MEASUREMENTS OF HYDRAULIC CONDUCTIVITY USING SLUG TESTS IN COMPARISON TO EMPIRICAL CALCULATIONS FOR TWO STREAMS IN THE PACIFIC NORTHWEST, USA

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of COLETTE MCKENZIE find it satisfactory and recommend that it be accepted.

Chair

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Measurements of Hydraulic Conductivity Using Slug Tests in Comparison to Empirical Calculations for Two Streams in the Pacific Northwest, USA

Abstract

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Seasonal water shortages caused by natural climate variations coupled with intensified agricultural production and municipal growth demands can be highly detrimental to aquatic habitats. Two streams, Bertrand and Fishtrap Creeks, located in Washington State, Pacific Northwest, USA, are examples of important anadromous fish habitats impacted by seasonal water shortages. This study was aimed at elucidating streambed hydraulic conductivity (*K*) and the patterns of spatial variation for the aforementioned Bertrand and Fishtrap Creeks. Detailed field investigations were carried out and two approaches were adopted to determine *K* values. Instream slug tests following the Bouwer and Rice method were performed to obtain *K* for two depths at multiple sites in each stream. Additionally, samples were taken at the surface and subsurface of the streambed to estimate *K* using four commonly applied empirical formulas, i.e., the Hazen, Harleman, Krumbien and Monk, and Kozeny-Carmen equations.

Comparison of results from the instream slug tests and empirical calculations showed that Hazen and Harleman equations produced results of *K* similar to those from the slug tests whereas the Krumbien and Monk and the Kozeny-Carmen equation overestimated the *K* values of the streambed material. For the future, we recommend the slug test method if accuracy and reliability of the *K* values are desired as in a detailed study, such as modeling surface- and ground-water

interaction. If *K* is not a dominant factor, then the empirical methods would be a more cost-effective approach.

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1. INTRODUCTION

Seasonal water shortages caused by natural climate variations coupled with intensified agricultural production and municipal growth demands can be highly detrimental to aquatic habitats. As our knowledge and understanding of ecosystem water requirements increases, there is a growing concern over the adequacy of water resources for sustaining stream habitats. This is particularly true for streams in the Pacific Northwest, USA, where flows during dry summer periods are sustained by ground-water base flows that are subject to reduction due to increased ground-water pumping. Recognizing this concern, management options, such as changing from direct surface-water diversions to ground-water withdrawals in order to temporarily mitigate low stream flows and to protect anadromous fish species, have recently been proposed (Washington State University Cooperative Extension, 2005). However, to evaluate whether or not these efforts maintain adequate flow for fish habitat throughout the year, a better understanding of the interaction between ground water and surface water is imperative. Such understanding in turn provides vital information for developing sound strategies for managing available water resources.

Hydrologists and ecologists have increasingly recognized that subsurface properties of natural streambeds have a high degree of spatial variability (Stanford and Ward, 1993; Boulton, 1998; Calver, 2001). Packman showed that the spatial variability of the interaction zone, also referred to as the hyporheic zone, directly affects ground- and surface-water exchange (Packman and Salehin, 2003; Packman et al., 2004; Leek, 2006). Furthermore, studies have shown that streambed characteristics, such as bed material, thickness, topography, and channel curvature, influence the streambed hydraulic properties and thus water movement (Packman et al., 2004). Studies investigating physical streambed properties, including the material composition and compaction, are essential in determining hydraulic conductivity (*K*) values for predicting ground- and surface-water interchange (Packman et al., 2004).

K has traditionally been determined through empirical methods, among which are the commonly used relationships by Hazen (1892), Harleman et al. (1963), Krumbein and Monk (1943), and Kozeny-Carman (1972). These methods are primarily based on grain-size distribution, porosity, or the combination of the two, of geological materials, and were developed for specific applications, such as sand dams (Hazen, 1911) or petroleum fields (Domenico and Schwartz, 1998). Hazen (1892) submitted the original equation using representative grain size to determine *K*. Harleman et al. (1963) adapted Hazen's equation for broader uses to porous media that are generally isotropic by using a smaller empirical coefficient. Another approach was developed by Krumbein and Monk (1943) who derived permeability and thus *K* from grain-size distribution. The Kozeny-Carman equation was a modification of the Kozeny's (1927) original equation by Carman (1937) who modifyed the geometric shape coefficient of the particles (Bear,1972). The Kozeny-Carman equation uses both grain-size distribution and porosity in obtaining *K* (Fetter, 2001).

Slug tests have also been used for determining *K*, in particular for aquifers (Hvorslev, 1951; Freeze and Cherry, 1979). A slug test uses a small observation well inserted into the geological material where the rate at which the water level rises or falls is measured (Bouwer, 1976). Although originally designed for unconfined aquifers, slug tests have been used to determine *K* of streambed materials. Hanrahan et al. (2005) conducted instream slug tests to estimate *K* ranges that characterize the physical habitat and its effect on the life cycle of salmon in Hells Canyon of the Snake River in the state of Idaho, USA. Leek (2006) used slug tests to determine the spatial variation of *K* and thus the heterogeneous hydraulic properties of streambeds and potential egg survival rates in a representative stream of the Pacific Northwest, USA.

Many streams in the Pacific Northwest are experiencing low stream-water levels for salmon spawning during the dry season of June–September due to high water-use demands. Local agricultural practices directly impact ground- and surface-water levels because of irrigation diversions. In areas with irrigated agricultural production, irrigation application rates often govern up- and down-welling of a stream (Packman and Salehin, 2003; Packman et al., 2004). To establish sound water resource management plans, a better understanding of the relationship between local water uses and available water resources is needed. The major goal in local water resource management is to develop practices that maintain adequate water levels in the streams while allowing withdrawals for agricultural production. A cost-effective approach is to develop models of surface- and ground-water interaction. The first step is determining the spatial variation in streambed *K* values. The hypothesis is that empirical equations may be used to adequately predict streambed *K* values compared to the more time-consuming and costly approach of instream measurements, e.g., slug tests.

The main objectives of this study were:

(1) to measure hydraulic conductivity values and the spatial variability along two Pacific Northwest streams using slug tests,

(2) to evaluate four empirical equations for estimating hydraulic conductivity, and

(3) to compare the hydraulic conductivity determined using the four afore mentioned empirical methods to the values determined by the slug tests.

This study, with detailed field investigation and statistical analyses, will provide valuable information about streambed hydraulic conductivity values and the patterns of spatial variation in the two study streams as well as those within the study region. Comparison of results from the instream slug tests and empirical calculations will allow us to identify an approach to determining

K that is both reliable and cost-effective.

2. STUDY AREA AND METHODS

2.1 Study Site

Bertrand and Fishtrap Creeks, located in Northwest Washington State, USA, are two important areas that are in need of a sound management plan to balance conflicting needs for water resources in each watershed. The two creeks are tributaries to the Nooksack River located in Whatcom County, Washington (Figure 1). The Nooksack River is a major river in the region, and discharges into the Pacific Ocean via the Strait of Georgia. The USA-Canada border intersects both watersheds with approximately 54% of the Bertrand Creek watershed and 61% of the Fishtrap Creek watershed located in Canada. The study site consisted of 10-km reaches of the Bertrand and Fishtrap Creeks from the Canadian boarder to the Nooksack River.

The primary uses for these creeks are agricultural irrigation as well as salmon spawning and rearing, although tributary ground water is also used for domestic and municipal supplies. The local climate includes warm, dry summers and mild, rainy winters. The mean annual temperature is 9 °C (48 °F), with the maximum monthly temperature of 22 °C (71 °F) occurring in July and August and minimum monthly temperature −1 °C (31 °F) in January (NOAA NCDC, 2007)(Appendix G).

Figure1. Study site map.

The long-term (1949–2001) mean annual precipitation is 90 cm yr^{-1} (35 in yr^{-1}), with the majority (82%) of rainfall in fall, winter and spring, and the remaining (18%) in summer (NOAA NCDC, 2007). The regional soils have been developed since the Fraser Glaciation 18,000 years ago, including Lynden sandy loam, Hale silt loam, and Tromp loam (Cox and Kahle, 1999). Both creeks are located on gentle landscapes, with a slope gradient for Bertrand and Fishtrap Creeks being 0.26% and 0.24% respectively, as measured in this study.

The area was originally populated primarily with cedar, hemlock, and douglas fir, but was steadily changed to agricultural use in the last century (Cox and Kahle, 1999). The flat terrain of the region supports dairy and berry farming, making Whatcom County one of the largest producers in the state for raspberries, blueberries, and dairy products (Cox and Kahle, 1999).

For the purpose of this study the stream reaches were divided into cross-sections (referred to as 'sites') of approximately one every mile progressing downstream (Figure 2). Accessibility to the sites was limited and permission from land owners was required. As a result, Bertrand Creek contained seven sampling sites and Fishtrap Creek contained six sampling sites.

2.2 Field Testing

At each site, instream slug tests for in-situ determination of streambed hydraulic conductivity were conducted. Grab samples of streambed material for particle-size analysis and core samples for both particle-size analysis and porosity measurements were collected.

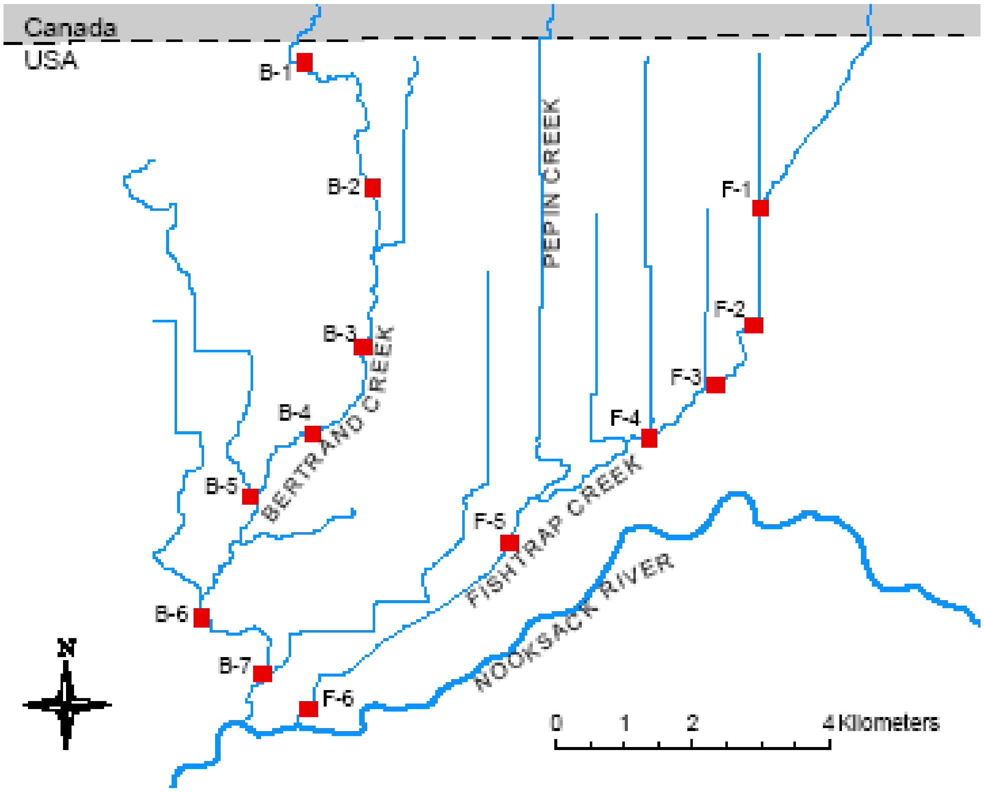

Figure 2. Locations of slug test sites. B and F stand for Bertrand Creek and Fishtrap Creek, respectively.

2.2.1 Slug tests

At each site, two locations roughly 0.5 m apart transverse to the stream flow were identified. At each location, a mini-piezometer was manually driven below the streambed to the depths of 0.5-m and 1.0-m sequentially. At each depth the slug test was replicated three times, producing a total of 12 slug tests at each site.

Construction of piezometers and the instream slug tests were primarily following Leek (2006). For completeness, adapted excerpts from Leek (2006) describing the assembly and field test procedures are included below. The piezometers were constructed of 15-cm long, commercial-grade well-screen (Johnson Screens^{TM}) welded at the lower end of the 12-cm drive point and at the upper end to a galvanized steel pipe with an outside diameter of 4 cm. Each piezometer was installed using a steel drive rod to penetrate the streambed. A control manifold was threaded to the top of the piezometer before each slug test and kept above the water surface during the test, allowing pressurization and rapid release of the pressure to facilitate the test. Once the piezometer and manifold were in place, a pressure transducer (Model PS-9805, Instrumentation Northwest, Kirkland, WA, USA) was lowered into the piezometer until it reached the bottom of the screen section. The pressure transducer was then lifted 10 cm off the bottom to avoid potential interference from fine silt (Figure 3).

The probe communicated to a Campbell Scientific CR10X data logger (Campbell Scientific, Logan, UT, USA) located on-shore. The data logging was monitored via a laptop computer. The slug test was conducted by forcing the water level in the piezometer down with air pressure, releasing the pressure rapidly, and recording the rate of head recovery. Data from the slug test perturbation were collected at 0.25-s time steps. All slug tests were conducted during the end of July and the beginning of August 2006.

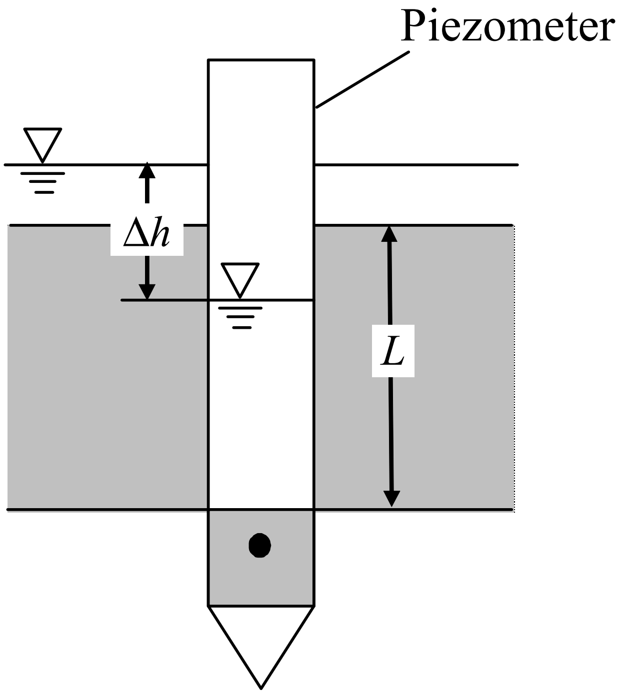

Fig. 3. Piezometer schematic. Drawdown is measured using a pressure transducer (black dot) connected to a data logger.

2.2.2 Soil sampling

Three grab samples, each about 500 g, were taken from the surface of the streambed at each site. The grab samples were sealed in bags for transport and subsequent laboratory analysis of particle-size distribution was conducted. Core samples, 3 cm long, were taken from the streambed surface to about 45 cm and roughly 0.25 m from the location of the slug test towards the stream bank at each site. The samples used for determining the particle-size distribution as well as the porosity of the subsurface material were those from 15 cm below the streambed surface. These samples were cut into 3-cm segments and those regarded unrepresentative (e.g., containing large voids or pebbles) were discarded. The remaining samples were capped and wrapped with tissue and stored in soil cans for transport back to the laboratory.

2.3 *Slug Test Analysis*

The rate of recovery in conjunction with the geometry of the piezometer was used to solve for *K* following Bouwer and Rice (1976)

$$K = \frac{r^2 \ln(R_e/R)}{2L_e} \frac{1}{t} \ln\left(\frac{H_o}{H_t}\right) \tag{1}$$

where K is in m s^{-1}, r is the inside radius of the well casing (m), L_e is the length of the well screen (m), R_e/R is the ratio of the distance away from the well over which the average K is being measured to the radius of the screen's outside diameter. H_o is the drawdown (m) at time $t = 0$ (s), H_t is the drawdown at time t (s). A regression relationship was determined from the fitted exponential trend line to the raw data of the initial head H_o over the rising head H_t on a semi-log plot (Appendix A).

2.4 Particle-Size Analysis

A 100-g sample was randomly collected from each grab sample and oven-dried for 24 hrs at 107 °C following standard procedures of the USDA (Klute, 1986). The sample was then cooled in a desiccator and run through a Rowtap™ sieve shaker. The sieves in the shakers were arranged in order of largest to smallest following the sieve distribution recommendations of the USDA (Klute, 1986). The sieves were weighed before each run. The soil sample was poured into the set of sieves. The sieve shaker was then run for five minutes. Each sieve was weighed again and the difference between the initial weight and the final weight was calculated to obtain the particle-size distribution.

The 3-cm samples used for estimating the porosity of the subsurface materials were those closest to the 0.5-m depth for comparison of K estimations from the empirical Kozeny-Carman equation and slug tests. Dry bulk density was determined by oven-drying the samples for 24 hrs at 107 °C and weighing the dried samples and measuring sample volumes. The porosity was then determined from the dry bulk density as

$$f = 1 - \frac{\rho_b}{\rho_s} \tag{2}$$

where f is porosity, ρ_b is dry bulk density (g cm^{-3}), and ρ_s is the particle density, taken as 2.65 g cm^{-3} (Hillel, 1982).

2.5 Empirical Estimation of K

The Hazen (1911) equation is given by

$$K = C(d_{10})^2 \tag{3}$$

where K is the hydraulic conductivity in cm s^{-1}, C is an empirical coefficient taken as 100 (cm s)$^{-1}$

for fine to medium sized sand particles, and d_{10} is the effective diameter compared to which 10 percent by weight of the particles are finer (cm).

The Harleman et al. (1963) equation takes the form of

$$K = k\left(\frac{\rho_w g}{\mu}\right) \tag{4}$$

$$k = (6.54\times10^{-4})\ d_{10}^2 \tag{5}$$

where k is the permeability (cm^2), d_{10} is as previously defined, ρ_w is the density of water (1000 kg m^{-3}), g is the acceleration due to gravity (9.81 m s^{-2}), and μ is the viscosity of water (0.001002 N s m^{-2} at 20 °C)

The Krumbein-Monk (1943) equation is described by

$$k = 760 d^2 e^{-1.31\sigma} \tag{6}$$

$$K = k(1.04\times10^3) \tag{7}$$

where k is permeability (darcys), d is the geometric mean diameter (mm), and σ is the log standard deviation of the geometric mean diameter.

The Kozeny-Carman (1972) equation is

$$K = \left(\frac{\rho_w g}{\mu}\right)\frac{n^3}{(1-n)^3}\left(\frac{d_m^2}{180}\right) \tag{8}$$

where d_m is the geometric mean diameter (cm), n is the porosity of the sample, and ρ_w, g and μ are as previously defined.

For the surface samples only the first three methods were applied to estimate K because the core sampling procedure used for the subsurface was not possible for the surface material and therefore porosity could not be determined. For the subsurface materials all four empirical methods were applied to determine *K* from single samples.

2.6 Statistical Analyses

Analysis of variance (ANOVA) tests were preformed at a significance level $\alpha=0.05$ using the General Linear Model (GLM) in SAS (SAS Institute Inc., 2005) to compare the means of *K* (1) from the slug tests at 0.5-m and 1.0-m depths within each reach and between the two reaches, (2) from the different empirical formulas for the surface and subsurface samples within each reach, respectively, (3) from the Hazen method between the two reaches, for the surface and subsurface, respectively, and (4) from both the slug test and the empirical methods for the subsurface. Single-replicate ANOVA tests were performed wherever no replicates were available, including all comparisons made for the means of *K* from the empirical formulas for the subsurface.

3. RESULTS AND DISCUSSION

3.1 Slug Test

The slug tests yielded satisfactory results for both the 0.5-m and 1.0-m depths for five of the seven sites in Bertrand Creek. At site B1, the water-level readings at the 1.0-m depth for the second location did not change, rendering the test invalid. Clay was present throughout this site and a small pocket of water may have been isolated by the clay from the aquifer when excessive pressure was applied during the slug test. Results were not obtained for the test at the 0.5-m depth for the second location at site B7 due to operational errors likely caused by application of insufficient pressure.

