Estimation of Hydraulic Conductivity from Injection Tests using Mini-Piezometers with Drilled-Hole Screens

Bisesh Joshi

Follow this and additional works at: https://digitalcommons.memphis.edu/etd

Recommended Citation
https://digitalcommons.memphis.edu/etd/3266

This Thesis is brought to you for free and open access by University of Memphis Digital Commons. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of University of Memphis Digital Commons. For more information, please contact khggerty@memphis.edu.
ESTIMATION OF HYDRAULIC CONDUCTIVITY FROM INJECTION TESTS USING MINI-PIEZOMETERS WITH DRILLED-HOLE SCREENS

By

Bisesh Joshi

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

Major: Civil Engineering

The University of Memphis
August 2022
This thesis is dedicated to the scientific community.
ACKNOWLEDGEMENT

First of all, I would like to express my deep gratitude to my major advisor, Dr. Claudio Meier, for his untiring guidance, motivation, and support without which this work would never have been successful. I was very lucky to have such a knowledgeable advisor whose mentorship significantly enhanced my research and personal skills during my master’s study.

I would like to give special thanks to my co-advisor Dr. Farhad Jazaei for his input with the experimental design, facilitating the test materials, and providing important insights during the experiments and data analyses. I would also like to thank Dr. Roger Meier for being on my committee and giving valuable advice and comments which helped in the successful completion of this research. I am also thankful to Barry Craig Wymore for his continuous support in building the experimental apparatus and ancillary equipment.

I would like to thank my friends who helped me with the research when I needed it. And finally, I cannot thank enough my family members who are always there for me as source of motivation.
Abstract

Cost- and time-effective injection methods using mini-piezometers are widely used in hyporheic research for estimating hydraulic conductivity ($K$). To check the performance of a range of mini-piezometer screens with drilled holes, we simulated constant-head injection tests in a uniform, isotropic streambed, using a specially designed laboratory apparatus.

Applying accepted methods by Hvorslev and Cardenas & Zlotnik, with subsequent modifications, we studied the effects of screen length, hole diameter, and hole spacing on the shape factor ($F$), and thus on the estimated $K$. We also investigated the nature of the injected flow by studying the spatial distribution of piezometric head within the porous medium.

When the proportion of screen openings is above 6%, both methods predict $K$ adequately, while the shape factor proposed by Bouwer & Rice underestimates consistently. A proposed empirical equation for $F$ as a function of the well-screen parameters results in more precise estimates for our test conditions.
# TABLE OF CONTENTS

**LIST OF FIGURES** .............................................................................................................. vii  
**LIST OF TABLES** ................................................................................................................ ix  

**CHAPTER 1: INTRODUCTION** .......................................................................................... 1  

**CHAPTER 2: LITERATURE REVIEW** .................................................................................. 6

2.1 Field injection tests........................................................................................................... 6

2.2 Shape factors from Hvorslev (1951) and Bouwer & Rice (1976)......................................... 8

2.3 Analytical and numerical studies of injection zone effects ................................................. 9

2.4 Experimental studies of injection zone effects .................................................................... 11

2.5 The need for this research ................................................................................................. 12

**CHAPTER 3: METHODOLOGY** ......................................................................................... 15

3.1 Design and construction of the experimental apparatus ..................................................... 15

3.2 Porous medium ................................................................................................................. 17

3.3 Design of the well screens and measurement piezometers ................................................. 19

3.3.1 Well screens .................................................................................................................. 19

3.3.2 Measurement piezometers ............................................................................................ 23

3.4 Experimental setup and data collection .............................................................................. 24

3.4.1 Column experiment ....................................................................................................... 24

3.5 Data analysis ...................................................................................................................... 31

**CHAPTER 4: RESULTS AND DISCUSSION** .................................................................... 34

4.1 Results from constant-head permeameter tests ................................................................. 34
4.2 Initial experiments with variable tank size................................................................. 35
4.3 Estimating K with mini-piezometers: effects of screen design and method ............... 37
4.4 Univariate effects of different screen parameters ......................................................... 40
  4.4.1 Effects of hole diameter......................................................................................... 40
  4.4.2 Effects of well-screen length................................................................................ 41
  4.4.3 Effects of the spacing between holes..................................................................... 41
  4.4.4 Effects of injection head....................................................................................... 43
4.5 Combined effects of screen parameters ....................................................................... 44
4.6 Potential control due to low screen conductivity ......................................................... 45
4.7 Prediction of the shape factor based on well-screen parameters................................. 47
4.8 Study of the flow field around mini-piezometers......................................................... 49
  4.8.1 Radius of dissipation ......................................................................................... 50
  4.8.2 Piezometric head 1-D distribution along the central axis ..................................... 51
  4.8.3 Piezometric head 2-D distribution in the central vertical plane ............................. 51
  4.8.4 Detailed 3-D analysis of piezometric head distribution ....................................... 52
CHAPTER 5: CONCLUSIONS ......................................................................................... 55
REFERENCES .............................................................................................................. 59
LIST OF FIGURES

Figure 1: Constant-head injection test ............................................................. 8

Figure 2: Top view of the experimental apparatus showing test porous material in the first two compartments ............................................................ 16

Figure 3: Side view of the experimental apparatus showing the porous medium (in this case filling the three compartments), the water levels, and the testing compartments (labeled 1, 2, and 3). ............................................................................. 17

Figure 4: Front view of the experimental apparatus .................................................................................................................. 18

Figure 5: Ranges for the opened area (cm$^2$, at left) as well as the proportion of the screen opened (%, to the right) for the different well-screen combinations obtained from three different hole diameters ......................................................................... 20

Figure 6: Nine different well screens, obtained by combining three different spacings between holes with three different screen lengths. We also varied the hole size (three different diameters) for a total of 27 different screens tested. ........................................................................... 21

Figure 7: Mini-piezometer well screens ................................................................................................................................. 23

Figure 8: Example of hole arrangement in injection mini-piezometer ...................................................................................... 24

Figure 9: Piezometers to measure the pressure head at different points within the porous medium. ...................................................................................... 25

Figure 10: Column experiment for determining the “true” $K$ value ...................................................................................... 26

Figure 11: Schematic representation of the experiment ........................................................................................................ 27

Figure 12: Laboratory set-up of the experimental apparatus ................................................................................................... 30

Figure 13: Comparison of $K$ estimates from Hvorslev (1951) with $F$ modified by Chapuis (1989) and Cardenas & Zlotnik (2003) with $R_e$ from our experimental plots ................................................................. 38

Figure 14: Effects of the screen-hole diameter on $K$ estimates ................................................................................................. 40

Figure 15: $K$ estimates for different screen lengths; screen-hole diameter of 0.26 cm in the upper plot and 0.56 cm in the lower plot ........................................................................................................ 42

Figure 16: $K$ estimates as a function of spacing between screen holes ...................................................................................... 43
Figure 17: Effects of varying injection head on $K$ estimates ........................................... 43

Figure 18: Combined effects of the well-screen parameters on $K$ estimates for the case of injection head of 35 cm. L/D is the ratio between the length and diameter of the well screen. ... 46

Figure 19: Analysis of potential screen conductivity effects in injection tests with and without test material in the experimental apparatus. ................................................................. 47

Figure 20: Predicting shape factors with the proposed mathematical model. ......................... 49

Figure 21: Experimental determination of $R_e$ by measuring piezometric head at different locations along the central axis of flow. ................................................................. 50

Figure 22: Piezometric head as a function of vertical distance from the centerline (in abscissae), measured at different fixed locations along the central axis of flow (colors) in the vertical plane. ................................................................................................................................. 52

Figure 23: Flow field developed over a vertical plane (at 10 degrees from the left wall of the apparatus) within the injection zone, around the 20 cm long well-screen with 0.60 cm diameter holes drilled at a spacing of 3 cm. ........................................................................................................... 53

Figure 24: Piezometric head distribution in the horizontal plane along the axis passing through center of the screen, when water is injected through the 20 cm long well-screen with 0.60 cm diameter holes drilled at a spacing of 3 cm. ........................................................................................................... 54
LIST OF TABLES

Table 1: Screen combinations for injection tests ................................................................. 22
Table 2: $K$ results from column permeameter tests .............................................................. 35
Table 3: $K_{20}$ values estimated from injection tests using different screen designs and methods.. 39
CHAPTER 1: INTRODUCTION

The interactions between groundwater and surface waters have been a topic of interest for the last few decades. Issues related to water supply, aquatic ecosystem health, and water quality have become evident as concerns over water resources and the environment have increased. Surface waters are connected to groundwater through unconfined zones, hydrogeologic windows in confining units, and fractures. The hyporheic zone is that sector below the riverbed where mixing of surface water and groundwater occurs, while the flow dynamics within it are referred to as hyporheic flow.

Flows into and out of the hyporheic zone, known as hyporheic exchanges, are crucial elements of a healthy river corridor, affecting the fluvial ecosystem and its aquatic life in myriad ways. For example, hyporheic biogeochemical processes significantly alter a stream’s solute loads, while the upwelling and downwelling of water creates a range of thermal environments, different from the stream’s water column, creating unique habitats for some organisms (Wondzell, 2011). Therefore, hyporheic exchange is essential for understanding the ecology of freshwater ecosystems such as wetlands and streams (Baxter et al., 2003).

As hyporheic exchange occurs through the porous sediment in the streambed, knowledge of its hydraulic characteristics is needed to describe the dynamics of flow in the hyporheic zone. The main property that needs to be assessed in order to understand hyporheic exchange is the saturated hydraulic conductivity of the streambed, which describes the ease with which water can flow through the bed sediments.

Darcy (1856) was the first to quantify the movement of water through porous media. He found that the rate of water flow (discharge per unit area perpendicular to the flow, also known as
Darcy or apparent velocity) through a porous medium is directly proportional to the rate at which the hydraulic head is dissipated (this is the hydraulic gradient, equal to the total head driving the flow divided by the macroscopic length of the flow path), as described in Equation (1):

\[ Q = K A \frac{(h_1 - h_2)}{l} \]  

(1)

where \( Q \) is the discharge, \( A \) is the cross-sectional area of flow, \( l \) is the macroscopic length of the path through the sand bed, \( h_1 \) and \( h_2 \) are the hydraulic heads at the entrance and exit of the sand bed, respectively, and \( K \) is the proportionality constant.

