The Establishment and Application of the Relationship between Effective Porosity and Specific Capacity of Sediments, using Data from Well Drilling Records

March 2012

James M. Wilkinson

The Establishment and Application of the Relationship between Effective Porosity and Specific Capacity of Sediments, using Data from Well Drilling Records

March 2012 **James M. Wilkinson**

The Establishment and Application of the Relationship between Effective Porosity and Specific Capacity of Sediments, using Data from Well Drilling Records

March 2012

James M. Wilkinson

A Thesis for the Degree of Ph.D. in Engineering

The Establishment and Application of the Relationship between Effective Porosity and Specific Capacity of Sediments, using Data from Well Drilling Records

March 2012

Graduate School of Science and Technology
Keio University

James M. Wilkinson

To my Parents,

Wife,

and

son Ray

PREFACE

I, James M. Wilkinson, declare that the Ph.D. thesis entitled **"The Establishment, Calibration, and Application of the Relationship between Effective Porosity and Specific Capacity of Sediments, Using Data from Drillers' Records"** is the author's own research. This thesis contains no material, in whole or part, for the award of any other academic degree or diploma.

____

Signature and Date

ACKNOWLEDGEMENTS

The author expresses his sincere appreciation and indebtedness to his wise and respected supervisor, Dr. Naotatsu Shikazono, Professor, School of Science for Open and Environmental Systems, Graduate School of Science and Technology, Keio University, Yokohama, 223-8522, Japan, for his continued patience and insightful guidance during the tenure of my research and in the preparation of this manuscript.

The author would like to acknowledge his profound appreciation to Professor Hishida and Professor Ueda for their constructive suggestions and criticisms during the preparation of this manuscript.

The author is very appreciative for the continued financial support provided by Dr. Naotatsu Shikazono and the Keio Leading-edge Laboratory of Science and Technology Research Grant for the Ph.D. Program. Without this support the author would not have been able to complete and publish this research.

The author would like to express his sincere appreciation to Dr. Atsunao Marui of the AIST and Geological Survey of Japan for his continued motivational support and reviews. Additionally the author would like to show his gratitude to Mr. Daniel Snyder of the US Geological Survey for providing documents and data essential for this research.

Additionally the author would like to acknowledge the assistance of Dr. L M Lopez of Tokyo University of Social Welfare, Mr. Stephen Lacey of Oriental Consultants, Dr. Simon Clippingdale of Nihon Housou Kyokai, and Dr. Christopher Tancredi of Keio University for their invaluable advice, suggestions, and reviews of my research.

Most importantly, the author would like to show his sincere and humble appreciation to his wife, who has been so understanding, and providing unending help and support. Additionally I must not forget my son who has endured my devotion to my research, learning from it and expanding his own frontiers.

The author

TABLE OF CONTENTS

TABLE OF CONTENTS, CONT'D

TABLE OF CONTENTS, CONT'D

TABLE OF CONTENTS, CONT'D

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

ABSTRACT

This research was conducted 1) to determine if a relationship exists between specific capacity and effective porosity, and 2) to establish a direct relationship between specific capacity and effective porosity, and 3) to calibrate and test the relationship between specific capacity and effective porosity with a variation of sedimentary and rock environments, and 4) to confirm the reliability of this direct relationship between specific capacity and effective porosity. Conceptually the relationship between specific capacity and effective porosity existed. A thorough review of academic literature indicated that a direct relationship between specific capacity and effective porosity does not exist, although effective porosity has been studied and is one of many parameters that determine the flow of groundwater. However, effective porosity can not be measured from field studies. When a well is drilled, a drillers log is recorded with the construction details, usually including the depth of the well, screened sections, and water levels under static and pumping conditions, etc. From these data, we can easily calculate the specific capacity. Data obtained from direct measurement and simulated pump tests with a variety of sediment sizes in a laboratory were used to define the initial relationship between specific capacity and effective porosity. The equation that describes that relationship was further modified to determine the best solution for the laboratory test data. The equation developed in the laboratory experiments were subsequently applied to a field well database of 609 selected wells which penetrate a range of a variety of sediments and rocks. Through an

iterative process, the relationship developed in the laboratory was applied successfully to field data.

The final resultant equation that describes the relationship between specific capacity and effective porosity was successfully determined and calibrated using field data and revised for application to the selected wells which met the criteria to be used for this research. Individual values of effective porosity were calculated for each well using only the calculated specific capacity. The equation accurately produced effective porosity results that reflect conditions in the groundwater system of 9 layers of aquifers and aquitards of various lithologic descriptions ranging from unconsolidated sediments to volcanic rocks. The result is that this relationship to calculate effective porosity directly from specific capacity was confirmed and can be applied without knowing any details of the well construction or lithology. This is a major breakthrough in understanding the direct relationship between specific capacity and effective porosity and is shows that effective porosity can be easily calculated and used to determine aquifer characteristics. The result shows a significant advance over traditional methods of determining effective porosity from field data, making parameter estimation for groundwater flow models and simulations much simpler.

CHAPTER I

INTRODUCTION

1.1 Introduction

The United States Geological Survey (USGS) has been researching groundwater and the various relationships that exist within the underground environment for well over 100 years. The USGS has located, collected, sampled, and compiled many earth science data and made many discoveries and established many standards for geology and groundwater which are recognized worldwide, one of which is a groundwater study in the Portland area of Oregon. The research and results for "The Portland Basin Project", a groundwater project in the Portland Oregon area, have been published (D. T Snyder, Wilkinson, & Orzol, 1998; Swanson, McFarland, Gonthier, & Wilkinson, 1993) and are a source for some of the basic well construction data used in this research. Additional published research from the USGS was referred to as necessary during the course of this research (Hinkle & Snyder, 1997; McCarthy & Anderson, 1990; McFarland & Morgan, 1996; Morgan & McFarland, 1996). Several years ago the author was employed as a Professional Hydrologist at the USGS and responsibilities included locating, collecting and compiling field data such as construction information, water levels, water samples, usage, etc. from wells (McCarthy & Anderson, 1990; McCarthy, McFarland, Wilkinson, & White, 1992; Swanson et al., 1993). Additionally geologic field data was collected to confirm and update previous mapping as well as mapping previously unmapped areas (Swanson et al., 1993). Also he authored and coauthored several reports and maps of this project (McCarthy et al., 1992; D. T Snyder et al., 1998; Daniel T. Snyder, Wilkinson, & Orzol, 1996; Swanson et al., 1993; Thomas, Wilkinson, & Embrey, 1997). Around 1992 the hydrogeologic mapping was concluded and published (Swanson et al., 1993). With this data the groundwater model could be programmed, however there were other parameters that were needed. Hydraulic conductivity and transmissivity were estimated but the effective porosity of the aquifer sediments was not known. The author worked on a possible relationship for calculating effective porosity from hydraulic conductivity. However it was quickly realized that this method was not more reliable than just choosing a value from published ranges (Morris & Johnson, 1967). Some time was used to explore other relationships for effective porosity but with little success at that time. It was concluded that a method to calculate effective porosity directly from other accurate parameters did not exist (D. T Snyder et al., 1998). Therefore a compromised method was used to determine the effective porosities (McFarland & Morgan, 1996; Morgan & McFarland, 1996; D. T Snyder et al., 1998). The issue of a direct method to calculate effective porosity was never resolved. However, the author has maintained this conceptual hypothesis since that time and that is the focus of this thesis. He has continued to collect data for over 20 years for this research. The scope of this research is very narrow and specific. A relationship was established, calibrated, and tested successfully both in the laboratory and with field data and this thesis provides a complete and detailed description and explanation of this research and the results of this major breakthrough in understanding effective porosity. Effective porosity is essential to understand the flow of groundwater since it represents the limiting parameter to the volume and rate of groundwater flow. The volume and rate of groundwater flow is inversely related to the effective porosity. Additionally the effective porosity is the determining parameter for the volume of water that an aquifer can contain that can be released under natural or anthropogenic influences. These points are very important for understanding groundwater flow and estimating the volume of water in an aquifer. Without effective porosity data it would be very difficult if not impossible to estimate the volume of water in an aquifer. This research represents a completely new approach to evaluating effective porosity accurately. The ability to readily calculate effective porosity will enhance parameter estimation for groundwater models as well as the ability to estimate the volume of groundwater reserves. Please refer to Appendix I for a list and explanation of symbols used in this document.

1.2 Research Questions

The primary question that was answered in this research is whether or not there is a direct relationship between effective porosity and specific capacity that can be described mathematically, and if so, determine the equation that relates effective porosity and specific capacity. Additional questions that were addressed and answered were,

- Under what conditions is this relationship valid?
- Can this relationship be used with any type of geologic environment?
- What are the requirements for using this relationship?

1.3 Assumptions

Although it is possible to describe groundwater flow, it is common for groundwater experts to make assumptions and generalizations to account for unknown or estimated parameters. Typically very little is known about the aquifer and groundwater flow if no previous research has been done in that specific area, so assumptions are made about the lithology, heterogeneity, homogeneity, isotropy, compressibility, water density, etc. Additionally, data in the driller's log may or may not have accurate descriptions of the lithology, and therefore are open to interpretation, or misinterpretation, and hence, not necessarily reliable. This is also why a groundwater model must be run through several iterations to adjust the parameters to achieve results that match measured and observed data. The research and results presented here can and will help modelers calculate effective porosity, which is a necessary parameter for groundwater flow modeling, more quickly and accurately.

CHAPTER II
LITERATURE REVIEW

2.1 Overview

For many decades many researchers have analyzed and studied groundwater and the movement of groundwater. They have established many parameters and equations to describe relationships between the parameters which have laid the foundation for modern research and groundwater modeling. The theories and equations that were established many years ago have been subsequently used to establish the equations used to describe groundwater flow under a variety of conditions. These also include the various equations that have been developed for the various types of groundwater modeling, movement of groundwater, as well as chemical reactions in the groundwater environment. However there is one common limiting theme found among the published literature. Hydraulic conductivity and transmissivity are difficult to determine directly in field or laboratory conditions, whereas specific capacity is easily obtained through direct measurements.

Some textbooks that are considered definitive sources of hydrogeology (Fetter, 2000), and drilling methods and groundwater (Driscoll, 1986; Sterrett, 2007) and contain excellent descriptions about the development and establishment of groundwater parameters. Additionally other researchers have determined relationships between hydraulic conductivity and effective porosity (Ahuja, Cassel, Bruce, & Barnes, 1989) as well as between transmissivity and specific capacity (Ahuja et al., 1989; Custer, Donohue, & Bruce, 1991; Driscoll, 1986; Kauffman, 1999; Mace, 1997; Razack & Huntley, 1991) in studies of various hydrogeologic environments. However, in each case the research is limited in scope and application. For example, Ahuja et al. (1989) focus on the hydraulic properties of near surface soils, while Mace (1997) worked in a karst environment. Driscoll (1986) established purely empirical equations and it is unknown what kind of geologic environment that Kauffman (1999) because it is an unpublished work. An empirical relationship between hydraulic conductivity and effective porosity was established by Morgan & McFarland (1996) that combined the results from Ahuja et al. (1989) with data from Morris and Johnson (1967) to calculate effective porosity, however it limited the values to a maximum effective porosity of 31 percent (Hinkle & Snyder, 1997; Morgan & McFarland, 1996). However, details of how this relationship was established were not included in the report. Subsequently this method was further modified with a multiplier function to allow a maximum effective porosity of 35 percent (Snyder et al., 1998). However it was pointed out that the estimated hydraulic conductivity spans over 5 orders of magnitude and can have significant error. This is because hydraulic conductivity and transmissivity are estimated parameters and can not be directly observed or measured. Hence any calculations based on these estimated values will contain a corresponding amount of error.

Other researchers have pointed out sources of interference with determining hydraulic parameters. These sources of interference with determining effective porosity are tidal and atmospheric pressure (Rojstaczer & Agnew, 1989), and biological clogging from a form of bacteria referred to as slime (Vandevivere & Baveye, 1992).

2.2 Theoretical Background

This section is based on explanations in Fetter (2000) except where noted. It reviews and discusses the fundamental principles of physics upon which groundwater flow and associated parameters are based. Groundwater has energy in the forms of mechanical, thermal, and chemical energy. There are 3 forces which influence groundwater, gravity, external pressure, and molecular attraction. When groundwater flows through a porous medium there are forces resisting the flow, collectively known as friction.

2.2.1 Basic Principles of Mechanical Energy

There are different types of mechanical energy, but this explanation will focus on those that are related to fluids; kinetic energy, gravitational energy, and pressure energy.

Kinetic energy refers to the motion or movement of a body or substance and in Newtonian physics and is defined as:

$$E_k = 1/2mv^2 \tag{2.1}$$

where E_k is the kinetic energy (ML^2/T^2), m is mass (M), and v is the velocity (L/T). The unit of kinetic energy is the joule which is one newton-meter. The joule is also the unit of work. When a mass m of water is moved upward a distance of z from a reference point (a datum), then work has been done to move the water upward. This work is defined as:

$$W = Fz = (mg)z \tag{2.2}$$

where W is work (ML^2/T^2), z is the elevation of the center of gravity of the fluid above the reference elevation (L), m is the mass (M), g is the acceleration of gravity (L/T^2), and F is the force (ML/T^2). The mass of water now has the energy equal to the work done in lifting it. This is known as potential energy that is related to gravity, or gravitational potential energy:

$$W = E_g = (mg)z \tag{2.3}$$

where E_g is the gravitational potential energy.

However, another source of potential energy from pressure of the fluid is also influencing it. This pressure is defined as:

$$P = F / A \tag{2.4}$$

where P is the pressure (M/LT^2), and A is the cross-sectional area perpendicular to the direction of the force (L^2). This pressure is the potential energy per unit volume of fluid. For a unit volume of fluid, the mass m is numerically equivalent to the density ρ since density is defined as mass per unit volume.

The total energy per unit volume of fluid is the total of the kinetic, gravitational, and fluid-pressure energies:

$$E_{tv} = \frac{1}{2}\rho v^2 + \rho g z + P \tag{2.5}$$

where E_{tv} is the total energy per unit volume. And if Equation 2.5 is divided by ρ , then the result is total energy per unit mass, E_{tm}

$$E_{tm} = \frac{v^2}{2} + gz + \frac{P}{\rho} \tag{2.6}$$

which is also known as the Bernoulli equation. The derivation of the Bernoulli equation can be found in fluid mechanics textbooks (Hornberger, Raffensperger, Wiberg, & Eshleman, 1998).

Under steady state flow conditions, the flow is considered to be frictionless and incompressible along a smooth line of flow. Under these conditions the three components of Equation 2.6 are constant:

$$\frac{v^2}{2} + gz + \frac{P}{\rho} = \text{constant} \tag{2.7}$$

Equation 2.7 is useful for comparing the components of mechanical energy. If Equation 2.7 is divided by g:

$$v^2/2g + z + P/\rho g = \text{constant} \tag{2.8}$$

This equation has all terms in units of energy per unit weight (J/N) and all units in length dimensions. The sum of these three factors is the total mechanical energy per unit weight, also known as hydraulic head, *h*.

2.2.2 Force Potential and Hydraulic Head

The total potential energy, which consists of kinetic, elevation, and pressure energy, is also referred to as the force potential:

$$\Phi = gz + P/\rho = gz + \rho g h_p / P = g\left(z + h_p\right) \tag{2.9}$$

where h_p is the pressure head. Since $z+h_p= h$, the hydraulic head,

$$\Phi = gh \tag{2.10}$$

where Φ is the force potential. In theory, the force potential is the force behind groundwater flow. However, gravity can be considered constant, eliminating the need for force potential. Therefore, hydraulic head is the potential to use for as the energy per unit weight, which has only the dimension of length, which is easily measured.

2.2.3 Porosity

Two important parameters that are related to storage of water in an aquifer are porosity and specific yield. The voids, cracks, and pore spaces in rocks and sediments are extremely important in hydrogeology since water can occupy and pass through these otherwise impenetrable solid rocks. The porosity is the percentage of the rocks or sediments that consists of voids and is defined as:

$$\phi = 100V_v / V \tag{2.11}$$

where ϕ is the porosity (percentage), V_v is the volume of the void space in a unit volume of material (L^3), and V is the unit volume of the material, including voids and solids (L^3). Porosity can also be expressed as:

$$\phi = 100\left[1-\left(\rho_b/\rho_d\right)\right] \tag{2.12}$$

where ρ_b is the bulk density of the aquifer material (M/L^3) and ρ_d is the particle density of the aquifer material (M/L^3).

Peyton et al. (1986) concluded that at the molecular level porosity and effective porosity are the same and therefore effective porosity does not exist in a groundwater based environment. However, Sterrett (2007) explains that in addition to primary and secondary porosity there is effective porosity which is defined as the percentage of interconnected pore space. It is also pointed out that the volume of water contained in an aquifer is of interest; however it is more important to consider how much water can actually be released from storage, or the effective porosity. Porosity is the volume of water that an aquifer can hold but it does not show how much water that can be yielded from the aquifer. Additionally, Domenico et al. (1991) points out that an important distinction is the difference between total porosity, which does not require pore connectivity, and effective porosity, which is defined as the percentage of interconnected pore space. It is emphasized that when evaluating groundwater properties effective porosity is very important to understand.

Additionally porosity can be affected by several factors such as sorting, packing, induration, fractures, reworking, and depositional environment.

2.2.4 Specific Yield

Sterrett (2007) defines specific yield as the volume of water that can be drained from a saturated material under the force of gravity. However, this volume of water drained from the saturated material is only a part of the total volume of water in the saturated material. Therefore specific yield is equivalent to effective porosity. As noted, not all of the water is drained; some of the water is retained in the material by molecular attraction and capillarity. This is known as the specific retention and is inversely proportional to specific yield. The specific yield plus the specific retention equals the porosity of the aquifer. Specific yield and specific retention are expressed as percentages. Another closely related term is the storage coefficient which is the volume of water added or released from storage per unit change in head per unit area.

2.2.5 Darcy's Law

Darcy (1856) conducted a series of experiments to estimate the volume of water that would pass through sand filters using a vertical pipe filled with sand. He discovered through observations and measurements that the rate of flow through a column of saturated sand is proportional to the difference in hydraulic head at the ends of the column, and is inversely proportional to the length of the column. The constant of proportionality that linked the parameters is hydraulic conductivity. This relationship is now known as Darcy's Law and can be shown as:

$$\frac{Q}{A} = q = -K\left[\frac{(h_1 - h_2)}{L}\right] \tag{2.13}$$

where Q is the flow rate (L^3/T), A is the cross-sectional area perpendicular to groundwater flow (L^2), q is the volumetric flow rate perpendicular to the direction of groundwater flow (L/T), h_1-h_2 is the difference in hydraulic head (L), L is the distance along the flow path between the points where h_1 and h_2 are measured (L), and K is the hydraulic conductivity (L/t).

Energy is lost due to friction between the water and walls of the pores. Equation 2.13 states that energy loss is proportional to the velocity of flow under laminar conditions; the faster the flow, the higher the energy loss.

2.2.6 Hydraulic Conductivity

Hydraulic conductivity is a property of water bearing material that relates its ability to transmit water at a standard temperature and density. Intrinsic permeability is the ability of material to transmit a fluid. Hydraulic conductivity is:

$$k = \frac{K\mu}{\rho g} \tag{2.14}$$

where k is the intrinsic permeability (L^2), K is the hydraulic conductivity (L/T), μ is the dynamic viscosity of a particular fluid (M/LT), ρ is the density of a particular fluid (M/L^3), and g is the acceleration of gravity (L/T^2). Intrinsic permeability is generally used in the petroleum industry because of the different phases and densities (eg. gas, oil, water) are analyzed for the rate of movement through the porous materials. As expected, hydraulic conductivity is strongly influenced by pore shape and size, the interconnectivity between pores, and the physical and chemical properties of the water. This relationship is explained further in section 2.3.

2.2.7 Permeability

Permeability is used in place of hydraulic conductivity which can lead to confusion. However, permeability uses intrinsic permeability in the calculations to account for different fluid densities, whereas hydraulic conductivity is used for groundwater calculations. Therefore permeability and intrinsic permeability are used in a wider range of environments and the equations have many variations to account for the different environments, which are not needed for groundwater. A relationship between permeability and effective porosity was not considered since permeability is not applicable to this study.

2.2.8 Transmissivity

Transmissivity is the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the material with a hydraulic gradient of 1. Transmissivity is related to hydraulic conductivity by using the saturated thickness in the equation:

$$T = bK \tag{2.15}$$

where T is the transmissivity (L^2/T), b is the saturated thickness (L), and K is the hydraulic conductivity (L/T). Transmissivity assumes that the water flows horizontally, which is not always a valid assumption.

Other related parameters are elasticity, storativity, specific storage, and specific yield. In the saturated zone the head creates pressure on the sediments. Any change of head will result in the expansion or contraction of the sediments; this is elasticity and can affect the effective porosity. Storativity (dimensionless) is the volume of water that a porous unit will absorb or expel from storage per unit surface area per unit change in head. The specific storage, also known as the elastic storage coefficient, is the amount of water per unit volume of a saturated material that is stored or expelled from storage due to compressibility and pore water per unit change in the head. It is described as:

$$S_s = \rho_\omega g(\alpha + \phi\beta) \tag{2.16}$$

where S_s is the storage coefficient (1/L), ρ_ω is the density of the water (M/L^3), g is the acceleration of gravity (L/T^2), α is the compressibility of the sediments ($1/(M/LT^2)$), ϕ is the porosity (L^3/L^3), and β is the compressibility of water ($1/(M/LT^2)$). There are variations of Equation 2.16 for various conditions such as confined and unconfined aquifers. Another important parameter is specific yield which refers to the storage or release of water due to head change; specific yield is the same as effective porosity. This can also be described by storativity and in an unconfined aquifer they are related by:

$$S = S_y + bS_s \tag{2.17}$$

where S is the storativity (dimensionless), S_y is the specific yield (dimensionless), b is the saturated thickness of the material (L), and S_s is the specific storage (1/L).

2.2.9 Homogeneity and Isotropy

In addition to hydraulic conductivity and specific yield (effective porosity), another important property is the thickness.

Homogeneity refers to a hydrogeologic layer that has the same properties at all locations. This would include grain size and distribution, effective porosity, transmissivity, and storativity.

A heterogeneous layer would have spatial changes in hydraulic properties such thickness. A heterogeneous layer is nonhomogeneous and properties can and do vary in all dimensions.

If the intrinsic permeability is the same in all directions then the layer is isotropic. Conversely, a layer in which the intrinsic permeability is variable is anisotropic.

2.3 Laboratory Methods

A common method for estimating or calculating effective porosity is through extensive laboratory testing of sediment properties such as particle size, shape, packing, sorting, pore space, etc. (Barr, 2001; Bernabé, Mok, Evans, & Herrmann, 2004; Dias, Teixeira, Mota, & Yelshin, 2004; Dunning, 2005; Jarvis et al., 2002; Kamann, Ritzi, Dominic, & Conrad, 2007; Morin, 2006; Morris & Johnson, 1967; Sperry & Peirce, 1995; Zhang, Ward, & Keller, 2011). The laboratory research of Morris & Johnson (1967) is considered one of the definitive works for establishing effective porosity ranges for virtually every type of sediment and rock. These data were established through extensive analyses of over 10,000 field samples from 42 states over a period of 12 years and have been compiled to establish these ranges of effective porosity. These established ranges of effective porosity are all based on laboratory tests and not related to any other parameters such as specific capacity. Other researchers have quoted portions of Morris & Johnson (1967) or have focused on very specific environments relevant to the scope their work (Ahuja et al., 1989). However, due to the limited scope of their work the application of their results are restricted to those environments. The research in this thesis can not be limited to these environments to be valid. A similar type of analysis uses binary mixtures in laboratory experiments to represent combinations of sediment sizes (Bernabé et al., 2004; Dias et al., 2004; Zhang et al., 2011). However it has been pointed out that the weak point of this method is the inability to duplicate ideal packing of large and small sediments, not to mention the infinite combinations. Research by Zhang *et al*. (2011) was based on glass beads to simulate sediments, and reassures us that the results from the laboratory testing either overestimate or underestimate effective porosity values with this method. Additionally none of these researches established relationships with other parameters. For the research in this thesis these data are unusable for the above stated reasons and conclusions.

It should be noted that although there has been extensive laboratory tests of sediments, none of the results have been applied to field data successfully. Although these ranges are useful for illustrative purposes, choosing a value from a range can introduce considerable error in models and simulations. It requires several iterations of trial and error to arrive at a value of effective porosity to match the field data or calibrate a model. However, this method does not take into account the spatial variability of effective porosity that exists due to the inhomogeneous nature of the lithology inherent to the depositional environment. This is an important point for consideration since the focus of this thesis was to develop a relationship that can be applied in any environment regardless of those conditions.

2.4 Field Methods

Using tracers is common when there are at least 1 or more wells available to sample (Domenico & Schwartz, 1991; Gloaguen, Chouteau, Marcotte, & Chapuis, 2001; Haggerty, Schroth, & Istok, 1998; Hall, Luttrell, & Cronin, 1991; Javandel, 1989; Stephens et al., 1998; White, 1988; Yeh, Lee, & Chen, 2000). This method is time consuming and expensive (Stephens et al., 1998), as well as highly dependent upon the groundwater gradient and hydraulic conductivity (Javandel, 1989). Additionally Hall *et al*. (1991) concluded that laboratory tracer experiments did not accurately coincide with estimated results. Furthermore tracer tests are generally used for estimating hydraulic conductivity or transmissivity to use for calculating effective porosity. Remedial workers tend to favor this method over others, and it is widely used in remedial applications. However this method can not be used to measure effective porosity of underground sediments directly or indirectly and it is still difficult to measure hydraulic conductivity or transmissivity accurately. However, when pumping the water for tracer tests the drawdown and pumping rate can be obtained very easily to calculate specific capacity.

2.5 Geophysical Methods

Several other methods have been utilized to determine the effective porosity, total porosity, and other hydraulic parameters. Cunningham (2004) describes the use of ground-penetrating radar, digital optical borehole images, and core analyses to determine effective porosity and hydraulic conductivity. These methods tend to be expensive, time consuming, and require the proper equipment. Wang *et al*. (2003) used laser polarized xenon nuclear magnetic resonance (NMR) methods to simultaneously determine permeability and effective porosity of oil reservoir rocks with reasonable accuracy. This method can be very useful but it does require equipment that makes it very impractical for quick surveys. Resistivity, seismic, and magnetic surveys are common but are very limited in the scope of the data they can collect. Most can and are used to determine differences in lithology and depth to water bearing zones. They have no relation for this research.

2.6 Summary

A continuing and ongoing literature search for over 20 years has not turned up any references to calculating effective porosity directly from calculated or measured specific capacity. However, effective porosity is essential to estimate the volume of groundwater in an aquifer. Most of the published research focuses on establishing ranges of effective porosity and project specific explanations of methods used to estimate hydraulic conductivity and transmissivity, which are subsequently used to estimate effective porosity. None of these published results relate laboratory results to field data, nor do they focus on the type of research presented in this thesis. Additionally since hydraulic conductivity and transmissivity are estimated, they contain and undetermined amount of error. This inherent error is then passed on through subsequent calculations that are based on these estimated parameters.

CHAPTER III
METHODS AND CALCULATIONS

3.1 General Description

Since a relationship between specific capacity and effective porosity had not been established yet, it was determined that an initial equation to describe the relationship between specific capacity and effective porosity should be established in the laboratory under controlled conditions. The laboratory experiments included direct measurement of effective porosity and simulated pumping tests. Once the initial relationship was established, the equation was applied to a database of selected field wells and revised as necessary to establish the final equation that describes the relationship between specific capacity and effective porosity. The flowchart in Figure 1 shows the step by step process.

Step one represents the acquisition and construction of the laboratory equipment and supplies, and the rental of an suitable space. This step also includes selecting and buying the sediments used for the subsequent experiments as explained in section 3.2.

The purpose of steps two and three were to collect baseline data under a controlled environment, to be used to establish the initial relationship. Step two established the effective porosity for each sediment size, and referred to as the initial effective porosity as explained in section 3.2.1. Step three established the drawdown at various pumping rates for each sediment size as explained in section 3.2.2.

Step four is the analysis and selection of established equations to use for testing with the data from steps two and three and is explained in sections 3.3 and 3.3.1.

The data and information generated in steps two through four were used to establish the initial relationship between drawdown, pumping rate, and effective porosity. After several iterations an initial relationship was established based on the laboratory data as explained in sections 3.3.1 and 3.3.2.

Well construction data (section 3.4) and hydrogeologic data (section 3.5) were used in step five to select the wells for the database used in this research as explained in section 3.6.

The selected wells from step five were used in step six to apply the initial equation from section 3.3.2 as explained in section 3.7. The initial results of this equation had to be revised through several iterations as explained in section 3.7.1 to arrive at a stable equation that represents relationship between specific capacity and effective porosity (section 3.7.2).

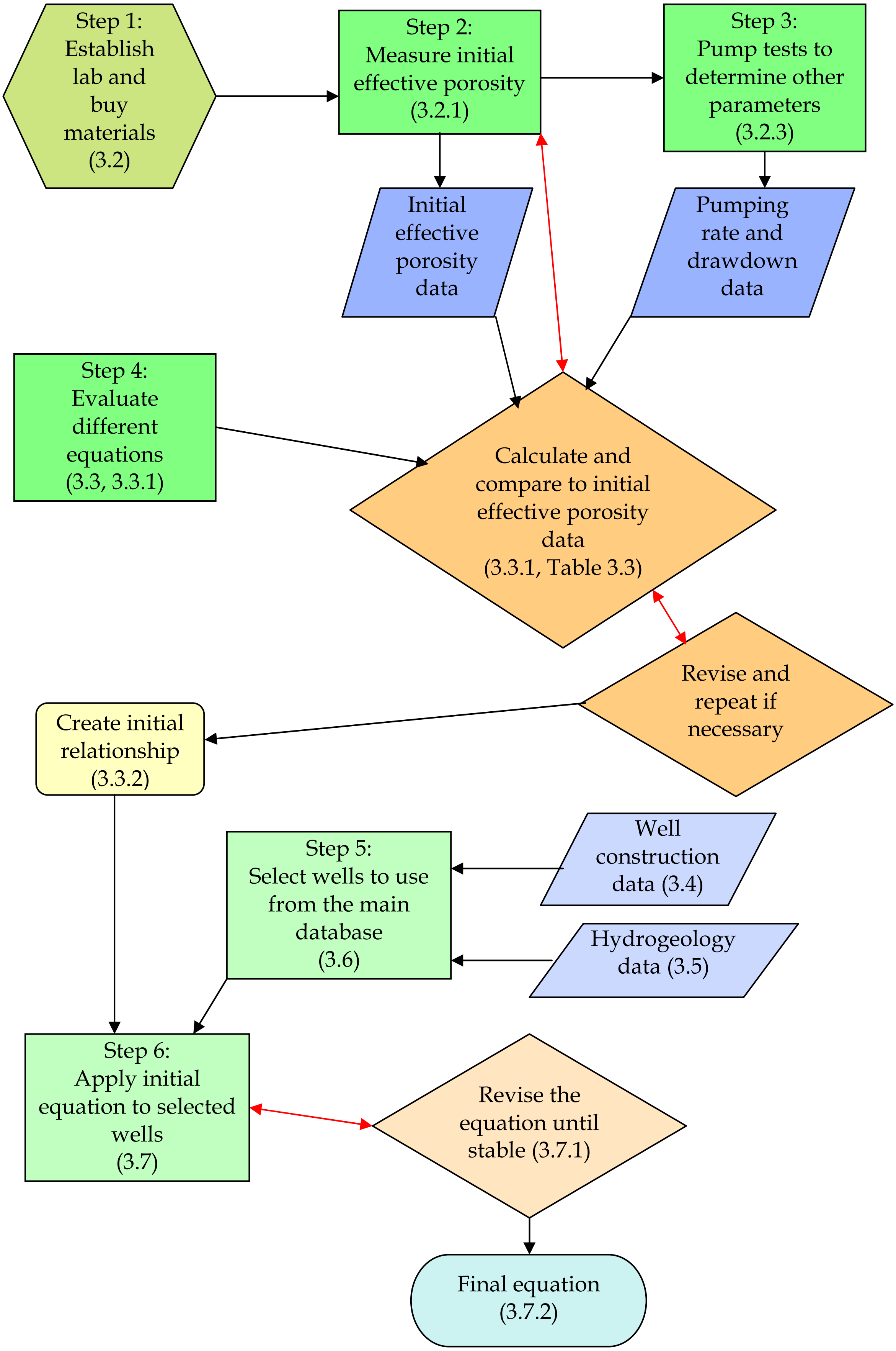

Fig. 3.1: Flowchart of the methodology

3.2 Laboratory Experiments

3.2.1 Sample Materials

It was determined that it would be better to obtain very well sorted sediments for the laboratory experiments from a local supplier. Five sediments of specific sizes were used for the experiments and shown in Figure 3.2. They are medium sand (MS), 0.25-0.5 mm (Figure 3.3a), coarse sand (CS), 0.5-1.0 mm (Figure 3.3b), fine gravel (FG), 4.0-8.0 mm (Figure 3.3c), medium gravel (MG), 8.0-16.0 mm (Figure 3.3d), and coarse gravel (CG) 16.0-32.0 mm (Figure 3.3e). All of the sediments were well sorted and rounded. These sediments were used to determine the initial effective porosity using direct measurements. Pump tests were simulated with each sediment size using graduated pumping rates. The data generated from these two steps were used to determine a preliminary relationship between effective porosity and specific capacity. It should be noted that packing and sorting affect the measurements; however, these effects were minimized during the experiments by using very well sorted sediments as well as thoroughly packing the sediments.

