2001

Flow through well screens as a function of pump intake location

Kristjan F. Bekker
University of North Dakota

FLOW THROUGH WELL SCREENS AS A FUNCTION OF PUMP INTAKE LOCATION

By

Kristján F. Bekker
Bachelor of Science, Western Michigan University, 1994

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

August

2001

This thesis, submitted by Kristján F. Bekker in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

(Chairperson)

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of Graduate School

Date

PERMISSION

Title	Flow through Well Screens as a Function of Pump Intake Location
Department	Geology and Geological Engineering
Degree	Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree that for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the chairman of the department or the dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature [signature]

Date 19th July, 2001

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to thank the following people for the help they have provided: Gary Dubuque, Jay Evenstad, Allen Schlag, Scott Korom, Rich LeFever, and Phil Gerla.

UND Plant Services Personel

UND Paint Shop

UND Civil Engineering Department

Scott Tolbert

Otto Helweg

Blaise Mibeck, Damian C. Mathews, Christopher Milleford, Lee Stone, Mitchell Mussetter, Jason Warne, Paul Skubinna, Hans Kishel, Ben Ziegler, Brian Moritz, Michelle Manley, and Forrest Ames.

Equipment Funds provided by North Dakota EPSCoR through NSF grant #EPS-9874802.

DEDICATION

I would like to dedicate this final result of my scholarly efforts over the years to my family, especially my parents Fred and Liz Bekker, without whose support I would not have succeeded.

ABSTRACT

Greater well efficiency and lower production costs may result from a knowledge of water flow through well screens. Current practice generally locates the intake of a pump in the cased section of the well above the screen. This work shows that placing the pump within the screen will increase well efficiency and therefore lower energy cost. This work also shows a correlation of increased well efficiency with respect to larger sand size, larger screen slot size, and lower flow rates.

A semicircular model based on the radial symmetry of a well and screen was used to simulate water flow from surrounding aquifer material. Pump intake location was varied between experiments. Two sand sizes, 12-20 and 16-30, were used for the experiments with a 0.25-mm screen slot size. The larger sand was used for experiments with two screens of 0.51-mm and 0.76-mm slot sizes. Hydraulic head data were recorded in twenty piezometers in a vertical cross section in the sand during experiments. The data were gridded and contoured and the resulting plots used to infer direction of flow. Data sets with different intake locations but identical well discharge, screen sizes, and sand size were subtracted from each other to examine the effect of intake location on head. The efficiency of different well configurations was determined comparing drawdown within the well to the hydraulic head in the aquifer surrounding the well.

For the experiments done in this study, flow through well screens was concentrated around the pump intake. The magnitude of this preferential flow increased with the pumping rate. Higher pumping rates were less efficient than lower pumping rates regardless of screen, sand, and intake location. This work suggests that pump intakes placed within the well screen are more efficient than intakes placed inside the cased section of the well. Of the intakes located within the screen section of the well the one 87 cm within the well screen was more efficient than the one only 26 cm within the screen. The larger the open area of a well screen, the more efficient flow will be through that well screen.

CHAPTER 1

INTRODUCTION

Experiments were conducted with a physical model to confirm the hypothesis that flow through a well screen in an unconfined homogeneous aquifer is concentrated near the pump intake. Furthermore, these results indicate that locating the intake in the screened portion of a well increases well efficiency, which is indicative of lower differential screen entrance velocities. Such results are contrary to current well design guidelines, which recommend against locating the intake of a pump within the well screen because it would increase entrance velocities (Driscoll, 1986; Roscoe Moss Company, 1990). High velocities lead to higher incrustation rates, corrosion, sand pumping (Driscoll, 1986), and reduced well productivity (Roscoe Moss Company, 1990). Current guidelines locate pump intakes in the casing above a well screen.

Von Hofe and Helweg (1998) using a numerical finite difference model of well hydrodynamics, were apparently the first investigators to show that locating the pump intake inside the screened portion of a well minimizes the differential entrance velocities and maximizes well efficiencies. Their model builds on earlier work done by Garg and Lal (1971), the first to detect non-uniform flow-along well screens, Cooley and Cunningham (1979), and Kaleris (1989). Garg and Lal (1971) and Cooley and Cunningham (1979) located the pump intake above the top of the well screen in the casing. Kaleris (1989) located the pump intake at the screen bottom.