Darcy's Law for flow through porous media is valid only in the linear-laminar regime, which is the case when the Reynolds number does not exceed a value between one and ten (Bear, 1972). The proportionality constant in Darcy's Law is termed the saturated hydraulic conductivity (hereafter known as \( K \)), defined as the ability of a given fluid to pass through a porous medium in the presence of a hydraulic gradient. Thus, \( K \) is a function of both the porous medium and the fluid passing through it (Hubbert, 1956). Various field and laboratory methods have been proposed to determine \( K \), typically for water or air flowing through different materials. Because the viscosity of most fluids depends on their temperature, it will affect the value of \( K \).

Injection tests, in which water is poured into a well and flows through the screen into the porous medium, are widely used to estimate \( K \) in the field, as they are quick and less expensive than traditional methods such as aquifer pumping tests. Different types of injection tests are used in practice, which can be classified as constant-head or falling-head; in all the cases, their results are interpreted assuming that Darcy’s Law holds. Using piezometers, Hvorslev (1951) carried out both slug tests (a type of falling-head test) as well as constant-head injection tests to estimate the hydraulic conductivity of porous media for various screen-porous medium configurations.
Bouwer & Rice (1976) developed a variable-head slug-test method which has become a frequently used tool in groundwater investigations (Bouwer, 1989). Both the methods by Hvorslev (1951) and Bouwer & Rice (1976) were developed with large-scale, water-production wells in mind; e.g., the latter method considers a gravel pack around the well screen. Nowadays, inexpensive and easy to drive mini-piezometers, built of plastic or metallic pipe with screens fabricated with drilled holes, are widely used for injection tests to determine the saturated hydraulic conductivity of streambeds, e.g., in river bed seepage and hyporheic exchange research. In this context, no gravel pack is installed around the screen, as the mini-piezometer is repeatedly driven and then pulled out after each measurement in order to estimate $K$ at multiple locations. For this specific case, Cardenas & Zlotnik (2003) developed a simple Constant-Head Injection Test (CHIT), which is partially based on Bouwer & Rice’s (1976) work, as will be explained below.

Even though it is clear that the number of screen openings, their sizes, and their spatial arrangement along the screened portion of the mini-piezometer or well should all affect the way energy (i.e., available head) is dissipated as water flows from the well into the medium, none of the above methods incorporate any parameters describing the screen in their equations, beyond its length; they just assume that the screen is fully opened, so that its design and characteristics do not affect $K$’s estimation.

It should be noted that these potential screen effects are just one aspect of a broader concept that affects the estimation of $K$ when using injection tests: as water flows out of a well screen and interacts with the surrounding porous medium, it is the nature of the flow and resulting spatial pattern of head dissipation that determine the discharge (for constant-head tests) as well as its temporal variability (in the case of variable-head tests). The net effect of these interactions is
represented by the so-called shape factor $F$ which, for the case of homogeneous and isotropic materials, depends on the geometry of the flow domain (e.g., well diameter, distance to any impervious boundaries), screen design (length as well as type, area, and arrangement of the openings), characteristics of the porous material, and injection head. The shape factor $F$ can be defined as the proportionality constant between hydraulic conductivity and the ratio of flow rate to injection head at steady state. If $Q$ is the constant flow rate, $H$ is the injection head and $K$ is the hydraulic conductivity, the shape factor $F$ is given by Equation (2):

$$F = \frac{Q}{KH} \quad (2)$$

Many researchers have quantified the shape factor for the case at hand, which corresponds to a partially penetrating well screened into an unconfined aquifer, but the vast majority of this work assumes that conditions for Darcy’s Law hold (i.e., the flow is linear-laminar), and also disregards any possible screen effects, assuming a fully opened screen, as explained above. Moreover, most of this effort has been driven by the need to understand the behavior of conventional (i.e., large-diameter, production-type) wells, with long, continuously slotted screens. A detailed literature search could not retrieve any experimental studies assessing $K$ estimation with injection tests, using either the methods of Hvorslev (1951) or Cardenas & Zlotnik (2003) and their subsequent modifications. Additionally, the spatial pattern of head dissipation around mini-piezometers used as injection wells has not been studied experimentally.

This research addresses the above-mentioned issues using constant-head injection tests. We perform laboratory experiments in a custom-built apparatus, reproducing as closely as possible the case of radial flow due to injecting water into a well that partially penetrates an isotropic, uniform medium. Moreover, we determine adequate values for the shape factor when estimating
using mini-piezometers with relatively short screens made up of drilled holes. Specifically, we analyze the effects of screen length, number of holes in the screen, and diameter of the holes (which, together with the pipe diameter, determine the proportion of the screen that is opened). Using the equations proposed by Hvorslev (1951) – with the shape factor corrected as suggested by Chapuis (1989), and Cardenas & Zlotnik (2003) – which in its original version uses the shape factor of Bouwer & Rice (1976), $K$ values are derived for the different experimental tests and are then compared with the “true” $K$ value independently determined from a series of constant-head permeameter tests. A non-linear regression equation is proposed that explicitly incorporates the screen variables that are observed to affect the estimation of $K$. In order to better understand the spatial distribution of hydraulic head near the injection zone, we also experimentally describe the flow field around mini-piezometers driven in a homogeneous, isotropic porous medium. From this data, we experimentally derive the so-called effective radius of dissipation, $R_e$, which is a measure or index of the radial distance from a well screen at which most head has been already dissipated, as injected water flows into the medium.
CHAPTER 2: LITERATURE REVIEW

In this chapter, which is divided into five parts, we review research relevant to determining streambed $K$ with injection tests using mini-piezometers with drilled holes, analyzing the different factors that play a role in its precise estimation. We first discuss field injection tests that have been developed to estimate $K$ of subsurface materials, and then describe those shape factors commonly used in injection tests. The third part presents the mathematical approaches (both analytical and numerical) that have been proposed to understand the effects of the injection zone on the shape factor, and thus on $K$ estimates, while the fourth recounts some of the experimental studies that have looked into such effects. This includes Baptiste & Chapuis’s (2015) novel idea of considering three different conductivities when interpreting injection test results: that of the screen, of the gravel pack (when one is present), and that of the actual medium. The fifth and final part identifies a research gap, illustrating the need for this research.

2.1 Field injection tests

Field studies have suggested that permeameter tests in the laboratory produce inappropriate results for low-permeability sediments (Pollock et al., 1983), thus calling for the use of injection tests. Multiple hydrological studies have applied such tests in order to estimate $K$ for river, lake, and wetland beds. Not only are they simple and economical to use, they also take relatively little time, so that $K$ can be determined at multiple places to better describe its spatial variation (Woessner, 2017). Injection tests can be conducted in monitoring wells (typically with a gravel pack) or in mini-piezometers (without one) and are classified in two categories based on the time variability of the applied injection head: constant head and variable head. Two widely used injection methods are those proposed by Hvorslev (1951) and Bouwer & Rice (1976; see also
Bouwer, 1989). While Hvorslev (1951) provided equations for constant-head and variable-head injection tests covering a range of different well-medium configurations, Bouwer & Rice (1976) developed a slug test (a special case of variable-head test) for a vertical well screened either partially or fully into a confined or an unconfined aquifer. Cardenas & Zlotnik (2003) proposed a simple constant-head injection test to determine streambed $K$ with piezometers inserted at shallow depths. Their approach, which is partly based on Bouwer & Rice (1976), has been increasingly used in hyporheic flow research. Pitz (2007) assessed this method and found that $K$ estimates are within the primary permeability range for the tested streambed. Baxter et al. (2003) also developed a simple field injection technique using mini-piezometers, for a case similar to that of Cardenas & Zlotnik (2003), which they recommend as a labor/cost-efficient way to estimate $K$ values of streambeds when dealing with multiple and/or remote locations.

However, even though injection tests are extensively used to determine $K$, estimates from these tests are often uncertain for different practical reasons (Black, 2010). Chapuis (2009) compared the methods of Hvorslev (1951) and Bouwer & Rice (1976), focusing on their respective shape factors; he found that the latter yields less precise estimates because of its unrealistic assumptions. Brown et al. (1995) observed that the Bouwer & Rice method tends to underestimate $K$ because of the presence of a damaged zone - due to the gravel pack or skin around the well, which creates a lower permeability zone. In his experiments with mini-piezometers, Regmi (2019) found that various injection test equations offered in the literature for estimating $K$ did a poor job over the range of his five different porous materials.
2.2 Shape factors from Hvorslev (1951) and Bouwer & Rice (1976)

The above tests do not consider all the ways in which a screen interacts with the resulting flow in the injection zone, determining the shape factor. Our case of interest, that of a constant-head injection test in a partially screened well, is depicted in Figure 1, where \( L \) is the screen length, \( H \) is the head available for the flow, and \( D \) is the diameter of the piezometer. The two most commonly used methods for this case are those proposed by Hvorslev (1951), using a shape factor compiled in his report (page 49, case G), and by Cardenas & Zlotnik (2003), which is based on the shape factor of Bouwer & Rice (1976). It should be noted that both constant-head injection methods are essentially identical, based on applying Darcy’s Law. The only difference is in the shape factor that they use to relate discharge and head to hydraulic conductivity \( K \).