For the Bertrand Creek, the mean *K* values at 0.5 m ranged 0.8–351 m d^{-1} among the seven sites. The mean *K* values at 1.0 m ranged 7.6–136 m d^{-1} (Figure 4, Table 1, Appendix A). These values fall within the ranges from previous studies for similar materials (Table 2).

The ANOVA tests failed to indicate a statistically significant difference in mean *K* values for the 0.5-m and 1.0-m depths at $\alpha=0.05$ ($F = 4.07$, $P = 0.08$, Table 3), suggesting that sampling at the shallower level may suffice in relevant future studies in this stream. The insignificant variation between the two depths could be explained by a lack of layering in the glacial deposits in the Bertrand Creek watershed.

Both the site, and the interaction of site and depth significantly affect the means of *K*. The significant effect of site location suggests there is substantial variation along the creek. Sand and gravel glaciofluvial outwash comprises the major surficial materials. Sediments become finer towards Canada and transition to coarser materials on the US side (Scibek and Allen, 2005). The variation in lithology is a likely cause of substantial spatial variation of streambed composition and hydraulic conductivity.

For the Fishtrap Creek, the slug tests resulted in reasonable values for both the 0.5-m and 1.0-m depths for all sites. However, at site F1, location one, there was only one valid replicate at 1.0 m. The error occurred likely because insufficient pressure was applied during the test.

The mean *K* values ranged 3.7–79.7 m d^{-1} at 0.5 m, and 2.7–149 m d^{-1} at 1.0 m (Figure 4, Table 1, Appendix A). The ANOVA tests indicated that the means of *K* at 0.5 m and 1.0 m did not differ statistically at $\alpha = 0.05$ ($F = 14.3$, $P < 0.001$, Table 3), again suggesting the relative homogeneity of the streambed materials with depth. The tests showed, however, a significant difference among the sites, and the effect of interaction between site and depth was not statistically significant.

Table 1. Reported hydraulic conductivity values for similar riverbed materials (Calver, 2001).

Method	**Study Area**	**Soil Material**	***K*, m/d**	**Source**
Field measurements	Danube at Vienna, Austria	Gravel and sand aquifer; clogged bed layer	0.86–8.63	Sengschmitt et al., 2003
Field pumping and analytical cals.	White River, ID, USA	Channel in glacial outwash, sand and gravel	0.86–86.4	Meyer, 1978
Field pumping tests	Overijssel, Netherlands	Sands	0.12–25.9	Lamsvelt, 1985
Field pumping and analysis	Scioto River, OH, USA	silty alluvium, sand and gravel over shale bedrock	0.3–69.12	Norris 1983a,b, Nortz et al., 1994
Slug test analysis from tests bores	Grand Calumet River, ID, USA	Fine- grain sediments and fill over silty-sand aquifer	0.06–604.8	Prince et al., 1988

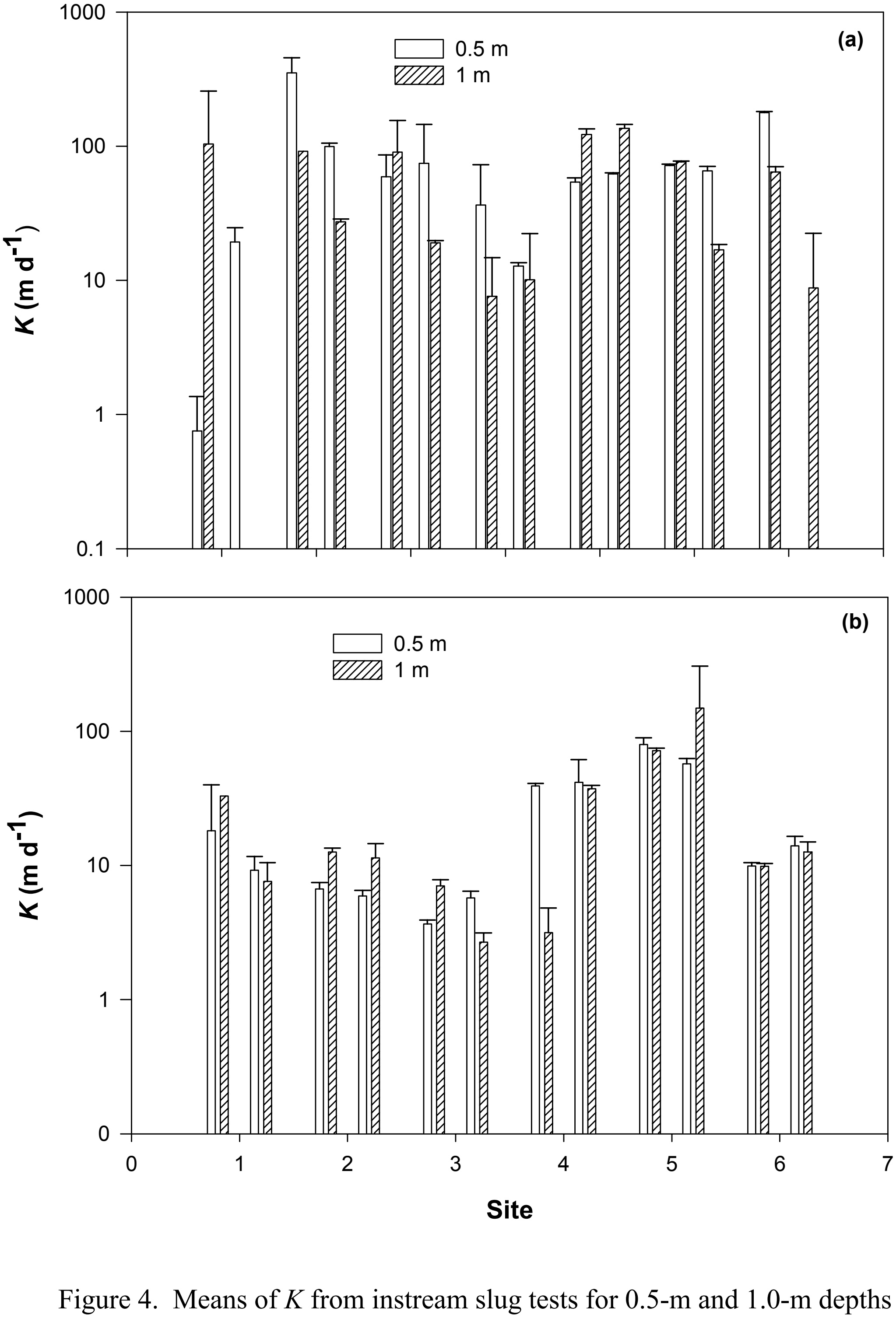

Figure 4. Means of *K* from instream slug tests for 0.5-m and 1.0-m depths for (a) Bertrand Creek (B) and (b) Fishtrap Creek (F). Data are missing for location 2 at Bertrand site 1 and site 7, and Fishtrap site 1.

Table 2. Results of instream slug tests (ft d^{-1}) at Bertrand and Fishtrap Creeks, Washington, USA.

Depth	**Mean (ft d^{-1})**	**Std Dev**	**Minimum**	**Maximum**
		Bertrand Creek		
0.5 m	70.7	88.2	0.13	472.6
1.0 m	56.9	58.0	0.43	280.4
		Fishtrap Creek		
0.5 m	21.6	22.8	3.5	90.7
1.0 m	36.6	63.2	1.4	300.9

Table 3. ANOVA results ($\alpha = 0.05$) comparing means of K from the slug tests.

	***F*-value**	***p*-value**	**Test**
	Bertrand Creek		
Site	6.80	0.001	**
Depth	4.07	0.080	NS
Site*Depth[a]	7.08	0.001	**
	Fishtrap Creek		
Site	14.3	0.001	**
Depth	0.22	0.639	NS
Site*Depth[a]	1.51	0.199	NS
	Reach		
Reach	21.4	0.001	**
Reach*Depth[b]	1.61	0.206	NS

** Significant

[a] Site*Depth, interactive effect of site and depth

[b] Reach*Depth, interactive effect of reach and depth

This difference may be attributed to the differences in the geological materials and soils underlain the streams. Soil consists primarily of well-drained fine sandy loam to silt loam along the Bertrand Creek whereas Fishtrap Creek is covered with loam, silt loam and muck (Goldin, 1992).

Differences in land use and management practices within the two watersheds were also observed. In the Bertrand Creek watershed, land use was mainly dairy farming on the north end of our study area (B1–B3), changing to berry production (B4), and returning to dairy farming before the creek reaches the Nooksack River.

A buffer zone of roughly 5 m wide is established along the reach of the Bertrand Creek within our study domain. On the other hand, the surrounding land use of the Fishtrap Creek is predominantly dairy farming. The Fishtrap Creek runs through residential areas of the city of Lynden before reaching the Nooksack River. The Fishtrap Creek has large portions that are not well protected by a buffer zone compared to the Bertrand Creek. Future studies investigating how land use and management practices may affect the material composition of the streambed would be valuable.

A comparison of the slug tests at the two reaches showed a significant difference between the two reaches. Overall, the mean of K measured at the Bertrand Creek was larger than that measured at the Fishtrap Creek (Table 4). The ANOVA test comparing the means of K from the Hazen equation for the two creeks showed that there was a significant difference at the surface, but there was no statistically significant difference at the subsurface (Table 5), indicating differences in the materials of the two layers.

3.2 K Estimation from Empirical Formulas

The analysis of grain-size distribution for surface and subsurface materials in both Bertrand and Fishtrap Creeks revealed that the streambed deposits were all sand in texture (Figure 5, Appendix F) following US Department of Agriculture soil classification (Hillel, 1982). Yet the hydraulic conductivities derived from the empirical equations still varied considerably. The results have missing data at B3 and B4 for the subsurface values. Ranges of the mean *K* values at the 0.5-m depth and one standard deviation are shown in Figure 6. For the surface materials of Bertrand Creek, the mean *K* ranged 13.6–300 m d^{-1} from the Hazen equation, and 8.7–63.2 m d^{-1} from the Harleman equation. Both ranges fall within the literature values (Table 2). However, these two methods did not capture the extreme values as did the slug tests.

The mean *K* values from the Krumbien and Monk equation ranged 33.3–2900 m d^{-1}, with the maximum value exceeding literature values for this type of bed material (Table 2). Foster et al. (2003), in a study of permeability of sands in the coastal region of the Baltic Sea, found that the Krumbien and Monk formula overestimated the permeability by a factor 2.6 on average. ANOVA tests indicated that the site, method, and the interaction between site and methods all have a significant effect on the means of *K* (Table 6, Appendix B). Hence, longitudinal variation in particle size and bed material composition varies substantially in Bertrand Creek.

Site F2 of the Fishtrap Creek, no viable samples were collected for the surface or subsurface material. For the remaining sites, the mean *K* for the surface materials ranged 22.1–115.0 m d^{-1} from the Hazen equation and 14.2–42.7 m d^{-1} from the Harleman equation (Figure 6). These results are within the range of typical values reported in the literature for similar bed materials(Table 2).

Table 4. ANOVA results ($\alpha = 0.05$) comparing the mean values of K for the slug tests, Hazen, Harleman, Krumbien-Monk, and the Kozeny-Carmen equations for subsurface soil material.

	***F*-value**	***p*-value**	**Test**
	Bertrand Creek		
Site	1.96	0.149	NS
Method	3.82	0.023	**
	Fishtrap Creek		
Site	1.23	0.336	NS
Method	1.04	0.418	NS

** Significant

Table 5. ANOVA results of comparing means of *K* values from the Hazen method for both creeks.

	***F*-value**	***p*-value**	**Test**
		Surface	
Reach	4.37	0.046	**
		Subsurface	
Reach	0.87	0.378	NS

** Significant

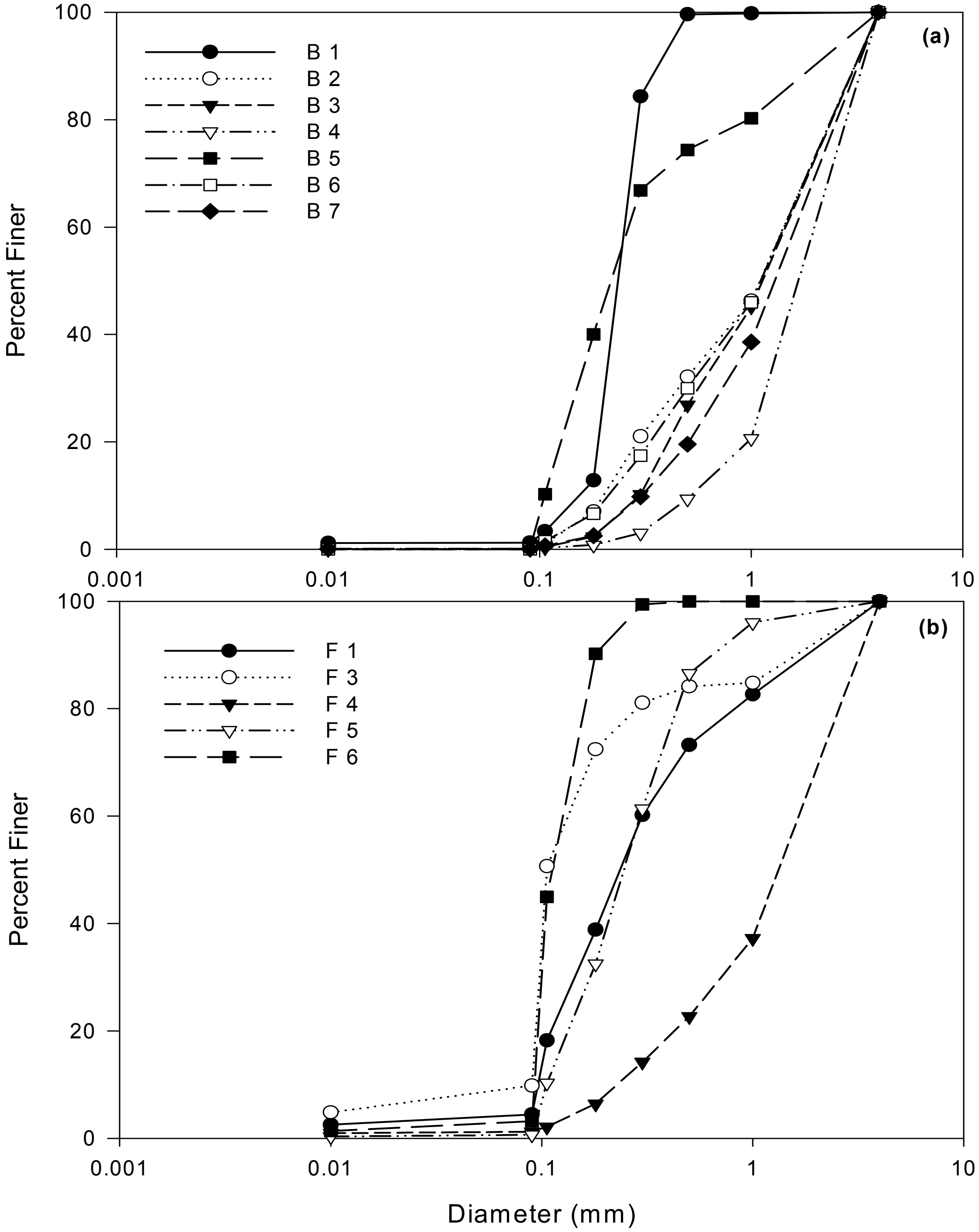

Figure 5. Particle size distribution for Bertrand and Fishtrap Creeks.

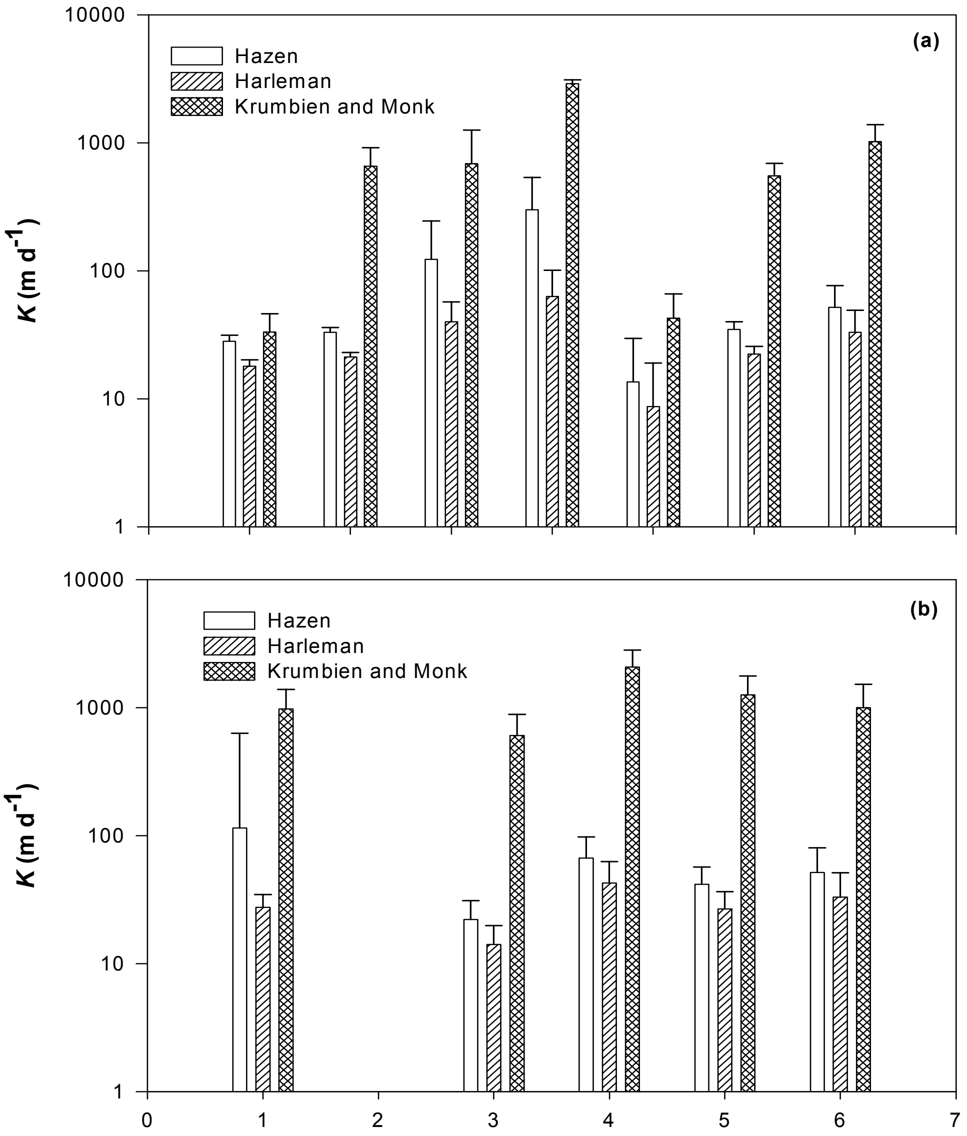

Figure 6. Empirical estimates of mean *K* for surface materials for (a) Bertrand Creek and (b) Fishtrap Creek. Note missing data at Fishtrap site 2

However, these results do not capture the extreme values obtained in the slug tests. The *K* values from the Krumbien and Monk equation ranged 602–2071 m d^{-1}, exceeding the range of literature values (Table 2). The ANOVA test indicated that the effects of site, method, and the interaction between the site and method on the mean of *K* were all significant (Table 6, Appendix B).

For the subsurface materials in Bertrand Creek, the mean of *K* ranged 8.7–45.7 m d^{-1}, 5.6–29.3 m d^{-1}, 10.7–1050 m d^{-1}, and 14–626 m d^{-1} from the Hazen, Harleman, Krumbien and Monk, and the Kozeny-Carman methods, respectively. The mean *K* values from the Hazen and Harlman equations were within the literature range, but the mean *K* values from both the Krumbien and Monk and the Kozeny-Carman methods exceeded the literature maximums (Table 2, Figure 7, Appendix D). The ANOVA test suggested that the means of *K* from the four empirical methods were significantly different (Table 7).