Using a hypothetical 30.5-m (100-ft) long, 0.41-m (16-in.) diameter screen with various intake locations and intake diameters, Von Hofe and Helweg (1998, page 1202) concluded:

> "Engineers should consider locating pump intakes in well screens as a matter of practice. First, this will allow more water to be extracted from the well without causing sand drive. Second, it will minimize the total drawdown of the well, which may decrease energy costs. Finally, though beyond the scope of this paper, the size of the pump intake diameter should be ~60% of the screen diameter."

Other than testing my hypothesis that flow through a well screen is concentrated near the pump intake, my goal was to verify the finding by Von Hofe and Helweg (1998) that locating the intake in the screen increases well efficiencies. To do so in a physical model necessitated the following simplifications: 1) due to size limitations a screen length of only 1.52 m (5 ft) was used; and 2) because the physical model was not adapted to directly measure screen entrance velocities, a hydraulic head profile was used to infer the velocity distribution along the outside of the screen.

CHAPTER 2

MODEL DESCRIPTION

Knowing that water flows in the direction of decreasing head this experiment used a semi-full scale model of a well that allows the hydraulic head profile recorded by a series of piezometers located in a plane to imply velocities around well screens. The relative magnitude of the head field generated during a particular experiment was assumed to be directly proportional to the velocity in this plane. The model was constructed such that experiments could be designed that compared model conditions resulting from various model configurations. Sand size, screen size, flow rate and intake locations were changeable between experiments.

A semicircular well system can be used to represent the symmetry of a circular system, and was modeled using a semicircular tank 3.05 m (10 ft) in height and 1.83 m (6 ft) in diameter (Figure 1). This tank was mounted in a frame on bearings that allowed it to be rotated to aid in emptying it of sand. The frame adds another 0.45 m to the height of the model, making the top of the model 3.5 m (11.6 ft) above the floor. The front of the model was made of two sheets of 12.7-mm (0.5-in.) Plexiglas that allowed viewing of the interior of the well during operation. The semicircular sides and bottom of the tank were made of reinforced 3.2-mm (0.125-in.) stainless steel. All of this was mounted in a