![Figure 1: Constant-head injection test.](image)
For this case, the shape factor proposed by Hvorslev (1951) is that originally derived by Dachler (1936) on theoretical grounds, given by Equation (3):

\[ F_H = \frac{2 \pi L H}{\ln \left[ \frac{L}{D} + \sqrt{1 + \left( \frac{L}{D} \right)^2} \right]} \] (3)

While Bouwer & Rice's (1976) shape factor for this same configuration is calculated as shown in Equation (4):

\[ F_{BR} = 2\pi L P \] (4)

It should be noted that as shown by Equation (5) below, the shape factor in Equation (4) depends on parameter \( P \) in Bouwer & Rice (1976), which employs the idea of an effective radius of dissipation \( R_e \), the radial distance into the medium over which “most” of the injection head dissipates. Bouwer & Rice (1976) determined the term \( \ln \left( \frac{R_e}{r_w} \right) \) in Equation (5) from an electrical analogue for a partially penetrating well (common condition in hyporheic research, and the case that we study in this work), as shown in Equation (6):

\[ P = \frac{1}{\ln \left( \frac{R_e}{r_w} \right)} \] (5)

\[ \ln \left( \frac{R_e}{r_w} \right) = \left[ \frac{1.1}{\ln \left( \frac{1.1 + L}{r_w} \right)} + \frac{A + B \ln \left( \frac{b - \frac{L}{r_w}}{r_w} \right)}{r_w} \right]^{-1} \] (6)

where \( A \) and \( B \) are dimensionless parameters given in Fig. 2 of Bouwer & Rice (1976), as functions of the geometric ratio \( L/r_w \) (which is a type of slenderness ratio of the screen).

**2.3 Analytical and numerical studies of injection zone effects**

A review of the literature detected several drawbacks as relates to the applicability of current approaches to the case of mini-piezometers with drilled holes. In many cases, the authors
hypothesize a fully opened screen (an “ideal screen,” sensu Klammler et al., 2014), i.e., there is no concern for the actual geometry of the slots or holes, as it is assumed that the whole right-cylindrical lateral surface making up the screen is opened to the medium; this neglects any potential effect of the screen from the very beginning. Because of this, the actual flow dynamics in the injection zone, which depend on the interaction of the flow coming out of the holes (or slots) with the porous medium, are not represented correctly. In this way, beyond those effects due to the screen length-to-radius ratio, most field studies on injection tests overlook the consequences that the type and arrangement of the openings, and the resulting percentage opening of the well screen, may have on the shape factor, and thus on $K$ estimates.

However, some analytical and numerical approaches have been applied to study the effects of the injection zone and the efficacy of conventional injection tests. For example, Brown et al. (1995) used synthetic slug test data to investigate the role of the screen length, well diameter, and effective radius of dissipation $R_e$ on $K$ estimates. They found $K$ values to be more sensitive to the distance between the top of the screen and the water table, and also noticed that flow patterns deviate from the radial geometry of flow for the shorter (i.e., lower $L/r_w$ ratios) screens. Chapuis (1989) compared a series of shape factors obtained both analytically and with numerical approaches, including those compiled by Hvorslev (1951). After reporting an unexpectedly large variability, with differences of up to 40% for long screens and more than 100% for short screens, he proposed analytical corrections to obtain shape factors for partially penetrating wells. Other studies have also demonstrated that injection tests yield better $K$ estimates for larger $L/r_w$ well-screen ratios, which better approximate the ideal case of fully radial flow (Dagan, 1978; Hayashi & Quinton, 2004; Novakowski, 1993). Zhang et al. (2020) conducted a comprehensive numerical study of shape factors for the case of injection field tests with partially screened wells, covering a
range of porous media. They incorporated the effects of partly unsaturated seepage, for both steady and unsteady cases, of the screen length, and of the vertical distance to the impervious boundary, and analyzed how the radial distance to the domain boundary affected their simulation results. Using a semi-analytical approach, Klammler et al. (2014) studied the effects of different slot geometries and finite lengths of the screen, finding that circumferential and longitudinal slots yield identical results for the case of long screens.

2.4 Experimental studies of injection zone effects

All results described in Section 2.3 are based on analytical or numerical solutions to the Laplace equation, but a few experimental studies have also been conducted to understand the effects of well-screen parameters on $K$ estimation, even though most of them refer to commercial, slotted well screens as installed in production wells. Clarke & Turner (1983) claimed that when a well-screen has an opening of more than 10%, its hydraulic performance is independent of well screen type or design. Ahmad (1983) disagreed with this notion, noting that screen efficiency should be defined by considering both head loss and discharge; according to his results, the hydraulic performance of well screens does not increase, above a minimum proportion of openings of about 3-5%, as long as the entrance velocity is kept below 2.5 ft/s (0.76 m/s). In a Norfolk (UK) floodplain, Surridge et al. (2005) conducted a study to determine $K$ in peat, using PVC standpipe piezometers with a screen with 70% opening of the total screen area. When comparing results with laboratory permeameter tests, they found that injection tests in the field gave similar estimates to the laboratory tests. Baptiste & Chapuis (2015) used water tank tests to obtain the conductivity of typical, slotted, 2-inch PVC well screens with open areas in the range from 0.6 to 6.6% of the total screen area. They noted that the presence of air bubbles in the slots resulted in higher head losses, as they decreased the available area for the flow, and thus suggested using
deaired water for injection tests. It should be noted that this effect is probably irrelevant for the case of screens consisting of drilled holes, as is the case in the present study. For their case, using a 2-inch well – which is larger than the PVC pipes typically employed in hyporheic research, Baptiste & Chapuis (2015) found that the highest $K$ value that can be estimated is in the order of $5 \times 10^{-3}$ m/s, using the largest proportion of open area. For screens with smaller slots, in typical field conditions (which precludes using deaired water), the maximum $K$ that can be measured will be in the range of $10^{-5}$ to $10^{-4}$ m/s but might be as low as $10^{-6}$ m/s for poorly designed screens. They also suggested that three different conductivities – $K_s$, $K_f$, and $K$, for the screen, the filter pack, and the test material, respectively – interact in injection tests. In order to obtain adequate estimates of the conductivity of the porous medium, both $K_s$ and $K_f$ should be sufficiently larger than $K$. As mini-piezometers used in hyporheic research do not have a filter pack around them, field researchers should ensure that $K_s$ is sufficiently larger than $K$ (see Section 4.6).

2.5 The need for this research

Most methods for estimating $K$ using injection tests in mini-piezometers use either the shape factors compiled by Hvorslev (1951) or the procedure and equations proposed by Bouwer & Rice (1976). But mini-piezometers display a series of special characteristics which need to be considered when selecting adequate values for the shape factor. First, most researchers plug the bottom of the pipe to avoid infilling with sediment while driving the well into the riverbed. Second, mini-piezometers typically have short screens and a narrow diameter (down to half-inch PVC pipe); in other words, they have small $L/r_w$ well-screen slenderness ratios. Third, most researchers build their mini-piezometer screens by drilling lines of holes, as it is much quicker,
cheaper, and easier than attempting to mount a slotted screen, also resulting in a sturdier, one-piece well. In their experiments, Singh & Shakya (1989) found that flow through slotted screens is different from orifice flow, which strongly suggests that screens made of drilled holes will behave differently than slotted screens, beyond the fact that microbubbles should have no effect on the flow. Finally, all shape factors used to interpret injection tests have been derived under the assumption that Darcy’s Law is applicable; but for the typical combinations of injection heads, screen designs, and streambed materials, it is clear that the flow’s Reynolds number will be too high for this to hold true, at least in that part of the injection zone closest to the well screen. We propose that experimental research is needed to check whether such local effects can have relevant impacts on $K$ estimation.

In general, all of the above characteristics related to drilled-holes screens should be considered when determining the shape factor for any specific injection test. For starters, when using the shape factor proposed by Hvorslev (1951), it should be noted that it is only applicable to screened piezometers that are also opened at the bottom. Thus, it should be corrected as suggested by Chapuis (1989) in order to get unbiased $K$ estimates when using mini-piezometers with a plugged end (impervious or closed bottom end). On the other hand, as mentioned before, it has been found that the shape factor proposed by Bouwer & Rice (1976) typically underestimates $K$ values (Brown et al., 1995; Rupp et al., 2005; Chapuis, 2009). Chapuis (2009) found a conceptual mistake in their derivation using an analogy between electric potential and groundwater, which explains this issue, calling into question the use of Bouwer & Rice’s (1976) shape-factor methodology. Specifically, this error affects the correct determination of the effective radius of dissipation $R_e$, which is needed to estimate the shape factor.
It should be noted here that the simple and increasingly used CHIT method developed by Cardenas & Zlotnik (2003; see also Cardenas & Zlotnik, 2007) for hyporheic research requires knowing \( R_e \) for determining the shape factor. This index summarizes how energy dissipates along the radial flow path as injected water discharges from the screen into the porous medium. As the Bouwer & Rice (1976) approach is incorrect, we suggest that alternative ways of determining \( R_e \) or \( F \) are needed when using the method of Cardenas & Zlotnik (2003).

Our literature review indicates that there are no experimental studies that simultaneously: (i) consider the aforementioned modifications of the shape factor needed to estimate \( K \) precisely, (ii) analyze the specific screen-parameter effects of mini-piezometers with drilled holes, under conditions similar to those expected in the field, and (iii) describe the nature and spatial extent of energy dissipation as water radially flows from the screen’s drilled holes into the porous medium. This research aims at experimentally addressing all of the above issues, by reproducing constant-head injection tests into a homogeneous and isotropic porous medium in a specifically built laboratory apparatus using mini-piezometers with drilled holes.
CHAPTER 3: METHODOLOGY

This chapter explains the procedures adopted to conduct the research work, in five sections. First, the design of the experimental apparatus is presented; the second section explains the design of the tested well screens, as well as that of the measurement piezometers used to measure water pressure in the medium around the well to determine $R_z$; the third describes the porous medium chosen for the test experiments, while the fourth section presents the constant-head injection test set-up as well as the data-collection protocol. Finally, the fifth section presents the procedures to estimate $K$ from the data with different approaches, and their comparative analysis.