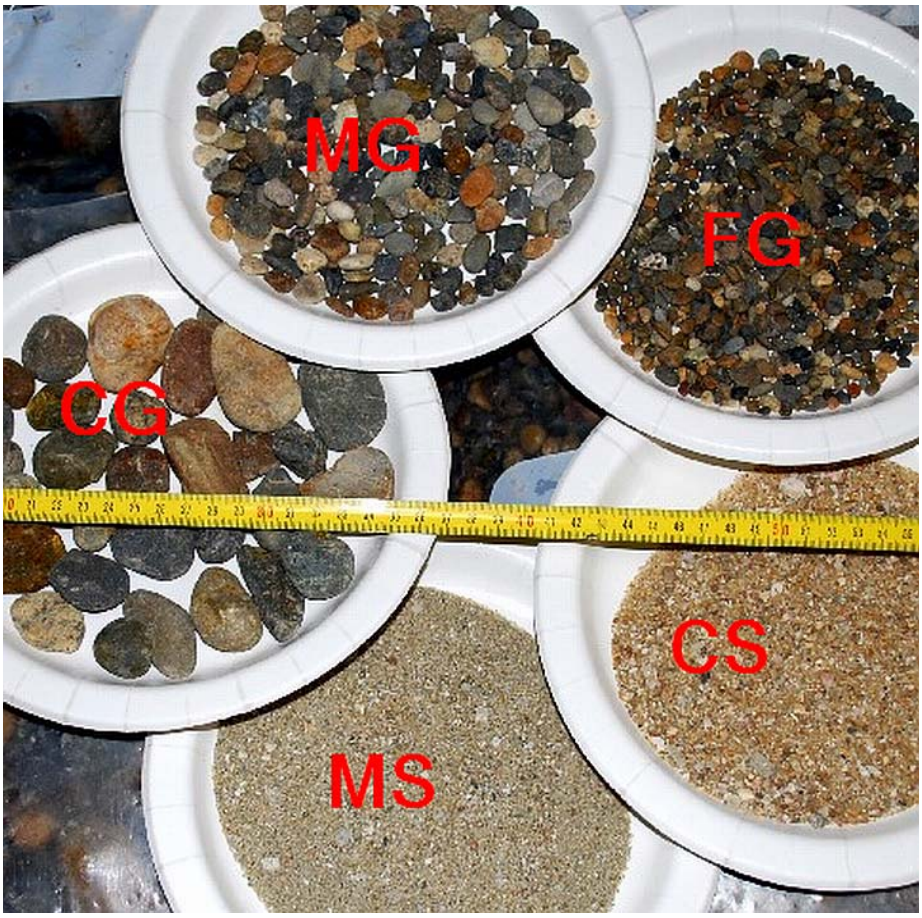

Fig. 3.2: Five selected sizes of sediments used for laboratory tests

Fig. 3.3a: Medium sand

Fig. 3.3b: Coarse sand

Fig. 3.3c: Fine gravel

Fig. 3.3d: Medium gravel

Fig. 3.3e: Coarse gravel

3.2.2 Direct Measurements

This method of measurement is based on the total weight of the water divided by the weight of the saturated sediments and expressed as a percentage. This method is based on the standard definition of porosity, a percentage defined by the volume of the void space divided by the total volume of the material. More precisely, one minus the ratio of the total bulk density to the density of the particle density and expressed as a percentage.

3.2.2.1 Materials and Equipment

Direct measurement is a relatively simple procedure requiring a minimum of equipment. Clean 3 liter and 5 liter plastic containers were weighed and calibrated. A scale was used to weigh the sediments and water. The scale specifications were 0 to 30 kg within +/- 1% tolerance. Enough of each sediment size was used to completely fill the plastic container.

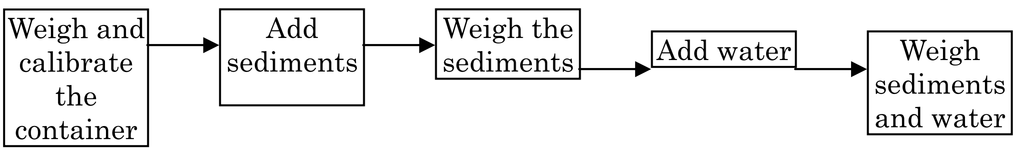

Fig. 3.4: Schematic diagram of the direct measurement method

3.2.2.2 Procedure

The 3 liter plastic container was cleaned, weighed, and the scale zeroed, and then the container was completely filled and packed with air dried sediment and weighed. Initially unpacked sediments were used, and then repeated with packed sediments. Packing consisted of adding some sediment, then alternately vibrating and tamping the sediments, then add more sediment and repeating this procedure to achieve the maximum density. The weight of the dry sediments was determined by subtracting the weight of the container. Then the container of dry sediment was filled with water to the brim, completely saturating the sediment, and then weighed. Examples are shown in Figures 3.5a and 3.5b.

Fig. 3.5a: Packed dry gravel

Fig. 3.5b: Saturated gravel

The weight of the water was determined by subtracting the weight of the sediments from the total weight of the saturated sediments. The ratio of the weight of the water to the weight of the saturated sediments was used to calculate effective porosities for each sediment size.

3.2.2.3 Results of the Direct Measurements

Each sediment size was measured at least 3 times to ensure the results were consistent and could be duplicated for both packed and unpacked sediments. The average results of the measurements are shown in Table 3.1.

Table 3.1 Average measured effective porosity for each sediment size (+/- 0.01)

Sediment	MS	CS	FG	MG	CG
Average measured effective porosity (%), unpacked	35.4	30.2	37.8	38.5	40.5
Average measured effective porosity (%), packed	28.9	22.4	29.8	30.7	34.6

3.2.3 Pump Tests

Pump tests were simulated in the laboratory to measure the sediment properties under simulated pumping conditions. Using pumping rate and drawdown data from the pump tests, specific capacity was calculated to use for the development of the initial relationship between specific capacity and effective porosity.

3.2.3.1 Materials and Equipment

To simulate pump tests with each sediment size, the main equipment consisted of a 200 liter tank, a 50 liter/minute pump, a flow meter, and PVC pipes with valves; a schematic diagram of the equipment and plumbing is shown in Figure 3.6 and shown in a photograph in Figure 3.7. Inside the tank, a 55 cm long, 4 cm wide slotted PVC pipe, which represents the well, was installed in the center and connected to the external pump through the plumbing in the bottom of the tank (Figure 3.8). The pump was connected to the plumbing, a network of PVC pipes and valves to control and monitor the flow (Figure 3.9). One of the channels routed the water through the flow meter, which allowed direct observation and control of the flow up to 30 liters/min. By bypassing the flow meter, the pump could run at full capacity, 50 liters/min. The water was then routed back to the tank where the water was distributed around the perimeter of the tank, forming a recharge boundary to prevent the water level in the tank from becoming too low (Figure 3.10).

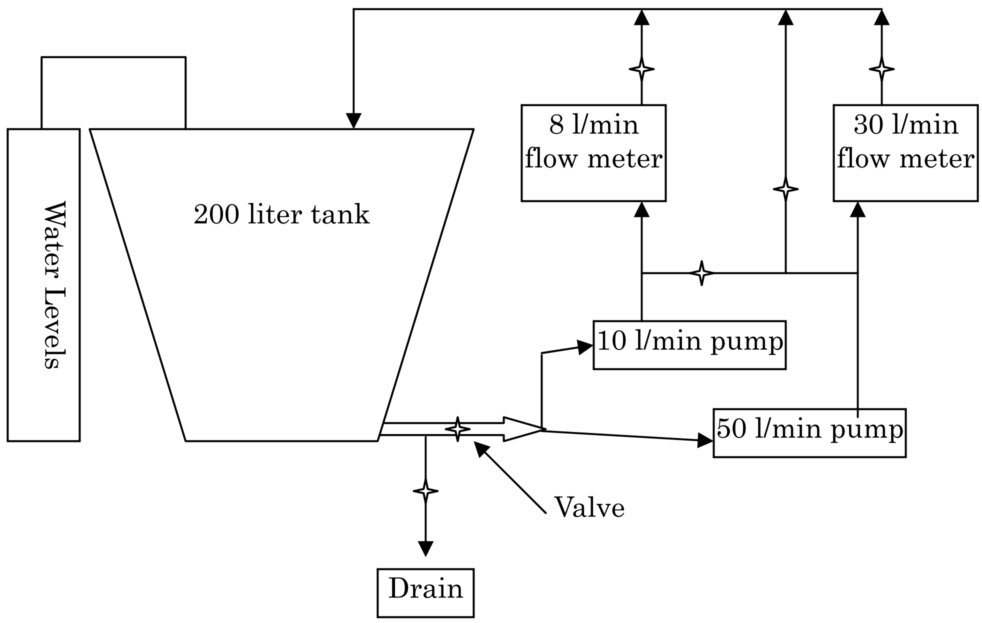

Fig. 3.6: Schematic diagram of the equipment and plumbing connections

Fig. 3.7: Overview of the equipment showing the 200 liter tank, pump, flow meter, water level monitor, and PVC pipes and valves

Fig. 3.8: Top view showing the center slotted pipe, plumbing, recharge ring, and water level tubes

Additionally 5 mm tubes were used at equal spacing from the center to the edge of tank to monitor water levels from the center of the tank to the perimeter of the tank (Figure 3.8). These tubes were connected to vinyl tubing attached to a board with calibration marks for the water levels (Figure 3.11). A steel tape was used to mark the water level board at 1 centimeter intervals. These reference marks have an estimated tolerance of +/- 1 mm.

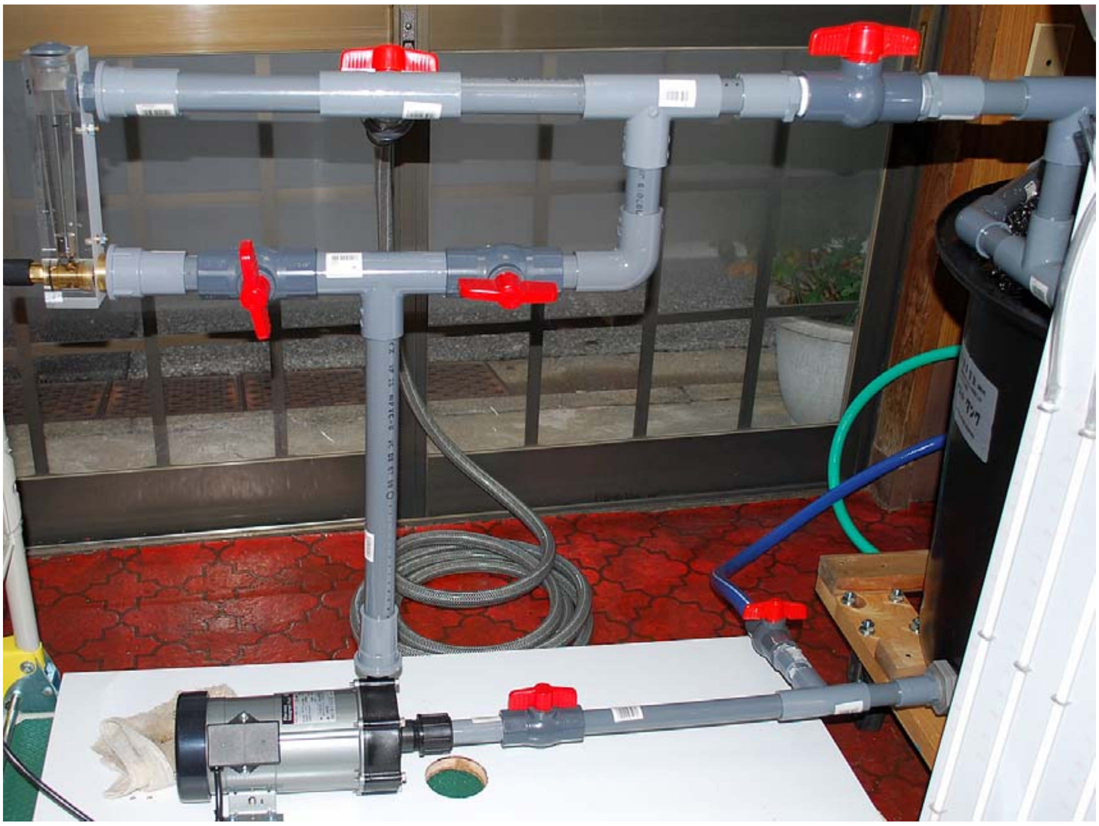

Fig. 3.9: PVC plumbing and valves

Fig. 3.10: Oblique view of the water level tubes, center slotted pipe, and recharge ring

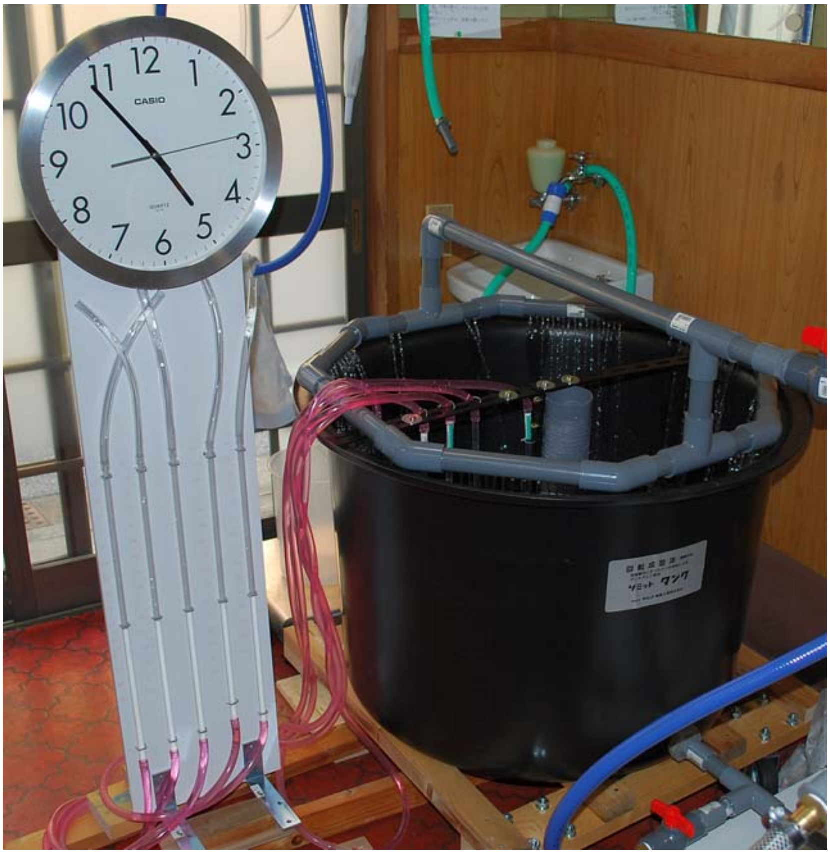

Fig. 3.11: Water level board with connecting tubing

Later, when trying to conduct pump tests with the fine grained sediments it was found that the 50 liter/min pump was too strong. So a smaller pump and flow meter were added to the plumbing for controlled pumping rates below 10 liters/min (Figure 3.12). Additionally, the course and medium sands entered the slotted center pipe and subsequently the pump jammed. The center slotted pipe and the water level tubes all had to be wrapped in fine mesh screen and surrounded by gravel packing to create a filter to block the sand from entering the center pipe and jamming the pump. Figure 3.13 shows the screened center slotted pipe and Figure 3.14 shows the array of water level tubes after being screened and filled with gravel. Figure 3.15 shows the tank with the screened pipe and tubes with gravel packing. Figure 3.16 shows the bags of sediments of each size that were used to fill the tank for the pump tests.

Fig. 3.12: Dual pump and flow meters with PVC plumbing and valves

Fig. 3.13: Double layer screened center pipe

Fig. 3.14: Screened water level tubes with gravel packing

Fig. 3.15: Screened and packed water level tubes and center pipe installed in the tank

Fig. 3.16: Bags of sediments of each size used for the laboratory tests

3.2.3.2 Methods

The 200 liter tank was filled and packed with the selected sediment size, 2 bags of sediment at a time, tamping the sediments to pack them, then adding 2 more bags of sediment and repeating the procedure until the tank was filled with packed sediments (Figure 3.17).

Fig. 3.17: Filling and tamping the tank with sediments

Then the tank was filled with water to saturate the sediments. The water was added from the bottom of the tank to ensure that the sediments became fully saturated (Figure 3.18).

Fig. 3.18: 200 liter tank filled with saturated sediments

Using the flow meter to control and monitor the flow rate, several pump tests were conducted at different pumping rates for each sediment size (Figures 3.19 and 3.20). The pumping rates for each sediment size are shown in Table 3.2. Each pump test continued until the water levels in the tank had stabilized, which didn't take very long because of the scale of pump test.

Fig. 3.19: Flowmeter at 20 liter/min

Fig. 3.20: Digital flowmeter at 3 liters/min

A high-speed digital camera photographically recorded the water levels for each pump test and some examples are shown in Figures 3.21 and 3.22. A total of 1274 pictures were taken to record all of the pump tests and care was taken to adjust the tripod for a parallel angle.

The water in the tubes formed a meniscus and the water levels were measured by observing the base of the meniscus. However many of the water levels were not precisely on the calibration marks. In those cases a metal measuring rule was used to determine the water level to the nearest millimeter at the base of the meniscus. It is estimated that human error accounted for about +/- 1 mm of error in the observations. However the error was minimized by using the same point of reference for each measurement.

These pump tests generated values for Q, s, and b, and are summarized in Table 2. Note that b is constant, but it is not a constant in the equations. It represents the open interval corresponding to the saturated zone of the sediments. In this experiment the equipment did not change, only the sediments and pumping rates, therefore the value of b remained the same for all tests.

Fig. 3.21: Start of the pump test for MS at 4 liters/min (0.0 cm)

Fig. 3.22: End of the pump test for MS at 4 liters/min (15.3 cm)

Table 3.2 Pump test results for each sediment size

Lithology	Q liters/min +/- 0.05 liters	b cm +/- 0.5 mm	s cm +/- 0.5 mm
CG	30.0	55.0	2.0
CG	50.0	55.0	3.0
MG	30.0	55.0	2.1
MG	50.0	55.0	3.6
FG	30.0	55.0	3.0
FG	50.0	55.0	5.0
CS	1.0	55.0	4.1
CS	2.0	55.0	7.9
CS	3.0	55.0	11.4
CS	4.0	55.0	15.3
CS	8.0	55.0	25.1
CS	10.0	55.0	30.1
MS	0.5	55.0	8.8
MS	1.0	55.0	12.2
MS	1.5	55.0	18.7
MS	2.0	55.0	28.0
MS	2.5	55.0	36.8

Where Q is the pumping rate, b is the saturated thickness (a constant), and s is the drawdown.

3.2.3.3 Summary

The direct measurements of the effective porosity of the sediments had some limitations. For example, it was not possible to remove all of the moisture from the sediments prior to the measurements since a large oven was not available. Also, packing and grain shape affect the effective porosity. Although every effort was made to overcome these obstacles, the results were quite reasonable for each sediment size.

The pump tests for the gravels did not produce very much drawdown because the pump was not strong enough. Perhaps at 100 liters/min or more there would have been more substantial drawdown. However, this is not a factor that affects the relationship. The relationship should work with all types of conditions. The initial pump tests with the sand failed because sand entered the plumbing and jammed the pump motor. Additionally the 50 liter/min pump was too strong. A smaller pump was installed and the plumbing modified to use either or both of the pumps. Additionally the water level tubes and slotted center pipe needed to be protected from sand entering the plumbing. Using common well construction procedures (Driscoll, 1986; Sterrett, 2007) a screen with gravel packing was used to ensure that sand would not enter the plumbing but still allow unhindered water flow through the plumbing.

Overall the pump tests and direct measurements produced reliable data to establish an initial relationship between the specific capacity and effective porosity.

3.3 Initial Calculations

Initially equations from various researchers were explored to determine their applicability to the development of the initial relationship between specific capacity and effective porosity. These researchers and their equations are listed below.

Ahuja et al. (1989) developed a relationship between saturated hydraulic conductivity (cm^2/hour) and effective porosity based on 473 undisturbed samples of soils based on a modified version of the Kozeny-Carmen equation. The Kozeny-Carmen equation describes a relationship between hydraulic conductivity and porosity based on uniform sands. However, this equation did not work well with a wider range of pore sizes and thus was modified. These soils consisted of Cecil (Clayey, kaolinitic, thermic, Typic Hapludults), Lakeland (sandy, thermic, coated, Typic Quartzipsamments), Norfolk (fine-loamy, siliceous, thermic, Typic Paleudults), and Wagram (loamy, siliceous, thermic, Arenic Paleudults). The samples were taken from depths of 0 to 2 meters, which limits the measurements and data to a relatively shallow environment. Ahuja et al. (1989) measured the saturated hydraulic conductivity under constant head conditions and measured water retention or a combination of bulk density and particle density to obtain effective porosity values to establish the relationship. Ahuja et al. (1989) states in his research that there is significant error due to entrapped air and macoropore channels in the undisturbed core samples, with error of up to 25 magnitudes of order for the hydraulic conductivity, and up to 25% error in effective porosity measurements. However this equation is the only one that relates effective porosity to hydraulic conductivity. This relationship could be applied to other sedimentary environments but it might need to be reevaluated for deeper sediments (Ahuja, personal communication).

$$K_{sat} = \phi_e^{3.29} \tag{3.1}$$

where K_{sat} is the saturated hydraulic conductivity (cm/h), and ϕ_e is the effective porosity (dimensionless).

Driscoll (1986) developed two empirical equations relating transmissivity and specific capacity developed from the modified nonequilibrium equation (Cooper & Jacob, 1946), assuming average well diameter, average pumping duration, and typical values for the storage coefficient. The equations are not based on laboratory experiments or samples and he states that there can be up to 7% error in the results and that both equations are only estimates. Equation 3.2 is for confined aquifers, and equation 3.3 is for unconfined aquifers:

$$T = \frac{2000Q}{s} \tag{3.2}$$

$$T = \frac{1500Q}{s} \tag{3.3}$$

where T is transmissivity in gpd/ft, Q is the pumping rate in gpm, and s is the drawdown in feet. Neither of these equations use or take into account effective porosity.

Razack and Huntley (1991) developed an equation to relate transmissivity to specific capacity based on transmissivity and specific capacity data in well records of 215 wells obtained from the Direction de l'Hydraulique of Marrakech, Morocco. The wells are located in a heterogeneous aquifer that consists of sediments ranging from clays to coarse deposits (sand, gravel, pebble). In a comparison of empirical and analytical methods the empirical solution had less error than the analytical solution and the log-log fit for the data had an R^2 of .63 whereas the linear fit had and R^2 of 0.40. The resulting best fit equation is:

$$T = 15.3\left(\frac{Q}{s}\right)^{0.67} \tag{3.4}$$

where T is transmissivity in m^2/sec, Q is the pumping rate in m^3/sec, s is drawdown in meters and 15.3 is a constant based on the units of measure. Razack and Huntley (1991) also include a conversion table of constants to convert the equation to a variety of SI or US units.

Kauffman (1999) developed a logarithmic relationship between transmissivity and specific capacity in a model of groundwater – surface water interaction in an unpublished MS thesis. Attempts to contact this person or obtain a copy of the MS thesis were unsuccessful; therefore additional details of the sources of data used are not available.

$$\log T = 1.58\log\left(\frac{Q}{s}\right) + 2.53 \tag{3.5}$$

where T is transmissivity in gpd/ft, Q is the pumping rate in gpm, and s is drawdown in feet.

Mace (1997) developed a similar empirical relationship between transmissivity and specific capacity using data from 71 time drawdown tests and 32 step drawdown tests obtained from state and water district well files, water-resource documents, published research, and consultant reports. Many data from the well files and records were recorded at the time of drilling. Of the 71 time drawdown tests, 60 of the tests were conducted on only 10 wells; the total number of wells is unknown. Physical samples and observations were not taken or used for this research, and effective porosity was not used or considered for this research. All of the data are based on a confined karst aquifer. The empirical relationship that was determined had an R^2 of 0.89 with a polynomial fit with 1 iteration, however he concluded that the fit could be improved with second and third iterations. He also stresses that the data for transmissivity and specific capacity span over 5 magnitudes of order, hence this is only a rough estimate.

$$T = 0.76\left(\frac{Q}{s}\right)^{1.08} \tag{3.6}$$

where T is transmissivity in m^2/d, Q is pumping rate in m^3/d and s is drawdown in meters

The Ahuja et al. (1989) equation can easily be solved for transmissivity (T) based on the standard definition of $K = \frac{T}{b}$, resulting in:

$$T = 764.5b\phi_e^{3.29} \tag{3.7}$$

where T is transmissivity in cm^2/hr, b is the saturated thickness in cm, and ϕ_e is the effective porosity which is dimensionless.

By converting equation 3.7 into the correct units, the correct version of the equation was substituted for T, and then the other equations were solved for specific capacity and effective porosity. The variations based on equation 3.7 are shown below.

Converting to m^2/day per meter,

$$T = 183.48 b \phi_e^{3.29} \tag{3.8}$$

Converting to ft²/day per foot,

$$T = 601.97 b \phi_e^{3.29} \tag{3.9}$$

Converting to gpd/ft per foot,

$$T = 4502.72 b \phi_e^{3.29} \tag{3.10}$$

Converting to gpm/ft per foot,

$$T = 3.127 b \phi_e^{3.29} \tag{3.11}$$

The resulting equations are shown below.

By substituting equation 3.2 for *T* in equation 3.11 the results are

$$\frac{Q}{s} = 2.25 b \phi_e^{3.29} \tag{3.12}$$

and

$$\phi_e = \sqrt[3.29]{\frac{Q}{2.25 sb}} \tag{3.13}$$

for confined aquifers.

By substituting equation 3.3 for *T* in equation 3.11 the results are

$$\frac{Q}{s} = 3.0 b \phi_e^{3.29} \tag{3.14}$$

and

$$\phi_e = \sqrt[3.29]{\frac{Q}{3.0 sb}} \tag{3.15}$$

for unconfined aquifers.

By substituting equation 3.4 for *T* in equation 3.8 the results are

$$\frac{Q}{s} = \sqrt[0.67]{11.99 b \phi_e^{3.29}} \tag{3.16}$$

and

$$\phi_e = \sqrt[3.29]{\frac{\left(\frac{Q}{s}\right)^{0.67}}{11.99b}} \tag{3.17}$$

By substituting equation 3.5 for T in equation 3.11 the results are

$$\frac{Q}{s} = \sqrt[1.58]{13.29b\phi_e^{3.29}} \tag{3.18}$$

and

$$\phi_e = \sqrt[3.29]{\frac{\left(\frac{Q}{s}\right)^{1.58}}{13.29b}} \tag{3.19}$$

By substituting equation 3.6 for T in equation 3.8 the results are

$$\frac{Q}{s} = \sqrt[1.08]{241.4b\phi_e^{3.29}} \tag{3.20}$$

and

$$\phi_e = \sqrt[3.29]{\frac{\left(\frac{Q}{s}\right)^{1.08}}{241.4b}} \tag{3.21}$$

3.3.1 Comparison of Equations

Equations 3.13, 3.15, 3.17, 3.19, and 3.21 were applied to the experimental data generated in the laboratory experiments to calculate effective porosity and determine which would be the best fit to the experimental data. The equations were programmed into a spreadsheet and the experimental data were added. Table 3.3 shows the results.

It is obvious that the ranges of all of these equations were unsuitable for calculating effective porosity since they all span more than 1 magnitude of order, especially with the gravels, which are all above 100%.

The experimental data were used to calculate specific capacity using equations 3.12, 3.14, 3.16, 3.18, and 3.20 and are shown in Table 3.4. The initial effective porosity results in Table 3.3 were plotted against these calculated values of specific capacity and are shown in Figure 3.23.

It can be seen that the range of specific capacity for each equation spans at least 2 magnitudes of order. Each resulting fit to each experimental data set is a very good fit using power-based solutions on Log-Log axis. All of the results showed an R^2 of 1.0 for the 17 data points and suggest a logarithmic function to apply to the existing equations.

A regression analysis of the results ranged from 3.4 up to 19.2, with the Razack equation with lowest value of 3.4 and the Kauffman equation with highest of 19.2 despite the similarity in the equations. The others ranged from 7 to 14. The Razack equation had the flattest fit meaning the best overall fit and range, justifying consideration for additional consideration for a final fit.

Table 3.3: Initial experimental results of effective porosity of the test sediments calculated with equations 3.13, 3.15, 3.17, 3.19, and 3.21

Lithology	Effective porosity (measured in the lab) +/- 1%	Driscoll (confined) +/- 7%	Driscoll (unconfined) +/- 7%	Kauffman Unknown margin of error	Mace +/- 11%	Razack SI +/- 5%	Razack US +/- 5%
CG	0.35	2.80	2.57	3.81	2.81	2.69	2.69
CG	0.35	2.90	2.65	4.00	2.91	2.75	2.75
MG	0.31	2.76	2.53	3.72	2.77	2.67	2.67
MG	0.31	2.74	2.51	3.67	2.74	2.65	2.65
FG	0.30	2.48	2.27	3.13	2.46	2.48	2.48
FG	0.30	2.48	2.27	3.13	2.46	2.48	2.48
CS	0.22	0.80	0.74	0.53	0.73	1.16	1.16
CS	0.22	0.81	0.74	0.54	0.74	1.17	1.17
CS	0.22	0.82	0.75	0.55	0.75	1.18	1.18
CS	0.22	0.82	0.75	0.54	0.75	1.18	1.18
CS	0.22	0.87	0.80	0.60	0.80	1.23	1.23
CS	0.22	0.88	0.81	0.61	0.81	1.24	1.24
MS	0.29	0.52	0.47	0.26	0.45	0.87	0.87
MS	0.29	0.58	0.53	0.31	0.51	0.93	0.93
MS	0.29	0.57	0.52	0.31	0.51	0.93	0.93
MS	0.29	0.55	0.51	0.29	0.49	0.91	0.91
MS	0.29	0.54	0.50	0.29	0.48	0.90	0.90

Table 3.4: Initial experimental results of specific capacity of the test sediments calculated with equations 3.12, 3.14, 3.16, 3.18, and 3.20

Lithology	Driscoll (confined) variable error	Driscoll (unconfined) variable error	Kauffman Unknown margin of error	Mace +/- 40%	Razack SI +/- 20%	Razack US +/- 20%
CG	120.8	120.8	120.8	2160.0	2160.0	120.8
CG	134.2	134.2	134.2	2400.0	2400.0	134.2
MG	115.0	115.0	115.0	2057.1	2057.1	115.0
MG	111.8	111.8	111.8	2000.0	2000.0	111.8
FG	80.5	80.5	80.5	1440.0	1440.0	80.5
FG	80.5	80.5	80.5	1440.0	1440.0	80.5
CS	2.0	2.0	2.0	35.1	35.1	2.0
CS	2.0	2.0	2.0	36.5	36.5	2.0
CS	2.1	2.1	2.1	37.9	37.9	2.1
CS	2.1	2.1	2.1	37.6	37.6	2.1
CS	2.6	2.6	2.6	45.9	45.9	2.6
CS	2.7	2.7	2.7	47.8	47.8	2.7
MS	0.5	0.5	0.5	8.2	8.2	0.5
MS	0.7	0.7	0.7	11.8	11.8	0.7
MS	0.6	0.6	0.6	11.6	11.6	0.6
MS	0.6	0.6	0.6	10.3	10.3	0.6
MS	0.5	0.5	0.5	9.8	9.8	0.5

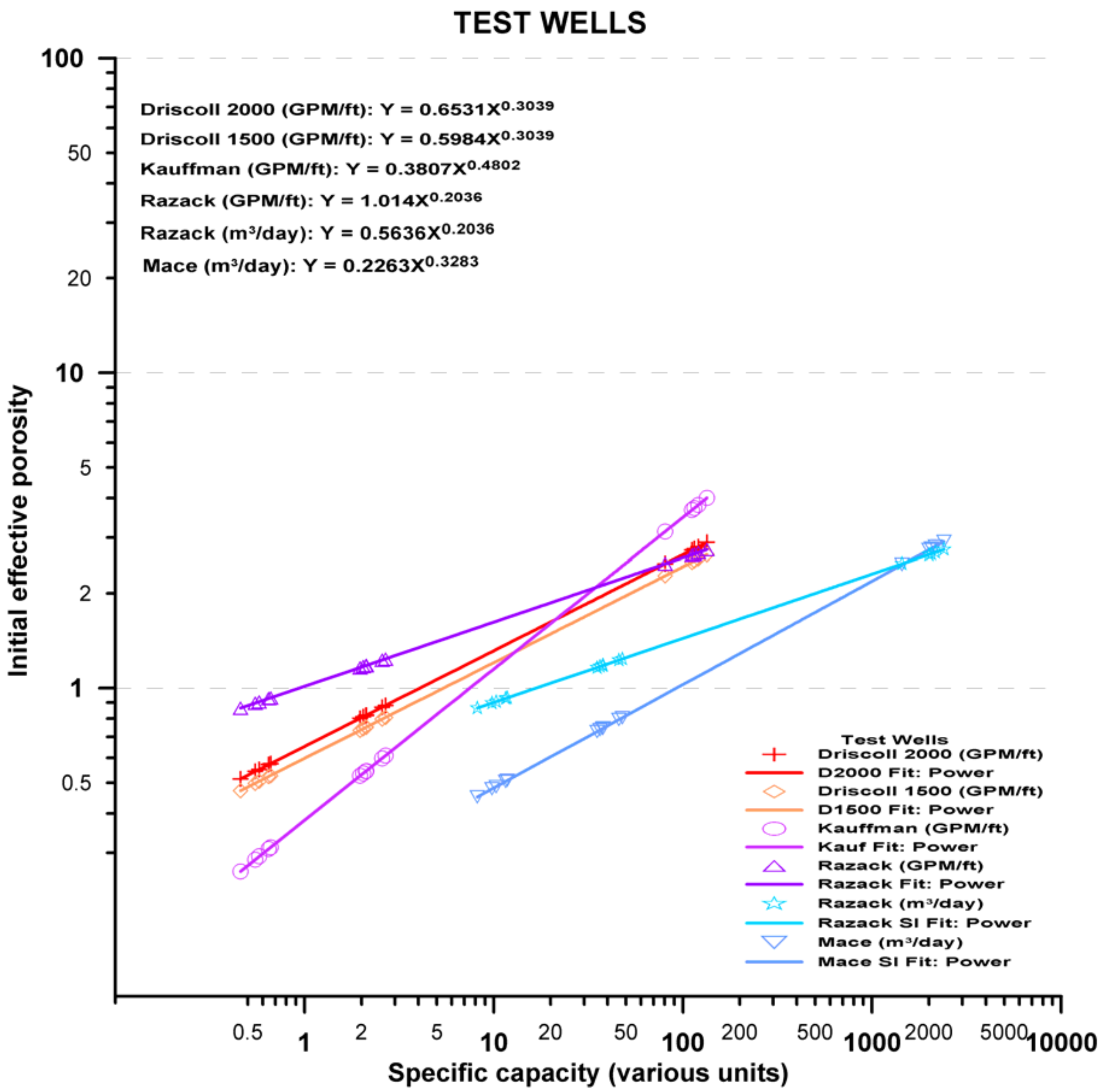

Fig. 3.23: Graph of specific capacity and the initial effective porosity for each equation using data from the laboratory experiments

3.3.2 Revision of Equations

Since some of the initial effective porosity results are less than 1.0, and the natural logarithm of a number less than one returns a negative number, the value had to be increased by a nominal amount. Since the natural logarithm of 1 is 0, adding 1 would have the least influence on the smaller initial values of effective porosity. Adding, multiplying, or dividing the natural logarithm affects the upper and lower ends of the initial values of effective porosity and can shift the ranges of the effective porosities up or down. It was determined that a variation of the natural logarithm would be needed for each equation. The results in Table 3.5 show that this combination is very effective in normalizing the effective porosity.

