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Bridge Deck Drainage: Evaluation of KDOT's Current Design Guidance

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16 Abstract

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

DISCLAIMER

Abstract

Proper drainage of bridge decks is essential for vehicle safety and bridge sustainability. The evaluation of Kansas Department of Transportation (KDOT) design guidelines could reduce the likelihood of future deck drainage problems. Therefore, this research investigated current bridge deck drainage design guidelines and related literature and surveyed 22 Departments of Transportation (DOTs) to identify deck drainage issues, solutions, designs, and guidance. This study utilized a scaled physical model and varying downspout shapes and sizes to investigate the hydraulic performance of current KDOT deck drainage design and evaluate grate efficiency and lateral spread. Experimental variables included deck cross slope, longitudinal slope, and approach discharge. This study also compared a curved vane grate to the current KDOT bar grate to determine differences in drainage efficiency. An erosion rate test was performed between the two grate types to determine if changing from a rectangular vane to a curved vane could increase cleanout potential, thereby alleviating problems related to inlet clogging. Experimental results indicated increasing the downspout size from 8 inches to 10 inches or changing the downspout shape from circular to square could increase drainage efficiency with no negative impacts to performance. The curved vane grate showed similar hydraulic performance (i.e., efficiency) to the KDOT rectangular vane grate, and erosion results indicated that the curved vane grate performed similarly to the rectangular grate for cleanout of accumulated debris within the grate. Although experimental results indicated similar performance of rectangular and curved vane grates, DOT survey results showed superior in-field performance of curved-vane grates.

Acknowledgments

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Chapter 1: Introduction

Efficient removal of precipitation from bridge decks is essential for highway safety and bridge sustainability. Poor bridge deck drainage can result in the excessive spread of water on the deck, which can transfer into the roadway and increase the chances of vehicle hydroplaning. Additionally, for areas in which chemical deicers are used in the winter, insufficient drainage prevents complete removal of corrosive chemicals, which then causes the deterioration of bridge decks. Currently, the state of Kansas must address clogging issues that limit hydraulic performance metrics such as efficiency because routine maintenance is costly and difficult to implement. Therefore, this study investigated inlet construction (i.e., downspout cross section), grate type, and design procedures to update Kansas Department of Transportation (KDOT) design practices for deck drainage to improve hydraulic performance and lower associated initial and long-term maintenance costs.

1.1 Problem Statement

Bridge deck drainage designs and procedures related to inlet type, downspout size, grate type, and design curves must be identified to optimize hydraulic efficiency, even with performance-limiting scenarios such as clogging.

1.2 Objectives

One of the primary objectives of this study was to compare current KDOT bridge deck drainage design procedures with design guidelines from other state and federal organizations to determine the effect of downspout cross section shape and size on inlet efficiency. This study also sought to determine if the use of a curved vane grate improves debris clean-out capabilities compared to the current rectangular grate design used by KDOT.

1.3 Methodology

A literature review was conducted to assess common design procedures used for bridge deck drainage and to identify the type of inlet and grate designs used in the field. A deck drainage survey was sent to 50 Departments of Transportation (DOTs) to compare design procedures, type of inlet and grate designs, and safety factors to account for clogging; as well as to obtain feedback about potential solutions to common maintenance problems. The KDOT team recommended which inlet downspout sizes and shapes to examine.

Deck drainage performance is governed by longitudinal slope, cross slope, approach discharge, and inlet size. To determine the difference in hydraulic performance metrics between inlet designs, a scaled model was developed to conduct comparative experiments and accurately quantify performance. A $1/9^{th}$ physical scale model was constructed in the University of Kansas Water Resources laboratory to represent a single lane and shoulder on a bridge deck. Many experiments (more than 500) were conducted to cover real-world roadway geometries and expected flow conditions. The model also quantified the possible change to material de-clogging between grate types using a particle-scaled cohesive mix.

Chapter 2: Literature Review

Previous studies have examined the performance (i.e., efficiency) of roadway inlets, including curved inlets, grate drains, slotted drains, and scuppers (Johnson & Chang, 1984; Holley et al., 1992; Young et al., 1993; Hammonds & Holley, 1995; McEnroe et al., 1999; Brown et al., 2009; Qian et al., 2012, 2016; Muhammad, 2018; Schalla et al., 2017). Bridge deck drainage design is a modification of standard roadway design that utilizes grate, slotted, or scupper drains depending upon state specific guidelines. The primary manuals referenced in design are *Hydraulic Engineering Circular-12* (HEC-12; Johnson & Chang, 1984), *Hydraulic Engineering Circular-21* (HEC-21; Young et al., 1993), and *Hydraulic Engineering Circular-22* (HEC-22; Brown et al., 2009). HEC-21 is solely related to bridge deck drainage with specific design procedures, charts, and examples, while HEC-12, which is condensed into chapter 4 of HEC-22, is a generalized roadway drainage manual not specific to bridge deck drainage.

2.1 Gutter Flow

A uniform cross slope is typically used for bridge deck drainage due to structural considerations in deck construction (Young et al., 1993). The current study used a uniform cross slope to examine related equations to determine the effect of deck drain design on efficiency. The governing equation for bridges is the Manning's equation for flow because it is subject to gravity-driven sheet flow. However, a modified equation is required for a uniform cross slope on a roadway gutter because the spread of water from the curb is approximately equal to the wetted perimeter and can be over 40 times the depth of water. The modified Manning's equation, or Izzard equation, is represented as follows:

$$\boldsymbol{Q = (\frac{k_g}{n}) S_x^{1.67} S^{0.5} T^{2.67}} \qquad \textbf{Equation 2.1}$$

Where:

Q = the flow rate (ft^3/s),

k_g = a constant of 0.56,

n = the Manning's coefficient,

T = the width of flow (ft),

S_x = the cross slope (ft/ft), and

S = the longitudinal slope (ft/ft).

For uniform cross slope, the spread depth of flow is given by the flowing equation:

$$\boldsymbol{d = TS_x} \qquad \textbf{Equation 2.2}$$

Where:

d = the depth of flow in feet.

Flow depth is important to bridge drainage design as it impacts vehicle safety since hydroplaning is a function of water depth on a roadway as well as tire and pavement characteristics (Qian et al., 2012). All components of deck drainage design are dependent on Equation 2.1 and 2.2. The following section highlights common equations applied to bridge decks from HEC-21, where the *Q*, or gutter flow, refers to Equation 2.1.

2.2 Deck Drainage Equations

The main component of the design and the impetus of this study was the hydraulic efficiency of a deck drain. Efficiency (*E*) of an inlet is the percentage of total flow intercepted for a given gutter flow, which was defined by Johnson & Chang (1984) as:

$$\boldsymbol{E = \frac{Q_i}{Q}} \qquad \textbf{Equation 2.3}$$

Where:

Q = the total gutter flow, and

Q_i = the intercepted flow.

For grated inlets, the efficiency is a function of the fraction of frontal flow and the fraction of side flow, represented as:

$$\boldsymbol{E = R_f E_o + R_s(1 - E_o)} \qquad \textbf{Equation 2.4}$$

Where:

R_f = the fraction of frontal flow entering the inlet,

R_s = the fraction of side flow, and

E_o = the ratio of frontal flow to total gutter flow.

Each of these variables are defined by the following equations:

$$\boldsymbol{E_o = 1 - (1 - \frac{W}{T})^{8/3}} \qquad \textbf{Equation 2.5}$$

$$\boldsymbol{R_f = 1 - 0.09(v - v_o)} \qquad \textbf{Equation 2.6}$$

$$R_s = 1/(1 + \frac{0.15v^{1.8}}{S_x W^{2.3}})$$ **Equation 2.7**

Where:

v = the gutter flow velocity (ft/s) determined for the modified Manning's equation (Equation 2.1),

v_o = the gutter velocity where splash over first occurs (ft/s), and

W = the width of the drain (ft).

Width divided by spread is commonly referred to as the width-to-spread ratio (WT) which is expressed as such throughout this study.

Splash-over velocity depends on grate type, grate width, and gutter velocity, with corresponding design plots in HEC-12 (chart 7) or chart 10 in HEC-21. Side-flow efficiency can be deduced for chart 8 of HEC-12 as a function of cross slope, grate width, and approach velocity. These plots are included in the 2016 edition of the KDOT Design Manual. However, design procedures typically neglect side flow and design as if no decrease occurs in frontal-flow capture due to splash over, where E is equivalent to E_o. Each reference manual contains the standard design curve (Equation 2.4), shown in Figure 2.1. Because this curve is the standard for design, this study focused on the efficiency curve. Using the standard efficiency curve (Equation 2.4), Brown et al. (2009) provided theoretical plots for various grated inlets based on the longitudinal slope and cross slope (Figure 2.2).

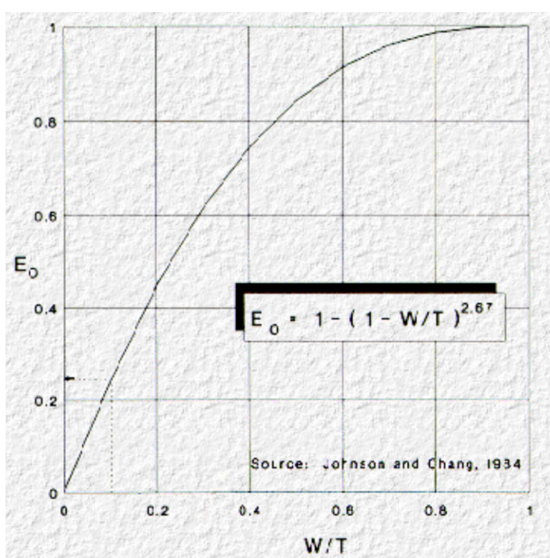


Figure 2.1: Inlet Efficiency Curve
Source: Young et al. (1993)

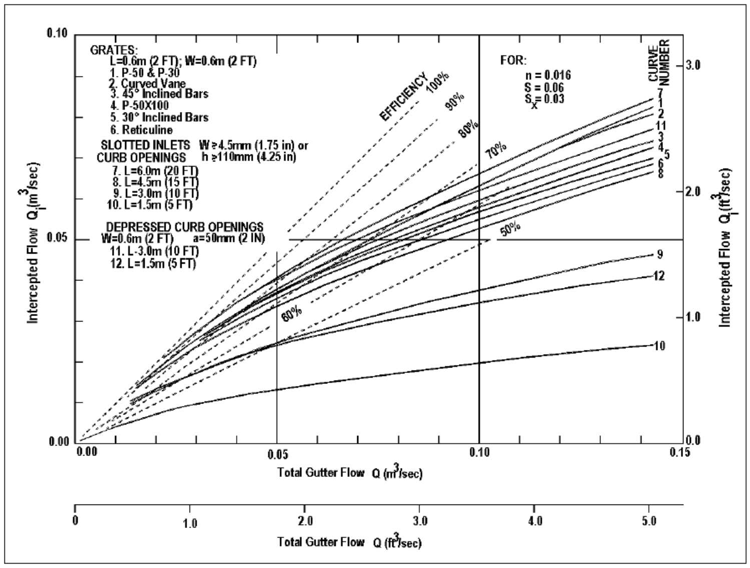


Figure 2.2: Intercepted Discharge and Gutter Flow for Grate Types from HEC-22
Source: Brown et al. (2009)

The other primary equations used in bridge deck drainage design pertain to inlet spacing. Equations and the design process are functions of gutter flow determined by the Rational method and represented by the modified Manning's equation (Equation 2.1) which have been used to derive the following spacing equations for constant grade bridges (exact derivation is in Appendix B of HEC-21):

$$L_o = \frac{43560 \times Q}{C \times i \times W}$$ **Equation 2.8 (first inlet)**

$$L_c = \frac{43560 \times Q}{C \times i \times W} \times E$$ **Equation 2.9 (between inlets)**

Where:

i = the design rainfall intensity (inches/hr),

L_c = the constant distance between inlets (ft),

L_o = the distance to the first inlet (ft), and

C = the Rational runoff coefficient typically ranging from 0.7 to 0.9 according to HEC-21.

Complex scenarios such as vertical curve bridges with design aids are presented in Appendix A of HEC-21, and design equations for flat bridges are included in Section 9.2 of HEC-21. Illustrative examples are described in Chapter 10 of HEC-21.

Similar to an orifice, vertical downspouts can control hydraulic efficiency. However, drainage capacity when an inlet is flowing full is limited by the following orifice equation:

$$q_x = 0.6A_x\sqrt{2gx}$$ **Equation 2.10**

Where:

q_x = the capacity (cfs),

0.6 = the orifice coefficient,

A_x = the area of pipe exiting the box (ft^2),

g = the acceleration due to gravity (ft/s^2), and

x = the depth of the drain box plus the water depth in the gutter (ft).

Examination of standard design procedures in HEC-12, HEC-21, and HEC-22 indicated that hydraulic efficiency directly impacts bridge deck drainage design because inlet spacing is a direct function of efficiency as shown in Equation 2.9. Furthermore, examination of Equation 2.1 showed that discharge is a function of spread of water on the roadway, which must be controlled to improve highway safety. Our study is centered around two design variables of grate type and downspout as standard design procedures indicate these features directly control hydraulic efficiency.

2.3 Debris Removal

A common issue plaguing deck drainage in Kansas is the buildup of debris in inlets. A review of literature revealed that no studies have specifically examined the impact of grate type on sediment transport. The impact of debris on inlets must be investigated since increases in deposited debris decrease the amount of capture area, thereby lowering efficiency and increasing the spread of water, which can negatively impact highway safety. The movement of sediment during open channel flow depends on the amount of shear stress exerted on the bed due to approach discharge and particle characteristics (i.e., size, shape) which control the amount of shear force that can be resisted. If the bed shear exceeds the critical shear stress, then particle motion occurs, causing an erosion of sediment material. For scour-related sediment movement, the initial movement of sediment is represented as a dimensionless parameter called the Shields particle number, represented in Chang (1988) as:

$$\boldsymbol{\tau_* = \frac{\tau_o}{(\gamma_s - \gamma)d}}$$ **Equation 2.11**

$$\boldsymbol{\tau_o = \gamma R S}$$ **Equation 2.12**

Where:

τ_* = the dimensionless critical shear stress,

τ_o = the bed shear stress (psf),

d = the median particle diameter (ft),

γ = the specific weight of water (pcf),

γ_s = the specific weight of the sediment,

R = the hydraulic radius (ft), and

S = the longitudinal slope.

When applied to clogged inlets, the Shields particle number suggests a relationship between bridge deck configuration, flow depth, and sediment type.

An experimental approach to sediment transport was revealed when this study examined the literature pertaining to sediment entrainment rates. Van Rijn (1984) analyzed sediment at the bed surface in a flume over a section of mobile particles using sand to estimate the sediment pick-up rate for a flow depth of 1.6 ft with velocity ranging from 1.6 to 3.3 ft/s. He determined the pick-up rate for the sediment as:

$$\varepsilon = \frac{\boldsymbol{M}}{\boldsymbol{A\Delta t}}$$ **Equation 2.13**

Where:

ε = the pick-up rate in mass per unit area and time (lb/s-ft^2),

M = the total sediment mass lost (lb),

A = the area of movable surface (ft^2), and

Δt = the measurement period (s).

This experimental data was used to examine the movement of non-cohesive bed-load particles in terms of dimensionless parameters of pick-up rate (Φ_p). For cohesive sediment, Walder (2015) found a relationship between Φ_p and critical stress for a cohesive dimensionless parameter $\widetilde{\Phi}$ and a dimensionless transport parameter (R), defined as:

$$\boldsymbol{\widetilde{\Phi} = \frac{E}{\rho_s(\tau_c/\rho)^{0.5}}}$$ **Equation 2.14**

$$R = \frac{u_*^2 - u_{cr}^2}{u_{cr}^2}$$ **Equation 2.15**

Where:

ρ_s = the density of the sediment (lb/ft^3),

ρ = the density of water (lb/ft^3),

τ_c = the critical shear stress (psf),

u_* = the shear velocity (ft/s) determined as $u_* = \sqrt{gRS}$, and

u_{cr} = the critical shear velocity (ft/s).

From the experimental data, Walder (2015) generated an empirical equation for the two parameters for various types of sediment mixes throughout the United States. Concepts from the reviewed literature were used to examine the potential differences in entrainment rates between different grate types under various discharge and slope configurations were used to determine if grate type choice would impact the removal of debris buildup in inlets.

2.4 Related Studies

A literature review for this study revealed the shortage of references specifically related to bridge deck drainage. Most existing literature on roadway drainage pertains to street drains that operate under large-flow regimes. Studies used for the current research were all associated with the Texas Department of Transportation (TXDOT), and they each used a variation of the same model. The experimental design and procedure of this study was based on their collective work.

2.4.1 Hydraulic Performance of Rectangular Deck Drain

Qian et al. (2012) researched the hydraulic performance characteristics of a new rectangular deck drain for TXDOT. The rectangular drain inlets measured 4 inches by 8 inches and 6 inches by 8 inches. The study compared the Federal Highway Administration (FHWA) slotted drain method and grate inlet method from HEC-21 to experimental results to determine if the slotted drain method could be used for design with new rectangular drain inlets measuring 4 inches by 8 inches. Results showed that the slotted drain method underestimated capacity, while the grate inlet method overestimated capacity for longitudinal slopes less than 0.005. Therefore, the following equation was developed to replace Equation 2.1 for the 4x8 drains:

$$Q_{c100\%} = k_{100\%}(N_m(L+W))^{16/7} n^{9/7} \frac{S_x^{0.7136}}{S_0^{0.4046}}$$ **Equation 2.16**

Where:

N_m = the number of drains required,

L = the length of the drain,

W = the width of the drain, and

$k_{100\%}$ = 1.4598.

These values were developed from the statistical analysis of results for fitted coefficients.

Qian et al. (2012, 2016) utilized a bridge deck model measuring 10.5 ft wide and 64 ft long and consisting of a plywood deck with two curbs reinforced by angle iron. The deck was coated with granular material and resin to provide a correct Manning's roughness coefficient. The deck contained 2x6 joists with a W12x16 steel lifting beam and two W18x35 steel beams measuring 60 ft long each. Two five-ton hoists were used to adjust the cross slope and longitudinal slope with the downstream end sitting on a support for adjustment. The deck drains were made of plexiglass and placed 18 inches apart to close off drains to allow use from 1 to 5 in a series. The first deck drain was placed 46.6 ft from the headbox to allow flow to simulate sheet flow on a deck. A 5-ft head box was used at the upstream end of the structure, and two water pumps discharged directly onto the bridge.

Qian et al. (2012, 2016) conducted a total of 586 tests on the 4x8 drain, and 236 tests were performed on the 6x8 drain. The main variables were capture discharge, approach discharge, flow curb depth, number of drains, cross slope, longitudinal slope, drain length, and drain width. Each variable was used to analyze Izzard's equation for discharge to develop Equation 2.16. Qian et al. (2012, 2016) provided the critical concepts for the experimental setup of the current study.

2.4.2 Hydraulic Characteristics of Inlets

Holley et al. (1992) performed tests on curb inlets and bridge decks to determine hydraulic characteristics at various flow conditions and geometries. The objective was to test two types of inlets and develop design equations for bridge deck drains. The two drains were identical except for orientation. The drains each contained a 0.5-ft 90° PVC elbow at the outlet pipe. A 0.75 scale model was used (Figure 2.3).

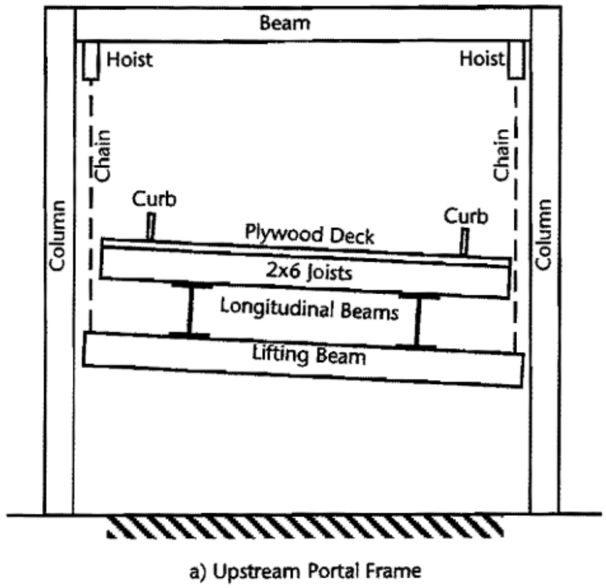


Figure 2.3: Experimental Model Diagram
Source: Holley et al. (1992)

Model scaling required that the model and the prototype have hydraulic similitude determined by the following ratios based on the length ratio (Λ_r):

$$\boldsymbol{Q_r} = \Lambda_{\boldsymbol{r}}^{\boldsymbol{5/2}}$$ **Equation 2.17**

$$\boldsymbol{n_r} = \Lambda_{\boldsymbol{r}}^{\boldsymbol{1/6}}$$ **Equation 2.18**

Where:

Q_r = the discharge ratio and

n_r = the ratio of Manning's roughness coefficient.

The grain size needed to achieve the required Manning's *n* was determined by the following equation:

$$\boldsymbol{n = 0.041 d_{50}^{1/6}}$$ **Equation 2.19**

Where d_{50} = the median sand grain size.

Holley et al. (1992) used a grain size of 0.0787 inches. Equation 2.17 through Equation 2.19 were used for the scaling aspect in the current study, and the physical model in this experiment was the original variation of the model presented in Qian et al. (2012).

One significant result of the study by Holley et al. (1992) was efficiency curves for curbed inlets on roadways (Figure 2.4), which they represented similarly to the efficiency curve by Johnson & Chang (1984). This result guided the current study's representation of results.

Experimental results for the curbed inlets revealed that the efficiency curve provided by Equation 2.4 overestimated efficiency (dotted line in Figure 2.4), as represented by a cubic function for the width-to-spread ratio.

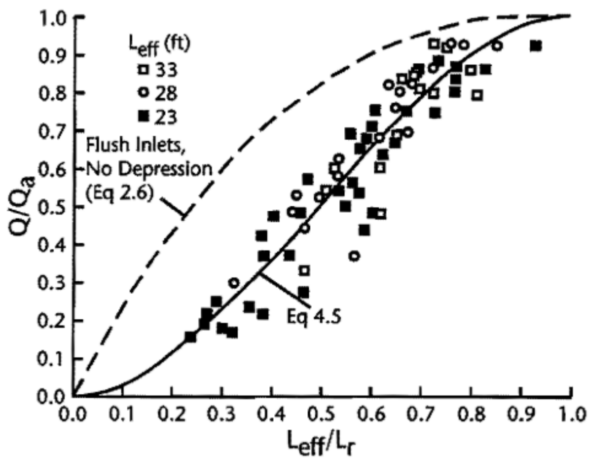


Figure 2.4: Experimental Efficiency Curve for Recessed Inlets
Source: Holley et al. (1992)

Another significant result of the research by Holley et al. (1992) was the classification of bridge deck drain behavior as low-flow control, weir/orifice control (i.e., inlet capacity controlled by the grate as weir control or by the inlet downspout as orifice control), and high-flow control (i.e., capacity limited by back pressure of the pipe system). Results showed that efficiency was much higher for weir/orifice control compared to pipe-system control. For a configuration of longitudinal and cross slopes, increased flow rate in the weir/orifice control regime increased captured flow, but the same increase in flow rate in the pipe-system control regime caused less increase in captured flow. The authors also found that weir control occurred when water freely fell into the pan, whereas orifice control occurred only when the drain pan was full. These findings influenced the contextualization of inlet capacity control results of the current study.

2.4.3 Hydraulic Capacity of Drains

The Hammonds and Holley (1995) study used the same model Holley et al. (1992) used to study scaling on curbed inlets and bridge deck drains, although they added another drain type (Figure 2.5) with the downspout opposite of the curb. Their experimental work examined the capacities of three drain types across a range of discharges (0.01–0.07 m^3/s) with longitudinal slopes ranging from 0.004 to 0.06 and cross slopes ranging from 0.0208 to 0.0417. Results showed that when a downspout was opposite the bridge curb, a decreased capacity occurred compared to a downspout next to the curb. The additional drain type (Figure 2.5) showed increased hydraulic capacity due to its larger drain pan volume, inclined vane grate, and larger downspout cross sectional area. The authors created an empirical formula to estimate capture discharge for each drain type (solid line Figure 2.4), demonstrating that capture discharge is a function of normal depth, longitudinal slope, and cross slope.

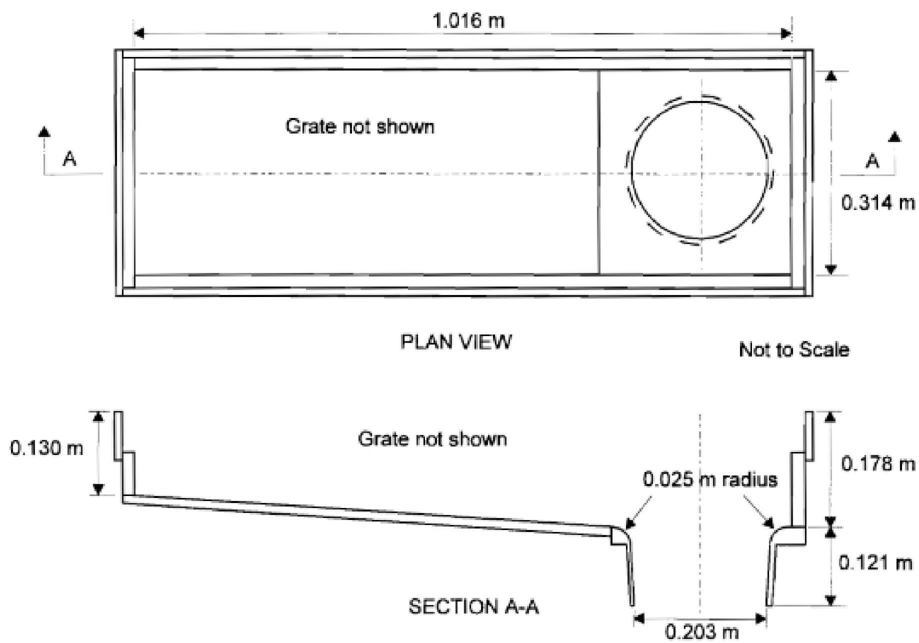


Figure 2.5: Drain 4 Pan
Source: Hammonds and Holley (1995)

2.5 DOT Design Manuals

This study collected and examined design manuals from 12 states (Kansas, Arkansas, Colorado, Florida, Illinois, Iowa, Michigan, Minnesota, Missouri, Nebraska, Oklahoma, and Texas) to compare states' design practices to recommend optimal procedures. A detailed analysis is included in Appendix A. Design guidance was similar between the states in accordance with guidelines set forth by hydraulic circulars; differences primarily related to drain designs. The Illinois Department of Transportation (IDOT) was shown to excel in design clarity, organization, and thoroughness, with multiple detailed design guides that follow HEC-21 and standard spacing preferences for specific situations, clogging factor adjustments, and calculation guidance.

Chapter 3: Survey of DOTs

3.1 Survey Intent

This study sought to determine the most common design procedures, drain types, grate types, and solutions to drainage issues to better inform the study's experimental design. A survey was sent to 50 DOTs in the United States to assess common design methods and inlet types as well as information relating to inlet clogging (Appendix B). Responses were received from 22 states, and the most relevant information related to field issues, drain design, and design guidance are outlined in Table 3.1.

3.2 Survey Results

Survey analysis showed that 14 of the 22 states use HEC-21 for design guidance, whereas only Nevada uses HEC-12 as does Kansas. Common drain types are scuppers, grated inlets, and slotted openings. States that reported using scuppers were Alaska, Connecticut, Delaware, Georgia, Illinois, Louisiana, Maryland, Nevada, New Hampshire, Ohio, Pennsylvania, South Dakota, and West Virginia. Arkansas, Colorado, Delaware, Illinois, Minnesota, Nebraska, Nevada, New York, and Oregon each reported using a grated inlet. Slotted openings were specified as common in Hawaii and North Carolina. Similarly, grate type also varied by state, with identified types being bar, vane, crosshatch, and none. Colorado, Illinois, and West Virginia indicated use of the vane grate, while Minnesota and New Hampshire use a crosshatch grate. Only South Dakota reported using no grate. The typical size of drains varied from a 4-inch scupper used in South Dakota to a 3.5 ft x 1.5 ft grated inlet used in Nebraska. Although each state follows similar guidelines, survey results revealed that DOTs use vastly different inlet and grate combinations. Therefore, since designs are not standardized, hydraulic performance curves must be examined and compared to standard design curves to verify accuracy.