For the subsurface materials of the Fishtrap Creek, the mean of *K* ranged 7.0–47.8 m d^{-1} from the Hazen equation, 2.5–30.6 m d^{-1} from the Harleman equation, 9.6–1460 m d^{-1} from the Krumbien and Monk equation, and 46.5–16800 m d^{-1} from the Kozeny-Carman equation (Figure 7, Appendix D). The ANOVA test found no significant effect of either the site factor or the method factor (Table 7).

Overall, streambed *K* estimates from the Hazen and Harleman equations were similar and fell within the range of the literature values for both studied creeks, but did not capture the extremes that were revealed in the slug tests. These values are supported by the grain-size distribution measurements found in Figure 6. The Krumbien and Monk and the Kozeny-Carman equations tended to over-estimate the *K* values.

Table 6. ANOVA results ($\alpha = 0.05$) comparing the mean values of K for the Hazen, Harleman, and Krumbien and Monk equations with the use of surface soil tests.

Surface	***F*-value**	***p*-value**	**Test**
	Bertrand Creek		
Site	15.2	0.001	**
Depth	76.4	0.001	**
Site*Depth[a]	13.0	0.001	**
	Fishtrap Creek		
Site	9.88	0.001	**
Depth	129	0.001	**
Site*Depth[a]	8.56	0.001	**

** Significant

[a] Site*Depth, interactive effect of site and depth

[b] Reach*Depth, interactive effect of reach and depth

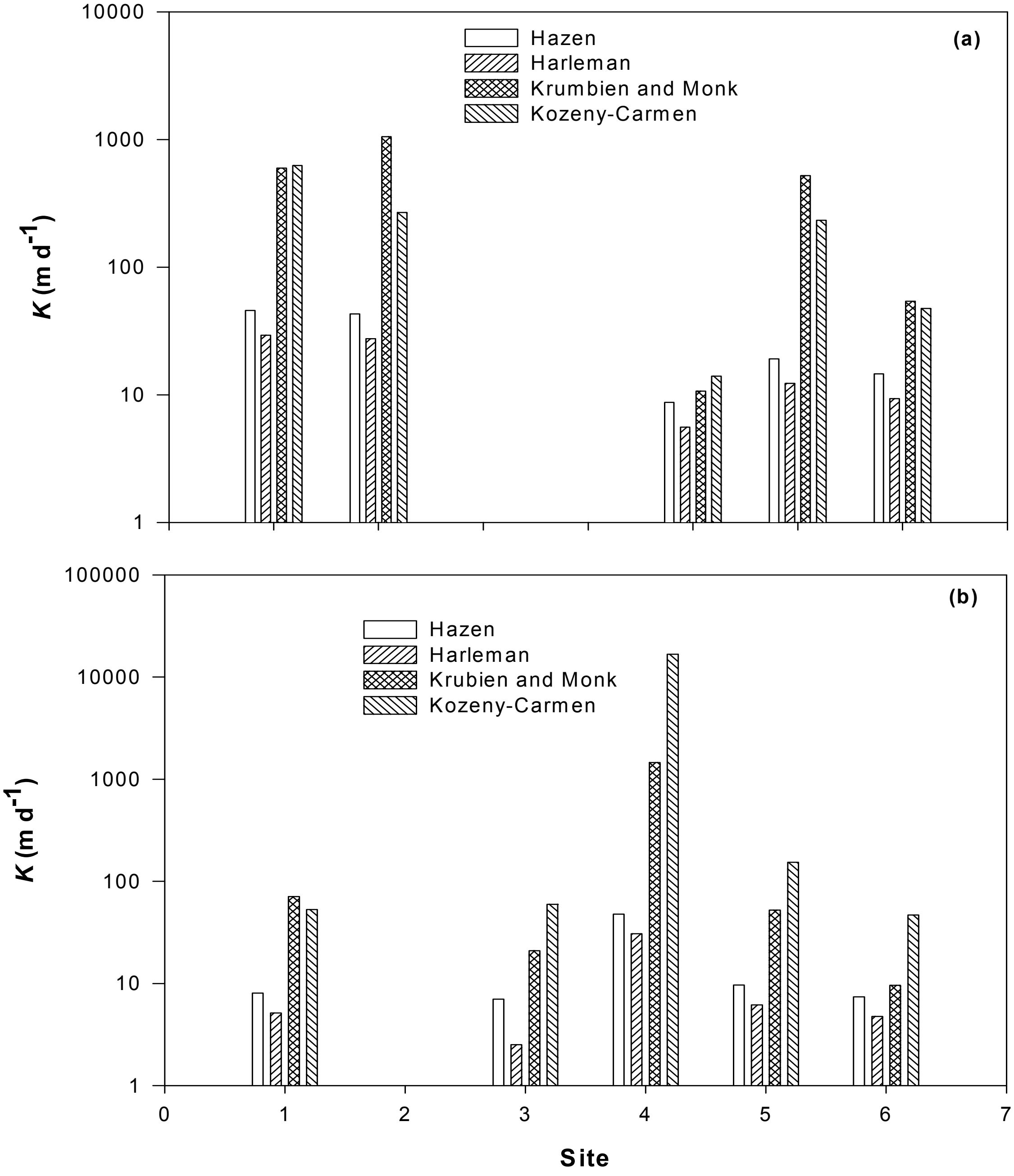

Figure 7. Results of empirical estimates of *K* for (a) Bertrand Creek (B) and (b) Fishtrap Creek (F) subsurface material. Note missing data at Bertrand site 3 and site 4, and Fishtrap site.

Table 7. ANOVA results ($\alpha = 0.05$) comparing the mean values of K for the Hazen, Harleman, Krumbien-Monk, and Kozeny-Carmen equations with the use of subsurface soil materials.

Subsurface	***F*-value**	***p*-value**	**Test**
		Bertrand Creek	
Site	2.09	0.145	NS
Method	4.34	0.027	**
		Fishtrap Creek	
Site	1.25	0.342	NS
Method	1.04	0.410	NS

** Significant

Comparison of results from the slug tests and the four empirical equations suggested that the mean *K* values at the 0.5-m depth by the five methods were significantly different (*F*-value 3.82, *p*-value 0.023) for the Bertrand Creek but were not significantly different for the Fishtrap Creek (*F*-value 1.04, *p*-value 0.418, Table 4).

3.3 Slug Test vs. Empirical Calculations

Slug tests are a common field method for estimating aquifer *K*. The applicability of the procedure to testing streambeds has been documented (Cardenas and Zlotnik, 2003; Hanrahan et al., 2005; Leek, 2006). Slug tests are useful for many studies that are focused on streambed habitat. The slug test allows for a better understanding of the connectivity to ground-water, which influences the quality and quantity of stream flow including spawning beds, and overall stream health (Meyer, 1978; Hanrahan et al., 2005). Even though the slug test method is labor-intensive and can be time-consuming if numerous tests are required this study proved to show the most representative data compared to the empirical methods.

In contrast, particle-size analysis for use in the empirical *K* estimations requires primarily sample collections with basic tools, oven-drying at 107°C, and sieving with a shaker to reduce the analysis time. The sieve shaker is the most expensive device among all needed. The particle-size analysis can be costly if it is performed by professional labs. In addition, if the streambed materials are silty or clayey in texture, a hydrometer test would be needed for a thorough analysis of particle-size distribution, which can increase both cost and time needed. The test for porosity involves mainly oven-drying and weighing, the cost of which is typically modest. Overall, the empirical methods can be less labor-demanding and less costly, and may be suited for preliminary surveying projects.

From this study, it is recommended that slug test and empirical estimations be used to determine *K* values when their accuracy and reliability are crucial, e.g., in detailed modeling of surface- and ground-water interactions. If *K* is not a dominant factor as compared to other physical properties e.g., in preliminary assessment for land and water resources management, the generally more cost-effective empirical procedures would be adequate.

4. SUMMARY AND CONCLUSIONS

This study investigated streambed hydraulic conductivity of two salmon-habitat streams, Bertrand Creek and Fishtrap Creek, in the state of Washington, Pacific Northwest, USA. The two streams are typical examples in the region where water levels in stream are impacted by seasonal water shortages during summer months. Streambed *K* was measured using slug tests and analyzed following the Bouwer-Rice method. A second, low-cost approach of empirical formulas based on measurement of representative particle-size distribution was also used to estimate *K*. Comparisons were made of mean *K* values within and between the two streams from the slug tests, and of mean *K* values determined from the slug tests vs. the empirical estimation. Major findings from this study included:

- *K* values from the slug tests at the two streams of Bertrand Creek and Fishtrap Creek fell in the literature range for similar streambed materials.
- There was no significant difference between mean *K* values between the 0.5-m and 1.0-m depths from the slug tests for both Bertrand Creek and Fishtrap Creeks, suggesting sampling at the shallower level may suffice in relevant future studies.
- The mean of *K* for Bertrand Creek from the combined surface and subsurface samples was significantly higher than that of the Fishtrap Creek due to the difference in geological deposits at the two sites.

- For the surface and subsurface materials of both Bertrand and Fishtrap Creeks, estimates of *K* from the Hazen and Harleman showed no significant difference. However, the Krumbien and Monk and the Kozeny-Carmen equations resulted in much higher estimations than the previous two methods and exceeded literature values. Hence, the Hazen and Harleman equations may be used for future studies and the Krumbien andMonk and the Kozeny-Carmen equations may not be applicable to this region.
- Comparison of mean *K* values estimated for the different sites using the Hazen method showed that there was a significant difference along the studied reach of Bertrand Creek but not along the studied reach of Fishtrap Creek.
- Comparison of results from the slug tests and empirical estimations indicated that the mean *K* values at the 0.5-m depth by the five methods were significantly different for the Bertrand Creek but were not significantly different ere for the Fishtrap Creek.

In determining the appropriate method for obtaining *K* in relevant future studies, we recommend the following. If accuracy and reliability of the *K* values are desired for a detailed study, e.g., development of models of surface- and ground-water interaction, the slug test method is well suited. If *K* is not a dominant factor in the study, then the empirical method would be a more cost-effective approach.

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APPENDICES

APPENDIX *A*

Calculations of *K* from the instream slug tests, Bertrand Creek and Fishtrap Creek, Washington State, USA

Estimation of K from a Slug Test Using Four Different Approaches *(based on notes from Li Wang, PhD student, BSYSE, WSU)*

Four slightly different approaches were used to solve for *K* of a single slug test following the Bouwer and Rice equation (Bouwer and Rice, 1976): curve matching, least-squares, and arithmetic and harmonic means of *K* calculated for each time step for the entire data set.

1. Curve matching

In Bouwer and Rice (1976), a straight line was fitted with measured data $\ln(H_t)$ vs t. An arbitrary point (t, H_t) on the line together with the intercept H_0 was selected to calculate *K* using the following equation

$$K = \frac{r^2 \ln(R_e/R)}{2L_e} \frac{1}{t} \ln\left(\frac{H_0}{H_t}\right) \tag{A.1}$$

K was obtained by curve matching, i.e., by automatically fitting the equation

$$\frac{H_t}{H_0} = \exp(b\,t) \tag{A.2}$$

to the measured data, where $b = -\frac{K}{C}$ and $C = \frac{r^2 \ln(R_e/R)}{2L_e}$. The fitted coefficient *b* was then used to calculate $K = -bC$.

If, after visual inspection and selection from the original data, we find that the point (t_0, H_0) still departs from the major trend of the remaining data, we may decide to use another form of the Bouwer-Rice equation

$$\frac{H_t}{H_0} = \exp(b\,t) \tag{A.3}$$

2. Least-squares

If we use equation (A.2) and assume a reasonable *K* for an initial guess, H_t can be calculated for every pair of data corresponding to time 0–t. The *K* value of the slug test can then be calculated by comparing the predicted with the measured H_t's and minimizing their MSE (mean squared error). This can be done by using the Solver function of Microsoft Excel.

3 and 4. Arithmetic and Harmonic means

Theoretically, K can be calculated by using any two points of measured data (t_1, H_1) and (t_2, H_2) or (t_1, $\frac{H_1}{H_0}$) and (t_2, $\frac{H_2}{H_0}$) during a single slug test. The equation is

$$K = \frac{C}{t_2 - t_1} \ln\left(\frac{H_1}{H_2}\right) \tag{A.4}$$

When $t_1 = 0$, let $t = t_2$, $H_0 = H_1$, and $H_t = H_2$. , Then, the above equation resumes the form of equation (A.1).

A series of K values can be calculated using the selected data (t_0, H_0) and the data points thereafter. If the resultant K's exhibit a declining trend with time, the harmonic mean should be used to obtain an average K; otherwise, the arithmetic mean may be used.

Additional notes that are crucial and helpful are included below.

- In equation (A.1), point (t_0, H_0) is very important for the result of K, since it is used as many times as the number of data points, while other points are used only once. From field experience, the recovery curve is likely to have a larger slope or fluctuations at the beginning part. Hence, one should check this part carefully. Setting different points as the (t_0, H_0) point and only using this point and the data points after it would favor different stages of the slug test or different influence areas.
- In using equation (A.2), if we force the intercept $a = 1$, the (t_0, H_0) point is favored. The resultant equation is equivalent to the Bouwer-Rice (1976) equation.
- In using equation (A.3), if we fit both coefficients a and b in the equation, the main trend of the data set is favored. Doing so eliminates the dominant influence of the (t_0, H_0) point. Such approach is equivalent to the one used by Bouwer and Rice (1976), in which the fitted intercept H_0 was used instead of the theoretical value.
- Visual data inspection and selection is important in perhaps any slug test analysis.
- The term $\frac{K}{C}t$ may be considered as the dimensionless K.
- Equation (A.4) is similar to that of the falling-head method in measuring saturated hydrauclic conductivity typically used in soil physics.
- By comparing the resultant K vs t, it may also be helpful to understand the behavior of the heterogeneous porous media surrounding the piezometer. Although the Bouwer and Rice equation (1976) is generally applied under conditions of homogeneous porous media, heterogeneity naturally occur at any spatial scale. It is only a matter of how heterogeneous the porous media are.

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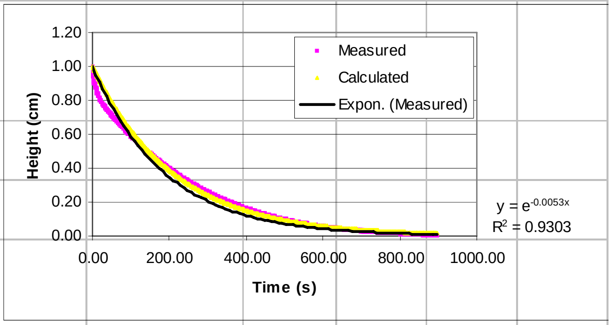
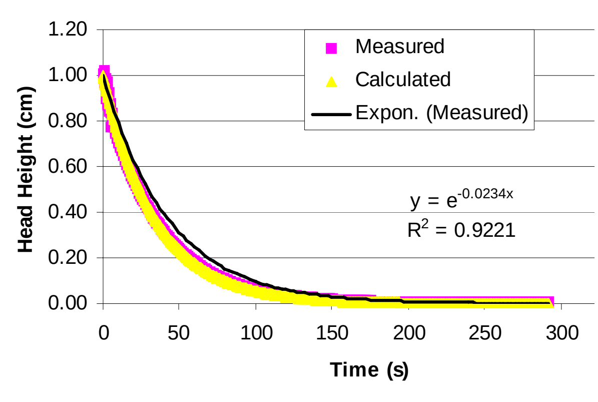
Example 1. Bertrand Creek site one, location one, 0.5-m depth, replicate one. This is an example of a valid slug test and adequate curve fitting. Listed are only the data points for the beginning of the test.

				Slug Test --- Estimate K							
				Inputs (m)			Solver---> K	1.50E-05	m/s	<---run solver	
	H (m)-- (Assume)	6.00	Radius of the well casing	r	0.033		2. Curve ---> Co	-0.0053			
	Lw (m)	1.09	Distance for measuring K	Re	0.103		K	1.67E-05	m/s		
	Transducer Position above bottom of pizometer (m)	0.10	Radius of the gravel envelop	R	0.043						
			length of the screen	Le	0.152						
x	A	B	Drawdowm at t=0	H0	0.796						
0.553	1.75	0.23	Initial Water level	DOW	0.992						
			Constant	C	0.003	3. Arithmetic Average K	4. n/Σ(1/Ki)				
				sum()	2.707	1.70E-05	1.60E-05				
	t (s)	Ht (cm)	measured H_t/H_{t0}	Calculated H_t/H_{t0}	(E-F)^2	Ki					
	0.00	79.63	1.00	1.00	0.00						
	0.25	78.52	0.99	1.00	0.00	1.8E-04	5.6E+03				
	0.50	78.00	0.98	1.00	0.00	1.3E-04	7.7E+03				
	0.75	76.36	0.96	1.00	0.00	1.8E-04	5.7E+03				
	1.00	75.10	0.94	1.00	0.00	1.8E-04	5.4E+03				

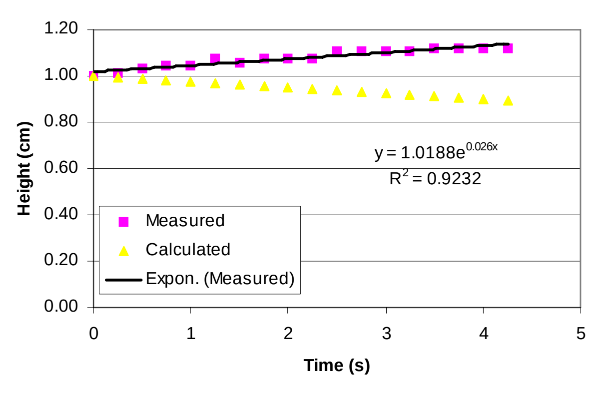
Example 2. Fishtrap Creek, site one, location one, 0.5-m depth, second replicate. This is an example of a valid slug test and adequate curve fitting. Listed are only the data points for the beginning of the test.

				Slug Test --- Estimate K				
				Inputs (m)			Solver--->	9.03E-05
	H (m)-- (Assume)	6	Radius of the well casing	r	0.03302		2. Curve --	-0.234
	Lw (m)	0.957	Distance for measuring K	Re	0.1015		K	7.25E-04
	Transducer Position above bottom of pizometer (m)	0.1	Radius of the gravel envelop	R	0.04267			
			length of the screen	Le	0.1524			
x	A	B	Drawdowm at t=0	H0	0.82236			
0.553	1.747	0.233	Initial Water level	DOW	0.857			
			Constant	C	0.0031	3. Arithmetic Average K	4. n/Σ(1/Ki)	
				sum()	0.0931	1.18E-01	1.71E-03	
	t (s)	Ht (cm)	measured H_t/H_{t0}	Calculated H_t/H_{t0}	(E-F)^2	Ki		
	0	82.236	1.00	1.00	0.00			
	0.25	81.056	0.99	0.99	0.00	1.00	1	
	0.5	83.047	1.01	0.99	0.00	0.99	1.007307	



Example 3. Bertrand Creek, site one, location two, 1.0-m depth, replicate one. This is an example of a non-usable slug-test measurement. Listed are only the data points for the beginning of the test.