Table 3.5: Results of effective porosity of the test sediments calculated with equations 3.13, 3.15, 3.17, 3.19, and 3.21 substituted for x in the logarithmic functions

Lithology	Measured	Driscoll (confined) +/- 7% $\frac{\ln(x+1.2)}{3}$	Driscoll (unconfined) +/- 7% $\frac{\ln(x+1.2)}{3}$	Kauffman Unknown margin of error $\frac{\ln(x+1.3)}{3}$	Mace +/- 11% $\frac{\ln(x+1.2)}{3}$	Razack SI +/- 5% $\frac{\ln(x+1)}{3}$	Razack US +/- 5% $\frac{\ln(x+1)}{3}$
CG	0.35	0.46	0.44	0.54	0.46	0.44	0.54
CG	0.35	0.47	0.45	0.56	0.47	0.44	0.55
MG	0.31	0.46	0.44	0.54	0.46	0.43	0.54
MG	0.31	0.46	0.44	0.53	0.46	0.43	0.54
FG	0.30	0.43	0.42	0.50	0.43	0.42	0.52
FG	0.30	0.43	0.42	0.50	0.43	0.42	0.52
CS	0.22	0.23	0.22	0.20	0.22	0.26	0.34
CS	0.22	0.23	0.22	0.20	0.22	0.26	0.34
CS	0.22	0.23	0.22	0.20	0.22	0.26	0.34
CS	0.22	0.23	0.22	0.20	0.22	0.26	0.34
CS	0.22	0.24	0.23	0.21	0.23	0.27	0.35
CS	0.22	0.24	0.23	0.22	0.23	0.27	0.35
MS	0.29	0.18	0.17	0.15	0.17	0.21	0.28
MS	0.29	0.19	0.18	0.16	0.18	0.22	0.29
MS	0.29	0.19	0.18	0.16	0.18	0.22	0.29
MS	0.29	0.19	0.18	0.16	0.17	0.22	0.29
MS	0.29	0.19	0.18	0.15	0.17	0.21	0.29

The modified equations used to calculate effective porosity produced acceptable values but the ranges differed considerably. The Kauffman variation produced the most extreme range of values, with both the high and low values being too extreme. The other equations produced more reasonable ranges but the low values were all too extreme, with the exception of the Razack variations. The data from Table 3.5 is plotted with the calculated specific capacity again and shown in Figure 3.24. Each of the fits had an R^2 of 1.0, and although the ranges are more acceptable, the slopes of the fits show significant differences.

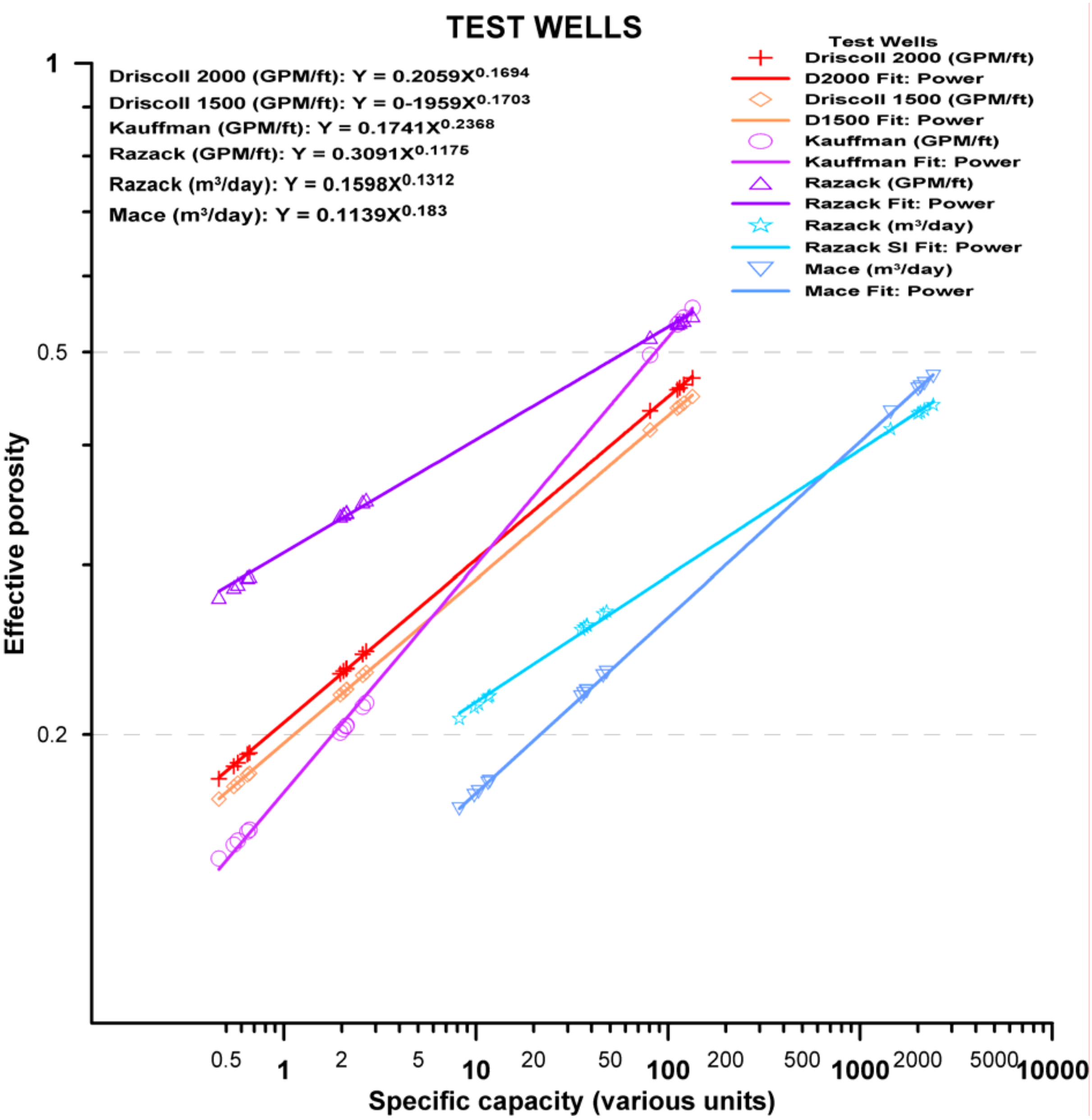

Fig. 3.24: Graph of specific capacity and the revised effective porosities for each equation using data from the laboratory experiments

Overall the Razack equation fit has the flattest slope within the most acceptable range of effective porosities as compared to the other equations. All of the equations span about 2.5 magnitudes of order for specific capacity. The flattest slope will be an important factor later as this research narrows the focus on the development of the relationship between specific capacity and effective porosity.

3.4 Description of the Well Database

Figure 3.25 shows the location and distribution of the wells, along the Oregon-Washington border in the United States, in the Portland area. The well database of 1586 located and confirmed wells includes the construction details of the wells, including location (latitude and longitude), altitude (feet), well depth (feet), open interval (feet), well diameter (inches), and well performance data that includes test method, yield (Gpm), drawdown (feet), test period (hours), and other miscellaneous information (Swanson, McFarland, Gonthier, & Wilkinson, 1993). The sources for these well data came from industrial, public supply, agricultural and private owners wells. It should be noted that the author was an employee of the USGS at the time that these wells were located and participated in the data collection for these wells. All units were converted to metric for use in this paper.

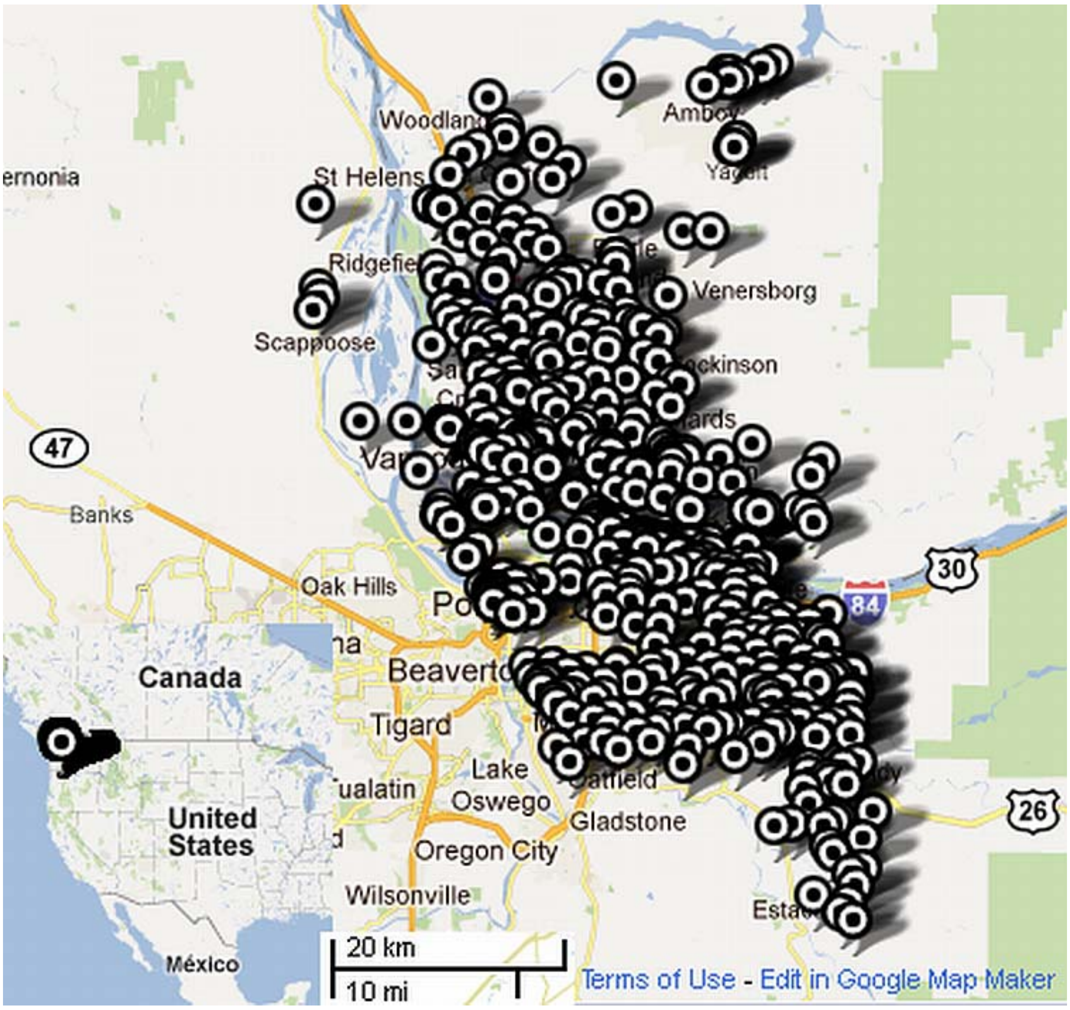

Fig. 3.25: Location of the well database in the Oregon-Washington area of the USA (Source: Google Maps. Modified after USGS WRIR 90-4196, OFR 90-126)

The location is a basin with nine hydrogeologic layers, some of which have been grouped together and some that have been divided into subunits (Snyder et al., 1998). The initial hydrogeology is defined and discussed in detail (Swanson, McFarland, Gonthier, & Wilkinson, 1993) and includes an appendix showing the altitude of each unit as intersected by the wells. The author was responsible for most of the field data collection for this report.

3.5 Description of the Hydrogeologic Units

The following is a summary description of each hydrogeologic unit based on the original descriptions in Swanson et al. (1993) and McFarland and Morgan (1996).

Unit US (Unconsolidated Sediments aquifer) is a combination of flood deposits and glacial outwash. It lacks cementation and commonly has been disturbed by subsequent reworking from the local river and streams. This is a generally very productive source for groundwater; however since it is the uppermost unit it is highly susceptible to contaminants.

Unit TG (Troutdale Gravel aquifer) is a sandy conglomerate with lenses of lava and soil horizons. This unit lacks cementation and is generally a very productive source of groundwater.

Unit UF (Undifferentiated Fine-Grained Sediments) is fine-grained and similar to the confining units. This unit is present where C1 and C2 are not separated by TS. It consists of clay, silt, and fine sand lenses. It is not considered to be a good source of groundwater except at the local level.

Unit C1 (Confining Unit 1) is composed of clay and silt, with local lenses of fine sand. It is not used for public water supplies, although some personal water supplies draw groundwater from this unit.

Unit TS (Troutdale Sandstone aquifer) is coarse-grained sandstone with lenses of finer-grained sands. This unit is poorly to well cemented and has primary and secondary effective porosity as the result of partial dissolution of the cementation.

Unit C2 (Confining Unit 2) is composed of clay and silt, with local lenses of fine sand. Similar to C1, it is not used for public water supplies, although some personal water supplies draw groundwater from this unit.

Unit SG (Sand and Gravel aquifer) is composed of sandy gravel with some finer-grained lenses. However, the SG unit is subdivided into an upper coarse grained unit designated as SC, and a lower fine grained unit designated as SF (McFarland & Morgan, 1996). In this thesis this unit is referred to as SG since the original data (Swanson, McFarland, Gonthier, &

Wilkinson, 1993) didn't differentiate between the upper and lower units. This unit is generally a very productive source of old groundwater, meaning that it hasn't been subjected to anthropogenic influences.

Unit OR (Older Rocks) consists mostly of volcanic and marine sedimentary rocks. The volcanic rocks were deposited from several different episodes of volcanism, each with a different mineral profile. The marine sediments are very fine grained clay and silt. Generally this unit is not used as a source of groundwater except in outlying rural areas where it is used as a household source of water.

UF, C1, C2, SF, and OR are considered to be aquitards and generally poor sources for water supplies, while US, TG, TS, and SC are generally good aquifers and good sources for water supplies. This hydrogeologic environment represents a wide variety of conditions for effective porosity, which can vary extensively from one hydrogeologic unit to the next as well as spatially within the each hydrogeologic unit.

3.6 Selection of the Wells

The selection of wells was based on completeness of the data in the published database from both sources (McCarthy & Anderson, 1990; Swanson et al., 1993), both of which I collected data for. The criteria for valid data were location, altitude, depth, open interval, yield, and drawdown. The resultant selection of wells was cross-referenced to the hydrogeologic descriptions (Swanson, McFarland, Gonthier, & Wilkinson, 1993) to assign the hydrogeologic unit to the open interval of the wells. This resulted in 609 wells that met the basic criteria. However, not all of the initially selected wells matched with the hydrogeology data. Many wells are open to multiple units, but for this research single unit exposure was required. The final result which is shown in Figure 3.26 was that 572 wells met all of the selection criteria.

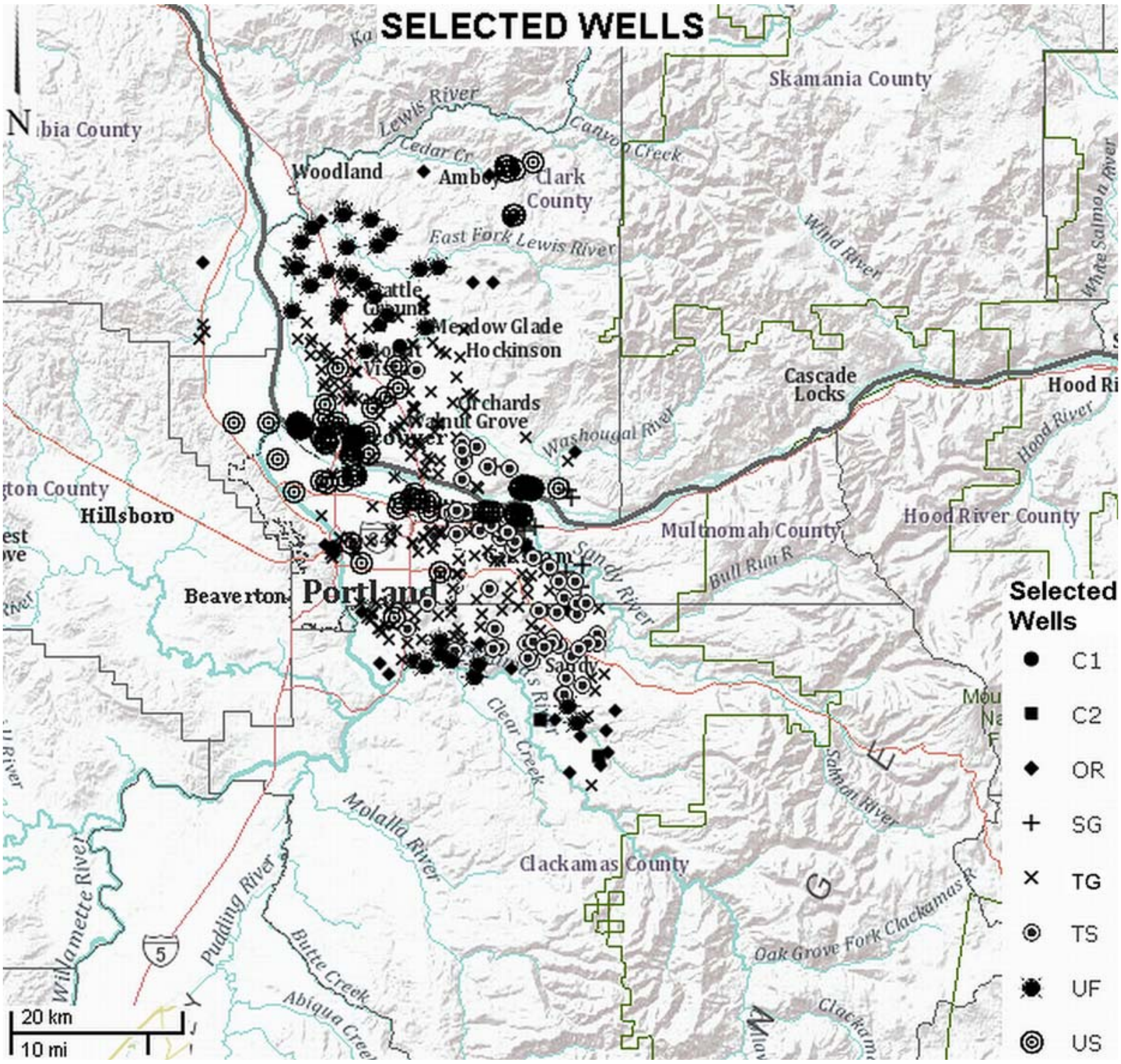

Fig. 3.26: Selected wells showing the hydrogeologic unit (Source: Google Maps. Modified after USGS WRIR 90-4196, OFR 90-126)

3.7 Application of the Initial Equations

The results of the application of the equations modified by the logarithmic functions to the laboratory test data had an R^2 of 0.70. These modified equations were applied to the 572 selected wells, and the results are summarized in Table 3.6. Since the results in Table 3.6 were somewhat inconsistent and generally, too low or too high, it was determined that the modified equations would need to be revised. The data in Table 3.6 show that the two Razack equations produced nearly identical results for metric and western units, with low but reasonable ranges of effective porosity and the overall flattest fit to the data. Also, the results of the Mace and Kauffman equations are generally too low due to the limited environments of their research. The Driscoll equations were empirical and based on confined and unconfined aquifers; however the overall ranges of effective porosity are high for both equations. Additionally the goal of this research was to determine a relationship that was independent of those factors.

Table 3.6: Results of the application of the initial modified equations to the data from the selected wells to calculate effective porosity

Lithology Data points	Razack US (+/- 5%)			Razack SI (+/- 5%)			Mace (+/- 11%)		
	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
US (114)	0.15	0.28	0.55	0.15	0.28	0.55	0.13	0.33	0.62
TG (213)	0.05	0.17	0.44	0.05	0.17	0.44	0.08	0.18	0.55
C1 (3)	0.12	0.16	0.19	0.12	0.16	0.19	0.12	0.15	0.16
TS (68)	0.08	0.15	0.30	0.08	0.15	0.30	0.11	0.16	0.34
C2 (6)	0.06	0.16	0.27	0.06	0.16	0.27	0.09	0.16	0.25
SG (35)	0.11	0.16	0.26	0.11	0.16	0.26	0.12	0.17	0.24
UF (35)	0.06	0.17	0.26	0.06	0.17	0.26	0.09	0.16	0.22
OR (40)	0.02	0.09	0.22	0.09	0.09	0.22	0.07	0.11	0.21

Table 3.6: Continued

Lithology Data points	Kauffman Unknown margin of error			Driscoll, unconfined (+/- 7%)			Driscoll, confined (+/- 7%)		
	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
US (114)	0.12	0.41	0.80	0.14	0.31	0.59	0.17	0.39	0.73
TG (213)	0.09	0.20	0.74	0.08	0.18	0.51	0.10	0.22	0.63
C1 (3)	0.13	0.15	0.17	0.13	0.15	0.17	0.16	0.19	0.21
TS (68)	0.11	0.18	0.42	0.11	0.16	0.32	0.13	0.20	0.40
C2 (6)	0.10	0.17	0.25	0.09	0.16	0.25	0.11	0.20	0.31
SG (35)	0.13	0.19	0.26	0.12	0.17	0.24	0.15	0.21	0.30
UF (35)	0.11	0.16	0.22	0.09	0.16	0.22	0.12	0.21	0.28
OR (40)	0.09	0.13	0.24	0.07	0.11	0.21	0.08	0.14	0.26

3.7.1 Selection and Revision of the Equation

At this point it was clear that one of the equations would need to be selected for further development and eliminate the others. Therefore, since the logarithmic version was not consistent it was discarded and research reverted back to the basic relationship that was used to establish the initial effective porosity. Based on the information in Table 3.6 the Razack equations had the least amount of variation and were selected for further development.

The initial effective porosity values were plotted against effective porosity calculated with the modified equations and is shown in Figure 3.27. The fit was automatically generated for these data by the graphing software and are in the form of a polynomial (Eq. 3.24) with an R^2 of 0.998 and a margin of error of +/- 14%.

$$\phi_e = 0.1303 + (0.1544\phi_i) - (0.0165\phi_i^2) \tag{3.24}$$

where ϕ_e is the effective porosity (dimensionless) and ϕ_i is the initial effective porosity (dimensionless).

Substituting equation 3.17 into equation 3.24 to yield the full equation,

$$\phi_e = 0.1304 + \left[0.1544 \times \sqrt[3.29]{\frac{\left(\frac{Q}{s}\right)^{0.67}}{11.992b}} \right] - \left(0.0165 \times \left[\sqrt[3.29]{\frac{\left(\frac{Q}{s}\right)^{0.67}}{11.992b}} \right]^2 \right) \tag{3.25}$$

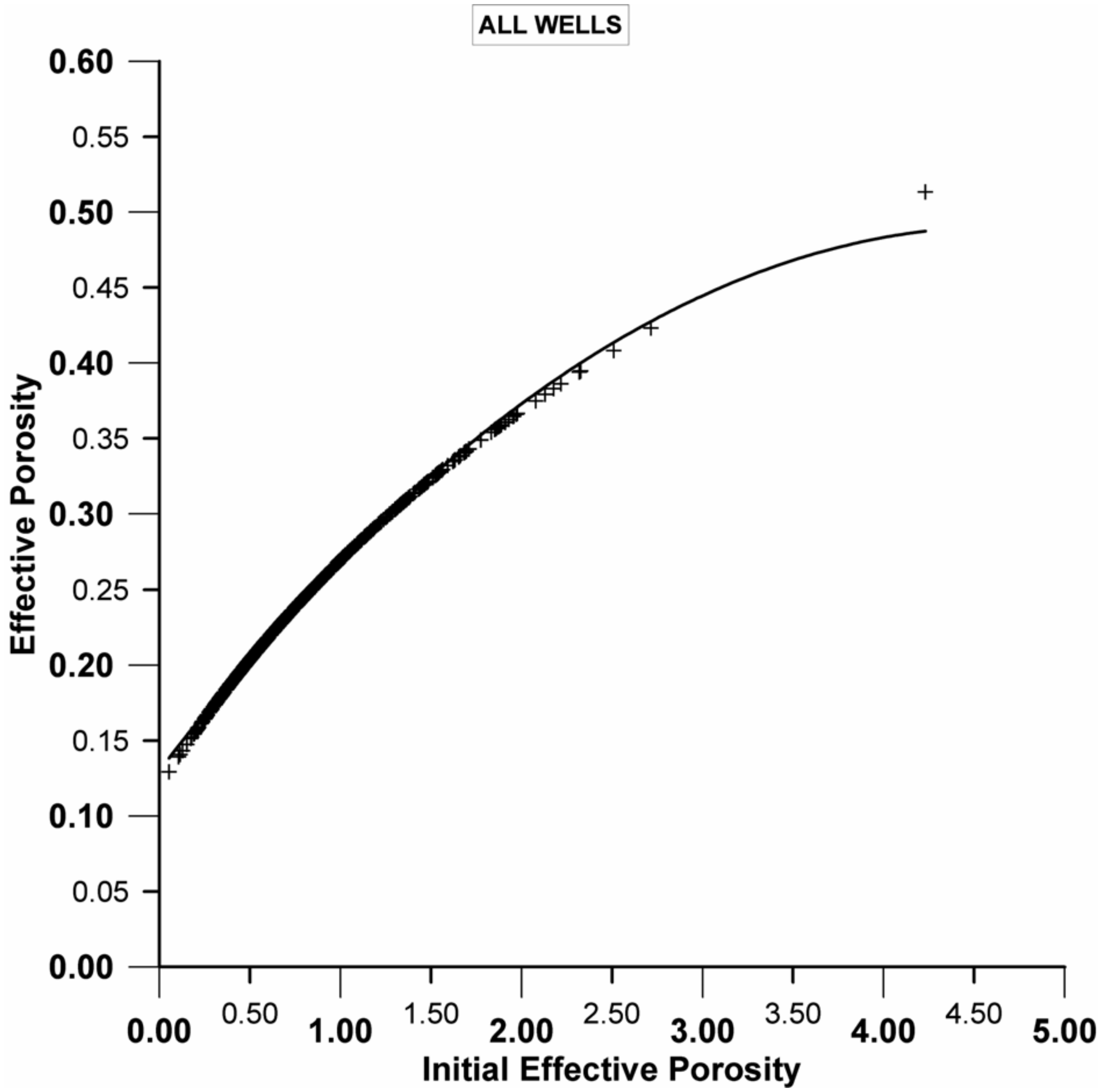

Fig. 3.27: Initial effective porosity vs. effective porosity calculated with the modified equations

Equation 3.27 was applied to the initial effective porosity values and the results are summarized in Table 3.7 and plotted and shown in Figure 3.28.

Table 3.7: Values of effective porosity calculated from equation 3.25, +/- 7%

Hydrogeologic Unit (Data points)	Minimum effective porosity	Average effective porosity	Maximum effective porosity
US (114)	0.21	0.31	0.49
TG (213)	0.15	0.23	0.43
C1 (3)	0.20	0.22	0.24
TS (68)	0.17	0.22	0.32
C2 (6)	0.16	0.22	0.29
UF (35)	0.16	0.23	0.29
SG (35)	0.19	0.22	0.29
OR (40)	0.14	0.18	0.26

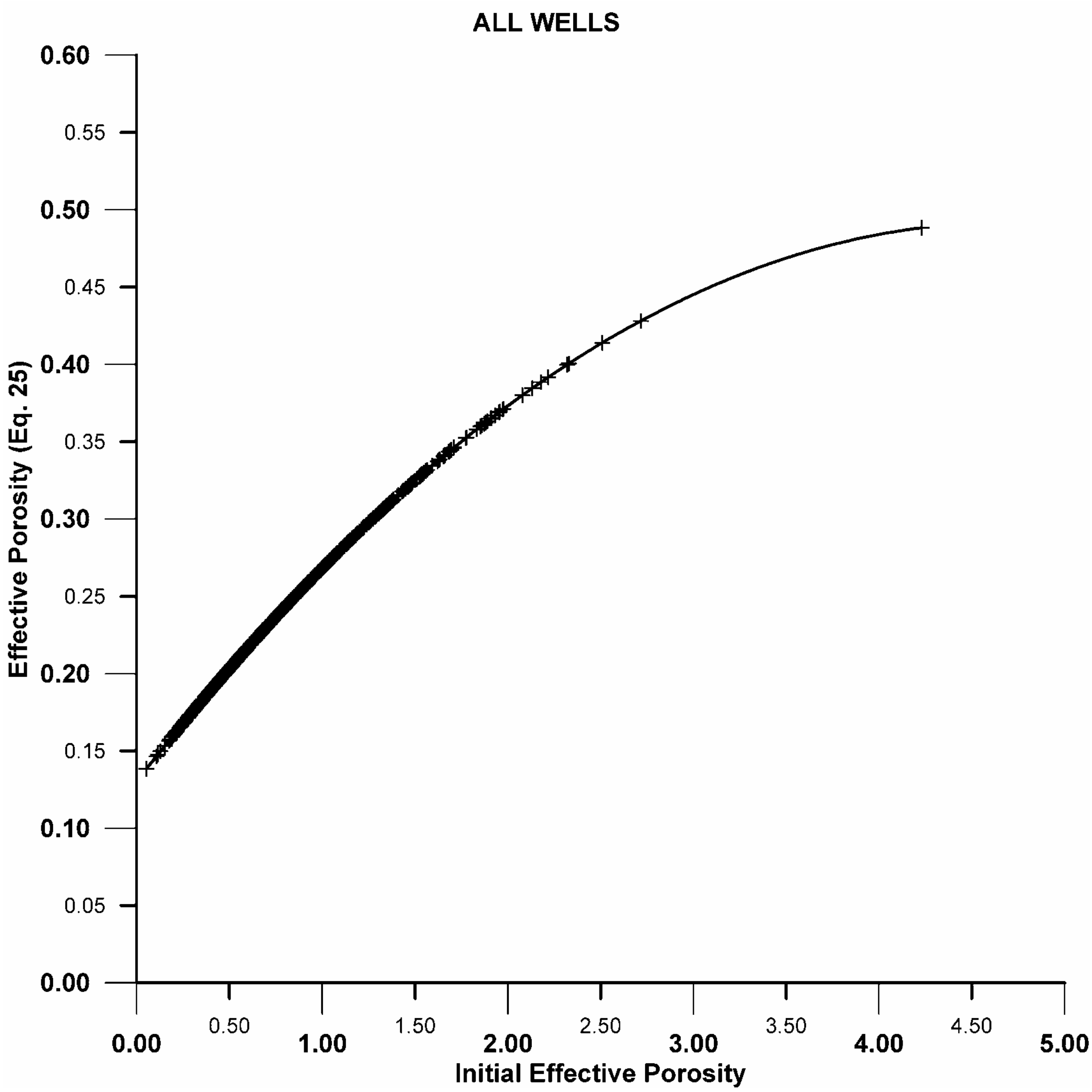

Fig. 3.28: Initial effective porosity vs. effective porosity using Eq. 3.25

However, the equation that describes the fit that was generated has an R^2 of 0.997 and a margin of error of +/- 11% and is slightly different from equation 3.24.

$$\phi_e = 0.1304 + (0.1544\phi_i) - (0.0165\phi_i^2) \tag{3.26}$$

Therefore, an iterative process of using the software to generate fit solutions and re-apply them to the initial effective porosity was used to arrive at the best fit. The following equations and plots show each step of the iterative process.

Equation 3.26 was used to calculate effective porosity from the initial effective porosity and is shown in Figure 3.29.

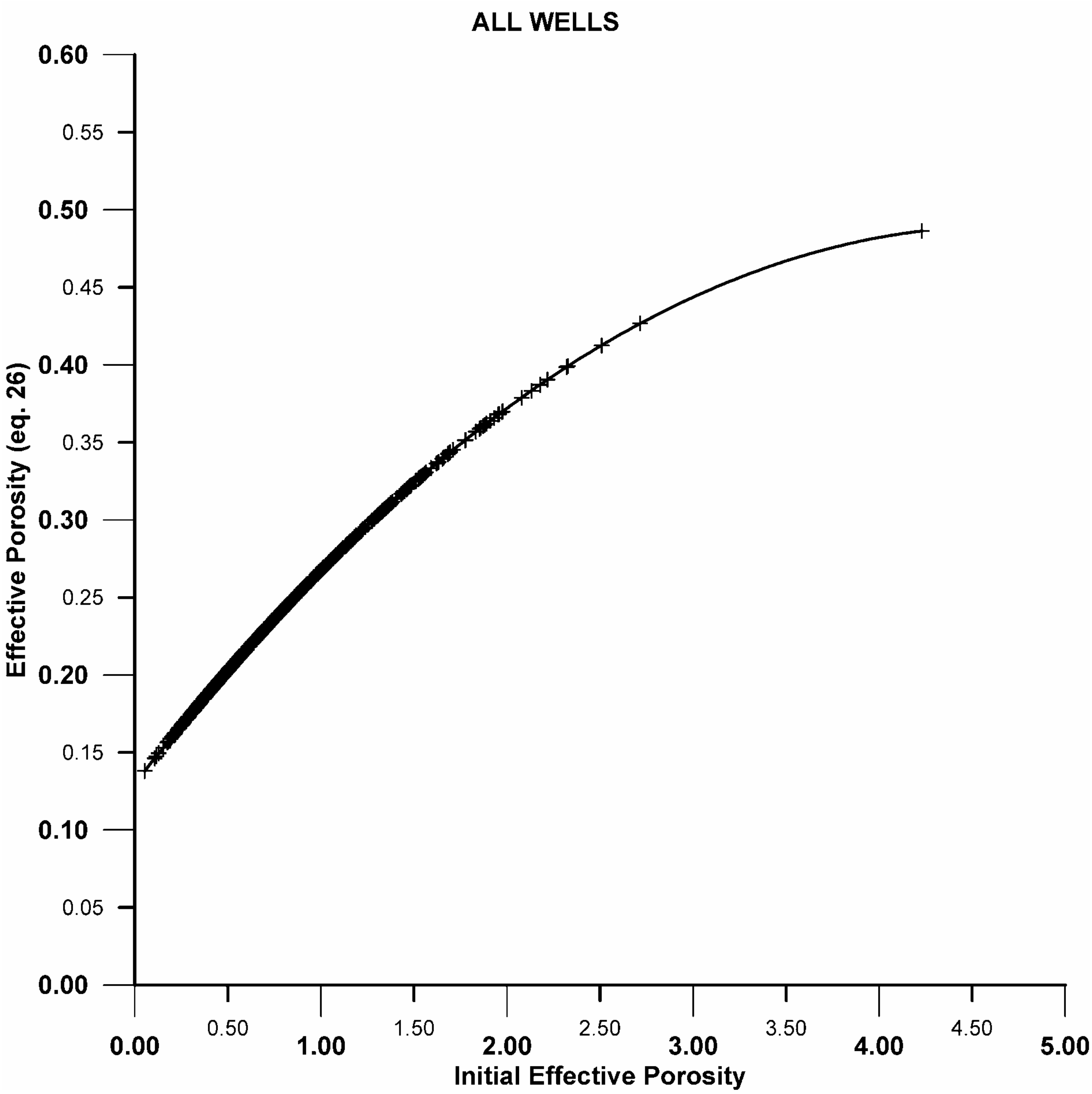

Fig. 3.29: Initial effective porosity vs. effective porosity using Eq. 3.26

The fit generated for Figure 3.29 had a significantly better fit with an R^2 of 1.0 and a margin of error of +/- 1% and is shown in equation 3.27,

$$\phi_e = 0.1301 + (0.1544\phi_i) - (0.0165\phi_i^2) \tag{3.27}$$

Once the equation had stabilized as shown in equation 3.27 with an R^2 of 1.0, it was applied to the selected well database and is summarized in Table 3.8.