Twenty-one of the 22 states reported that the most common issue plaguing bridge deck drainage is clogging of the drain or downspout no matter the size or type of drain. Solutions commonly include routine maintenance, although three states did not identify a solution. Colorado and Indiana indicated that they design for clogging, while Maryland's DOT designs bridges with high longitudinal slopes. Ohio's DOT indicated that they lowered the speed limit and increased the shoulder width to account for clogging of inlets. IDOT responded that they commonly use a curved vane grate and do not have any issues with clogging. Although most of the state DOTs base design on the assumption that inlets are clean, Indiana, Louisiana, and Minnesota assume a safety factor of 2 (or 50%) to account for clogging, whereas Nevada uses a 50% clogging factor for a sag curve, a 25% factor for designated high debris areas, and a 10% safety factor for everywhere else.

Overall, the survey responses revealed the impact of drain and grate type on efficiency due to the vast range of combinations to verify adequate performance curves. Additionally, almost every state surveyed indicated issues with clogging, meaning the effects of debris on performance must be examined to determine which grate type (IDOT vane) potentially reduces the amount of debris. A clogging factor also should be investigated to verify the accuracy of listed values and to eliminate clogging.

Table 3.1: Results of Bridge Deck Drainage Survey

State	Drain Type	Typical Size	Grate Type	Common Issues	Solutions to Issues	Clogging Factor	Design Reference
Alaska	Scuppers	6” to 8”	Varies	Clogging	Routine maintenance	None	HEC-21
Arkansas	Grated Inlet	24” x 14”	Bar	Clogging	Routine maintenance	None	HEC-21
Colorado	Grated Inlet	Varies	Vane	Clogging	Design for clogging/ increase maintenance	None	HEC-21
Connecticut	Scupper	2’ x 2’	Bar	Clogging	Routine maintenance	None	HEC-21
Delaware	Scupper and Grated Inlet	12” x 12”	N/A	Clogging	No solution	None	HEC-22
Georgia	Scupper	4” dia.	Bar	Capacity, Clogging	No solution	None	HEC-21
Hawaii	Slotted Openings	3’ x 2’	Bar	Clogging	Add drains, maintenance	Location Dependent	HEC-12
Illinois	Scupper and Grated Inlet	1’ x 1’ 1’ x 2’	Vane	No issues	N/A	None	HEC-21
Indiana	Grated Inlet	1'8" x 1'7"	Bar	Clogging	Using clogging factor	Assume 50% clogged	Indiana Design Manual
Louisiana	Scupper	8" dia.	N/A	Clogging	Routine maintenance	Safety factor of 2	HEC-21
Maryland	Scupper	Varies	Bar	Clogging	Design bridge with higher longitudinal slopes	None	HEC-22

Minnesota	Grated Inlet	1'5" x 1'5"	Cross hatch	Clogging	Avoid underdeck pipe system	Assume 50% clogged	HEC-22
Nebraska	Grated Inlet	3.5' x 1.5'	Bar	Clogging	Routine maintenance	None	HEC-21
Nevada	Scupper and Grated Inlet	2 'x 3', 9" x 18"	Bar	Designing for maintenance	Avoid deck drains	Assume 50% for sag, 25% for high debris, 10% all other	HEC-12, HEC-21, HEC-22
New Hampshire	Scupper	18" x 6" to 48" x 15"	Cross hatch	Rusting, Clogging	Increase routine maintenance	None	HEC-21
New York	Grated Inlet	1'10" x 1'5"	Bar	Clogging, Downspout disconnection	Use bridge washing program	None	HEC-21
North Carolina	Slotted Openings	6" dia.	N/A	Clogging	Paved approach shoulders	None	HEC-21
Ohio	Scupper	Varies	Varies	Clogging	Widen shoulders, reduce speed limits	None	OHDOT Manuals
Oregon	Grated Inlet	2'8" x 1'2"	Bar	Clogging	Routine maintenance	None	ODOT Hydraulics Design manual
Pennsylvania	Scupper	1'9" x 1'6"	Bar	Clogging	Routine maintenance	None	HEC-22
South Dakota	Scupper	4" dia.	Open	Capacity	More or larger inlets	None	HEC-21
West Virginia	Scupper	6" or 8" dia.	Bar or Vane	Clogging	Increase routine maintenance	Designers Discretion	HEC-21

Chapter 4: Physical Model

A scale model experiment was developed to determine the impact of downspout-shape grate type on hydraulic efficiency and spread of gutter flow. Variability in the use of grate types based on survey responses prompted investigation of the influence of grate type on hydraulic efficiency and spread, especially since literature on their impacts is only briefly discussed in HEC-12/HEC-22. Similarly, Holley et al. (1992) prompted investigation of hydraulic efficiency relationships with spread since their curves differ from standard design curves in the HEC manuals. Because most states identified clogging as their primary issue, this study investigated if changing from a bar grate to a vane grate would alleviate clogging as well as if a clogging factor could be determined based on grate type. Investigation of sediment transport and bridge drains provides a vital basis for future study in a minimally researched subject area.

4.1 Model Construction

The 1/9th scale model for this study was constructed in four sections using a framing support measuring 2 inches by 4 inches and topped with 5/16-inch plywood sheets to provide a surface for the deck coating. The model was placed in a 3-ft wide flume at the Water Resources Lab at the University of Kansas. To support the structure, aircraft cable was attached to the sides of the deck structure vertically up to a threaded rod supported by eight boards (2 inches by 4 inches each) that rested on the rails of the flume (Figure 4.1). The threaded rods on top of the support board each had a washer and a nut, which allowed cross slope and longitudinal slope adjustability. Aluminum sheeting was used as a curb on the low side of the cross slope. The model simulated a 10-ft shoulder with an 11-ft single lane.

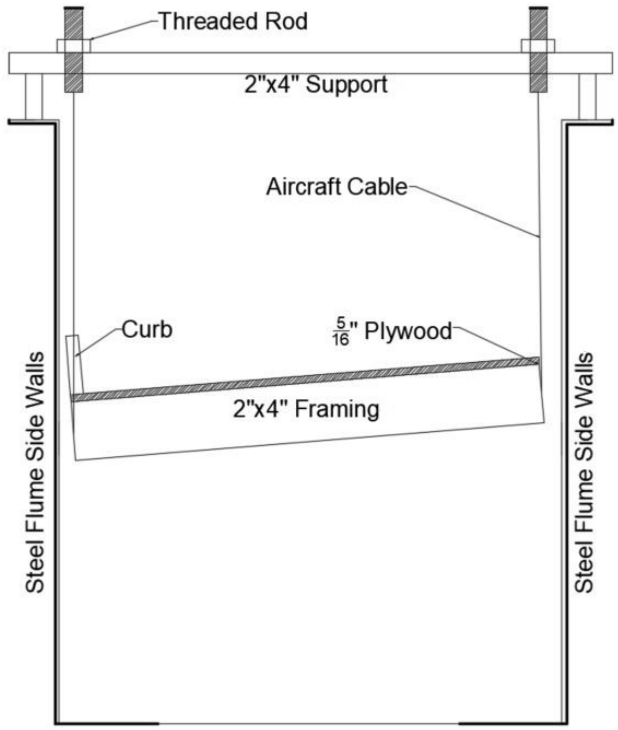


Figure 4.1: Scale Model Cross Section

4.2 Model Layout

The deck surface of the model measured 28 inches wide and 33.3 ft long, as shown in Figure 4.2. At the upslope most point on the model (Figure 4.3), inflow was discharged from a single point through a tube connected to a garden hose valve that was attached to one of the main pipe systems for the building. Inflow was simulated using a single-entry point because it allowed for accurate examination of gutter flow in the model. A rainfall simulator was originally planned, but initial results produced high variability in measurements supporting the switch to the aforementioned single inflow point. Four drains were placed at 5-ft spacings from center to center with the ability to configure various drain and grate types. The distance from the inflow tube to the center of the first inlet was 13.2 ft. A measuring tape was placed across the flume 2.5 ft upstream of each inlet to measure the spread of water.

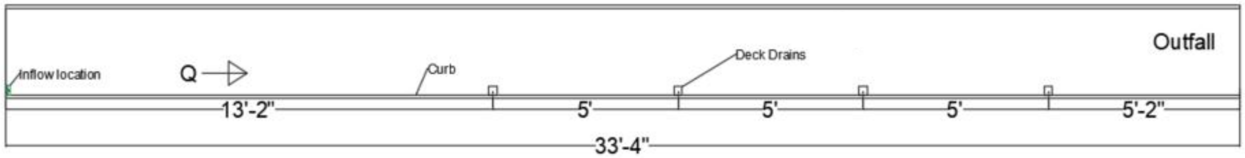


Figure 4.2: Model Layout

Figure 4.3: Single Inflow from High Side of Scale Bridge Deck Model

4.3 Surface Roughness Coating

The surface of the model simulated a bridge deck surface based on the scaling of Manning's *n* coefficient. A uniform sand size was distributed evenly across the deck, and an aerosol glue was applied on top of the sand to provide a non-removable coating for deck roughness. The typical Manning's *n* coefficient used by KDOT is 0.016, but the equivalent of this value at a $1/9^{th}$ scale was 0.012 according to Equation 2.18. The medium particle size required to achieve the scaled *n* value was 0.0197 inches, as determined from Equation 2.19.

4.4 Deck Drains

The deck drains in this study were variations of KDOT's standard design (2 ft by 2 ft) with four types of downspouts with circular or square openings measuring 8 inches and 10 inches, totaling in four different configurations (Figure 4.4). Additionally, the standard bar grate was used with a curved vane grate according to designs provided by IDOT (Appendix C). The drains and grates were created in Rhino6, a 3D modeling software that allows designs to be scaled accurately.

The designs were then exported and 3D printed with a Polylactic Acid (PLA) printer provided by the School of Architecture and Design at the University of Kansas. The drains were placed so that the grates would be flush with the deck surface, and modeling clay was used to seal around the edges of the opening.

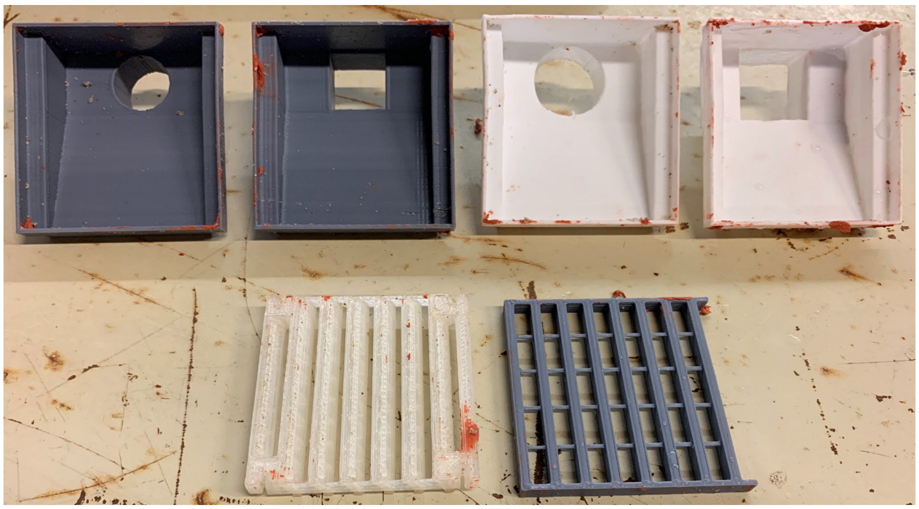


Figure 4.4: Inlet Designs (Left to Right): 8-inch Round, 8-inch Square, 10-inch Round, 10-inch Square; Grate designs (Left to Right): Vane Grate, KDOT Grate

4.5 Measurements

This study measured inflow using a SOTERA 1-inch 2-35 GPM Digital In-Line flow meter (Figure 4.5), which provided the flow rate in gallons per minute (GPM). The flow meter was calibrated for water using a premeasured volume container to verify results. The outflow, or captured flow, by each drain was measured using a plastic storage container on electronic scales to measure the amount of weight per experiment time. Measured weighted per time could be converted to a discharge using the unit weight of water as follows:

$$Q_c = \frac{\omega}{\gamma t} \qquad \textbf{Equation 4.1}$$

Where:

Q_i = the captured flow (cfs),

ω = the weight measurement taken to the nearest tenth of a pound, and

t = the length of the experiment (seconds).

Since the containers were inaccessible underneath the deck, electronically controlled solenoid values were used to drain water through a garden hose to the exit of the flume (Figure 4.6). Final measurements were the spread of water (*T*) at locations 2.5 ft upstream of each inlet, taken to the nearest tenth of a centimeter with measuring tapes placed level across the top of the flume. Water depth measurements were recorded because the small scale made depth difficult to accurately measure.

Figure 4.5: Flow Meter to Measure Inflow and Set Up Water Valve

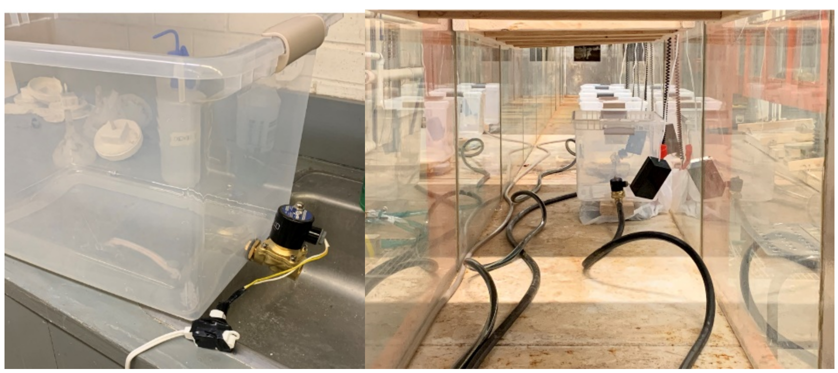


Figure 4.6: Capture-Flow Measuring Containers with Electronically Controlled Valves

4.6 Model Procedures

The experimental procedure was designed to obtain the data required for analysis of inlet efficiency between drain and grate configurations. The cross slope of the model was either 2% or 6%, with longitudinal slopes of 0.5%, 1%, 2%, or 4%. The approach discharge was tested at approximately 3, 4.5, and 7 GPM to generate a range of spread and capture measurements. The experimental series is listed in Table 4.1. Three-minute trials were used because the first drain outflow container filled up after 3.5 minutes at most configurations. The experimental series was completed three times at each configuration to estimate an average and uncertainty estimate for the experiments.

Table 4.1: Experimental Series for Hydraulic Efficiency

Component	Number of Iterations	Iteration Types
Cross Slope	2	2%, 6%
Longitudinal Slope	4	0.5%, 1%, 2%, 4%
Inflow	3	0.68 m^3/h, 1.02 m^3/h, 1.59 m^3/h
Downspout Shape	2	Circular, Square
Downspout Size	2	20 cm, 25 cm
Grate Type	2	Bar, Vane
Replicates	3	-
Number of Trials	**576**	

4.7 Hydraulic Efficiency Experimental Procedure

The initial experimental procedure for this study was comprised of the following steps:

1. Set the cross slope and longitudinal slope using the height-setting spreadsheet. The height measurement in inches given for each support is measured from the top of the deck to the bottom of the 2x4 at each support location. Start at the high side of the cross slope and work down the high side and then the low side. Check to make sure all support cables are tensioned by making final adjustments after the initial heights are set.
2. Once the deck is set to the required height, ensure that all downspouts and end drainage lead into the container. If not, adjust so that all water is directed into the containers.
3. Choose the required scaled inlet to place in the openings, and then use brown modeling clay to fill the gaps between the inlet and opening to prevent water leakage. Make sure the clay is pressed as flat as possible to avoid unintentional misdirection of gutter flow.
4. Adjust plastic sheathing to capture splash from raindrops.
5. Wet the deck before each experiment using a bucket to gently pour water across the entire surface.

6. Turn on all scales and verify that the readout is zero.
7. Open discharge input to correct turn amount to simulate required discharge. (Low inflow: 3 GPM, Medium inflow: 4.5 GPM, High inflow: 7 GPM)
8. Record the starting weight and time at each measuring container as well as the width of water at the locations where the measuring tape is located. Note, the starting measurement at the curb must be removed for the width of water.
9. After 3 minutes, record the end weight and time. Shut off the inflow valve and open the solenoids.
10. Once the containers are empty, turn off the solenoids and repeat Step 2 through Step 9 for all iterations before returning to Step 1.

4.8 Modification for Sediment Removal

After completing initial experiments, the deck was reconfigured to measure the clean-out potential of the grate types for a subset of trials using the 8-inch square downspout drain at each cross slope and longitudinal slope as well as inflows for bar and vane grates (Table 4.2). Only the most upstream inlet was used; all other openings were sealed. A cohesive mix of No. 35 (0.0197 inches) silica and clay were used to simulate the vegetative mixture found in the field for clogged inlets (Figure 4.7). The mix had a density of 127 lb/ft^3 with a dry density of 124 lb/ft^3. Ten-minute trials had to be used to adequately capture entrainment rates. The capture flow container under the inlet had to be removed as it would fill up after four minutes. The measured variables were the inflow (GPM), upstream and downstream spread width, time of experiment, and weight of sediment lost.

Figure 4.7: Clogged Inlet (Left); Simulated Experimental Mix (Right)

Table 4.2: Experimental Series for Clogging Cleanout

Component	**Number of Iterations**	**Iteration Types**
Cross Slope	2	2%, 6%
Longitudinal Slope	4	0.5%, 1%, 2%, 4%
Inflow	3	0.68 m^3/h, 1.02 m^3/h, 1.59 m^3/h
Downspout Shape	1	Square
Downspout Size	1	20 cm
Grate Type	2	Bar, Vane
Replicates	3	-
Number of Trials	**144**	

4.9 Sediment Removal Experimental Procedure

The final experimental procedure for this study consisted of the following steps:

1. Weigh the amount of material in the inlet with a width of 1 inch.
2. Place the grate over the inlet top flush with the opening.
3. Open the inflow valve and record the flow rate and starting time.
4. Measure the upstream and downstream spread of water after 30 seconds of run time.
5. Let the experiment run for 10 minutes, record the end time, and weigh the fully saturated weight of remaining material.
6. Let the material dry for 24 hours and weigh the dry amount.

Chapter 5: Experimental Results

A total of 576 efficiency tests were completed in which three trial replicates were used for each configuration listed in Table 4.1. Twenty-four tests were completed for each configuration of inlets (e.g., 8-inch round with a bar grate, etc.). The primary variables were captured flow (*Qc*), approach flow (*Q*), spread width upstream of an inlet (*T*), cross slope (*Sx*), longitudinal slope (*S*), and drain length (*W*). The drain length for all drains was 2 ft or scaled to 2.7 inches. Approach flow was calculated using a continuity mass balance where approach flow at the first inlet was the sum of captured flow and total captured flow minus the captured flow at each upslope inlet to the last inlet, thereby ensuring that efficiency could not exceed 1 (dimensionless).

A total of 144 sediment-removal tests were conducted using a single inlet (8-inch square) with a breakdown of 72 each for the bar and vane grate. Three trials were performed for each combination of grate type, flow rate, cross slope, and longitudinal slope. The main variables were the weight of sediment before (*wb*) and after (*wa*) each run, time of experiment (*t*), inflow rate (*Q*), the cross slope (*Sx*), the longitudinal slope (*S*), and the area of removable sediment (*A*). All results were reported in imperial units except erosion rates, which were reported in grams due to the small magnitude of the numbers, and the experimental data remained in the units used during measurements. Experimental data for the efficiency and sediment transport tests are listed in Appendix D and Appendix E, respectively.

5.1 Bridge Deck Roughness Coefficient

This study experimentally validated the scaled Manning's coefficient of 0.012, and the standard Manning's equation for rectangular channels was utilized by setting the cross slope to zero on the model and measuring the flow depth for each configuration of discharge and longitudinal slope. Depth measurements were taken at three locations and averaged for each trial. Three trials were conducted for each configuration of longitudinal slope and discharge. The longitudinal slopes were S = 0.5%, 1%, 2%, 3%, and 4%, and the discharges were based on the number of turns of the inflow valve with equivalent values of 8, 10, and 20 GPM. The average was taken across the discharge range, as shown by the red line in Figure 5.1. The grey, blue, and orange dotted lines represent the Manning's n coefficient across the slope range for discharges of 8, 10, and 20 GPM, respectively. The average Manning's coefficient across all values was equal to 0.012, with a standard deviation of 0.002. These results indicate that the coating consistently represented real-world conditions for the study's range of longitudinal slopes and inflows.

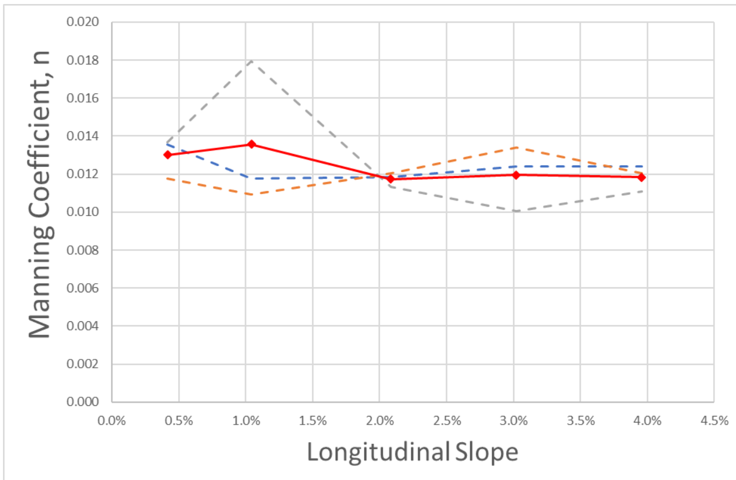


Figure 5.1: Manning's Coefficient as a Function of Longitudinal Slope: Discharge Setting– 3 GPM (Grey Dotted Line), 4.5 GPM (Blue Dotted line), and 7 GPM (Orange Dotted Line); Average Based on Longitudinal Slope (Solid Red Line)

5.2 Data Analysis

5.2.1 Measurement Uncertainty

To quantify the uncertainty between experimental runs, the deviation for efficiency and spread were determined as the value for the trial, with the average for the three trials removed. Consequently, the data were centered around a mean of zero. Histograms were used to assess the distribution fit for both variables. Figure 5.2 shows that the efficiency variation had an approximate normal distribution fit. The deviation in efficiency was very small (1.9%) with a 95% level of uncertainty at +/-3.8%. Because of the small deviations, this experiment also examined the statistical difference in efficiency between inlet configurations.

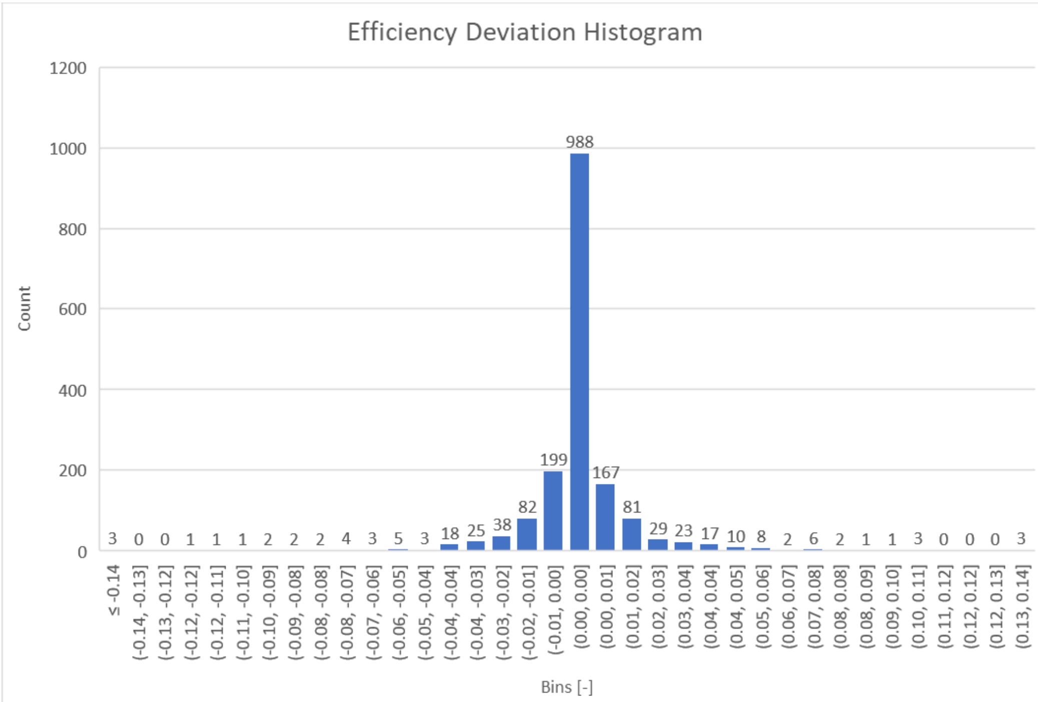


Figure 5.2: Histogram of Measured Efficiency Deviations

The measurement of spread in this experiment was more uncertain than efficiency, with a standard spread deviation of 0.35 inches. Histograms revealed that the data fit a normal distribution for the spread deviation (Figure 5.3). Analysis of the uncertainty interval at a 95% level found a +/-31% uncertainty for the spread measurement, which was the most difficult experimental variable to measure because surface roughness does not produce a single width, especially with a complex micro-geometry. Therefore, this study shifted the research focus to the efficiency of the experimental results.

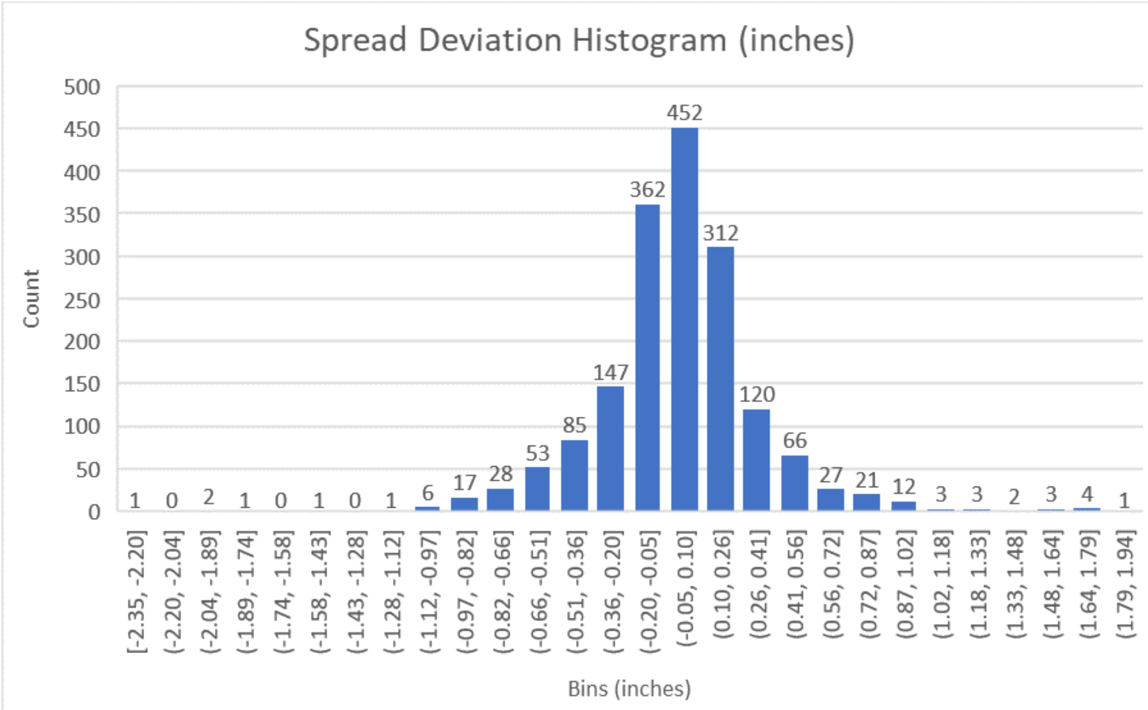


Figure 5.3: Histogram of Spread Deviation in Measurements

5.2.2 Efficiency and Spread-Average Analysis

A primary objective of this study was to compare efficiency breakdown under similar experimental conditions. However, not every experimental trial used all four inlets; most trials used two or three inlets based on the configuration of cross slopes and longitudinal slopes. A breakdown of averages per deck drain design based on inflow showed that increased downspout size led to increased efficiency for all flow conditions (Table 5.1). Additionally, under high-flow conditions (7 GPM), the first inlet was full-flowing, meaning it reached orifice control limits. As shown in Table 5.1, changing from a round downspout to a square downspout increased the capture capacity of the inlet as did increasing downspout size from 8 inches to 10 inches. Although the difference between grate types was minimal, downspout efficiency increased for the high-flow regime, with the exception of the 10-inch square downspout, indicating that at high flows a grate control condition exists as well.