					Slug Test --- Estimate K							
				Inputs (m)			Solver--->	7.70E-05	m/s	<---run solver		
	H(m)--(Assume)	6	Radius of the well casing	r	0.03302		2. Curve ---	0.026		<---type Coef. in Fig. 1		
	Lw(m)	0.549	Distance for measuring K	Re	0.0958		K	7.53E-05	m/s			
	Transducer Position above bottom of pizometer (m)	0.1	Radius of the gravel envelop	R	0.04267							
			length of the screen	Le	0.1524							
x	A	B	Drawdowm at t=0	H0	0.0495							
0.553	1.747	0.233	Initial Water level	DOW	0.449							
			Constant	C	0.00289	3. Arithmetic Average K	4. n/Σ(1/Ki)					
				sum()	0.4000	1.16E-04	1.09E-04					
	t (s)	Ht (cm)	measured H_t/H_{t0}	Calculated H_t/H_{t0}	(E-F)^2	Ki						
	0	4.95	1.00	1.00	0.00							
	0.25	5.02	1.01	0.99	0.00	1.6E-04	6.2E+03					
	0.5	5.1	1.03	0.99	0.00	1.7E-04	5.8E+03					



Estimated K for Streambeds of Bertrand Creek and Fishtrap Creek

Bertrand Creek
Slug Tests

Site/ Replicate	Solver	Curve Method	Arithmetic Average K	n/Σ(1/Ki)
	m/day	m/day	m/day	m/day
BC11-0.5-1	1.43E-01	1.348E-01	1.909E-01	1.616E-01
BC11-0.5-2	3.37E-01	3.732E-01	3.724E-01	4.113E-01
BC11-0.5-3	1.10E+00	1.063E+00	1.236E+00	1.166E+00
BC11-0.5-4	1.30E+00	1.443E+00	1.469E+00	1.382E+00
AVG	7.18E-01	7.53E-01	8.17E-01	7.80E-01
STD	5.64E-01	6.05E-01	6.30E-01	5.86E-01
BC11-1-1	2.60E+01	2.804E+02	2.514E+01	2.411E+01
BC11-1-2	1.40E+01	1.512E+01	1.529E+01	1.477E+01
BC11-1-3	1.41E+01	1.633E+01	1.572E+01	1.521E+01
AVG	1.80E+01	1.04E+02	1.87E+01	1.80E+01
STD	6.91E+00	1.53E+02	5.57E+00	5.27E+00
BC12-0.5-1	2.62E+01	2.549E+01	2.678E+01	2.566E+01
BC12-0.5-2	1.41E+01	1.564E+01	1.555E+01	1.495E+01
BC12-0.5-3	1.43E+01	1.685E+01	1.598E+01	1.538E+01
AVG	1.82E+01	1.93E+01	1.94E+01	1.87E+01
STD	6.93E+00	5.37E+00	6.36E+00	6.06E+00
BC21-0.5-1	6.15E+02	4.726E+02	6.670E+02	3.966E+02
BC21-0.5-2	2.48E+02	2.825E+02	2.609E+03	2.583E+02
BC21-0.5-3	2.59E+02	2.972E+02	2.791E+02	2.748E+02
AVG	3.74E+02	3.51E+02	1.19E+03	3.10E+02
STD	2.09E+02	1.06E+02	1.25E+03	7.55E+01
BC21-1-1	8.25E+01	9.158E+01	1.616E+04	1.996E+03
BC21-1-2	7.73E+01	9.158E+01	1.521E+04	1.477E+03
BC21-1-3	8.01E+01	9.158E+01	1.642E+04	2.143E+03
AVG	8.00E+01	9.16E+01	1.59E+04	1.87E+03
STD	2.59E+00	0.00E+00	6.37E+02	3.50E+02
BC22-0.5-1	1.05E+02	1.054E+02	1.140E+02	1.115E+02
BC22-0.5-2	9.07E+01	1.002E+02	9.158E+01	9.158E+01
BC22-0.5-3	9.07E+01	9.331E+01	9.158E+01	9.158E+01
AVG	9.56E+01	9.96E+01	9.91E+01	9.82E+01
STD	8.48E+00	6.07E+00	1.30E+01	1.15E+01
BC22-1-1	2.93E+01	2.765E+01	2.894E+01	2.860E+01
BC22-1-2	2.82E+01	2.843E+01	2.765E+01	2.739E+01
BC22-1-3	2.78E+01	2.583E+01	2.704E+01	2.687E+01
AVG	2.84E+01	2.73E+01	2.79E+01	2.76E+01
STD	7.68E-01	1.33E+00	9.71E-01	8.87E-01
BC31-0.5-1	2.42E+01	2.203E+01	1.400E+04	9.158E+02
BC31-0.5-2	9.16E+01	7.534E+01	9.763E+03	8.182E+01
BC31-0.5-3	8.81E+01	5.694E+01	7.033E+03	3.128E+00
BC31-0.5-4	8.26E+01	8.260E+01	1.797E+04	5.512E+02
AVG	7.16E+01	5.92E+01	1.22E+04	3.88E+02
STD	3.18E+01	2.70E+01	4.80E+03	4.27E+02

BC31-1-1	1.41E+02	1.408E+02	1.279E+04	4.787E+02
BC31-1-2	1.13E+02	1.132E+02	1.754E+04	2.713E+03
BC31-1-3	1.69E+01	1.693E+01	1.823E+04	3.637E+03
AVG	9.03E+01	9.03E+01	1.62E+04	2.28E+03
STD	6.50E+01	6.50E+01	2.96E+03	1.62E+03
BC32-0.5-1	7.90E+01	7.897E+01	1.132E+04	2.549E+02
BC32-0.5-2	7.35E+01	7.387E+01	1.668E+04	2.298E+03
BC32-0.5-3	7.09E+01	7.093E+01	1.581E+04	1.806E+03
AVG	7.45E+01	7.46E+01	1.46E+04	1.45E+03
STD	4.10E+00	4.07E+00	2.88E+03	1.07E+03
BC32-1-1	1.75E+01	1.875E+01	2.160E+04	6.774E+03
BC32-1-2	1.84E+01	1.832E+01	1.823E+04	3.637E+03
BC32-1-3	1.76E+01	1.961E+01	2.246E+04	7.612E+03
BC32-1-4	1.90E+01	1.979E+01	1.685E+04	2.635E+03
AVG	1.81E+01	1.91E+01	1.98E+04	5.16E+03
STD	7.21E-01	7.00E-01	2.68E+03	2.40E+03
BC41-0.5-1	3.67E+01	3.897E+01	1.961E+04	4.717E+03
BC41-0.5-2	4.67E+01	4.588E+01	1.650E+04	2.316E+03
BC41-0.5-3	3.59E+01	3.275E+01	1.486E+04	1.426E+03
BC41-0.5-4	3.43E+01	2.782E+01	1.270E+04	5.988E+02
AVG	3.84E+01	3.64E+01	1.59E+04	2.26E+03
STD	5.63E+00	7.82E+00	2.91E+03	1.78E+03
BC41-1-1	1.76E+02	1.581E+01	1.598E+03	
BC41-1-2	3.04E+00	3.102E+00	1.633E+04	2.350E+03
BC41-1-3	3.95E+00	3.940E+00	1.408E+04	1.149E+03
AVG	6.11E+01	7.62E+00	1.07E+04	1.75E+03
STD	9.97E+01	7.11E+00	7.94E+03	8.49E+02
BC42-0.5-1	1.32E+01	1.201E+01	1.296E+04	7.214E+02
BC42-0.5-2	1.21E+01	1.244E+01	1.866E+04	4.026E+03
BC42-0.5-3	1.25E+01	1.296E+01	1.858E+04	3.931E+03
BC42-0.5-4	1.32E+01	1.365E+01	1.840E+04	3.845E+03
AVG	1.28E+01	1.28E+01	1.72E+04	3.13E+03
STD	5.53E-01	7.07E-01	2.80E+03	1.61E+03
BC42-1-1	5.99E+00	2.825E+01	7.214E+03	6.350E+00
BC42-1-2	5.38E+00	5.702E+00	1.944E+04	4.735E+03
BC42-1-3	3.27E+00	3.430E+00	3.275E+00	3.430E+00
BC42-1-4	3.01E+00	3.015E+00	3.007E+00	3.015E+00
AVG	4.41E+00	1.01E+01	6.67E+03	1.19E+03
STD	1.49E+00	1.22E+01	9.17E+03	2.37E+03
BC51-0.5-1	5.18E+01	5.426E+01	1.598E+04	1.996E+03
BC51-0.5-2	5.24E+01	5.772E+01	1.581E+04	1.892E+03
BC51-0.5-3	4.99E+01	4.994E+01	1.590E+04	1.953E+03
AVG	5.14E+01	5.40E+01	1.59E+04	1.95E+03
STD	1.27E+00	3.90E+00	8.64E+01	5.21E+01
BC51-1-1	9.85E+01	1.149E+02	1.443E+04	1.089E+03
BC51-1-2	1.16E+02	1.365E+02	1.650E+04	2.065E+03
BC51-1-3	1.07E+02	1.149E+02	1.210E+04	3.871E+02
AVG	1.07E+02	1.22E+02	1.43E+04	1.18E+03
STD	8.64E+00	1.25E+01	2.20E+03	8.43E+02
BC52-0.5-1	6.33E+01	6.057E+01	1.365E+04	8.726E+02
BC52-0.5-2	6.48E+01	6.273E+01	1.287E+04	6.204E+02

BC52-0.5-3	6.29E+01	6.273E+01	1.598E+04	1.918E+03
AVG	6.37E+01	6.20E+01	1.42E+04	1.14E+03
STD	9.96E-01	1.25E+00	1.62E+03	6.88E+02
BC52-1-1	1.23E+02	1.469E+02	1.668E+04	2.151E+03
BC52-1-2	1.11E+02	1.296E+02	1.521E+04	1.426E+03
BC52-1-3	1.15E+02	1.313E+02	1.702E+04	2.402E+03
AVG	1.16E+02	1.36E+02	1.63E+04	1.99E+03
STD	5.75E+00	9.52E+00	9.63E+02	5.07E+02
BC61-0.5-1	1.72E+02	8.519E+01	9.158E+03	3.033E+00
BC61-0.5-2	1.39E+02	7.284E+01	1.115E+04	1.210E+01
BC61-0.5-3	1.37E+02	4.709E+01	5.383E+03	5.772E-02
BC61-0.5-4	1.68E+02	8.156E+01	3.313E+04	2.825E+00
AVG	1.54E+02	7.17E+01	1.47E+04	4.50E+00
STD	1.85E+01	1.72E+01	1.25E+04	5.24E+00
BC61-1-1	1.18E+02	9.245E+01	1.080E+04	1.676E+02
BC61-1-2	9.94E+01	8.113E+01	1.287E+04	5.607E+02
BC61-1-3	8.48E+01	6.523E+01	1.132E+04	2.557E+02
BC61-1-4	7.35E+01	6.627E+01	1.503E+04	1.400E+03
AVG	9.38E+01	7.63E+01	1.25E+04	5.96E+02
STD	1.90E+01	1.30E+01	1.90E+03	5.62E+02
BC62-0.5-1	1.02E+02	6.947E+01	1.253E+04	4.856E+02
BC62-0.5-2	1.04E+02	5.944E+01	7.906E+03	1.089E+01
BC62-0.5-3	9.68E+01	6.748E+01	1.071E+04	1.659E+02
AVG	1.01E+02	6.55E+01	1.04E+04	2.21E+02
STD	3.60E+00	5.31E+00	2.33E+03	2.42E+02
BC62-1-1	2.09E+01	1.581E+01	1.296E+04	7.119E+02
BC62-1-2	2.06E+01	1.884E+01	1.814E+04	3.568E+03
BC62-1-3	1.75E+01	1.754E+01	1.408E+04	1.115E+03
BC62-1-4	1.93E+01	1.547E+01	1.305E+04	7.292E+02
AVG	1.96E+01	1.69E+01	1.46E+04	1.53E+03
STD	1.53E+00	1.57E+00	2.44E+03	1.37E+03
BC71-0.5-1	1.53E+02	1.788E+02	1.771E+04	2.635E+03
BC71-0.5-2	1.38E+02	1.737E+02	1.987E+04	4.320E+03
BC71-0.5-3	1.48E+02	1.806E+02	2.056E+04	4.838E+03
AVG	1.46E+02	1.78E+02	1.94E+04	3.93E+03
STD	7.45E+00	3.60E+00	1.49E+03	1.15E+03
BC71-1-1	5.77E+01	5.772E+01	1.374E+04	8.986E+02
BC71-1-2	5.88E+01	6.636E+01	4.311E+04	3.430E+04
BC71-1-3	5.94E+01	6.903E+01	4.285E+04	3.404E+04
AVG	5.86E+01	6.44E+01	3.32E+04	2.31E+04
STD	8.39E-01	5.92E+00	1.69E+04	1.92E+04
BC72-0.5-1	7.42E+00	7.880E+00	1.909E+04	4.450E+03
BC72-1-1	3.89E-01	4.277E-01	4.018E+04	3.810E+04
BC72-1-2	1.05E+00	1.313E+00	8.510E+04	8.510E+04
BC72-1-3	1.96E+00	2.462E+01	3.361E+04	2.186E+04
AVG	1.13E+00	8.79E+00	5.30E+04	4.84E+04
STD	7.89E-01	1.37E+01	2.80E+04	3.28E+04

Fishtrap Creek Slug Test Results

Site/ Replicate	**Solver**	**Curve Method**	**Arithmetic Average K**	**n/Σ(1/Ki)**
	m/day	m/day	m/day	m/day
FT11-0.5-1	5.76E+00	5.676E+00	1.754E+04	3.650E-02
FT11-0.5-2	7.80E+00	6.264E+01	1.020E+04	1.710E-03
FT11-0.5-3	9.24E+00	8.009E+00	1.158E+04	4.180E-03
FT11-0.5-4	1.25E+01	1.201E+01	1.823E+04	4.290E-02
FT11-0.5-5	1.01E+01	1.020E+01	2.065E+04	6.750E-02
FT11-0.5-6	1.03E+01	1.020E+01	1.503E+04	1.810E-02
AVG	9.29E+00	1.81E+01	1.554E+04	2.85E-02
STD	2.31E+00	2.19E+01	4.046E+03	2.53E-02
FT11-1-3	2.51E+01	3.292E+01	2.687E+01	2.630E-04
FT12-0.5-1	8.64E+00	5.797E+00	9.936E+03	1.480E-03
FT12-0.5-2	1.04E+01	1.106E+01	1.909E+04	5.140E-02
FT12-0.5-3	1.05E+01	1.097E+01	1.953E+04	5.540E-02
FT12-0.5-4	1.05E+01	8.986E+00	1.279E+04	7.630E-03
AVG	9.98E+00	9.20E+00	1.53E+04	2.90E-02
STD	8.94E-01	2.46E+00	4.74E+03	2.84E-02
FT12-1-1	5.75E+00	5.737E+00	5.685E+00	5.930E-05
FT12-1-2	5.30E+00	5.072E+00	5.201E+00	5.930E-05
FT12-1-3	7.08E+00	8.113E+00	7.491E+00	8.480E-05
FT12-1-4	1.31E+01	1.149E+01	1.538E+01	1.450E-04
AVG	7.82E+00	7.60E+00	8.44E+00	8.71E-05
STD	3.62E+00	2.90E+00	4.73E+00	4.04E-05
FT21-0.5-1	6.34E+00	6.540E+00	6.575E+00	7.530E-05
FT21-0.5-2	6.83E+00	6.281E+00	6.558E+00	7.510E-05
FT21-0.5-3	6.77E+00	6.463E+00	6.722E+00	7.700E-05
FT21-0.5-4	7.18E+00	7.992E+00	7.517E+00	8.600E-05
FT21-0.5-5	6.69E+00	6.100E+00	6.376E+00	7.300E-05
AVG	6.76E+00	6.68E+00	6.75E+00	7.73E-05
STD	3.00E-01	7.56E-01	4.46E-01	5.08E-06
FT21-1-1	1.20E+01	1.106E+01	1.210E+01	1.360E-04
FT21-1-2	1.55E+01	1.296E+01	1.564E+01	1.640E-04
FT21-1-3	1.47E+01	1.313E+01	1.512E+01	1.670E-04
FT21-1-4	1.65E+01	1.279E+01	1.572E+01	1.680E-04
FT21-1-5	1.46E+01	1.322E+01	1.443E+01	1.630E-04
AVG	1.47E+01	1.26E+01	1.46E+01	1.60E-04
STD	1.66E+00	8.95E-01	1.49E+00	1.34E-05
FT22-0.5-1	5.91E+00	6.195E+00	6.428E+00	7.140E-05
FT22-0.5-2	5.32E+00	5.659E+00	5.633E+00	6.420E-05
FT22-0.5-3	5.37E+00	5.262E+00	5.737E+00	6.380E-05
FT22-0.5-4	6.40E+00	6.592E+00	6.998E+00	7.700E-05
AVG	5.75E+00	5.93E+00	6.20E+00	6.91E-05
STD	5.10E-01	5.86E-01	6.39E-01	6.32E-06
FT22-1-1	1.44E+01	1.158E+01	1.901E+01	1.550E-04
FT22-1-2	7.52E+00	7.042E+00	7.500E+00	8.550E-05
FT22-1-3	1.24E+01	1.305E+01	1.348E+01	1.510E-04
FT22-1-4	9.85E+00	1.037E+01	1.080E+01	1.190E-04
FT22-1-5	2.51E+01	1.624E+01	2.773E+01	2.170E-04
FT22-1-6	9.59E+00	9.936E+00	1.020E+01	1.150E-04
AVG	1.31E+01	1.14E+01	1.48E+01	1.40E-04
STD	6.31E+00	3.11E+00	7.45E+00	4.54E-05
FT31-0.5-1	3.34E+00	3.948E+00	3.758E+00	4.110E-05
FT31-0.5-2	3.19E+00	3.499E+00	3.707E+00	3.940E-05
FT31-0.5-3	3.40E+00	3.534E+00	3.646E+00	4.030E-05
AVG	3.31E+00	3.66E+00	3.70E+00	4.03E-05
STD	1.08E-01	2.50E-01	5.62E-02	8.50E-07
FT31-1-1	6.61E+00	7.932E+00	7.154E+00	8.130E-05
FT31-1-2	5.95E+00	6.800E+00	6.420E+00	7.310E-05
FT31-1-3	5.74E+00	6.394E+00	6.134E+00	7.030E-05

AVG	6.10E+00	7.04E+00	6.57E+00	7.49E-05
STD	4.54E-01	7.97E-01	5.26E-01	5.72E-06
FT32-0.5-1	5.33E+00	5.728E+00	5.659E+00	6.100E-05
FT32-0.5-2	5.75E+00	6.437E+00	6.100E+00	5.720E-05
FT32-0.5-3	4.65E+00	5.020E+00	4.994E+00	5.650E-05
AVG	5.24E+00	5.73E+00	5.58E+00	5.82E-05
STD	5.58E-01	7.08E-01	5.57E-01	2.42E-06
FT32-1-1	2.33E+00	2.592E+00	2.860E-05	2.860E-05
FT32-1-2	2.13E+00	2.264E+00	2.570E-05	2.570E-05
FT32-1-3	3.13E+00	3.180E+00	3.660E-05	3.660E-05
AVG	2.53E+00	2.68E+00	3.03E-05	3.03E-05
STD	5.29E-01	4.64E-01	5.65E-06	5.65E-06
FT41-0.5-1	4.07E+01	4.121E+01	4.113E+01	4.700E-04
FT41-0.5-2	3.91E+01	3.758E+01	3.862E+01	4.430E-04
FT41-0.5-3	3.98E+01	3.810E+01	3.931E+01	4.500E-04
AVG	3.99E+01	3.90E+01	3.97E+01	4.54E-04
STD	7.79E-01	1.96E+00	1.29E+00	1.40E-05
FT41-1-1	2.80E+00	3.413E+00	2.877E+00	3.010E-05
FT41-1-2	4.54E+00	5.296E+00	4.933E+00	5.300E-05
FT41-1-3	1.19E+00	1.417E+00	1.331E+00	1.490E-05
FT41-1-4	2.01E+00	2.480E+00	2.272E+00	2.520E-05
AVG	2.64E+00	3.15E+00	2.85E+00	3.08E-05
STD	1.43E+00	1.65E+00	1.53E+00	1.61E-05
FT42-0.5-1	5.64E+01	6.420E+01	6.013E+01	6.820E-04
FT42-0.5-2	3.60E+01	3.309E+01	3.482E+01	4.010E-04
FT42-0.5-3	3.74E+01	2.756E+01	3.266E+01	3.630E-04
AVG	4.33E+01	4.16E+01	4.25E+01	4.82E-04
STD	1.14E+01	1.97E+01	1.53E+01	1.74E-04
FT42-1-1	4.07E+01	3.983E+01	4.078E+01	4.690E-04
FT42-1-2	4.47E+01	3.810E+01	3.819E+01	4.390E-04
FT42-1-3	3.68E+01	3.681E+01	3.776E+01	4.330E-04
FT42-1-4	3.57E+01	3.465E+01	3.534E+01	4.080E-04
AVG	3.95E+01	3.73E+01	3.80E+01	4.37E-04
STD	4.08E+00	2.19E+00	2.23E+00	2.51E-05
FT51-0.5-1	7.72E+01	9.072E+01	8.441E+01	9.540E-04
FT51-0.5-2	6.74E+01	7.396E+01	6.584E+01	7.530E-04
FT51-0.5-3	6.80E+01	7.430E+01	7.197E+01	8.210E-04
AVG	7.08E+01	7.97E+01	7.41E+01	8.43E-04
STD	5.47E+00	9.58E+00	9.46E+00	1.02E-04
FT51-1-1	7.21E+01	6.964E+01	7.163E+01	8.260E-04
FT51-1-2	7.00E+01	6.972E+01	7.042E+01	8.130E-04
FT51-1-3	7.82E+00	7.551E+01	7.785E+01	8.940E-04
AVG	5.00E+01	7.16E+01	7.33E+01	8.44E-04
STD	3.65E+01	3.37E+00	3.99E+00	4.35E-05
FT52-0.5-1	6.55E+01	6.152E+01	6.402E+01	7.380E-04
FT52-0.5-2	6.84E+01	5.098E+01	5.918E+01	6.650E-04
FT52-0.5-3	6.72E+01	5.875E+01	6.489E+01	7.460E-04
AVG	6.70E+01	5.71E+01	6.27E+01	7.16E-04
STD	1.48E+00	5.47E+00	3.07E+00	4.46E-05
FT52-1-1	6.54E+01	5.901E+01	6.238E+01	7.170E-04
FT52-1-2	5.08E+01	5.737E+01	5.452E+01	6.020E-04
FT52-1-3	2.91E+02	3.309E+02	3.119E+02	3.310E-03
AVG	1.36E+02	1.49E+02	1.43E+02	1.54E-03
STD	1.35E+02	1.57E+02	1.46E+02	1.53E-03
FT61-0.5-1	1.00E+01	9.936E+00	1.020E+01	1.120E-04
FT61-0.5-2	1.03E+01	9.245E+00	1.089E+01	1.170E-04
FT61-0.5-3	1.03E+01	1.045E+01	1.123E+01	1.210E-04
AVG	1.02E+01	9.88E+00	1.08E+01	1.17E-04
STD	1.50E-01	6.07E-01	5.28E-01	4.51E-06