Table 3.8: Values of effective porosity calculated from equation 3.27, +/- 1%

Hydrogeologic Unit (Data points)	Minimum effective porosity	Average effective porosity	Maximum effective porosity
US (114)	**0.21**	**0.31**	**0.49**
CG (213)	**0.15**	**0.23**	**0.43**
C1 (3)	**0.20**	**0.22**	**0.24**
TS (68)	**0.17**	**0.22**	**0.32**
C2 (6)	**0.16**	**0.22**	**0.29**
SG (35)	**0.19**	**0.22**	**0.29**
UF (35)	**0.16**	**0.23**	**0.29**
OR (40)	**0.14**	**0.18**	**0.26**

3.7.2 Determination of the Final Equation to the Wells

Specific capacity was calculated for all of the selected wells using measured and observed data and plotted against the effective porosity for all wells calculated from equation 3.27 and is shown below in Figure 3.30. The fit generated for this distribution of data is

$$\phi_e = 0.15108 \times \left(\frac{Q}{s}\right)^{0.0826} \tag{3.28}$$

where Q/s is in m^2/day. The fit had an R^2 of 0.71 and a marginal error of +/- 6%. Equation 3.28 uses only the specific capacity with a constant in the equation for the fit in Figure 3.30. The constant is in terms of time divided by length squared, which cancels out all units to yield dimensionless effective porosity. Subsequently equation 3.28 was used to calculate effective porosity using only specific capacity and is shown in Figure 3.31 and summarized in Table 3.9. The fit generated for Figure 3.31 had an R^2 of 1.0 with a minimal error of +/- .5%, indicating that equation 3.28 is the final equation to describe the relationship between specific capacity and effective porosity.

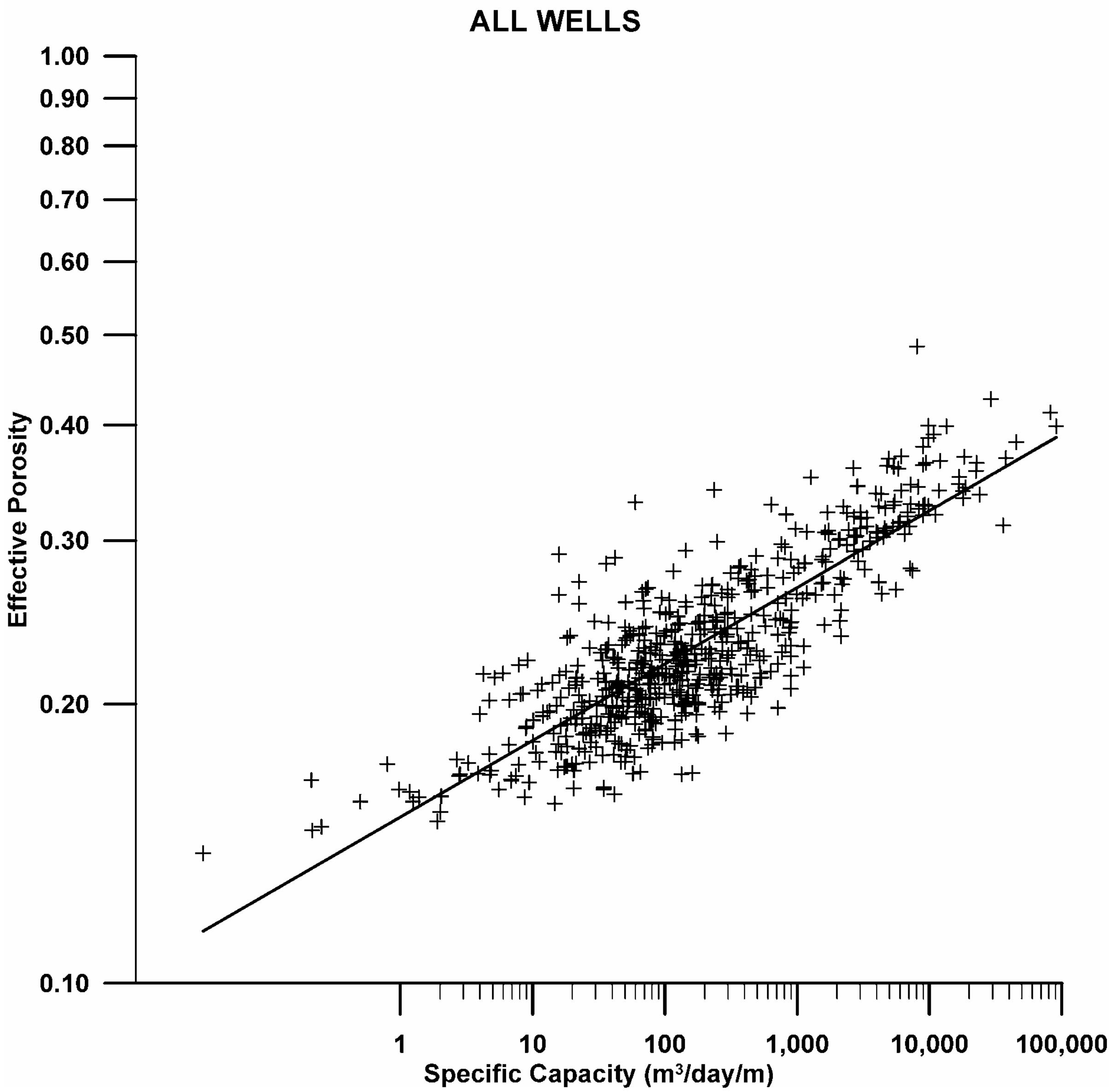

Fig. 3.30: Specific capacity vs. effective porosity from Eq. 3.27

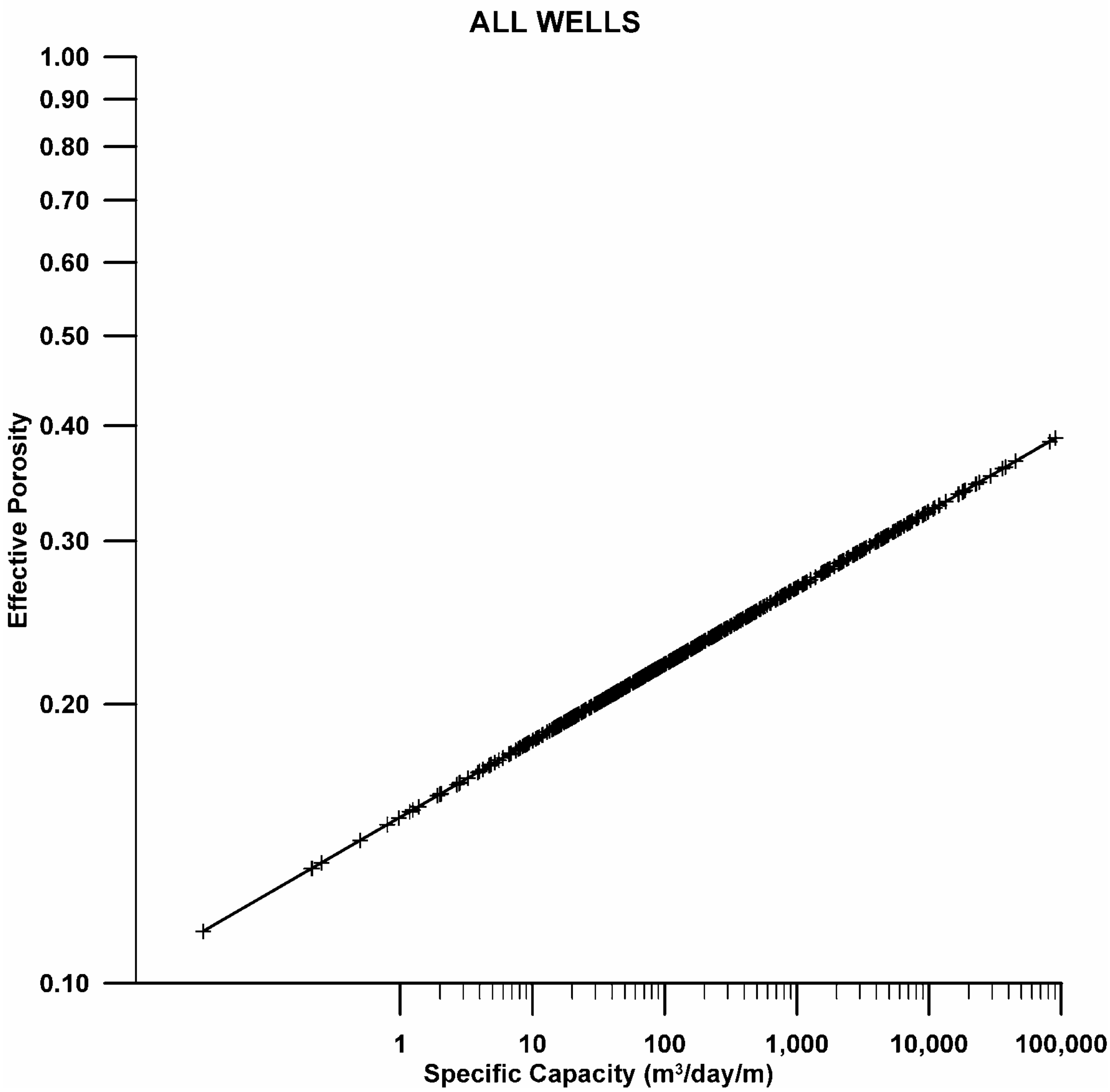

Fig. 3.31: Effective porosity calculated from Eq. 3.28

Table 3.9: Values of effective porosity from Eq. 3.28, +/- .5%

Hydrogeologic unit (data points)	Effective porosity		
	Mininmum	Average	Maximum
US (114)	0.17	0.29	0.39
TG (213)	0.14	0.22	0.35
C1 (3)	0.19	0.20	0.21
TS (68)	0.18	0.22	0.30
C2 (6)	0.17	0.21	0.24
SG (35)	0.19	0.23	0.27
UF (35)	0.17	0.21	0.24
OR (40)	0.11	0.19	0.27

3.8 Summary of the methods

Various laboratory results exist and have been published for various parameters of sediments and rocks; however there are very few databases of field data with directly observed data.

To establish the initial relationship the effective porosities, each of the laboratory sediments were measured under controlled conditions. Since no evidence of this type of laboratory experiment existed it was determined that it would need to be accomplished in the author's laboratory and fully documented. These sediments were ordered and purchased with specific size parameters from a supplier. Subsequently a controlled scale model of an aquifer with a pump and recharge conditions was created and used to measure specific capacity for the each of the laboratory sediments. Over 1000 pictures were taken with a high speed camera to document the laboratory methods. These data were used to establish the initial relationship between specific capacity and effective porosity based on the sediments used in the laboratory. The relationship was tested and refined using several sources of equations.

Well data were selected from a published well database (McCarthy & Anderson, 1990; Swanson et al., 1993) that the author helped create using specified criteria which resulted in 572 wells that met the criteria. The equations were applied to the selected wells and it was determined that the equations produced very wide ranges of results. Therefore the equations had to be modified to fit the field data. During this process it was concluded that the Razack equation had the best distribution of effective porosity and was used for continued refining of the relationship. This equation was refined through an iterative process of using Grapher software to plot the data and generate the fits to arrive at the final equation that describes the relationship between specific capacity and effective porosity, equation 3.28. This shows that the laboratory generated relationship could be adapted and used with field data, a process or method that usually can not be accomplished easily. However, this thesis demonstrates that adapting the laboratory results to field data could be accomplished successfully.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Data Analyses

Effective porosity values were calculated using equation 3.28 for all 609 initially selected wells. This includes the 572 wells that were open to only one hydrogeologic unit as well as the remaining 38 wells that were open to multiple hydrogeologic units. The results for all 609 wells are shown in Table 4.1. The results show that even when the lithology is unknown or the well is open to multiple hydrogeologic units the relationship is still valid. The equation can be used to accurately calculate effective porosity in wells that are open to more than one hydrogeologic unit or an unknown hydrogeologic unit and represents a major breakthrough in the understanding of effective porosity and how it can be derived directly from specific capacity. It also represents a major breakthrough for the methods and used to determine this relationship.

Table 4.1: Effective porosity for all 609 wells calculated with equation 3.28

Hydrogeologic	Effective Porosity		
unit	Minimum	Average	Maximum
US	0.17	0.29	0.39
TG	0.14	0.22	0.35
C1	0.19	0.20	0.21
TS	0.18	0.22	0.30
C2	0.17	0.21	0.24
SG	0.19	0.23	0.27
UF	0.17	0.21	0.24
OR	0.11	0.19	0.27
Unknown	0.15	0.23	0.36

This shows that the equation that describes the relationship between specific capacity and effective porosity is valid for various and multiple hydrogeologic units of virtually any lithology, regardless of the construction details or well history. However, it should be noted that there is one serious limitation. The source of the data used to calculate effective porosity is the specific capacity, which is the pumping rate divided by the drawdown. The calculated effective porosity will only be valid for the point in time that the specific capacity data was established, which is usually at the time of a pump test.

4.1.1 Comparison of Methods

As mentioned previously in Chapter 2, there are various methods for calculating or estimating effective porosity, none of which is ideal, simple, or fast to use. Tracer tests which are widely used to establish groundwater parameters in remedial work are expensive, time consuming, usually require multiple wells, and computationally intensive. Borehole and surface geophysical methods are expensive, generally difficult to interpret, and may require access and ideal conditions for correct application.

Most wells used for water sources already have functioning pumps installed. Therefore, if current specific capacity data are not available, it is simply a matter of accessing the pump and with permission from the owner turn on the pump at a fixed rate until the water level in the well stabilizes and make a note of the pumping rate, drawdown, and time to reach a stable water level to establish the current specific capacity.

Since tracer tests require access to multiple pumps, access is already established and the owner will not be put off by the idea of a tracer showing up in the well that is used for the water supply. Since most water supply wells are already equipped with a functional pump, additional equipment is not required. If using borehole geophysical methods the task of removing part of or the entire pump may be required. With other methods access may be required for geophysical equipment or large vehicles. The relationship in this research can be established using only a functional pump, a water level measurement tape, and the consent of the owner.

When conducting a pump test, or aquifer test, the well is pumped at a fixed rate and the water level is monitored constantly to establish a drawdown curve. This is standard to a full evaluation of the aquifer parameters but the specific capacity only requires the initial and ending water levels. Once the specific capacity is determined and effective porosity calculated, most of the other parameters can be more accurately and quickly calculated directly from published equations.

4.1.2 Comparison of Data Results

A comparison was made between the effective porosity from a previous groundwater modeling project that the author participated in while employed by the USGS and reevaluated effective porosity from the previous groundwater modeling project with the new relationship between specific capacity and effective porosity. A series of maps were published that show the hydraulic conductivity in each hydrogeologic model layer (Morgan & McFarland, 1996). The data from these maps were then used to calculate effective porosity and create maps showing the effective porosity (Hinkle & Snyder, 1997). Hinkle and Snyder (1997) used the hydraulic conductivity maps from Morgan and McFarland (1996) to calculate effective porosity using a relationship between hydraulic conductivity and effective porosity developed from Ahuja et al. (1989) and Morris and Johnson (1967). However with over 5 orders of magnitude of hydraulic conductivity (0.0003 to 21,500 m/day) the resulting linear regression for effective porosity deviates with large values of hydraulic conductivity. For this reason they assigned an effective porosity value of 31% where the value of hydraulic conductivity exceeded 4.6 meters/day. This was later refined by Snyder et al. (Snyder et al., 1998). Hinkle & Snyder (1997) explained that the age of groundwater is inversely related to groundwater velocity, which is inversely related to effective porosity. That is, as the effective porosity decreases, the velocity increases, resulting in a decrease in the age of the groundwater. The effective porosity values used for the particle-tracking model were calibrated by comparing groundwater ages determined from CFC age dating with groundwater ages calculated from the particle tracking model (Snyder et al., 1998). This comparison of results showed that the effective porosity values calculated previously did not agree with the results of the CFC age dating results. Through a series of statistical analyses stepping through multiplication correction factors from 0.50 to 1.50 in 100 steps Hinkle & Snyder (1997) narrowed the range of multiplication factors to 1.09 to 1.33 times the base effective porosity with 78% agreement. The result that was achieved was a multiplication factor of 1.09, with a 78% agreement which allowed effective porosity values up to 35%.

The areas of hydraulic conductivity above 4.6 m/day (15 ft/day on the maps) were outlined to determine the percentage of model cells that were limited to effective porosity values of 31%. Among all model cells, 99% for US, 41% for TG, 55% for TS, 2% for SG, and 8% for all fine grained units were above the 4.6 m/day level and subjected to the 4.6 m/day limitation.

It is obvious that estimating hydraulic conductivity and transmissivity are not easily accomplished, and further, neither of these parameters can be measured directly. Hydraulic conductivity can be described as the quantity of water that can flow through a cross sectional unit area of a porous medium per unit of time, at a specific temperature, and under a hydraulic gradient of 1 (ie. 1 meter of head change per 1 meter of distance). It is generally expressed as m^3/day. Transmissivity is similar to hydraulic conductivity but is defined as 1 meter of head change per 1 meter of distance through the fully saturated column of the aquifer. Transmissivity can usually be estimated by one of three methods, 1: using data collected during pump tests, 2: analyzing the hydraulic properties of aquifer material, and 3: making calculations based on laboratory tests. Transmissivity is related to hydraulic conductivity where hydraulic conductivity is equal to the transmissivity divided by the saturated thickness of the aquifer. Both of these parameters are susceptible to changes in the environmental conditions and dependent on the effective porosity of the aquifer, which implies that any variability in temperature, effective porosity, gradient, or physical characteristics of the aquifer will impact the values of hydraulic conductivity and transmissivity, further implying that lithologic variability in the aquifer will mean that hydraulic conductivity and transmissivity values will be different throughout the aquifer.

The equation that defines the relationship between specific capacity and effective porosity established in this research was used to calculate effective porosity values for the wells and plotted on maps. The series of maps for each hydrogeologic unit are shown in Figures 4.1 to 4.8.

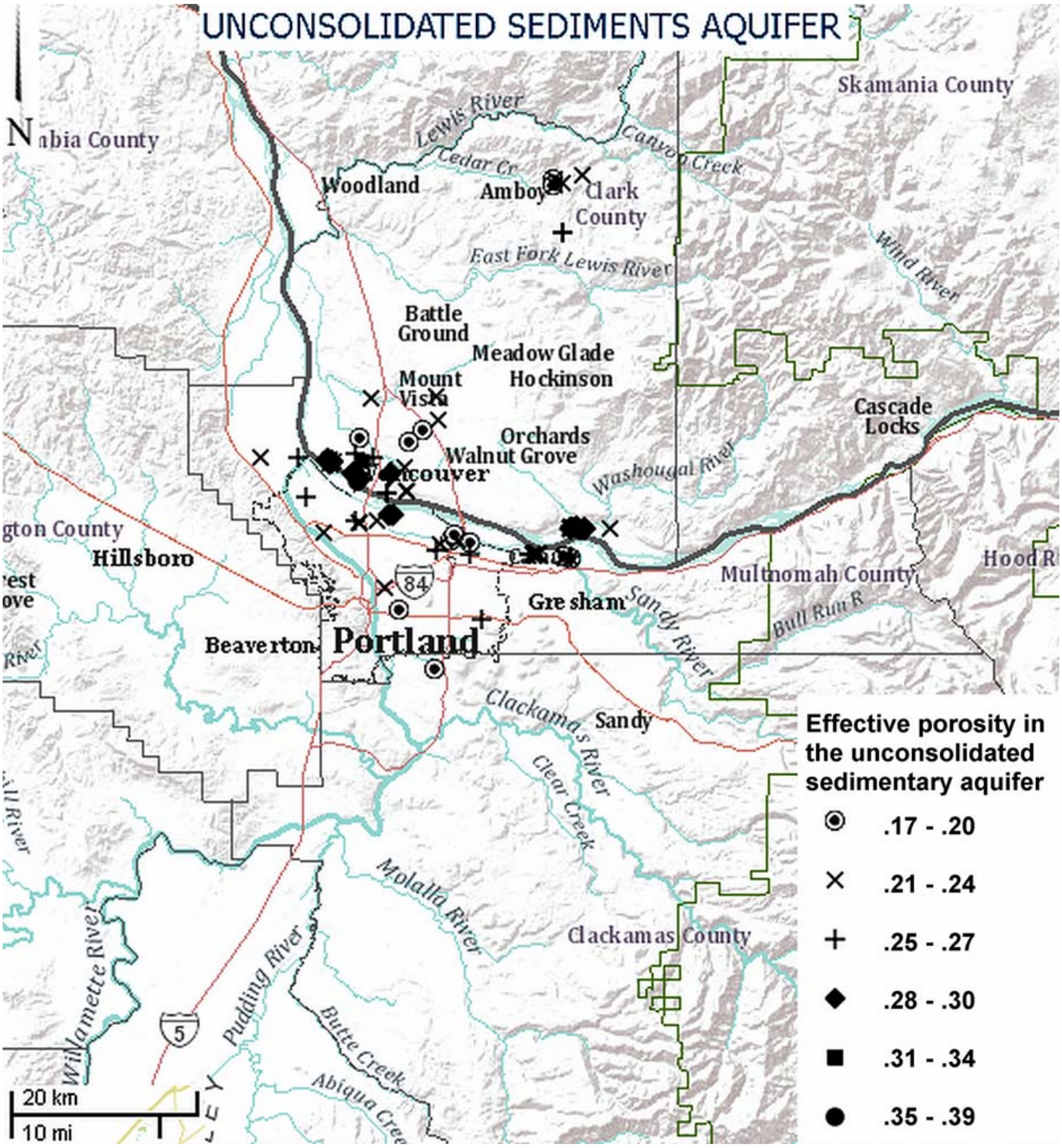

Fig. 4.1: Effective porosity values for the unconsolidated sediments unit calculated using equation 3.28.

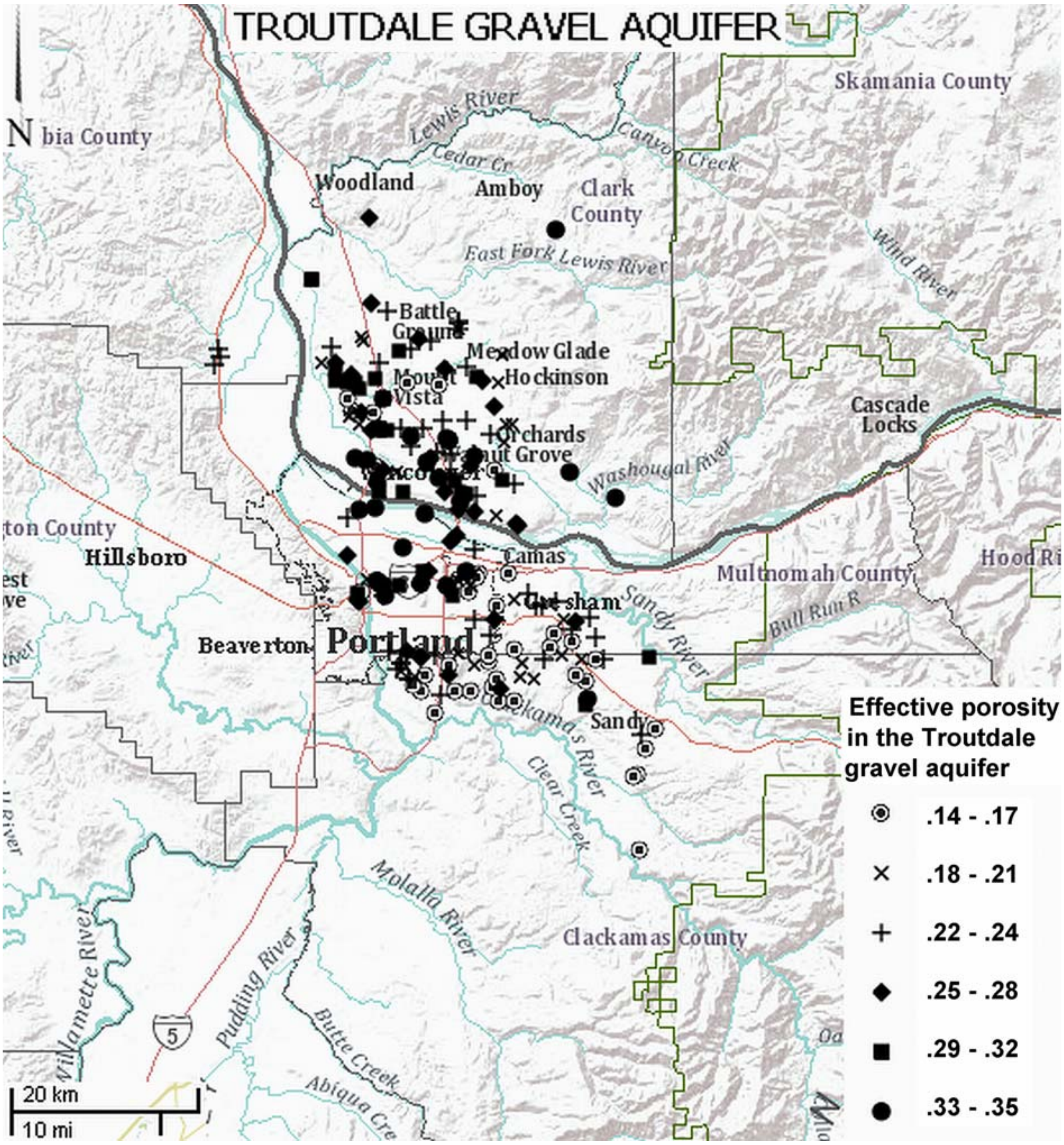

Fig. 4.2: Effective porosity values for the Troutdale gravel unit calculated using equation 3.28.

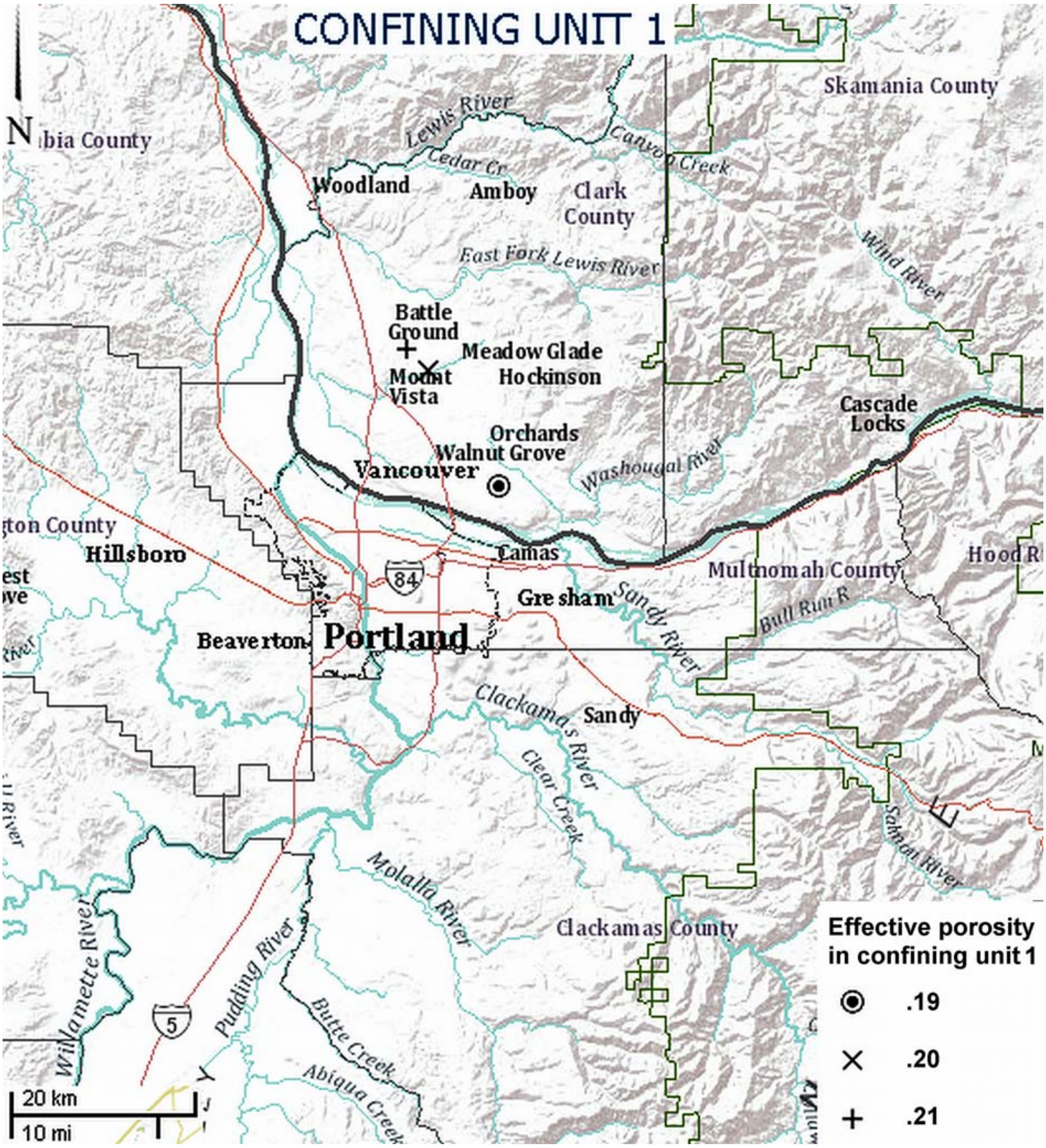

Fig. 4.3: Effective porosity values for the confining unit 1 calculated using equation 3.28.

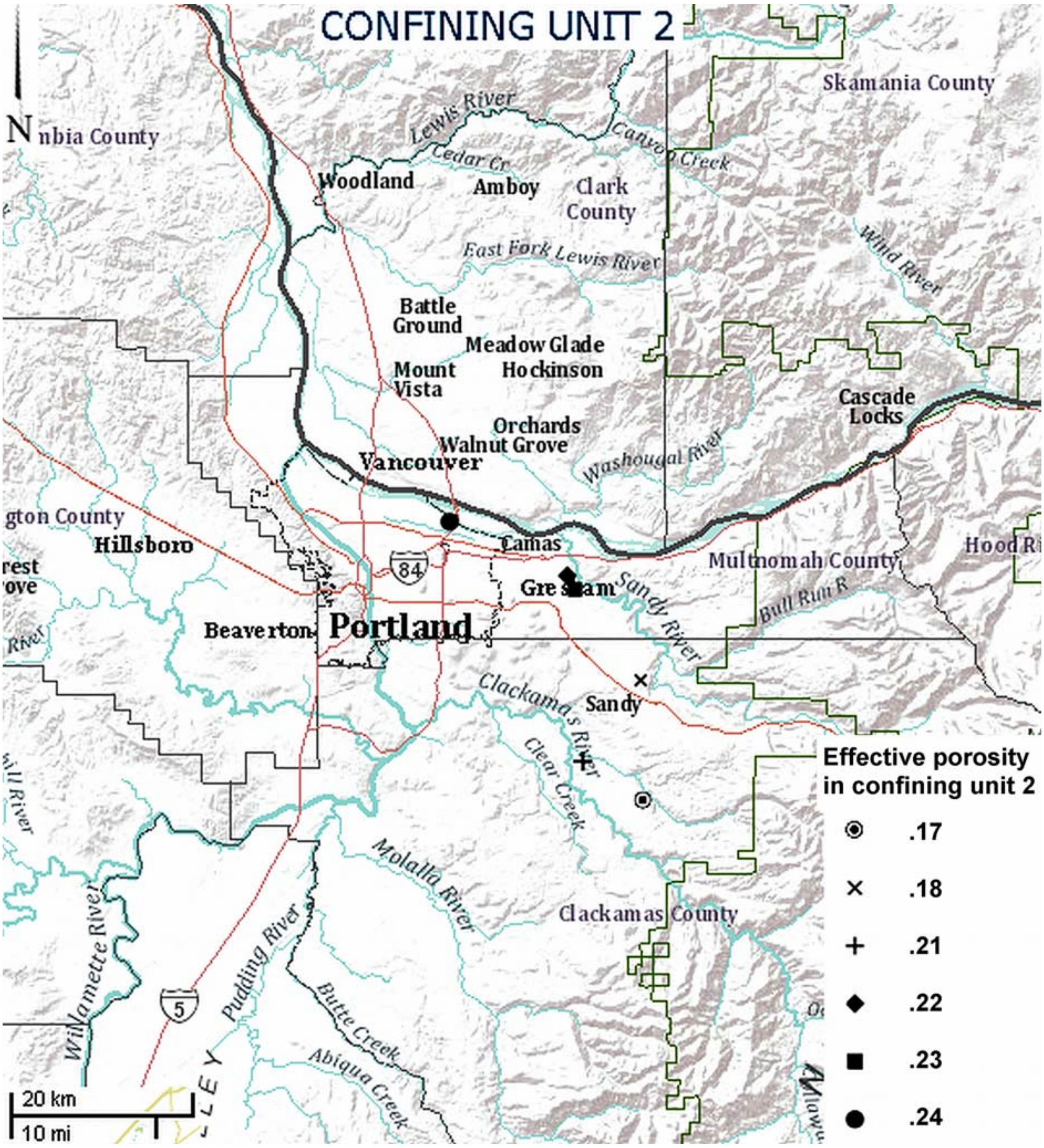

Fig. 4.4: Effective porosity values for the confining unit 2 calculated using equation 3.28.