Table 5.1: Efficiency and Spread as the Average (±1σ) Based on Inlet and Grate Design

Inlet	Number of Measurements		Average Efficiency (-)		Average Spread (inches)	
	Bar Grate	Vane Grate	Bar	Vane	Bar	Vane
8" Round	76	76	0.79 ± 0.15	0.79 ± 0.110	7.5 ± 3.1	7.6 ± 2.7
8" Square	72	74	0.81 ± 0.15	0.83 ± 0.124	7.4 ± 3.1	7.0 ± 2.9
10" Round	70	71	0.83 ± 0.14	0.84 ± 0.134	7.2 ± 3.2	7.1 ± 2.9
10" Square	69	69	0.82 ± 0.13	0.84 ± 0.126	7.2 ± 3.2	6.8 ± 3.0

Because the drainage designs demonstrated similar performances, the efficiency results were analyzed based on grate type. A breakdown of averages per grate design based on inflow showed that increased inflow rate caused decreased efficiency and increased spread as expected (Table 5.2). As shown in Table 5.2, changing from a bar grate to a curved vane grate slightly increased the capture capacity of the inlets, while at the high-inflow regimes, the grate type performances were nearly identical, indicating that potential choke conditions may be reached. Overall, no negative impact on hydraulic efficiency was observed from changing the grate type and downspout type.

Table 5.2: Hydraulic Efficiency and Spread Width as the Average (±1σ) across Inflows and Grate Design

Inflow (gpm)	Number of Measurements		Average Efficiency (-)		Average Spread (inches)	
	Bar Grate	Vane Grate	Bar Grate	Vane Grate	Bar Grate	Vane Grate
3	89	89	0.82 ± 0.22	0.84 ± 0.21	7.2 ± 4.4	6.9 ± 4.4
4.5	93	93	0.77 ± 0.22	0.80 ± 0.21	8.3 ± 4.7	8.0 ± 4.6
7	105	108	0.74 ± 0.25	0.75 ± 0.21	8.7 ± 5.0	8.5 ± 5.0

This study also examined efficiency breakdowns across slope configurations to determine drivers of hydraulic efficiency. Figure 5.4 and Figure 5.5 compare the average efficiencies for each grate type and drain type based on cross slopes and longitudinal slopes. With a 2% cross slope (Figure 5.4), results showed that highest efficiency occurred at a longitudinal slope of 0.5%, with the second highest efficiency occurring at a longitudinal slope of 4%, and efficiencies at each longitudinal slope were lower than its longitudinal slope counterpart at a 6% cross slope (Figure 5.5). For a cross slope of 2%, the water readily spread with a shallow depth, resulting in decreased gutter flow in the inlet width. For the 6% cross slope, flow channeled immediately, and the water depth was significantly higher near the curb of the deck. As shown in Figure 5.4 and Figure 5.5, comparative efficiencies between deck drain designs were very similar where changing the outlet minimally impacted efficiency. The largest efficiency increase occurred at the 0.5% longitudinal slope with a vane grate between the 8-inch and the 10-inch round downspout (Figure 5.5). However, the efficiency difference between the bar and vane grates based on slope was minimal; the vane grate performed more efficiently at the 2% cross slope, and the bar grate performed more efficiently at the 6% cross slope.

The curves in Figure 5.4 and Figure 5.5 all show high efficiency at the 0.5% and 4% longitudinal slopes. At 0.5% longitudinal slope, the water was slow-moving with less potential for splash over and capture by a fewer number of inlets compared to the other longitudinal slopes, as expected. The 1% and 2% longitudinal slopes predictably demonstrated decreased efficiency likely due to increased water velocity, which resulted in less side-flow capture. Increased efficiency at the 4% longitudinal slope was attributed to water channelization that prevented spreading and bypassed the sides of the inlet due to the experimental setup of inflow in the gutter, whereas under real-world conditions, even distribution of rainfall would create even sheet flow across the surface.

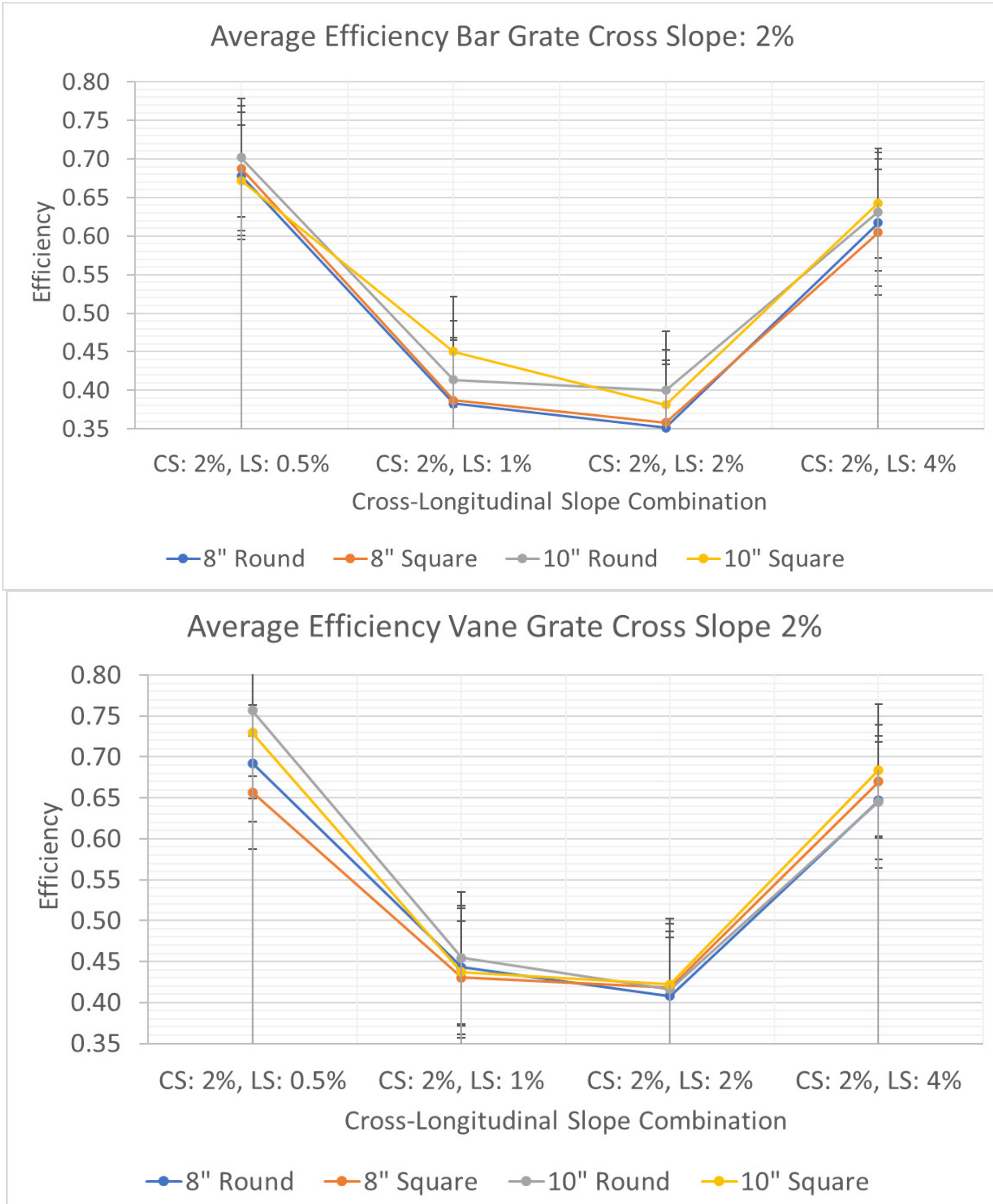
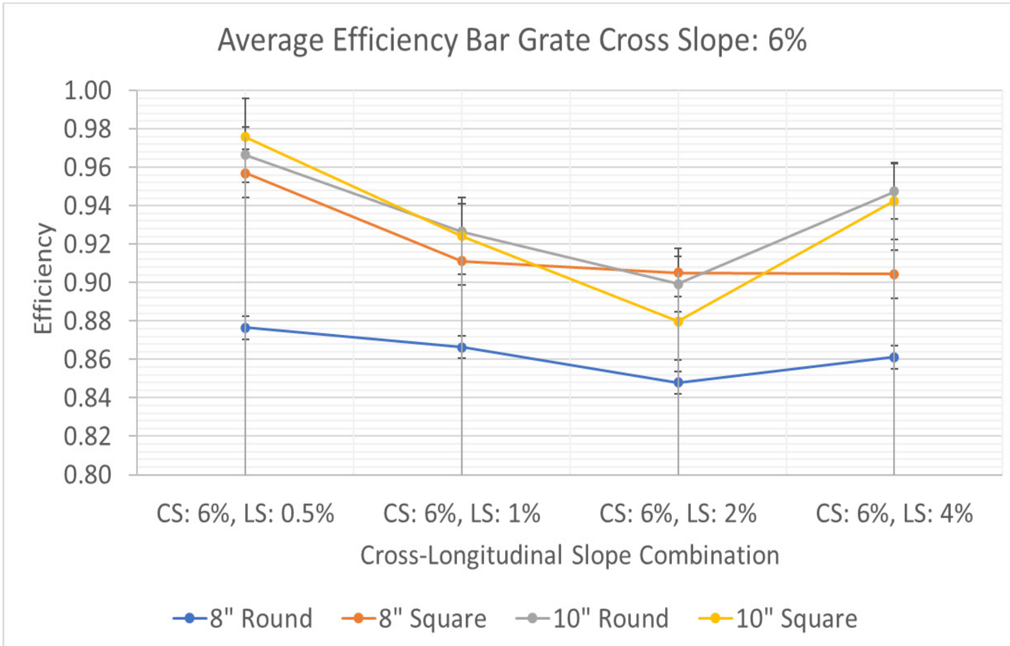


Figure 5.4: Average Efficiency for Longitudinal Slopes at 2% Cross Slope



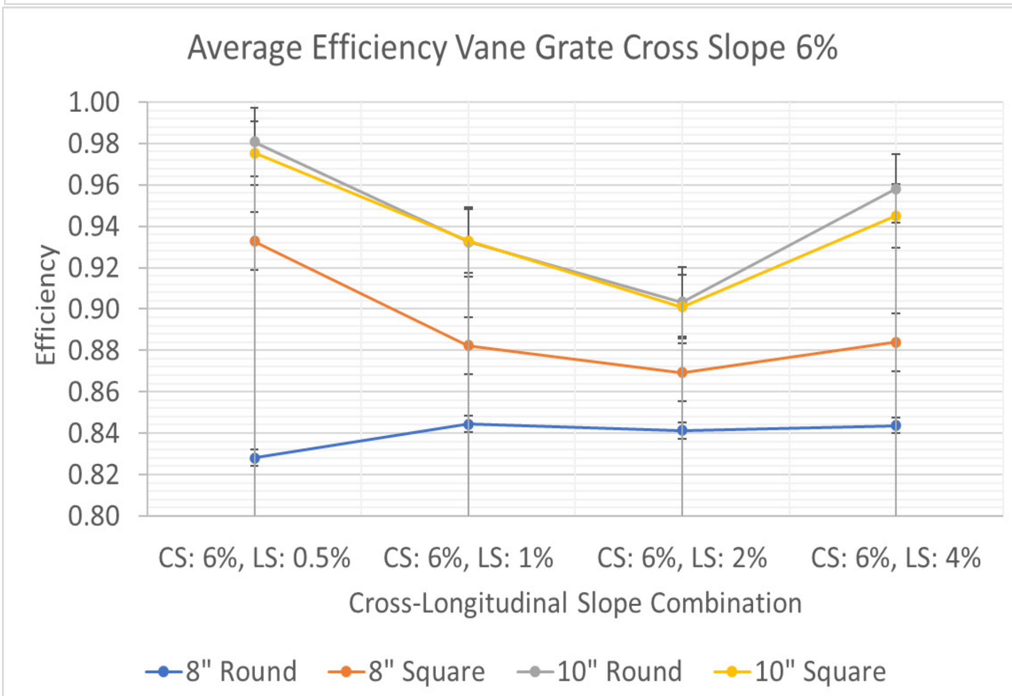


Figure 5.5: Average Efficiency for Longitudinal Slopes at 6% Cross Slope

5.2.3 Regression Analysis

Regression analysis was used to determine the effect of drain configuration on the efficiency of two different curves to explain trends in the data. The first attempt at quantifying the data utilized a forward-backward regression model with measured parameters to find the best fit.

The regression analysis did not find a strong solution due to uncertainty in the spread measurements at the model's scale. Modification of the efficiency equation (Equation 2.5) yielded fairly accurate results (R2 > 0.50), represented as:

$$E_o = 1 - (1 - \frac{W}{T})^a \qquad \textbf{Equation 5.1}$$

Where a = the optimized parameter.

Analysis results are shown in Figure 5.6. The fitted curves condensed to similar lines with minimal variation indicate that the performance of the eight design combinations was similar for all inlet and grate designs. However, Equation 5.1 did not accurately explain the data behavior, as observed with the high deviations of points in Figure 5.6.

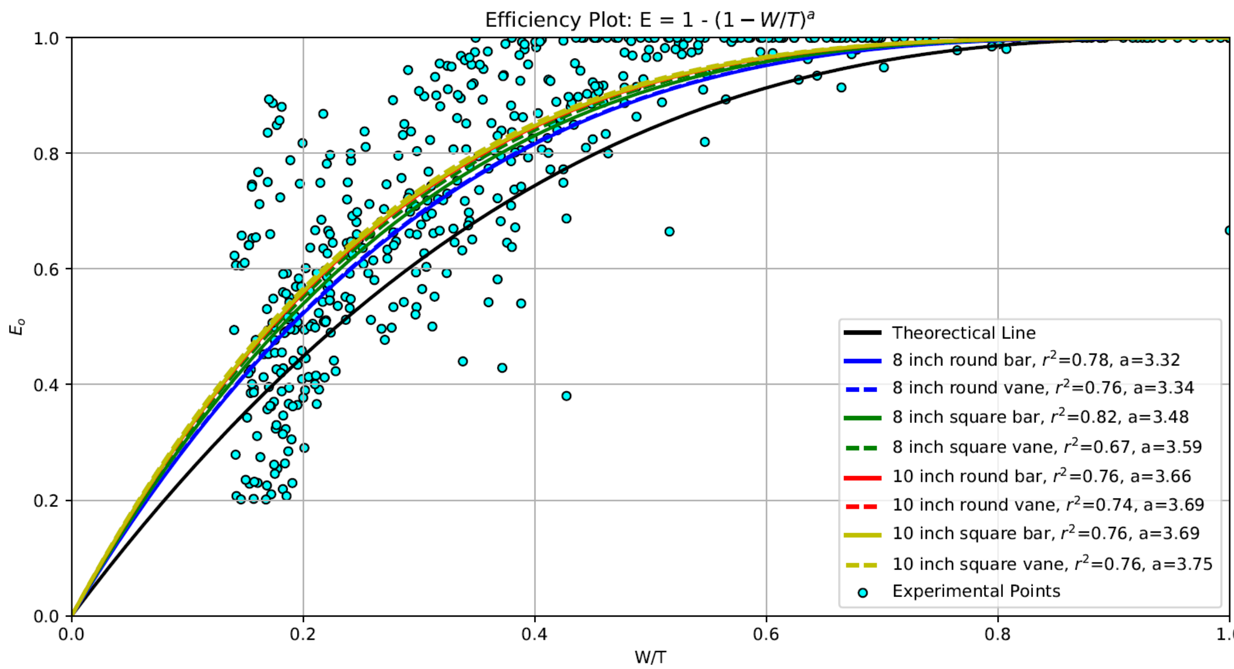


Figure 5.6: Simple Regression Fit with the Standard Efficiency Equation and Optimized Power Value

5.2.4 Statistical Comparison of Designs

Statistical testing was used to determine if efficiency changes due to inlet and grate configuration were significant. Efficiency data distribution for each configuration was examined to identify parametric or non-parametric differences in the mean test. Distributions of normal, lognormal, EV-1, gamma, Pearson type III, log Pearson type III, and beta were analyzed for each inlet configuration using Q-Q plots to determine the best fit based on the R^2 value for *C* moments. Beta distribution was the best fit for all configurations, as shown in Figure 5.7.

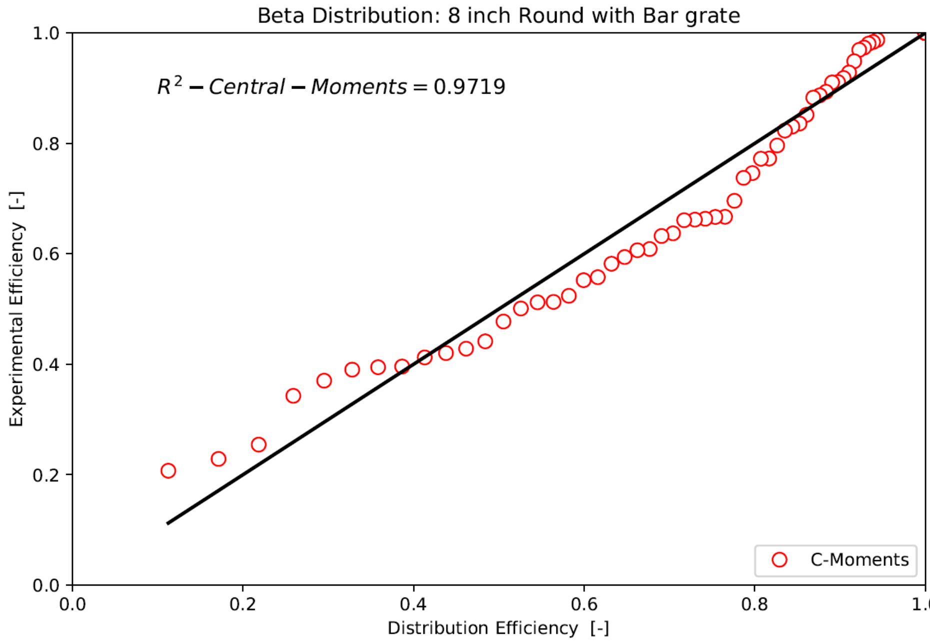


Figure 5.7: Beta Distribution Fit of Efficiency for 8-inch Round Downspout with Bar-Grate Configuration

Because distribution was not Normal, a non-parametric difference of the mean test was utilized to determine the statistical significance of efficiency between designs. A Mann-Whitney U-test in Python was conducted because it is a non-parametric version of the two-sample t-test (Wilks, 2011). The null hypothesis was that the two independent samples were selected for populations with the same distribution. This test was performed at a 95% confidence level in two scenarios. The first scenario compared drain configurations other than the standard KDOT design (8-inch round downspout, bar grate) to the KDOT design. Results showed no statistically significant difference in efficiency between designs. The second scenario performed the Mann Whitney U-test between the bar and vane grates to compare efficiency of grate types. Results showed no statistically significant differences in efficiency at a 95% level based on grate type.

5.3 First-Inlet Analysis

High uncertainty within the analysis of all the inlets prompted a focus on analyzing only the first inlet. The experimental data at the first inlet was consistent throughout all the experiments because the initial inflow was controlled. Statistical tests such as the Mann Whitney U-test and Analysis of Variance (ANOVA) were applied for the analysis. Similar to previous experimental results, the first-inlet results were non-parametric. All trial points were used to examine efficiency trends instead of grouping by three trial averages to obtain more measurements. The analysis focused on points at the 6% cross slope.

5.3.1 Inflow Regime Influence

A one-way ANOVA test indicated that the inflow regime significantly ($p < 0.05$) influenced efficiency ($F(2, 285) = 150.02$, $p = 0.00$). In addition, statistical testing showed significantly higher ($p < 0.05$) efficiency for low (0.93 ± 0.06) and medium inflow conditions (0.85 ± 0.09) compared to high (0.69 ± 0.13) inflow conditions. The results proved that inflow is a primary control on the performance metrics of efficiency and spread. Further statistical analysis in this subsection was performed within each inflow regime. Design must focus on rainfall related to precipitation intensity because inflow has the most direct impact on bridge deck drainage performance.

5.3.2 Bridge Slope Influence

The relationship between efficiency and WT was markedly different for the two cross slopes (Figure 5.8): 6% cross slope efficiency trended with spread compared to at the 2% cross slope where less visible relationship is found. At the shallow 2% cross slope, the efficiency held constant with no observable change in WT. The increased spread was due to the dispersion of gutter flow at less depth due to the shallow 2% cross slope, in which low flow energy caused friction, or surface roughness, to control water movement downslope.

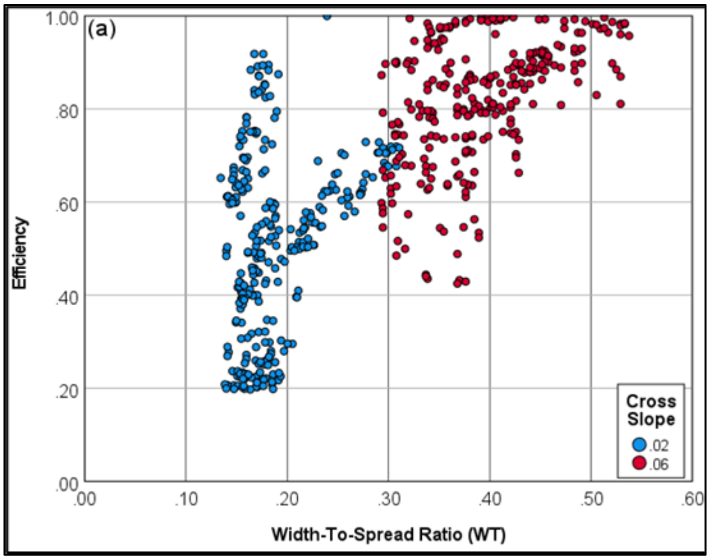


Figure 5.8: Cross Slope Comparison of Experimental Data for Hydraulic Efficiency Versus Width-to-Spread Ratio for the First Inlet

As shown in Figure 5.8, the cluster of points at the 2% cross slope at a WT from 0.21 to 0.31 follows a trend similar to the cluster for the 6% cross slope. The 2% cluster from WT 0.21 to 0.31 occurred at the longitudinal slope of 4% due flow channelization based to the placement of the inlet hose. Due to uncertainty in the 2% cross slope, further analysis for the longitudinal slope was completed at the 6% setting.

A breakdown of longitudinal slope by inflow category at the first inlet revealed that longitudinal slope influenced efficiency. At low inflows, ANOVA showed that longitudinal slope significantly influenced ($p < 0.05$) efficiency ($F(3, 92) = 102.64$, $p = 0.00$), and all longitudinal slopes showed significant differences ($p < 0.05$) between their mean efficiencies (Table 5.3). Similarly, the medium inflow group was shown to significantly affect efficiency ($F(3, 92) = 21.17$, $p = 0.00$), where mean efficiency was statistically different ($p < 0.05$) between all groupings of 0.5%, 1%, 2%, and 4%, except between 1% and 4% longitudinal slopes. Although longitudinal slope in the high-inflow regime significantly influenced efficiency ($F(3, 92) = 5.57$, $p = 0.00$), with significant difference for mean efficiency observed between 0.5% and 2% and 4%, no significant difference was shown between the 1% slope or between the 2% and 4% slopes. Overall, longitudinal slope was shown to significantly impact efficiency for low and medium flows that were not controlled by inlet capacity. As longitudinal slope increased, efficiency decreased, meaning flow could splash over or bypass the inlet due to increased flow velocity. Discrepancies at the 4% slope were observed due to the placement of the inflow hose.

Table 5.3: Average Efficiency (±1σ) per Inflow Based on Longitudinal Slope at the First Inlet for a 6% Cross Slope (n = 24)

Inflow (GPM)	0.5%	1%	2%	4%
3	0.99 ± 0.01	0.91 ± 0.03	0.85 ± 0.05	0.97 ± 0.03
4.5	0.93 ± 0.09	0.84 ± 0.05	0.78 ± 0.05	0.85 ± 0.08
7	0.77 ± 0.03	0.65 ± 0.10	0.71 ± 0.10	0.65 ± 0.13

ANOVA testing found that longitudinal slope significantly influenced ($p < 0.05$) WT at the low ($F(3, 92) = 25.53$, $p = 0.00$), medium ($F(3, 92) = 94.21$, $p = 0.00$), and high ($F(3, 92) = 64.84$, $p = 0.00$) inflow categories. The average for the 0.5% longitudinal slope was significantly less ($p < 0.05$) than at the 1%, 2%, and 4% slopes at low inflow. Similarly, significant difference ($p < 0.05$) was observed between slopes 0.5% and 1% as well as 2% and 4% for WT at medium inflow, with significant difference between all slopes except 1% and 2%. Additionally, WT demonstrated significant difference between all pairings of longitudinal slopes at the high-inflow regime. Table 5.4 shows the average WT based on each slope-inflow configuration; all categories show that increasing longitudinal slope increases WT (decreases spread). As the slope became steeper, flow channelized more efficiently and increased flow energy reduced spread. As shown in the table, increasing the discharge at each longitudinal slope decreased WT or increased spread. Overall, these results align with relationships anticipated by the modified Manning's equation (Equation 2.1), meaning the consideration of bridge slope impacts on bridge deck design is essential.

Table 5.4: Average WT (±1σ) per Inflow Based on Longitudinal Slope at the First Inlet for a 6% Cross Slope (n = 24)

Inflow (GPM)	0.5%	1%	2%	4%
3	0.40 ± 0.02	0.44 ± 0.05	0.46 ± 0.06	0.50 ± 0.03
4.5	0.34 ± 0.01	0.38 ± 0.03	0.40 ± 0.02	0.44 ± 0.01
7	0.31 ± 0.02	0.32 ± 0.02	0.36 ± 0.02	0.38 ± 0.01

5.3.3 Inlet Design Impact

In this study, hydraulic efficiency increased on average across inflow regimes for both tested grate types. Average efficiencies for the bar grate across low, medium, and high inflows were 0.93 (±0.07), 0.86 (±0.07), and 0.74 (±0.10), respectively. Vane grate efficiency values were nearly identical to bar grate values, with averages of 0.93 (±0.06), 0.84 (±0.09), and 0.65 (±0.14) at low, medium, and high inflows, respectively. A statistically significant difference was observed between grate types at high inflow. Statistical comparison of WT between grate types showed average values at low, medium, and high inflows of 0.45, 0.39, and 0.34, respectively. The large opening area in the bar grate allowed more captured flow at the high-inflow regime compared to the vane grate, which resulted in the difference in efficiency. Overall, results showed that grate type only impacts efficiency when the slit opening area acts as a hydraulic control condition.

Efficiency between the square and circular downspouts demonstrated significant difference ($p < 0.05$) at medium and high inflows. Average efficiencies for low, medium, and high inflows for the square downspout were 0.94 (±0.05), 0.87 (±0.07), and 0.73 (±0.11), respectively, compared to 0.92 (±0.07), 0.82 (±0.09), and 0.66 (±0.13) for the circular downspout. Similarly, average efficiencies for downspout widths of 8 inches were 0.92 (±0.07), 0.82 (±0.09), and 0.61 (±0.11) for low, medium, and high inflows, respectively, compared to 0.94 (±0.06), 0.87 (±0.07), and 0.73 (±0.11) for downspouts with widths of 10 inches. For each metric, the larger average cross-sectional area (square shape, 25 cm) had higher efficiencies, indicating downspout area controlled the capture efficiency in a bridge deck drainage system.

Analysis of downspout area indicated that increasing downspout opening size improved efficiency for medium and high inflows. One-way ANOVA testing at the low-inflow regime showed that downspout area did not significantly influence efficiency ($F(3, 92) = 2.53$, $p = 0.06$). Conversely, downspout area did significantly influence ($p < 0.05$) efficiency for medium ($F(3, 92) = 16.34$, $p = 0.00$) and high inflows ($F(3, 92) = 40.31$, $p = 0.00$). Figure 5.9 shows efficiency results for downspout openings, in which mean efficiency was significantly different between all opening areas at the high-inflow regime.