FT61-1-1	9.24E+00	1.028E+01	1.002E+01	1.110E-04
FT61-1-2	9.94E+00	9.936E+00	1.080E+01	1.160E-04
FT61-1-3	1.03E+01	9.245E+00	1.089E+01	1.170E-04
AVG	9.82E+00	9.82E+00	1.06E+01	1.15E-04
STD	5.28E-01	5.28E-01	4.76E-01	3.21E-06
FT62-0.5-1	1.54E+01	1.668E+01	1.624E+01	1.830E-04
FT62-0.5-2	1.53E+01	1.175E+01	1.356E+01	1.510E-04
Ft62-0.5-3	1.49E+01	1.365E+01	1.426E+01	1.630E-04
AVG	1.52E+01	1.40E+01	1.47E+01	1.66E-04
STD	2.78E-01	2.48E+00	1.39E+00	1.62E-05
FT62-1-1	1.59E+01	9.504E+00	1.365E+01	1.380E-04
FT62-1-2	1.93E+01	1.400E+01	1.426E+01	1.620E-04
FT62-1-3	1.46E+01	1.486E+01	1.503E+01	1.700E-04
FT62-1-4	1.28E+01	1.218E+01	1.287E+01	1.43E-04
AVG	1.56E+01	1.26E+01	1.40E+01	1.53E-04
STD	2.73E+00	2.37E+00	9.16E-01	1.52E-05

Appendix B Estimation of K from four empirical formulas, Bertrand Creek and Fishtrap Creek, Washington State, USA: Examples

Bertrand Creek

K	Hydraulic Conductivity		
C	100–150		
d_{10}	Effective Grain Size Diameter where 10 % of particles are finer in cm		
k	Permeability in cm^2		
ρ_w	Density of Water	1000 kg/m^3	
g	Acceleration due to gravity		
μ	Viscosity of water	$0.001002\ N\ s/m^2$	at 20°C
n	Porosity		
s	log standard deviation of geometric mean diameter		
	Conversion to *K*	$K=k*\rho_w \times g/\mu$	

BC1-149

Hazen $K=Cd_{102}$

C $(cm/s)^{-1}$	$\boldsymbol{d_{10\ (cm)}}$	***K*** (cm/s)	**m/s**	**m/day**
100.000	0.023	0.053	5.291E-04	4.571E+01

Harleman $k=(6.54*10^{-4})d_{102}$ $K=k*\rho_w*g / \mu$

$\boldsymbol{d_{10\ (cm)}}$	***k* (cm2)**	***K* (cm/s)**	**m/s**	**m/day**
0.023	3.460E-07	0.034	3.388E-04	2.927E+01

Krumbien and Monk $k= 760 *d^2e^{-1.31\sigma}$

d geometric mean (mm)	σ (mm)	***k*** (darcy)	***K* (cm/s)**	**m/s**	**m/day**
1.136	0.238	718.471	0.691	0.007	5.969E+02

Kozeny-Carmen Bear $K=(\rho_w g/\mu) * (n^3/(1-n)^2) * (d^{2m}/180)$

Used Geometric Mean

n = f	***d* (cm)**	***K* (cm/s)**	**m/s**	**m/day**
0.351	0.114	7.243E-01	7.243E-03	6.258E+02

Fishtarap Creek

FT1-20

Hazen $K=Cd_{102}$

C $(cm/s)^{-1}$	**d** $_{\mathbf{10\ (cm)}}$	**K** (cm/s)	**m/s**	**m/day**
100.000	0.010	0.009	9.300E-05	8.035E+00

Harleman			$k=(6.54*10^{-4})d_{102}$		$K=k*\rho_w*g/\mu$	
		$d_{10\ (cm)}$	**k (cm2)**	**K (cm/s)**	**m/s**	**m/day**
		0.010	6.082E-08	0.006	5.955E-05	5.145E+00
Krumbien and Monk				$k= 760 *d^2e^{-1.31\sigma}$		
	d geometric mean (mm)	σ (mm)	**k** (darcy)	**K (cm/s)**	**m/s**	**m/day**
	0.394	0.243	85.673	0.082	0.001	7.117E+01
Kozeny-Carmen Bear				$K=(\rho_w g/\mu) * (n^3/(1-n)^2) * (d^{2m}/180)$		
		Used Geometric Mean				
	n = *f*	**d (cm)**		**K (cm/s)**	**m/s**	**m/day**
	0.322	0.039		6.139E-02	6.139E-04	5.304E+01

Estimated K for streambeds of Bertrand and Fishtrap Creek.

Site #	**Hazen (m/day)**	**Harleman (m/day)**	**Krumbien and Monk (m/day)**	**Kozeny-Carmen (m/day)**
1-Avg	28.01	17.94	33.17	50.67
1-1	31.95	20.46	35.30	48.66
1-2	25.50	16.33	28.80	54.48
1-3	26.79	17.15	35.73	65.85
				39.85
Avg K	28.08	17.98	33.28	56.33
Std	3.41	2.19	3.89	8.75
2-Avg	33.17	21.23	804.27	103.35
2-1	31.95	20.46	834.45	107.32
2-2	31.22	20.00	354.27	9.63
2-3	36.40	23.29	772.56	
Avg K	33.19	21.25	653.76	58.48
Std	2.81	1.78	261.21	69.07
3-Avg	1034.45	67.77	804.27	
3-1	31.95	20.46	1014.94	
3-2	76.25	48.84	1021.34	
3-3	261.04	50.95	26.88	
K Avg	123.08	40.08	687.72	
Std	121.51	17.02	572.31	
4-Avg	247.99	48.41	33.93	
4-1	31.95	20.46	2673.48	
4-2	391.16	76.34	2942.07	
4-3	475.91	92.90	3076.22	

K-Avg	299.67	63.23	2897.26	
Std	235.70	37.95	205.08	
5-Avg	11.83	6.60	40.49	83.17
5-1	31.95	20.46	69.57	159.51
5-2	1.83	1.17	31.83	77.77
5-3	6.89	4.41	26.31	59.12
5-4				36.65
K-Avg	13.56	8.68	42.57	83.26
Std	16.13	10.33	23.55	53.54
6-Avg	34.79	22.27	545.73	701.52
6-1	31.95	20.46	461.89	2140.55
6-2	40.85	26.17	709.15	1101.83
6-3	31.86	20.40	482.93	316.46
6-4				227.59
K-Avg	34.89	22.34	551.32	946.61
Std	5.17	3.31	137.08	887.63
7-Avg	49.85	31.92	1000.00	2031.10
7-1	31.95	20.46	1429.57	4868.90
7-2	79.85	51.13	892.07	2239.63
7-3	43.48	27.84	741.16	1592.38
7-4				644.82
K-Avg	51.76	33.14	1020.93	2336.43
Std	25.00	16.01	361.85	1810.89

Appendix C Comparison of Means of K from the Instream Slug Tests Using the GLM Procedure in SAS

Comparison of means of K for the 0.5-m and 1.0-m depths for Bertrand Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\BCSLUG.PRN';
INPUT SITE DEPTH $ K @@;
PROC PRINT;
PROC GLM;
CLASS SITE DEPTH;
MODEL K = SITE DEPTH SITE*DEPTH;
MEANS DEPTH/TUKEY ALPHA=0.01;
MEANS DEPTH/TUKEY;
MEANS DEPTH/TUKEY ALPHA=0.1;
RUN;
```

SAS results

```
Obs    SITE    DEPTH       K

  1      1      0.5      0.13
  2      1      0.5      0.37
  3      1      0.5      1.06
  4      1      0.5      1.44
  5      1      1.0    280.37
  6      1      1.0     15.12
  7      1      1.0     16.33
  8      1      0.5     25.49
  9      1      0.5     15.64
 10      1      0.5     16.85
 11      2      0.5    472.61
 12      2      0.5    282.53
 13      2      0.5    297.22
 14      2      1.0     91.58
 15      2      1.0     91.58
 16      2      1.0     91.58
 17      2      0.5    105.41
 18      2      0.5    100.22
 19      2      0.5     93.31
 20      2      1.0     27.65
 21      2      1.0     28.43
 22      2      1.0     25.83
 23      3      0.5     22.03
 24      3      0.5     75.34
 25      3      0.5     56.94
 26      3      0.5     82.60
 27      3      1.0    140.83
 28      3      1.0    113.18
 29      3      1.0     16.93
 30      3      0.5     78.97
```

31	3	0.5	73.87
32	3	0.5	70.93
33	3	1.0	18.75
34	3	1.0	18.32
35	3	1.0	19.61
36	3	1.0	19.79
37	4	0.5	38.97
38	4	0.5	45.88
39	4	0.5	32.75
40	4	0.5	27.82
41	4	1.0	15.81
42	4	1.0	3.10
43	4	1.0	3.94
44	4	0.5	12.01
45	4	0.5	12.44
46	4	0.5	12.96
47	4	0.5	13.65
48	4	1.0	28.25
49	4	1.0	5.70
50	4	1.0	3.43
51	4	1.0	3.02
52	5	0.5	54.26
53	5	0.5	57.72
54	5	0.5	49.94
55	5	1.0	114.91
56	5	1.0	136.51
57	5	1.0	114.91
58	5	0.5	60.57
59	5	0.5	62.73
60	5	0.5	62.73
61	5	1.0	146.88
62	5	1.0	129.60
63	5	1.0	131.33
64	6	0.5	85.19
65	6	0.5	72.84
66	6	0.5	47.09
67	6	0.5	81.56
68	6	1.0	92.45
69	6	1.0	81.13
70	6	1.0	65.23
71	6	1.0	66.27
72	6	0.5	69.47
73	6	0.5	59.44
74	6	0.5	67.48
75	6	1.0	15.81
76	6	1.0	18.84
77	6	1.0	17.54
78	6	1.0	15.47
79	7	0.5	178.85
80	7	0.5	173.66
81	7	0.5	180.58
82	7	1.0	57.72
83	7	1.0	66.36
84	7	1.0	69.03
85	7	0.5	7.88

```
                    86          7        1.0     0.43
                    87          7        1.0     1.31
                    88          7        1.0    24.62

                      Class Level Information

                  Class       Levels    Values
                  SITE             7    1 2 3 4 5 6 7
                  DEPTH            2    0.5 1

                 Number of Observations Read        88
                 Number of Observations Used        88

Dependent Variable: K
                                 Sum of
     Source              DF       Squares    Mean Square   F Value   Pr > F
     Model               13   269572.9467     20736.3805      6.72   <.0001
     Error               74   228442.8137      3087.0650
     Corrected Total     87   498015.7603

               R-Square    Coeff Var     Root MSE      K Mean
               0.541294     83.05546     55.56136    66.89670

     Source              DF     Type I SS    Mean Square   F Value   Pr > F

     SITE                 6   125893.1626     20982.1938      6.80   <.0001
     DEPTH                1    12563.7539     12563.7539      4.07   0.0473
     SITE*DEPTH           6   131116.0302     21852.6717      7.08   <.0001

                 Tukey's Studentized Range (HSD) Test for K

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II error rate than
REGWQ.


                Alpha                                     0.01
                Error Degrees of Freedom                  74
                Error Mean Square                         3087.065
                Critical Value of Studentized Range       3.73910
                Minimum Significant Difference            31.328
                Harmonic Mean of Cell Sizes               43.97727

                    NOTE: Cell sizes are not equal.

             Means with the same letter are not significantly different.


             Tukey Grouping        Mean     N    DEPTH

                   A                  76.48     45   0.5
                   A                  56.87     43   1
```

Comparison of means of K for the 0.5-m and 1.0-m depths for Fishtrap Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\FTSLUG.PRN';
INPUT SITE DEPTH $ K @@;
PROC PRINT;
PROC GLM;
CLASS SITE DEPTH;
MODEL K = SITE DEPTH SITE*DEPTH;
MEANS DEPTH/TUKEY ALPHA=0.01;
MEANS DEPTH/TUKEY;
MEANS DEPTH/TUKEY ALPHA=0.1;
RUN;
```

SAS results

```
                    Obs    SITE    DEPTH      K

                     1             1        0.5      5.68
                     2             1        0.5     62.64
                     3             1        0.5      8.01
                     4             1        0.5     12.01
                     5             1        0.5     10.20
                     6             1        0.5     10.20
                     7             1        0.5      5.80
                     8             1        0.5     11.06
                     9             1        0.5     10.97
                    10             1        0.5      8.99
                    11             1        1       5.74
                    12             1        1       5.07
                    13             1        1       8.11
                    14             1        1      11.49
                    15             2        0.5      6.54
                    16             2        0.5      6.28
                    17             2        0.5      6.46
                    18             2        0.5      7.99
                    19             2        0.5      6.10
                    20             2        1      11.06
                    21             2        1      12.96
                    22             2        1      13.13
                    23             2        1      12.79
                    24             2        1      13.22
                    25             2        0.5      6.19
                    26             2        0.5      5.66
                    27             2        0.5      5.26
                    28             2        0.5      6.59
                    29             2        1      11.58
                    30             2        1       7.04
                    31             2        1      13.05
                    32             2        1      10.37
                    33             2        1      16.24
                    34             2        1       9.94
                    35             3        0.5      3.95
                    36             3        0.5      3.50
                    37             3        0.5      3.53
                    38             3        1       7.93
                    39             3        1       6.80
```

```
     40          3          1       6.39
     41          3          0.5      5.73
     42          3          0.5      6.44
     43          3          0.5      5.02
     44          3          1       2.59
     45          3          1       2.26
     46          3          1       3.18
     47          4          0.5     41.21
     48          4          0.5     37.58
     49          4          0.5     38.10
     50          4          1       3.41
     51          4          1       5.30
     52          4          1       1.42
     53          4          1        2.48
     54          4          0.5      64.20
     55          4          0.5      33.09
     56          4          0.5      27.56
     57          4          1       39.83
     58          4          1       38.10
     59          4          1       36.81
     60          4          1       34.65
     61          5          0.5      90.72
     62          5          0.5      73.96
     63          5          0.5      74.30
     64          5          1       69.64
     65          5          1       69.72
     66          5          1       75.51
     67          5          0.5      61.52
     68          5          0.5      50.98
     69          5          0.5      58.75
     70          5          1       59.01
     71          5          1       57.37
     72          5          1      330.91
     73          6          0.5       9.94
     74          6          0.5       9.24
     75          6          0.5      10.45
     76          6          1       10.28
     77          6          1        9.94
     78          6          1        9.24
     79          6          0.5      16.68
     80          6          0.5      11.75
     81          6          0.5      13.65
     82          6          1        9.50
     83          6          1       14.00
     84          6          1       14.86
     85          6          1       12.18

      Class Level Information
   Class       Levels    Values
   SITE             6     1 2 3 4 5 6
   DEPTH            2      0.5 1

 Number of Observations Read         85
 Number of Observations Used         85
```

```
Dependent Variable: K
                                        Sum of
        Source                  DF         Squares     Mean Square    F Value    Pr > F
        Model                   11        71049.5951       6459.0541       7.19    <.0001
        Error                   73        65583.0681        898.3982
        Corrected Total         84       136632.6633

                    R-Square     Coeff Var      Root MSE        K Mean
                    0.520004      124.3050      29.97329      24.11271

        Source                  DF       Type I SS     Mean Square    F Value    Pr > F

        SITE                     5     64089.13268     12817.82654      14.27    <.0001
        DEPTH                    1       199.64322       199.64322       0.22    0.6388
        SITE*DEPTH               5      6760.81923      1352.16385      1.51    0.1988

                        Tukey's Studentized Range (HSD) Test for K

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II error rate than
REGWQ.


                         Alpha                                       0.01
                         Error Degrees of Freedom                    73
                         Error Mean Square                           898.3982
                         Critical Value of Studentized Range         3.74045
                         Minimum Significant Difference              17.199
                         Harmonic Mean of Cell Sizes                 42.49412

                              NOTE: Cell sizes are not equal

                  Means with the same letter are not significantly different

                  Tukey Grouping          Mean      N    DEPTH

                            A                       26.074     42    1
                            A                       22.197     43    0.5
```