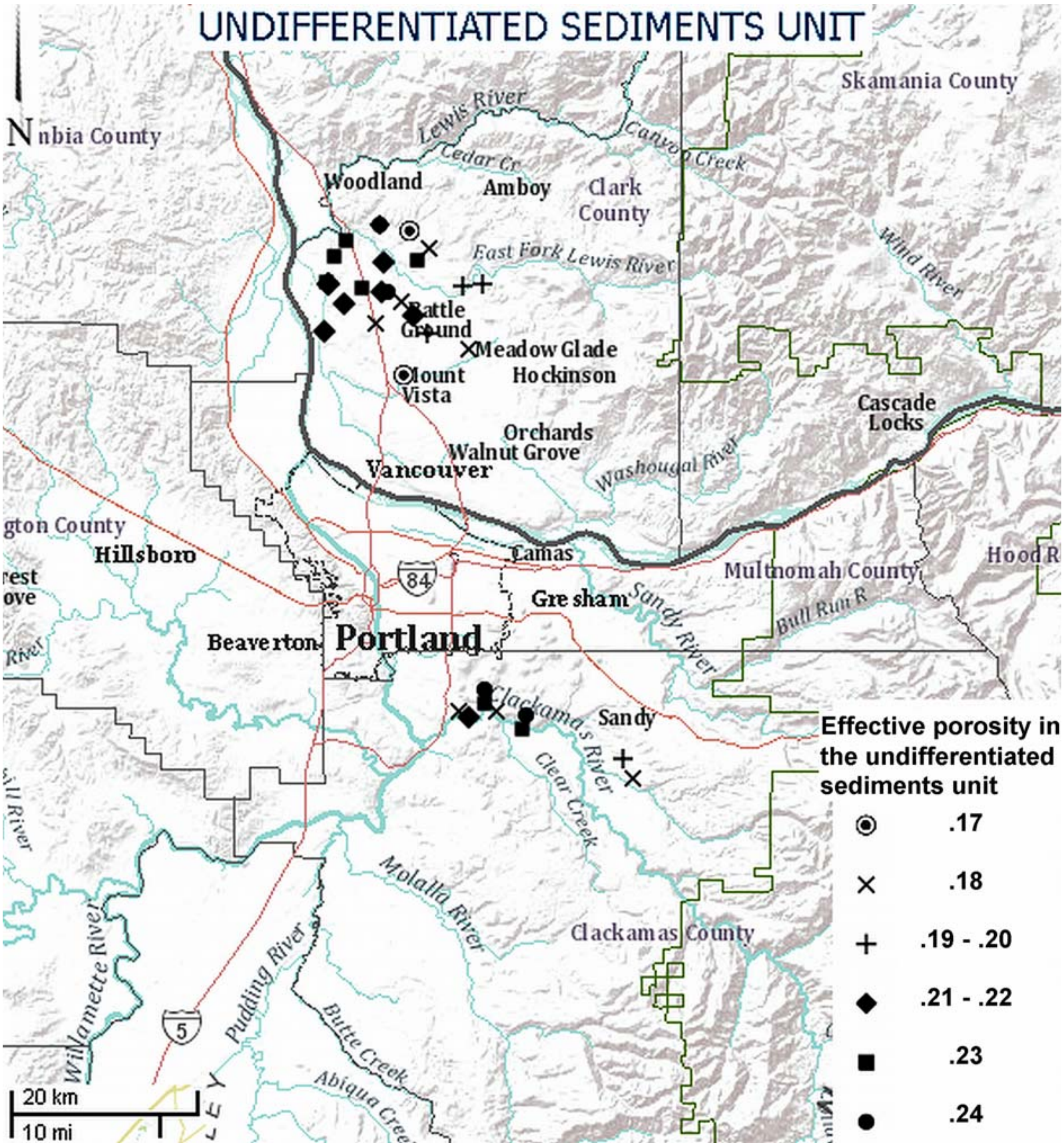

Fig. 4.5: Effective porosity values for the undifferentiated fine-grained unit calculated using equation 3.28.

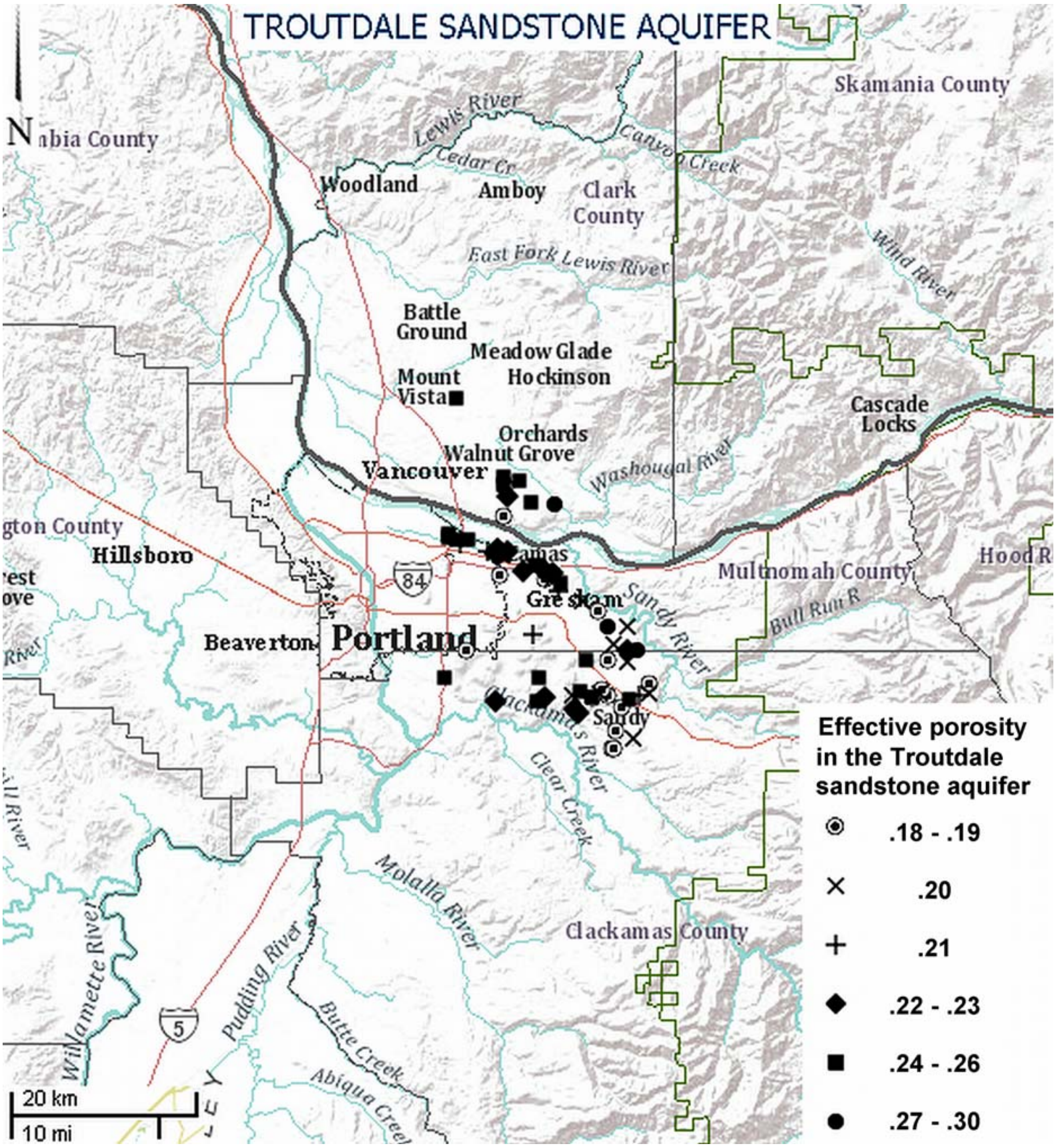

Fig. 4.6: Effective porosity values for the Troutdale sandstone unit calculated using equation 3.28.

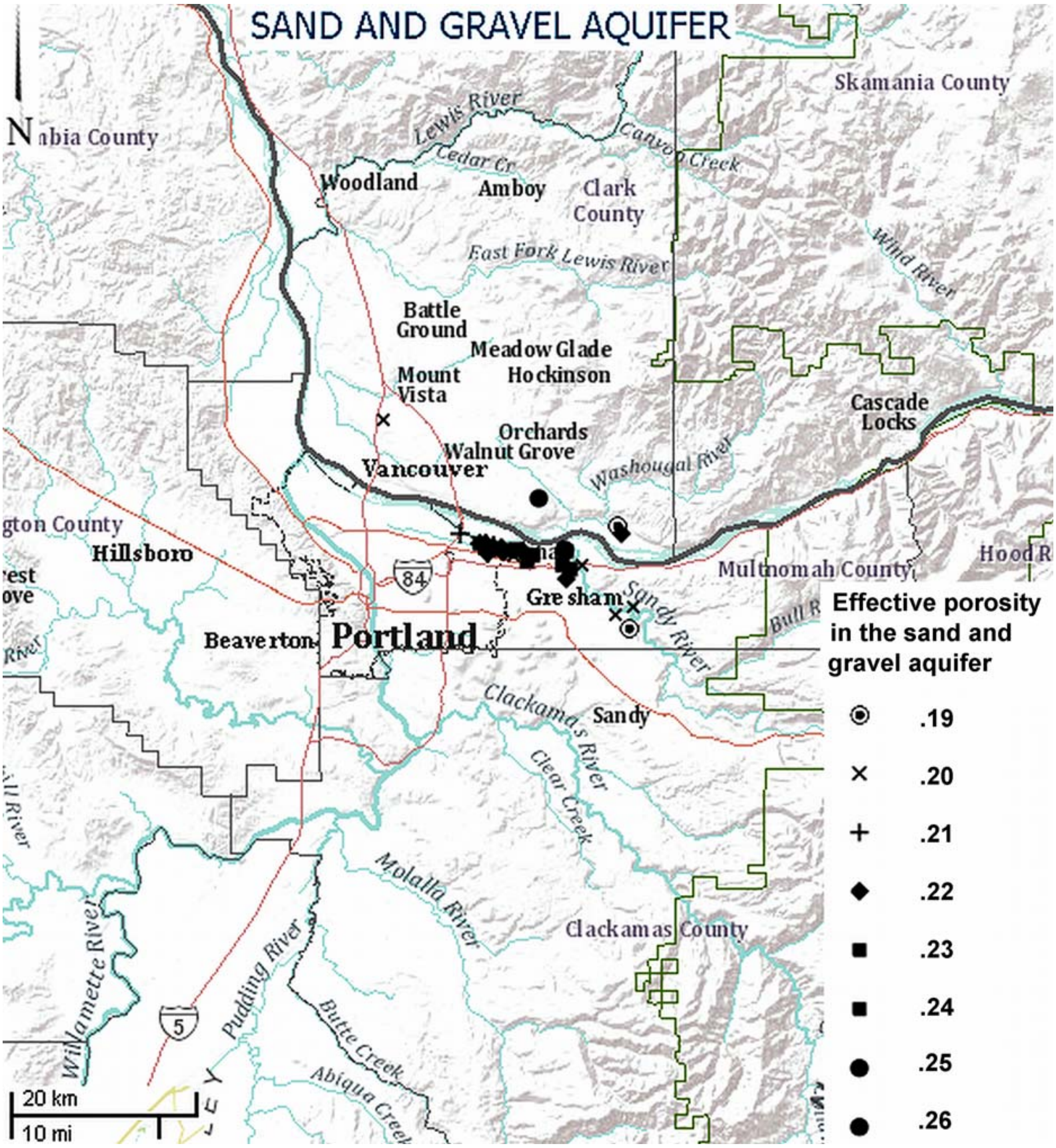

Fig. 4.7: Effective porosity values for the sand and gravel unit calculated using equation 3.28.

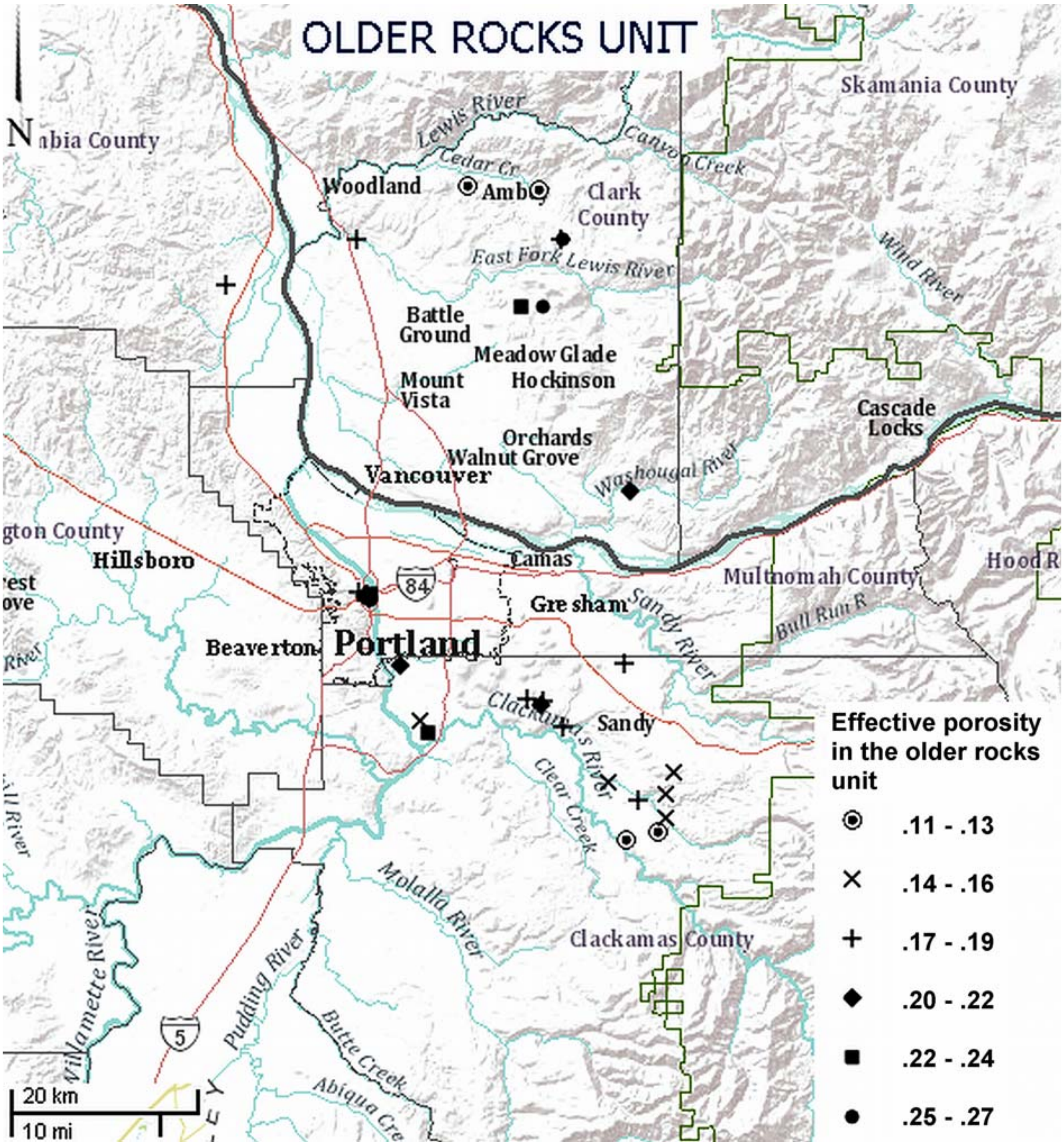

Fig. 4.8: Effective porosity values for the older rocks unit calculated using equation 3.28.

4.2 Discussion

The initial equation was based on a laboratory investigation that used 5 different sizes of sediments. The initial equation satisfied the conditions of the sediments in the laboratory and established a basis for testing with a well database. However, the hydrogeology in the study area is complex and does not reflect the very basic sediments and conditions used in the laboratory experiments. This was anticipated and the subsequent revisions were expected.

The laboratory generated initial equation was applied to the selected well data and initially produced values of effective porosity ranging from near 0% to over 400%. The solution to the fit turned out to be a polynomial; hence, the subsequent iterations were based on polynomial variations. Three iterations were needed to achieve an R^2 of 1.0 which resulted in the final equation (Eq. 28), a power based equation. This demonstrates that the results from the laboratory experiments could be successfully used to establish the field relationship, which is a major breakthrough in determining effective porosity from direct observations.

The wells in the area yield from 27 m^3/day up to 55,000 m^3/day (Swanson et al., 1993), indicating very a large distribution of effective porosity values in the groundwater system and within each of the hydrogeologic units. Hence the need for the original solution used in the groundwater model, which placed a limit on the effective porosity at 31% and subsequently applied a multiplier factor to raise the limit to 35%. This required a significant amount of time and effort resulting in a large number of man-hours to calibrate and stabilize the model. The efficiency of calibrating and stabilizing the model could have been improved significantly with the use of the relationship developed in this research.

As shown in the series of figures in this chapter there are significant differences in the effective porosity values as well as significant correlations. Clearly the method of limiting effective porosity values was successful for the original groundwater model but there were still significant differences between the wells and the model cells. If this relationship had been known then the calibration time would have decreased and the results would have been more accurate. Numerous groundwater models of various types and scales have been used to help understand groundwater conditions in many different places with many different environments. Had this major breakthrough in understanding effective porosity been established much earlier then subsequent models would have been faster to calibrate and achieve more accurate results. The importance of this major breakthrough can not be understated. It represents a significant contribution to the earth sciences.

4.2.1 Interpretation

The relationship between specific capacity and effective porosity was established, tested, and refined to successfully calculate effective porosity without knowing any of the construction parameters or lithology. However, well conditions change over time and even more significantly when impacted by disasters and anthropogenic influences. Therefore the most accurate results can only be obtained by using recent pump test information. The implication of this is that older data may increase the margin of error in the calculations. It also implies that it is in the best interest to obtain the best data by pursuing a simple pump and drawdown test at the pump site, or consult with the owner if there are a time series of water level records available with pumping rates.

The relationship was shown to be valid in geologic environments ranging from unconsolidated sediments to volcanic rocks. It is also important to understand that this relationship is also valid for artesian wells where the water level is above land surface. This is because pumping will cause a drawdown in the water level which can be used for calculating effective porosity. This shows that the relationship is only limited by the age of the input data. It also shows that this relationship is valid for a wide range of geologic environments which is a major advance in the understanding and calculating effective porosity.

An example of how this new relationship could be used is illustrated in Figure 4.9 which shows a schematic diagram of a simplified aquifer with several different zones of differing thickness, lithology, and effective porosity. Zone 1 consists of the main aquifer that consists of well sorted and packed sand with an average effective porosity of 34% and an average thickness of 150 meters. Zone 2 consists of a consolidated coarse grained lens with an average effective porosity of 23% and an average thickness of 75 meters. Zone 3 consists of a remnant layer of older fine-grained cemented sandstone that has fractures and an average effective porosity of 19% and an average thickness of 60 meters. Zone 4 consists of a more recent episode of deposition of consolidated sand and gravel that has an average effective porosity of 28% and an average thickness of 120 meters. If the areal extent of each zone is known then a simple calculation can be made to estimate the amount of groundwater in the aquifer system. The extent in m^2 is multiplied by the average thickness and again by the effective porosity estimate the volume of water in that zone. This can be repeated with each zone and then summed for an estimate of the total groundwater volume in the aquifer. Under realistic conditions specific retention needs to be taken into consideration since some water will cling to the sediments and can not be pumped out. With additional well data showing water levels and recharge data a model could be created to simulate the groundwater conditions under pumping conditions to estimate the amount that could be safely pumped from this aquifer on a regular or semi-regular basis.

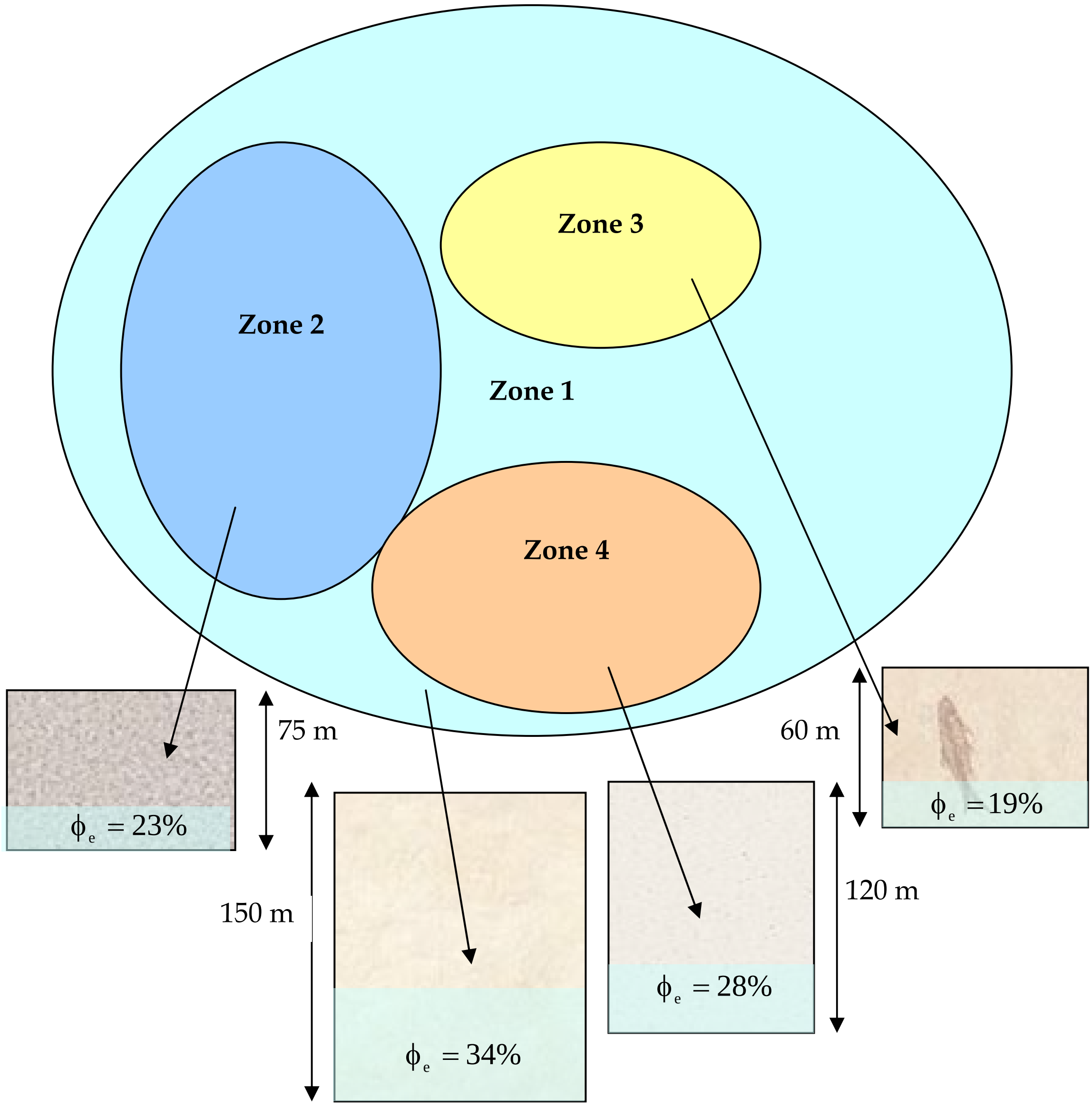

Fig. 4.9: Schematic diagram of a hypothetical aquifer showing different zones within the aquifer and their properties.

4.3 Summary of the Results

The results of this research represent a major breakthrough and clearly established the validity of the relationship between specific capacity and effective porosity postulated in this research. It was calibrated and applied to a variety of geologic environments without the need for construction details or lithology details. The only significant limitation is the age, or freshness of the pump test data used for the calculation since well conditions can and do change over time.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary

The postulated relationship between specific capacity and effective porosity was established and calibrated in the laboratory under controlled conditions. This relationship was then extended to field conditions by applying it to field data consisting of a well database selected from published data. However it was determined that the initial relationship established in the laboratory did not work well with the field data. The relationship was revised and calibrated to the field data with a confidence level (R^2) of 1.0. This relationship was shown to exist without knowledge of construction details or lithology. The transfer of this concept from the laboratory to the field is a remarkable accomplishment. The ability to apply this relationship to any geologic condition represents a major breakthrough in understanding the relationship between specific capacity and effective porosity. The only significant limitations are that the most accurate results can only be obtained from fresh pump test data. Also, the development and establishment of this relationship was based on groundwater conditions and is only valid for saturated sediments.

5.2 Conclusions

The relationship between specific capacity and effective porosity did not exist prior to this research and has been determined in equation 3.28 in this research. This is a major breakthrough in understanding the relationship between specific capacity and effective porosity that did not exist prior to this research. Further, it will be a significant advance in field methods since the effective porosity can be calculated in the field at the time of construction.

Among hydrogeologic relationships it is concluded that this relationship can and will revolutionize future groundwater studies and models and become a world standard. It will simplify parameter estimation as well as yield more accurate results. It can be used to update previous groundwater studies as well as used in future groundwater studies. This equation that describes this relationship is relatively basic, making it easy to use and easily programmed into a spreadsheet or integrated into modeling software code. In time this relationship will appear in textbooks, helping students to learn more easily about effective porosity.

The goals of this research were successfully achieved and the results will impact future studies in groundwater. It is hoped that additional research using this relationship will adapt it to other environments such as parameter estimation, contaminant modeling, and the flow of other fluids.

CHAPTER VI

RECOMMENDATIONS

6.1 Recommendations for Future Study

It is hoped that other researchers will take this research one step further and adapt it to other fluids. The specific density of water is around 1.0, but other fluids have denser properties. It is believed that this relationship can be adapted to use in the petroleum industry with minor modifications to account for density properties. Therefore I strongly encourage other researchers to further develop this relationship for use in environments other than with water.

Additionally this relationship was developed and established in the metric units. There are several variations of the metric system as well as the American system of units. Razack et al. (1991) provide a table of conversions and can be used to convert this relationship for use in other units of measure. It would be extremely useful to be useable globally and it is hoped that another researcher will undertake this task.

In section 4.2.1 a hypothetical example of how effective porosity can impact the analysis of an aquifer was shown. This type of application can be further explored and applied to field data by another ambitious researcher.

REFERENCES

Ahuja, L. R., Cassel, D. K., Bruce, R. R., & Barnes, B. B. (1989). Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. *Soil Science*, *148*(6), 404-411.

Barr, D. W. (2001). Coefficient of permeability determined by measurable parameters. *Ground Water*, *39*(3), 356−361.

Bernabé, Y., Mok, U., Evans, B., & Herrmann, F. (2004). Permeability and storativity of binary mixtures of high-and low-porosity materials. *Journal of Geophysical Research*, *109*, B12207.

Cooper, H. H., & Jacob, C. E. (1946). A Gereralized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History. *Transactions, American Geophysical Union*, *27*(4).

Cunningham, K. J. (2004). Application of ground-penetrating radar, digital optical borehole images, and cores for characterization of porosity hydraulic conductivity and paleokarst in the Biscayne aquifer, southeastern Florida, USA. *Journal of applied geophysics*, *55*, 61−76.

Darcy, H. (1856). Les Fontaines Publiques de la Ville de Dijon. *Victor Dalmont*.

Dias, R. P., Teixeira, J. A., Mota, M. G., & Yelshin, A. I. (2004). Particulate binary mixtures: dependence of packing porosity on particle size ratio. *Industrial & engineering chemistry research*, *43*(24), 7912−7919.

Domenico, P. A., & Schwartz, F. W. (1991). Physical and Chemical Hydrogeology. *John Wiley & Sons Inc.*

Driscoll, F. G. (1986). Groundwater and Wells (2nd ed.). *Johnson Division.*

Dunning, C. P. (2005). Lithology, hydraulic properties, and water quality of the Sandstone Aquifer in the northwestern part of the Bad River Indian Reservation, Wisconsin, 1998-1999 (Open File Report No. 2004-1425) (p. 47). *US Geological Survey.*

Fetter, C. W. (2000). *Applied Hydrogeology* (4th ed.). Prentice Hall.

Gloaguen, E., Chouteau, M., Marcotte, D., & Chapuis, R. (2001). Estimation of hydraulic conductivity of an unconfined aquifer using cokriging of GPR and hydrostratigraphic data. *Journal of* *applied geophysics, 47*, 135−152.

Haggerty, R., Schroth, M., & Istok, J. (1998). Simplified method of“ push-pull” test data analysis for determining in situ reaction rate coefficients. *Ground Water*, *36*(2), 314−324.

Hall, S. H., Luttrell, S. P., & Cronin, W. E. (1991). A Method for Estimating Effective Porosity and Ground‐Water Velocity. *Ground Water*, *29*(2), 171-174.

Hinkle, S., & Snyder, D. T. (1997). Comparison of chlorofluorocarbon-age dating with particle-tracking results of a regional ground-water flow model of the Portland Basin, Oregon and Washington (Water Supply Paper No. 2483) (p. 47). *US Geological Survey.*

Hornberger, G. M., Raffensperger, J. P., Wiberg, P. L., & Eshleman, K. N. (1998). *Elements of Physical Hydrology. Johns Hopkins University Press.*

Jarvis, N., Zavattaro, L., Rajkai, K., Reynolds, W., Olsen, P. A., McGechan, M., Mecke, M., et al. (2002). Indirect estimation of near-saturated hydraulic conductivity from readily available soil information. *Geoderma*, *108*, 1−17.

Javandel, I. (1989). On the field determination of effective porosity. *National Conference on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, Dallas, TX* (pp. 155-170).

Kamann, P. J., Ritzi, R. W., Dominic, D. F., & Conrad, C. M. (2007). Porosity and permeability in sediment mixtures. *Ground Water*, *45*(4), 429-438.

Kauffman, M. H. (1999). *An investigation of ground water-surface water interaction in the Flint Creek Valley, Granite County, Montana.* Unpublished thesis. *Montana State University−Bozeman.*

Mace, R. E. (1997). Determination of transmissivity from specific capacity tests in a karst aquifer. *Ground Water, 35*(5), 738−742.

McCarthy, K. A., & Anderson, D. B. (1990). Ground-water data for the Portland Basin, Oregon and Washington (Open File Report No. 90-126) (p. 56). *US Geological Survey.*

McCarthy, K. A., McFarland, W. D., Wilkinson, J. M., & White, L. D. (1992). The dynamic relationship between ground water and the Columbia River: using deuterium and oxygen-18 as tracers. *Journal of Hydrology*, *135*, 1−12.

McFarland, W. D., & Morgan, D. S. (1996). Description of the ground-water flow system in the Portland Basin, Oregon and Washington (Water Supply Paper). 2470-A (p. 58). *US Geological Survey*.

Morgan, D. S., & McFarland, W. D. (1996). Simulation analysis of the ground-water flow system in the Portland Basin (Water Supply Paper 2470-B) (p. 83). *US Geological Survey*.

Morin, R. H. (2006). Negative correlation between porosity and hydraulic conductivity in sand-and-gravel aquifers at Cape Cod, Massachusetts, USA. *Journal of Hydrology*, *316*, 43−52.

Morris, D. A., & Johnson, A. I. (1967). Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey, 1948-60 (Water Supply Paper No. 1839-D) (p. 42). *US Geological Survey*.

Peyton, G. R., Gibb, J. P., LeFaivre, M. H., Ritchey, J. D., Burch, S. L., & Barcelona, M. J. (1986). Effective Porosity of Geologic Materials. *Proceedings of the Twelfth Annual Research Symposium* (pp. 21-28). Presented at the Twelfth Annual Research Symposium, U.S. Environmental Protection Agency.

Razack, M., & Huntley, D. (1991). Assessing transmissivity from specific capacity in a large and heterogeneous alluvial aquifer. *Ground Water*, *29*(6), 856−861.

Rojstaczer, S., & Agnew, D. C. (1989). The influence of formation material properties on the response of water levels in wells to earth tides and atmospheric loading. *Journal of Geophysical Research*, *94*(B9), 12403−12411.

Snyder, D. T, Wilkinson, J. M., & Orzol, L. L. (1998). Use of a ground-water flow model with particle tracking to evaluate ground-water vulnerability, Clark County, Washington (Water Supply Paper No. 2488) (p. 72). *US Geological Survey*.

Snyder, Daniel T., Wilkinson, J. M., & Orzol, L. L. (1996). Use of a ground-water flow model with particle tracking to evaluate ground-water vulnerability, Clark County, Washington (Open File Report No. 96-328) (p. 71). *US Geological Survey*.

Sperry, J. M., & Peirce, J. J. (1995). A model for estimating the hydraulic conductivity of granular material based on grain shape, grain size, and porosity. *Ground Water*, *33*(6), 892−898.

Stephens, Hsu, K., Ankeny, M. D., Ankeny, M. D., Blandford, N., Kelsey, J. A., Kelsey, J. A., et al. (1998). A comparison of estimated and calculated effective porosity. *Hydrogeology Journal*, *6*(1), 156-165.

Sterrett, R. J. (2007). Groundwater and Wells (3rd ed.). *Smyth Co Inc.*

Swanson, R. D., McFarland, W. D., Gonthier, J. B., & Wilkinson, J. M. (1993). A description of hydrogeologic units in the Portland basin, Oregon and Washington (Water Resources Investigation Report No. 90-4196) (p. 56). *US Geological Survey.*

Thomas, B. E., Wilkinson, J. M., & Embrey, S. S. (1997). The ground-water system and ground-water quality in western Snohomish County, Washington (Water Resources Investigation Report 96-4312) (p. 224). *US Geological Survey.*

Vandevivere, P., & Baveye, P. (1992). Effect of bacterial extracellular polymers on the saturated hydraulic conductivity of sand columns. *Applied and Environmental Microbiology*, *58* (5), 1690.