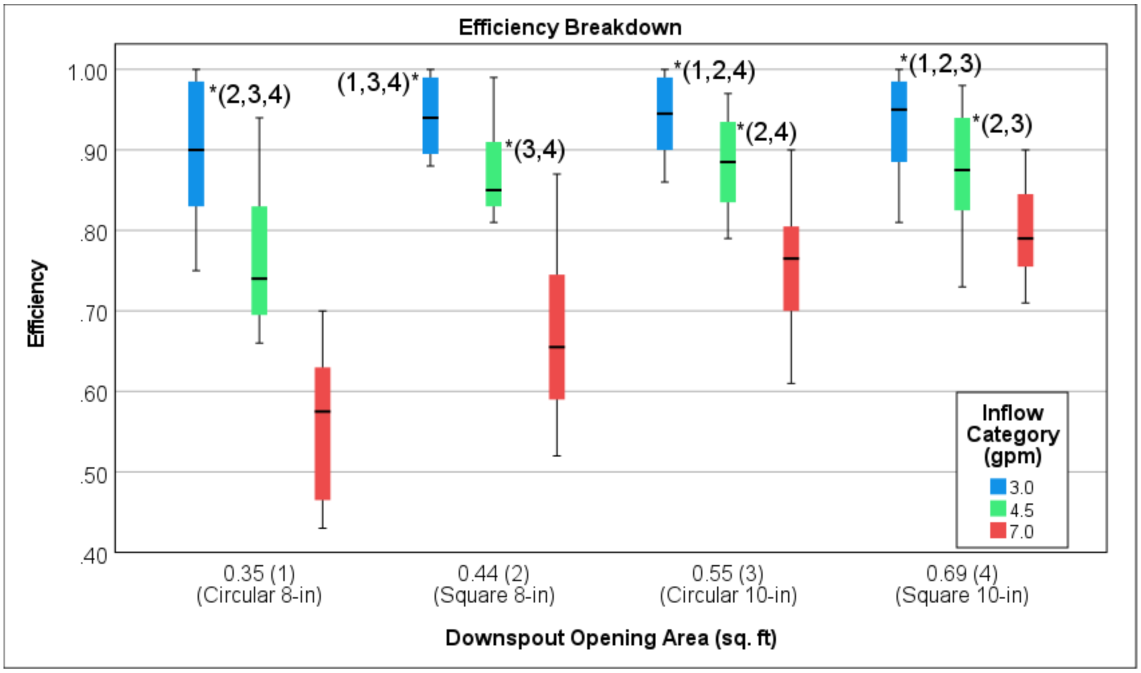


Figure 5.9: Efficiency Boxplot Comparing Inflow Category across Downspout Opening
(*) indicates statistical similarity ($p > 0.05$) between means with numbers corresponding to opening size given on the x-axis

According to Figure 5.9, downspout opening sizes larger than 0.34 ft^2 had higher efficiencies with significance in the medium-flow regime. Conversely, no statistical difference was observed between opening areas with low inflow. Overall, as downspout area increased, efficiency increased, as evidenced in the high-inflow regime, where downspout capacity was always reached, indicating that increasing downspout opening size can positively impact design.

Analysis of spread for the first inlet at 6% cross slope showed that the downspout area was a significant influence ($p < 0.05$) for the low ($F(3, 92) = 10.67$, $p = 0.00$), medium ($F(3, 92) = 3.66$, $p = 0.02$), and high ($F(3, 92) = 4.67$, $p = 0.00$) inflows. Downspout areas with statistical similarity between average spread are indicated in Figure 5.10 with a (*). As shown in the figure, the smallest downspout area in the low-inflow regime had significant increases in spreads compared to the three larger downspout areas. For the medium inflow, spread gradually decreased as the opening area increased, with significant difference between areas of 0.34 and 0.69 ft^2. A transition region likely occurred in which spread was partially controlled by downspout design, but the largest downspout opening size alleviates the control condition. For the high-inflow regime, Figure 5.10 shows significant difference ($p < 0.05$) only between the 10-inch square downspout and the two 8-

inch downspout designs. Overall, the spread analysis proved that increasing downspout size beneficially controls spread across all conditions.

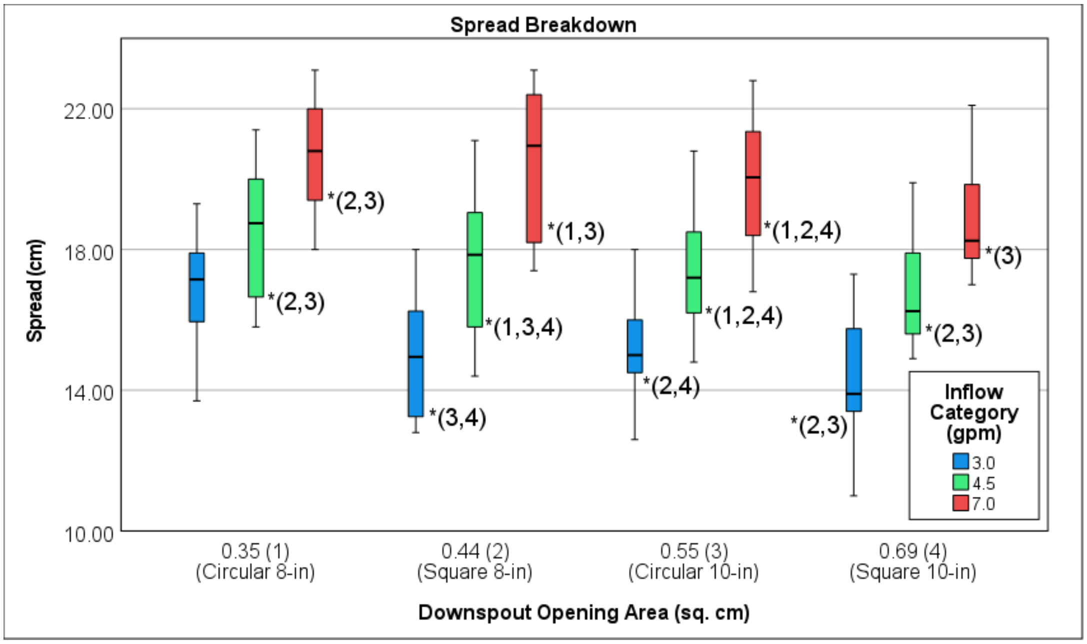


Figure 5.10: Spread Measurement Boxplot Comparing Inflow Category across Downspout Opening

(*) indicates statistical similarity ($p > 0.05$) between means with numbers corresponding to opening size given on the x-axis

5.4 Sediment Transport Data Analysis

The main parameters analyzed in the second set of experimental data were related to the erosion rate between bar and vane grates across a range of approach flow and slope combinations. A Mann Whitney U signified test was performed to find any statistically significant difference between slope configurations and all data per vane type. At a 95% confidence level, the results show that the average erosion rates were not significantly different based on slope configurations, inflow, and slope-inflow configurations except at a 6% cross slope and a 4% longitudinal slope for all inflows; the vane grate performed statistically better with larger average erosion rates. The standard difference of the mean test supported these results except for comparisons based on configurations and slope. The bar grate had increased erosion rates (with statistical significance at a 95% level) with low inflow at a 6% cross slope and 0.5% longitudinal slope and with high inflow at a 2% cross slope and 1% longitudinal slope. Comparatively, the vane grate had increased average erosion rates (with statistical significance at 95% level) with low flow at a 2% cross slope and longitudinal slope, and with medium flow at a 6% cross slope and 2% longitudinal slope.

Overall, the erosion rates showed an average bar grate rate of 0.056 g/s, while the vane grate had an average rate of 0.061 g/s. As shown in Table 5.5, only the 2% and 4% longitudinal slopes at a 6% cross slope presented a difference in erosion rate between grates, resulting in the average difference across all inflow regimes. Analysis of all slope configurations revealed that, on average, the erosion rate of the bar grate increased as the inflow increased, and the bar grate was not significantly limited by opening capacity (Table 5.6). However, the clean-out potential of the vane grate increased from low to medium inflows and then decreased at high flows, which was likely due to a choke condition of the grate opening. These trends are similar to observations from the efficiency analysis. The vane grate had increased clean-out rates at low and medium flows.

Table 5.5: Erosion Rate (g/s) as the S and S_x Average (±1σ) for Grate Designs (n = 18)

6% Cross Slope Erosion Rates (g/s)				
Grate	**LS: 0.04**	**LS: 0.02**	**LS: 0.01**	**LS: 0.005**
Bar	0.084 ± 0.071	0.046 ± 0.012	0.055 ± 0.010	0.045 ± 0.008
Vane	0.114 ± 0.062	0.066 ± 0.021	0.051 ± 0.025	0.041 ± 0.010
2% Cross Slope Erosion Rates (g/s)				
Grate	**LS: 0.04**	**LS: 0.02**	**LS: 0.01**	**LS: 0.005**
Bar	0.063 ± 0.032	0.054 ± 0.021	0.042 ± 0.008	0.057 ± 0.017
Vane	0.064 ± 0.050	0.051 ± 0.019	0.041 ± 0.016	0.063 ± 0.032

Table 5.6: Erosion Rate (g/s) as Inflow Average (±1σ) for Grate Designs (n = 48)

Inflow (GPM)	Bar	Vane
3	0.045 ± 0.0153	0.049 ± 0.0220
4.5	0.056 ± 0.0228	0.075 ± 0.0592
7	0.067 ± 0.0448	0.059 ± 0.0225

The experimental results were analyzed using the dimensionless parameters from Walder (2015) and Equation 2.14 and Equation 2.15 to represent dimensionless erosion rate and particle mobility, respectively. A critical shear stress of 0.0031 psf, as determined from experimental testing of the upstream bed shear, was used with a specific gravity of 2.04 and a dimensionless critical shear stress of 0.14. Figure 5.11 shows the results, where the bar grate is represented by blue dots and the vane grate is represented by orange dots. A power law equation from Walder (2015) was plotted with the experimental results for various cohesive mixes to determine the applicability of the parameters. The log relationship was represented as:

$$\log(\widetilde{\boldsymbol{\Phi}}) = \boldsymbol{\beta_o} + \boldsymbol{n_0} \log(\boldsymbol{R}) \qquad \textbf{Equation 5.2}$$

Where:

β_o = a regression coefficient equal to -5.22 and is dependent upon the material type of the sediment mixture for an optimal correlation value, and

n_0 = the regression coefficient for the slope of the line (1.78 for the trendline in Figure 5.11) and is also dependent upon the sediment mixture.

As the figure shows, the experimental results plotted near similar sediment cohesive mixtures giving validity to this study's results. The dimensionless equations helped to collapse the data for analysis. Compared to similar experiments, the cohesive sediment mixture for this study trended in the upper portion of the x and y axis of the results, with a fit close to the trend line (Figure 5.11). Experimental results showed that the bar and vane grates demonstrated nearly identical performances, as evidenced by the lack of statistical significance in the results.

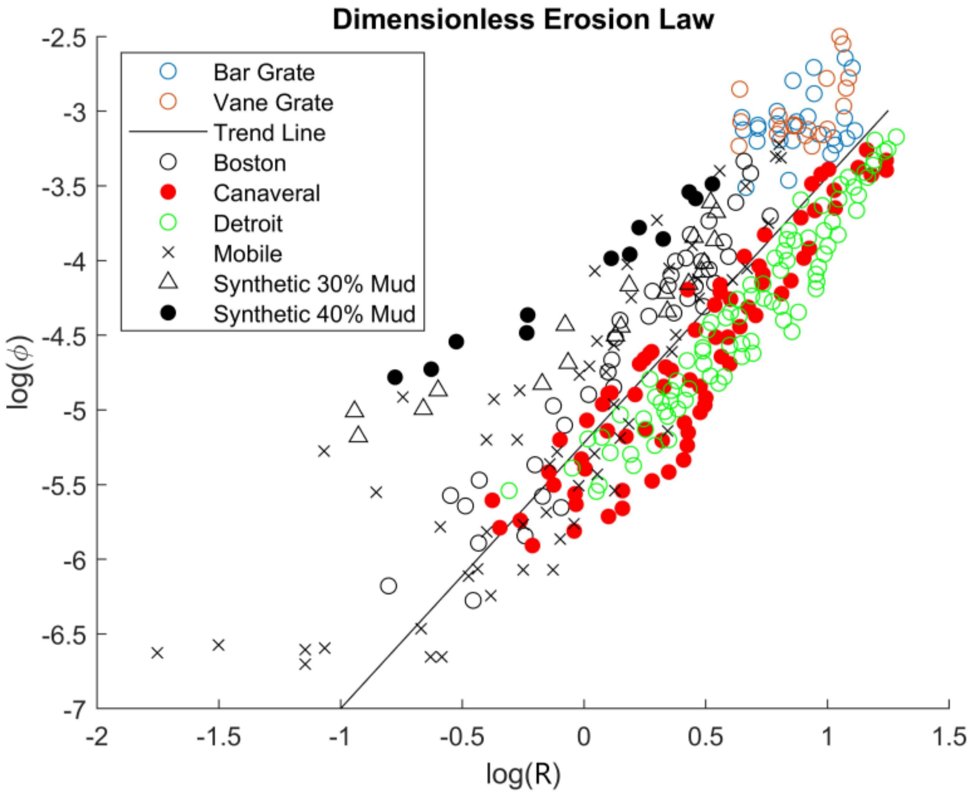


Figure 5.11: Dimensionless Erosion Rate Compared to Data
Source: Walder (2015)

Chapter 6: Discussion

6.1 Inlet Designs

Analysis based on efficiency showed no negative impact when switching from a round to a square cross section for the 8-inch downspout, as shown in the average analysis in Table 5.1 and Table 5.2. Under similar inflow and slope configurations the square downspout showed an increase in efficiency and a decrease in spread. Although the 10-inch downspouts had better efficiency and spread performance than the 8-inch downspouts (round and square), there were no clear differences in efficiency for the 10-inch downspouts. On average, spread decreased with increased efficiency and increased opening area. The experimental testing and literature review showed that the cross and longitudinal slopes negatively impact efficiency when a system is not designed with an orifice-control condition. The use of shallow longitudinal slopes, such as 0.5%, allow for increased interception of gutter flow with less grate splash over.

Regression analysis of the experimental data showed that all bridge deck designs performed similarly in their efficiency curve characteristics. Survey results showed that DOTs use multiple types of inlets with current design practices, and no problems were indicated with standard practices. The most critical design factor is verification that when designing near downspout capacity that it must be checked whether downspout opening size will be a hydraulic control. However, in-depth analysis of similar inlet research proved that hydraulic efficiency can improve with larger downspout opening areas. For example, use of the largest tested downspout design (10-inch square) most effectively eliminated loss of efficiency between flow regimes. The application of larger opening sizes can be used as a proactive design approach to combat unknown future increases in rainfall intensity due to climate uncertainty.

6.2 Grate Designs

This study investigated the impact of grates on bridge deck design based on IDOT's positive experience of no debris build-up due to the use of a curved vane grate inlet. The experimental results did not show a significant difference in efficiency using either a bar or vane grate. The vane grate operated with higher erosion rates at low- and medium-inflow regimes, whereas the bar grate had higher erosion rates at high flows because the grate did not act as a control due to the bar grate's larger area of slit openings. Additionally, analysis of the clean-out potential of grate types did not show significant difference in erosion rates except at a cross slope of 6% and longitudinal slopes of 2% and 4%, in which the vane grate had higher erosion rates on average but not enough for statistical significance. Two of the DOTs surveyed use both bar and vane grates in their design. This study's experimental testing proved that the use of either grate type does not significantly impact bridge deck design.

6.3 Debris Removal

Further investigation is needed to better understand the relationship between grate behavior and debris buildup and clean-out to remediate clogging issues, with multiple sediment mixes representing debris buildup. At steeper slopes, a curved vane grate may help alleviate clogging as results showed increases in erosion rates compared to the bar grate. In this study, clogging increased water spread with the bar grate from 10.9 inches to 11.0 inches, or 8.2 ft to 8.3 ft at full scale, and from 10.8 inches to 11.4 inches, or 8.1 ft to 8.5 ft for the vane grate. Depending on the bridge deck configuration, the change in spread widths could be significant to roadway safety, thereby highlighting the need for a design safety factor. Six DOTs use clogging factors, as shown in Table 3.1, indicating that consideration of a clogging factor may help alleviate clogging issues in the field.

Chapter 7: Summary and Recommendations

7.1 Summary

This study analyzed new techniques and designs to update current bridge deck design practices in Kansas. A survey of current DOT practices revealed similar design practices in Kansas and the 22 states that responded to the survey. The primary objectives of this study were to determine the effects of changing the size and shape of a deck drain outlet on the efficiency of a bridge deck inlet, and to identify the impact grate design has on hydraulic features. A physical model was constructed to represent a shoulder and a one-lane constant slope bridge, and to configure cross slope and longitudinal slope configurations. Four downspout configurations representing full-scale models (8-inch round, 8-inch square, 10-inch round, 10-inch square) were 3D-printed at a 1/9th scale with two grate types, bar and vane, so that efficiency and spread could be evaluated at approach discharge (Q), longitudinal slope (S), and cross slope (S_x). A partially clogged, single inlet design was tested to analyze the sediment removal rate based on a curved or rectangular grate type.

7.2 Recommendations

Although the KDOT Design Manual describes the basics of deck drainage design, this study found that the HEC-21 reference provides a more streamlined approach to the design process. The survey results from this study also indicated that DOTs commonly use HEC-21. Currently, KDOT primarily references HEC-12 which should be updated to include HEC-21.

The experimental results also showed that changing the downspout cross section from circular to square can potentially increase the efficiency of the drainage system and decrease water spread because of increases in the choke limit since the square provides a larger cross-sectional area. Increasing the downspout size from 8 inches to 10 inches also showed increasing efficiency and decreasing spread. Overall, the trend shows that downspout cross section area drives efficiency at high flows, and the use of larger downspout sizes increases efficiency and decreases spread. The research team recommend switching to square downspout size as well as using a 10-inch opening width.

Concerning bridge deck drainage, 21 of the 22 surveyed DOTs identified clogging as the most common issue. Only three DOTs claimed to use a safety factor; most increase maintenance of drainage inlets to remedy clogging. Further investigation should be made into the use of safety factors to improve bridge deck design, especially since related studies by Guo and MacKenzie (2012) and Gómez et al. (2019) have described design success with safety factors.

The data results from the clogging removal test of this study showed that at steeper cross slopes (6%), the curved vane grate provides better sediment removal capability. Further investigation should be made into the use of curved vane grates because it may help remove debris buildup, as indicated by ILDOT.

7.3 Future Directions

To further expand the investigation of bridge deck drainage, a proof-of-concept was developed to apply artificial intelligence (AI) and deep-learning models to classify clogging from Google Street View images. This study developed a simple model with 135 bridges in Kansas. The model identified 250 grate images from 45 (of the 135) bridges, and a clogging analysis was completed on the images using human classification for clogging, debris type, grate type, and inlet size. A trend analysis of clogging to bridge length and age was completed but did not yield a trend, most likely due to the small sample size. Additionally, a spatial analysis of debris type was conducted, as shown in Figure 7.1, which identified sediment type debris near large population areas such as Johnson and Wyandotte Counties. Further investigation would be necessary to understand the trends in clogging and debris type, but initial results are promising as the sample of images could be used to generate data for a debris analysis. Another analysis was conducted for the clogging level, which was a range from 1 (no clogging) to 5 (fully clogged) based on the month that an image was recorded. Figure 7.2 shows a seasonal pattern of the clogging level, with lower clogging levels in the winter and higher levels in the spring, which indicates that precipitation patterns may impact clogging in an inlet.

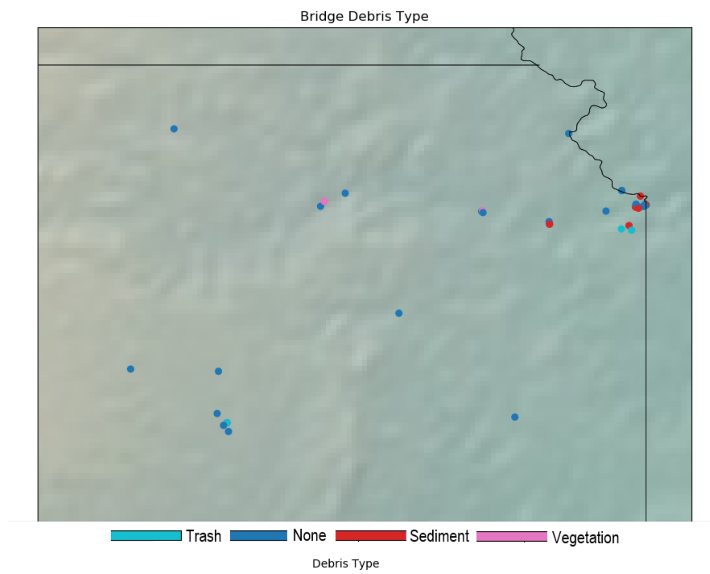


Figure 7.1: Spatial Map of Common Debris Type per Bridge based on Image Classifications

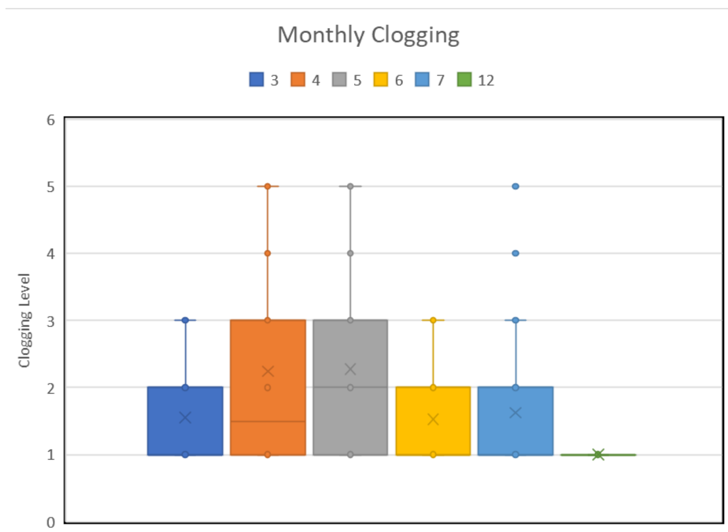


Figure 7.2: Clogging Level Based on the Month of the Google Street View Image

A future project should train AI models to determine whether or not bridges use deck drainage and identify grate images and non-grate images from the sampling area. Then a model of grate images could classify the percentage of clogging at a bridge location, the debris type, the grate type, and the size of the inlet. This information could be included in a directory for KDOT that could indicate locations most susceptible to clogging. Then a spatial analysis based on bridge location could be developed, similar to the analysis completed above, to analyze trends between clogging and parameters, including area population, roadway use, precipitation frequency, seasonal analysis, and inlet designs, to help inform future KDOT decisions regarding bridge deck drainage maintenance and design. This project would take approximately two years and could be expanded to multiple states for further in-depth analysis.

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Appendix A: Literature for Departments of Transportation

A.1 Kansas Department of Transportation

The first procedure examined in this study was for the Kansas Department of Transportation. KDOT's standard procedure for bridge deck drainage is provided in their *Design Manual: Volume III Bridge Section.* Section 8.1 of the manual provides general design considerations regarding bridge deck drainage for Kansas. KDOT states that the drainage on bridge decks is a maintenance problem and should be used only as necessary. Since maintenance is time consuming and costly, design of the drainage system should consider a 50% inlet capacity to account for clogging due to debris. KDOT's manual states that drainage for bridges with long lengths need to be scuppers or grates, and for short length bridges, the runoff coming onto the bridge may be removed before the bridge and the shoulder of the bridge may adequately contain spread and flow. Short continuous overpasses may be constructed without inlets but must use a flume or inlet near the end of the bridge, with an open flume running down the side or fore slope for ease of access. In addition, bridges with expansion joints must include inlets designed to remove as much flow as possible before the flow crosses the joint. For bridges with required curbing, the shoulder should be used as a gutter to convey flow. Each of these aspects, as well as the safety of roadway users, must be examined during the design process.

Section 8.2 of KDOT's bridge design manual discusses the design procedure for bridge deck drainage based on HEC-12 and HEC-21. Discharge is calculated using the rational method. The given runoff coefficient used for KDOT is 0.9, with intensity derived from a trial-and-error solution for the time of concentration. The time of concentration is based on the kinematic wave equation provided in HEC-12 and HEC-21 but does not factor in the side-flow time of concentration, as shown in HEC-21. Storm frequency is either 10 years for route Designation A and Designation B or 5 years for Designation C, Designation D, and Designation E. KDOT policy is to use the 5-minute storm for the design of bridge drains if the calculated time of concentration is less than 5 minutes. The time of concentration is estimated starting with an estimated drain location and the 5-minute storm to find rainfall intensity from the Rainfall Intensity Tables for Kansas. These values are then compared, and multiple iterations are done until the times match. Drain locations are to be placed so that drainage does not fall on the width of railroad ballast onto the shoulder of a road beneath an overpass. Drains can be placed near abutments if a splash guard is used. For sag, vertical curves located on a drain must be placed at the low point of the curve with flanking inlets on both sides of the low point. The flanking inlets must limit the spread of water and act as a relief point for clogged inlets. HEC-12 is used as the design guide.

Design top width should not exceed 10 ft or one-half a thru lane for at least a two-lane highway in one direction. For urban areas with high traffic volume, the designer should select a spread that excludes all lanes from flooding. For two-lane highways, traffic lanes in each direction should not be less than 10 ft wide. The design top width is calculated based on a modified Manning's equation for gutter flow in which the variables affecting design flow in gutters as the Manning's equation applies to bridge decks are the cross slope of the bridge way (S_x,) the road grade (S), Manning's coefficient n, and a constant (K), which is 0.56 for Kansas. The captured discharge at the first point is calculated using the discharge from the rational method multiplied by the scupper efficiency equation. For each point after this, the Manning's equation is used to calculate the discharge at each successive inlet to determine if the spacing meets the design spread requirements. This is a trial-and-error process and is done throughout the bridge deck length as required, as described in Section 8.3 and Section 8.4 of KDOT's manual. The next section describes and compares other DOT processes.

A.2 Arkansas Department of Transportation

The only available manual relating to drainage for the Arkansas DOT (ARDOT) was the Arkansas Highway and Transportation Department (AHTD) *Drainage Manual* from 1982, which is based on concepts in HEC-12. The bridge hydraulics section of the manual primarily addresses the hydraulics of bridge piers for stream crossings, while the remainder of the section provides general principles of roadway drainage design that can be applied to the design of bridge deck drainage. No standard drawings were found for typical bridge deck drains. Further investigation is required for exact systems used in the state of Arkansas.

Chapter 5 of ARDOT's design manual describes the design of storm sewers and roadway drainage inlets, and section 5-200 states that runoff discharge is to be determined using the rational method. Roadway ponding requirements are divided into four classes based on roadway type. For interstate and fully controlled access, types of spread are limited to one-half the outside lane width using a 50-year design storm. For federal aid projects, the spread is limited to the width of the outer lane using a 10-year design storm, while for non-federal roadways, the spread is limited to the outside lane using a 2-year design storm. Finally, for minor two-lane highways and streets, the spread is limited to the depth allowed for one lane of traffic to pass.

The inlet's capacity for a curb inlet in a sag (section 5-502) is governed by weir flow, and two equations are given for the case of submerged versus unsubmerged cases controlled by the length of the inlet, depth of water, and height of the inlet opening (for the submerged case only). In the case of grate inlets in a sag (e.g., on a bridge deck), the equations for capacity are given in section 5-504. The capacity of this configuration is independent of inlet geometry, and for depths less than 0.4 ft, it is governed by weir flow, which is based on the perimeter of the grate opening (*P*) and the depth of water (*d*). For an inlet against a curb, one side of the perimeter must be removed. If depth exceeds 1.4 ft, grate capacity is controlled by weir flow, which is based on the clear waterway area of the grate (*A*) and the depth of water above the top of the grate (*d*). For grate inlets on grade (section 5-505), the length of the grate is calculated based on velocity, water depth, and an *m* factor for various grate configurations. Discharge is determined using the orifice equation for rectangular orifices based on the coefficient of discharge (*C*), area of the opening (*A*), gravity, and depth of water above the grate (*h*). However, the grate inlets only operate at 50% capacity of the determined discharge from the orifice equation. Section 5-505 and Section 5-506 analyze combination inlets and slotted drainpipes.