Comparison of means of K between Bertrand Creek and Fishtrap Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\SLUG.PRN';
INPUT REACH SITE DEPTH $ K @@;
PROC PRINT;
PROC GLM;
CLASS REACH DEPTH;
MODEL K = REACH DEPTH REACH*DEPTH;
MEANS DEPTH/TUKEY ALPHA=0.01;
MEANS DEPTH/TUKEY;
MEANS DEPTH/TUKEY ALPHA=0.1;
RUN;
```

SAS results

Obs	REACH	SITE	DEPTH	K
1	BC	1	0.5	0.13
2	BC	1	0.5	0.37
3	BC	1	0.5	1.06
4	BC	1	0.5	1.44
5	BC	1	1.0	280.37
6	BC	1	1.0	15.12
7	BC	1	1.0	16.33
8	BC	1	0.5	25.49
9	BC	1	0.5	15.64
10	BC	1	0.5	16.85
11	BC	2	0.5	472.61
12	BC	2	0.5	282.53
13	BC	2	0.5	297.22
14	BC	2	1.0	91.58
15	BC	2	1.0	91.58
16	BC	2	1.0	91.58
17	BC	2	0.5	105.41
18	BC	2	0.5	100.22
19	BC	2	0.5	93.31
20	BC	2	1.0	27.65
21	BC	2	1.0	28.43
22	BC	2	1.0	25.83
23	BC	3	0.5	22.03
24	BC	3	0.5	75.34
25	BC	3	0.5	56.94
26	BC	3	0.5	82.60
27	BC	3	1.0	140.83
28	BC	3	1.0	113.18
29	BC	3	1.0	16.93
30	BC	3	0.5	78.97
31	BC	3	0.5	73.87
32	BC	3	0.5	70.93
33	BC	3	1.0	18.75
34	BC	3	1.0	18.32
35	BC	3	1.0	19.61
36	BC	3	1.0	19.79
37	BC	4	0.5	38.97
38	BC	4	0.5	45.88
39	BC	4	0.5	32.75
40	BC	4	0.5	27.82
41	BC	4	1.0	15.81
42	BC	4	1.0	3.10
43	BC	4	1.0	3.94
44	BC	4	0.5	12.01
45	BC	4	0.5	12.44
46	BC	4	0.5	12.96
47	BC	4	0.5	13.65
48	BC	4	1.0	28.25
49	BC	4	1.0	5.70
50	BC	4	1.0	3.43
51	BC	4	1.0	3.02
52	BC	5	0.5	54.26
53	BC	5	0.5	57.72

54	BC	5	0.5	49.94
55	BC	5	1.0	114.91
56	BC	5	1.0	136.51
57	BC	5	1.0	114.91
58	BC	5	0.5	60.57
59	BC	5	0.5	62.73
60	BC	5	0.5	62.73
61	BC	5	1.0	146.88
62	BC	5	1.0	129.60
63	BC	5	1.0	131.33
64	BC	6	0.5	85.19
65	BC	6	0.5	72.84
66	BC	6	0.5	47.09
67	BC	6	0.5	81.56
68	BC	6	1.0	92.45
69	BC	6	1.0	81.13
70	BC	6	1.0	65.23
71	BC	6	1.0	66.27
72	BC	6	0.5	69.47
73	BC	6	0.5	59.44
74	BC	6	0.5	67.48
75	BC	6	1.0	15.81
76	BC	6	1.0	18.84
77	BC	6	1.0	17.54
78	BC	6	1.0	15.47
79	BC	7	0.5	178.85
80	BC	7	0.5	173.66
81	BC	7	0.5	180.58
82	BC	7	1.0	57.72
83	BC	7	1.0	66.36
84	BC	7	1.0	69.03
85	BC	7	0.5	7.88
86	BC	7	1.0	0.43
87	BC	7	1.0	1.31
88	BC	7	1.0	24.62
89	FT	1	0.5	5.68
90	FT	1	0.5	62.64
91	FT	1	0.5	8.01
92	FT	1	0.5	12.01
93	FT	1	0.5	10.20
94	FT	1	0.5	10.20
95	FT	1	0.5	5.80
96	FT	1	0.5	11.06
97	FT	1	0.5	10.97
98	FT	1	0.5	8.99
99	FT	1	1.0	5.74
100	FT	1	1.0	5.07
101	FT	1	1.0	8.11
102	FT	1	1.0	11.49
103	FT	2	0.5	6.54
104	FT	2	0.5	6.28
105	FT	2	0.5	6.46
106	FT	2	0.5	7.99
107	FT	2	0.5	6.10
108	FT	2	1.0	11.06

109	FT	2	1.0	12.96
110	FT	2	1.0	13.13
111	FT	2	1.0	12.79
112	FT	2	1.0	13.22
113	FT	2	0.5	6.19
114	FT	2	0.5	5.66
115	FT	2	0.5	5.26
116	FT	2	0.5	6.59
117	FT	2	1.0	11.58
118	FT	2	1.0	7.04
119	FT	2	1.0	13.05
120	FT	2	1.0	10.37
121	FT	2	1.0	16.24
122	FT	2	1.0	9.94
123	FT	3	0.5	3.95
124	FT	3	0.5	3.50
125	FT	3	0.5	3.53
126	FT	3	1.0	7.93
127	FT	3	1.0	6.80
128	FT	3	1.0	6.39
129	FT	3	0.5	5.73
130	FT	3	0.5	6.44
131	FT	3	0.5	5.02
132	FT	3	1.0	2.59
133	FT	3	1.0	2.26
134	FT	3	1.0	3.18
135	FT	4	0.5	41.21
136	FT	4	0.5	37.58
137	FT	4	0.5	38.10
138	FT	4	1.0	3.41
139	FT	4	1.0	5.30
140	FT	4	1.0	1.42
141	FT	4	1.0	2.48
142	FT	4	0.5	64.20
143	FT	4	0.5	33.09
144	FT	4	0.5	27.56
145	FT	4	1.0	39.83
146	FT	4	1.0	38.10
147	FT	4	1.0	36.81
148	FT	4	1.0	34.65
149	FT	5	0.5	90.72
150	FT	5	0.5	73.96
151	FT	5	0.5	74.30
152	FT	5	1.0	69.64
153	FT	5	1.0	69.72
154	FT	5	1.0	75.51
155	FT	5	0.5	61.52
156	FT	5	0.5	50.98
157	FT	5	0.5	58.75
158	FT	5	1.0	59.01
159	FT	5	1.0	57.37
160	FT	5	1.0	330.91
161	FT	6	0.5	9.94
162	FT	6	0.5	9.24
163	FT	6	0.5	10.45

```
                 164   FT      6     1.0     10.28
                 165   FT      6     1.0      9.94
                 166   FT      6     1.0      9.24
                 167   FT      6     0.5     16.68
                 168   FT      6     0.5     11.75
                 169   FT      6     0.5     13.65
                 170   FT      6     1.0      9.50
                 171   FT      6     1.0     14.00
                 172   FT      6     1.0     14.86
                 173   FT      6     1.0     12.18

                     Class Level Information
                   Class       Levels   Values
                   REACH           2    BC FT
                   DEPTH           2   0.5 1

                 Number of Observations Read        173
                 Number of Observations Used        173

Dependent Variable: K
                               Sum of
   Source                DF        Squares     Mean Square   F Value   Pr > F
   Model                  3     87914.4607      29304.8202      7.91   <.0001
   Error                169    625878.0071       3703.4202
   Corrected Total      172    713792.4678

             R-Square    Coeff Var     Root MSE       K Mean
             0.123165     132.6536     60.85573     45.87566

   Source                DF      Type I SS     Mean Square   F Value   Pr > F

   REACH                  1    79144.04423     79144.04423     21.37   <.0001
   DEPTH                  1     2812.49135      2812.49135      0.76   0.3847
   REACH*DEPTH            1     5957.92517      5957.92517      1.61   0.2064

                 Tukey's Studentized Range (HSD) Test for K

 NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher
                   Type II error rate than REGWQ.

                Alpha                                   0.01
                Error Degrees of Freedom               169
                Error Mean Square                       3703.42
                Critical Value of Studentized Range     3.68452
                Minimum Significant Difference         24.112
                Harmonic Mean of Cell Sizes            86.47399

                   NOTE: Cell sizes are not equal.
              Means with the same letter are not significantly different.
              Tukey Grouping          Mean      N    REACH

                   A                66.897     88    BC
                   B                24.113     85    FT
```

Appendix D Comparison of Means of *K* from Empirical Formulas Using the GLM Procedure in SAS

Comparison of means of K from Hazen, Harleman, and Krumbien and Monk equations for the streamed surface samples for Bertrand Creek.

SAS Codes

```
DATA A;
INFILE 'C:\JOAN\CM\BSREMP.PRN';
INPUT SITE METHOD $ K @@;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = SITE METHOD SITE*METHOD;
MEANS METHOD/TUKEY ALPHA=0.01;
MEANS METHOD/TUKEY;
MEANS METHOD/TUKEY ALPHA=0.1;
RUN;
```

SAS results

```
Obs            SITE   METHOD        K
   1            1       HAZ         21.57
   2            1       HAZ         29.59
   3            1       HAZ         26.79
   4            1       HAR         13.81
   5            1       HAR         18.95
   6            1       HAR         17.15
   7            1       KM          37.37
   8            1       KM          36.61
   9            1       KM          38.51
  10            2       HAZ         31.97
  11            2       HAZ         31.23
  12            2       HAZ         36.42
  13            2       HAR         20.47
  14            2       HAR         20.00
  15            2       HAR         23.32
  16            2       KM          889.20
  17            2       KM          765.10
  18            2       KM          905.50
  19            5       HAZ         9.31
  20            5       HAZ         9.63
  21            5       HAZ         13.79
  22            5       HAR         5.96
  23            5       HAR         6.17
  24            5       HAR         8.83
  25            5       KM          73.44
  26            5       KM          84.48
  27            5       KM          88.74
  28            6       HAZ          31.96
  29            6       HAZ         40.87
  30            6       HAZ         31.86
  31            6       HAR         20.46
```

```
                 32          6         HAR            26.17
                 33          6         HAR            20.40
                 34          6         KM             490.80
                 35          6         KM             1049.00
                 36          6         KM             626.60
                 37          7         HAZ            64.78
                 38          7         HAZ            79.69
                 39          7         HAZ            43.48
                 40          7         HAR            41.48
                 41          7         HAR            51.02
                 42          7         HAR            27.84
                 43          7         KM             1522.00
                 44          7         KM             1698.00
                 45          7         KM             780.30
                 Class      Levels   Values
               SITE           5      1 2 5 6 7
               METHOD         3       HAR HAZ KM

Dependent Variable: K
                             Sum of
     Source            DF        Squares        Mean Square  F Value    Pr > F
     Model             14    6954355.118     496739.651      22.68    <.0001
     Error             30     656921.604      21897.387

     Corrected Total   44    7611276.722

               R-Square     Coeff Var     Root MSE       K Mean

               0.913691      67.19049      147.9777      220.2360

     Source            DF      Type I SS     Mean Square    F Value    Pr > F

     SITE               4     1327836.235     331959.059      15.16     <.0001
     METHOD             2     3344370.553    1672185.276      76.36     <.0001
     SITE*METHOD        8     2282148.331     285268.541      13.03     <.0001


                        Tukey's Studentized Range (HSD) Test for K

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II error rate than
REGWQ.

                 Alpha                                     0.01
                 Error Degrees of Freedom                  30
                 Error Mean Square                        21897.39
                 Critical Value of Studentized Range       4.45446
                 Minimum Significant Difference            170.19

            Means with the same letter are not significantly different.

            Tukey Grouping         Mean      N    METHOD

                A                605.71     15     KM
                B                 33.53     15     HAZ
                B                 21.47     15     HAR
```

Comparison of means of K from Hazen, Harleman, and Krumbien and Monk equations for the streamed surface samples for Fishtrap Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\FTSREMP.PRN';
INPUT SITE METHOD $ K @@;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = SITE METHOD SITE*METHOD;
MEANS METHOD/TUKEY ALPHA=0.01;
MEANS METHOD/TUKEY;
MEANS METHOD/TUKEY ALPHA=0.1;
RUN;
```

SAS results

```
Obs   SITE   METHOD      K

  1    1      HAZ      39.30
  2    1      HAZ      54.46
  3    1      HAZ      42.02
  4    1      HAR      25.16
  5    1      HAR      34.87
  6    1      HAR      26.91
  7    1      KM      896.90
  8    1      KM     1298.00
  9    1      KM      885.40
 10    3      HAZ      31.96
 11    3      HAZ      19.65
 12    3      HAZ      14.68
 13    3      HAR      20.46
 14    3      HAR      12.58
 15    3      HAR       9.40
 16    3      KM      313.90
 17    3      KM      619.00
 18    3      KM      591.00
 19    4      HAZ      96.35
 20    4      HAZ      77.48
 21    4      HAZ      90.82
 22    4      HAR      61.69
 23    4      HAR      49.61
 24    4      HAR      58.15
 25    4      KM     2954.00
 26    4      KM     2386.00
 27    4      KM     2719.00
 28    5      HAZ      25.76
 29    5      HAZ      59.07
 30    5      HAZ      33.67
 31    5      HAR      16.49
 32    5      HAR      37.82
```

```
                     33   5          HAR       21.56
                     34   5          KM       704.50
                     35   5          KM      1761.00
                     36   5          KM      1244.00
                     37   6          HAZ       56.24
                     38   6          HAZ       84.26
                     39   6          HAZ       38.39
                     40   6          HAR       36.01
                     41   6          HAR       53.95
                     42   6          HAR       24.58
                     43   6          KM      1600.00
                     44   6          KM      2635.00
                     45   6          KM       989.90

                    Class        Levels    Values
                    SITE              5      1 3 4 5 6
                    METHOD            3     HAR HAZ KM

                  Number of Observations Read          45
                  Number of Observations Used          45
Dependent Variable: K

                                  Sum of
       Source                DF        Squares       Mean Square    F Value    Pr > F
       Model                 14    27734258.41      1981018.46       26.13    <.0001
       Error                 30     2274696.82        75823.23

       Corrected Total       44    30008955.23

               R-Square     Coeff Var      Root MSE       K Mean
               0.924199      54.22623      275.3602       507.7989

       Source                DF       Type I SS     Mean Square    F Value    Pr > F

       SITE                   4      2996351.01       749087.75       9.88     <.0001
       METHOD                 2     19548283.64      9774141.82     128.91     <.0001
       SITE*METHOD            8      5189623.76       648702.97       8.56     <.0001


                      Tukey's Studentized Range (HSD) Test for K

NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher Type II

                  Alpha                                 0.01
                  Error Degrees of Freedom              30
                  Error Mean Square                      75823.23
                  Critical Value of Studentized Range   4.45446
                  Minimum Significant Difference        316.7

             Means with the same letter are not significantly different.

             Tukey Grouping          Mean      N    METHOD

                     A             1439.8     15    KM
                     B               50.9     15    HAZ
```

```
                B                  32.6      15    HAR
```

Comparison of means of K from Hazen, Harleman, Krumbien and Monk, and Kozeny-Carmen equations for the streamed subsurface (~0.5 m) samples for Bertrand Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\BSSEMP.PRN';
INPUT SITE METHOD $ K;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = SITE METHOD;
RUN;
```

SAS results

```
                Obs    SITE    METHOD         K

                  1      1          HAZ       45.71
                  2      1          HAR       29.27
                  3      1          KM       596.90
                  4      1          KCB      625.80
                  5      2          HAZ       43.00
                  6      2          HAR       27.53
                  7      2          KM      1049.00
                  8      2          KCB      268.40
                  9      5          HAZ        8.73
                 10      5          HAR        5.59
                 11      5          KM        10.66
                 12      5          KCB       13.97
                 13      6         HAZ       19.18
                 14      6         HAR       12.28
                 15      6         KM       521.50
                 16      6         KCB      232.90
                 17      7         HAZ       14.61
                 18      7         HAR        9.36
                 19      7         KM        54.27
                 20      7         KCB       47.52

            Class Level Information
              Class        Levels    Values

              SITE              5        1 2 5 6 7
              METHOD         4        HAR HAZ KCB KM

              Number of Observations Read         20
              Number of Observations Used         20

Dependent Variable: K
                                   Sum of
     Source                DF        Squares     Mean Square    F Value    Pr > F
```

```
Model                    7     1023192.577      146170.368       3.05    0.0432
Error                   12      574269.055       47855.755
Corrected Total         19     1597461.632

              R-Square     Coeff Var      Root MSE        K Mean
              0.640512      120.3238      218.7596      181.8090

Source                  DF       Type I SS     Mean Square    F Value    Pr > F

SITE                     4     400217.6721     100054.4180       2.09    0.1451
METHOD                   3     622974.9045     207658.3015       4.34    0.0274
```

Comparison of means of K from Hazen, Harleman, Krumbien and Monk, and Kozeny-Carmen equations for the streamed subsurface (~0.5 m) samples for Fishtrap Creek

SAS Code

```
DATA A;
INFILE 'C:\JOAN\CM\FTSSEMP.PRN';
INPUT SITE METHOD $ K;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = SITE METHOD;
RUN;
```

SAS Results

```
                Obs    SITE    METHOD          K

                  1      1           HAZ        8.04
                  2            1           HAR         5.15
                  3            1           KM         71.17
                  4            1           KCB        53.04
                  5            3           HAZ         7.01
                  6            3           HAR         2.52
                  7            3           KM         20.83
                  8            3           KCB        59.62
                  9            4           HAZ        47.82
                 10            4           HAR        30.62
                 11            4           KM       1455.00
                 12            4           KCB     16760.00
                 13            5           HAZ         9.62
                 14            5           HAR         6.16
                 15            5           KM         52.23
                 16            5           KCB       153.40
                 17            6           HAZ         7.41
                 18            6           HAR         4.77
                 19            6           KM          9.58
                 20            6           KCB        46.58

                   Class Level Information

                Class        Levels    Values
```

```
               SITE            5     1 3 4 5 6
               METHOD          4     HAR HAZ KCB KM

               Number of Observations Read        20
               Number of Observations Used        20

                         Dependent Variable: K

                                Sum of
     Source              DF        Squares       Mean Square    F Value    Pr > F
     Model                7     107113383.9      15301912.0       1.16    0.3912
     Error               12     158253362.7      13187780.2
     Corrected Total     19     265366746.5


             R-Square    Coeff Var     Root MSE      K Mean
             0.403643     386.1129     3631.498    940.5277

     Source              DF       Type I SS     Mean Square   F Value    Pr > F
     SITE                 4     65990806.97     16497701.74      1.25    0.3417
     METHOD               3     41122576.90     13707525.63      1.04    0.4103
```

Comparison of means of K using Hazen equation for surface samples, Bertrand Creek and Fishtrap Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\HAZENSr.PRN';
INPUT REACH SITE METHOD $ K @@;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = REACH;
MEANS REACH/TUKEY ALPHA=0.01;
MEANS REACH/TUKEY;
MEANS REACH/TUKEY ALPHA=0.1;
RUN;
```

SAS results

```
            Obs     REACH    SITE    METHOD          K

             1        FT       1      HAZ          39.300
             2        FT       1      HAZ          54.460
             3        FT       1      HAZ          42.020
             4        FT       3      HAZ          31.960
             5        FT       3      HAZ          19.650
             6        FT       3      HAZ          14.680
             7        FT       4      HAZ          96.350
             8        FT       4      HAZ          77.480
             9        FT       4      HAZ          90.820
            10        FT       5      HAZ          25.760
```

```
                    11      FT     5    HAZ           59.070
                    12      FT     5    HAZ           33.670
                    13      FT     6    HAZ           56.240
                    14      FT     6    HAZ           84.260
                    15      FT     6    HAZ           38.390
                    16      BC     1    HAZ           21.570
                    17      BC     1    HAZ           29.590
                    18      BC     1    HAZ           26.790
                    19      BC     2    HAZ           31.970
                    20      BC     2    HAZ           31.230
                    21      BC     2    HAZ           36.420
                    22      BC     5    HAZ           9.307
                    23      BC     5    HAZ           9.632
                    24      BC     5    HAZ           13.790
                    25      BC     6    HAZ           31.960
                    26      BC     6    HAZ           40.870
                    27      BC     6    HAZ           31.860
                    28      BC     7    HAZ           64.780
                    29      BC     7    HAZ           79.690
                    30      BC     7    HAZ           43.480

                          Class Level Information

                      Class       Levels   Values
                      REACH            2    BC FT

                    Number of Observations Read          30
                    Number of Observations Used          30
Dependent Variable: K
                                   Sum of
    Source                  DF        Squares    Mean Square    F Value    Pr > F
    Model                    1     2273.67637     2273.67637       4.37    0.0458
    Error                   28    14565.63392      520.20121
    Corrected Total         29    16839.31029

                R-Square     Coeff Var      Root MSE        K Mean
                0.135022      54.00246      22.80792      42.23497

    Source                  DF      Type I SS     Mean Square    F Value    Pr > F
    REACH                    1    2273.676375     2273.676375       4.37    0.0458

                      Tukey's Studentized Range (HSD) Test for K

 NOTE: This test controls the Type I experiment wise error rate, but it generally has a higher
                     Type II error rate than REGWQ.

                   Alpha                                          0.01
                   Error Degrees of Freedom                       28
                   Error Mean Square                              520.2012
                   Critical Value of Studentized Range            3.90784
                   Minimum Significant Difference                 23.013

              Means with the same letter are not significantly different.

               Tukey Grouping   Mean      N    REACH
```

```
          A                    50.941     15    FT
          A                    33.529     15    BC
```

Comparison of means of K using Hazen equation for subsurface samples, Bertrand Creek and Fishtrap Creek

SAS codes

```
DATA A;
INFILE 'C:\JOAN\CM\HAZENSs.PRN';
INPUT REACH SITE METHOD $ K @@;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = REACH;
RUN;
```