Wang, R., Mair, R., Rosen, M., Cory, D., & Walsworth, R. (2003). Simultaneous measurement of rock permeability and effective porosity using laser-polarized noble gas NMR. *Arxiv preprint cond-mat/0312543*.

White, P. A. (1988). Measurement of Ground-Water Parameters Using Salt-Water Injection and Surface Resistivity. *Ground water*, *26* (2), 179−186.

Wilkinson, J. M. (1991). Hydrogeology of an alluvial aquifer in the Blue Lake area, east Multnomah County, Oregon. Unpublished thesis. *Portland State University.*

Wilkinson, J. M., & Shikazono, N. (2012). Experimental Determination of Effective porosity and Specific Capacity under Controlled Conditions in a Laboratory. *International Journal of Applied Environmental Sciences*, *In Press*.

Yeh, Y., Lee, C., & Chen, S. (2000). A Tracer Method to Determine Hydraulic Conductivity and Effective Porosity of Saturated Clays Under Low Gradients. *Ground Water*, *38* (4), 522-529.

Zhang, Z. F., Ward, A. L., & Keller, J. M. (2011). Determining the Porosity and Saturated Hydraulic Conductivity of Binary Mixtures. *Vadose Zone Journal*, *10* (1), 313-321.

APPENDIX I

SYMBOLS AND TERMINOLOGY

For the benefit of the reader and in an effort to minimize the use of terminology, the terms, symbols, and a brief explanation of each term and how it is related to other terms is presented here in an effort to make this thesis easier to understand. The terms, symbols, and descriptions are not presented in any specific order.

b : This symbol represents the saturated thickness of the sediments, usually determined by a static water level compared with the depth of the well. Units of measurement in this document are meters (m).

k : This symbol represents permeability, which is a measure of the ability of sediments or rocks to allow fluid to pass through it. This term is used primarily in petroleum geology and soil sciences. However, it is related to hydraulic conductivity alternatively but rarely used in groundwater applications. Units of measurement are square meters (m^2).

K : This symbol represents hydraulic conductivity, which is defined as the ease with which water can move through pore spaces or fractures. It generally refers to horizontal flow of groundwater, although there is also vertical hydraulic conductivity. It is directly related to transmissivity and saturated thickness. Hydraulic conductivity is equal to the transmissivity divided by the saturated thickness. Units of measurement in this document are meters per day (m/day).

K_{sat} : This symbol represents saturated hydraulic conductivity and is used specifically to indicate hydraulic conductivity in the saturated zone of an aquifer. Hydraulic conductivity implies that it is saturated hydraulic conductivity, but can be interpreted in other ways such as vertical, horizontal, partially saturated, etc. Units of measurement for saturated hydraulic conductivity are the same as for hydraulic conductivity, meters per day (m/day).

Q: This symbol represents the rate of flow, used to describe the pumping rate in a well. Units of measurement in this document are cubic meters per day (m^3/day).

s : This symbol represents the drawdown, which is the change in the water level in a well. Drawdown usually occurs when water is pumped from the well. Units of measurement in this document are meters (m).

T : This symbol represents transmissivity, which is defined as the rate at which water is transmitted through a unit width of an aquifer with a unit hydraulic gradient. Transmissivity is directly related to the hydraulic conductivity and saturated thickness of the aquifer and dependent on the properties of the liquid. Units of measurement in this document are square meters per day (m^2/day).

ϕ: This symbol represents total porosity, which includes all pore spaces, interconnected and not connected. It is the ratio of total volume of the total void space to the total volume of the whole rock. Other similar terms are effective porosity, primary porosity, and secondary porosity, each of which will never be more than the total porosity. Units of measurement are non dimensional and typically expressed as a decimal between 0 and 1, or as a percentage of 0 to 100 percent.

ϕ_e: This symbol represents effective porosity, which includes all interconnected pore space that can allow water to flow. It is the ration of the interconnected void spaces to the whole rock. Units of measurement are non dimensional and typically expressed as a decimal between 0 and 1, or as a percentage of 0 to 100 percent.

ϕ_i: This symbol represents the initial effective porosity that was measured in the laboratory experiments and is used to differentiate between the initial effective porosity and subsequent calculated effective porosity in this thesis. Units of measurement are non dimensional and typically expressed as a decimal between 0 and 1, or as a percentage of 0 to 100 percent.

Homogeneity: This term refers to a substance that is of uniform composition.

Heterogeneity: This term refers to a substance that not uniform in composition. It should be noted that in geology all rocks and sediments are heterogeneous.

Isotropy or isotropic: This term refers to having identical values of a property in all directions. Conversely, anisotropy refers to the lack of isotropy.

These represent all of the terms and symbols used in this thesis.

APPENDIX II

WELL DATABASE

ORIGINAL CONSTRUCTION DATA

(McCarthy & Anderson, 1990)

Well ID	Location Latitude	Longitude	Altitude feet	Depth feet	Well Dia inches	Lith	Yield gal/min	Drawdown feet
1	45.6197	-122.4795	282	236	10	C1	65	90
2	45.7331	-122.5783	256	248	6	C1	330	87
3	45.7550	-122.6083	200	215	8	C1	50	49
4	45.3000	-122.2795	985	245	6	C2	21	67
5	45.4194	-122.2814	814	1560	6	C2	180	20
6	45.3375	-122.3659	362	240	6	C2	75	133
7	45.5222	-122.3879	225	354	8	C2	300	93
8	45.5100	-122.3750	270	450	8	C2	180	10
9	45.5758	-122.5531	22	364	10	C2	200	25
10	45.2822	-122.3225	720	466	6	OR	1	292
11	45.9164	-122.5417	435	459	6	OR	3	286
12	45.2908	-122.2765	1115	227	6	OR	2	140
13	45.9131	-122.4432	437	400	8	OR	40	374
14	45.3386	-122.3456	380	300	10	OR	70	85
15	45.3264	-122.2672	930	301	6	OR	12	171
16	45.3039	-122.2665	635	158	6	OR	16	142
17	45.3483	-122.2556	1202	685	6	OR	8	145
18	45.3981	-122.6083	132	488	8	OR	292	151
19	45.8644	-122.6956	120	400	6	OR	4	334
20	45.3217	-122.3054	810	338	6.6	OR	8	51
21	45.8214	-122.8761	135	300	8	OR	68	255
22	45.4542	-122.3248	660	1783	12	OR	1179	158
23	45.5183	-122.6773	50	765	16	OR	750	206
24	45.5231	-122.6912	125	563	8	OR	65	75
25	45.8642	-122.4132	680	160	8	OR	42	96

26	45.4197	-122.4582	548	1066		OR	170	61
27	45.4175	-122.4364	590	715		OR	100	159
28	45.5211	-122.6804	60	591	12	OR	650	250
29	45.3931	-122.4104	190	600	8	OR	30	200
30	45.6222	-122.3147	715	435	6	OR	5	9
31	45.5192	-122.6826	110	772	12	OR	500	52
32	45.4517	-122.6351	50	227	8	OR	250	140
33	45.4128	-122.4387	522	212	8	OR	300	105
34	45.7997	-122.4682	662	435	10	OR	635	27
35	45.3872	-122.5947	88	304	10	OR	200	5
36	45.5208	-122.6768	38	508	14	OR	700	32
37	45.7992	-122.4379	662	425	6	OR	100	2
38	45.8642	-122.4101	680	125	6	OR	120	30
39	45.5147	-122.6770	85	228	16	OR	520	98
40	45.4800	-122.3079	648	520		SG	250	70
41	45.5814	-122.3265	102	336	10	SG	300	146
42	45.5583	-122.4682	26	435		SG	1999	255
43	45.5511	-122.4712	20	448	24	SG	2499	266
44	45.5419	-122.3758	48	85	6	SG	50	38
45	45.4944	-122.3286	650	602	6	SG	60	40
46	45.6850	-122.6536	220	544	10	SG	779	139
47	45.5019	-122.3048	120	335	8	SG	75	40
48	45.5531	-122.5082	39	558		SG	2499	127
49	45.5564	-122.4579	22	358		SG	2499	175
50	45.5733	-122.5459	24	667		SG	3198	160
51	45.5628	-122.5094	20	569	8	SG	350	27
52	45.5639	-122.5172	20	585		SG	2549	178
53	45.5614	-122.4990	25	531	12	SG	2399	80
54	45.5564	-122.4579	23	358	6	SG	720	55
55	45.5628	-122.5094	20	568	12	SG	2998	167
56	45.5600	-122.4879	23	550	6	SG	300	22
57	45.5736	-122.3212	25	187	20	SG	500	134
58	45.5286	-122.3981	312	550	12	SG	500	101
59	45.5558	-122.4864	24	490		SG	2499	71

60	45.5597	-122.4990	25	490	6	SG	647	37
61	45.5558	-122.4864	24	486		SG	370	65
62	45.5556	-122.399	28	584	20	SG	1099	48
63	45.5531	-122.5082	39	561	6	SG	425	45
64	45.5547	-122.3987	26	584	20	SG	1474	101
65	45.5556	-122.3978	28	592	20	SG	1499	30
66	45.5383	-122.3904	135	571	16	SG	590	52
67	45.5419	-122.4031	78	200		SG	140	20
68	45.5569	-122.4993	17	509	12	SG	2998	128
69	45.5583	-122.4682	26	450		SG	479	32
70	45.5519	-122.4428	14	226	10	SG	200	18
71	45.5639	-122.5172	20	582		SG	450	23
72	45.5453	-122.4531	80	368	10	SG	450	62
73	45.5569	-122.3998	26	268	10	SG	400	20
74	45.6067	-122.4353	380	240	6	SG	40	45
75	45.4111	-122.5487	122	312	10	SGUF	250	60
76	45.4525	-122.5011	745	395	6	TG	2	18
77	45.3686	-122.2851	1015	135		TG	3	90
78	45.4231	-122.5468	380	676		TG	135	352
79	45.3867	-122.2712	960	110		TG	8	50
80	45.3422	-122.2953	930	143	6.6	TG	25	92
81	45.6942	-122.6912	215	351	12	TG	334	345
82	45.4153	-122.4884	418	260	6	TG	60	60
83	45.4331	-122.3672	535	290		TG	50	42
84	45.4394	-122.5900	185	271		TG	150	80
85	45.4653	-122.4644	390	280		TG	160	70
86	45.4481	-122.5564	625	532		TG	20	75
87	45.7206	-122.5697	278	247	8	TG	120	130
88	45.4278	-122.4959	348	310	8	TG	250	180
89	45.4544	-122.3518	615	139	6	TG	15	12
90	45.4714	-122.3851	475	278		TG	210	125
91	45.7211	-122.6132	232	246	8	TG	120	118
92	45.5206	-122.6758	38	544	16	TG	999	223
93	45.4800	-122.4104	365	210	10	TG	250	95

94	45.5314	-122.5419	288	485	6	TG	300	120
95	45.4669	-122.4157	575	510		TG	250	47
96	45.5378	-122.515	251	490	12	TG	220	94
97	45.4358	-122.4907	365	442	6	TG	310	68
98	45.6419	-122.6564	211	356	16	TG	70	35
99	45.7075	-122.6972	215	316	8	TG	100	74
100	45.4394	-122.3808	535	310	8	TG	175	105
101	45.6931	-122.6614	210	278	10	TG	325	82
102	45.5375	-122.4748	184	389		TG	305	140
103	45.4025	-122.5765	112	172	8	TG	125	81
104	45.3406	-122.3006	865	79	6.6	TG	10	20
105	45.4147	-122.4642	528	310	8	TG	100	85
106	45.2694	-122.2912	1160	95	6	TG	100	98
107	45.4231	-122.5950	100	203	8	TG	135	58
108	45.5075	-122.4904	245	273	12	TG	100	22
109	45.4592	-122.5020	545	357		TG	109	100
110	45.4233	-122.5253	355	404	8	TG	141	27
111	45.4306	-122.6064	125	480		TG	725	165
112	45.5203	-122.5278	305	330	8	TG	150	45
113	45.6372	-122.4925	292	338	8	TG	110	165
114	45.5347	-122.5175	258	445	12	TG	150	36
115	45.6822	-122.4778	275	255	8	TG	230	110
116	45.4581	-122.3998	611	282	6	TG	17	76
117	45.4508	-122.4536	620	210	8	TG	110	28
118	45.4436	-122.6228	105	327	14	TG	899	112
119	45.4542	-122.3718	586	163	6	TG	10	15
120	45.7619	-122.6750	303	168	8	TG	30	40
121	45.7658	-122.6758	300	196	8	TG	55	48
122	45.5125	-122.4647	255	290	16	TG	300	125
123	45.6642	-122.4801	202	78	8	TG	135	60
124	45.4931	-122.3956	440	360		TG	102	30
125	45.4597	-122.5412	735	967	10	TG	100	73
126	45.5925	-122.4892	228	250	6	TG	75	88
127	45.6364	-122.6268	175	300	8	TG	65	38

128	45.4375	-122.4564	415	335		TG	280	75
129	45.5317	-122.6690	70	300	14	TG	1499	100
130	45.7219	-122.4883	281	180	8	TG	109	37
131	45.7494	-122.4832	353	130	6.6	TG	30	80
132	45.4381	-122.6015	155	336		TG	800	187
133	45.5267	-122.5253	298	500		TG	500	133
134	45.5372	-122.5197	255	400	12	TG	240	50
135	45.6822	-122.6795	218	407	16	TG	275	69
136	45.7408	-122.7317	127	240	8	TG	120	45
137	45.4489	-122.5215	470	160	6	TG	50	55
138	45.6897	-122.6937	215	303	12	TG	230	66
139	45.6811	-122.4693	283	290	8	TG	300	12
140	45.7733	-122.5422	280	149	12	TG	77	34
141	45.4353	-122.4387	600	305	8	TG	200	27
142	45.5303	-122.5419	291	490		TG	575	63
143	45.4519	-122.6203	168	383		TG	750	89
144	45.4781	-122.4981	255	136	6	TG	15	32
145	45.6533	-122.5528	205	198	8	TG	220	44
146	45.7539	-122.6083	200	100	8	TG	365	51
147	45.4936	-122.4940	275	341	12	TG	133	39
148	45.6606	-122.6083	300	485	20	TG	2199	94
149	45.5603	-122.5193	20	215	10	TG	80	40
150	45.4356	-122.6101	85	285	16	TG	849	123
151	45.5914	-122.6975	31	363	20	TG	2099	42
152	45.6728	-122.4987	215	91	8	TG	230	49
153	45.7369	-122.5301	280	171	8	TG	43	41
154	45.4758	-122.3539	550	300	8	TG	197	78
155	45.5067	-122.4348	296	285	12	TG	335	128
156	45.7908	-122.6417	272	199	8	TG	100	12
157	45.7733	-122.5422	280	141	12	TG	100	30
158	45.7475	-122.8718	30	177		TG	450	107
159	45.7553	-122.8750	62	163	8	TG	300	54
160	45.4458	-122.6278	100	304	16	TG	619	249
161	45.6122	-122.5178	300	332	8	TG	75	114

162	45.7572	-122.719	179	233	8	TG	35	45
163	45.5169	-122.6470	111	212		TG	170	70
164	45.4619	-122.6397	50	82	6	TG	12	6
165	45.3825	-122.2897	896	178	4	TG	20	10
166	45.6778	-122.6218	281	201	6	TG	45	34
167	45.4944	-122.3607	388	130	6	TG	24	20
168	45.4511	-122.6209	170	273	12	TG	465	64
169	45.6542	-122.5731	200	361	12	TG	950	125
170	45.5250	-122.5589	294	304	12	TG	300	22
171	45.4586	-122.5740	208	254	8	TG	82	47
172	45.7342	-122.5598	264	148	8	TG	75	63
173	45.4539	-122.3422	585	178	8	TG	125	30
174	45.6772	-122.5912	253	315	10	TG	380	63
175	45.4539	-122.4245	650	432	8	TG	300	46
176	45.5278	-122.5934	240	295	12	TG	350	29
177	45.7397	-122.8795	70	227	12	TG	500	72
178	45.6303	-122.5543	315	248	10	TG	290	58
179	45.4358	-122.6107	85	300		TG	700	68
180	45.7403	-122.6528	280	190	10	TG	80	14
181	45.6306	-122.5483	318	321	8	TG	315	59
182	45.5067	-122.4283	310	375	12	TG	300	70
183	45.4839	-122.3864	472	197	6	TG	50	20
184	45.7800	-122.5417	290	152	12	TG	400	52
185	45.6847	-122.5642	230	159	8	TG	100	82
186	45.6853	-122.5308	263	111	8	TG	110	45
187	45.6236	-122.4650	257	180	8	TG	220	90
188	45.4192	-122.5669	95	120	10	TG	257	65
189	45.6333	-122.5543	314	327	20	TG	800	109
190	45.4508	-122.6218	172	290	12	TG	580	20
191	45.4936	-122.5194	222	412	12	TG	550	159
192	45.7631	-122.5806	274	170	8	TG	150	28
193	45.7806	-122.5417	290	144	8	TG	332	42
194	45.5183	-122.4456	248	176	8	TG	135	55
195	45.5108	-122.4076	318	300	10	TG	250	34

196	45.4931	-122.4917	288	261		TG	300	46
197	45.7306	-122.6915	180	314	14	TG	900	36
198	45.4619	-122.6129	100	283	14	TG	275	34
199	45.4917	-122.3817	493	283		TG	90	11
200	45.8811	-122.6657	595	158	6	TG	130	30
201	45.7642	-122.5968	225	127	10	TG	255	63
202	45.6381	-122.6465	185	325	16	TG	180	10
203	45.6422	-122.5261	231	202	8	TG	110	54
204	45.5992	-122.5417	55	138	12	TG	307	25
205	45.6781	-122.6536	250	260	12	TG	600	68
206	45.6486	-122.5795	210	221	12	TG	999	22
207	45.6994	-122.4937	266	180	10	TG	390	44
208	45.4567	-122.5943	150	167	10	TG	265	100
209	45.4258	-122.4844	362	400		TG	545	105
210	45.5103	-122.6789	130	240	16	TG	440	90
211	45.5547	-122.6959	22	189	16	TG	999	48
212	45.7981	-122.6622	280	295	8	TG	60	9
213	45.5975	-122.5197	160	235	8	TG	190	49
214	45.5836	-122.4601	200	309	6	TG	80	28
215	45.5686	-122.5526	17	235		TG	5996	50
216	45.7411	-122.7117	179	171	6	TG	50	9
217	45.6172	-122.5609	304	277	8	TG	125	41
218	45.6781	-122.6536	227	220	10	TG	180	20
219	45.6939	-122.6783	197	350	16	TG	900	87
220	45.4567	-122.5953	151	147	10	TG	275	57
221	45.5392	-122.5844	204	417	12	TG	340	7
222	45.6767	-122.6626	195	243	12	TG	400	27
223	45.7244	-122.5101	280	158	10	TG	420	73
224	45.5856	-122.4637	280	350	10	TG	425	64
225	45.4389	-122.5558	395	760	14	TG	250	15
226	45.6517	-122.5200	266	198	20	TG	922	58
227	45.7353	-122.5604	258	139	6	TG	115	41
228	45.5736	-122.5459	23	228		TG	4198	47
229	45.5131	-122.6820	140	232		TG	525	55

230	45.6425	-122.5869	210	143	20	TG	19.7	990
231	45.6672	-122.5561	220	109	10	TG	31	400
232	45.7058	-122.6456	110	102	6	TG	10.5	143
233	45.6761	-122.6536	230	293	16	TG	19.5	750
234	45.5192	-122.6826	110	193	12	TG	32	600
235	45.7261	-122.6573	206	171	8	TG	25	175
236	45.6769	-122.6425	238	228	16	TG	32	1000
237	45.4106	-122.3678	641	250	8	TG	6	100
238	45.7167	-122.6793	171	220	6	TG	5	30
239	45.5378	-122.5351	245	377	8	TG	23	140
240	45.7361	-122.7126	174	187	6	TG	9	35
241	45.6781	-122.6536	225	198	10	TG	47	380
242	45.6781	-122.6536	226	211	10	TG	30	400
243	45.5392	-122.5928	182	265	12	TG	9.5	380
244	45.7278	-122.5172	295	195	10	TG	85	240
245	45.6269	-122.5483	312	208	8	TG	25	200
246	45.8214	-122.7470	55	144	10	TG	60	230
247	45.6136	-122.5323	302	254	8	TG	27	285
248	45.7058	-122.6459	110	172	16	TG	13	1000
249	45.7228	-122.6956	125	142	8	TG	14	350
250	45.7211	-122.6859	171	200	10	TG	15	400
251	45.6275	-122.4811	235	111	8	TG	5	20
252	45.7231	-122.7139	190	217	6	TG	12	50
253	45.5167	-122.5511	261	228		TG	9	300
254	45.7519	-122.6253	272	215	8	TG	14	150
255	45.8211	-122.7470	55	143	8	TG	7.9	100
256	45.6167	-122.6187	39	113	8	TG	15	360
257	45.6172	-122.6528	31	140	26	TG	41	3600
258	45.4567	-122.2786	537	50	6	TG	20	25
259	45.6308	-122.6551	130	165	10	TG	20.7	480
260	45.5267	-122.6237	220	230	10	TG	15	400
261	45.5397	-122.5314	272	410	10	TG	4.5	150
262	45.6308	-122.5690	305	272	8	TG	7.4	130
263	45.7058	-122.6456	110	162	12	TG	4.7	850

264	45.6153	-122.5372	303	218	8	TG	6	122
265	45.5258	-122.6456	130	182	12	TG	24	500
266	45.6111	-122.3250	550	110	6	TG	10	20
267	45.5633	-122.6197	145	350		TG	14	900
268	45.6361	-122.3897	315	231	8	TG	7	350
269	45.5167	-122.6447	138	380	12	TG	10	400
270	45.5992	-122.6800	5	175	12	TG	11	300
271	45.6061	-122.5400	211	184	8	TG	2	300
272	45.5278	-122.5933	210	295	12	TG	8	360
273	45.6672	-122.5561	220	200	20	TG	47	2000
274	45.5261	-122.5597	292	252	12	TG	18	250
275	45.6006	-122.6572	20	217	12	TG	1.5	300
276	45.5308	-122.6547	133	271	16	TG	7	1100
277	45.6511	-122.5200	239	146	20	TG	15.6	1500
278	45.6672	-122.5561	220	106	10	TG	8	725
279	45.8703	-122.4078	708	93	8	TG	1.3	220
280	45.4164	-122.3633	608	259	12	TG	8	1500
281	45.6467	-122.6678	210	285	16	TG	5	840
282	45.6261	-122.6550	85	146	12	TG	2	600
283	45.5950	-122.5881	15	129		TG	1	35
284	45.5306	-122.6547	133	272		TG	3	1200
285	45.6711	-122.6094	300	237	6	TG	18	60
286	45.6456	-122.5875	218	88	6	TG	1.4	100
287	45.6686	-122.5581	235	111	8	TG	1	146
288	45.6486	-122.6844	65	130	18	TG	0.5	800
289	45.4872	-122.4070	400	282	10	TGC1	214	180
290	45.6983	-122.6167	252	449	12	TGC1	114	763
291	45.7372	-122.5864	245	304	8	TGC1	42	140
292	45.7203	-122.6137	231	655	8	TGC1	27	525
293	45.7044	-122.6212	250	434	14	TGC1	42.6	1250
294	45.2764	-122.2826	1120	193	8	TGC2	80	48
295	45.5475	-122.7064	30	574	12	TGOR	275	315
296	45.3147	-122.3008	887	233	6.6	TGOR	26	10
297	45.7289	-122.5614	290	290	12	TGSG	130	350

298	45.5483	-122.4720	18	498		TGSG	143	2000
299	45.5183	-122.6778	58	368	14	TGSG	140	500
300	45.4578	-122.2783	646	345	6	TGTS	89	10
301	45.4622	-122.4369	830	500	6	TGTS	70	15
302	45.4844	-122.3536	525	541	12	TGTS	220	225
303	45.5006	-122.5526	485	572	10	TGTS	110	20
304	45.4981	-122.3687	375	440	12	TGTS	45	130
305	45.4828	-122.3520	549	450	8	TGTS	59	180
306	45.4422	-122.4617	776	616	6	TGTS	135	50
307	45.4647	-122.4864	345	440	8	TGTS	20	150
308	45.4622	-122.3753	435	330		TGTS	55	250
309	45.4167	-122.4144	575	465	12	TGTS	167	237
310	45.4411	-122.4245	552	300		TGTS	51	225
311	45.4567	-122.3419	566	257		TGTS	9	60
312	45.5342	-122.4397	185	355	16	TGTS	124	325
313	45.4933	-122.4298	355	715	16	TGTS	40	303
314	45.7044	-122.5126	269	237	8	TGTS	73	600
315	45.7283	-122.5289	293	323	8	TGTS	55	200
316	45.7167	-122.5495	287	295	12	TGTS	52	500
317	45.3778	-122.3281	700	105	8	TGTS	21	158
318	45.7619	-122.6086	193	252	12	TGTS	95	365
319	45.5822	-122.5637	19	418		TGTS	16	800
320	45.6781	-122.6536	230	632	10	TGUF	116	770
321	45.7169	-122.4937	262	164	10	TGUF	47	200
322	45.7914	-122.6907	229	170	6	TGUF	34	45
323	45.5033	-122.6582	55	490	16	TGUF	84	800
324	45.5122	-122.6770	80	317	12	TGUF	90	600
325	45.5139	-122.6582	52	385	14	TGUF	17	500
326	45.7611	-122.7404	95	471	8	TGUF	26	360
327	45.4289	-122.2832	779	450	8	TS	90	100
328	45.4528	-122.3412	592	475	10	TS	122	400
329	45.5358	-122.4922	205	700	7	TS	80	70
330	45.3831	-122.3283	710	180		TS	60	60
331	45.4622	-122.5387	800	902	12	TS	10	100

332	45.5931	-122.4842	235	439	6	TS	178	240
333	45.4172	-122.3394	592	242		TS	52	42
334	45.4244	-122.3490	541	205	8	TS	66	100
335	45.6217	-122.4823	285	388	14	TS	164	300
336	45.5306	-122.4283	176	405	12	TS	73	350
337	45.3653	-122.3332	712	177	6	TS	58	70
338	45.3661	-122.3314	725	164	6	TS	35	60
339	45.4997	-122.3531	364	386	10	TS	40	300
340	45.4061	-122.3194	535	175	8	TS	44	110
341	45.4164	-122.3626	608	270	8	TS	31	300
342	45.4194	-122.3508	563	375	6	TS	10	145
343	45.3744	-122.3045	905	300	12	TS	70	250
344	45.4681	-122.3317	612	413	8	TS	33	150
345	45.4186	-122.3897	597	300	8	TS	35	102
346	45.4194	-122.2814	825	400	8	TS	50	120
347	45.5319	-122.4172	170	360	10	TS	100	200
348	45.4842	-122.3139	672	480	8	TS	15	150
349	45.5106	-122.3768	283	350	10	TS	28	180
350	45.4506	-122.3126	663	465	8	TS	19	335
351	45.4778	-122.4447	595	431	6	TS	33	20
352	45.5575	-122.5082	15	375		TS	196	2500
353	45.4158	-122.4270		330		TS	85	285
354	45.4186	-122.2959	755	250		TS	30	90
355	45.5656	-122.5470	22	448		TS	193	1900
356	45.5400	-122.4326	120	360	16	TS	53	324
357	45.5583	-122.4795	24	284		TS	137	1400
358	45.5564	-122.4993	17	320	6	TS	50	730
359	45.5197	-122.4086	357	485	9.5	TS	79	350
360	45.5553	-122.4925	17	340	10	TS	115	2430
361	45.6128	-122.4811	277	378	10	TS	26	120
362	45.4006	-122.3808	586	266	6	TS	30	10
363	45.4039	-122.3857	580	220	6	TS	22	22
364	45.5583	-122.4793	25	287	6	TS	49	400
365	45.4125	-122.4970	338	405		TS	55	165

366	45.5378	-122.4175	133	300	12	TS	20	250
367	45.5389	-122.4576	145	96	8	TS	12	100
368	45.4617	-122.3126	612	400		TS	11	440
369	45.4158	-122.4270	618	305		TS	58	200
370	45.5400	-122.4293	110	390	10	TS	45	370
371	45.5606	-122.4937	24	319	7.7	TS	25	300
372	45.5553	-122.4925	17	340	6	TS	25	300
373	45.5606	-122.4937	18	317	12	TS	145	2400
374	45.5689	-122.5523	16	460	9.5	TS	203	3400
375	45.4347	-122.4348	628	325	5	TS	15	170
376	45.4133	-122.3089	676	257	6	TS	2	25
377	45.4533	-122.3703	581	444	12	TS	29	200
378	45.6058	-122.4468	295	252	16	TS	43	650
379	45.6231	-122.4848	287	310	8	TS	66	507
380	45.6306	-122.4854	287	240	8	TS	59	280
381	45.4353	-122.5675	205	431		TS	34	252
382	45.4217	-122.3776	551	245		TS	5	100
383	45.5689	-122.5361	22	448		TS	105	2500
384	45.6267	-122.4642	248	209	10	TS	50	140
385	45.4156	-122.3617	611	300	10	TS	5	200
386	45.5725	-122.5611	15	400	6	TS	28	720
387	45.5281	-122.4064	340	458	12	TS	83	313
388	45.7083	-122.5528	283	68	6	TS	44	72
389	45.4128	-122.4389	522	212	8	TS	37	500
390	45.5450	-122.4419	51	92	12	TS	36	400
391	45.5756	-122.5634	23	345	8	TS	35	180
392	45.4619	-122.2992	650	420	7	TS	1	240
393	45.6042	-122.4129	230	140	6	TS	10	65
394	45.4853	-122.3397	573	402	8	TS	0.3	50
395	45.6239	-122.4270	264	400	8	TSC2	150	73
396	45.4108	-122.3579	600	300	5	TSC2	60	25
397	45.4844	-122.3545	523	540	10	TSC2	217	250
398	45.4186	-122.4220	615	275	8	TSC2	17	50
399	45.4853	-122.3142	672	1031	8	TSC2	12	150

400	45.4233	-122.5250	352	400		TSC2	37	165
401	45.5486	-122.4733	15	490		TSSG	174	1400
402	45.5222	-122.3876	230	591	10	TSSG	2.5	300
403	45.5311	-122.3914	292	552	12	TSSG	5	330
404	45.7281	-122.6304	147	748	12	UF	43	100
405	45.8678	-122.6237	541	125	6	UF	8	4
406	45.4019	-122.5556	104	347	10	UF	52	340
407	45.3369	-122.3119	510	65	6	UF	30	8
408	45.4014	-122.5018	158	365	9.7	UF	239	300
409	45.7778	-122.6684	215	285	8	UF	31	14
410	45.7542	-122.5394	273	270	8	UF	51	60
411	45.7992	-122.6329	261	216	6	UF	25	30
412	45.8522	-122.5962	495	155	6	UF	31	9
413	45.8736	-122.6644	410	255	8	UF	37.5	72
414	45.7681	-122.5981	215	255	10	UF	156	530
415	45.3547	-122.3261	535	119	6	UF	27	12
416	45.8172	-122.5218	442	370	8	UF	40	282
417	45.8186	-122.7357	35	167	8	UF	69.5	255
418	45.8178	-122.7357	40	195	8	UF	41.4	400
419	45.8144	-122.5475	265	273	8	UF	53	120
420	45.8175	-122.7351	40	193	8	UF	42.5	400
421	45.7975	-122.7144	280	411	8	UF	34	62
422	45.8092	-122.6609	257	296	9.9	UF	51	180
423	45.3958	-122.5394	65	95	6	UF	50	100
424	45.8172	-122.7342	40	208	8	UF	37.9	400
425	45.8381	-122.6592	200	187	6	UF	10	15
426	45.7706	-122.7417	132	245	8	UF	25	97
427	45.7858	-122.6178	230	209	6	UF	36	75
428	45.8139	-122.6894	260	458	5	UF	20.2	330
429	45.8183	-122.7372	35	163	8	UF	23.7	130
430	45.8597	-122.7109	248	300	6	UF	12	13
431	45.4092	-122.5187	148	820	8	UF	48	300
432	45.3853	-122.4667	120	122	8	UF	10	21
433	45.8400	-122.6117	258	202	8	UF	15	150

434	45.8433	-122.7273	242	335	6	UF	7	40
435	45.3975	-122.4611	250	135	5	UF	20	25
436	45.8733	-122.6644	400	231	8	UF	85	75
437	45.8092	-122.6536	267	214	6	UF	8	30
438	45.4233	-122.5192	132	800	8	UF	85	200
439	45.9036	-122.6836	661	93	6	UFOR	65	3
440	45.5225	-122.6781	49	690	14	UFOR	78	250
441	45.6472	-122.7294	30	136	19	US	9	100
442	45.6436	-122.6253	170	167	10	US	50	300
443	45.6192	-122.6244	55	122	12	US	18	1000
444	45.5583	-122.4469	28	195		US	4.1	500
445	45.6514	-122.7317	33	163	24	US	13	3000
446	45.6481	-122.7258	33	163	24	US	13	3000
447	45.5831	-122.3964	48	113	20	US	8	950
448	45.6194	-122.6244	50	127	20	US	19	1000
449	45.5583	-122.4469	28	169		US	24	10000
450	45.5583	-122.4428	25	165		US	25	10000
451	45.5794	-122.7378	38	95		US	18	1030
452	45.5836	-122.3394	85	120	14	US	10.3	650
453	45.5831	-122.3964	16	66	18	US	23	2100
454	45.9217	-122.4161	439	40	12	US	6	515
455	45.5831	-122.3964	48	140	18	US	7	1220
456	45.9256	-122.3786	497	115	8	US	1.3	130
457	45.5833	-122.3831	50	85	16	US	12	1600
458	45.8703	-122.4069	713	101	8	US	1.9	220
459	45.5575	-122.5342	30	65		US	17	2000
460	45.5836	-122.3942	15	66	18	US	6	1500
461	45.6522	-122.6706	215	278	18	US	13	2000
462	45.5619	-122.5814	70	84		US	5	750
463	45.5578	-122.4522	26	118		US	22	8000
464	45.6481	-122.7275	32	145	20	US	6	1500
465	45.6303	-122.6894	28	80	18.5	US	8.8	2000
466	45.5578	-122.4522	25	120		US	1.8	400
467	45.6381	-122.6464	177	255	20	US	6.8	1800