Section 5-508 provides hydraulic analysis as it relates to curved vane inlets. For this analysis, the flow is divided into frontal flow and side flow, which is consistent with design procedures in HEC-12 and HEC-21 for design of bridge deck drains. The hydraulic efficiency of a grate is the ratio of flow intercepted by the gutters. Frontal flow efficiency primarily depends on bar configuration, grate length, and flow velocity. Splash over occurs on steep slopes in which only a portion of frontal flow is captured. For side flow, interception increases with longer grates and lower velocities. The equation for the ratio of frontal flow can be rewritten from the modified Manning's equation, which utilizes grate width and top width of waters. These design criteria are consistent with other DOTs and HEC-21 that use the same equations. A typical safety factor of 1.5

is recommended for bridge deck design to account for clogging. Section 5-508.2 discusses the selection of grate types and provides a table listing the efficiencies of six types of grates. The larger the spacing between bars in the direction parallel to flow, the higher the efficiency, but the effect on the safety of pedestrians must be considered as people can step through large enough openings causing injury. Overall, ARDOT's drainage manual follows procedures developed in HEC-12 and current bridge deck drainage application in HEC-21.

A.3 Colorado Department of Transportation

The Colorado DOT (CDOT) addresses bridge deck drainage systems in Section 9 of the *CDOT Bridge Design Manual* and section 10 of the *CDOT Drainage Design Manual*. Section 9.15 of the bridge design manual recommends following procedures laid out in AASHTO 9.4.2, HEC-21, and HEC-22 to develop the size and type of grated inlet to be used based on bridge characteristics. The designer must minimize the amount of deck drains to limit future maintenance, intercept water before expansion joints, and avoid discharging on girders, piers, roadways, and railways.

Chapter 10, Section 10.5.4 of the drainage design manual states that poorly designed deck drainage systems can cause corrosion, icing, and hydroplaning. The manual asserts that an ideal bridge is located on a crest vertical curve and that super elevation due to cross flow is not acceptable. Bridge decks must be watertight, and drainage should be taken to the end of the bridge. If flow is to be intercepted along the bridge, the design must follow HEC-21. Chapter 13 of the *CDOT Drainage Design Manual*, which describes the generic design procedure for pavement design and inlets, recommends use of the rational method to estimate flows and time of concentrations. Design frequency and spread are to be selected based on the highway classification, as shown in Section 13.2.3 and Section 13.2.4. For interstates with a design frequency of 2–5 years, the spread width is limited to the shoulder; for a 10-year frequency, the spread width is limited to the shoulder plus 3 ft. For arterials with speeds less than 45 mph, design frequencies of 2–5 years have a spread width of the shoulder plus 4 ft, and 10-year frequencies use a design spread of the shoulder plus 3 ft. Arterials with speeds greater than 45 mph require a design frequency of 2–10 years, and the design spread is limited to the shoulder. For collector roads with speeds less than 45 mph, the design frequency can be 2–10 years and design spread width is half the driving lane. Collectors with speeds greater than 45 mph have design frequency categories of 2–5 years and 10 years with design spreads of the shoulder plus 4 ft and just the shoulder, respectively. For local streets, the design frequency is 2–10 years with a spread of half the driving lane.

Section 13.4 of the manual states that inlets should be located at sag points, upstream of exit/entrance ramps, and in areas to collect snow melt no matter if hydraulic design calls for them or not. To prevent cross flow, inlets are required 10 ft from the point where the cross slope begins to super elevate. Sag vertical curves require inlets at the low point, with flanking inlets on each side of the low point. Appendix A of the manual provides nomographs for the inlet capacities of common inlets on constant grades used in Colorado, and section 13.4.5 gives the inlet debris capacity reduction for clogging. For inlet openings less than 20 in.^{2}, the reduction to flow is 30%–60%. For inlets with areas of 20–60 in.^{2}, the reduction is 20%–50%, and for inlets with openings larger than 60 in.^{2}, the reduction of flow is 10%–30%. Although CDOT provides general criteria for bridge deck drainage, a designer primarily must follow HEC-21 and AASHTO guidelines.

A.4 Florida Department of Transportation

FDOT's website contains two documents pertaining to the design of bridge deck drainage: *State of Florida Department of Transportation Drainage Manual* and *FDOT Drainage Design Guide.* The design guidelines refer to the use of HEC-21 for hydraulic analysis of bridge deck drainage. Section 4.9.4 of the drainage manual presents information on bridge deck drainage, and section 3.9 of the manual provides spread standards for bridge decks based on a rainfall intensity of inches/hr. For full-width shoulders, the encroachment is limited to the shoulder width at all speeds. For all other conditions, design speeds less than 45 mph allow for the shoulder width plus half the outside lane. For speeds between 45 and 55 mph, 8 ft of the outside lane must remain clear, and for design speeds greater than 55 mph, spread is limited to the shoulder only.

Section 4.9.4, Subset 4.9.4.2 of the manual addresses scupper drains, describing the standard scupper as 4 inches in diameter at 10 ft on center spacing. The standard spacing only changes if spread calculations show that closer spacing is required. As is typical with other DOTs, scuppers cannot discharge onto railways, roadways, paths, or sidewalks. Analysis is required for structures exposed to severe wave attacks, which this study did not investigate because it does not pertain to the state of Kansas.

Section 5.6 of the *FDOT Drainage Design Guide* provides guidelines for deck drainage. FDOT has three options for draining bridge decks. The first and most preferred method uses a longitudinal grade of the bridge to carry runoff to the bridge end drain, although this method is limited by spread width. The second option utilizes an open system, or scuppers and inlets, that freely drain. If discharge cannot fall directly under the bridge deck, then the third option, or a closed system that uses a pipe system, must be used to take discharge to the pier or bridge ends. Section 5.6.2 of the design guide focuses on the first option. Spread must be checked to meet width requirements where the curb wall ends at the approach slab and at the first off-bridge inlet to avoid the use of scuppers or inlets. Spread is calculated based on the gutter flow equation in Section 6.3.2 of HEC-12 and shown in HEC-21. To reduce spread, FDOT recommends making the longitudinal slope of the bridge steeper and placing a crest or high point near the middle of the bridge. Example 5.6-1 illustrates checking spread for viability using the first option.

Section 5.6.3 of the design guide discusses the use of scuppers in an open system. FDOT scuppers are made from PVC pipe set in place before bridge deck concrete is poured. The scupper is placed a 0.5 inch below the top of the deck, and an inlet measuring 10 inches by 9 inches is created to direct flow to the scupper pipe. As stated in the *State of Florida Department of Transportation Drainage Manual*, scuppers must not be placed over travel ways, navigation channels, bridge bents, or wildlife areas and must use a 10-ft spacing. Intercepted flow for 4-inch scuppers can be verified with capacity curves developed from laboratory studies at the University of South Florida in 1973. Grated scuppers or inlets, which are uncommon in Florida for open systems, are primarily used in closed systems or bridges with sidewalks. FDOT does not have a standard grate scupper or grate inlet and no standard capacity charts, which must be calculated using Section 6.3.1.5 or Section 7.4 of the *FDOT Drainage Design Guide* or manufacturer-provided design charts. Standard inlets are preferred for use in the field because they are prefabricated and meet structural constraints. Section 6.3.1.5 and Section 7.4 provide three examples of analysis of grate scuppers based on the rational method and gutter flow equations included in HEC-12. Section 6.3.1.5 and Section 7.4 also describes the analysis setup in Excel. For vertical curves, a detailed analysis in Section 5.6.4 can be used as the gutter flow equations based on a normal depth, although the manual states they may be overconservative. Section 5.6.4 details analysis procedure for sag vertical curves.

Grated inlets are to be used to limit debris entering the collection system. The procedure shown in Section 5.6.3 of the *State of Florida Department of Transportation Drainage Manual* for grated inlets is to be used as a guideline, except that a more detailed approach is required to account for deck design that violates equilibrium assumptions for previous cases. Analysis considers flow at each scupper as opposed to total flow of the deck. Two types of collection systems are used with the first discharges at the piers or bridge bents. Inlets are typically located near piers to minimize horizontal pipe segments, which makes the inlet entrance the controlling factor. The second type of system sends drainage to the bridge ends, requiring the use of longitudinal pipes to carry flow from multiple inlets.

Design of under-deck piping is described in Chapter 6 of the *Drainage Design Guide*. The layout of the collection system should have a minimum velocity of 3 ft per second to allow debris flushing in the system. Clean-out locations should be accessible and reach all areas of the collection system, and system design should minimize the use of corners and junctions while utilizing Y-connections and bends for downspouts to reduce clogging. Chapter 22, Section 22.3 of the *FDOT Structures Detailing Manual* lists collection system materials and size guidelines. Pipes should be 8 inches in diameter with a 6-inch minimum, and 12-inch diameter pipes are recommended for longitudinal pipes. Recommended materials include PVC, fiberglass, or ductile cast iron.

To assess inlet capacities, designers are to consult Chapter 6 of the drainage design guide, which describes general practices for storm drains. The rational method is used for all inlet capacity calculations with a 10-year design frequency. Section 6.3.2 discusses pavement hydraulics, revealing that FDOT uses 4 inches/hr for the intensity. Gutter flow rate is calculated from the Manning's equation in HEC-21, and analysis is done only if grated inlets are used at non-standard spacing. The design guide recommends using the procedures described in HEC-12, HEC-21, and HEC-22. Spread calculation is done by noting overland flow at all locations and adding the bypass flow calculated via charts to find the spread at each point; then spacing is adjusted as needed. This process is similar to KDOT's and other DOT's procedures that follow general guidelines of HEC-21. For the pipe system, designers should consult Section 6.5.2 of the *State of Florida Department of Transportation Drainage Manual* for partially full-flowing pipes, which states that only the values of lower-end hydraulic gradient, upper-end hydraulic gradient, and flow velocity are needed to determine pipe selection due to analysis difficulties. Florida has easy-to-follow guidelines as they have a standard scupper and spacing to use with bridge decks.

A.5 Illinois Department of Transportation

The Illinois DOT (IDOT) uses the *IDOT Bridge Manual*, which is the primary source of design reference, and the *IDOT Drainage Manual* for design and hydraulic analysis of bridge deck drainage for Illinois. IDOT's website provides a scupper design guide from AASHTO called 2.3.6.1.8 Bridge Scupper Placement and drawings that show typical scupper details and the 4-inch by 12-inch floor drains used. These policies are primarily based on HEC-21.

Section 2.3.6.1.8 of the *IDOT Bridge Manual* is the main source for bridge deck design. IDOT states that each bridge shall be evaluated to see if drainage is required for control. Drainage scuppers and floor drains are only to be used when they are needed to limit the spread of water on superstructure elements, and drainage should be considered when establishing road profile to limit drainage effects. IDOT specifies minimum cross slopes of 1.56% and prefers to eliminate crossroad flow.

Two subsections describe the types of drainage used in the manual. The first subsection discusses bridge drainage scuppers. IDOT requires scuppers on bridge decks to prevent gutter flow from spreading into traffic lanes or spread-width limitations. The spread for scuppers cannot exceed more than 1 ft onto the outer lane when the design speed is 50 mph or greater and not more than 3 ft onto the outer lane for speeds less than 50 mph. These limits are assessed at a 6 inches/hr rainfall intensity. Drainage scuppers are to be placed at distance *D1* from the high point on the bridge and spaced at distances determined by the Drainage Scupper Location by Hydraulic Analysis subset of this section in the bridge manual. Scuppers are required at the low point of any sag curve on a bridge deck and areas in which there is a super-elevation transition to prevent cross flow and upslope of any expansion joints. For scuppers with free fall systems, the locations should be at least 10 ft away from the face of substructure elements, and for areas in which an open system is not allowed, a closed system must be used that attaches to the downspouts of the scuppers. IDOT prefers the free fall system over the closed system.

The other type of drainage detailed in this section is floor drains. For bridge decks on road grades less than 0.5%, free fall floor drains are to be used with a spacing of 25 ft on center. This should also be used for crest vertical curves with roadway design K-values of 167 or greater with road grades 0.3% or less. Additionally, fall floor drains must be at least 10 ft away from substructure surfaces. Designers must determine if the specified spacing is adequate with a closed system.

The second subsection pertaining to the design of bridge deck drainage focuses on drainage scupper location using hydraulic analysis in the *IDOT Bridge Manual*. This subsection provides the equations necessary to determine the number of required drains and their spacing. The equations, which are for triangular flow in channels, are derived from the gutter flow equations in HEC-21. Design Guide 2.3.6.1.8 - Scupper Placement describes the procedure with an example for scupper placement. The process determines the distance to the first scupper location and is iterative due to varying longitudinal slopes since most bridges are located on crest vertical curves. Step 1 of the procedure is to assume the longitudinal slope at an arbitrary distance to the first scupper location based on a location perceived to intercept the most flow. Step 2 of the process calculates the flow rate at the first location using the assumed values with the modified Manning's equation based on the maximum allowable depth of water dependent on the allowable gutter spread. Step 3 determines the actual location of the first scupper using the flow rate determined from the previous step. The equation for distance is the same as that of HEC-21, and the rainfall intensity is 6 inches/hr. Step 4 compares the assumed and calculated values to verify if slope is correct. If the values match, the slope is valid; if not, then Step 1 through Step 4 are repeated until the calculations converge on the correct slope.

The process to determine the distance between the first and second scupper is a 10-step procedure that requires the use of an iterative process if assumed values do not match calculated values. This process may be used to determine the scupper distance from a high point. The flow for the second scupper includes the drainage area discharge and bypass discharge. The first step of the process is to find the depth of flow at the curb face of the first scupper using a rearranged gutter flow equation. Step 2 determines the actual spread at the first scupper using the previous depth determined by Step 1 and the reciprocal of the cross slope. Step 3 determines the velocity at the first scupper with the Manning's equation for gutter flow, and Step 4 finds the fraction of frontal flow capture at the first scupper. (IDOT lists splash-over velocities in this step as 5.8 and 2.8 ft/sec depending on the grate set up.) Step 5 determines the flow that bypasses the first scupper using the frontal flow ratio and depth of flow at distance from the curb and the first calculated depth, while Step 6 assumes a distance between scuppers and determines the longitudinal slope from the profile at that location. Step 7 determines the flow rate at the second scupper locations. Step 8 finds the total discharge at the second scupper by combining bypass discharge and drainage area discharge, Step 9 determines the depth of flow at the curb face of the second scupper, and Step 10 verifies if the assumed distance is correct by comparing the maximum flow depth and the calculated flow depth. If they are similar, then the process is complete; otherwise, the process repeats until they match. This process is used to determine the remaining subsequent scupper locations.

The final document reviewed from IDOT was the *IDOT Drainage Manual.* The section that discusses bridge deck drainage gives encroachment values and recommendations. The drainage manual states that the rainfall intensity for the limit is 7 inches/hr, while the bridge manual uses 6 inches/hr. This document also asserts that theoretical distances of scuppers should be reduced from 25% to 50% to account for clogging. The rest of the design procedures are identical to those stated in the bridge manual. IDOT follows all rules and recommendations for bridge drainage as well as the exact analysis plan derived from HEC-21 for an easy-to-follow format.

A.6 Iowa Department of Transportation

The Iowa DOT's bridge deck drainage design procedure is outlined in their *LRFD Bridge Design Manual*. Hydraulic analysis for deck drains is based on protocols set forth in HEC-21 and HEC-22. Stated benefits of deck drains include water removal from rain events and during snowmelt to limit freezing. The policy also states that the removal of deck drainage before it reaches the bridges' ends will reduce damage to joints and approaches. Deck drains require routine maintenance and cleaning but the available financial resources to clean the drains may not be available, thereby reducing their efficiency. The Iowa DOT states that the need for deck drains is based on engineering judgment, bridge-feature maintenance practices, and hydraulic evaluation. Iowa refers to two types of systems in their manual: the open system, which is a simple drain assembly with minimal piping that drains directly downward below the structure, and a closed system in which a piping assembly removes drainage horizontally to a pier and is directed to the ground.

Section 5.8.4.2.1 of the manual provides analysis and design guidelines for edge drains. The first set of guidelines applies to drain location. The manual states that a minimum of one deck drain should be placed in each interior span and two deck drains in each end span. For normal crown roads, the drains should be placed in the low edge of the roadway and spacing should not exceed 50 ft for tube drains and 100 ft for scuppers. For super-elevated bridges, the drains should be placed on the low edge only and flow should be intercepted before the transition points. The grade of the road determines if deck drainage is needed; grades less than 0.3% require additional drains. When low points are located on a bridge, a drain should be placed at the low point and a flanking drain should be placed in each direction from the low point spaced 5–10 ft. For bridges with a crest curve, the first drain should be placed 50 ft away from the crest and not on the high point. Deck drains should be placed 10–15 ft from the bridge end and expansion joints to capture water from flow into these areas. Drains in open systems must be 10 ft from the piers to prevent corrosion from deicers and 20 ft if the free fall height is 25 ft or more. If these criteria are met, then hydraulic analysis may not be needed. Situations that require confirmation through analysis include stub abutments, low points, super elevations, and bridge widths larger than 60 ft.

The second subset of section 5.8.4.2.1 discusses location restrictions of deck drains as they relate to the use of an open system. Open systems do not allow drainage over current or future traffic lanes and shoulders or railroad right of ways, and free fall is not allowed to land on sidewalks, walking trails, or biking trails. To prevent erosion and undermining in sensitive areas, the drains cannot be placed above concrete slope protection or retaining walls. Finally, the open system may not be placed over levees or drainage towards levees.

Subset 3 of the analysis and design section discusses the type and size selection criteria for typical bridges. The first type of hydraulic analysis is the tube drain, or open system, which consists of 4-inch by 8-inch galvanized tubes without grates (located at the deck railings) that drain directly below the inlet. Drain tubes are attached to the outside of the girders and are visible to passing traffic. The second type of selection is the scupper drain in an open system that is located near the deck railings and discharges directly below through an 8-inch galvanized pipe at the low end of the drain trench. The scupper consists of a deck grate, and the discharge pipe is not visible to traffic passing under the bridge, making it aesthetically pleasing. The final drainage system used is scupper drains in a closed system with a deck grate, scupper, and under-deck collection system, which directs captured discharge to a bridge pier and the ground. This system is generally avoided due to the financial cost and time to perform preventative maintenance to remove debris. The piping system consists of a minimum 8-inch diameter pipe, and it must be sloped at 8% or more with clean-outs. The commentary section states that the downspouts that run down the bridge piers should be 6–8 inches in diameter.

Subset 4 in this section provides an overview of hydraulic analysis guidelines. The hydraulic analysis should be completed using HEC-21 with a 10-year, 5-minute rainfall event and consider a 25-year, 5-minute check event. The rainfall intensity used throughout the state is 8 inches/hr for bridge deck drains. Iowa's DOT limits the design spread to the width of the shoulder or part of the traffic lane if no shoulder is available. For two-lane highways with speeds less than 45 mph, the maximum spread is up to 3 ft of the traveled lane. For two or more lanes in each direction, the spread is up to 6 ft of the outside lane. If a bridge is in an urban area with a curb and gutter, the spread is limited to 7 ft from the bridge barrier. For all other cases, the office of design should be consulted. This section also contains a table for the bridge deck drain rainfall criteria and all equations from HEC-21 and HEC-22 to be used for hydraulic analysis. The reduction for clogging is usually left at 100% or no reduction due to the rare cause of major problems from clogging on inlet interception.

The final section (5.8.4.2.2) for bridge deck drainage details requirements for the systems. For drain tubes in an open system, the downspout must extend 12 inches below the bottom flange of the bridge beams and 6 inches below the slab for slab bridges. Grates for scupper drains must have bars that are perpendicular to the traffic flow for motorist and bicyclist safety. Section C5.8.4:4 provides the Iowa DOT drain dimensions and layouts for each type of drain system.

A.7 Michigan Department of Transportation

The Michigan DOT (MDOT) uses three useful documents for bridge deck drainage. The first document is the *Michigan Bridge Design Manual*, specifically section 7.02.26 on drain castings, which recommends that drain castings should be avoided when possible. If necessary, then design must be based on HEC-21 or an equivalent manual. Deck drains are to not fall on slopes or roadways below the bridge deck. Drain castings for Michigan are listed under a special details section on the state's website, which lists two types of drain castings, both with 12.875-inch by 13-inch rectangular grate with 1.125-inch parallel grate bars spaced at 1.5 inches on center. They both also use a 9.5-inch square opening with a square-to-round transition to 8-inch diameter downspouts made of fiberglass or polyethylene plastic. The first type of drain drains directly below itself, whereas the second type of drain has a square casting angled at 45° sloping to the vertical downspout.

Bridge deck drainage is discussed further in the *Michigan Department of Transportation Drainage Manual.* Chapter 6 of the MDOT drainage manual discusses hydraulic design guidelines as they relate to bridges. Section 6.3.4 provides the policy for bridge deck drainage, stating that pavement drainage for a bridge should conform to the criteria used on the approach roadway and follow, as stated in the bridge manual, HEC-21 for design and spacing of drainage at intermediate points along the bridge as well as determine which inlets are required. However, a collection system is necessary when intermediate interceptors are used. The drainage manual also recommends considering the complexity of the drain systems since they require design and maintenance. Other considerations include use of an 8-inch minimum projection below the flange of the bridge beams as well as application of erosion control for areas beneath free drops. Section 6.4.8 includes design guidelines for deck drainage systems, stating that deck drains are less efficient due to flat cross slopes and more potential debris that complicate maintenance. Therefore, flow from preceding roadways must be intercepted before the bridge deck. Gutter spread of deck drainage must be compared with spread criteria in Chapter 7 of the drainage manual.

Chapter 7 of the MDOT drainage manual provides the design frequency and spread criteria for pavement and bridge decks. Spread and frequency is based on the speed and traffic volume of a roadway. For high-volume roads, a 10-year design storm is to be used where spread is limited to the shoulder. A 50-year storm should be used for a sag curve, with the spread limited to the shoulder. Similar to other DOTs, no rainfall intensity limits are given, meaning HEC-21 guidelines should be followed. MDOT literature clearly asserts that HEC-21 is to be used for the design of bridge deck drainage systems along with the use of the two types of grated scuppers given in the standard details.

A.8 Minnesota Department of Transportation

The Minnesota DOT (MnDOT) references bridge deck drainage in the *Minnesota LRFD Bridge Design Manual* and the *MnDOT Drainage Manual.* Four standard bridge deck drains are given in their standards drawings. Section 9.1.1 of the bridge manual offers considerations for deck drainage, including discouraging the use of deck drains due to required maintenance from debris clogging as well as leaks in the inlet box that cause structural damage. Bridges less than 500 ft in length may not need deck drains if they are located over lakes or streams, while bridges over 500 ft in length may require deck drains due the larger gutter flow generated compounding across the length of the bridge. The bridge manual also requires that drains extend at least 1 inch below the bottom of the superstructure, although a 1-ft extension is preferred if possible. As is standard with other DOTs, MnDOT requires that drainage avoid discharging over roads, road shoulders, sidewalks, railways, and streams.

Standard bridge details B701, B702, B705, and B706 are the standard bridge drains utilized by MnDOT. Detail B701 depicts a welded box floor drain with a downspout directly underneath the drain pan. The box at the surface is 1.5 ft^2 with a drain pan sloped toward the inlet downspout. The downspout is a TS 10-inch by 6-inch by 0.25-inch square tube, and the vanes at the inlet grate are at a 45° angle to the road. Detail B702 shows the structural tube floor drain that consists of a TS 6-inch by 6-inch by 0.25-inch structural tube draining directly down below the deck at a slight angle with a 0.75-inch grate bar in the middle of the tube at the surface. B705 is used when an offset of the rectangular tube is required for the weld box drain. Drain B705 is essentially the same as B701, except the drain inlet is moved down in the deck and over to avoid the bridge beams. B706 uses a 6-inch scupper placed at the required distance so that the structural tube drain attached to the scupper can drain directly vertical and avoid the bridge deck beams. Each design requires 1 ft on each side of the deck to be sloped toward the drain.

Hydraulic analysis procedure of deck drains is given in the *MnDOT Drainage Manual.* This manual references HEC-12 and HEC-21 for storm drainage systems. Chapter 3 in the drainage manual focuses on hydrology, giving the design frequency and spread for storm drains. For traffic volumes greater than 6000 vehicles per day (VPD), the design frequency is a 10-year storm with an allowable spread of the shoulder width or the driving lane if there is no shoulder. Although the criteria for traffic volumes between 2000 and 600 VPD are the same, the allowable spread for no shoulder conditions is half the driving lane width. A 5-year storm with the allowable spread limited to the shoulder is used for average daily traffic (ADT) between 1000 and 1999, and a 3-year storm with the same spread width is used for less than 1000 VPD. Section 3.4 provides time of concentration equations from HEC-12 and the triangular gutter flow equation to estimate travel time from the HEC-12 nomographs. Section 3.5 offers the rational method equation with runoff coefficients from Section 3.5.3 and rainfall intensity tables from Section 3.5.4. No intensity limit is given for bridge deck drains because it is included in HEC-21 and other DOT manuals.

Section 8.5.6 of the manual discusses drainage design for bridge decks. The design is similar to curbed roadways except that bridge decks are usually less efficient due to cross slopes. Deck drainage cannot directly drain into water bodies in Minnesota, and MnDOT asserts that many bridges will not require any drainage structure. MnDOT use the following equation to determine if the deck length can achieve allowable spread:

$$L = \frac{24400\,(S_x^{1.67})(S^{0.5})(T^{2.67})}{CnIW}$$ **Equation A.1**

Where:

S = the longitudinal slope,

S_x = the cross slope,

W = the width of the drained deck in feet,

C = the runoff coefficient,

I = the rainfall intensity in inches per hour,

n = the Manning's coefficient, and

T = the allowable spread.

If the length is longer than the bridge length, then deck drainage is not required. If deck drainage is required, however, then Section 8.6 for gutter flow and Section 8.7 for inlet spacing are to be followed. Each section is directly from HEC-12, but use of HEC-21 is not explicitly stated in this section, although it is referenced at the end of Chapter 8. In addition, the drainage manual does not have a section detailing the collection system necessary for bridge decks. MnDOT's deck drainage closely follows HEC-12 and HEC-21 while using standardized inlets for each bridge if required.

A.9 Missouri Department of Transportation

The Missouri DOT (MoDOT) uses an online engineering policy guide for their design references. Section 751.10.3 focuses on bridge deck drainage, stating that bridges use a combination of slab drains and drain basins. The type of slab drains used are either steel or fiberglass-reinforced polymer measuring 8 inches by 4 inches by 0.25 inch with the 8-inch side orientated perpendicular to the curb for standard crown roadways and parallel for super-elevated roadways. Slab drain spacing is designed in accordance with a 1986 FHWA report (FHWA/RD-87/014, Bridge Deck Drainage Guidelines), a 1995 University of Missouri Rolla report (Scupper Interception Efficiency), and HEC-21. The general requirements for slab drain spacing include a minimum slab drain spacing of 8 ft, the omission of drains on the high side of super-elevated bridges, and the prohibition of drain locations over unprotected fill or in locations where water will fall on railroad and/or roadway overpasses. For bridges with less than 0.5% slopes, spacing should be 10 ft on center; spacing is to be consistent when possible. In addition, drains must be at least 5 ft from the face of substructure beams. For sag vertical curves with a slope of 0.5%, 10 ft spacing is to be used on either side, all gutter flow should be intercepted above transition points and expansion devices, and for all crest vertical curves with less than 0.5% slope, 10 ft spacing should be used if possible.

The MoDOT policy guide also provides an equation for calculating the location of the first drain spacing using a modified Manning's equation based on the cross slope (S_x), longitudinal slope (S), design spread (T), ratio of impervious to pervious drain area (C), Manning's coefficient of friction (n), and design rainfall intensity (I). According to the policy, $C = 1.0$ and $n = 0.016$. I is based on the HEC-12 rational method with a 10-year design storm at a 10-minute time period and is recommended to be 6.50 inches/hr. Design spread is listed for interstates of all speeds and major roadways with speeds greater than 45 mph as a maximum shoulder width of 10 ft. For major roads less than 45 mph and all minor roads, design spread is the shoulder width plus 3 ft up to 10 ft.