3.1 Design and construction of the experimental apparatus

An apparatus was designed to perform constant-head injection tests in a uniform and isotropic porous medium, simulating the case of an injection well partly penetrating into streambed sediment. Considering the mini-piezometer sizes typically used in hyporheic research, simulating the complete radial flow around a well for a full-scale model would have required a very large apparatus and huge volumes of sediment. To circumvent this issue, our apparatus represents exactly one-sixth of the radial flow case, as seen from above. It consists of a radial tank with its walls extended at 60 degrees from the central, 3.9 cm-diameter (outer dimension) cylindrical column, to a radial distance of 69.7 cm. The apparatus was constructed in the workshop at the Herff College of Engineering, University of Memphis; the design drawings with dimensions are shown in Figures 2, 3, and 4. The 65 cm-high apparatus has three compartments to contain the test materials, separated by mesh screens located at radial distances of 15 cm, 30 cm, and 60 cm from the center of the mini-piezometer, as shown in the top view of the apparatus (Figure 2). This allowed us to test different downstream boundary conditions. The small space behind the
third compartment was left empty in all cases in order to have a boundary condition with water at
the same, known hydraulic head. During testing, water flowed out of the downstream end of the
apparatus through a broad spillway, whose crest was located at an elevation of 59.6 cm with
respect to the base of the tank, as shown in the side view in Figure 3; this allowed us to maintain
a constant downstream head, independently of the flow rate. The water spilling over the weir was
collected to compute the steady-state discharge for each experiment. Three different constant
heads were maintained within the overhead cylindrical tank, which had 14.4-cm inner diameter
and a conical section at its base to connect it to the injection piezometer. In order to maintain a
constant head, three horizontal slot openings were carved into the side of the overhead tank at
elevations of 35, 43, and 51 cm above the downstream spillway-crest level.

Figure 2: Top view of the experimental apparatus showing test porous material in the first two
compartments.
Figure 3: Side view of the experimental apparatus showing the porous medium (in this case filling the three compartments), the water levels, and the test compartments (labeled 1, 2, and 3).

### 3.2 Porous medium

For the experiments, glass beads were chosen over natural sand materials because their smooth spherical shape and consistent grain size guarantee a uniform and isotropic behavior. The use of glass beads eliminates any variability that could be introduced due to the heterogeneity of natural sand, making it easier to isolate the effects due to other factors, such as screen parameters.
Initially, we tried glass beads of various sizes (0.50 - 0.75 mm, 1.00 - 1.30 mm, 2.40 - 2.90 mm, and 3.40 - 4.00 mm) in a smaller, 30-degree central angle radial tank. Boiling of the glass beads occurred for the smaller particle size (0.50-0.75 mm) due to the high resistance to the flow under the relatively large injection heads, while glass beads with the largest grain sizes (above 2.40 mm) would not provide sufficient resistance, resulting in very large discharge rates. Therefore, glass beads of particle size 1-1.3 mm were selected for the experiment. Ten 44-lb buckets of

Figure 4: Front view of the experimental apparatus.
GSR-11-SL (1.0-1.3 mm) glass beads were purchased from Ceroglass Technologies Inc. and used for the research.

3.3 Design of the well screens and measurement piezometers

3.3.1 Well screens
To study the effects that well-screen parameters have on flow rates in constant-head injection tests, we designed multiple well screens by varying the following three parameters: length of the screen, hole diameter, and spacing between the holes. It is important to mention here that all the tested screens represent a single type of actual mini-piezometer screen with six vertical lines with drilled (and thus circular) holes, with the lines arranged around the pipe every 60 degrees. These are the types of mini-piezometer screens that would typically be used in hyporheic field research, as they are easy to manufacture with PVC pipe and a home drill. Of course, because our experimental apparatus covers 60° instead of the full 360° radial case, our experimental screens consisted of a single vertical line of circular holes, instead of six lines.

We selected three different diameters of holes, three different nominal screen lengths, and three different spacings between the holes, for a total of 27 different combinations, achieving a broad range of values for the total opened area as well as the proportion of the screen that is opened (hereafter referred to as “% of openings”), as shown in Figure 5.

The three different nominal screen lengths (10, 20, and 30 cm) were chosen based on typical mini-piezometer designs used in the field. Given the dimensions of our apparatus, the maximum screen length results in a screen that was located sufficiently below the top surface of the porous medium to avoid particle boiling at the surface (in most cases, but not all), while the minimum length was still large enough not to overly disturb the radial flow pattern.
Figure 5: Ranges for the opened area (cm$^2$, at left) as well as the proportion of the screen opened (%, to the right) for the different well-screen combinations obtained from three different hole diameters.

In order to generate the 27 different screen combinations presented in Table 1 (of which nine are shown in Figure 6, for one of the three hole diameters) without using so much stainless-steel pipe, we devised a system with two pipes: an outer stainless-steel pipe of nominal diameter 1.25 inch, acting as our actual mini-piezometer, with an inner PVC pipe of nominal diameter 1 inch, used to selectively block screen holes; these were found to fit tightly when the PVC pipe was slid inside the steel pipe. The holes in the inner (PVC) pipe were made slightly larger than those on the outer (stainless-steel) pipe so that it was the dimensions of the outer holes that governed head dissipation during injection; in other words, except for the slightly higher vertical velocity down the pipe, due to the space taken by the inner PVC pipe, our set-up basically reproduces the case of a well built with the outer, stainless-steel pipe.
Figure 6: Nine different well screens, obtained by combining three different spacings between holes with three different nominal screen lengths. We also varied the hole size (three different diameters) for a total of 27 different screens tested.

An example of the inner and outer pipes is given in Figure 7, in which the outer (stainless steel) pipe is in the foreground, while the other three are the inner (PVC) pipes. In order to ensure that the inner and outer holes are concentric, a small hole was made on the top portion of the inner and outer pipes, in which a dowel pin was inserted, thus allowing to line them up perfectly before each test.

The well screen was always centered at the elevation corresponding to the middle of the height of the porous medium, as shown in Figure 8, so that the flow distribution of the vertical profile
remained symmetrical above and below a horizontal plane coinciding with the central axis through the sediment.

Table 1: Screen combinations for injection tests

<table>
<thead>
<tr>
<th>Well screen</th>
<th>Hole diameter (cm)</th>
<th>Screen length (cm)</th>
<th>Spacing (cm)</th>
<th>No. of holes</th>
<th>Opened area (cm²)</th>
<th>Percentage of openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.26</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>0.53</td>
<td>2.81</td>
</tr>
<tr>
<td>2</td>
<td>0.26</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>0.21</td>
<td>1.12</td>
</tr>
<tr>
<td>3</td>
<td>0.26</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>0.11</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>0.26</td>
<td>20</td>
<td>1</td>
<td>20</td>
<td>1.06</td>
<td>2.70</td>
</tr>
<tr>
<td>5</td>
<td>0.26</td>
<td>20</td>
<td>3</td>
<td>6</td>
<td>0.32</td>
<td>1.02</td>
</tr>
<tr>
<td>6</td>
<td>0.26</td>
<td>20</td>
<td>5</td>
<td>4</td>
<td>0.21</td>
<td>0.68</td>
</tr>
<tr>
<td>7</td>
<td>0.26</td>
<td>30</td>
<td>1</td>
<td>30</td>
<td>1.59</td>
<td>2.67</td>
</tr>
<tr>
<td>8</td>
<td>0.26</td>
<td>30</td>
<td>3</td>
<td>10</td>
<td>0.53</td>
<td>0.95</td>
</tr>
<tr>
<td>9</td>
<td>0.26</td>
<td>30</td>
<td>5</td>
<td>6</td>
<td>0.32</td>
<td>0.62</td>
</tr>
<tr>
<td>10</td>
<td>0.56</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>2.46</td>
<td>12.6</td>
</tr>
<tr>
<td>11</td>
<td>0.56</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>0.99</td>
<td>5.05</td>
</tr>
<tr>
<td>12</td>
<td>0.56</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>0.49</td>
<td>4.34</td>
</tr>
<tr>
<td>13</td>
<td>0.56</td>
<td>20</td>
<td>1</td>
<td>20</td>
<td>4.93</td>
<td>12.3</td>
</tr>
<tr>
<td>14</td>
<td>0.56</td>
<td>20</td>
<td>3</td>
<td>6</td>
<td>1.48</td>
<td>4.65</td>
</tr>
<tr>
<td>15</td>
<td>0.56</td>
<td>20</td>
<td>5</td>
<td>4</td>
<td>0.99</td>
<td>3.10</td>
</tr>
<tr>
<td>16</td>
<td>0.56</td>
<td>30</td>
<td>1</td>
<td>30</td>
<td>7.39</td>
<td>12.2</td>
</tr>
<tr>
<td>17</td>
<td>0.56</td>
<td>30</td>
<td>3</td>
<td>10</td>
<td>2.46</td>
<td>4.38</td>
</tr>
<tr>
<td>18</td>
<td>0.56</td>
<td>30</td>
<td>5</td>
<td>6</td>
<td>1.48</td>
<td>2.83</td>
</tr>
<tr>
<td>19</td>
<td>0.6</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>2.83</td>
<td>14.4</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>1.13</td>
<td>5.77</td>
</tr>
<tr>
<td>21</td>
<td>0.6</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>0.57</td>
<td>4.95</td>
</tr>
<tr>
<td>22</td>
<td>0.6</td>
<td>20</td>
<td>1</td>
<td>20</td>
<td>5.65</td>
<td>14.1</td>
</tr>
<tr>
<td>23</td>
<td>0.6</td>
<td>20</td>
<td>3</td>
<td>6</td>
<td>1.70</td>
<td>5.33</td>
</tr>
<tr>
<td>24</td>
<td>0.6</td>
<td>20</td>
<td>5</td>
<td>4</td>
<td>1.13</td>
<td>3.55</td>
</tr>
<tr>
<td>25</td>
<td>0.6</td>
<td>30</td>
<td>1</td>
<td>30</td>
<td>8.48</td>
<td>14.0</td>
</tr>
<tr>
<td>26</td>
<td>0.6</td>
<td>30</td>
<td>3</td>
<td>10</td>
<td>2.83</td>
<td>5.02</td>
</tr>
<tr>
<td>27</td>
<td>0.6</td>
<td>30</td>
<td>5</td>
<td>6</td>
<td>1.70</td>
<td>3.25</td>
</tr>
</tbody>
</table>
3.3.2 Measurement piezometers