468	45.8703	-122.4056	718	101	8	US	2.3	220
469	45.4939	-122.5194	222	412	12	US	4	550
470	45.5564	-122.3958	28	190	12	US	24	1300
471	45.5831	-122.3964	35	123	20	US	9	2300
472	45.6531	-122.7753	20	257	10	US	3.5	1040
473	45.6469	-122.7264	30	140	20	US	4	1570
474	45.6367	-122.6444	182	233	12	US	4	1300
475	45.6367	-122.6450	185	235	12	US	3	1000
476	45.6500	-122.7322	28	137	20	US	16	3000
477	45.6503	-122.7333	28	135	20	US	20	3000
478	45.5831	-122.3964	16	89	20	US	6	2300
479	45.6369	-122.6458	187	243	18	US	4	2000
480	45.6478	-122.7258	32	138	20	US	3.3	2045
481	45.5961	-122.6483	10	132		US	5	230
482	45.5831	-122.3778	50	103	12	US	9	1200
483	45.6481	-122.7319	30	138	12	US	9	850
484	45.5831	-122.3964	29	116	20	US	6	2300
485	45.5850	-122.3950	13	105	20	US	6	2800
486	45.5844	-122.3886	45	78	14	US	7	1800
487	45.6136	-122.7622	45	108	10	US	2	250
488	45.6372	-122.6467	188	244	20	US	2	1100
489	45.6356	-122.6467	222	280	16	US	4	2000
490	45.6472	-122.7278	30	145	20	US	3	1500
491	45.6356	-122.6481	210	250	12	US	1	500
492	45.5853	-122.3947	13	104	20	US	6	3100
493	45.6336	-122.6489	175	215	12	US	1	300
494	45.6514	-122.7325	32	160	24	US	3	3000
495	45.6172	-122.6506	31	96	26	US	3	4000
496	45.6478	-122.7278	30	122	12	US	5	1200
497	45.6172	-122.6514	31	85	26	US	4	4000
498	45.6369	-122.6453	185	240	14	US	3.5	1200
499	45.5842	-122.3869	33	84	14	US	1.5	1000
500	45.5908	-122.6953	30	65	10	US	1	450
501	45.5806	-122.3817	38	71	8	US	1	156

502	45.6564	-122.6944	25	63	8	US	3	1200
503	45.5972	-122.6433	12	172		US	2.7	2500
504	45.6372	-122.6453	178	266	20	US	1.7	1600
505	45.6364	-122.6972	33	95	18	US	1.1	1400
506	45.5828	-122.3767	50	102	14	US	3.3	1080
507	45.5964	-122.6486	10	135		US	5	1500
508	45.6508	-122.7328	31	133	16	US	4.5	1200
509	45.5831	-122.3772	50	101	12	US	4	2000
510	45.5831	-122.3964	16	81	20	US	3.8	2000
511	45.6353	-122.6922	28	53	20	US	4	1100
512	45.6472	-122.7292	30	136	12	US	0.5	1040
513	45.5842	-122.3864	34	87	14	US	1.5	1540
514	45.6361	-122.6969	33	105	18	US	3.5	1200
515	45.6483	-122.7278	28	111	12	US	3	1500
516	45.6511	-122.7325	33	133	22	US	1	2500
517	45.6308	-122.6900	28	123	24	US	2	1100
518	45.6492	-122.7283	29	117	20	US	2	1100
519	45.6492	-122.7281	32	116	20	US	2.5	1500
520	45.6478	-122.7269	34	119	24	US	2	1500
521	45.6467	-122.7275	33	130	24	US	0.5	2500
522	45.6314	-122.6897	28	128	20	US	1.1	610
523	45.6478	-122.6836	21	46	12	US	610	1.11
524	45.5856	-122.3939	13	103	20	US	2250	0.5
525	45.6303	-122.6908	30	115	18	US	900	2
526	45.5050	-122.6351	120	180	8	US	73	215
527	45.4472	-122.5861	190	235	8	US	90	80
528	45.6714	-122.6900	50	135	6	US	85	20
529	45.6794	-122.6018	269	75	6	US	35	18
530	45.5536	-122.3962	28	270		US	35	1090
531	45.5717	-122.5634	7	399		US	29	800
532	45.5692	-122.5359	22	270		US	64	4000
533	45.6683	-122.6206	265	42	12	US	31.2	206
534	45.9228	-122.4194	435	50	12	US	18	240
535	45.9172	-122.4200	428	50	12	US	21	235

536	45.5569	-122.4054	22	279	16	US	11	545
537	45.5775	-122.5579	31	218	10	US	50	350
538	45.9167	-122.4162	430	44	12	US	20	205
539	45.5578	-122.4382	16	193		US	72.2	8500
540	45.7117	-122.5829	195	60	8	US	22	350
541	45.6528	-122.8276	30	104	8	US	3	150
542	45.7103	-122.6722	25	65	20	US	24	1100
543	45.5256	-122.6531	112	126		US	6	100
544	45.5678	-122.5773	21	80		US	36	450
545	45.5847	-122.3947	15	120	20	US	21	2250
546	45.5725	-122.5533	25	328	8	US	11	725
547	45.5881	-122.6889	35	76	8	US	30	450
548	45.5550	-122.3953	27	275	26	US	51	1350
549	45.5903	-122.6639	15	163	10	US	12	200
550	45.6894	-122.5801	205	166	8	US	24	308
551	45.5886	-122.6892	32	76	8	US	35	450
552	45.9194	-122.4051	450	47	12	US	13.8	335
553	45.5539	-122.4028	20	310		US	25	1090
554	45.5569	-122.4026	25	282	12	US	30	750
555	45.5467	-122.7089	35	679	12	USOR	190	365
556	45.9292	-122.3665	530	553	12	USOR	60	800
557	45.7603	-122.5583	282	195	10	USTG	23	50
558	45.5836	-122.6382	10	149	14	USTG	98	500
559	45.6158	-122.6190	38	130	8	USTG	25.1	200
560	45.7494	-122.6184	220	220	8	USTG	20	60
561	45.5719	-122.7253	172	247	12	USTG	6	250
562	45.5856	-122.6879	49	217		USTG	20	875
563	45.7125	-122.7478	13	293	10	USTG	20	500
564	45.5800	-122.7387	38	130	12	USTG	26	1600
565	45.6756	-122.6481	258	255	12	USTG	2	625
566	45.6422	-122.5878	208	124	20	USTG	11.7	1000
567	45.6422	-122.5872	209	112	20	USTG	7.9	1000
568	45.6425	-122.5878	207	118	20	USTG	6.2	1000
569	45.5861	-122.7367	143	248		USTG	4	350

570	45.5569	-122.5328	35	63		USTG	8	1800
571	45.6239	-122.6750	35	184	30	USTG	3	6000
572	45.6375	-122.6444	174	266	20	USTG	2.4	2500
573	45.5481	-122.5531	210	265	12	USTG	0.8	1000
574	45.6381	-122.6450	178	255	16	USTG	3	2000
575	45.5692	-122.5361	23	415		USTS	30	805
576	45.5842	-122.3950	13	120	20	USTS	23	1125
577	45.3708	-122.3036	915	303	6		79	6
578	45.4517	-122.3404	610	195	8		95	50
579	45.4833	-122.3675	510	350	8		40	60
580	45.4444	-122.3869	520	316	8		71	200
581	45.4089	-122.2820	750	221	6		73	43
582	45.4186	-122.4220		310	6		65	100
583	45.4453	-122.3558	575	290	8		90	140
584	45.4383	-122.3709	571	600	14		31	500
585	45.4492	-122.3194	635	345	10		50	200
586	45.4194	-122.3508	565	200	8		165	150
587	45.5511	-122.4715	24	278	6		71	710
588	45.4392	-122.2804	760	435	12		30	130
589	45.5017	-122.4139	345	547	10		82	200
590	45.4189	-122.3203	715	495	8		70	148
591	45.5114	-122.5261	289	325			124	296
592	45.7433	-122.7250	171	196	6		15	65
593	45.5425	-122.4548	83	284	8		55	135
594	45.5292	-122.4006	315	362	10		28	100
595	45.5686	-122.5533	17	226	6		14	702
596	45.5497	-122.4357	10	265			100	1500
597	45.4619	-122.6119	100	205	10		20	150
598	45.4406	-122.2814	755	388	8		59	400
599	45.4306	-122.3351	575	300			80	150
600	45.4411	-122.2761	763	398	8		60	140
601	45.4528	-122.3033	700	392	10		11	470
602	45.7303	-122.7258	49	210	8		16	375
603	45.7614	-122.5934	230	131	10		57	250

604	45.4542	-122.2975	695	360	8	4	200
605	45.5575	-122.5082	15	389		27.3	450
606	45.5739	-122.5462	23	228		25	800
607	45.6306	-122.6689	100	146	10	1.5	350
608	45.6019	-122.7025	13	125	12	5	1100
609	45.5581	-122.4383	17	245	8	2.5	400

APPENDIX III

WELL DATABASE

CALCULATED DATA FROM THIS STUDY

Well ID	s m	Input Q m3/d	b m	Calculated with Eq. 28	Calculated with Eq. 27	Calculated with Eq. 26	Calculated with log Equation.	Initial Results	Q/s m3d/m
1	19.8	486.0	71.9	0.19	0.20	0.20	0.20	0.45	12.9
2	100.6	469.8	75.6	0.21	0.22	0.22	0.22	0.63	67.8
3	15.2	264.6	65.5	0.19	0.24	0.24	0.24	0.75	18.2
4	6.4	361.8	74.7	0.17	0.16	0.16	0.16	0.21	5.6
5	54.9	108.0	475.5	0.23	0.17	0.17	0.17	0.26	160.8
6	22.9	718.2	73.2	0.18	0.19	0.19	0.19	0.42	10.1
7	91.4	502.2	107.9	0.21	0.24	0.24	0.24	0.76	57.7
8	54.9	54.0	137.2	0.24	0.26	0.26	0.26	0.96	321.5
9	61.0	135.0	110.9	0.23	0.29	0.29	0.29	1.22	143.1
10	0.2	1576.8	142.0	0.11	0.14	0.14	0.13	0.05	0.0
11	1.0	1544.4	139.9	0.13	0.15	0.15	0.14	0.11	0.2
12	0.6	756.0	69.2	0.13	0.15	0.15	0.14	0.11	0.3
13	12.2	2022.3	121.9	0.16	0.15	0.15	0.14	0.13	1.9
14	21.3	459.0	91.4	0.19	0.16	0.16	0.15	0.17	14.7
15	3.7	923.4	91.7	0.15	0.16	0.16	0.15	0.18	1.2
16	4.9	766.8	48.2	0.16	0.16	0.16	0.15	0.19	2.0
17	2.4	783.0	208.8	0.15	0.16	0.16	0.16	0.21	1.0
18	89.0	815.4	148.7	0.20	0.16	0.16	0.16	0.22	34.6
19	1.2	1803.6	121.9	0.13	0.17	0.17	0.16	0.24	0.2
20	2.4	275.4	103.0	0.16	0.17	0.17	0.16	0.25	2.8
21	20.7	1377.0	91.4	0.17	0.17	0.17	0.16	0.25	4.8
22	359.7	853.2	543.5	0.23	0.17	0.17	0.17	0.25	133.6
23	228.6	1112.4	233.2	0.21	0.17	0.17	0.17	0.26	65.1
24	19.8	405.0	171.6	0.19	0.17	0.17	0.17	0.27	15.5
25	12.8	518.4	48.8	0.18	0.17	0.17	0.17	0.28	7.8
26	51.8	329.4	324.9	0.21	0.17	0.17	0.17	0.29	49.8
27	30.5	858.6	217.9	0.18	0.17	0.17	0.17	0.29	11.2
28	198.1	1350.0	180.1	0.21	0.17	0.17	0.17	0.29	46.5
29	9.1	1080.0	182.9	0.16	0.17	0.17	0.17	0.30	2.7
30	1.5	48.6	132.6	0.18	0.18	0.18	0.18	0.35	10.0
31	152.4	280.8	235.3	0.23	0.19	0.19	0.19	0.38	172.0
32	76.2	756.0	69.2	0.20	0.19	0.19	0.19	0.39	31.9

33	91.4	567.0	64.6	0.21	0.19	0.19	0.19	0.43	51.1
34	193.5	145.8	132.6	0.25	0.20	0.20	0.20	0.45	420.6
35	61.0	27.0	92.7	0.26	0.20	0.20	0.20	0.47	717.2
36	213.4	172.8	154.8	0.25	0.21	0.21	0.21	0.52	391.4
37	30.5	8.6	129.5	0.27	0.22	0.22	0.22	0.62	1113.8
38	36.6	162.0	38.1	0.21	0.24	0.24	0.24	0.80	71.5
39	158.5	529.2	69.5	0.22	0.26	0.26	0.26	0.94	94.9
40	76.2	378.0	158.5	0.21	0.19	0.19	0.19	0.38	63.8
41	91.4	788.4	102.4	0.20	0.19	0.19	0.19	0.39	36.8
42	609.6	1377.0	132.6	0.23	0.20	0.20	0.20	0.47	140.3
43	762.0	1436.4	136.6	0.23	0.20	0.20	0.20	0.48	168.1
44	15.2	205.2	25.9	0.20	0.20	0.20	0.20	0.49	23.5
45	18.3	216.0	183.5	0.20	0.20	0.20	0.20	0.49	26.8
46	237.7	753.3	165.8	0.22	0.20	0.20	0.20	0.50	100.0
47	22.9	216.0	102.1	0.20	0.20	0.20	0.20	0.51	33.5
48	762.0	685.8	170.1	0.25	0.21	0.21	0.21	0.53	352.0
49	762.0	945.0	109.1	0.24	0.21	0.21	0.21	0.53	255.5
50	975.4	864.0	203.3	0.25	0.21	0.21	0.21	0.54	357.6
51	106.7	145.8	173.4	0.24	0.21	0.21	0.21	0.55	231.8
52	777.2	961.2	178.3	0.24	0.21	0.21	0.21	0.55	256.2
53	731.5	432.0	161.8	0.25	0.21	0.21	0.22	0.58	536.5
54	219.5	297.0	109.1	0.24	0.22	0.22	0.22	0.59	234.1
55	914.4	901.8	173.1	0.24	0.22	0.22	0.22	0.59	321.3
56	91.4	118.8	167.6	0.24	0.22	0.22	0.22	0.60	244.2
57	152.4	723.6	57.0	0.21	0.22	0.22	0.22	0.60	66.7
58	152.4	545.4	167.6	0.22	0.22	0.22	0.22	0.60	88.6
59	762.0	383.4	149.4	0.26	0.22	0.22	0.22	0.60	629.7
60	197.2	199.8	149.4	0.24	0.22	0.22	0.22	0.61	312.6
61	112.8	351.0	148.1	0.22	0.22	0.22	0.22	0.62	101.8
62	335.3	259.2	178.0	0.25	0.22	0.22	0.22	0.63	409.9
63	129.5	243.0	171.0	0.23	0.22	0.22	0.22	0.63	168.9
64	449.6	545.4	178.0	0.24	0.22	0.22	0.22	0.65	261.2
65	457.2	162.0	180.4	0.26	0.23	0.23	0.23	0.67	894.6
66	179.8	280.8	174.0	0.23	0.23	0.23	0.23	0.68	202.9
67	42.7	108.0	61.0	0.23	0.23	0.23	0.23	0.68	125.1
68	914.4	693.9	155.1	0.25	0.23	0.23	0.23	0.70	417.4
69	146.0	171.2	137.2	0.24	0.23	0.23	0.24	0.73	270.3
70	61.0	97.2	68.9	0.23	0.24	0.24	0.24	0.79	198.6
71	137.2	124.2	177.4	0.25	0.24	0.24	0.24	0.79	349.8
72	137.2	334.8	112.2	0.23	0.24	0.25	0.25	0.81	129.8

73	121.9	108.0	81.7	0.25	0.27	0.27	0.28	1.05	357.4
74	12.2	243.0	73.2	0.19	0.29	0.29	0.29	1.19	15.8
75	76.2	324.0	95.1	0.22	0.18	0.18	0.18	0.33	74.5
76	0.6	97.2	120.4	0.16	0.15	0.15	0.15	0.15	2.0
77	0.8	486.0	41.1	0.14	0.16	0.16	0.15	0.18	0.5
78	41.1	1900.8	206.0	0.18	0.17	0.17	0.16	0.24	6.9
79	2.4	270.0	33.5	0.16	0.17	0.17	0.17	0.25	2.8
80	7.6	496.8	43.6	0.17	0.17	0.17	0.17	0.26	4.9
81	101.8	1863.0	107.0	0.19	0.17	0.17	0.17	0.27	17.3
82	18.3	324.0	79.2	0.19	0.17	0.17	0.17	0.28	17.9
83	15.2	226.8	88.4	0.19	0.17	0.17	0.17	0.28	21.3
84	45.7	432.0	82.6	0.20	0.18	0.18	0.17	0.31	33.5
85	48.8	378.0	85.3	0.21	0.18	0.18	0.17	0.31	40.9
86	6.1	405.0	162.2	0.17	0.18	0.18	0.18	0.31	4.7
87	36.6	702.0	75.3	0.19	0.18	0.18	0.18	0.32	16.5
88	76.2	972.0	94.5	0.20	0.18	0.18	0.18	0.32	24.8
89	4.6	64.8	42.4	0.20	0.18	0.18	0.18	0.33	22.4
90	64.0	675.0	84.7	0.20	0.18	0.18	0.18	0.33	30.0
91	36.6	637.2	75.0	0.19	0.18	0.18	0.18	0.34	18.2
92	304.8	1204.2	165.8	0.22	0.18	0.18	0.18	0.34	80.2
93	76.2	513.0	64.0	0.21	0.18	0.18	0.18	0.34	47.0
94	91.4	648.0	147.8	0.21	0.18	0.18	0.18	0.35	44.7
95	76.2	253.8	155.4	0.22	0.18	0.18	0.18	0.35	95.1
96	67.1	507.6	149.4	0.21	0.18	0.18	0.18	0.35	41.9
97	94.5	367.2	134.7	0.22	0.18	0.18	0.18	0.36	81.5
98	21.3	189.0	108.5	0.20	0.19	0.19	0.18	0.37	35.8
99	30.5	399.6	96.3	0.20	0.19	0.19	0.18	0.38	24.1
100	53.3	567.0	94.5	0.20	0.19	0.19	0.19	0.39	29.8
101	99.1	442.8	84.7	0.21	0.19	0.19	0.19	0.39	70.9
102	93.0	756.0	118.6	0.20	0.19	0.19	0.19	0.40	38.9
103	38.1	437.4	52.4	0.20	0.19	0.19	0.19	0.40	27.6
104	3.0	108.0	24.1	0.18	0.19	0.19	0.19	0.40	9.0
105	30.5	459.0	94.5	0.19	0.19	0.19	0.19	0.41	21.0
106	30.5	529.2	29.0	0.19	0.19	0.19	0.19	0.41	18.2
107	41.1	313.2	61.9	0.21	0.19	0.19	0.19	0.42	41.6
108	30.5	118.8	83.2	0.22	0.19	0.19	0.19	0.42	81.5
109	33.5	540.0	108.8	0.19	0.19	0.19	0.19	0.43	19.5
110	43.0	145.8	123.1	0.22	0.19	0.19	0.19	0.43	93.4
111	221.0	891.0	146.3	0.22	0.19	0.19	0.19	0.43	78.6
112	45.7	243.0	100.6	0.21	0.19	0.19	0.19	0.43	59.6

113	33.5	891.0	103.0	0.19	0.19	0.19	0.19	0.44	11.9
114	45.7	194.4	135.6	0.22	0.19	0.20	0.19	0.44	74.6
115	70.1	594.0	77.7	0.20	0.20	0.20	0.20	0.44	37.4
116	5.2	410.4	86.0	0.17	0.20	0.20	0.20	0.44	4.0
117	33.5	151.2	64.0	0.21	0.20	0.20	0.20	0.45	70.2
118	274.3	604.8	99.7	0.23	0.20	0.20	0.20	0.45	143.7
119	3.0	81.0	49.7	0.19	0.20	0.20	0.20	0.45	12.0
120	9.1	216.0	51.2	0.19	0.20	0.20	0.20	0.45	13.5
121	16.8	259.2	59.7	0.19	0.20	0.20	0.20	0.46	20.5
122	91.4	675.0	88.4	0.21	0.20	0.20	0.20	0.47	42.9
123	41.1	324.0	23.8	0.20	0.20	0.20	0.20	0.47	40.2
124	31.1	162.0	109.7	0.21	0.20	0.20	0.20	0.47	60.8
125	30.5	394.2	294.7	0.20	0.20	0.20	0.20	0.47	24.5
126	22.9	475.2	76.2	0.19	0.20	0.20	0.20	0.47	15.2
127	19.8	205.2	91.4	0.20	0.20	0.20	0.20	0.48	30.6
128	85.3	405.0	102.1	0.21	0.20	0.20	0.20	0.48	66.8
129	457.2	540.0	91.4	0.24	0.20	0.20	0.20	0.49	268.3
130	33.2	197.1	54.9	0.21	0.20	0.20	0.20	0.49	53.4
131	9.1	432.0	39.6	0.18	0.20	0.20	0.20	0.49	6.7
132	243.8	1009.8	102.4	0.22	0.20	0.20	0.20	0.50	76.5
133	152.4	718.2	152.4	0.21	0.20	0.20	0.20	0.50	67.2
134	73.2	270.0	121.9	0.22	0.20	0.20	0.20	0.50	85.8
135	83.8	372.6	124.1	0.21	0.20	0.20	0.20	0.50	71.3
136	36.6	243.0	73.2	0.21	0.20	0.20	0.20	0.50	47.7
137	15.2	297.0	48.8	0.19	0.20	0.20	0.20	0.50	16.2
138	70.1	354.8	92.4	0.21	0.20	0.20	0.20	0.51	62.6
139	91.4	64.8	88.4	0.25	0.20	0.20	0.20	0.51	447.0
140	23.5	186.3	45.4	0.20	0.20	0.20	0.21	0.51	39.9
141	61.0	145.8	93.0	0.23	0.20	0.20	0.21	0.51	132.5
142	175.3	340.2	149.4	0.23	0.20	0.21	0.21	0.51	163.2
143	228.6	480.6	116.7	0.23	0.20	0.21	0.21	0.51	150.7
144	4.6	172.8	41.5	0.18	0.21	0.21	0.21	0.52	8.4
145	67.1	235.4	60.4	0.22	0.21	0.21	0.21	0.52	90.3
146	111.3	274.3	30.5	0.23	0.21	0.21	0.21	0.52	128.6
147	40.5	210.6	103.9	0.21	0.21	0.21	0.21	0.53	60.9
148	670.6	507.6	147.8	0.25	0.21	0.21	0.21	0.53	418.5
149	24.4	216.0	65.5	0.20	0.21	0.21	0.21	0.53	35.8
150	259.1	664.2	86.9	0.22	0.21	0.21	0.21	0.53	123.6
151	640.1	226.8	110.6	0.26	0.21	0.21	0.21	0.54	894.3
152	70.1	264.6	27.7	0.22	0.21	0.21	0.21	0.54	84.0

153	13.1	221.4	52.1	0.19	0.21	0.21	0.21	0.54	18.8
154	60.0	421.2	91.4	0.21	0.21	0.21	0.21	0.54	45.2
155	102.1	691.2	86.9	0.21	0.21	0.21	0.21	0.54	46.8
156	30.5	64.8	60.7	0.23	0.21	0.21	0.21	0.55	149.1
157	30.5	162.0	43.0	0.21	0.21	0.21	0.21	0.55	59.6
158	137.2	577.8	53.9	0.22	0.21	0.21	0.21	0.55	75.2
159	91.4	291.6	49.7	0.22	0.21	0.21	0.21	0.55	99.4
160	189.0	1344.6	92.7	0.21	0.21	0.21	0.21	0.55	44.5
161	22.9	615.6	101.2	0.19	0.21	0.21	0.21	0.55	11.8
162	10.7	241.4	71.0	0.19	0.21	0.21	0.21	0.56	14.1
163	51.8	378.0	64.6	0.21	0.21	0.21	0.21	0.56	43.4
164	3.7	32.4	25.0	0.20	0.21	0.21	0.21	0.56	35.4
165	6.1	54.0	54.3	0.20	0.21	0.21	0.21	0.56	35.9
166	13.7	183.6	61.3	0.20	0.21	0.21	0.21	0.56	23.6
167	7.3	108.0	39.6	0.19	0.21	0.21	0.21	0.56	21.5
168	141.7	345.6	83.2	0.23	0.21	0.21	0.21	0.57	130.0
169	289.6	675.0	110.0	0.23	0.21	0.21	0.21	0.57	135.9
170	91.4	118.8	92.7	0.24	0.21	0.21	0.21	0.57	244.2
171	25.0	253.8	77.4	0.20	0.21	0.21	0.21	0.57	31.2
172	22.9	340.2	45.1	0.19	0.21	0.21	0.21	0.58	21.3
173	38.1	162.0	54.3	0.22	0.21	0.21	0.21	0.58	74.5
174	115.8	340.2	96.0	0.22	0.21	0.21	0.22	0.58	107.9
175	91.4	248.4	131.7	0.22	0.21	0.21	0.22	0.58	116.7
176	106.7	156.6	89.9	0.24	0.21	0.21	0.22	0.58	215.8
177	152.4	388.8	69.2	0.22	0.21	0.22	0.22	0.59	124.2
178	88.4	313.2	75.6	0.22	0.21	0.22	0.22	0.59	89.4
179	213.4	367.2	91.4	0.23	0.22	0.22	0.22	0.59	184.2
180	24.4	75.6	57.9	0.22	0.22	0.22	0.22	0.59	102.2
181	96.0	318.6	97.8	0.22	0.22	0.22	0.22	0.60	95.5
182	91.4	378.0	114.3	0.22	0.22	0.22	0.22	0.60	76.7
183	15.2	108.0	60.0	0.21	0.22	0.22	0.22	0.62	44.6
184	121.9	280.8	46.3	0.23	0.22	0.22	0.22	0.63	137.5
185	30.5	442.8	48.5	0.19	0.22	0.22	0.22	0.63	21.8
186	33.5	243.0	33.8	0.21	0.22	0.22	0.22	0.64	43.7
187	67.1	486.0	54.9	0.21	0.22	0.22	0.22	0.64	43.7
188	78.3	351.0	36.6	0.21	0.22	0.22	0.22	0.65	70.7
189	243.8	588.6	99.7	0.23	0.22	0.22	0.22	0.65	131.3
190	176.8	108.0	88.4	0.25	0.22	0.22	0.22	0.65	519.0
191	167.6	858.6	125.6	0.21	0.22	0.22	0.22	0.65	61.9
192	45.7	151.2	51.8	0.22	0.22	0.22	0.23	0.65	95.9

193	101.2	227.9	43.9	0.23	0.22	0.22	0.23	0.65	140.8
194	41.1	297.0	53.6	0.21	0.22	0.22	0.23	0.65	43.9
195	76.2	183.6	91.4	0.23	0.22	0.23	0.23	0.66	131.5
196	91.4	248.4	79.6	0.22	0.23	0.23	0.23	0.67	116.7
197	274.3	196.6	95.7	0.25	0.23	0.23	0.23	0.67	442.4
198	83.8	183.6	86.3	0.23	0.23	0.23	0.23	0.67	144.7
199	27.4	59.4	86.3	0.23	0.23	0.23	0.23	0.68	146.6
200	39.6	162.0	48.2	0.22	0.23	0.23	0.23	0.68	77.5
201	77.7	342.9	38.7	0.22	0.23	0.23	0.23	0.68	71.8
202	54.9	54.0	99.1	0.24	0.23	0.23	0.23	0.69	321.5
203	33.5	291.6	61.6	0.20	0.23	0.23	0.23	0.70	36.4
204	93.6	136.6	42.1	0.24	0.23	0.23	0.23	0.70	217.0
205	182.9	367.2	79.2	0.23	0.23	0.23	0.23	0.71	157.8
206	304.8	118.8	67.4	0.26	0.23	0.23	0.23	0.71	813.5
207	118.9	237.6	54.9	0.23	0.23	0.23	0.23	0.71	158.5
208	80.8	540.0	50.9	0.21	0.23	0.23	0.23	0.71	47.4
209	166.1	567.0	121.9	0.22	0.23	0.23	0.23	0.72	92.8
210	134.1	486.0	73.2	0.22	0.23	0.23	0.23	0.72	87.4
211	304.8	259.2	57.6	0.25	0.23	0.23	0.23	0.72	372.5
212	18.3	48.6	89.9	0.22	0.23	0.23	0.24	0.73	119.3
213	57.9	262.4	71.6	0.21	0.23	0.23	0.24	0.73	69.9
214	24.4	151.2	94.2	0.21	0.24	0.24	0.24	0.75	51.2
215	1828.8	270.0	71.6	0.28	0.24	0.24	0.24	0.75	2145.8
216	15.2	48.6	52.1	0.22	0.24	0.24	0.24	0.76	99.3
217	38.1	221.4	84.4	0.21	0.24	0.24	0.24	0.76	54.5
218	54.9	108.0	67.1	0.23	0.24	0.24	0.24	0.76	160.8
219	274.3	469.8	106.7	0.23	0.24	0.24	0.24	0.76	185.0
220	83.8	307.8	44.8	0.22	0.24	0.24	0.24	0.77	86.2
221	103.6	37.8	127.1	0.26	0.24	0.24	0.24	0.77	870.1
222	121.9	145.8	74.1	0.24	0.24	0.24	0.24	0.77	264.9
223	128.0	394.2	48.2	0.22	0.24	0.24	0.24	0.78	102.9
224	129.5	343.4	106.7	0.22	0.24	0.24	0.24	0.78	119.6
225	76.2	81.0	231.6	0.24	0.24	0.24	0.24	0.79	298.1
226	281.0	315.9	60.4	0.24	0.24	0.24	0.24	0.79	281.9
227	35.1	221.4	42.4	0.21	0.24	0.24	0.24	0.80	50.1
228	1280.2	253.8	69.5	0.28	0.24	0.24	0.25	0.81	1598.6
229	160.0	297.0	70.7	0.23	0.24	0.24	0.25	0.81	170.7
230	301.8	106.4	43.6	0.26	0.25	0.25	0.25	0.82	899.3
231	121.9	167.4	33.2	0.24	0.25	0.25	0.25	0.82	230.7
232	43.6	56.7	31.1	0.24	0.25	0.25	0.25	0.83	243.5

233	228.6	105.3	89.3	0.26	0.25	0.25	0.25	0.83	688.2
234	182.9	172.8	58.8	0.24	0.25	0.25	0.25	0.84	335.4
235	53.3	135.0	52.1	0.23	0.25	0.25	0.25	0.85	125.1
236	304.8	172.8	69.5	0.25	0.25	0.25	0.25	0.85	559.0
237	30.5	32.4	76.2	0.24	0.25	0.25	0.25	0.87	297.4
238	9.1	27.0	67.1	0.22	0.25	0.25	0.25	0.87	108.0
239	42.7	124.2	114.9	0.22	0.25	0.25	0.25	0.87	108.9
240	10.7	48.6	57.0	0.21	0.25	0.25	0.26	0.89	69.4
241	115.8	253.8	60.4	0.23	0.25	0.26	0.26	0.90	144.6
242	121.9	162.0	64.3	0.24	0.26	0.26	0.26	0.90	238.5
243	115.8	51.3	80.8	0.26	0.26	0.26	0.26	0.91	714.0
244	73.2	459.0	59.4	0.21	0.26	0.26	0.26	0.92	50.5
245	61.0	135.0	63.4	0.23	0.26	0.26	0.26	0.92	143.1
246	70.1	324.0	43.9	0.21	0.26	0.26	0.26	0.93	68.6
247	86.9	145.8	77.4	0.23	0.26	0.26	0.26	0.95	188.8
248	304.8	70.2	52.4	0.27	0.26	0.26	0.26	0.96	1376.4
249	106.7	75.6	43.3	0.25	0.26	0.27	0.27	0.97	446.8
250	121.9	81.0	61.0	0.25	0.27	0.27	0.27	0.98	477.1
251	6.1	27.0	33.8	0.22	0.27	0.27	0.27	0.99	72.0
252	15.2	64.8	66.1	0.22	0.27	0.27	0.27	1.00	74.4
253	91.4	48.6	69.5	0.26	0.27	0.27	0.27	1.00	597.0
254	45.7	75.6	65.5	0.23	0.27	0.27	0.27	1.01	191.6
255	30.5	42.7	43.6	0.24	0.27	0.27	0.27	1.01	226.5
256	109.7	81.0	34.4	0.25	0.27	0.27	0.27	1.02	429.5
257	1097.3	221.4	42.7	0.28	0.27	0.27	0.27	1.02	1569.8
258	7.6	108.0	15.2	0.20	0.27	0.27	0.27	1.03	22.4
259	146.3	111.8	50.3	0.25	0.27	0.27	0.27	1.04	414.7
260	121.9	81.0	70.1	0.25	0.27	0.28	0.28	1.06	477.1
261	45.7	24.3	125.0	0.26	0.28	0.28	0.28	1.07	597.0
262	39.6	40.0	82.9	0.24	0.28	0.28	0.28	1.08	313.5
263	259.1	25.4	49.4	0.29	0.28	0.28	0.28	1.10	3240.5
264	37.2	32.4	66.4	0.25	0.28	0.28	0.28	1.11	363.5
265	152.4	129.6	55.5	0.25	0.28	0.28	0.28	1.12	372.9
266	6.1	54.0	33.5	0.20	0.28	0.28	0.28	1.13	35.9
267	274.3	75.6	106.7	0.27	0.28	0.28	0.29	1.14	1149.0
268	106.7	37.8	70.4	0.26	0.29	0.29	0.29	1.16	895.8
269	121.9	54.0	115.8	0.26	0.29	0.29	0.29	1.17	714.8
270	91.4	59.4	53.3	0.25	0.29	0.29	0.29	1.18	488.3
271	91.4	10.8	56.1	0.29	0.29	0.29	0.29	1.21	2681.7
272	109.7	43.2	89.9	0.26	0.30	0.30	0.30	1.24	804.4