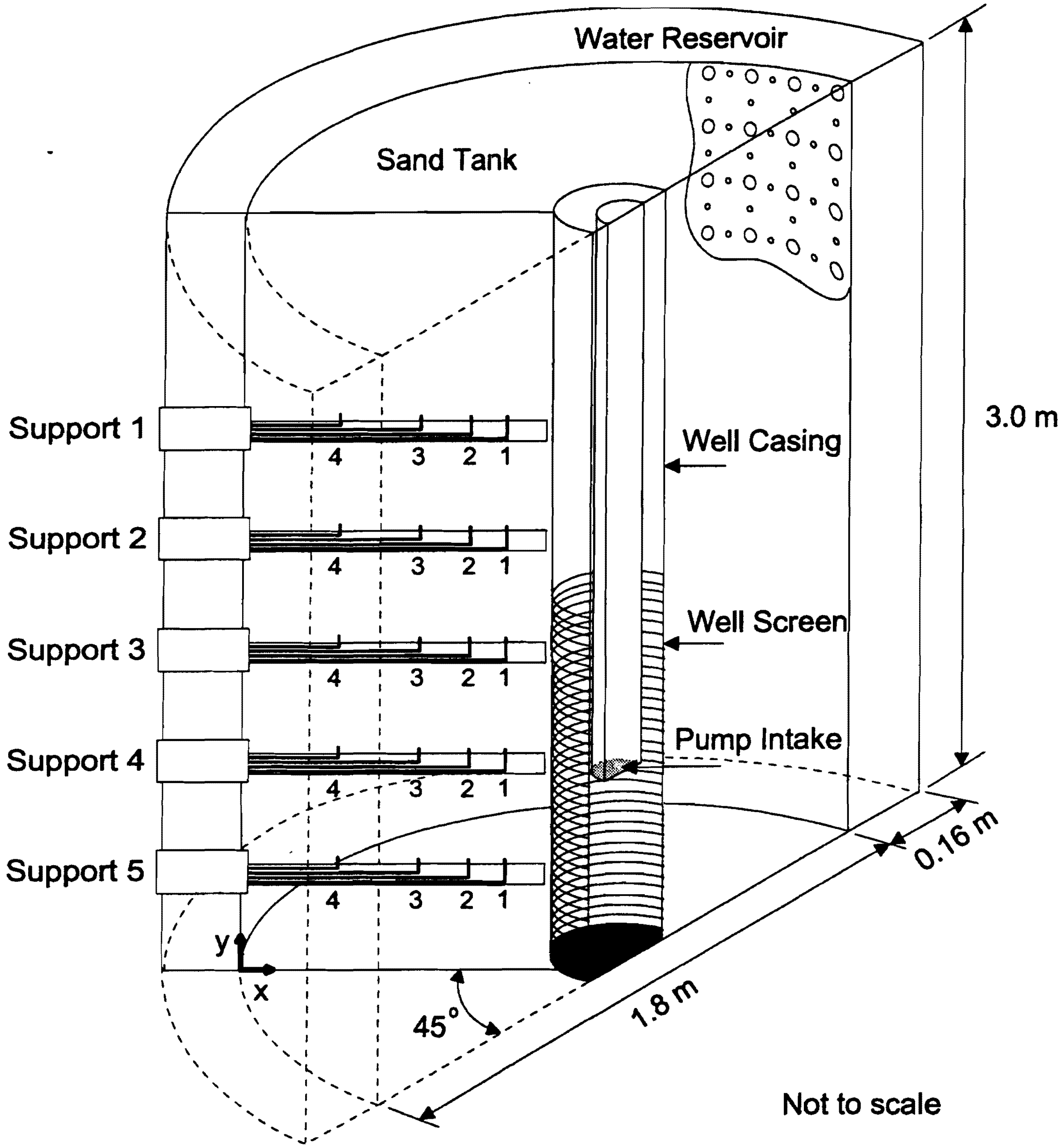

Figure 1. Schematic representation of the well model. The stippled area in the upper right corner represents the screened holes that allow water to flow between the outer water reservoir into the sand tank.

framework of cross-braced 51-mm (2-in.) square steel tubing with a large steel plate for a base.

Hydraulic head measurements were taken with piezometers located within the sand. The piezometers were located in a plane at a 45° angle from the well model face (Figure 1). The piezometers positions did not shift more than 6 mm (0.25 in.) during repeated emptying and filling of the model with sand or with changing of well screens. All piezometer measurements were later correlated to a datum at the bottom corner of the tank represented by the small X and Y axes on Figure 1.

The piezometers are made of metal tubes placed on a steel bar, labeled "support" on Figure 1, with steel mesh protecting the piezometer entrances from sand. Each steel piezometer tube followed along a support and entered a steel pipe sealed with O-rings that goes through the inner and outer walls of the well model. Each steel tube was then connected to flexible plastic tubing that connects to the piezometers.

The flexible tubes were set vertically in series on a piezometer board that was mounted on two circular rails that allow for vertical adjustment. The piezometer board position relative to the top tank reference point was always noted when the piezometer board location was shifted. Coordinates of piezometers are given in Table 1.

Table 1. Coordinates (in meters) of piezometers in well model sand tank (X / Y values with origin shown in Figure 1).

Probe #	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	0.752/2.319	0.714/2.302	0.638/2.275	0.335/2.324
2	0.746/1.784	0.721/1.764	0.645/1.743	0.321/1.792
3	0.751/1.268	0.711/1.259	0.635/1.232	0.327/1.248
4	0.756/0.652	0.694/0.645	0.629/0.629	0.318/0.668
5	0.748/0.203	0.705/0.160	0.635/0.156	0.316/0.191

Screen Construction

Three screens were made using continuously-wound PVC Vee-Wire® screens of three different slot sizes, 0.25 mm (0.010 in.), 0.51 mm (0.020 in.), and 0.76 mm (0.030 in.) with 6.7%, 12.5 %, and 17.6% open area, respectively. The screened sections were constructed by cutting 1.52-m (5-ft) lengths of the screen in half. Upon cutting, the wound PVC screens became oblate. The circular shape of screen was restored by compressing and mounting the screen halves within trenches created by gluing a 3.2-mm (0.125-in.) section of Plexiglas on a backboard of 12.7-mm (0.5-in.) thick Plexiglas. Once the screened sections were adhered to the Plexiglas backing a 1.52-m (5-ft) section of straight-walled schedule 40 PVC pipe was cut in half, glued to the Plexiglas, and connected to the screen with a watertight coupling. A smaller segment of PVC pipe was used to construct a 70-mm (2.76-in.) sump attached to the screen bottom.