The calculation of additional drains is determined based on the amount of intercepted flow for the first drain. Capture efficiency is determined from the scupper efficiency equation based on scupper width and design spread. MoDOT uses an empirical formula for this equation based on empirical coefficients a and b, which depend on cross slope. MoDOT provide design tables for spacing and efficiency for when design spread is 6 ft, otherwise HEC-22 must be applied. Additional slab drains are located where the runoff minus intercepted flow is equal to the gutter flow at the design spread. Spacing is constant for tangent sections but spacing is variable for vertical curve sections and must be repeated for the entire bridge length. The policy gives some guidelines for calculations, noting that the length of the approach slab must be included in the length of the bridge for spacing calculations. For round drains, spacing is determined by the same method as the previously mentioned drains except the number of round drains must achieve a total cross section equal to the rectangular drains. MoDOT also lists many standard details to show the orientation and design of their drainage systems.

A.10 Nebraska Department of Transportation

The Nebraska DOT primarily uses the *Bridge Office Policies and Procedures Manual* for floor drain policies for bridge deck drainage. The vertical tubing of the floor drains must extend at least below the bottom flange of the bridge girder or bridge slab, a collection system must be used if water cannot fall directly below the inlets, and the system must provide clean-outs. However, the manual does not provide specifics regarding collection system design, although drainage usage must be investigated when closed rail or concrete barriers are used. For roadway speeds greater than 45 mph, the allowable design spread is the lowest edge of the driving lane; for speeds under 45 mph, the spread is the shoulder width of the highway plus half the outer lane width. Design spreads are based on a 10-year, 5-minute storm event.

The Nebraska DOT also uses the *Drainage Design and Erosion Control Manual* for bridge deck design. Chapter 1 of the manual specifies procedures for general pavement drainage, which is based on HEC-12. Section 6.C of the manual discusses design storm frequencies for each type of design location. For roadway gutters, the design storm of interstates, expressways, and roadways with an ADT over 7500 is 50 years; for roadways with an ADT of 7499 or less, the design storm is 10 years. Section 10 discusses Manning's equation in its general form based on cross slope, longitudinal slope, and depth of flow/width of flow. Section 10.B.3.a discusses the capacity of grate inlets on continuous grade based on the ratio of frontal flow to gutter flow. This equation, which is the same equation used in HEC-21, helps determine side and frontal flow efficiency of a grated inlet. The ratios of side and frontal flow are then used in the grate efficiency equation to determine the amount of captured total gutter flow. Additional designs sections are available for low points, weir, and orifice conditions, as well as for slotted pipe design. The drainage section primarily focuses on the drainage of non-bridge deck pavements, but parameters for gutter flow can be applied to bridge deck hydraulics.

A.11 Oklahoma Department of Transportation

An initial literature review revealed that the Oklahoma DOT (ODOT) uses only one manual relating to bridge deck drainage, the *ODOT Roadway Drainage Manual.* The ODOT website does not contain a bridge design manual or specific bridge drainage information. Chapter 10 of the drainage manual focuses on stormwater drainage and gives limits for design frequency, design spread, and inlet types and spacing based on the AASHTO Drainage Manual and HEC-22.

Section 10.4 of the drainage manual discusses ODOT policy on drainage and states that the rational method is used with 5-minute and 10-minute times of concentrations. Section 10.10 describes the procedure for gutter flow, which is the same procedure used in HEC-22, where the capacity is the modified Manning's equation for flow in triangular channels based on the design spread and road geometric properties. ODOT uses a K value of 0.56 and a Manning's n from 0.012 to 0.016. Procedures and equations are given for uniform and non-uniform gutter sections.

Only grate inlets are discussed in the manual, and Section 10.12 highlights the spacing of inlets and their capacity. Inlets should be placed at all low points in areas and flanking inlets should be placed upslope on both sides of the low point. The location of the first inlet is determined based on the rational method, as is used in HEC-21 and HEC-22 for inlet spacing. Section 10.12.3 discusses the capacity of grate inlets on grade, using frontal flow ratio equations and side flow equations from HEC-22. The section also includes splash-over velocity equations for various grate configurations. Efficiency, which is determined based on the ratio of side flow, is used to determine the interception capacity of the grate inlet. Section 10.12.4 discusses use of grate inlets in a sag curve in which the grate capacity depends on whether the inlet is in weir or orifice flow according to depth and HEC-22 procedure.

Although no ODOT manuals are solely devoted to bridge deck drainage, the principles in HEC-22 can be applied directly to the design process from bridge deck gutter flow. ODOT has set up a database through the University of Oklahoma to store DOT documents.

A.12 Texas Department of Transportation

The Texas DOT (TxDOT) uses the *Texas Department of Transportation Bridge Design Guide, TxDOT Hydraulic Manual,* and bridge drain details BD-1, BD-2, and BD-3 for bridge deck drainage procedures. Detail BD-1 shows a cast grate drain with a length of 3 ft, 7 inches and a width of 1 ft, 3.375 inches with an 8-inch diameter inlet pipe, with both grate bars running parallel and perpendicular at a 2-inch spacing along the width. Detail BD-2 is the same grate drain but is welded instead of cast. The grated drain is moved between girders in BD-3 so it can be used for bridges with wide girders that do not work with BD-1. The drainpipe is set outside the drain pain, eliminating 1 ft, 4.25 inches of length. TxDOT utilizes rectangular deck drains as demonstrated in the study by Qian et al. (2012, 2016).

The *Texas Department of Transportation Bridge Design Guide, TxDOT Hydraulic Manual* for TxDOT only addresses bridge deck drainage in Chapter 5, where it recommends designing drainage with surface drains, so water does not flow over expansion points. Chapter 9 in the hydraulic manual discusses deck drainage in greater detail. Section 7 specifically states that deck drainage can be improved by providing sufficient gradient, avoiding zero grades and sag curves, intercepting all flow from roadways before it reaches the bridge, and using open rails when possible. TxDOT commonly uses watertight joints to carry all drainage to bridge ends, thereby alleviating the problems of intercepting all flow before expansion joints. As with other DOTs, deck drains cannot drain directly onto roadways below, and downspouts should avoid erosion-prone areas. The use of a collection system is to be avoided if possible, otherwise clean-outs, short runs, and steep slopes should be provided, and a closed conduit down the fore slope is preferable to an open chute because it controls the water. Section 7 references the use of HEC-21 with bridge deck drainage design, specifically Chapter 10, Section 4 for spread limitations. TxDOT spread limits include half the outer lane width for highways and controlled access highways, width of the outer lane for major highways with two or more lanes, and the safest width for passage of one lane on a minor road. TxDOT standard design for deck drains is similar to other DOTs that use a trapezoidal pan and round inlet. TxDOT has also studied new inlets designs.

Appendix B: Survey for Departments of Transportation

DOT Bridge Deck Drainage Survey

DOT State:____

DOT Engineer Name:____

Phone: ___________________________ Email: ____

Questionnaire Section

1) Inlet Type Used: Scupper Grated Inlet Other (Please Specify):_____________________

2) Typical Inlet Size____

3) Material type of Inlet: ____

4) Inlet Manufacturer: ____

5) What are the most common issues that affect the bridge deck drainage (i.e., clogging, debris, collection system, capacity, etc.):____

____

____

____

Solutions:____

6) What type of data sets are available? Are maintenance records or accident reports available?

____

____

____

____

7) What type of collection system is used (i.e., 8” fiberglass, closed system)? Are there any problems with the system, such as clogging, that affect the drainage as a whole?

____

____

____

____

8) What type of grate system is commonly used? What is the efficiency of the grate?

____

____

____

9) For design, what factor is used to account for clogging? ___________________________________

10) What reference document is used for design: HEC-12 HEC-21 HEC-22 Other:_______

11) Is inlet spacing based solely on design or is a standard spacing used? _________________________

____

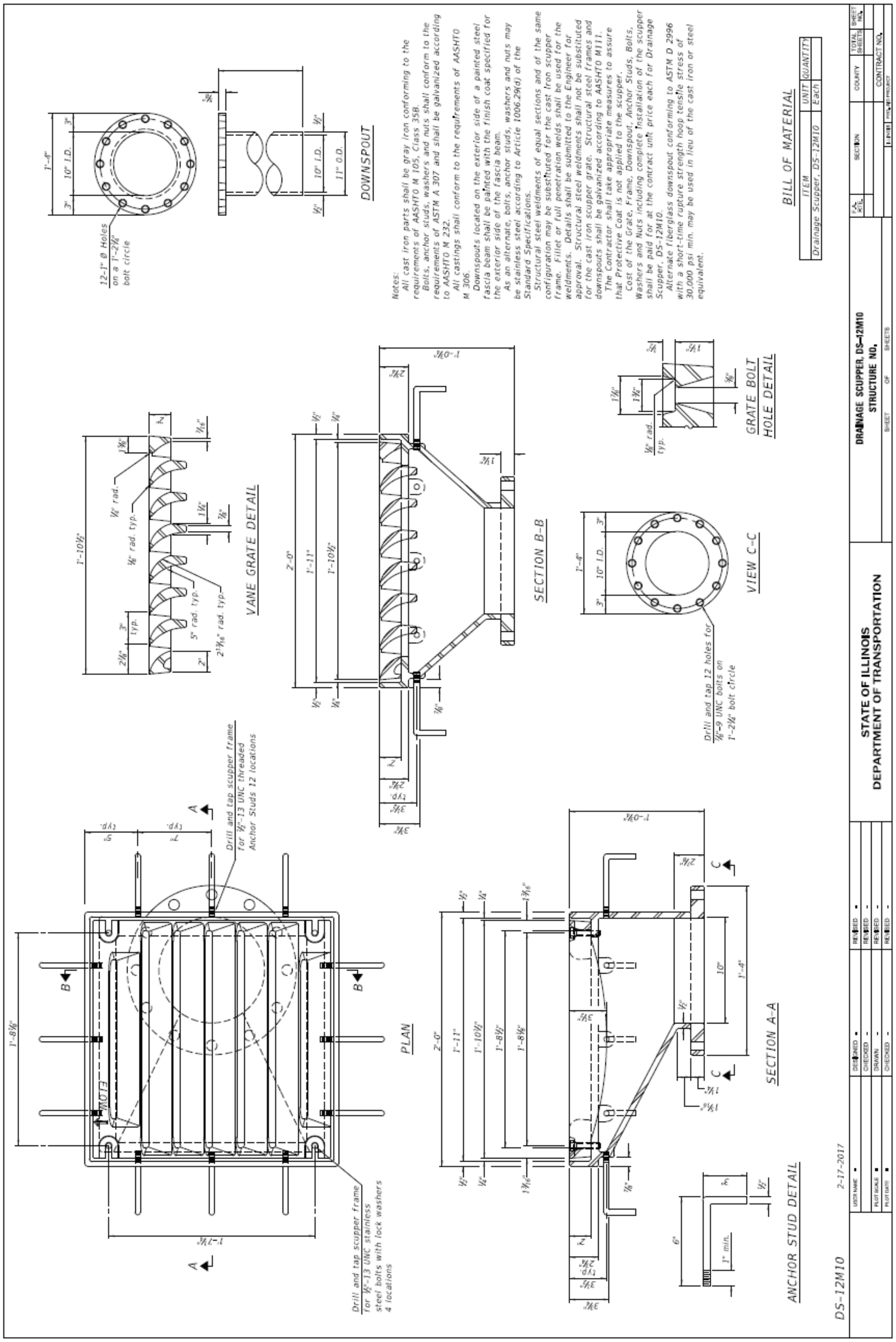
____

12) Additional provided reference material (details of typical inlets, design documents, etc.):__________

____

____

Appendix C: Curved Vane Grate Detail



Appendix D: Experimental Data for Efficiency Tests

Table D.1: Efficiency Experiment Measurements

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
1	1	Vane	Round	8	0.02	0.005	0.0068	0.0061	0.0052	38.27	0.85	0.18
1	2	Vane	Round	8	0.02	0.005	0.0068	0.0009	0.0008	23.60	0.85	0.29
1	3	Vane	Round	8	0.02	0.005	0.0068	0.0001	0.0001	8.57	1.00	0.79
4	1	Vane	Round	8	0.02	0.005	0.0116	0.0115	0.0075	43.43	0.65	0.16
4	2	Vane	Round	8	0.02	0.005	0.0116	0.0039	0.0029	23.23	0.73	0.29
4	3	Vane	Round	8	0.02	0.005	0.0116	0.0011	0.0011	14.20	0.97	0.48
4	4	Vane	Round	8	0.02	0.005	0.0116	0.0000	0.0000	2.03	1.00	1.00
7	1	Vane	Round	8	0.02	0.005	0.0161	0.0143	0.0071	48.30	0.49	0.14
7	2	Vane	Round	8	0.02	0.005	0.0161	0.0072	0.0047	27.33	0.65	0.25
7	3	Vane	Round	8	0.02	0.005	0.0161	0.0025	0.0024	19.07	0.95	0.36
7	4	Vane	Round	8	0.02	0.005	0.0161	0.0001	0.0001	6.13	1.00	1.00
10	1	bar	Round	8	0.02	0.005	0.0069	0.0068	0.0057	40.03	0.84	0.17
10	2	bar	Round	8	0.02	0.005	0.0069	0.0011	0.0007	21.70	0.66	0.31
10	3	bar	Round	8	0.02	0.005	0.0069	0.0004	0.0004	9.67	0.95	0.70
10	4	bar	Round	8	0.02	0.005	0.0069	0.0000	0.0000	1.93	1.00	1.00
13	1	bar	Round	8	0.02	0.005	0.0108	0.0099	0.0074	43.50	0.75	0.16
13	2	bar	Round	8	0.02	0.005	0.0108	0.0025	0.0020	24.03	0.80	0.28
13	3	bar	Round	8	0.02	0.005	0.0108	0.0005	0.0005	12.43	0.91	0.55
13	4	bar	Round	8	0.02	0.005	0.0108	0.0001	0.0001	3.50	1.00	1.00
16	1	bar	Round	8	0.02	0.005	0.0163	0.0138	0.0084	47.77	0.61	0.14
16	2	bar	Round	8	0.02	0.005	0.0163	0.0054	0.0033	26.90	0.61	0.25
16	3	bar	Round	8	0.02	0.005	0.0163	0.0021	0.0019	20.87	0.91	0.32
16	4	bar	Round	8	0.02	0.005	0.0163	0.0002	0.0002	6.53	1.00	1.00
19	1	Vane	Sq.	8	0.02	0.005	0.0072	0.0066	0.0058	39.03	0.89	0.17
19	2	Vane	Sq.	8	0.02	0.005	0.0072	0.0007	0.0003	15.87	0.38	0.43
19	3	Vane	Sq.	8	0.02	0.005	0.0072	0.0005	0.0004	10.67	0.96	0.64
19	4	Vane	Sq.	8	0.02	0.005	0.0072	0.0000	0.0000	1.33	1.00	1.00
22	1	Vane	Sq.	8	0.02	0.005	0.0104	0.0100	0.0074	43.57	0.74	0.16
22	2	Vane	Sq.	8	0.02	0.005	0.0104	0.0026	0.0017	23.23	0.66	0.29
22	3	Vane	Sq.	8	0.02	0.005	0.0104	0.0009	0.0009	17.33	0.98	0.39
22	4	Vane	Sq.	8	0.02	0.005	0.0104	0.0000	0.0000	3.23	1.00	1.00
25	1	Vane	Sq.	8	0.02	0.005	0.0162	0.0142	0.0088	48.20	0.62	0.14
25	2	Vane	Sq.	8	0.02	0.005	0.0162	0.0054	0.0035	30.07	0.65	0.23
25	3	Vane	Sq.	8	0.02	0.005	0.0162	0.0019	0.0018	20.90	0.95	0.32
25	4	Vane	Sq.	8	0.02	0.005	0.0162	0.0001	0.0001	5.80	1.00	1.00
28	1	bar	Sq.	8	0.02	0.005	0.0070	0.0065	0.0051	35.90	0.79	0.19
28	2	bar	Sq.	8	0.02	0.005	0.0070	0.0014	0.0010	20.90	0.73	0.32
28	3	bar	Sq.	8	0.02	0.005	0.0070	0.0004	0.0004	10.60	1.00	0.64

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
31	1	bar	Sq.	8	0.02	0.005	0.0112	0.0107	0.0070	42.60	0.65	0.16
31	2	bar	Sq.	8	0.02	0.005	0.0112	0.0037	0.0026	25.13	0.70	0.27
31	3	bar	Sq.	8	0.02	0.005	0.0112	0.0011	0.0011	17.53	0.97	0.39
31	4	bar	Sq.	8	0.02	0.005	0.0112	0.0000	0.0000	7.30	1.00	0.93
34	1	bar	Sq.	8	0.02	0.005	0.0160	0.0144	0.0087	46.17	0.61	0.15
34	2	bar	Sq.	8	0.02	0.005	0.0160	0.0057	0.0037	28.53	0.64	0.24
34	3	bar	Sq.	8	0.02	0.005	0.0160	0.0020	0.0019	20.67	0.95	0.33
34	4	bar	Sq.	8	0.02	0.005	0.0160	0.0001	0.0001	5.63	1.00	1.00
37	1	Vane	Round	10	0.02	0.005	0.0066	0.0062	0.0056	39.77	0.89	0.17
37	2	Vane	Round	10	0.02	0.005	0.0066	0.0007	0.0005	17.70	0.67	0.38
37	3	Vane	Round	10	0.02	0.005	0.0066	0.0002	0.0002	10.13	1.00	0.67
40	1	Vane	Round	10	0.02	0.005	0.0101	0.0092	0.0070	42.07	0.77	0.16
40	2	Vane	Round	10	0.02	0.005	0.0101	0.0021	0.0016	24.93	0.75	0.27
40	3	Vane	Round	10	0.02	0.005	0.0101	0.0005	0.0005	16.47	0.93	0.41
40	4	Vane	Round	10	0.02	0.005	0.0101	0.0000	0.0000	6.70	1.00	1.00
43	1	Vane	Round	10	0.02	0.005	0.0155	0.0142	0.0093	46.17	0.66	0.15
43	2	Vane	Round	10	0.02	0.005	0.0155	0.0048	0.0033	27.57	0.68	0.25
43	3	Vane	Round	10	0.02	0.005	0.0155	0.0015	0.0015	21.33	0.96	0.32
43	4	Vane	Round	10	0.02	0.005	0.0155	0.0001	0.0001	6.43	1.00	1.00
46	1	bar	Round	10	0.02	0.005	0.0065	0.0059	0.0052	37.37	0.88	0.18
46	2	bar	Round	10	0.02	0.005	0.0065	0.0007	0.0005	20.37	0.75	0.33
46	3	bar	Round	10	0.02	0.005	0.0065	0.0002	0.0002	12.90	1.00	0.53
49	1	bar	Round	10	0.02	0.005	0.0109	0.0101	0.0072	41.80	0.71	0.16
49	2	bar	Round	10	0.02	0.005	0.0109	0.0029	0.0019	24.20	0.65	0.28
49	3	bar	Round	10	0.02	0.005	0.0109	0.0011	0.0010	17.50	0.93	0.39
49	4	bar	Round	10	0.02	0.005	0.0109	0.0001	0.0001	6.37	1.00	1.00
52	1	bar	Round	10	0.02	0.005	0.0158	0.0131	0.0084	44.37	0.64	0.15
52	2	bar	Round	10	0.02	0.005	0.0158	0.0047	0.0025	28.23	0.53	0.24
52	3	bar	Round	10	0.02	0.005	0.0158	0.0022	0.0020	18.17	0.94	0.37
52	4	bar	Round	10	0.02	0.005	0.0158	0.0001	0.0001	6.47	1.00	1.00
55	1	Vane	Sq.	10	0.02	0.005	0.0065	0.0059	0.0051	37.77	0.86	0.18
55	2	Vane	Sq.	10	0.02	0.005	0.0065	0.0008	0.0006	18.83	0.77	0.36
55	3	Vane	Sq.	10	0.02	0.005	0.0065	0.0002	0.0002	10.03	1.00	0.68
58	1	Vane	Sq.	10	0.02	0.005	0.0102	0.0086	0.0065	40.03	0.75	0.17
58	2	Vane	Sq.	10	0.02	0.005	0.0102	0.0021	0.0015	21.43	0.72	0.32
58	3	Vane	Sq.	10	0.02	0.005	0.0102	0.0006	0.0006	14.43	1.00	0.47
61	1	Vane	Sq.	10	0.02	0.005	0.0157	0.0139	0.0089	44.27	0.64	0.15
61	2	Vane	Sq.	10	0.02	0.005	0.0157	0.0050	0.0032	24.87	0.63	0.27
61	3	Vane	Sq.	10	0.02	0.005	0.0157	0.0018	0.0017	19.53	0.92	0.35
61	4	Vane	Sq.	10	0.02	0.005	0.0157	0.0001	0.0001	6.77	1.00	1.00
64	1	bar	Sq.	10	0.02	0.005	0.0067	0.0060	0.0044	37.63	0.72	0.18

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
64	2	bar	Sq.	10	0.02	0.005	0.0067	0.0017	0.0011	21.33	0.67	0.32
64	3	bar	Sq.	10	0.02	0.005	0.0067	0.0006	0.0006	17.83	1.00	0.38
67	1	bar	Sq.	10	0.02	0.005	0.0103	0.0093	0.0061	39.53	0.66	0.17
67	2	bar	Sq.	10	0.02	0.005	0.0103	0.0032	0.0022	22.13	0.69	0.31
67	3	bar	Sq.	10	0.02	0.005	0.0103	0.0010	0.0010	19.43	1.00	0.35
70	1	bar	Sq.	10	0.02	0.005	0.0156	0.0137	0.0083	45.37	0.61	0.15
70	2	bar	Sq.	10	0.02	0.005	0.0156	0.0053	0.0036	25.40	0.68	0.27
70	3	bar	Sq.	10	0.02	0.005	0.0156	0.0017	0.0015	21.30	0.88	0.32
70	4	bar	Sq.	10	0.02	0.005	0.0156	0.0002	0.0002	7.27	1.00	0.93
73	1	Vane	Round	8	0.06	0.005	0.0069	0.0057	0.0056	18.10	0.99	0.37
73	2	Vane	Round	8	0.06	0.005	0.0069	0.0001	0.0001	5.13	1.00	1.00
76	1	Vane	Round	8	0.06	0.005	0.0109	0.0106	0.0076	21.13	0.72	0.32
76	2	Vane	Round	8	0.06	0.005	0.0109	0.0031	0.0029	12.37	0.94	0.55
76	3	Vane	Round	8	0.06	0.005	0.0109	0.0002	0.0002	7.10	1.00	0.95
79	1	Vane	Round	8	0.06	0.005	0.0160	0.0141	0.0079	22.40	0.57	0.30
79	2	Vane	Round	8	0.06	0.005	0.0160	0.0061	0.0056	14.77	0.92	0.46
79	3	Vane	Round	8	0.06	0.005	0.0160	0.0005	0.0005	9.80	1.00	0.69
82	1	bar	Round	8	0.06	0.005	0.0069	0.0062	0.0061	16.90	0.98	0.40
82	2	bar	Round	8	0.06	0.005	0.0069	0.0001	0.0001	5.13	1.00	1.00
85	1	bar	Round	8	0.06	0.005	0.0104	0.0090	0.0082	19.63	0.92	0.35
85	2	bar	Round	8	0.06	0.005	0.0104	0.0007	0.0007	8.40	0.98	0.81
85	3	bar	Round	8	0.06	0.005	0.0104	0.0000	0.0000	4.00	0.67	1.00
88	1	bar	Round	8	0.06	0.005	0.0158	0.0139	0.0083	22.80	0.59	0.30
88	2	bar	Round	8	0.06	0.005	0.0158	0.0056	0.0052	13.73	0.93	0.49
88	3	bar	Round	8	0.06	0.005	0.0158	0.0004	0.0004	9.10	1.00	0.75
91	1	Vane	Sq.	8	0.06	0.005	0.0070	0.0063	0.0063	17.43	0.99	0.39
91	2	Vane	Sq.	8	0.06	0.005	0.0070	0.0000	0.0000	3.10	1.00	1.00
94	1	Vane	Sq.	8	0.06	0.005	0.0103	0.0092	0.0088	19.23	0.95	0.35
94	2	Vane	Sq.	8	0.06	0.005	0.0103	0.0004	0.0004	7.00	1.00	0.97
97	1	Vane	Sq.	8	0.06	0.005	0.0158	0.0139	0.0092	22.73	0.66	0.30
97	2	Vane	Sq.	8	0.06	0.005	0.0158	0.0047	0.0047	12.93	0.99	0.52
97	3	Vane	Sq.	8	0.06	0.005	0.0158	0.0000	0.0000	7.33	1.00	0.92
100	1	bar	Sq.	8	0.06	0.005	0.0068	0.0060	0.0060	16.70	1.00	0.41
100	2	bar	Sq.	8	0.06	0.005	0.0068	0.0000	0.0000	2.67	1.00	1.00
103	1	bar	Sq.	8	0.06	0.005	0.0112	0.0089	0.0086	20.17	0.97	0.34
103	2	bar	Sq.	8	0.06	0.005	0.0112	0.0003	0.0003	5.07	1.00	1.00
106	1	bar	Sq.	8	0.06	0.005	0.0156	0.0139	0.0112	22.73	0.80	0.30
106	2	bar	Sq.	8	0.06	0.005	0.0156	0.0027	0.0026	10.07	0.97	0.67
106	3	bar	Sq.	8	0.06	0.005	0.0156	0.0001	0.0001	6.70	1.00	1.00
109	1	Vane	Round	10	0.06	0.005	0.0073	0.0066	0.0065	15.97	0.99	0.42
109	2	Vane	Round	10	0.06	0.005	0.0073	0.0000	0.0000	1.90	1.00	1.00

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
112	1	Vane	Round	10	0.06	0.005	0.0113	0.0102	0.0098	19.97	0.96	0.34
112	2	Vane	Round	10	0.06	0.005	0.0113	0.0004	0.0004	6.37	1.00	1.00
115	1	Vane	Round	10	0.06	0.005	0.0156	0.0142	0.0115	20.57	0.81	0.33
115	2	Vane	Round	10	0.06	0.005	0.0156	0.0027	0.0027	10.00	0.98	0.68
115	3	Vane	Round	10	0.06	0.005	0.0156	0.0001	0.0001	7.20	1.00	0.94
118	1	bar	Round	10	0.06	0.005	0.0072	0.0068	0.0067	17.33	0.99	0.39
118	2	bar	Round	10	0.06	0.005	0.0072	0.0001	0.0001	4.27	1.00	1.00
121	1	bar	Round	10	0.06	0.005	0.0114	0.0104	0.0099	19.63	0.95	0.35
121	2	bar	Round	10	0.06	0.005	0.0114	0.0005	0.0005	7.60	1.00	0.89
124	1	bar	Round	10	0.06	0.005	0.0161	0.0143	0.0128	22.27	0.90	0.30
124	2	bar	Round	10	0.06	0.005	0.0161	0.0014	0.0014	8.87	0.98	0.76
124	3	bar	Round	10	0.06	0.005	0.0161	0.0000	0.0000	4.87	1.00	1.00
127	1	Vane	Sq.	10	0.06	0.005	0.0066	0.0060	0.0060	16.93	0.99	0.40
127	2	Vane	Sq.	10	0.06	0.005	0.0066	0.0000	0.0000	2.87	1.00	1.00
130	1	Vane	Sq.	10	0.06	0.005	0.0105	0.0093	0.0091	19.47	0.98	0.35
130	2	Vane	Sq.	10	0.06	0.005	0.0105	0.0002	0.0002	5.77	1.00	1.00
133	1	Vane	Sq.	10	0.06	0.005	0.0155	0.0136	0.0121	20.18	0.90	0.34
133	2	Vane	Sq.	10	0.06	0.005	0.0155	0.0014	0.0014	8.47	0.99	0.80
133	3	Vane	Sq.	10	0.06	0.005	0.0155	0.0000	0.0000	2.23	1.00	1.00
136	1	bar	Sq.	10	0.06	0.005	0.0071	0.0062	0.0062	16.77	0.99	0.40
136	2	bar	Sq.	10	0.06	0.005	0.0071	0.0000	0.0000	4.67	1.00	1.00
139	1	bar	Sq.	10	0.06	0.005	0.0105	0.0091	0.0089	18.87	0.98	0.36
139	2	bar	Sq.	10	0.06	0.005	0.0105	0.0002	0.0002	5.87	1.00	1.00
142	1	bar	Sq.	10	0.06	0.005	0.0160	0.0143	0.0128	21.53	0.90	0.31
142	2	bar	Sq.	10	0.06	0.005	0.0160	0.0014	0.0014	8.53	0.98	0.79
142	3	bar	Sq.	10	0.06	0.005	0.0160	0.0000	0.0000	3.17	1.00	1.00
145	1	Vane	Round	8	0.02	0.01	0.0067	0.0060	0.0033	38.93	0.55	0.17
145	2	Vane	Round	8	0.02	0.01	0.0067	0.0027	0.0012	33.53	0.45	0.20
145	3	Vane	Round	8	0.02	0.01	0.0067	0.0015	0.0009	26.47	0.59	0.26
145	4	Vane	Round	8	0.02	0.01	0.0067	0.0006	0.0006	9.70	1.00	0.70
148	1	Vane	Round	8	0.02	0.01	0.0106	0.0096	0.0044	40.83	0.45	0.17
148	2	Vane	Round	8	0.02	0.01	0.0106	0.0053	0.0023	34.73	0.43	0.20
148	3	Vane	Round	8	0.02	0.01	0.0106	0.0030	0.0018	31.00	0.60	0.22
148	4	Vane	Round	8	0.02	0.01	0.0106	0.0012	0.0012	12.73	1.00	0.53
151	1	Vane	Round	8	0.02	0.01	0.0157	0.0139	0.0054	43.83	0.39	0.15
151	2	Vane	Round	8	0.02	0.01	0.0157	0.0086	0.0033	37.37	0.39	0.18
151	3	Vane	Round	8	0.02	0.01	0.0157	0.0052	0.0024	34.10	0.46	0.20
151	4	Vane	Round	8	0.02	0.01	0.0157	0.0028	0.0028	15.33	1.00	0.44
154	1	bar	Round	8	0.02	0.01	0.0072	0.0062	0.0027	37.10	0.43	0.18
154	2	bar	Round	8	0.02	0.01	0.0072	0.0036	0.0014	33.63	0.39	0.20
154	3	bar	Round	8	0.02	0.01	0.0072	0.0022	0.0014	28.30	0.64	0.24

