-mL plastic sample bottles at 10-to-20-s intervals and later analyzed for KCl conductivity and concentration using an electrical conductivity probe (Omega CDS106) and standard calibration curve. Infiltration water was sampled with the conductivity probe in real-time at 20-s intervals by placing the probe directly into the infiltration discharge drain pipe. The experiment was continued until the conductivity of the infiltration water returned to baseline levels. The conductivity meter was then used to measure the conductivity of the upstream and downstream samples by placing directly into the sample bottles after sufficiently shaking the samples. Sample conductivities were converted to KCl concentrations by establishing a standard calibration curve and multiplying sample conductivities by the observed proportionality constant of 0.569 mg cm\(^{-1}\) µS\(^{-1}\) L\(^{-1}\).

### 3 ANALYSIS

Concentration vs. time data for the upstream, downstream and infiltration samples were analyzed based on the properties of concentration distributions and moment analysis techniques as described by Fischer, List, Koh, Imberger, and Brooks (1979). The mass load is calculated by multiplying the time series of concentration \( C \) by the respective volumetric flow rate \( Q \) at each location, and the \( n \)th moment of the mass load is computed with

\[
M_n = \int_0^\infty t^n Q C(x, t) dt \tag{1}
\]

where \( x \) is longitudinal position along the model prairie strip. In this case, the run-on flow partitions into two separate outlets, the downstream surface (runoff) and the subsurface (infiltration samples), and a mass balance using the 0th moment gives

\[
M_{0,\text{Total}} = M_{0,\text{us}} = M_{0,i} + M_{0,\text{ds}} \tag{2}
\]

where subscripts us, i, and ds represent the upstream (run-on), infiltration, and downstream (runoff) locations, respectively.

The times of the centroid of the component BTCs are calculated with

\[
\mu = \frac{M_1}{M_0} \tag{3}
\]

The mean velocities along the model prairie strip surface and through the subsurface are calculated by dividing the distance between respective sampling locations by the times of centroid.

\[
V = \frac{\Delta x}{\mu_2 - \mu_1} \tag{4}
\]

with subscripts 1 and 2 representing relative upstream and downstream (or surface and subsurface) locations, and where \( \Delta x = 1.35 \) m along the surface from upstream to downstream sampling locations, and \( \Delta x = 0.089 \) m, the thickness of the soil layer, for the infiltration velocity calculation. The variance of each distribution (BTC) is found from the moments by the equation

\[
\sigma^2 = \frac{M_2}{M_0} - \mu^2 \tag{5}
\]

Estimates of the dispersion coefficients (\( D \)) along the surface and through the subsurface were obtained by applying the frozen cloud approximation described in Rutherford (1994) and the following equation adapted from Fischer et al. (1979).

\[
D = \frac{1}{2} V^2 \frac{\sigma_2^2 - \sigma_1^2}{(\mu_2 - \mu_1)} \tag{6}
\]

Dimensionless Péclet numbers associated with the surface and subsurface dispersion coefficients were calculated as the ratio of the rate of advective transport to the rate of dispersion as follows

\[
P_e = \frac{V L}{D} \tag{7}
\]

where \( L \) is the length of the test section along the surface or the thickness of the subsurface soil layer. The saturated hydraulic conductivity of the model prairie strip system was estimated by treating the test section as a vertical, rectangular column and applying Darcy’s law.

\[
Q_i = K_s A \frac{\Delta H}{L_s} \tag{8}
\]

where \( Q_i \) is the observed infiltration flow rate, \( K_s \) is the saturated hydraulic conductivity, \( A \) is the footprint area of the test section (length times width), \( \Delta H \) is the hydraulic head imposed on the test section, and \( L_s \) is the thickness of the soil layer within the test section.
RESULTS AND DISCUSSION

4.1 Conservative tracer experiment

The facility, experimental design, and sampling scheme provided sufficient data for well-resolved mass load BTCs (Figure 7). Integrations of the mass load curves yielded recovered mass estimates at each sampling location with respect to the injected mass of 192.4 g (99.8%), 110.4 g (57.3%), and 69.7 g (36.2%) for the upstream, downstream, and infiltration samples, respectively. The total mass recovered from the infiltration and downstream samples with respect to the mass of the injected pulse was 180.1 g (93.5%), exhibiting the high degree of confidence and accuracy in the experimental design in this proof of concept run. For comparison, McGuire, Weiler, and McDonnell (2007) recovered 53% of injected bromide (Br\textsuperscript{−}) mass in a tracer test conducted in the field. Mean surface and infiltration velocities were calculated based on the distance traveled between sampling locations and the computed time of centroid from each of the BTCs. The mean surface velocity was found to be 0.02 m s\textsuperscript{−1} with an associated dispersion coefficient of 0.014 m\textsuperscript{2} s\textsuperscript{−1}. The mean infiltration pore velocity was found to be 3.4 × 10\textsuperscript{−4} m s\textsuperscript{−1} with an associated dispersion coefficient of 8.94 × 10\textsuperscript{−6} m\textsuperscript{2} s\textsuperscript{−1}. Information obtained from the BTCs such as velocity, times of centroid, times of arrival and trailing edge, dispersion coefficients and Péclet numbers are all informative pieces of information that can aid in designing sampling protocols for future work. For example, Péclet numbers were found to be 1.89 along the surface of the prairie strip and 3.38 through the subsurface profile. These Péclet numbers contrast with values in the range 32–1,419 computed from a dataset from rivers (Rehmann, 2015). They indicate that advection is slightly more important than dispersion in a prairie strip and that dispersion is worth consideration in subsequent model development.