We refer here to the small-diameter tubes that were used for measuring the pressure head of water in the porous medium during the injection test for later determination of $R_e$. They were made of 60 cm-long stainless-steel tubing with 0.3 cm inside diameter and 0.5 cm outer diameter. A flexible transparent plastic tube was attached to each piezometer as shown in Figure 9. The piezometer was then inserted in the glass beads at different locations to measure the pressure head. The plastic tubes were extended outside the apparatus and attached to its exterior wall, keeping their tip vertically upright to observe the water column elevation at the chosen measurement location. We ensured that the measuring piezometers were driven vertically into the porous medium with the help of a two-vial pipe level.
3.4 Experimental setup and data collection

3.4.1 Column experiment

We conducted simple constant-head permeameter tests to obtain the true $K$ value of the glass beads. Our test column was a glass cylinder with a length of 61 cm and a diameter of 5.3 cm, screened with nylon mesh at its bottom. After placing the cylinder under water, it was filled with
test material up to a height of 20.5 cm under fully saturated conditions. Next, with the help of a previously calibrated, high-precision peristaltic pump, we poured a constant discharge in the test column, as shown in Figure 10. By varying the flow rate with the pump, different constant heads (of 23.8 cm, 27.8 cm, and 30 cm of water) were achieved in the test column. The flow rate coming out of the bottom of the jar was measured three times for each head, gravimetrically, as was the water’s temperature, and then Darcy's Law was validated and applied to calculate the saturated hydraulic conductivity for water flowing through the glass beads.

Figure 9: Piezometers to measure the pressure head at different points within the porous medium.
Figure 10: Column experiment for determining the “true” $K$ value.

The injection was done through these partially penetrated wells by fixing lower boundary of the tested porous material at 29.8 cm from the center of the well screens for all the experiments. While waiting for steady-state conditions to be reached, we arranged the setup for measuring energy dissipation within the medium. This was done by measuring piezometric head at a series of different locations in the tank, where measurement piezometers were inserted vertically, allowing us to map the pressure head. To estimate the effective radius of dissipation, we focused
on the changes in piezometric head along the centerline flow path, in a horizontal, radial direction from the center of the screen (at an elevation of 29.8 cm from the bottom, see Figure 11). These heads were plotted as a function of radial distance from the outer edge of the well screen to estimate that distance $R_e$ where the head above water level approaches zero.

![Schematic representation of the experiment](image)

**Figure 11:** Schematic representation of the experiment

Each experiment was conducted for three different injection heads: 35, 43, and 51 cm above the constant water level in the downstream compartment. The injection tests were performed for three different cases with respect to the radial extension of the porous material and corresponding
location of the downstream constant-head boundary condition: (i) material only in the 1st compartment; (ii) material in both the 1st and 2nd compartments; and (iii) porous material in all three compartments. For those tests with glass beads only in the first compartment, three piezometers were inserted, for measuring head along the centerline, at horizontal distances of 3, 8, and 13 cm from the outer edge of the well screen. Similarly, we used four piezometers when testing with material in the first and second compartments, at distances of 3.5, 11, 19, and 27.2 cm from the well screen. When all three compartments were filled with material, we used six piezometers, located at radial distances of 2.5, 7.5, 15, 25, 40, and 55 cm from the outer edge of the well screen.

After the setup was completed, for each combination of screen design, constant head, and number of compartments with material, the water levels in the piezometers were read, and the steady-state flow rate was measured gravimetrically by weighing the volume of water collected in the bucket over a specified time. As mentioned before, each screen design and combination of compartments with material was tested for three different discharge rates, which were obtained by maintaining three different constant heads in the upper tank. This exact same sequence of measurements was then repeated for the other 26 well screen designs, as well as for most combination of compartments.

To study the two-dimensional spatial distribution of the piezometric head within the central vertical plane (that plane which contains the centerline flow path as well as the centerline of the mini-piezometer well), more detailed measurements of pressure head were taken, at multiple locations on this plane, for a subset of our experiments. These injection experiments were performed for nine different screen designs (considering all combinations of hole diameter and well-screen lengths, but only for the case of least spacing between holes), for the intermediate
value of injection head, and only for the case with glass beads in all three compartments, to better simulate the case of a laterally semi-infinite medium. Head measurements were taken on an irregular rectangular grid: six piezometers were vertically inserted along the plane at radial distances of 2.5, 7.5, 15, 25, 40, and 55 cm from the outer edge of the well-screen, and were then shifted vertically by 2 cm steps, allowing us to map piezometric head on the plane. After the first two experiments were performed, we noticed that there was perfect symmetry around the centerline, between the lower and upper halves of the plane, so that we only measured the upper half thereafter.

To further understand the spatial distribution of energy dissipation within the porous medium, we performed three-dimensional measurements of piezometric head for a single case, consisting of all three compartments with porous material, the intermediate value for the injection head, and a well-screen design with the intermediate screen length (20 cm), a hole diameter of 0.60 cm (the largest size) and an intermediate spacing between holes of 3.0 cm. This specific screen design has a total opened area of 1.70 cm$^2$, corresponding to 5.3% of the screen’s outer surface area. The measurements were taken over five vertical planes radiating from the central axis of the mini-piezometer, including the central plane that includes the centerline flow path, as well as four other vertical planes located at -20º, -10º, 10º, and 20º from the central one. For each one of these planes, piezometric head was measured over an irregular rectangular grid, at the same six radial distances (2.5, 7.5, 15, 25, 40, and 55 cm from the outer edge of the well screen), and at vertical steps of 5.0 cm, resulting in a grand total of 360 measurements.

The actual experimental apparatus, as set in the laboratory, is shown in Figure 12. Unconfined conditions were maintained in the system to simulate injection tests in streambeds. The water temperature was measured for each experiment as the dynamic viscosity and the density of water
change with the temperature, altering the $K$ values. For comparison, $K$ estimates obtained at different water temperatures were converted to the $K$ value at 20 C using Equation 7:

$$K_{20} = \frac{K_T \eta_T \rho_{20}}{\eta_{20} \rho_T}$$  \hspace{1cm} (7)

where $K_{20}$ is the $K$ value at 20 C, $K_T$ is the $K$ value obtained experimentally at the prevailing water temperature, $T$, while $\eta_T$ and $\eta_{20}$ are the dynamic viscosities, and $\rho_T$ and $\rho_{20}$ are the densities of water at the respective temperatures of $T$ and 20 C.

Figure 12: Laboratory set-up of the experimental apparatus.
3.5 Data analysis

As discussed in the literature review, modified shape factor equations obtained from the base methods of Hvorslev (1951) and Bouwer & Rice (1976) were used for calculating the shape factor and then estimating $K$ for each injection test at constant head. The Hvorslev (1951) shape factor (actually proposed by Dachler, 1936), as modified by Chapuis (1989) for bottom-closed injection wells, $F_C$, is shown in Equation 8:

$$F_C = \frac{2 \pi L H}{ln\left[\frac{L}{D} + \sqrt{1 + (\frac{L}{D})^2}\right]} - 2.75 \quad (8)$$

Equation 9 gives the shape factor $F_{BR}$ proposed by Bouwer & Rice (1976), as used by Cardenas & Zlotnik (2003). In this work, for comparison purposes, we estimate $F_{BR}$ in two different ways: based on our experimentally determined $R_e$ values and following the plot (Figure 3) in Bouwer & Rice (1976), notwithstanding the previously mentioned error.

$$F_{BR} = \frac{2\pi L}{ln\left(\frac{R_e}{r_w}\right)} \quad (9)$$

To determine the radius of dissipation $R_e$ for each experiment, we first plotted the piezometric heads collected along the centerline flow path. Because actual dissipation in a semi-infinite porous medium would be asymptotic, while our test medium had finite dimensions, we arbitrarily selected that distance from the outer edge of the well screen at which 95% of the initial head has dissipated as the radius of dissipation $R_e$, for each case.

In this way, using the collected discharge, water temperature, and piezometric head measurements, $K$ estimates were obtained for each experiment applying the following three methods:
a. Hvorslev (1951) with shape factor as corrected by Chapuis (1989): Solving Equation (2) for unknown $K$, with $F = F_C$ obtained from Equation (8)

b. Cardenas & Zlotnik (2003) with the shape factor based on the curves and equations developed by Bouwer and Rice (1976): Solve Equation (2) for $K$, with $F = F_{BR}$ obtained from Equation (9), in which the value of $\ln(R_e/r_w)$ comes from Equation (6), with the values of parameters $A$ and $B$ obtained from Figure 3 in Bouwer and Rice (1976).

c. Cardenas & Zlotnik (2003) with the shape factor computed from our experimentally determined $R_e$ values: Solving Equation (2) with $F = F_{BR}$ directly computed using Equation (9), with known value for $R_e$, obtained from the plot of piezometric heads.