SAS results

```
            Obs    REACH    SITE    METHOD    K

              1     BC         1     HAZ      45.710
              2     BC         2     HAZ      43.000
              3     BC         5     HAZ       8.726
              4     BC         6     HAZ      19.180
              5     BC         7     HAZ      14.610
              6     FT         1     HAZ       8.035
              7     FT         3     HAZ       7.011
              8     FT         4     HAZ      47.820
              9     FT         5     HAZ       9.615
             10     FT         6     HAZ       7.409

                  Class Level Information

                Class        Levels    Values

                REACH             2    BC FT

              Number of Observations Read        10
              Number of Observations Used        10

Dependent Variable: K
                                 Sum of
    Source                  DF       Squares     Mean Square    F Value    Pr > F
    Model                    1    263.538490      263.538490       0.87    0.3782
    Error                    8   2423.145893      302.893237
    Corrected Total          9   2686.684382


             R-Square     Coeff Var      Root MSE       K Mean
             0.098091      82.43728      17.40383     21.11160

    Source                  DF       Type I SS     Mean Square    F Value    Pr > F
```

```
REACH                    1     263.5384896     263.5384896       0.87    0.3782
```

Appendix E Comparison of Means of *K* at the 0.5-m Depth from Five Methods (Slug Test and Four Empirical Formulas) Using the GLM Procedure in SAS

SAS Code

```
DATA A;
INFILE 'C:\CM\FTAll.PRN';
INPUT SITE METHOD $ K;
PROC PRINT;
PROC GLM;
CLASS SITE METHOD;
MODEL K = SITE METHOD;
RUN;
```

SAS Results

```
                         Obs   SITE   METHOD        K

                           1    1          HAZ       8.04
                           2    1          HAR       5.15
                           3    1          KM       71.17
                           4    1          KCB      53.04
                           5    1          SLUG     13.65
                           6    3          HAZ       7.01
                           7    3          HAR       2.52
                           8    3          KM       20.83
                           9    3          KCB      59.62
                          10    3          SLUG      4.97
                          11    4          HAZ      47.82
                          12    4          HAR      30.62
                          13    4          KM     1455.00
                          14    4          KCB   16760.00
                          15    4          SLUG     40.30
                          16    5          HAZ       9.62
                          17    5          HAR       6.16
                          18    5          KM       52.23
                          19    5          KCB     153.40
                          20    5          SLUG     68.40
                          21    6          HAZ       7.41
                          22    6          HAR       4.77
                          23    6          KM        9.58
                          24    6          KCB      46.58
                          25    6          SLUG     11.94


                    Class       Levels    Values
                    SITE             5       1 3 4 5 6
                    METHOD       5       HAR HAZ KCB KM SLUG
                      Number of Observations Read        25
                      Number of Observations Used        25

Dependent Variable: K
                                    Sum of
       Source                  DF         Squares     Mean Square    F Value    Pr > F
       Model                    8     97340274.4      12167534.3       1.14    0.3920
```

```
Error               16    171361131.5     10710070.7
Corrected Total     24    268701405.9


          R-Square    Coeff Var    Root MSE      K Mean
          0.362262     431.7485    3272.624    757.9932

Source              DF      Type I SS    Mean Square   F Value   Pr > F

SITE                 4    52885815.46    13221453.87      1.23   0.3357
METHOD               4    44454458.95    11113614.74      1.04   0.4183
```

Appendix F Calculations of Particle-size Distribution for the Subsurface Bed Materials of the Bertrand and Fishtap Creeks

Bertrand Creek

Location;	BC1-149	40-43 cm										
		Sieve										
		soil weight into seives =	**73.66**									
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**% of soil**	
5	4000	Fine Gravel +	500.23	530.29	30.06	0.41	8.29	3.38		73.66	100.00	
10	1000	ne Gravel/ Very Coarse Sa	483.54	493.93	10.39	0.14	6.91	0.97		43.6	59.19	
20	500	Coarse sand	409.8	428.78	18.98	0.26	6.21	1.60		33.21	45.09	
40	300	Medium Sand	381.89	393.66	11.77	0.16	5.70	0.91		14.23	19.32	
d10	230					0.00	5.44	0.00			10.00	
60	180	Medium/Fine Sand	347.66	349.53	1.87	0.03	5.19	0.13		2.46	3.34	
170	106	Fine/Very Fine Sand	339.91	340.26	0.35	0.00	4.66	0.02		0.59	0.80	
270	90	Very Fine Sand/ Silt	332.85	332.92	0.07	0.00	4.50	0.00		0.24	0.33	
Pan	10	Silt	371.2	371.37	0.17	0.00	2.30	0.01		0.17	0.23	
STDDEV	1268.41		3167.08	3240.74	73.66	1.00		SUM	1136			
STDDEV (mm)	1.268405635							7.04				
σ (mm)	0.237760706											
Location;	BC2-147	8-11 cm										
		Sieve										
		soil weight into seives =	**90.5**									
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**% of soil**	
5	4000	Fine Gravel +	500.24	549.57	49.33	0.67	8.29	5.55		90.5	122.86	
10	1000	ne Gravel/ Very Coarse Sa	483.57	496.9	13.33	0.18	6.91	1.25		41.17	55.89	
20	500	Coarse sand	409.79	423.01	13.22	0.18	6.21	1.12		27.84	37.80	
40	300	Medium Sand	381.89	390.58	8.69	0.12	5.70	0.67		14.62	19.85	
d10	200					0.00	5.30	0.00			10.00	
60	180	Medium/Fine Sand	347.67	351.43	3.76	0.05	5.19	0.27		5.93	8.05	
170	106	Fine/Very Fine Sand	339.89	341.8	1.91	0.03	4.66	0.12		2.17	2.95	
270	90	Very Fine Sand/ Silt	332.85	332.97	0.12	0.00	4.50	0.01		0.26	0.35	
Pan	10	Silt	371.19	371.33	0.14	0.00	2.30	0.00		0.14	0.19	
STDDEV	1269.88		3167.09	3257.59	90.5	1.23		SUM	8027			
STDDEV (mm)	1.269881284							8.99				
σ (mm)	0.238923419											
Location;	BC5-37	28-31 cm										
		Sieve										
		soil weight into seives =	**69.04**									
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**% of soil**	
5	4000	Fine Gravel +	500.24	502.57	2.33	0.03	8.29	0.26		69.04	93.73	
10	1000	ne Gravel/ Very Coarse Sa	483.57	487.74	4.17	0.06	6.91	0.39		66.71	90.56	
20	500	Coarse sand	409.79	410.53	0.74	0.01	6.21	0.06		62.54	84.90	
40	300	Medium Sand	381.89	383.49	1.6	0.02	5.70	0.12		61.8	83.90	
60	180	Medium/Fine Sand	347.67	360.24	12.57	0.17	5.19	0.89		60.2	81.73	
170	106	Fine/Very Fine Sand	339.89	384.27	44.38	0.60	4.66	2.81		47.63	64.66	
d10	101					0.00	4.61	0.00			10.00	
270	90	Very Fine Sand/ Silt	332.85	335.33	2.48	0.03	4.50	0.15		3.25	4.41	
Pan	10	Silt	371.19	371.96	0.77	0.01	2.30	0.02		0.77	1.05	
STDDEV	1275.28		3167.09	3236.13	69.04	0.94		SUM	111			
STDDEV (mm)	1.275281757							4.71				
σ (mm)	0.24316714											

Location;	BC6-6										
		Sieve									
		soil weight into seives =	**97.88**								
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	541.1	40.86	0.55	8.29	4.60		97.88	132.88
10	1000	ne Gravel/ Very Coarse Sa	483.57	502.08	18.51	0.25	6.91	1.74		57.02	77.41
20	500	Coarse sand	409.79	420.09	10.3	0.14	6.21	0.87		38.51	52.28
40	300	Medium Sand	381.89	393.94	12.05	0.16	5.70	0.93		28.21	38.30
60	180	Medium/Fine Sand	347.67	362.87	15.2	0.21	5.19	1.07		16.16	21.94
d10	137					0.00	4.92	0.00			10.00
170	106	Fine/Very Fine Sand	339.89	340.5	0.61	0.01	4.66	0.04		0.96	1.30
270	90	Very Fine Sand/ Silt	332.85	332.98	0.13	0.00	4.50	0.01		0.35	0.48
Pan	10	Silt	371.19	371.41	0.22	0.00	2.30	0.01		0.22	0.30
STDDEV	1273.19		3167.09	3264.97	97.88	1.33		SUM	10549		
STDDEV (mm)	1.273191591							9.26			
σ (mm)	0.241526812										
Location;	BC7-61	20-23 cm									
		Sieve									
		soil weight into seives =	**81.45**								
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	506.31	6.07	0.08	8.29	0.68		81.45	110.58
10	1000	ne Gravel/ Very Coarse Sa	483.57	486.83	3.26	0.04	6.91	0.31		75.38	102.34
20	500	Coarse sand	409.79	421.5	11.71	0.16	6.21	0.99		72.12	97.91
40	300	Medium Sand	381.89	422.11	40.22	0.55	5.70	3.11		60.41	82.01
60	180	Medium/Fine Sand	347.67	365.51	17.84	0.24	5.19	1.26		20.19	27.41
d10	127					0.00	4.84	0.00			10.00
170	106	Fine/Very Fine Sand	339.89	342.06	2.17	0.03	4.66	0.14		2.35	3.19
270	90	Very Fine Sand/ Silt	332.85	332.9	0.05	0.00	4.50	0.00		0.18	0.24
Pan		Silt	371.19	371.32	0.13	0.00		SUM		0.13	0.18
STDDEV	1333.21		3167.09	3248.54	81.45	1.11		6.49	658		
STDDEV (mm)	1.333210141										
σ (mm)	0.287589674										

Fishtrap Creek

Location;	FT1-20	50-53 cm									
		Sieve									
		soil weight into seives =	**64.97**								
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	511.52	11.28	0.17	8.29	1.44		64.97	100.00
10	1000	Fine Gravel/ Very Coarse Sand	483.57	489.68	6.11	0.09	6.91	0.65		53.69	82.64
20	500	Coarse sand	409.78	418.26	8.48	0.13	6.21	0.81		47.58	73.23
40	300	Medium Sand	381.93	395.8	13.87	0.21	5.70	1.22		39.1	60.18
60	180	Medium/Fine Sand	347.69	361.08	13.39	0.21	5.19	1.07		25.23	38.83
170	106	Fine/Very Fine Sand	339.94	348.88	8.94	0.14	4.66	0.64		11.84	18.22
d10	96					0.00	4.57	0.00			10.00
270	90	Very Fine Sand/ Silt	332.84	334.1	1.26	0.02	4.50	0.09		2.9	4.46
Pan	10	Silt	371.23	372.87	1.64	0.03	2.30	0.06		1.64	2.52
STDDEV	1275.52		3167.22	3232.19	64.97	1.00		SUM	394		
STDDEV (mm)	1.2755239							5.98			
σ (mm)	0.243357										
Location;	FT3-186	6-9cm									
		Sieve									
		soil weight into seives =	**52.24**								
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	508.19	7.95	0.12	8.29	1.01		52.24	80.41
10	1000	Fine Gravel/ Very Coarse Sand	483.57	483.91	0.34	0.01	6.91	0.04		44.29	68.17
20	500	Coarse sand	409.78	411.36	1.58	0.02	6.21	0.15		43.95	67.65
40	300	Medium Sand	381.93	386.47	4.54	0.07	5.70	0.40		42.37	65.21
60	180	Medium/Fine Sand	347.69	359.07	11.38	0.18	5.19	0.91		37.83	58.23
170	106	Fine/Very Fine Sand	339.94	361.27	21.33	0.33	4.66	1.53		26.45	40.71
d10	91.03					0.00	4.51	0.00			10.00
270	90	Very Fine Sand/ Silt	332.84	335.45	2.61	0.04	4.50	0.18		5.12	7.88
Pan	10	Silt	371.23	373.74	2.51	0.04	2.30	0.09		2.51	3.86
STDDEV	1275.84		3167.22	3219.46	52.24	0.80		SUM	75		
STDDEV (mm)	1.2758438							4.31			
σ (mm)	0.2436077										
Location;	FT4-86	8-11 cm									
		Sieve									
		soil weight into seives =	**108.32**								
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	568.22	67.98	1.05	8.29	8.68		108.32	166.72
10	1000	Fine Gravel/ Very Coarse Sand	483.57	499.35	15.78	0.24	6.91	1.68		40.34	62.09
20	500	Coarse sand	409.78	418.96	9.18	0.14	6.21	0.88		24.56	37.80
40	300	Medium Sand	381.93	390.36	8.43	0.13	5.70	0.74		15.38	23.67
d10	174					0.00	5.16	0.00			10.00
60	180	Medium/Fine Sand	347.69	352.32	4.63	0.07	5.19	0.37		6.95	10.70
170	106	Fine/Very Fine Sand	339.94	340.92	0.98	0.02	4.66	0.07		2.32	3.57
270	90	Very Fine Sand/ Silt	332.84	333.14	0.3	0.00	4.50	0.02		1.34	2.06
Pan	10	Silt	371.23	372.27	1.04	0.02	2.30	0.04		1.04	1.60
STDDEV	1271.23		3167.22	3275.54	108.32	1.67		SUM	261005		
STDDEV (mm)	1.2712292							12.47			
σ (mm)	0.2399843										

Location;	FT5-8	24-27 cm								
		Sieve								
		soil weight into seives =	**77.52**							
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	503.32	3.08	0.05	8.29	0.39		77.52	119.32
10	1000	Fine Gravel/ Very Coarse Sand	483.57	490.93	7.36	0.11	6.91	0.78		74.44	114.58
20	500	Coarse sand	409.78	429.32	19.54	0.30	6.21	1.87		67.08	103.25
40	300	Medium Sand	381.93	404.28	22.35	0.34	5.70	1.96		47.54	73.17
60	180	Medium/Fine Sand	347.69	364.89	17.2	0.26	5.19	1.37		25.19	38.77
170	106	Fine/Very Fine Sand	339.94	347.44	7.5	0.12	4.66	0.54		7.99	12.30
d10	103					0.00	4.63	0.00			10.00
270	90	Very Fine Sand/ Silt	332.84	333.07	0.23	0.00	4.50	0.02		0.49	0.75
Pan	10	Silt	371.23	371.49	0.26	0.00	2.30	0.01		0.26	0.40
STDDEV	1275.15		3167.22	3244.74	77.52	1.19		SUM	1038		
STDDEV (mm)	1.2751496							6.95			
σ (mm)	0.2430635										
Location;	FT6-34	15-18 cm									
		Sieve									
		soil weight into seives =	**61.1**								
seive #	**particle size (µm)**	**Name of the particle size**	**seive weight**	**seive weight + Soil**	**weight (g)**	**weight %**	**ln xi (µm)**	**SUM wi LN xi (µm)**	**Geo Mean (µm)**	**Cumu. Soil weight (g)**	**%of soil**
5	4000	Fine Gravel +	500.24	500.24	0	0.00	8.29	0.00		61.1	94.04
10	1000	Fine Gravel/ Very Coarse Sand	483.57	483.6	0.03	0.00	6.91	0.00		61.1	94.04
20	500	Coarse sand	409.78	410.12	0.34	0.01	6.21	0.03		61.07	94.00
40	300	Medium Sand	381.93	387.54	5.61	0.09	5.70	0.49		60.73	93.47
60	180	Medium/Fine Sand	347.69	375.33	27.64	0.43	5.19	2.21		55.12	84.84
170	106	Fine/Very Fine Sand	339.94	365.46	25.52	0.39	4.66	1.83		27.48	42.30
d10	93					0.00	4.53	0.00			10.00
270	90	Very Fine Sand/ Silt	332.84	333.97	1.13	0.02	4.50	0.08		1.96	3.02
Pan	10	Silt	371.23	372.06	0.83	0.01	2.30	0.03		0.83	1.28
STDDEV	1275.74		3167.22	3228.32	61.1	0.94		SUM	107		
STDDEV (mm)	1.2757363							4.68			
σ (mm)	0.2435235										

Appendix G Long-term Climate Data for the Study Site from NOAA NCDC

Climate data was downloaded from NOAA-NCDC for Bellingham, WA Airport Station and saved in a Microsoft Excel file. The raw data is on sheet RAW. This sheet contains monthly mean max and min temperatures filtered from the raw data. A total of 53 years (1949–2001) of data were downloaded; however, only 47 years of data were used in analysis and those years with considerable missing data were not included. Temperature was originally in Fahrenheit and was converted to degree Celsius in the manuscript.

1. long-term mean maximum temperature (°F)

Mean Max	January	February	March	April	May	June	July	August	September	October	November	December
1950	26.6	46.2	47.7	55.4	60	69.8	71.2	73.7	67.9	55.9	48.2	49.9
1951	41.9	46.6	45.6	61.3	64.2	71.1	73.3	71.9	68.3	57.1	50.4	39.1
1952	40.3	47.7	49	57.1	63.5	63.8	71.8	72.1	70.2	63.4	50.4	47.6
1953	49.1	47.8	50.5	56.2	63.5	63.8	72.3	72.8	68.6	60.2	53.7	47.8
1954	38	48.8	50.7	53.5	63.3	64.5	68.2	67.3	66.7	57.7	55	46.8
1955	43.7	43.5	45	54	57.6	66	67.2	70.5	66.2	56.5	42.6	41.6
1956	43	40.1	47.3	59.5	67.2	64	74.4	73	65.9	55.8	47.8	44.6
1957	34.4	44.1	50.4	58.4	66.3	67.3	68.9	71.6	73.6	59.2	50.8	49.2
1958	49.3	51.8	53.4	58.6	69.6	72.6	79	75.5	67.8	61.5	48.3	47
1959	44.2	44.6	50.1	56.9	62.7	67.7	74.2	69.2	64.1	58.4	48.6	45.8
1960	42.3	48	49.6	57.6	60.1	66.4	75.5	68.7	65.8	59.8	49.3	45.6
1961	49.4	49.7	53.5	55.1	62.7	70.9	74.4	76.5	66.5	57.5	49	44.2
1962	43.6	49	49.7	57.5	58	67	70.7	68.5	67.4	58.9	52	47.5
1963	37.3	53.7	51	55.3	65.1	65.5	68.8	72.6	70.6	59.9	50.5	46.4
1964	46.5	47.1	48.9	53.2	60.3	64.8	68.8	68.7	64	60.8	47.4	38.7
1965	42	46.5	53.4	57.3	59.3	68.4	73.9	71.6	64.6	61.6	51.5	43.3
1966	43.3	46.9	50.8	56	61.3	64.9	67.2	70.8	66.4	56.4	50.2	47.8
1967	44.8	47.2	47.9	52.2	60.4	70.8	72.2	77.6	70.9	58.1	51.2	44.1
1968	44.7	53.2	52.3	54.4	64	66.6	74.8	69.8	64.8	57.4	51.7	40.7
1969	32.9	47.4	52.1	53.2	64.6	69.6	69.6	67.6	63.8	58	51.1	47.4
1970	43.4	52.2	53.4	53.8	61.5	69.9	70.8	70.7	64.6	57.6	49.8	42.5
1971	41.8	45.1	47.1	55.2	61.1	61.2	71.6	73.7	63.7	54.7	47.9	38.5
1972	37.6	46.3	50.1	52	63.7	63.8	71.6	72.8	62.4	56.2	50.7	40.8
1973	41.6	46.4	48.1	55.9	62.9	65.4	71.7	67.9	69	57.4	47.3	48
1974	43.7	47.1	52.1	55.5	59.1	66.6	69.4	71.8	73.6	60.2	50.6	47.3
1975	42.4	42.9	48.3	52.3	61.3	64	71.2	66.9	68.8	54.7	49.5	45.1
1976	45.9	44.9	46	56.7	60.6	64.6	71	66.7	67	59.2	52.5	48.4
1977	41.4	52.9	49.3	59.4	60.2	68.4	69.3	76.1	65.2	59.7	49.4	43.4
1978	44	50.5	54.7	57.4	63.6	70.6	72.4	70.4	63.2	59.2	44.3	40.5
1979	36.4	44.9	53.3	55.6	62.9	66.1	73.1	70.9	68.9	59.3	50	48.8
1980	38.7	49	48.8	60	60.7	63.9	68.6	67.5	65.4	60.6	51.3	44.8
1981	49.4	48.5	54.5	55.4	61.4	62.3	68.6	73.5	67	56.7	52.7	44.5
1982	39.8	45.8	49.9	54.3	61	70.3	67.5	70.1	67.3	59	47.2	45.6
1983	49.6	51.7	55.5	57.7	64.3	65.1	68.2	71.4	63.8	55.7	50.6	36.1
1984	45	48.7	52.5	54.9	58.2	63.6	70.6	70.5	64.3	53.8	48.9	36.8
1985	40.1	43.6	48.7	55.7	62.3	66.6	77.5	73	65.4	56.6	37.4	40.5
1986	52	47.3	54.4	53.3	62.5	69	67.2	74.7	65.5	60.5	48.6	47.7
1987	45.9	51.3	55.5	59	63.6	69	70.3	73	69.6	63.5	53.6	43.8
1988	44.6	49.1	51.5	56.7	62.5	66.1	71.5	71.5	66.5	59.5	50.1	46.5
1989	44.1	41.7	49.5	61.4	61.4	69.8	70.2	69.8	70.8	59.2	50.2	46.2
1990	46.5	44.8	53.9	58.3	61.7	65.9	75.1	74.9	68.9	56.2	50.9	39.5
1991	41.2	53.3	49.7	56.1	60.3	63.8	72.3	72.1	68.9	57.8	51.1	48
1992	50.1	53	57.9	60.3	66.6	70.7	70.8	71.8	64.8	59.2	49.5	41.4
1993	39.8	47.6	54.4	56.5	66.7	65.6	66.4	70.8	67.9	60.6	46.8	46.5
1994	50.6	44.9	55.5	58.1	64.4	65.9	73.5	73.2	69.2	58	47.3	46.2
1995	48.8	49.8	53.9	57.8	66.4	70	72.3	68.2	71.1	56.6	54.1	46.6
2000	43.6	48.7	49.9	57.1	59.1	67.2	70.2	68.5	66	58.7	48.4	43.3
AVERAGE (F)	43.1	47.7	51.0	56.4	62.4	66.8	71.26	71.33	67.1	58.4	49.6	44.5