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
154	4	bar	Round	8	0.02	0.01	0.0072	0.0008	0.0008	11.20	1.00	0.61
157	1	bar	Round	8	0.02	0.01	0.0104	0.0091	0.0036	39.80	0.40	0.17
157	2	bar	Round	8	0.02	0.01	0.0104	0.0055	0.0022	36.10	0.39	0.19
157	3	bar	Round	8	0.02	0.01	0.0104	0.0033	0.0022	32.23	0.67	0.21
157	4	bar	Round	8	0.02	0.01	0.0104	0.0011	0.0011	13.50	1.00	0.50
160	1	bar	Round	8	0.02	0.01	0.0162	0.0144	0.0049	44.73	0.34	0.15
160	2	bar	Round	8	0.02	0.01	0.0162	0.0095	0.0035	38.80	0.37	0.17
160	3	bar	Round	8	0.02	0.01	0.0162	0.0060	0.0031	36.17	0.51	0.19
160	4	bar	Round	8	0.02	0.01	0.0162	0.0029	0.0029	14.67	1.00	0.46
163	1	Vane	Sq.	8	0.02	0.01	0.0063	0.0059	0.0033	36.03	0.55	0.19
163	2	Vane	Sq.	8	0.02	0.01	0.0063	0.0027	0.0011	29.73	0.42	0.23
163	3	Vane	Sq.	8	0.02	0.01	0.0063	0.0015	0.0013	23.70	0.83	0.29
163	4	Vane	Sq.	8	0.02	0.01	0.0063	0.0003	0.0003	8.33	1.00	0.81
166	1	Vane	Sq.	8	0.02	0.01	0.0099	0.0088	0.0042	38.63	0.48	0.18
166	2	Vane	Sq.	8	0.02	0.01	0.0099	0.0046	0.0017	33.90	0.38	0.20
166	3	Vane	Sq.	8	0.02	0.01	0.0099	0.0029	0.0025	31.20	0.87	0.22
166	4	Vane	Sq.	8	0.02	0.01	0.0099	0.0004	0.0004	11.03	1.00	0.61
169	1	Vane	Sq.	8	0.02	0.01	0.0162	0.0139	0.0055	43.07	0.39	0.16
169	2	Vane	Sq.	8	0.02	0.01	0.0162	0.0085	0.0031	39.37	0.36	0.17
169	3	Vane	Sq.	8	0.02	0.01	0.0162	0.0054	0.0032	33.53	0.60	0.20
169	4	Vane	Sq.	8	0.02	0.01	0.0162	0.0022	0.0022	13.60	1.00	0.50
172	1	bar	Sq.	8	0.02	0.01	0.0069	0.0061	0.0030	33.70	0.49	0.20
172	2	bar	Sq.	8	0.02	0.01	0.0069	0.0031	0.0011	32.03	0.37	0.21
172	3	bar	Sq.	8	0.02	0.01	0.0069	0.0019	0.0012	31.20	0.64	0.22
172	4	bar	Sq.	8	0.02	0.01	0.0069	0.0007	0.0007	10.30	1.00	0.66
175	1	bar	Sq.	8	0.02	0.01	0.0103	0.0094	0.0039	40.90	0.41	0.17
175	2	bar	Sq.	8	0.02	0.01	0.0103	0.0055	0.0017	35.70	0.31	0.19
175	3	bar	Sq.	8	0.02	0.01	0.0103	0.0038	0.0022	32.97	0.56	0.21
175	4	bar	Sq.	8	0.02	0.01	0.0103	0.0017	0.0017	12.40	1.00	0.55
178	1	bar	Sq.	8	0.02	0.01	0.0144	0.0134	0.0052	43.10	0.39	0.16
178	2	bar	Sq.	8	0.02	0.01	0.0144	0.0082	0.0029	40.10	0.36	0.17
178	3	bar	Sq.	8	0.02	0.01	0.0144	0.0053	0.0026	36.60	0.49	0.19
178	4	bar	Sq.	8	0.02	0.01	0.0144	0.0027	0.0027	13.17	1.00	0.51
181	1	Vane	Round	10	0.02	0.01	0.0065	0.0055	0.0030	36.07	0.54	0.19
181	2	Vane	Round	10	0.02	0.01	0.0065	0.0025	0.0010	31.73	0.39	0.21
181	3	Vane	Round	10	0.02	0.01	0.0065	0.0015	0.0013	26.80	0.84	0.25
181	4	Vane	Round	10	0.02	0.01	0.0065	0.0003	0.0003	9.77	1.00	0.69
184	1	Vane	Round	10	0.02	0.01	0.0103	0.0088	0.0044	38.93	0.50	0.17
184	2	Vane	Round	10	0.02	0.01	0.0103	0.0044	0.0018	34.07	0.41	0.20
184	3	Vane	Round	10	0.02	0.01	0.0103	0.0026	0.0020	34.40	0.75	0.20
184	4	Vane	Round	10	0.02	0.01	0.0103	0.0007	0.0007	11.07	1.00	0.61

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
187	1	Vane	Round	10	0.02	0.01	0.0163	0.0141	0.0060	43.80	0.43	0.15
187	2	Vane	Round	10	0.02	0.01	0.0163	0.0081	0.0029	39.57	0.36	0.17
187	3	Vane	Round	10	0.02	0.01	0.0163	0.0051	0.0029	37.13	0.56	0.18
187	4	Vane	Round	10	0.02	0.01	0.0163	0.0023	0.0023	14.37	1.00	0.47
190	1	bar	Round	10	0.02	0.01	0.0066	0.0060	0.0031	36.33	0.52	0.19
190	2	bar	Round	10	0.02	0.01	0.0066	0.0029	0.0012	33.13	0.41	0.20
190	3	bar	Round	10	0.02	0.01	0.0066	0.0017	0.0014	30.37	0.80	0.22
190	4	bar	Round	10	0.02	0.01	0.0066	0.0003	0.0003	10.20	1.00	0.66
193	1	bar	Round	10	0.02	0.01	0.0100	0.0091	0.0041	39.90	0.45	0.17
193	2	bar	Round	10	0.02	0.01	0.0100	0.0050	0.0018	36.17	0.37	0.19
193	3	bar	Round	10	0.02	0.01	0.0100	0.0031	0.0026	34.00	0.82	0.20
193	4	bar	Round	10	0.02	0.01	0.0100	0.0006	0.0006	11.40	1.00	0.59
196	1	bar	Round	10	0.02	0.01	0.0156	0.0139	0.0056	43.53	0.40	0.16
196	2	bar	Round	10	0.02	0.01	0.0156	0.0083	0.0027	38.47	0.32	0.18
196	3	bar	Round	10	0.02	0.01	0.0156	0.0056	0.0033	36.47	0.59	0.19
196	4	bar	Round	10	0.02	0.01	0.0156	0.0023	0.0023	14.93	1.00	0.45
199	1	Vane	Sq.	10	0.02	0.01	0.0067	0.0060	0.0033	36.60	0.56	0.19
199	2	Vane	Sq.	10	0.02	0.01	0.0067	0.0027	0.0012	29.93	0.44	0.23
199	3	Vane	Sq.	10	0.02	0.01	0.0067	0.0015	0.0012	28.10	0.79	0.24
199	4	Vane	Sq.	10	0.02	0.01	0.0067	0.0003	0.0003	8.67	1.00	0.78
202	1	Vane	Sq.	10	0.02	0.01	0.0102	0.0087	0.0043	40.00	0.49	0.17
202	2	Vane	Sq.	10	0.02	0.01	0.0102	0.0044	0.0016	34.77	0.36	0.20
202	3	Vane	Sq.	10	0.02	0.01	0.0102	0.0028	0.0022	30.77	0.78	0.22
202	4	Vane	Sq.	10	0.02	0.01	0.0102	0.0006	0.0006	12.03	1.00	0.56
205	1	Vane	Sq.	10	0.02	0.01	0.0157	0.0138	0.0058	44.37	0.42	0.15
205	2	Vane	Sq.	10	0.02	0.01	0.0157	0.0080	0.0028	37.10	0.35	0.18
205	3	Vane	Sq.	10	0.02	0.01	0.0157	0.0052	0.0030	35.00	0.57	0.19
205	4	Vane	Sq.	10	0.02	0.01	0.0157	0.0023	0.0023	15.03	1.00	0.45
208	1	bar	Sq.	10	0.02	0.01	0.0067	0.0060	0.0035	37.10	0.59	0.18
208	2	bar	Sq.	10	0.02	0.01	0.0067	0.0024	0.0010	32.13	0.42	0.21
208	3	bar	Sq.	10	0.02	0.01	0.0067	0.0014	0.0011	28.13	0.80	0.24
208	4	bar	Sq.	10	0.02	0.01	0.0067	0.0003	0.0003	9.93	1.00	0.68
211	1	bar	Sq.	10	0.02	0.01	0.0105	0.0091	0.0048	40.20	0.53	0.17
211	2	bar	Sq.	10	0.02	0.01	0.0105	0.0042	0.0015	35.50	0.36	0.19
211	3	bar	Sq.	10	0.02	0.01	0.0105	0.0027	0.0020	31.57	0.75	0.21
211	4	bar	Sq.	10	0.02	0.01	0.0105	0.0007	0.0007	11.87	1.00	0.57
214	1	bar	Sq.	10	0.02	0.01	0.0162	0.0141	0.0067	42.63	0.48	0.16
214	2	bar	Sq.	10	0.02	0.01	0.0162	0.0073	0.0024	36.67	0.32	0.18
214	3	bar	Sq.	10	0.02	0.01	0.0162	0.0050	0.0032	32.90	0.64	0.21
214	4	bar	Sq.	10	0.02	0.01	0.0162	0.0018	0.0018	15.40	1.00	0.44
217	1	Vane	Round	8	0.06	0.01	0.0067	0.0061	0.0054	19.10	0.89	0.35

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
217	2	Vane	Round	8	0.06	0.01	0.0067	0.0007	0.0007	9.80	1.00	0.69
220	1	Vane	Round	8	0.06	0.01	0.0103	0.0089	0.0064	19.97	0.72	0.34
220	2	Vane	Round	8	0.06	0.01	0.0103	0.0025	0.0025	12.87	0.97	0.53
220	3	Vane	Round	8	0.06	0.01	0.0103	0.0001	0.0001	9.27	1.00	0.73
223	1	Vane	Round	8	0.06	0.01	0.0160	0.0137	0.0068	21.77	0.50	0.31
223	2	Vane	Round	8	0.06	0.01	0.0160	0.0068	0.0055	18.60	0.81	0.36
223	3	Vane	Round	8	0.06	0.01	0.0160	0.0013	0.0013	12.83	0.99	0.53
223	4	Vane	Round	8	0.06	0.01	0.0160	0.0000	0.0000	3.00	1.00	1.00
226	1	bar	Round	8	0.06	0.01	0.0067	0.0059	0.0052	17.87	0.88	0.38
226	2	bar	Round	8	0.06	0.01	0.0067	0.0007	0.0007	9.20	1.00	0.74
229	1	bar	Round	8	0.06	0.01	0.0102	0.0093	0.0079	19.90	0.85	0.34
229	2	bar	Round	8	0.06	0.01	0.0102	0.0014	0.0013	11.20	0.97	0.61
229	3	bar	Round	8	0.06	0.01	0.0102	0.0000	0.0000	6.07	1.00	1.00
232	1	bar	Round	8	0.06	0.01	0.0145	0.0131	0.0091	21.80	0.70	0.31
232	2	bar	Round	8	0.06	0.01	0.0145	0.0040	0.0035	14.20	0.89	0.48
232	3	bar	Round	8	0.06	0.01	0.0145	0.0005	0.0005	10.63	1.00	0.64
235	1	Vane	Sq.	8	0.06	0.01	0.0068	0.0061	0.0055	15.00	0.90	0.45
235	2	Vane	Sq.	8	0.06	0.01	0.0068	0.0006	0.0006	7.30	1.00	0.93
238	1	Vane	Sq.	8	0.06	0.01	0.0098	0.0089	0.0076	18.70	0.85	0.36
238	2	Vane	Sq.	8	0.06	0.01	0.0098	0.0013	0.0013	9.23	1.00	0.73
241	1	Vane	Sq.	8	0.06	0.01	0.0161	0.0133	0.0084	22.27	0.63	0.30
241	2	Vane	Sq.	8	0.06	0.01	0.0161	0.0050	0.0045	14.20	0.91	0.48
241	3	Vane	Sq.	8	0.06	0.01	0.0161	0.0004	0.0004	9.20	1.00	0.74
244	1	bar	Sq.	8	0.06	0.01	0.0066	0.0058	0.0051	15.73	0.88	0.43
244	2	bar	Sq.	8	0.06	0.01	0.0066	0.0007	0.0007	9.43	1.00	0.72
247	1	bar	Sq.	8	0.06	0.01	0.0097	0.0088	0.0074	18.27	0.84	0.37
247	2	bar	Sq.	8	0.06	0.01	0.0097	0.0014	0.0014	10.87	1.00	0.62
250	1	bar	Sq.	8	0.06	0.01	0.0157	0.0136	0.0104	22.00	0.77	0.31
250	2	bar	Sq.	8	0.06	0.01	0.0157	0.0031	0.0031	12.53	0.98	0.54
250	3	bar	Sq.	8	0.06	0.01	0.0157	0.0001	0.0001	7.73	1.00	0.88
253	1	Vane	Round	10	0.06	0.01	0.0066	0.0059	0.0055	15.07	0.92	0.45
253	2	Vane	Round	10	0.06	0.01	0.0066	0.0005	0.0005	6.83	1.00	0.99
256	1	Vane	Round	10	0.06	0.01	0.0101	0.0089	0.0077	17.73	0.86	0.38
256	2	Vane	Round	10	0.06	0.01	0.0101	0.0012	0.0012	8.80	1.00	0.77
259	1	Vane	Round	10	0.06	0.01	0.0164	0.0136	0.0101	21.83	0.74	0.31
259	2	Vane	Round	10	0.06	0.01	0.0164	0.0035	0.0034	13.60	0.98	0.50
259	3	Vane	Round	10	0.06	0.01	0.0164	0.0001	0.0001	8.50	1.00	0.80
262	1	bar	Round	10	0.06	0.01	0.0065	0.0058	0.0053	14.90	0.92	0.46
262	2	bar	Round	10	0.06	0.01	0.0065	0.0005	0.0005	8.10	1.00	0.84
265	1	bar	Round	10	0.06	0.01	0.0103	0.0088	0.0076	17.40	0.86	0.39
265	2	bar	Round	10	0.06	0.01	0.0103	0.0012	0.0012	9.80	1.00	0.69

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
268	1	bar	Round	10	0.06	0.01	0.0159	0.0137	0.0109	19.20	0.80	0.35
268	2	bar	Round	10	0.06	0.01	0.0159	0.0028	0.0027	11.90	0.99	0.57
271	1	Vane	Sq.	10	0.06	0.01	0.0065	0.0057	0.0053	14.23	0.93	0.48
271	2	Vane	Sq.	10	0.06	0.01	0.0065	0.0004	0.0004	6.53	1.00	1.00
274	1	Vane	Sq.	10	0.06	0.01	0.0102	0.0089	0.0077	16.83	0.87	0.40
274	2	Vane	Sq.	10	0.06	0.01	0.0102	0.0012	0.0012	7.20	1.00	0.94
277	1	Vane	Sq.	10	0.06	0.01	0.0155	0.0128	0.0102	19.30	0.80	0.35
277	2	Vane	Sq.	10	0.06	0.01	0.0155	0.0026	0.0026	10.23	1.00	0.66
280	1	bar	Sq.	10	0.06	0.01	0.0064	0.0056	0.0052	13.90	0.92	0.49
280	2	bar	Sq.	10	0.06	0.01	0.0064	0.0005	0.0005	6.00	1.00	1.00
283	1	bar	Sq.	10	0.06	0.01	0.0102	0.0086	0.0074	16.33	0.85	0.42
283	2	bar	Sq.	10	0.06	0.01	0.0102	0.0013	0.0013	7.63	1.00	0.89
286	1	bar	Sq.	10	0.06	0.01	0.0151	0.0131	0.0102	19.73	0.78	0.34
286	2	bar	Sq.	10	0.06	0.01	0.0151	0.0029	0.0029	9.87	1.00	0.69
289	1	Vane	Round	8	0.02	0.02	0.0063	0.0052	0.0017	38.33	0.33	0.18
289	2	Vane	Round	8	0.02	0.02	0.0063	0.0035	0.0019	28.67	0.55	0.24
289	3	Vane	Round	8	0.02	0.02	0.0063	0.0015	0.0012	23.80	0.76	0.28
289	4	Vane	Round	8	0.02	0.02	0.0063	0.0004	0.0004	9.73	1.00	0.70
292	1	Vane	Round	8	0.02	0.02	0.0099	0.0081	0.0025	42.33	0.31	0.16
292	2	Vane	Round	8	0.02	0.02	0.0099	0.0056	0.0028	32.57	0.51	0.21
292	3	Vane	Round	8	0.02	0.02	0.0099	0.0028	0.0019	27.97	0.69	0.24
292	4	Vane	Round	8	0.02	0.02	0.0099	0.0008	0.0008	10.20	1.00	0.66
295	1	Vane	Round	8	0.02	0.02	0.0165	0.0129	0.0036	47.87	0.28	0.14
295	2	Vane	Round	8	0.02	0.02	0.0165	0.0093	0.0040	38.33	0.43	0.18
295	3	Vane	Round	8	0.02	0.02	0.0165	0.0053	0.0029	30.40	0.55	0.22
295	4	Vane	Round	8	0.02	0.02	0.0165	0.0024	0.0024	15.00	1.00	0.45
298	1	bar	Round	8	0.02	0.02	0.0067	0.0054	0.0014	38.17	0.25	0.18
298	2	bar	Round	8	0.02	0.02	0.0067	0.0040	0.0021	31.77	0.52	0.21
298	3	bar	Round	8	0.02	0.02	0.0067	0.0019	0.0013	24.40	0.66	0.28
298	4	bar	Round	8	0.02	0.02	0.0067	0.0006	0.0006	9.87	1.00	0.69
301	1	bar	Round	8	0.02	0.02	0.0101	0.0083	0.0019	44.13	0.23	0.15
301	2	bar	Round	8	0.02	0.02	0.0101	0.0064	0.0028	35.40	0.44	0.19
301	3	bar	Round	8	0.02	0.02	0.0101	0.0036	0.0018	28.63	0.51	0.24
301	4	bar	Round	8	0.02	0.02	0.0101	0.0017	0.0017	12.50	1.00	0.54
304	1	bar	Round	8	0.02	0.02	0.0150	0.0133	0.0028	47.63	0.21	0.14
304	2	bar	Round	8	0.02	0.02	0.0150	0.0106	0.0044	37.50	0.42	0.18
304	3	bar	Round	8	0.02	0.02	0.0150	0.0061	0.0025	31.03	0.41	0.22
304	4	bar	Round	8	0.02	0.02	0.0150	0.0036	0.0036	15.57	1.00	0.44
307	1	Vane	Sq.	8	0.02	0.02	0.0063	0.0054	0.0015	36.23	0.28	0.19
307	2	Vane	Sq.	8	0.02	0.02	0.0063	0.0039	0.0026	30.60	0.67	0.22
307	3	Vane	Sq.	8	0.02	0.02	0.0063	0.0013	0.0012	21.60	0.93	0.31

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
307	4	Vane	Sq.	8	0.02	0.02	0.0063	0.0001	0.0001	6.43	1.00	1.00
310	1	Vane	Sq.	8	0.02	0.02	0.0098	0.0087	0.0023	38.77	0.26	0.17
310	2	Vane	Sq.	8	0.02	0.02	0.0098	0.0064	0.0037	34.20	0.57	0.20
310	3	Vane	Sq.	8	0.02	0.02	0.0098	0.0028	0.0022	26.70	0.81	0.25
310	4	Vane	Sq.	8	0.02	0.02	0.0098	0.0005	0.0005	9.27	1.00	0.73
313	1	Vane	Sq.	8	0.02	0.02	0.0155	0.0139	0.0033	45.10	0.24	0.15
313	2	Vane	Sq.	8	0.02	0.02	0.0155	0.0106	0.0052	36.90	0.49	0.18
313	3	Vane	Sq.	8	0.02	0.02	0.0155	0.0054	0.0030	28.13	0.55	0.24
313	4	Vane	Sq.	8	0.02	0.02	0.0155	0.0025	0.0025	13.80	1.00	0.49
316	1	bar	Sq.	8	0.02	0.02	0.0065	0.0058	0.0013	37.17	0.22	0.18
316	2	bar	Sq.	8	0.02	0.02	0.0065	0.0045	0.0026	30.67	0.57	0.22
316	3	bar	Sq.	8	0.02	0.02	0.0065	0.0019	0.0018	22.60	0.91	0.30
316	4	bar	Sq.	8	0.02	0.02	0.0065	0.0002	0.0002	8.50	1.00	0.80
319	1	bar	Sq.	8	0.02	0.02	0.0101	0.0091	0.0019	39.33	0.21	0.17
319	2	bar	Sq.	8	0.02	0.02	0.0101	0.0072	0.0036	35.20	0.49	0.19
319	3	bar	Sq.	8	0.02	0.02	0.0101	0.0036	0.0026	28.50	0.72	0.24
319	4	bar	Sq.	8	0.02	0.02	0.0101	0.0010	0.0010	11.57	1.00	0.59
322	1	bar	Sq.	8	0.02	0.02	0.0159	0.0140	0.0028	43.13	0.20	0.16
322	2	bar	Sq.	8	0.02	0.02	0.0159	0.0112	0.0051	38.63	0.45	0.18
322	3	bar	Sq.	8	0.02	0.02	0.0159	0.0061	0.0031	30.97	0.51	0.22
322	4	bar	Sq.	8	0.02	0.02	0.0159	0.0030	0.0030	13.13	1.00	0.52
325	1	Vane	Round	10	0.02	0.02	0.0070	0.0062	0.0016	36.80	0.26	0.18
325	2	Vane	Round	10	0.02	0.02	0.0070	0.0046	0.0030	27.53	0.66	0.25
325	3	Vane	Round	10	0.02	0.02	0.0070	0.0015	0.0013	20.37	0.86	0.33
325	4	Vane	Round	10	0.02	0.02	0.0070	0.0002	0.0002	5.73	1.00	1.00
328	1	Vane	Round	10	0.02	0.02	0.0104	0.0089	0.0022	38.63	0.25	0.18
328	2	Vane	Round	10	0.02	0.02	0.0104	0.0067	0.0039	30.77	0.59	0.22
328	3	Vane	Round	10	0.02	0.02	0.0104	0.0028	0.0020	26.37	0.71	0.26
328	4	Vane	Round	10	0.02	0.02	0.0104	0.0008	0.0008	8.30	1.00	0.82
331	1	Vane	Round	10	0.02	0.02	0.0156	0.0143	0.0033	42.20	0.23	0.16
331	2	Vane	Round	10	0.02	0.02	0.0156	0.0110	0.0055	35.90	0.50	0.19
331	3	Vane	Round	10	0.02	0.02	0.0156	0.0055	0.0030	29.50	0.54	0.23
331	4	Vane	Round	10	0.02	0.02	0.0156	0.0026	0.0026	11.27	1.00	0.60
334	1	bar	Round	10	0.02	0.02	0.0064	0.0058	0.0012	36.53	0.21	0.19
334	2	bar	Round	10	0.02	0.02	0.0064	0.0046	0.0031	31.43	0.69	0.22
334	3	bar	Round	10	0.02	0.02	0.0064	0.0014	0.0012	23.13	0.84	0.29
334	4	bar	Round	10	0.02	0.02	0.0064	0.0002	0.0002	5.77	1.00	1.00
337	1	bar	Round	10	0.02	0.02	0.0099	0.0086	0.0017	40.40	0.20	0.17
337	2	bar	Round	10	0.02	0.02	0.0099	0.0069	0.0040	34.57	0.58	0.20
337	3	bar	Round	10	0.02	0.02	0.0099	0.0029	0.0019	28.10	0.65	0.24
337	4	bar	Round	10	0.02	0.02	0.0099	0.0010	0.0010	10.87	1.00	0.62