273	609.6	253.8	61.0	0.26	0.30	0.30	0.30	1.26	760.8
274	76.2	97.2	76.8	0.24	0.30	0.30	0.30	1.27	248.1
275	91.4	8.1	66.1	0.30	0.30	0.30	0.30	1.27	3556.2
276	335.3	37.8	82.6	0.29	0.30	0.30	0.30	1.31	2815.1
277	457.2	84.2	44.5	0.28	0.31	0.31	0.31	1.32	1721.3
278	221.0	43.2	32.3	0.28	0.31	0.31	0.31	1.33	1619.4
279	67.1	7.0	28.3	0.29	0.31	0.31	0.31	1.36	2998.8
280	457.2	43.2	78.9	0.30	0.31	0.31	0.31	1.38	3351.0
281	256.0	27.0	86.9	0.29	0.32	0.32	0.32	1.48	3012.6
282	182.9	10.8	44.5	0.31	0.33	0.33	0.33	1.54	5361.0
283	10.7	5.4	39.3	0.26	0.33	0.33	0.33	1.54	633.6
284	365.8	16.2	82.9	0.31	0.33	0.33	0.33	1.55	7187.3
285	18.3	97.2	72.2	0.21	0.33	0.33	0.33	1.56	59.5
286	30.5	7.6	26.8	0.27	0.35	0.35	0.35	1.77	1269.2
287	44.5	5.4	33.8	0.29	0.36	0.36	0.36	1.86	2654.4
288	243.8	2.7	39.6	0.35	0.43	0.43	0.42	2.72	29068.8
289	54.9	1155.6	86.0	0.19	0.18	0.18	0.18	0.32	15.0
290	232.6	615.6	136.9	0.22	0.19	0.19	0.19	0.39	119.7
291	42.7	226.8	92.7	0.21	0.19	0.19	0.19	0.41	59.6
292	160.0	145.8	199.6	0.24	0.21	0.21	0.21	0.54	347.7
293	381.0	230.0	132.3	0.25	0.21	0.21	0.21	0.58	524.9
294	14.6	432.0	58.8	0.20	0.19	0.19	0.19	0.41	27.7
295	96.0	1485.0	175.0	0.19	0.16	0.16	0.16	0.21	20.5
296	3.0	140.4	71.0	0.18	0.17	0.17	0.16	0.24	6.9
297	106.7	702.0	88.4	0.21	0.20	0.20	0.20	0.45	48.2
298	609.6	772.2	151.8	0.24	0.20	0.21	0.21	0.51	250.1
299	152.4	756.0	112.2	0.21	0.24	0.24	0.24	0.76	63.9
300	3.0	480.6	105.2	0.16	0.16	0.16	0.15	0.19	2.0
301	4.6	378.0	152.4	0.17	0.17	0.17	0.17	0.26	3.8
302	68.6	1188.0	164.9	0.19	0.17	0.17	0.17	0.28	18.3
303	6.1	594.0	174.3	0.17	0.17	0.17	0.17	0.29	3.3
304	39.6	243.0	134.1	0.21	0.18	0.18	0.18	0.33	51.6
305	54.9	318.6	137.2	0.21	0.18	0.18	0.18	0.34	54.5
306	15.2	729.0	187.8	0.18	0.18	0.18	0.18	0.34	6.6
307	45.7	108.0	134.1	0.23	0.18	0.18	0.18	0.36	134.1
308	76.2	297.0	100.6	0.22	0.18	0.18	0.18	0.37	81.3
309	72.2	901.8	141.7	0.20	0.19	0.19	0.19	0.38	25.4
310	68.6	275.4	91.4	0.22	0.19	0.19	0.19	0.42	78.9
311	18.3	48.6	78.3	0.22	0.19	0.19	0.19	0.42	119.3
312	99.1	669.6	108.2	0.21	0.19	0.19	0.19	0.43	46.9

313	92.4	216.0	217.9	0.23	0.20	0.20	0.20	0.47	135.5
314	182.9	394.2	72.2	0.23	0.20	0.20	0.20	0.50	147.0
315	61.0	297.0	98.5	0.21	0.20	0.21	0.21	0.51	65.0
316	152.4	280.8	89.9	0.23	0.21	0.21	0.21	0.54	172.0
317	48.2	113.4	32.0	0.23	0.22	0.22	0.22	0.60	134.6
318	111.3	513.0	76.8	0.21	0.22	0.22	0.22	0.63	68.7
319	243.8	86.4	127.4	0.26	0.25	0.25	0.25	0.82	893.5
320	234.7	626.4	192.6	0.22	0.18	0.18	0.18	0.35	118.7
321	61.0	253.8	50.0	0.22	0.19	0.19	0.19	0.42	76.1
322	13.7	183.6	51.8	0.20	0.19	0.19	0.19	0.43	23.6
323	243.8	453.6	149.4	0.23	0.20	0.20	0.20	0.49	170.3
324	182.9	486.0	96.6	0.22	0.21	0.21	0.22	0.58	119.2
325	152.4	91.8	117.3	0.25	0.22	0.22	0.22	0.60	526.2
326	109.7	140.4	143.6	0.24	0.25	0.25	0.25	0.82	247.8
327	30.5	486.0	137.2	0.19	0.17	0.17	0.17	0.28	19.8
328	121.9	658.8	144.8	0.21	0.18	0.18	0.17	0.30	58.6
329	21.3	432.0	213.4	0.19	0.18	0.18	0.18	0.34	15.7
330	18.3	324.0	54.9	0.19	0.18	0.19	0.18	0.37	17.9
331	30.5	54.0	274.9	0.23	0.18	0.19	0.18	0.37	178.5
332	73.2	961.2	133.8	0.20	0.19	0.19	0.18	0.38	24.1
333	12.8	280.8	73.8	0.19	0.19	0.19	0.19	0.38	14.4
334	30.5	356.4	62.5	0.20	0.19	0.19	0.19	0.38	27.1
335	91.4	885.6	118.3	0.20	0.19	0.19	0.19	0.40	32.7
336	106.7	394.2	123.4	0.22	0.19	0.19	0.19	0.41	85.8
337	21.3	313.2	53.9	0.19	0.19	0.19	0.19	0.43	21.6
338	18.3	189.0	50.0	0.20	0.19	0.19	0.19	0.43	30.6
339	91.4	216.0	117.7	0.23	0.19	0.19	0.19	0.44	134.2
340	33.5	237.6	53.3	0.21	0.19	0.20	0.19	0.44	44.7
341	91.4	167.4	82.3	0.23	0.19	0.20	0.20	0.44	173.1
342	44.2	54.0	114.3	0.24	0.20	0.20	0.20	0.45	259.2
343	76.2	378.0	91.4	0.21	0.20	0.20	0.20	0.45	63.8
344	45.7	178.2	125.9	0.22	0.20	0.20	0.20	0.46	81.3
345	31.1	189.0	91.4	0.21	0.20	0.20	0.20	0.47	52.1
346	36.6	270.0	121.9	0.21	0.20	0.20	0.20	0.47	42.9
347	61.0	540.0	109.7	0.20	0.20	0.20	0.20	0.47	35.8
348	45.7	81.0	146.3	0.23	0.20	0.20	0.20	0.48	179.0
349	54.9	151.2	106.7	0.22	0.20	0.21	0.21	0.51	115.0
350	102.1	102.6	141.7	0.24	0.20	0.21	0.21	0.51	315.4
351	6.1	178.2	131.4	0.18	0.21	0.21	0.21	0.53	10.9
352	762.0	1058.4	114.3	0.24	0.21	0.21	0.21	0.53	228.1

353	86.9	459.0	100.6	0.21	0.21	0.21	0.21	0.54	60.0
354	27.4	162.0	76.2	0.21	0.21	0.21	0.21	0.54	53.7
355	579.1	1042.2	136.6	0.23	0.21	0.21	0.21	0.55	176.0
356	98.8	286.2	109.7	0.22	0.21	0.21	0.21	0.56	109.3
357	426.7	739.8	86.6	0.23	0.21	0.21	0.21	0.57	182.7
358	222.5	270.0	97.5	0.24	0.21	0.21	0.22	0.58	261.1
359	106.7	426.6	147.8	0.22	0.21	0.21	0.22	0.58	79.2
360	740.7	621.0	103.6	0.25	0.21	0.22	0.22	0.59	377.9
361	36.6	140.4	115.2	0.22	0.22	0.22	0.22	0.60	82.5
362	3.0	162.0	81.1	0.18	0.22	0.22	0.22	0.60	6.0
363	6.7	118.8	67.1	0.19	0.22	0.22	0.22	0.60	17.8
364	121.9	264.6	87.5	0.23	0.22	0.22	0.22	0.60	146.0
365	50.3	297.0	123.4	0.21	0.22	0.22	0.22	0.61	53.6
366	76.2	108.0	91.4	0.24	0.22	0.22	0.22	0.62	223.3
367	30.5	64.8	29.3	0.23	0.22	0.22	0.22	0.62	149.1
368	134.1	59.4	121.9	0.26	0.22	0.22	0.22	0.63	716.1
369	61.0	313.2	93.0	0.21	0.22	0.22	0.22	0.64	61.7
370	112.8	243.0	118.9	0.23	0.22	0.22	0.22	0.64	147.0
371	91.4	135.0	97.2	0.24	0.22	0.22	0.23	0.66	214.7
372	91.4	135.0	103.6	0.24	0.22	0.22	0.23	0.66	214.7
373	731.5	783.0	96.6	0.24	0.22	0.23	0.23	0.66	295.9
374	1036.3	1096.2	140.2	0.24	0.23	0.23	0.23	0.67	299.5
375	51.8	81.0	99.1	0.23	0.23	0.23	0.23	0.67	202.6
376	7.6	10.8	78.3	0.24	0.23	0.23	0.23	0.68	224.3
377	61.0	156.6	135.3	0.22	0.23	0.23	0.23	0.68	123.3
378	198.1	232.2	76.8	0.24	0.23	0.23	0.23	0.69	270.2
379	154.5	356.4	94.5	0.23	0.23	0.23	0.23	0.69	137.3
380	85.3	318.6	73.2	0.22	0.23	0.23	0.23	0.69	84.9
381	76.8	183.6	131.4	0.23	0.23	0.23	0.23	0.72	132.6
382	30.5	27.0	74.7	0.25	0.23	0.23	0.24	0.73	358.1
383	762.0	567.0	136.6	0.25	0.23	0.23	0.24	0.73	425.8
384	42.7	270.0	63.7	0.21	0.23	0.23	0.24	0.73	50.1
385	61.0	27.0	91.4	0.26	0.24	0.24	0.24	0.76	717.2
386	219.5	151.2	121.9	0.25	0.24	0.24	0.24	0.77	460.0
387	95.4	448.2	139.6	0.21	0.24	0.24	0.24	0.79	67.4
388	21.9	237.6	20.7	0.20	0.25	0.25	0.25	0.82	29.3
389	152.4	199.8	64.6	0.24	0.25	0.25	0.25	0.84	241.7
390	121.9	194.4	28.0	0.23	0.25	0.25	0.25	0.85	198.7
391	54.9	189.0	105.2	0.22	0.25	0.25	0.25	0.87	91.9
392	73.2	5.4	128.0	0.30	0.26	0.26	0.27	0.96	4358.4

393	19.8	54.0	42.7	0.22	0.28	0.28	0.28	1.09	116.1
394	15.2	1.6	122.5	0.29	0.32	0.32	0.32	1.43	3024.0
395	22.3	810.0	121.9	0.18	0.16	0.16	0.15	0.19	8.7
396	7.6	324.0	91.4	0.18	0.17	0.17	0.16	0.25	7.5
397	76.2	1171.8	164.6	0.19	0.17	0.17	0.17	0.26	20.6
398	15.2	91.8	83.8	0.21	0.20	0.20	0.20	0.49	52.5
399	45.7	64.8	314.2	0.24	0.21	0.21	0.21	0.55	223.5
400	50.3	199.8	121.9	0.22	0.22	0.22	0.22	0.62	79.7
401	426.7	939.6	149.4	0.23	0.20	0.20	0.20	0.49	143.9
402	91.4	13.5	180.1	0.28	0.25	0.25	0.25	0.88	2152.4
403	100.6	27.0	168.2	0.27	0.31	0.31	0.31	1.34	1183.3
404	30.5	232.2	228.0	0.21	0.16	0.16	0.16	0.20	41.5
405	1.2	43.2	38.1	0.18	0.19	0.19	0.19	0.40	8.9
406	103.6	280.8	105.8	0.22	0.20	0.20	0.20	0.48	116.9
407	2.4	162.0	19.8	0.17	0.20	0.20	0.20	0.49	4.7
408	91.4	1290.6	111.3	0.20	0.20	0.20	0.21	0.51	22.4
409	4.3	167.4	86.9	0.18	0.21	0.21	0.21	0.52	8.1
410	18.3	275.4	82.3	0.19	0.21	0.21	0.21	0.55	21.0
411	9.1	135.0	65.8	0.19	0.21	0.21	0.22	0.58	21.5
412	2.7	167.4	47.2	0.17	0.21	0.21	0.22	0.58	5.2
413	21.9	202.5	77.7	0.20	0.22	0.22	0.22	0.60	34.4
414	161.5	842.4	77.7	0.21	0.22	0.22	0.22	0.62	60.7
415	3.7	145.8	36.3	0.18	0.22	0.22	0.22	0.63	7.9
416	86.0	216.0	112.8	0.23	0.22	0.22	0.22	0.64	126.0
417	77.7	375.3	50.9	0.21	0.22	0.22	0.22	0.64	65.6
418	121.9	223.6	59.4	0.23	0.22	0.22	0.22	0.65	172.8
419	36.6	286.2	83.2	0.21	0.22	0.22	0.23	0.66	40.5
420	121.9	229.5	58.8	0.23	0.23	0.23	0.23	0.67	168.4
421	18.9	183.6	125.3	0.20	0.23	0.23	0.23	0.68	32.7
422	54.9	275.4	90.2	0.21	0.23	0.23	0.23	0.69	63.1
423	30.5	270.0	29.0	0.20	0.23	0.23	0.23	0.69	35.7
424	121.9	204.7	63.4	0.23	0.23	0.23	0.23	0.70	188.8
425	4.6	54.0	57.0	0.20	0.23	0.23	0.23	0.70	26.9
426	29.6	135.0	74.7	0.21	0.23	0.23	0.23	0.70	69.4
427	22.9	194.4	63.7	0.20	0.23	0.23	0.23	0.72	37.3
428	100.6	109.1	139.6	0.24	0.24	0.24	0.24	0.75	292.0
429	39.6	128.0	49.7	0.22	0.24	0.24	0.24	0.75	98.1
430	4.0	64.8	91.4	0.19	0.24	0.24	0.24	0.76	19.3
431	91.4	259.2	249.9	0.22	0.24	0.24	0.24	0.77	111.7
432	6.4	54.0	37.2	0.20	0.24	0.25	0.25	0.82	37.3

433	45.7	81.0	61.6	0.23	0.25	0.25	0.25	0.82	179.0
434	12.2	37.8	102.1	0.22	0.25	0.25	0.25	0.86	102.1
435	7.6	108.0	41.1	0.20	0.26	0.26	0.26	0.91	22.4
436	22.9	459.0	70.4	0.19	0.26	0.26	0.26	0.96	15.8
437	9.1	43.2	65.2	0.21	0.26	0.27	0.27	0.98	67.3
438	61.0	459.0	243.8	0.21	0.29	0.29	0.29	1.17	42.1
439	0.9	351.0	28.3	0.15	0.17	0.17	0.17	0.28	0.8
440	76.2	421.2	210.3	0.21	0.17	0.17	0.17	0.26	57.3
441	30.5	48.6	41.5	0.23	0.26	0.26	0.26	0.91	199.2
442	91.4	270.0	50.9	0.22	0.26	0.26	0.26	0.93	107.3
443	304.8	97.2	37.2	0.27	0.26	0.26	0.26	0.96	992.8
444	152.4	22.1	59.4	0.29	0.27	0.27	0.27	1.01	2180.7
445	914.4	70.2	49.7	0.30	0.27	0.27	0.27	1.02	4129.5
446	914.4	70.2	49.7	0.30	0.27	0.27	0.27	1.03	4129.5
447	289.6	43.2	34.4	0.28	0.27	0.27	0.28	1.05	2122.2
448	304.8	102.6	38.7	0.27	0.28	0.28	0.28	1.08	941.3
449	3048.0	129.6	51.5	0.32	0.28	0.28	0.28	1.09	7446.7
450	3048.0	135.0	50.3	0.31	0.28	0.28	0.28	1.11	7153.5
451	313.9	97.2	29.0	0.27	0.28	0.28	0.28	1.11	1022.7
452	198.1	55.6	36.6	0.27	0.28	0.28	0.28	1.14	1128.6
453	640.1	124.2	20.1	0.28	0.28	0.29	0.29	1.14	1632.9
454	157.0	32.4	12.2	0.28	0.29	0.29	0.29	1.16	1533.6
455	371.9	37.8	42.7	0.29	0.29	0.29	0.29	1.22	3122.0
456	39.6	7.0	35.1	0.28	0.29	0.29	0.29	1.23	1771.2
457	487.7	64.8	25.9	0.29	0.30	0.30	0.30	1.25	2383.1
458	67.1	10.3	30.8	0.28	0.30	0.30	0.30	1.28	2068.1
459	609.6	91.8	19.8	0.28	0.30	0.30	0.30	1.29	2104.7
460	457.2	32.4	20.1	0.30	0.30	0.30	0.30	1.30	4467.9
461	609.6	70.2	84.7	0.29	0.30	0.30	0.30	1.30	2753.1
462	228.6	27.0	25.6	0.29	0.30	0.31	0.30	1.32	2689.6
463	2438.4	118.8	36.0	0.31	0.31	0.31	0.31	1.32	6498.9
464	457.2	32.4	44.2	0.30	0.31	0.31	0.31	1.33	4467.9
465	609.6	47.5	24.4	0.30	0.31	0.31	0.31	1.33	4068.0
466	121.9	9.7	36.6	0.30	0.31	0.31	0.31	1.34	3963.9
467	548.6	36.7	77.7	0.30	0.31	0.31	0.31	1.34	4740.2
468	67.1	12.4	30.8	0.28	0.31	0.31	0.31	1.35	1713.6
469	167.6	21.6	125.6	0.29	0.31	0.31	0.31	1.35	2457.4
470	396.2	129.6	57.9	0.27	0.31	0.31	0.31	1.36	968.1
471	701.0	48.6	37.5	0.30	0.31	0.31	0.31	1.36	4575.4
472	317.0	18.9	78.3	0.31	0.31	0.31	0.31	1.38	5298.4

473	478.5	21.6	42.7	0.31	0.31	0.31	0.31	1.38	7014.7
474	396.2	21.6	71.0	0.31	0.31	0.31	0.31	1.40	5808.4
475	304.8	16.2	71.6	0.31	0.31	0.32	0.31	1.41	5989.5
476	914.4	86.4	41.8	0.30	0.32	0.32	0.32	1.44	3351.0
477	914.4	108.0	41.1	0.29	0.32	0.32	0.32	1.45	2680.8
478	701.0	32.4	27.1	0.31	0.32	0.32	0.32	1.45	6850.6
479	609.6	21.6	74.1	0.32	0.32	0.32	0.32	1.46	8936.3
480	623.3	17.8	42.1	0.33	0.32	0.32	0.32	1.46	11036.7
481	70.1	27.0	40.2	0.26	0.32	0.32	0.32	1.47	825.2
482	365.8	48.6	31.4	0.29	0.32	0.32	0.32	1.47	2387.0
483	259.1	48.6	42.1	0.28	0.32	0.32	0.32	1.48	1691.2
484	701.0	32.4	35.4	0.31	0.32	0.32	0.32	1.48	6850.6
485	853.4	32.4	32.0	0.32	0.32	0.33	0.32	1.51	8340.2
486	548.6	37.8	23.8	0.30	0.33	0.33	0.32	1.51	4606.6
487	76.2	10.8	32.9	0.29	0.33	0.33	0.33	1.52	2233.2
488	335.3	10.8	74.4	0.32	0.33	0.33	0.33	1.53	9839.2
489	609.6	21.6	85.3	0.32	0.33	0.33	0.33	1.53	8936.3
490	457.2	16.2	44.2	0.32	0.33	0.33	0.33	1.53	8985.0
491	152.4	5.4	76.2	0.32	0.33	0.33	0.33	1.53	9086.4
492	944.9	32.4	31.7	0.32	0.33	0.33	0.33	1.54	9234.1
493	91.4	5.4	65.5	0.31	0.33	0.33	0.33	1.56	5452.8
494	914.4	16.2	48.8	0.34	0.33	0.33	0.33	1.59	17969.9
495	1219.2	16.2	29.3	0.35	0.34	0.34	0.33	1.62	23961.0
496	365.8	27.0	37.2	0.30	0.34	0.34	0.34	1.63	4302.9
497	1219.2	21.6	25.9	0.34	0.34	0.34	0.34	1.65	17872.5
498	365.8	18.9	73.2	0.31	0.34	0.34	0.34	1.65	6112.6
499	304.8	8.1	25.6	0.33	0.34	0.34	0.34	1.65	11848.7
500	137.2	5.4	19.8	0.24	0.34	0.34	0.34	1.66	235.4
501	47.5	5.4	21.6	0.32	0.34	0.34	0.34	1.69	8174.4
502	365.8	16.2	19.2	0.29	0.34	0.34	0.34	1.69	2836.8
503	762.0	14.6	52.4	0.31	0.35	0.35	0.34	1.71	7187.3
504	487.7	9.2	81.1	0.34	0.35	0.35	0.34	1.71	16619.7
505	426.7	5.9	29.0	0.34	0.35	0.35	0.35	1.78	16773.2
506	329.2	17.8	31.1	0.35	0.36	0.36	0.35	1.83	22447.1
507	457.2	27.0	41.1	0.31	0.36	0.36	0.36	1.85	5828.4
508	365.8	24.3	40.5	0.31	0.36	0.36	0.36	1.87	5379.2
509	609.6	21.6	30.8	0.30	0.36	0.36	0.36	1.88	4774.1
510	609.6	20.5	24.7	0.32	0.36	0.36	0.36	1.89	8936.3
511	335.3	21.6	16.2	0.32	0.36	0.36	0.36	1.91	9398.5
512	317.0	2.7	41.5	0.30	0.37	0.37	0.36	1.95	4914.9

513	469.4	8.1	26.5	0.36	0.37	0.37	0.36	1.96	37795.2
514	365.8	18.9	32.0	0.34	0.37	0.37	0.37	1.97	18250.4
515	457.2	16.2	33.8	0.31	0.37	0.37	0.37	1.98	6112.6
516	762.0	5.4	40.5	0.32	0.38	0.38	0.37	2.08	8985.0
517	335.3	10.8	37.5	0.37	0.38	0.38	0.38	2.13	45427.2
518	335.3	10.8	35.7	0.32	0.39	0.39	0.38	2.18	9829.8
519	457.2	13.5	35.4	0.32	0.39	0.39	0.38	2.18	9829.8
520	457.2	10.8	36.3	0.33	0.39	0.39	0.39	2.22	10758.3
521	762.0	2.7	39.6	0.33	0.40	0.40	0.39	2.32	13403.8
522	185.9	5.9	39.0	0.39	0.40	0.40	0.39	2.32	90854.4
523	0.3	3294.0	14.0	0.32	0.40	0.40	0.39	2.33	9779.3
524	0.2	12150.0	31.4	0.38	0.41	0.41	0.41	2.51	81763.2
525	0.6	4860.0	35.1	0.32	0.49	0.49	0.51	4.23	8042.8
526	65.5	394.2	54.9	0.21	0.21	0.21	0.21	0.56	52.7
527	24.4	486.0	71.6	0.19	0.21	0.22	0.22	0.59	15.9
528	6.1	459.0	41.1	0.17	0.22	0.22	0.22	0.59	4.2
529	5.5	189.0	22.9	0.18	0.22	0.22	0.23	0.65	9.2
530	332.2	189.0	82.3	0.25	0.23	0.23	0.23	0.67	556.8
531	243.8	156.6	121.6	0.25	0.23	0.23	0.23	0.69	493.2
532	1219.2	345.6	82.3	0.27	0.23	0.23	0.23	0.71	1117.5
533	62.8	168.5	12.8	0.22	0.23	0.23	0.23	0.72	118.1
534	73.2	97.2	15.2	0.24	0.24	0.24	0.24	0.77	238.2
535	71.6	113.4	15.2	0.23	0.24	0.24	0.24	0.79	200.0
536	166.1	59.4	85.0	0.26	0.24	0.24	0.24	0.79	886.8
537	106.7	270.0	66.4	0.23	0.24	0.24	0.25	0.81	125.2
538	62.5	108.0	13.4	0.23	0.25	0.25	0.25	0.82	183.2
539	2590.8	389.9	58.8	0.28	0.25	0.25	0.25	0.82	2104.9
540	106.7	118.8	18.3	0.24	0.25	0.25	0.25	0.86	284.8
541	45.7	16.2	31.7	0.26	0.25	0.25	0.25	0.88	898.8
542	335.3	129.6	19.8	0.26	0.26	0.26	0.26	0.94	820.3
543	30.5	32.4	38.4	0.24	0.26	0.26	0.26	0.94	297.4
544	137.2	194.4	24.4	0.24	0.26	0.26	0.26	0.95	223.5
545	685.8	113.4	36.6	0.28	0.26	0.26	0.26	0.96	1916.1
546	221.0	59.4	100.0	0.27	0.26	0.26	0.27	0.97	1179.5
547	137.2	162.0	23.2	0.24	0.26	0.26	0.27	0.97	268.3
548	411.5	275.4	83.8	0.25	0.27	0.27	0.27	0.98	473.5
549	61.0	64.8	49.7	0.24	0.27	0.27	0.27	0.99	297.8
550	93.9	129.6	50.6	0.24	0.27	0.27	0.27	1.01	229.7
551	137.2	189.0	23.2	0.24	0.27	0.27	0.27	1.01	229.8
552	102.1	74.5	14.3	0.25	0.27	0.27	0.27	1.04	433.7

553	332.2	135.0	94.5	0.26	0.27	0.27	0.28	1.05	779.7
554	228.6	162.0	86.0	0.25	0.28	0.28	0.28	1.10	447.3
555	111.3	1026.0	207.0	0.20	0.16	0.16	0.16	0.21	34.4
556	243.8	324.0	168.6	0.24	0.20	0.20	0.20	0.47	238.4
557	15.2	124.2	59.4	0.20	0.19	0.19	0.19	0.43	38.8
558	152.4	529.2	45.4	0.22	0.23	0.23	0.23	0.67	91.3
559	61.0	135.5	39.6	0.23	0.23	0.23	0.23	0.70	142.5
560	18.3	108.0	67.1	0.21	0.24	0.24	0.24	0.78	53.6
561	76.2	32.4	75.3	0.26	0.25	0.25	0.25	0.83	781.8
562	266.7	108.0	66.1	0.26	0.25	0.25	0.25	0.84	744.4
563	152.4	108.0	89.3	0.25	0.25	0.25	0.25	0.86	446.9
564	487.7	140.4	39.6	0.27	0.26	0.26	0.26	0.94	1101.3
565	190.5	10.8	77.7	0.31	0.27	0.27	0.27	0.99	5585.3
566	304.8	63.2	37.8	0.28	0.27	0.27	0.27	1.02	1526.7
567	304.8	42.7	34.1	0.29	0.27	0.27	0.27	1.04	2261.6
568	304.8	33.5	36.0	0.29	0.29	0.29	0.29	1.15	2883.8
569	106.7	21.6	75.6	0.28	0.29	0.29	0.29	1.18	1563.9
570	548.6	43.2	19.2	0.30	0.30	0.30	0.30	1.30	4021.4
571	1828.8	16.2	56.1	0.36	0.31	0.31	0.31	1.38	35939.9
572	762.0	13.0	81.1	0.34	0.34	0.34	0.34	1.68	18668.7
573	304.8	4.3	80.8	0.35	0.36	0.37	0.36	1.91	22710.0
574	609.6	16.2	77.7	0.33	0.37	0.37	0.36	1.93	11980.5
575	245.4	162.0	126.5	0.25	0.21	0.21	0.21	0.54	480.1
576	342.9	124.2	36.6	0.26	0.24	0.24	0.24	0.79	874.7
577	1.8	426.6	92.4	0.16	0.16	0.16	0.15	0.19	1.4
578	15.2	513.0	59.4	0.18	0.16	0.17	0.16	0.23	9.4
579	18.3	216.0	106.7	0.20	0.17	0.17	0.17	0.29	26.8
580	61.0	383.4	96.3	0.21	0.18	0.18	0.17	0.31	50.4
581	13.1	394.2	67.4	0.18	0.18	0.18	0.18	0.32	10.5
582	30.5	351.0	94.5	0.20	0.18	0.18	0.18	0.35	27.5
583	42.7	486.0	88.4	0.20	0.19	0.19	0.18	0.37	27.8
584	152.4	167.4	182.9	0.24	0.19	0.19	0.19	0.38	288.5
585	61.0	270.0	105.2	0.21	0.19	0.19	0.19	0.39	71.5
586	45.7	891.0	61.0	0.19	0.19	0.19	0.19	0.40	16.3
587	216.4	383.4	84.7	0.23	0.20	0.20	0.20	0.48	178.9
588	39.6	162.0	132.6	0.22	0.20	0.20	0.20	0.50	77.5
589	61.0	442.8	166.7	0.21	0.21	0.21	0.21	0.52	43.6
590	45.1	378.0	150.9	0.20	0.21	0.21	0.21	0.54	37.8
591	90.2	669.6	99.1	0.21	0.21	0.21	0.21	0.54	42.7
592	19.8	81.0	59.7	0.22	0.21	0.21	0.21	0.56	77.5

593	41.1	297.0	86.6	0.21	0.21	0.21	0.21	0.57	43.9
594	30.5	151.2	110.3	0.21	0.21	0.21	0.22	0.58	63.8
595	214.0	75.6	68.9	0.26	0.21	0.22	0.22	0.59	896.0
596	457.2	540.0	80.8	0.24	0.22	0.22	0.22	0.59	268.3
597	45.7	108.0	62.5	0.23	0.22	0.22	0.22	0.60	134.1
598	121.9	318.6	118.3	0.22	0.22	0.22	0.22	0.62	121.3
599	45.7	432.0	91.4	0.20	0.22	0.22	0.22	0.65	33.5
600	42.7	324.0	121.3	0.21	0.22	0.23	0.23	0.66	41.7
601	143.3	59.4	119.5	0.26	0.23	0.23	0.23	0.68	764.7
602	114.3	86.4	64.0	0.25	0.23	0.23	0.23	0.70	418.7
603	76.2	307.8	39.9	0.22	0.23	0.23	0.23	0.71	78.4
604	61.0	21.6	109.7	0.26	0.23	0.23	0.23	0.71	893.5
605	137.2	147.4	118.6	0.24	0.24	0.24	0.24	0.76	294.8
606	243.8	135.0	69.5	0.26	0.24	0.24	0.25	0.80	572.2
607	106.7	8.1	44.5	0.30	0.33	0.33	0.33	1.53	4147.8
608	335.3	27.0	38.1	0.30	0.34	0.34	0.34	1.63	3944.8
609	121.9	13.5	74.7	0.29	0.34	0.34	0.34	1.69	2868.6

APPENDIX IV

DETAILS OF THE EQUATIONS

Grapher software version 7.4 was used to plot the data. It offers various options to fit curves to the data, and establish equations from the fits. Grapher is produced by Golden Software and is a very versatile graphing package to accommodate many data sources. The author has used Grapher for plotting data in several other publications (McCarthy, McFarland, Wilkinson, & White, 1992; Wilkinson, 1991; Wilkinson & Shikazono, 2012) The following data files were output from Grapher and show the progression of the iterations during the establishment of the equations to describe the fit to the data for each graph.

The fit results for figure 2.27 are shown below.

Fit: Polynomial

Equation Y = 0.1303514902 + 0.1543832675 * X - 0.01654135569 * pow(X,2)

Degree = 2

Number of data points used = 610

Average X = 0.777568

Average Y = 0.236837

Coefficients:

Degree 0 = 0.1303514902

Degree 1 = 0.1543832675

Degree 2 = -0.01654135569

Degree: 0

Residual sum of squares = 1.77

Coef of determination, R-squared = -2.22045E-016

Degree: 1

Residual sum of squares = 0.0387512

Coef of determination, R-squared = 0.978107

Degree: 2

Residual sum of squares = 0.00285802

Coef of determination, R-squared = 0.998385

The fit results for figure 3.28 are shown below.

Fit: Polynomial

Equation Y = 0.1304 + 0.1544 * X - 0.0165 * pow(X,2)

Degree = 2

Number of data points used = 610

Average X = 0.777568

Average Y = 0.236932

Coefficients:

Degree 0 = 0.1304

Degree 1 = 0.1544

Degree 2 = -0.0165

Degree: 0

Residual sum of squares = 1.77045

Coef of determination, R-squared = 0

Degree: 1

Residual sum of squares = 0.0357139

Coef of determination, R-squared = 0.979828

Degree: 2

Residual sum of squares = 5.0038E-029

Coef of determination, R-squared = 1

The fit results for figure 3.29 are shown below.

Fit: Polynomial

Equation Y = 0.1301 + 0.154 * X - 0.0165 * pow(X,2)

Degree = 2

Number of data points used = 610

Average X = 0.777568

Average Y = 0.236321

Coefficients:

Degree 0 = 0.1301

Degree 1 = 0.154

Degree 2 = -0.0165

Degree: 0

Residual sum of squares = 1.7584

Coef of determination, R-squared = -2.22045E-016

Degree: 1

Residual sum of squares = 0.0357139

Coef of determination, R-squared = 0.97969

Degree: 2

Residual sum of squares = 1.9475E-029

Coef of determination, R-squared = 1

The fit results for figure 3.30 are shown below.

Fit: Power

Equation ln(Y) = 0.08258430964 * ln(X) - 1.889963995

Alternate Y = pow(X,0.08258430964) * 0.1510772483

Number of data points used = 610

Average ln(X) = 5.13231

Average ln(Y) = -1.46612

Residual sum of squares = 7.98214

Regression sum of squares = 19.7012

Coef of determination, R-squared = 0.711662

Residual mean square, sigma-hat-sq'd = 0.0131285

And the fit results for the final equation from figure 3.31 are shown below.

Fit: Power

Equation ln(Y) = 0.08258430964 * ln(X) - 1.889963995

Alternate Y = pow(X,0.08258430964) * 0.1510772483

Number of data points used = 610

Average ln(X) = 5.13231

Average ln(Y) = -1.46612

Residual sum of squares = 4.3436E-027

Regression sum of squares = 19.7012

Coef of determination, R-squared = 1

Residual mean square, sigma-hat-sq'd = 7.14408E-030