2. long-term mean minimum temperature (°F)

Mean Min	January	Feburary	March	April	May	June	July	August	September	October	November	December

1950	13.4	32.1	35.7	37.2	41.7	49.5	51.8	50.4	45.9	41.7	35.6	38.7
1951	30.5	31.2	29.6	35.4	43.8	49.6	52.1	51	46.9	41.1	35.1	28.5
1952	28.6	32.1	35.2	37.5	43.5	46.9	49.9	51.3	46.5	40.4	30.9	34.9
1953	37.2	32.9	36.2	39.5	43.9	48	51.2	52.3	46.3	42.9	40.3	36.5
1954	26	34.2	29	36.6	42.3	46.1	49.2	51.1	48.3	39.7	40.4	35.1
1955	32.1	30.8	30.4	35	41.7	48.2	50.1	47.2	44.7	41.4	29.7	29.4
1956	31.2	28.7	33.1	37.9	44.4	49.1	51.7	52.5	47.2	41.2	33.6	33.2
1957	21.6	28.6	35.4	40.8	47.5	51.1	50.5	49.6	47	39.2	33.4	36
1958	36.1	38	33.4	38.6	47.2	54.4	56.9	54.7	48.2	41.6	35.8	35.8
1959	32.1	33.6	37.6	38.8	43.8	50.7	53	50.5	47.1	41.6	33.2	32.8
1960	32	33.6	35.1	40.9	45.5	48.7	53.1	52.7	46	43.8	36.8	31.1
1961	34.2	39	38.7	41	45.9	50.7	54.8	53.9	45.4	39.7	32.2	34.1
1962	30.7	35	32.5	41	44.2	48.3	51.9	52.9	46.7	44.2	40.6	36.5
1963	26.8	37	35.3	40.6	43.2	50.5	51.8	53.8	50.3	44.6	39	33.7
1964	37.2	32.7	36.6	37.9	43	50.1	52.5	51.4	46.7	41.4	34.4	26.9
1965	31.4	35.3	31	39.5	43	48.4	51.9	53.5	46.3	44	39.8	31
1966	30.9	32.5	34.6	38.3	41.7	48.6	52	51.2	49.8	40.1	37.1	37.6
1967	35.1	34.6	34.5	36.7	45.9	53	54.2	54.6	50.2	46.4	38.2	35.1
1968	33.9	33.1	40.3	39	45.1	50.5	54	53.8	48.2	43.2	38.4	29.7
1969	23.1	33	34.5	39.4	45.6	53.3	51.2	49.7	48.5	39.9	38.5	35.9
1970	31.7	35.6	35	39.8	44.1	50.7	53.4	52.5	47.2	40.2	36.7	32.2
1971	31.1	34.2	33.2	37.1	43.8	48.3	51.9	54.2	46.6	40.5	38.6	28.4
1972	27.2	32.9	38.6	37.9	45.5	50.5	52	52.9	44	36.8	37.6	30.1
1973	31.5	32.9	36.9	38.1	44.6	49.8	53.3	52.3	50.1	43.4	35.3	37.8
1974	33.2	38.1	37.9	42.1	44.3	51	52.2	52.7	48.8	41.1	37.9	36.7
1975	31.2	31.1	34.7	36.3	43.7	49	54.5	53.5	47.5	43.4	39.1	32.6
1976	35.7	34.9	33.4	38.5	44.5	48.9	54.2	55.3	50.5	43	36.7	37.4
1977	29.5	37.9	39.2	43.2	45.9	53	54.2	57.6	49.9	42.5	38.3	32.4
1978	33.8	36.3	39.3	42.9	46.5	52.6	54.5	54.9	50.5	41.8	32	30.2
1979	24	32.6	35.8	41	46.3	49.5	54.1	54.9	51.3	43.5	31.3	37.7
1980	26.5	36.4	36.9	40.8	46.1	50.1	53.1	52.4	50.3	41.6	38.6	35.7
1981	34.4	34.5	37.5	40.7	46.8	50	54.7	55.1	49.3	40.9	38.6	33.9
1982	30.5	34.5	33.6	36.2	43.8	51.3	53.5	52.3	49.6	41.6	32.7	33
1983	36.9	37	40	38.7	47.1	51.6	53.2	54.3	46.4	39.7	41.3	26
1984	33.5	36.5	38.3	39.8	44.3	50.3	52.3	53.5	46.4	40.6	38.4	27.1
1985	27.1	33.6	36.2	41.7	45.9	50.1	55.9	53.1	48.1	45.2	27.2	28.6
1986	38.5	32.7	39.8	40	46.1	51	52.1	55.1	49.1	42.5	37.7	33.2
1987	33.7	37.8	39.4	43.1	46.5	50.9	54.1	52.7	48.7	40.5	41.3	31.8
1988	31.3	35.7	37.2	41.7	46.5	49.8	53.1	53.6	47.6	46.5	40.7	35.3
1989	33.5	26	35.5	42.5	47	52.6	54	54.2	47.7	43.2	40.1	35.9
1990	36	31	36.3	44.2	48.2	52.2	56.5	56.4	50.8	43.5	39.8	27.7
1991	29.9	39.2	35.2	41.8	47.5	50.7	54.5	55.8	49.7	39.7	39.5	37
1992	36.9	37.2	39	43.1	47.9	54.3	56.6	54.3	48.2	45.6	38.2	31.3
1993	25.8	30.5	38.5	44.5	50.7	53.4	55.4	54.8	47.2	44.9	31.9	33.9
1994	39.3	32.9	38.6	44.7	48.2	50.6	55.2	56	51.5	42.8	35.3	34.3
1995	33.4	36.9	37.2	41.4	48.8	53.2	56.6	52.9	52.2	44	40.9	34.6
2000	32	33.4	35.8	40.8	44.4	49	52.8	51.1	47.1	41.6	32.9	30.3
AVERAGE (F)												
	31.3	34.0	35.9	39.9	45.3	50.4	53.2	53.1	48.1	42.1	36.6	33.1

3. long-term mean monthly temperature (°F)

	January	Feburary	March	April	May	June	July	August	September		October December	November
1950	20	39.2	41.7	46.3	50.9	59.6	61.5	62	56.9	48.8	41.9	44.3
1951	36.2	38.9	37.6	48.4	54	60.3	62.7	61.5	57.6	49.1	42.8	33.8
1952	34.5	39.9	42.1	47.3	53.5	55.4	60.8	61.7	58.4	51.9	40.6	41.2
1953	43.1	40.3	43.4	47.8	53.7	55.9	61.7	62.6	57.5	51.6	47	42.1
1954	32	41.5	39.9	45.1	52.8	55.3	58.7	59.2	57.5	48.7	47.7	41
1955	37.9	37.1	37.7	44.5	49.7	57.1	58.7	58.8	55.4	48.9	36.1	35.5
1956	37.1	34.4	40.2	48.7	55.8	56.6	63.1	62.7	56.6	48.5	40.7	38.9
1957	28	36.3	42.9	49.6	56.9	59.2	59.7	60.6	60.3	49.2	42.1	42.6
1958	42.7	44.9	43.4	48.6	58.4	63.5	68	65.1	58	51.5	42	41.4
1959	38.1	39.1	43.8	47.8	53.3	59.2	63.6	59.9	55.6	50	40.9	39.3
1960	37.1	40.8	42.4	49.2	52.8	57.5	64.3	60.7	55.9	51.8	43	38.4
1961	41.8	44.4	46.1	48	54.3	60.8	64.6	65.2	56	48.6	40.6	39.1
1962	37.2	42	41.1	49.2	51.1	57.7	61.3	60.7	57	51.5	46.3	42

1963	32.1	45.4	43.2	47.9	54.2	58	60.3	63.2	60.5	52.2	44.8	40
1964	41.9	39.9	42.8	45.6	51.7	57.4	60.7	60.1	55.3	51.1	40.9	32.8
1965	36.7	40.9	42.2	48.4	51.1	58.4	62.9	62.5	55.4	52.8	45.6	37.2
1966	37.1	39.7	42.7	47.2	51.5	56.7	59.6	61	58.1	48.2	43.6	42.7
1967	40	40.9	41.2	44.4	53.1	61.9	63.2	66.1	60.6	52.3	44.7	39.6
1968	39.3	43.1	46.3	46.7	54.5	58.6	64.4	61.8	56.5	50.3	45	35.2
1969	28	40.2	43.3	46.3	55.1	61.5	60.4	58.7	56.2	48.9	44.8	41.6
1970	37.6	43.9	44.2	46.8	52.8	60.3	62.1	61.6	55.9	48.9	43.2	37.4
1971	36.5	39.6	40.1	46.1	52.4	54.8	61.7	64	55.2	47.6	43.2	33.5
1972	32.4	39.6	44.4	45	54.6	57.1	61.8	62.9	53.2	46.5	44.2	35.5
1973	36.6	39.6	42.5	47	53.8	57.6	62.5	60.1	59.6	50.4	41.3	42.9
1974	38.4	42.6	45	48.8	51.7	58.8	60.8	62.3	61.2	50.6	44.2	42
1975	36.8	37	41.5	44.3	52.5	56.5	62.9	60.2	58.1	49.1	44.3	38.9
1976	40.8	39.9	39.7	47.6	52.5	56.8	62.6	61	58.8	51.1	44.6	42.9
1977	35.5	45.4	44.2	51.3	53	60.7	61.7	66.9	57.5	51.1	43.9	37.9
1978	38.9	43.4	47	50.2	55.1	61.6	63.4	62.6	56.8	50.5	38.2	35.4
1979	30.2	38.8	44.6	48.3	54.6	57.8	63.6	62.9	60.1	51.4	40.6	43.3
1980	32.6	42.7	42.9	50.4	53.4	57	60.9	60	57.9	51.1	45	40.3
1981	41.9	41.5	46	48	54.1	56.2	61.7	64.3	58.2	48.8	45.6	39.2
1982	35.1	40.2	41.8	45.3	52.4	60.8	60.5	61.2	58.4	50.3	40	39.3
1983	43.3	44.3	47.7	48.2	55.7	58.4	60.7	62.8	55.1	47.7	45.9	31
1984	39.3	42.6	45.4	47.3	51.2	57	61.5	62	55.4	47.2	43.6	32
1985	33.6	38.6	42.4	48.7	54.1	58.3	66.7	63.1	56.7	50.9	32.3	34.5
1986	45.3	40	47.1	46.6	54.3	60	59.7	64.9	57.3	51.5	43.1	40.5
1987	39.8	44.5	47.5	51.1	55	59.9	62.2	62.9	59.2	52	47.4	37.8
1988	38	42.4	44.3	49.2	54.5	58	62.3	62.6	57.1	53	45.4	40.9
1989	38.8	33.8	42.5	52	54.2	61.2	62.1	62	59.2	51.2	45.2	41
1990	41.3	37.9	45.1	51.2	55	59.1	65.8	65.6	59.8	49.8	45.3	33.6
1991	35.6	46.3	42.4	49	53.9	57.2	63.4	64	59.3	48.7	45.3	42.5
1992	43.5	45.1	48.5	51.7	57.2	62.5	63.7	63.1	56.5	52.4	43.8	36.3
1993	32.8	39.1	46.5	50.5	58.7	59.5	60.9	62.8	57.6	52.8	39.4	40.2
1994	45	38.9	47.1	51.4	56.3	58.3	64.3	64.6	60.4	50.4	41.3	40.3
1995	41.1	43.3	45.5	49.6	57.6	61.6	64.5	60.5	61.7	50.3	47.5	40.6
2000	37.8	41.1	42.8	48.9	51.7	58.1	61.5	59.8	56.6	50.1	40.6	36.8
COUNT	47	47	47	47	47	47	47	47	47	47	47	47
Yearly Average	28.9	40.2	42.3	47.6	51.3	58.9	61.5	60.9	56.8	49.5	41.3	40.6

4. long-term mean monthly precipitation (inch)

	January	Feburary	March	April	May	June	July	August	September	October	November	December
1949						1.35	1.2	0.82	2.23	3.56	5.33	8.38
1950	3.14	4.8	7.02	3.01	1.95	0.35	1.27	2.28	0.7	5.11	4.98	6.23
1951	5.59	6.13	5.07	0.95	2.42	0.26	0.05	0.34	2.25	4.82	3.1	4.23
1952	2.42	2.21	2.81	2.32	1.68	2.09	0.6	0.44	1.45	2.16	1.37	2.82
1953	9.23	2.83	2.58	2.43	1.29	2.58	0.94	0.68	2.06	3.68	7.24	7.18
1954	5.42	3.2	1.78	1.95	1.52	2.56	1.41	1.99	1.41	1.36	8.63	3.52
1955	3.1	4.12	2.09	2.58	2.61	1.94	1.96	0.17	1.03	4.43	6.68	5.66
1956	4.53	2.15	2.77	0.37	0.7	4.48	0.13	1.24	3.6	6.2	2.49	6.22
1957	2.12	2.57	4.35	2.6	0.69	1.02	1.56	0.41	0.8	2.55	2	3.44
1958	3.92	4.08	1.2	2.4	1.29	0.86	0	0.85	1.59	7.25	7.32	4.07
1959	5.66	3.31	2.82	3.86	2.34	1.34	0.73	1.45	4.51	3.7	5.08	4.38
1960	5.27	2.62	3.07	2.52	4.81	1.3	0	2.62	1.64	3.02	4.99	2.89
1961	4.25	7.43	4.32	2.48	2.27	1	1.54	1.21	1.12	4.43	3.31	4.92
1962	2.92	1.48	2.76	2.38	2.07	0.97	0.33	4.77	2.26	2.92	5.36	4.02
1963	1.22	2.92	1.7	3.01	1.14	1.1	2.07	0.3	1.14	4.4	7.06	7.39
1964	5.15	2.39	4.56	3.01	2.71	1.96	2.75	1.77	4.08	2.3	4.71	3.81
1965	7.71	7.59	0.76	2.93	1.97	0.56	0.21	3.63	1.39	4.08	4.77	4.51
1966	3.08	1.78	3.53	2.44	3.03	0.98	2.43	0.85	2.28	4.33	3.51	6.43
1967	7.86	4.04	3.69	1.76	1.41	1.28	0.69	0.46	2.1	7.93	2.23	6.15
1968	3.59	3.57	4.29	1.54	2.02	2.35	1.17	3.35	2.55	3.88	4.76	5.46
1969	4.35	1.14	2.66	4.56	1.62	1.48	0.59	0.56	4.71	2.39	2.34	3.17
1970	5.79	2.34	1.19	3.65	1.36	1.4	1.46	0.15	2.56	2.3	4.47	3.32
1971	10.58	3.68	3.19	1.26	1.32	4.78	1.34	0.31	3.66	3.44	6.23	7.39
1972	4.06	6.61	5.37	3.92	1.49	2.68	2.73	1.07	1.73	1.31	2.66	7.56
1973	2.45	1.74	1.8	1.55	2.08	1.52	0.3	0.56	0.9	4.44	6.89	4.61
1974	6.83	3.98	3.39	2.13	2.97	1.29	1.92	0.03	0.34	1.5	4.16	4.92

1975	5.21	4.1	1.69	1.41	1.88	0.73	1.55	4.02	0.43	4.49	6.03	8.29
1976	10.24	4.86	2.23	2.92	2.87	1.87	0.67	1.96	1.01	2.74	1.76	3.63
1977	3.45	1.78	4.64	2.21	3.69	0.25	1.24	2.38	1.82	2.65	5.08	5.04
1978	3.48	2.99	3.48	2.55	1.44	1.25	0.57	2.88	3.79	1.84	4.96	2.2
1979	1.92	3.31	2.03	2.53	1.56	1.96	0.87	1.25	0.89	2.8	1.38	9.99
1980	2.11	4.23	3.21	2.82	1.93	3.46	1.35	0.66	2.38	1.22	8.73	7.07
1981	1.72	5.05	2.84	4.3	2.16	4.11	2.3	0.72	2.07	6	3.07	5.1
1982	9.31	8.65	2.33	1.78	0.4	1.1	2.86	1.02	1.16	2.52	4.01	4.12
1983	4.38	2.61	2.49	2.6	1.85	1.59	2.59	0.66	4.2	1.91	6.14	2.8
1984	9.01	3.24	4.09	2.32	5.93	2.2	0.12	1.43	2.97	4.13	5.37	3.97
1985	0.77	2.07	2.01	2.9	2.01	1.9	0.07	0.4	0.87	6.82	5.01	1
1986	3.98	4.47	3.28	3.35	4.1	1.39	1.91	0	2.19	2.07	6.38	2.18
1987	3.61	2.12	2.57	3	1.72	1.38	1.93	0.4	0.66	0.29	2.35	5.4
1988	2.16	1.77	3.98	3.31	4.31	1.92	1.22	0.74	2.09	5.14	5.52	5.41
1989	5.56	1.83	4.91	2.63	3.05	0.84	1.04	2.57	0.25	2.87	10.09	4.02
1990	4.36	5.44	2.1	3.02	1.62	4.2	0.19	1.97	0.55	4.99	11.6	5.5
1991	4.98	3.36	2.65	3	1.47	0.6	0.15	3.34	0.05	1.27	6.93	2.88
1992	6.35	3.11	1.03	6.09	0.52	2.18	2.36	1.8	2.49	2.5	6.02	2.76
1993	3.53	0.49	3.09	3.1	3.96	2.48	2.07	0.61	0.32	1.86	2.4	3.94
1994	1.75	3.99	1.9	2.17	0.75	2.39	0.69	0.18	1.99	3.58	5	4.69
1995	3.93	3.71	2.38	1.75	0.57	0.77	2.13	2.51	0.96	5.12	9.01	5.46
1996	4.99	3.74	1.93	4.72	3.17							
1999				4.14	1.88	2.87	2.04	0.87	1.63	0.34	3.41	5.89
2000	5.26	3.1	1.93	2.83	2.61	4.34	2.32	1.46	0.97	2.45	0.73	2.08
2001	2.97	3.3	1.45	4.19	2.12	1.3	3.11					
SUM	225.27	172.03	143.01	137.25	106.33	90.56	64.73	66.14	89.83	167.09	242.65	236.1
AVERAGE (in)												
	4.62	3.51	2.97	2.64	2.11	1.81	1.24	1.37	1.83	3.47	4.98	4.72
AVERAGE (mm)												
	117	89	75	67	54	46	32	35	46	88	126	120