A comparative study of the $K$ estimates obtained with these three different approaches was then performed with respect to the “true” $K$ value from the permeameter tests, to describe the effects that well-screen parameters have on $K$ values estimated from constant-head injection tests, as well as the respective performance of the analytical methods. The comparative analysis was performed in two ways. First, by looking at the individual effects of the screen design parameters (screen length, hole diameter, and hole spacing) on $K$ estimates by varying one parameter at a time while keeping the other two constant, and comparing the results obtained with the three methods to the “true” $K$ value. Second, we investigated the combined effects of the well-screen parameters by employing the proportion of openings (%) as a combined parameter, looking at its effect on $K$ estimates obtained with the three methods, and comparing them with the “true” $K$ value. Moreover, to better incorporate screen parameter effects on $K$ estimates, we propose a nonlinear regression model for the shape factor as a function of the well-screen parameters (screen length, hole diameter, and hole spacing), based on the collected experimental data.
Piezometric heads at multiple locations in the injection system were next analyzed in order to understand the energy dissipation in the system. This task was carried out in three phases. First, the radial extent of energy dissipation along the central axis was studied for all the experiments, as it was needed to determine $R_e$ experimentally. Second, we constructed detailed 2-D contour maps with the piezometric heads collected at various vertical and horizontal locations on the central vertical plane. Finally, a detailed 3-D analysis of energy dissipation was performed for a specific well-screen design, resulting in piezometric head heatmaps for five different vertical planes crossing the porous material.
CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents and discusses the results obtained in the various experiments; it is divided into eight sections. The first section reports the “true” $K$ values obtained from the constant head permeameter tests, while the second discusses the initial experiments that were conducted to ensure that our set-up allowed for an adequate determination of $R_e$, the effective radius of dissipation. The third section covers the $K$ estimates obtained from injection tests and how these are affected by both the screen-design parameters and the method used for deriving $K$. Next, the fourth section talks about the effects of individual screen parameters on $K$ estimates, while the fifth details the combined effects of screen parameters on the $K$ estimates. The sixth section presents the experiments conducted in the tank filled only with water, to discard any potential flow control by the screen, while the seventh develops the equation for the shape factor based on the results we obtained. The eighth and final section describes the flow field developed around the injection well and how it is affected by the screen parameters.

Before carrying out these experiments, laboratory density measurements were conducted on the test material (glass beads). Average values for the saturated density and dry density were found to be 1.90 g/cm$^3$ and 1.52 g/cm$^3$, respectively, while the porosity of the glass bead medium was found to be 0.38.

4.1 Results from constant-head permeameter tests

Results for the saturated hydraulic conductivity ($K$) of the glass bead medium, found from the column tests, are shown below in Table 2. From multiple experiments, we found that $K$ estimates were highly consistent over the different discharge and water head ranges maintained in the constant head permeameter test. The average $K$ value was found to be 0.85 cm/s at 17 C; using
the ρ and η at 20 C, the corresponding K at 20 C is 0.92 cm/s (see equation 7). This value was regarded as the ‘true’ K value of the test material, which was used as a benchmark for comparisons with K estimates obtained from injection tests, as well as for developing the equation for the shape factor. The flow’s Reynolds number at the interface between the well screen and the porous material suggests that Darcy’s Law is valid for these tests.

Table 2: K results from column permeameter tests

<table>
<thead>
<tr>
<th>Trial</th>
<th>Q (cm³/s)</th>
<th>ΔH (cm)</th>
<th>ΔH/ΔL</th>
<th>Temp (C)</th>
<th>K at 20 C (cm/s)</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>17.07</td>
<td>19.00</td>
<td>0.606</td>
<td>17</td>
<td>0.89</td>
<td>7.17</td>
</tr>
<tr>
<td>2</td>
<td>17.10</td>
<td>19.00</td>
<td>0.605</td>
<td>17</td>
<td>0.91</td>
<td>7.18</td>
</tr>
<tr>
<td>3</td>
<td>17.11</td>
<td>19.00</td>
<td>0.605</td>
<td>17</td>
<td>0.91</td>
<td>7.18</td>
</tr>
<tr>
<td>Test 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21.42</td>
<td>23.00</td>
<td>0.712</td>
<td>17</td>
<td>0.94</td>
<td>8.99</td>
</tr>
<tr>
<td>2</td>
<td>21.46</td>
<td>23.00</td>
<td>0.711</td>
<td>17</td>
<td>0.94</td>
<td>9.01</td>
</tr>
<tr>
<td>3</td>
<td>21.50</td>
<td>23.00</td>
<td>0.710</td>
<td>17</td>
<td>0.94</td>
<td>9.02</td>
</tr>
<tr>
<td>Test 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>19.87</td>
<td>21.80</td>
<td>0.685</td>
<td>17</td>
<td>0.92</td>
<td>8.34</td>
</tr>
<tr>
<td>2</td>
<td>19.98</td>
<td>21.80</td>
<td>0.683</td>
<td>17</td>
<td>0.92</td>
<td>8.39</td>
</tr>
<tr>
<td>3</td>
<td>19.92</td>
<td>21.80</td>
<td>0.684</td>
<td>17</td>
<td>0.92</td>
<td>8.36</td>
</tr>
<tr>
<td></td>
<td>Corresponding average K at 20 C</td>
<td></td>
<td>0.92</td>
<td></td>
<td></td>
<td>8.18</td>
</tr>
</tbody>
</table>

4.2 Initial experiments with variable tank size

A grand total of 189 experiments were conducted for three different “tank sizes” (i.e., radial extents for the porous medium within the tank). This was achieved by filling different numbers of compartments; the short case is when only the first compartment is filled, the intermediate case considers the first and the second, while the long case is when all three compartments are filled with material (dimensions for each case are shown in Figure 2). We performed these tests
to get an idea of the minimum tank size (radial extent of porous material) that would be required so that the flow field, and the corresponding spatial pattern of head dissipation, became relatively independent of the radial extents, so that they resembled those that would be obtained for the case of an infinite medium. Using the plot and equation from Bouwer & Rice (1976), $R_e$ for our experiments would range between 2 and 13 cm; note that, according to their definition, $R_e$ is the radial distance at which 85% of the head would have dissipated. Chapuis (2009) states that “the effective radius is approximately equal to the length of the filter pack,” which for our case would be the effective length $L$ of the screen length (actual length between top and bottom screen-holes), where $5 \text{ cm} \leq L \leq 30 \text{ cm}$. In our experiments considering different radial extents for the porous medium, we found that the plots of piezometric head $h$ as a function of radial distance along the centerline $x$ were noticeably different when comparing the short extent with the intermediate case, as should have been expected. On the other hand, the $h(x)$ plots for the intermediate and long extents were quite similar, even for the largest injection discharges. Thus, we only used the results of the 81 experiments obtained with the long radial tank case (all three compartments filled with material) for all analyses. Even though we know that the $h(x)$ behavior would be slightly different for an even longer tank, we trust that the dimensions of our experimental apparatus are adequate to estimate that distance “over which most of the head has dissipated,” as the comparison between the intermediate and the large cases indicates that $R_e$ would not change appreciably for a longer tank. In more practical terms, there is also an arbitrary decision involved in the determination of the effective radius of dissipation, relating to what is the meaning of “most of the head,” which affects the actual $R_e$ value more than the tank length. In our case, we are defining $R_e$ as that distance over which 95% of the available head gets dissipated; for all our experiments with the full tank, this occurs within the first 35 cm from the
outer edge of the well-screen for the longer screen sizes, and much closer to the well for the intermediate and short screen lengths.

4.3 Estimating $K$ with mini-piezometers: effects of screen design and method

A total of 81 different experiments were performed in the laboratory apparatus to obtain $K$ estimates with the three different approaches: Hvorslev (1951) with shape factor $F_C$ as modified by Chapuis (1989); Cardenas & Zlotnik (2003) with $R_e$ and $F_{BR}$ from Bouwer & Rice (1976); and Cardenas & Zlotnik (2003) with $R_e$ and $F$ from our experiments. All $K$ values discussed hereafter correspond to $K_{20}$ estimates from applying these methods. Over the range of screen designs and heads used in our experimental results, we found that the different methods estimate $K$ values in the range from 0.01 to 0.99 cm/s, while the “true” $K$ obtained from the permeameter tests is 0.92 cm/s. The following sections discuss the observed variability in $K$ estimates, as affected by the well-screen parameters as well as the method used for estimation.

Table 3 shows the $K$ values from those 81 experiments in which all three compartments of the radial tank were filled with test material. The color codes in the table reflect the level of accuracy while estimating $K$: Values in red are the poorest estimates, with errors > 45%, those in blue are the best estimates, with errors < 8%, while those in black are intermediate. The $K$ estimates from Hvorslev (1951) with $F_C$ as modified by Chapuis (1989), and Cardenas & Zlotnik (2003, 2007) with shape factor $F$ calculated from our experimental, plot-determined $R_e$ are closer to the “true” $K$ value than using the Cardenas & Zlotnik (2003) approach with $F_{BR}$ from Bouwer & Rice (1976). While all three methods were found to underestimate $K$ in most of the cases, the Cardenas & Zlotnik (2003) approach with $F_{BR}$ from Bouwer & Rice (1976), which is probably the most commonly used method for interpreting injection test results, tends to yield consistently lower values than the other two approaches. On the other hand, Cardenas & Zlotnik's (2003)
method with $F$ from the plot yields quite similar results to those of Hvorslev’s (1951) with $F_C$ modified according to Chapuis (1989), as shown in Figure 13. For this reason, only those results obtained from these latter two methods are considered in the following discussions, even though all tables and plots depict results from all three methods.

Since our research was conducted to study the effects of different variables of the injection system on $K$ estimates, these are presented and analyzed in the subsequent sections.

Figure 13: Comparison of $K$ estimates from Hvorslev (1951) with $F_C$ as modified by Chapuis (1989) and Cardenas & Zlotnik (2003) with $R_e$ from our experimental plots.
Table 3: \( K_{20} \) values estimated from injection tests using different screen designs and methods.

<table>
<thead>
<tr>
<th>Notation</th>
<th>S</th>
<th>I</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>For Screen length</td>
<td>10 cm</td>
<td>20 cm</td>
<td>30 cm</td>
</tr>
<tr>
<td>For Hole size</td>
<td>0.26 cm</td>
<td>0.56 cm</td>
<td>0.60 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Screen length</th>
<th>Hole size (cm)</th>
<th>Head (cm)</th>
<th>( K_{20} ) estimate (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Screen length</th>
<th>Hole size (cm)</th>
<th>Head (cm)</th>
<th>( K_{20} ) estimate (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Screen length</th>
<th>Hole size (cm)</th>
<th>Head (cm)</th>
<th>( K_{20} ) estimate (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td>From C&amp;Z with ( R_s ) from plot</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color code</th>
<th>Red</th>
<th>Blue</th>
<th>Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>K estimation</td>
<td>Worst</td>
<td>Best</td>
<td>Mediocre</td>
</tr>
</tbody>
</table>

39
4.4 Univariate effects of different screen parameters

We performed comparative analyses of the effects that different screen geometrical parameters, as well as injection head, have on $K$ estimates. These analyses are conducted by varying only one test parameter at a time, while keeping the other constant, and are based on the results from the two methods with higher agreement. We found that even though both approaches on average slightly underestimate the true $K$ value, the estimates clearly are in the same order of magnitude. More importantly, the effects that the different well-screen parameters have on $K$ are highly consistent, independent of the method used.