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
340	1	bar	Round	10	0.02	0.02	0.0155	0.0139	0.0028	46.37	0.20	0.15
340	2	bar	Round	10	0.02	0.02	0.0155	0.0111	0.0056	39.10	0.51	0.17
340	3	bar	Round	10	0.02	0.02	0.0155	0.0055	0.0027	30.30	0.49	0.22
340	4	bar	Round	10	0.02	0.02	0.0155	0.0028	0.0028	14.10	1.00	0.48
343	1	Vane	Sq.	10	0.02	0.02	0.0066	0.0053	0.0015	33.73	0.29	0.20
343	2	Vane	Sq.	10	0.02	0.02	0.0066	0.0038	0.0024	26.97	0.64	0.25
343	3	Vane	Sq.	10	0.02	0.02	0.0066	0.0014	0.0013	19.73	0.97	0.34
343	4	Vane	Sq.	10	0.02	0.02	0.0066	0.0000	0.0000	3.93	1.00	1.00
346	1	Vane	Sq.	10	0.02	0.02	0.0099	0.0078	0.0024	37.17	0.31	0.18
346	2	Vane	Sq.	10	0.02	0.02	0.0099	0.0054	0.0028	31.13	0.51	0.22
346	3	Vane	Sq.	10	0.02	0.02	0.0099	0.0026	0.0023	24.43	0.89	0.28
346	4	Vane	Sq.	10	0.02	0.02	0.0099	0.0003	0.0003	8.17	1.00	0.83
349	1	Vane	Sq.	10	0.02	0.02	0.0151	0.0136	0.0037	41.60	0.27	0.16
349	2	Vane	Sq.	10	0.02	0.02	0.0151	0.0099	0.0050	34.73	0.51	0.20
349	3	Vane	Sq.	10	0.02	0.02	0.0151	0.0049	0.0032	30.40	0.66	0.22
349	4	Vane	Sq.	10	0.02	0.02	0.0151	0.0017	0.0017	11.60	1.00	0.58
352	1	bar	Sq.	10	0.02	0.02	0.0067	0.0062	0.0014	35.57	0.23	0.19
352	2	bar	Sq.	10	0.02	0.02	0.0067	0.0047	0.0030	30.70	0.63	0.22
352	3	bar	Sq.	10	0.02	0.02	0.0067	0.0018	0.0017	23.33	0.94	0.29
352	4	bar	Sq.	10	0.02	0.02	0.0067	0.0001	0.0001	4.97	1.00	1.00
355	1	bar	Sq.	10	0.02	0.02	0.0100	0.0091	0.0020	40.20	0.23	0.17
355	2	bar	Sq.	10	0.02	0.02	0.0100	0.0070	0.0036	35.17	0.52	0.19
355	3	bar	Sq.	10	0.02	0.02	0.0100	0.0034	0.0025	28.43	0.75	0.24
355	4	bar	Sq.	10	0.02	0.02	0.0100	0.0008	0.0008	10.40	1.00	0.65
358	1	bar	Sq.	10	0.02	0.02	0.0165	0.0146	0.0034	42.97	0.23	0.16
358	2	bar	Sq.	10	0.02	0.02	0.0165	0.0112	0.0051	37.33	0.46	0.18
358	3	bar	Sq.	10	0.02	0.02	0.0165	0.0061	0.0036	32.03	0.59	0.21
358	4	bar	Sq.	10	0.02	0.02	0.0165	0.0025	0.0025	11.80	1.00	0.57
361	1	Vane	Round	8	0.06	0.02	0.0068	0.0063	0.0051	17.47	0.81	0.39
361	2	Vane	Round	8	0.06	0.02	0.0068	0.0012	0.0012	11.10	1.00	0.61
364	1	Vane	Round	8	0.06	0.02	0.0099	0.0092	0.0063	18.30	0.68	0.37
364	2	Vane	Round	8	0.06	0.02	0.0099	0.0029	0.0029	11.73	1.00	0.58
367	1	Vane	Round	8	0.06	0.02	0.0161	0.0141	0.0062	20.07	0.44	0.34
367	2	Vane	Round	8	0.06	0.02	0.0161	0.0079	0.0066	14.70	0.83	0.46
367	3	Vane	Round	8	0.06	0.02	0.0161	0.0013	0.0013	7.63	1.00	0.89
370	1	bar	Round	8	0.06	0.02	0.0067	0.0063	0.0049	16.40	0.77	0.41
370	2	bar	Round	8	0.06	0.02	0.0067	0.0014	0.0014	7.87	1.00	0.86
373	1	bar	Round	8	0.06	0.02	0.0103	0.0092	0.0068	17.73	0.74	0.38
373	2	bar	Round	8	0.06	0.02	0.0103	0.0024	0.0024	9.93	1.00	0.68
376	1	bar	Round	8	0.06	0.02	0.0153	0.0142	0.0090	20.10	0.63	0.34
376	2	bar	Round	8	0.06	0.02	0.0153	0.0052	0.0051	12.53	0.99	0.54

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
376	3	bar	Round	8	0.06	0.02	0.0153	0.0001	0.0001	3.47	1.00	1.00
379	1	Vane	Sq.	8	0.06	0.02	0.0066	0.0059	0.0053	13.30	0.89	0.51
379	2	Vane	Sq.	8	0.06	0.02	0.0066	0.0007	0.0007	5.53	1.00	1.00
382	1	Vane	Sq.	8	0.06	0.02	0.0099	0.0090	0.0073	15.27	0.81	0.44
382	2	Vane	Sq.	8	0.06	0.02	0.0099	0.0017	0.0017	6.27	1.00	1.00
385	1	Vane	Sq.	8	0.06	0.02	0.0155	0.0142	0.0077	18.83	0.54	0.36
385	2	Vane	Sq.	8	0.06	0.02	0.0155	0.0065	0.0063	11.40	0.98	0.59
385	3	Vane	Sq.	8	0.06	0.02	0.0155	0.0002	0.0002	3.17	1.00	1.00
388	1	bar	Sq.	8	0.06	0.02	0.0065	0.0060	0.0055	14.90	0.91	0.46
388	2	bar	Sq.	8	0.06	0.02	0.0065	0.0006	0.0006	5.20	1.00	1.00
391	1	bar	Sq.	8	0.06	0.02	0.0105	0.0090	0.0075	17.03	0.83	0.40
391	2	bar	Sq.	8	0.06	0.02	0.0105	0.0016	0.0016	6.90	1.00	0.98
394	1	bar	Sq.	8	0.06	0.02	0.0154	0.0144	0.0100	19.77	0.70	0.34
394	2	bar	Sq.	8	0.06	0.02	0.0154	0.0043	0.0043	10.87	1.00	0.62
397	1	Vane	Round	10	0.06	0.02	0.0068	0.0062	0.0055	14.77	0.89	0.46
397	2	Vane	Round	10	0.06	0.02	0.0068	0.0007	0.0007	6.53	1.00	1.00
400	1	Vane	Round	10	0.06	0.02	0.0108	0.0093	0.0075	16.70	0.81	0.41
400	2	Vane	Round	10	0.06	0.02	0.0108	0.0018	0.0018	7.30	1.00	0.93
403	1	Vane	Round	10	0.06	0.02	0.0162	0.0146	0.0095	19.60	0.65	0.35
403	2	Vane	Round	10	0.06	0.02	0.0162	0.0051	0.0051	11.37	1.00	0.60
406	1	bar	Round	10	0.06	0.02	0.0065	0.0058	0.0050	16.07	0.86	0.42
406	2	bar	Round	10	0.06	0.02	0.0065	0.0008	0.0008	5.67	1.00	1.00
409	1	bar	Round	10	0.06	0.02	0.0094	0.0088	0.0070	17.20	0.79	0.39
409	2	bar	Round	10	0.06	0.02	0.0094	0.0018	0.0018	7.70	1.00	0.88
412	1	bar	Round	10	0.06	0.02	0.0163	0.0144	0.0106	19.27	0.74	0.35
412	2	bar	Round	10	0.06	0.02	0.0163	0.0038	0.0038	10.27	1.00	0.66
415	1	Vane	Sq.	10	0.06	0.02	0.0065	0.0061	0.0053	13.90	0.86	0.49
415	2	Vane	Sq.	10	0.06	0.02	0.0065	0.0008	0.0008	5.20	1.00	1.00
418	1	Vane	Sq.	10	0.06	0.02	0.0098	0.0088	0.0070	16.47	0.80	0.41
418	2	Vane	Sq.	10	0.06	0.02	0.0098	0.0018	0.0018	6.03	1.00	1.00
421	1	Vane	Sq.	10	0.06	0.02	0.0161	0.0142	0.0106	17.47	0.74	0.39
421	2	Vane	Sq.	10	0.06	0.02	0.0161	0.0037	0.0037	8.50	1.00	0.80
424	1	bar	Sq.	10	0.06	0.02	0.0067	0.0061	0.0050	12.40	0.82	0.55
424	2	bar	Sq.	10	0.06	0.02	0.0067	0.0011	0.0011	5.00	1.00	1.00
427	1	bar	Sq.	10	0.06	0.02	0.0102	0.0090	0.0068	15.97	0.75	0.42
427	2	bar	Sq.	10	0.06	0.02	0.0102	0.0023	0.0023	7.47	1.00	0.91
430	1	bar	Sq.	10	0.06	0.02	0.0158	0.0142	0.0101	17.87	0.71	0.38
430	2	bar	Sq.	10	0.06	0.02	0.0158	0.0041	0.0041	9.73	1.00	0.70
433	1	Vane	Round	8	0.02	0.04	0.0064	0.0057	0.0040	27.50	0.70	0.25
433	2	Vane	Round	8	0.02	0.04	0.0064	0.0017	0.0016	18.20	0.93	0.37
433	3	Vane	Round	8	0.02	0.04	0.0064	0.0001	0.0001	6.60	1.00	1.00

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
436	1	Vane	Round	8	0.02	0.04	0.0103	0.0090	0.0056	28.30	0.62	0.24
436	2	Vane	Round	8	0.02	0.04	0.0103	0.0034	0.0023	20.57	0.67	0.33
436	3	Vane	Round	8	0.02	0.04	0.0103	0.0011	0.0011	13.47	1.00	0.50
439	1	Vane	Round	8	0.02	0.04	0.0155	0.0143	0.0057	32.27	0.40	0.21
439	2	Vane	Round	8	0.02	0.04	0.0155	0.0086	0.0044	26.23	0.51	0.26
439	3	Vane	Round	8	0.02	0.04	0.0155	0.0042	0.0038	20.33	0.90	0.33
439	4	Vane	Round	8	0.02	0.04	0.0155	0.0004	0.0004	7.63	1.00	0.89
442	1	bar	Round	8	0.02	0.04	0.0067	0.0063	0.0041	26.30	0.66	0.26
442	2	bar	Round	8	0.02	0.04	0.0067	0.0021	0.0018	18.43	0.83	0.37
442	3	bar	Round	8	0.02	0.04	0.0067	0.0004	0.0004	7.77	1.00	0.87
445	1	bar	Round	8	0.02	0.04	0.0103	0.0091	0.0051	30.37	0.56	0.22
445	2	bar	Round	8	0.02	0.04	0.0103	0.0040	0.0022	21.63	0.55	0.31
445	3	bar	Round	8	0.02	0.04	0.0103	0.0018	0.0018	11.60	1.00	0.58
448	1	bar	Round	8	0.02	0.04	0.0161	0.0141	0.0071	32.87	0.50	0.21
448	2	bar	Round	8	0.02	0.04	0.0161	0.0070	0.0034	25.07	0.48	0.27
448	3	bar	Round	8	0.02	0.04	0.0161	0.0037	0.0030	21.90	0.82	0.31
448	4	bar	Round	8	0.02	0.04	0.0161	0.0007	0.0007	8.13	1.00	0.83
451	1	Vane	Sq.	8	0.02	0.04	0.0065	0.0060	0.0043	23.33	0.72	0.29
451	2	Vane	Sq.	8	0.02	0.04	0.0065	0.0017	0.0016	15.43	0.94	0.44
451	3	Vane	Sq.	8	0.02	0.04	0.0065	0.0001	0.0001	4.40	1.00	1.00
454	1	Vane	Sq.	8	0.02	0.04	0.0103	0.0090	0.0057	27.97	0.63	0.24
454	2	Vane	Sq.	8	0.02	0.04	0.0103	0.0034	0.0023	19.73	0.68	0.34
454	3	Vane	Sq.	8	0.02	0.04	0.0103	0.0011	0.0011	8.60	1.00	0.79
457	1	Vane	Sq.	8	0.02	0.04	0.0154	0.0141	0.0072	31.03	0.51	0.22
457	2	Vane	Sq.	8	0.02	0.04	0.0154	0.0069	0.0037	24.40	0.53	0.28
457	3	Vane	Sq.	8	0.02	0.04	0.0154	0.0032	0.0031	17.20	0.95	0.39
457	4	Vane	Sq.	8	0.02	0.04	0.0154	0.0001	0.0001	4.87	1.00	1.00
460	1	bar	Sq.	8	0.02	0.04	0.0068	0.0063	0.0041	24.37	0.64	0.28
460	2	bar	Sq.	8	0.02	0.04	0.0068	0.0023	0.0019	16.50	0.83	0.41
460	3	bar	Sq.	8	0.02	0.04	0.0068	0.0004	0.0004	5.70	1.00	1.00
463	1	bar	Sq.	8	0.02	0.04	0.0105	0.0092	0.0053	30.57	0.57	0.22
463	2	bar	Sq.	8	0.02	0.04	0.0105	0.0039	0.0023	20.93	0.59	0.32
463	3	bar	Sq.	8	0.02	0.04	0.0105	0.0016	0.0016	12.97	1.00	0.52
466	1	bar	Sq.	8	0.02	0.04	0.0158	0.0142	0.0071	32.23	0.50	0.21
466	2	bar	Sq.	8	0.02	0.04	0.0158	0.0071	0.0035	25.33	0.50	0.27
466	3	bar	Sq.	8	0.02	0.04	0.0158	0.0036	0.0029	19.90	0.81	0.34
466	4	bar	Sq.	8	0.02	0.04	0.0158	0.0007	0.0007	8.10	1.00	0.84
469	1	Vane	Round	10	0.02	0.04	0.0064	0.0059	0.0042	22.83	0.71	0.30
469	2	Vane	Round	10	0.02	0.04	0.0064	0.0017	0.0014	17.83	0.84	0.38
469	3	Vane	Round	10	0.02	0.04	0.0064	0.0003	0.0003	5.37	1.00	1.00
472	1	Vane	Round	10	0.02	0.04	0.0096	0.0093	0.0057	26.03	0.61	0.26

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
472	2	Vane	Round	10	0.02	0.04	0.0096	0.0036	0.0024	19.80	0.68	0.34
472	3	Vane	Round	10	0.02	0.04	0.0096	0.0012	0.0012	9.53	1.00	0.71
475	1	Vane	Round	10	0.02	0.04	0.0154	0.0141	0.0077	31.27	0.54	0.22
475	2	Vane	Round	10	0.02	0.04	0.0154	0.0065	0.0034	22.77	0.53	0.30
475	3	Vane	Round	10	0.02	0.04	0.0154	0.0030	0.0028	16.40	0.93	0.41
475	4	Vane	Round	10	0.02	0.04	0.0154	0.0002	0.0002	5.07	1.00	1.00
478	1	bar	Round	10	0.02	0.04	0.0065	0.0061	0.0041	22.47	0.68	0.30
478	2	bar	Round	10	0.02	0.04	0.0065	0.0020	0.0017	16.17	0.84	0.42
478	3	bar	Round	10	0.02	0.04	0.0065	0.0003	0.0003	5.30	1.00	1.00
481	1	bar	Round	10	0.02	0.04	0.0101	0.0092	0.0053	25.93	0.58	0.26
481	2	bar	Round	10	0.02	0.04	0.0101	0.0039	0.0023	22.13	0.60	0.31
481	3	bar	Round	10	0.02	0.04	0.0101	0.0015	0.0015	11.87	1.00	0.57
484	1	bar	Round	10	0.02	0.04	0.0153	0.0140	0.0071	30.87	0.51	0.22
484	2	bar	Round	10	0.02	0.04	0.0153	0.0068	0.0034	24.53	0.50	0.28
484	3	bar	Round	10	0.02	0.04	0.0153	0.0034	0.0027	14.63	0.80	0.46
484	4	bar	Round	10	0.02	0.04	0.0153	0.0007	0.0007	4.50	1.00	1.00
487	1	Vane	Sq.	10	0.02	0.04	0.0064	0.0058	0.0041	22.07	0.72	0.31
487	2	Vane	Sq.	10	0.02	0.04	0.0064	0.0016	0.0015	15.60	0.96	0.43
487	3	Vane	Sq.	10	0.02	0.04	0.0064	0.0001	0.0001	2.73	1.00	1.00
490	1	Vane	Sq.	10	0.02	0.04	0.0099	0.0088	0.0055	24.87	0.62	0.27
490	2	Vane	Sq.	10	0.02	0.04	0.0099	0.0034	0.0024	18.43	0.72	0.37
490	3	Vane	Sq.	10	0.02	0.04	0.0099	0.0009	0.0009	6.20	1.00	1.00
493	1	Vane	Sq.	10	0.02	0.04	0.0154	0.0140	0.0076	30.43	0.55	0.22
493	2	Vane	Sq.	10	0.02	0.04	0.0154	0.0064	0.0035	23.63	0.54	0.29
493	3	Vane	Sq.	10	0.02	0.04	0.0154	0.0029	0.0027	10.20	0.91	0.66
493	4	Vane	Sq.	10	0.02	0.04	0.0154	0.0003	0.0003	3.63	1.00	1.00
496	1	bar	Sq.	10	0.02	0.04	0.0064	0.0058	0.0041	23.20	0.70	0.29
496	2	bar	Sq.	10	0.02	0.04	0.0064	0.0017	0.0016	16.20	0.89	0.42
496	3	bar	Sq.	10	0.02	0.04	0.0064	0.0002	0.0002	2.13	1.00	1.00
499	1	bar	Sq.	10	0.02	0.04	0.0103	0.0092	0.0054	28.23	0.59	0.24
499	2	bar	Sq.	10	0.02	0.04	0.0103	0.0038	0.0024	20.50	0.65	0.33
499	3	bar	Sq.	10	0.02	0.04	0.0103	0.0013	0.0013	9.77	1.00	0.69
502	1	bar	Sq.	10	0.02	0.04	0.0155	0.0143	0.0072	30.90	0.51	0.22
502	2	bar	Sq.	10	0.02	0.04	0.0155	0.0070	0.0037	22.83	0.52	0.30
502	3	bar	Sq.	10	0.02	0.04	0.0155	0.0034	0.0028	15.07	0.82	0.45
502	4	bar	Sq.	10	0.02	0.04	0.0155	0.0006	0.0006	5.50	1.00	1.00
505	1	Vane	Round	8	0.06	0.04	0.0068	0.0067	0.0060	15.50	0.90	0.44
505	2	Vane	Round	8	0.06	0.04	0.0068	0.0007	0.0007	4.97	1.00	1.00
508	1	Vane	Round	8	0.06	0.04	0.0104	0.0089	0.0061	15.87	0.69	0.43
508	2	Vane	Round	8	0.06	0.04	0.0104	0.0028	0.0028	8.67	1.00	0.78
511	1	Vane	Round	8	0.06	0.04	0.0156	0.0143	0.0061	18.23	0.43	0.37

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
511	2	Vane	Round	8	0.06	0.04	0.0156	0.0082	0.0054	13.13	0.66	0.52
511	3	Vane	Round	8	0.06	0.04	0.0156	0.0027	0.0027	7.37	1.00	0.92
514	1	bar	Round	8	0.06	0.04	0.0066	0.0062	0.0060	14.00	0.97	0.48
514	2	bar	Round	8	0.06	0.04	0.0066	0.0002	0.0002	4.60	1.00	1.00
517	1	bar	Round	8	0.06	0.04	0.0105	0.0089	0.0069	15.97	0.77	0.42
517	2	bar	Round	8	0.06	0.04	0.0105	0.0020	0.0020	6.57	1.00	1.00
520	1	bar	Round	8	0.06	0.04	0.0159	0.0144	0.0084	18.43	0.58	0.37
520	2	bar	Round	8	0.06	0.04	0.0159	0.0060	0.0053	12.00	0.89	0.57
520	3	bar	Round	8	0.06	0.04	0.0159	0.0007	0.0007	4.53	1.00	1.00
523	1	Vane	Sq.	8	0.06	0.04	0.0067	0.0062	0.0060	13.00	0.98	0.52
523	2	Vane	Sq.	8	0.06	0.04	0.0067	0.0001	0.0001	3.83	1.00	1.00
526	1	Vane	Sq.	8	0.06	0.04	0.0101	0.0089	0.0075	15.63	0.85	0.43
526	2	Vane	Sq.	8	0.06	0.04	0.0101	0.0013	0.0013	6.07	1.00	1.00
529	1	Vane	Sq.	8	0.06	0.04	0.0154	0.0142	0.0077	17.47	0.54	0.39
529	2	Vane	Sq.	8	0.06	0.04	0.0154	0.0065	0.0061	10.53	0.93	0.64
529	3	Vane	Sq.	8	0.06	0.04	0.0154	0.0004	0.0004	3.27	1.00	1.00
532	1	bar	Sq.	8	0.06	0.04	0.0066	0.0062	0.0060	13.40	0.97	0.51
532	2	bar	Sq.	8	0.06	0.04	0.0066	0.0002	0.0002	3.97	1.00	1.00
535	1	bar	Sq.	8	0.06	0.04	0.0101	0.0086	0.0076	15.70	0.89	0.43
535	2	bar	Sq.	8	0.06	0.04	0.0101	0.0010	0.0010	5.63	1.00	1.00
538	1	bar	Sq.	8	0.06	0.04	0.0161	0.0142	0.0091	18.03	0.65	0.38
538	2	bar	Sq.	8	0.06	0.04	0.0161	0.0050	0.0047	10.80	0.93	0.63
538	3	bar	Sq.	8	0.06	0.04	0.0161	0.0004	0.0004	3.37	1.00	1.00
541	1	Vane	Round	10	0.06	0.04	0.0066	0.0063	0.0061	12.67	0.97	0.54
541	2	Vane	Round	10	0.06	0.04	0.0066	0.0002	0.0002	3.13	1.00	1.00
544	1	Vane	Round	10	0.06	0.04	0.0103	0.0090	0.0083	15.00	0.92	0.45
544	2	Vane	Round	10	0.06	0.04	0.0103	0.0008	0.0008	4.40	1.00	1.00
547	1	Vane	Round	10	0.06	0.04	0.0161	0.0143	0.0091	17.83	0.64	0.38
547	2	Vane	Round	10	0.06	0.04	0.0161	0.0052	0.0052	10.57	1.00	0.64
550	1	bar	Round	10	0.06	0.04	0.0063	0.0061	0.0060	14.03	0.99	0.48
550	2	bar	Round	10	0.06	0.04	0.0063	0.0000	0.0000	2.40	1.00	1.00
553	1	bar	Round	10	0.06	0.04	0.0103	0.0090	0.0081	15.80	0.90	0.43
553	2	bar	Round	10	0.06	0.04	0.0103	0.0009	0.0009	4.67	1.00	1.00
556	1	bar	Round	10	0.06	0.04	0.0161	0.0142	0.0113	18.30	0.80	0.37
556	2	bar	Round	10	0.06	0.04	0.0161	0.0029	0.0029	8.43	1.00	0.80
559	1	Vane	Sq.	10	0.06	0.04	0.0066	0.0062	0.0060	13.67	0.97	0.50
559	2	Vane	Sq.	10	0.06	0.04	0.0066	0.0002	0.0002	2.73	1.00	1.00
562	1	Vane	Sq.	10	0.06	0.04	0.0102	0.0089	0.0081	15.23	0.90	0.45
562	2	Vane	Sq.	10	0.06	0.04	0.0102	0.0009	0.0009	4.50	1.00	1.00
565	1	Vane	Sq.	10	0.06	0.04	0.0154	0.0141	0.0113	17.70	0.80	0.38
565	2	Vane	Sq.	10	0.06	0.04	0.0154	0.0028	0.0028	7.40	1.00	0.92

Starting Trial	Inlet Position	Grate Type	Shape	Downspout size (inch)	Cross Slope	Long Slope	Valve Reading (cfs)	Inflow (cfs)	Captured Flow (cfs)	Spread (cm)	Effici -ency	WT
568	1	bar	Sq.	10	0.06	0.04	0.0064	0.0060	0.0059	13.23	0.98	0.51
568	2	bar	Sq.	10	0.06	0.04	0.0064	0.0001	0.0001	3.03	1.00	1.00
571	1	bar	Sq.	10	0.06	0.04	0.0100	0.0086	0.0076	15.10	0.89	0.45
571	2	bar	Sq.	10	0.06	0.04	0.0100	0.0010	0.0010	4.10	1.00	1.00
574	1	bar	Sq.	10	0.06	0.04	0.0156	0.0141	0.0111	17.87	0.79	0.38
574	2	bar	Sq.	10	0.06	0.04	0.0156	0.0030	0.0030	8.43	1.00	0.80

Appendix E: Experimental Data for Grate Erosion Rate Test

LEGEND

TU = upstream spread measurement (cm)

TD = downstream spread measurement (cm)

wb = weight before test of clogging material (g)

ws = weight after experiment fully saturated (g)

wd = weight after experiment fully dry (g)

Table E.1: Experimental Data for Sediment Removal

Starting Trial	Grate	Cross Slope	Long Slope	Inflow (gpm)	TU (cm)	TD (cm)	wb (g)	ws (g)	wd (g)	Time (s)
1	bar	0.06	0.04	3.0	7.5	3.7	26.4	16.0	20.0	614
4	bar	0.06	0.04	4.6	10.0	5.0	28.4	13.1	15.1	405
7	bar	0.06	0.04	6.4	13.2	7.7	32.1	8.3	6.5	318
10	vane	0.06	0.04	3.0	8.8	1.0	30.2	12.7	10.7	500
13	vane	0.06	0.04	4.8	11.5	4.7	38.3	0.3	1.2	187
16	vane	0.06	0.04	5.8	13.9	8.1	36.5	5.5	3.0	342
19	bar	0.02	0.04	3.4	15.1	7.1	33.3	24.5	22.1	530
22	bar	0.02	0.04	4.6	18.6	10.7	34.0	30.0	26.9	584
25	bar	0.02	0.04	6.8	23.3	16.3	30.8	17.8	14.9	436
28	vane	0.02	0.04	3.3	19.3	13.0	31.2	24.1	18.7	540
31	vane	0.02	0.04	4.7	22.6	14.6	31.9	17.9	14.7	412
34	vane	0.02	0.04	7.0	28.8	19.4	32.9	20.9	17.7	640
37	bar	0.06	0.02	3.1	14.8	9.1	35.0	30.2	27.9	667
40	bar	0.06	0.02	4.7	20.0	10.7	34.6	17.9	14.7	654
43	bar	0.06	0.02	7.0	22.0	14.9	34.5	18.3	14.5	508
46	vane	0.06	0.02	3.1	15.8	10.0	28.1	14.0	11.7	544
49	vane	0.06	0.02	4.8	19.2	10.8	30.3	5.2	3.6	422
52	vane	0.06	0.02	7.0	22.3	12.5	29.7	15.3	12.7	417
55	bar	0.02	0.02	3.0	28.9	23.9	35.9	30.6	26.7	577
58	bar	0.02	0.02	4.6	33.3	31.8	30.9	20.2	17.3	556
61	bar	0.02	0.02	6.9	37.9	34.3	27.7	14.2	8.9	472
64	vane	0.02	0.02	3.1	33.1	31.1	33.2	24.8	20.5	617
67	vane	0.02	0.02	4.5	35.7	34.6	33.5	20.5	17.5	620
70	vane	0.02	0.02	7.1	40.9	40.0	28.5	8.5	7.1	426
73	bar	0.06	0.01	3.1	19.6	13.9	32.0	23.6	19.5	586
76	bar	0.06	0.01	4.7	23.7	17.5	35.6	12.7	10.2	544
79	bar	0.06	0.01	7.3	29.7	27.0	30.1	13.9	11.2	554
82	vane	0.06	0.01	3.1	18.4	15.0	32.7	19.3	15.4	496

Starting Trial	Grate	Cross Slope	Long Slope	Inflow (gpm)	TU (cm)	TD (cm)	wb (g)	ws (g)	wd (g)	Time (s)
85	vane	0.06	0.01	4.6	22.4	18.5	35.3	17.5	14.5	573
88	vane	0.06	0.01	7.2	29.2	21.3	31.9	20.6	16.4	585
91	bar	0.02	0.01	3.2	35.9	32.1	33.9	29.2	24.3	582
94	bar	0.02	0.01	4.8	39.2	36.9	29.5	28.8	22.1	583
97	bar	0.02	0.01	7.2	44.9	43.2	30.4	15.1	11.7	540
100	vane	0.02	0.01	2.9	35.3	25.0	33.7	25.7	21.6	582
103	vane	0.02	0.01	4.5	39.1	33.7	27.8	19.3	16.8	518
106	vane	0.02	0.01	7.1	44.7	44.8	29.5	19.2	15.8	569
109	bar	0.06	0.005	3.2	22.1	16.6	33.5	28.0	24.3	614
112	bar	0.06	0.005	4.7	25.9	20.2	28.5	19.0	16.0	536
115	bar	0.06	0.005	7.4	30.5	25.5	30.6	20.6	17.9	597
118	vane	0.06	0.005	3.2	23.0	18.0	27.9	20.0	17.4	684
121	vane	0.06	0.005	4.7	27.1	20.9	24.9	14.4	12.4	561
124	vane	0.06	0.005	7.1	30.5	23.2	27.5	17.7	14.9	610
127	bar	0.02	0.005	3.1	46.3	47.5	25.9	11.7	9.6	585
130	bar	0.02	0.005	4.8	49.1	52.2	30.7	16.6	13.0	473
133	bar	0.02	0.005	7.1	52.6	51.5	29.7	6.8	5.4	550
136	vane	0.02	0.005	3.0	43.8	41.7	27.4	16.4	15.9	568
139	vane	0.02	0.005	4.6	50.8	48.6	30.7	22.1	14.0	460
142	vane	0.02	0.005	7.0	57.3	51.9	35.6	0.0	0.0	474

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KANSAS TRANSPORTATION RESEARCH AND NEW-DEVELOPMENT PROGRAM

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