4.2 Merits of the laboratory flume system

In this system, we are able to directly measure the saturated hydraulic conductivity, \(K_s\), during an experiment through knowledge of the infiltration flow rate, free surface depth (which can be directly measured with a point gage), and soil profile thickness. In the conservative tracer test we obtained a \(K_s\) estimate of 1.13 × 10\textsuperscript{−4} m s\textsuperscript{−1}. This value is about one order of magnitude higher than that of the Clarion loam soil at the extraction site (USDA Web Soil Survey). This result is not unexpected, however. It is broadly accepted that VFS provide increased infiltration (Gilley, 2005;). In addition, the exponential decline in \(K_s\) with depth is a well-known characteristic of hillslope and catchment hydrology (Ameli, McDonnell, & Bishop, 2016; Jiang, Wan, Wang, Ge, & Liu, 2009). Magnitudes of \(K_s\) magnitudes in the field likely reflect values of deeper, more consolidated soil profiles that govern saturated water flow. In addition, several studies have shown differences in \(K_s\) among cropping and perennial treatments.
Soil under dense perennial vegetation, such as prairie strips, can have hydraulic conductivities nearly 10 times higher than in crop fields (Fuentes, Flury, & Bezdicek, 2004), similar to that observed in our case.

The flume and sectional model system was designed and built with a high level of control, access, convenience, and observation in mind. Inspection of the flow appearance, patterns and behavior prior to experimental runs is a valuable aspect of this physical modeling approach. Experiments can be conducted under nearly identical initial conditions with saturated soil and a constant infiltration rate established prior to the injection of contaminants. Most of the field and plot-scale experiments are limited by many changing variables, such as antecedent moisture and spatial and temporal variations in precipitation and runoff, which can confound interpretation of results (Kibet et al., 2014). From our own experiences with plot-scale rainfall simulator experiments, we have seen that it can often be difficult to generate measurable runoff due to limitations in the rainfall simulator flow rates, the type and condition of the soil in the field plots, and the lack of upland runoff contribution. In the flume and sectional model system, we can generate nearly any flow condition of interest and can focus on realistic conditions ranging from very low flows to high, flushing flow events.

In our approach, contaminants are vigorously mixed with rainwater in an auxiliary tank to ensure uniform mixing, and applied uniformly across the test section of the flume to ensure that the contaminant front entering the model prairie strip is evenly distributed spatially and consistently over time. We are able to make direct comparisons among run-on, infiltration, and runoff concentrations and mass loads. The ability to directly sample infiltrated water in this system is advantageous compared with field and plot-scale experimental setups where typically sampling is limited to runoff downstream of the test area.

The sectional model is full-scale, and therefore there are no model-to-prototype similitude criteria or scaling of flow rates, velocities, and other parameters to address, as there would be for a reduced-scale model. As examples, a model of a lake or bay may require a distorted vertical scale to avoid exaggeration of the surface tension behavior of water; or a reduced-scale model involving sediment transport would require the use of a model particle of density differing from that of the prototype particle (Muste et al., 2017). A high level of confidence in the component depths, velocities, flow rates, and other parameters is critical in understanding the hydraulic and hydrologic dynamics in an experiment.

The system we have developed allows us to design experiments with a large degree of flexibility and adaptability. Plans for future research include testing model prairie strips for their performance in mitigating the downstream dissemination of fecal indicator bacteria, antibiotic resistant bacteria, and antibiotics through injections of diluted swine manure slurry into the flume system. Experimental designs are highly adaptable in the laboratory setting and we expect this system to be a valuable asset in advancing the science and informing design and implementation of CP-43 Prairie Strips in the field.

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AUTHOR CONTRIBUTIONS
Andrew Craig: Corresponding Author; Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. Michelle Soupir: Conceptualization; Data curation; Funding acquisition; Project administration; Supervision; Writing-original draft; Writing-review & editing. Chris Rehmann: Formal analysis; Methodology; Writing-original draft; Writing-review & editing

CONFLICTS OF INTEREST
There are no conflicts of interest.

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