4.4.1 Effects of hole diameter

For the three different hole diameters used in our experiments (0.26 cm, 0.56 cm, and 0.60 cm), we found that $K$ estimates are lower than the true $K$ values for the smaller holes, approaching the true value for the intermediate and larger diameters, as shown in Figure 14 and Appendix 1.

![Figure 14: Effects of the screen-hole diameter on K estimates](image-url)
4.4.2 Effects of well-screen length

$K$ estimates were found to slightly increase with well-screen length $L$ for the case of small screen holes, but it should be recalled here that no screen with small holes could come close to the “true” $K$, so these results are moot. For the larger screen holes (0.56 cm and 0.60 cm), $K$ estimates from the two best performing methods were found to decrease with $L$; however, they are quite close to the “true” $K$ value, as shown in the second plot, Figure 15, and in Appendix 2. These results suggest that small screen holes should not be used, as they are not capable to inject the discharge that the porous medium can pass; following Baptiste & Chapuis (2015), the conductivity of a screen $(K_s)$ with our small hole size is not high enough to allow for a correct $K$ estimation. For the larger screen holes, $K$ estimates are near the “true” value for all three tested screen lengths, provided that the holes have the smallest possible spacing between them. This result is in accordance with the conclusions of Regmi (2019).

4.4.3 Effects of the spacing between holes

$K$ estimates were found to be consistently highest and closest to the true value for the smallest (1 cm) spacing between holes, and lowest for the largest (5 cm) spacing between the holes, as shown in Appendix 3 and Figure 16 (for the case of a 20 cm-long well screen with 0.56 cm diameter holes). It is clear that, given a fixed hole diameter and screen length, a larger spacing between openings will yield a smaller total % of openings. Independently of hole size or screen length, using the largest spacing in our experiments (5 cm) consistently resulted in underestimated $K$ values. This suggest that spacing between openings is an important parameter that needs to be considered when designing min-piezometers for injection tests.
Figure 15: $K$ estimates for different screen lengths; screen-hole diameter of 0.26 cm in the upper plot and 0.56 cm in the lower plot.
4.4.4 Effects of injection head

We found that our $K$ estimates were not significantly affected by the use of different injection head sizes.
heads, keeping other things constant. Figure 17 shows a typical case for a 20 cm-long (intermediate) screen, with 1 cm spacing between holes of diameter 0.56 cm, for three different heads: 35, 43, and 51 cm; the \( K \) estimates were found to be similar, though there is a slightly decreasing trend, which is probably due to the increase in turbulence as a larger head (and gradient) is used. The results shown in Appendix 4 suggests that changing injection head does not significantly affect the estimation of the \( K \) value of the porous medium.

### 4.5 Combined effects of screen parameters

We studied the combined effect of screen parameters on \( K \) estimates by using the proportion of screen openings as an integrated variable, representing the joint effects of hole diameter and spacing between the holes. The results are depicted with surface plots, representing percentage (%) of opening on the y-axis, ratio of screen length to well diameter (L/D) on the x-axis, and \( K \) estimates on the vertical axis. We find that \( K \) estimates from all three approaches are not that much affected by the L/D ratio. They are highly sensitive to the opened % of the screen, but only below a threshold of about 6%, as shown in Figure 18; further results are given in Appendix 5. The \( K \) estimates from Cardenas & Zlotnik (2003) with experimentally determined \( F \) and Hvorslev (1951) with \( F_C \) as modified by Chapuis (1989) are quite close to the true \( K \) value of 0.92 cm/s (shown as a horizontal plane) when the opened proportion of the screen is above 6%.

From this integrated approach of studying the effect of geometrical parameters of piezometer wells on \( K \) estimates, we conclude that a hydraulically efficient condition is obtained when the proportion of openings is equal or larger than 6%. As this value is easily obtainable by drilling holes in small-diameter pipe, this indicates the wide applicability of mini-piezometer screens constructed of drilled holes.
Surprisingly, we observed a slightly conflicting behavior in $K$ estimates when the % of openings lies between 3 and 5%: the $K$ values decreased between 3 and 4%, while they increased in the 4 to 5% range. This effect was seen in $K$ estimates from all screen lengths and all spacings between holes, for all approaches. We have no explanation for this inconsistent behavior, but it should be noted that all $K$ values in this range of opened proportion are obtained from the smallest (0.26 cm diameter) holes, which always underestimate $K$ (Section 4.3.1), so this effect is not worth explaining.

**4.6 Potential control due to low screen conductivity**

As mentioned before, Baptiste & Chapuis (2015) stress that the conductivity of the screen must be higher than that of the medium when performing injection tests. To check this, we measured the injection discharges for a range of well screens with the largest screen hole-diameter, but in the radial tank filled only with water. Only for the case of 10, 20 and 30 cm-long screens with large hole spacing, and 10 and 20 cm-long screens with medium hole spacing, were we able to maintain a constant head in the tank. For all other cases, the injection discharges were significantly higher than the maximum discharge that could be passed through the tested material without causing boiling, indicating that the screen conductivity is sufficiently large.

When comparing these discharges to those obtained for the same well screens but in the tank filled with material, we noticed that low screen-conductivity effects are significant for 10 cm and 20 cm long screens when using the largest spacing between the holes, while for 20 cm long screens with medium hole spacing and 30 cm long screens with the largest hole spacing, these effects decrease noticeably. The plots for these experiments are shown in Appendix 6.
Figure 18: Combined effects of the well-screen parameters on $K$ estimates for the case of injection head of 35 cm, $L/D$ is the ratio between the length and diameter of the well screen.
These experiments were only conducted for screens with the largest hole diameter as these consistently gave the better $K$ estimates; for screens with smaller holes, the effects due to a smaller conductivity of the screen are implicit in Table 3, as reflected in the significantly lower $K$ estimates, independently of hole spacing. A typical case of 20 cm-long screen with medium hole spacing, with an opening proportion of 5.44%, is shown in Figure 19.

![20 cm-long screen with 3 cm spacing between holes](image)

Figure 19 : Analysis of potential screen conductivity effects by comparing injection tests with and without test material in the experimental apparatus.

### 4.7 Prediction of the shape factor based on well-screen parameters

Because we found that the commonly used methods by Hvorslev (1951) and Cardenas & Zlotnik (2003) underestimate the true $K$ value as originally proposed, we developed an independent equation for shape factors from the experiments we performed. This equation is only valid for our porous medium and pipe diameter, as well as the tested ranges of screen parameters, and thus constitutes only a preliminary attempt. It was derived by applying non-linear regression to $K$
estimates obtained with the method that performed best, i.e., Hvorslev (1951) with shape factor modified by Chapuis (1989). Only values that were within ±40% from the “true” K value were considered in the analysis. The model predicts the shape factor as a function of the screen parameters, where the “true” shape factor for each case was computed from the “true” K value and the experimentally obtained given discharges, for the different heads. The model is given by Equation 10 below:

$$F_R = \frac{11 D_h^{0.73}}{S^{0.25} L_e^{0.41}}$$  \hspace{1cm} (10)$$

where $F_R$ is the dimensionless shape factor obtained from the non-linear regression, $D_h$ is the diameter of the screen holes (cm), $S$ is the spacing between screen holes (cm), and $L_e$ is the effective screen length (cm), which is the exact distance between the topmost part of the screen’s upper hole and the bottommost part of the lower hole. The Root Mean Square Error for the proposed equation is 0.0218, while the R$^2$ value is 0.927. Figure 20 shows the response of the mathematical model. Both error measures and the plot show that the equation reproduces well our experimental data, with residuals that are small and consistent (similar dispersion) across the range of values.

As explained above, the proposed model considers all those screen parameters needed to define a “drilled-hole screen,” for the case of vertical hole lines that we study here. It performs better at reproducing the shape factor in our experiments than any other available approaches that only consider the well screen length and diameter. We suggest that this general approach for empirically deriving a shape factor could be used in hyporheic research where mini-piezometers are used instead of traditional wells. However, it is clear that this is only a preliminary attempt, as any general equation would need to be derived for data obtained with various injection-well
diameters, as well as a range of sediment properties. In this study, these two factors were fixed so we could study the effects of the parameters describing drilled-hole screens, which have not been explicitly considered in the available literature.

![Graph: Predicting shape factors with the proposed mathematical model.](image)

Figure 20: Predicting shape factors with the proposed mathematical model.

### 4.8 Study of the flow field around mini-piezometers

We studied the flow field developed in the porous medium around the injection well screen in order to understand the flow pattern. We found that the spatial pattern of the flow is affected by parameters such as the screen-hole diameter, length of the well screen, spacing of screen holes, and injection head, showing effects on $K$ estimates as presented above. In this section, we discuss
the spatial pattern of piezometric head distribution in the porous system, and the resulting effective radius of dissipation of the injection head.

4.8.1 Radius of dissipation

Based on the explanations given by Bouwer & Rice (1976), the effective radius of dissipation $R_e$ was calculated from the piezometric heads measured in the system. Because head dissipates asymptotically with radial distance, we estimated $R_e$ as the distance from the outer edge of the well screen to that point where 95% of the initial head has been lost, as shown in Figure 21.

For $H = 43$ cm, $SL = 20$ cm & $D = 0.60$ cm

![Graph showing the determination of $R_e$](image)

Figure 21: Experimental determination of $R_e$ by measuring piezometric head at different locations along the central axis of flow.
4.8.2 Piezometric head 1-D distribution along the central axis

The piezometric heads measured at different locations along the horizontal central axis indicate that the head dissipates rapidly for the first few centimeters and then decreases more slowly, as shown in Figure 21. For all the cases, most of the energy was found to be dissipated within 30 cm from the well screen. The comparative analysis of piezometric head distribution in the 30-cm versus the 60-cm radial length “tank size” concluded that the latter is sufficiently long to study the head dissipation in the injection system, as discussed in Section 3.4.2. Appendix 7 presents the graphs obtained for all other experiments.

4.8.3 Piezometric head 2-D distribution in the central vertical plane

During the first injection test, piezometric heads were measured on the central vertical plane, for a range of locations covering from the bottom to the top of the porous medium. A detailed analysis of these results verified that there was an almost perfect mirror symmetry in piezometric head distribution, when comparing the upper and the lower half of the vertical plane. Thus, for all subsequent experiments, pressure head data were obtained and analyzed only for the upper half.

For each fixed position (i.e., radial distance) along the horizontal, central axis, we measured piezometric head over the upper half of the vertical plane, shifting the piezometer upwards by 2 cm at a time. An unexpected behavior was found for those radial distances (locations) closest to the well screen: instead of finding the largest head value along the centerline, it actually increased away from it, up to a certain distance, and then it decreased sharply, as shown in Figure 22. This happened whether there was a drilled hole or not lined up with the central axis. Appendix 8 presents the graphs obtained for the different experiments.
This effect could possibly arise as the cumulative result of turbulence created due to high flow velocities near the well screen, and disturbance of the porous medium while shifting the location of the measurement piezometer upwards, leaving a “wake” of less compacted material.

![Piezometric head graph](image)

*Figure 22: Piezometric head as a function of vertical distance from the centerline (in abscissae), measured at different fixed locations along the central axis of flow (colors) in the vertical plane.*

### 4.8.4 Detailed 3-D analysis of piezometric head distribution

The study of the flow field was further explored by conducting a 3-D analysis of the water pressure distribution within the medium for the case of a 20 cm long screen with holes 0.60 cm in diameter and a spacing of 3 cm between holes. To describe the 3-D flow pattern, head measurements were taken over 5 radial vertical planes (every 10°), and over 11 equidistant
horizontal planes (separated every 5 cm). Figure 23 shows the case for a vertical plane at 10 degrees from the left wall of the experimental apparatus and Figure 24 presents the case for a horizontal plane along the central axis. The flow fields obtained for all vertical planes, as well as three of the horizontal planes, are shown in Appendix 9.

![Flow field developed over a vertical plane](image)

Figure 23: Flow field developed over a vertical plane (at 10 degrees from the left wall of the apparatus) within the injection zone, around the 20 cm long well-screen with 0.60 cm diameter holes drilled at a spacing of 3 cm.

The piezometric heads at different locations within the 3-D system are represented by contours in the heatmaps. As illustrated in the figures depicting the flow for the different vertical planes, the head is distributed more or less like an ellipsoid for the first 20 cm to 30 cm, and then the flow follows a radial pattern, as shown by the parallel arrows beyond. Moreover, these results show
that there is no noticeable effect of the lower boundary on the flow pattern, as there is symmetry along the central axis. These experimentally determined flow patterns are in agreement with the results obtained by Chapuis (2009) from numerical simulations. Moreover, correct physical simulation of the radial flow in the experimental apparatus is verified from these results.

Figure 24: Piezometric head distribution in the horizontal plane along the axis passing through center of the screen, when water is injected through the 20 cm long well-screen with 0.60 cm diameter holes drilled at a spacing of 3 cm.
CHAPTER 5: CONCLUSIONS

Injection test methods initially developed for field tests in partially or fully penetrating wells are now widely used in hyporheic research but using mini-piezometers with drilled-hole screens. This research was focused on validating their use by studying the effects that screen design parameters have on $K$ estimates obtained with the commonly used approaches. As part of this work, we also determined the effective radius of dissipation $R_e$ experimentally by studying the flow through the porous medium in detail.

We conclude from our experimental results that for our porous medium, $K$ can be adequately estimated by injecting water at constant-head in a 1.25 inch-diameter mini-piezometer with a screen fabricated by drilling holes, using either of the traditional approaches proposed by Hvorslev (1951) or Cardenas & Zlotnik (2003, 2007). The former gave the best estimation as long as the original shape factor is modified as proposed by Chapuis (1989) for plugged piezometers. The latter works almost as well, but the effective radius of dissipation $R_e$, used to compute the shape factor, cannot be that proposed by Bouwer & Rice (1976), as originally proposed by Cardenas & Zlotnik (2003). In this work, we used experimentally determined values of $R_e$ in order to apply the method of Cardenas & Zlotnik (2003), but it is evident that this approach cannot be applied in the field, as it requires mapping the piezometric heads in the injection zone.

Anyhow, as was discussed before, both constant-head injection methods differ only in the shape factor they use. Thus, it seems preferable to simply conclude that, when using 1.25 inch-nominal diameter mini-piezometers, such constant-head tests are able to adequately estimate $K$ for homogeneous and isotropic streambed sediments, at least for sizes equal to or smaller than the
glass beads used in our experiments, as long as one uses either the shape factor $F_C$ of Chapuis (1989) or else the shape factor $F_R$ proposed herein, but not that of Bouwer & Rice (1976).

As has been proposed before, we find that the proportion of the screen that is opened, which depends on the spacing and size of the drilled holes, affects $K$ estimates until a threshold value is attained. When the proportion of screen openings is above 6%, the conductivity of the screen becomes sufficiently large, so that injection-test results interpreted with the above approaches yield consistent $K$ values that are close to the “true” $K$ value. Nonetheless, the three main parameters that describe a drilled-hole screen (hole diameter, screen length, and hole spacing) were all found to affect $K$ estimates. These effects are not taken into consideration by traditional approaches, which use shape factors that only incorporate the effect of the slenderness ratio of the well screen, function of screen length and well radius. For this reason, we propose a preliminary equation to derive the shape factor of mini-piezometers with drilled-holes, for the case of a uniform and isotropic medium, which is only valid for our tested conditions (diameter of the mini-piezometer, selected porous material, range of screen parameters). This regression model is based on that part of our experimental results for which the chosen screen design allowed us to adequately obtain the “true” $K$ value. It is only a function of the screen parameters and was better able to reproduce $K$ in our experiments. Further experimentation with different mini-piezometer diameters would allow for generalization, so that the screen slenderness ratio $(L/D)$ becomes a variable, instead of the screen length.

From comparative analyses of the injection discharges in the radial tank filled with water only versus those obtained in the presence of porous material, we found that well screens with either the intermediate or the largest hole spacings impose noticeable resistance to the injection discharge, which is also reflected in the $K$ estimates.
Finally, we also experimentally investigated the effective radius of dissipation that Bouwer & Rice use in their methodology to obtain the shape factor. We find that $R_e$ varies with the flow field developed in the system, which is in turn affected by the combination of the above-mentioned geometrical parameters with the porous medium. Moreover, we verified that the flow is both symmetric in the vertical plane, as well as radial in nature (beyond a certain distance from the screen), which strengthens the applicability of injection tests to the case studied.

However, some aspects warrant further investigation:

i) Mini-piezometers of different diameters must be tested, so that all geometrical parameters can be incorporated into a prediction equation for the shape factor.

ii) We obtained an unexpected result while studying the spatial pattern of head dissipation on vertical planes crossing the system radially: at locations close to the screen, the maximum head was not located along the central axis, but was shifted up and down, symmetrically. This might be due to flow dynamics created in the system while shifting measurement piezometers by a very small distance. Further research on this matter is recommended.

iii) The interacting effects of well diameter, screen length, hole size, and hole spacing need to be extensively studied over as continuous a range of variation as possible, and for different porous media sizes. This will allow for precise recommendations regarding optimized mini-piezometer well screens, and for obtaining a generalizable equation for determining the shape factor that can be used to better interpret injection test results.
iv) The effect of the lower boundary on $K$ estimates should be assessed in detail, either by varying the position of the injection wells in the test material or by changing the thickness of the test material.
REFERENCES


Appendix 2

K estimates Vs Well-screen length

Spacing increase

1 cm

| 0.26 cm |
| 0.56 cm |
| 0.60 cm |

Screen length (cm)

3 cm

5 cm

From C&Z with Re from plot
From C&Z with Re from S&F curves
From Hahnel with F from Chapulte
True K
Appendix 3

K estimates Vs Hole spacing

Hole diameter increase

Screen length increase
Appendix 4

K estimates Vs Injection head

Hole diameter increase

Screen length increase

0.26 cm

0.56 cm

0.60 cm
Appendix 5

Combined effects of screen parameters on K estimates

- K estimate from C&Z with Re from plot
- K estimate from C&Z with Re from B&R curves
- K estimate from Hvorslev with F from Chapuis

Injection head = 51 cm
Injection head = 43 cm
Injection head = 35 cm
Appendix 6

Screen conductivity tests

10 cm long screen with 5 cm spacing between holes

20 cm long screen with 5 cm spacing between holes

30 cm long screen with 5 cm spacing between holes

10 cm long screen with 3 cm spacing between holes

20 cm long screen with 3 cm spacing between holes
Appendix 7

Piezometric head distribution in injection system with 1 cm hole spacing well screen

Hole diameter increase

Screen length increase

10 cm

20 cm

30 cm
Piezometric head distribution in injection system with 3 cm hole spacing well screen

Hole diameter increase

Screen length increase

10 cm

20 cm

30 cm

0.26 cm

0.56 cm

0.60 cm
Piezometric head distribution in injection system with 5 cm hole spacing well screen

Hole diameter increase

Screen length increase

10 cm

20 cm

30 cm

0.26 cm

0.56 cm

0.60 cm

Horizontal distance from well screen (cm)
Appendix 8

Piezometric head distribution in the injection system in vertical plane

Screenlength

30 cm

0.26 cm

Screen hole diameter

20 cm

0.56 cm

10 cm

0.60 cm
Appendix 9

a) Vertical Planes

Piezometric head distribution in injection system
(With D = 0.60 cm, SL = 20 cm, S = 3 cm)
b) Horizontal Planes