The screen sections were mounted to the Plexiglas front of the well model with six clamps, three on each side. The clamps were made of half-inch angle iron that have no relief above the screen to interfere with flow of water toward screen.

With respect to the top of the well screen the short intake was 0.28 m above it; the medium intake was 0.33 m below it; and the long intake was 0.94 m below it. These correspond to the 1.85-m, 1.24-m and the 0.63-m intake locations, relative to take bottom, used in Appendix 1. The top of the intake pipe was connected with a right angle PVC joint having a pressure release valve to a flexible 0.10-m (3.9-in.) hose. The flexible hose brought the pumped water over the top of the well model and to a section of straight PVC pipe that contained an orifice type flow meter. This meter was reported to be accurate to 3% of scale, ± 0.2 L/s at low flow and ± 0.6 L/s at the highest flow rates (RCM Industries, Concord CA). After passing the flow meter the water entered the pump and was circulated back to the water reservoir. The rate of water flow was controlled at the point of reentry into the reservoir with a ball valve.

Sand Size and Characteristics

Two sizes of commercially available sand for well packs were used: Colorado Silica Sand, Inc. 16-30 and 12-20 sands. The 16-30 sand is composed of sands of which 90-100% pass a number 16 US sieve [1.180 mm (0.0465 in.)] and 0-10% is retained on a number 30 US sieve [0.60 mm (0.0236 in.)]. It has a specific gravity of 2.64 g/cc, a mean grain size of 0.85-mm (0.0335-in.), a porosity from 44 to 46%, a sphericity of 0.8, and a uniformity coefficient from 1.43 to 1.38. The 12-20 sand is composed of sands of which 95-100% pass a number 12 US sieve [1.70 mm (0.0669 in.)] and 0-5% is retained on a number 20 US sieve [0.85 mm (0.0335 in.)]. It has a specific gravity of 2.64 g/cc, a mean grain size of 1.32-mm (0.052-in.), a porosity of 45.9%, a sphericity of 0.8, and a uniformity coefficient from 1.30 to 1.47. Further information about these sands can be found in Appendix 2 (Colorado Silica Sand, Inc., Colorado Springs, CO).

CHAPTER 3

METHODOLOGY

Experimental Process

Installing a 0.76-mm screen (0.030-in.) in a model empty of sand started the experimental series. It was replaced by the 0.51-mm screen (0.020-in.) and then the 0.25-mm screen (0.010-in.). Experiments were done with each of these screens after filling with the coarse 12-20 sand. The experiments conducted with the 0.25-mm screen were repeated using the fine 16-30 sand. After filling with sand the model was filled with water, drained and filled again to compact and settle the sand. The intake was connected to the pumping system and then positioned. The pump system was primed, started, run for a few minutes and shut down. After the flow meter was calibrated and the initial positions of piezometers and model conditions were recorded, the model was ready for data collection.

Data Collection

At the start of an experimental series each piezometer was pumped with a hand pump for a period of time to remove any air from within the piezometer. The initial positions of water in the piezometers were recorded. The pump was then started and the bottom entrance valve was opened to the outer water reservoir until the orifice flow meter indicated the desired flow rate had been reached. The levels of the piezometers were recorded from support 1 through support 5. The levels in the tank and well were then recorded. The measurement of the piezometers was then repeated. If the water levels in the piezometers differed between the measurements an average was taken. On some of the higher flow rates the water levels in some tubes were below the piezometer board; for these readings measurements were taken with respect to the bottom of the sand tank. The experiment was then repeated two more times for the two other intake lengths.

Data Analysis

An adjustment factor was used to relate the piezometer data to the tank bottom. This adjustment factor changed for each experimental run and took into account the change in initial water level and movement of piezometer board. After the heads were corrected, they were grided and contoured using Golden Software's Surfer® program version 6.01 (1995). Figure 2 provides an example. The gridding method used in contouring was kriging with no smoothing. The plot shows the 0.79-m width of the well model. The top of the plot corresponds to the actual water level in the sand tank recorded during the experiment. This allowed for direct visual comparisons between plots; the difference between contour plots, however, was very difficult to discern and another way of analyzing the data was needed. As this thesis is concerned primarily with the importance of intake location, the data sets for different intake locations but identical flow rates

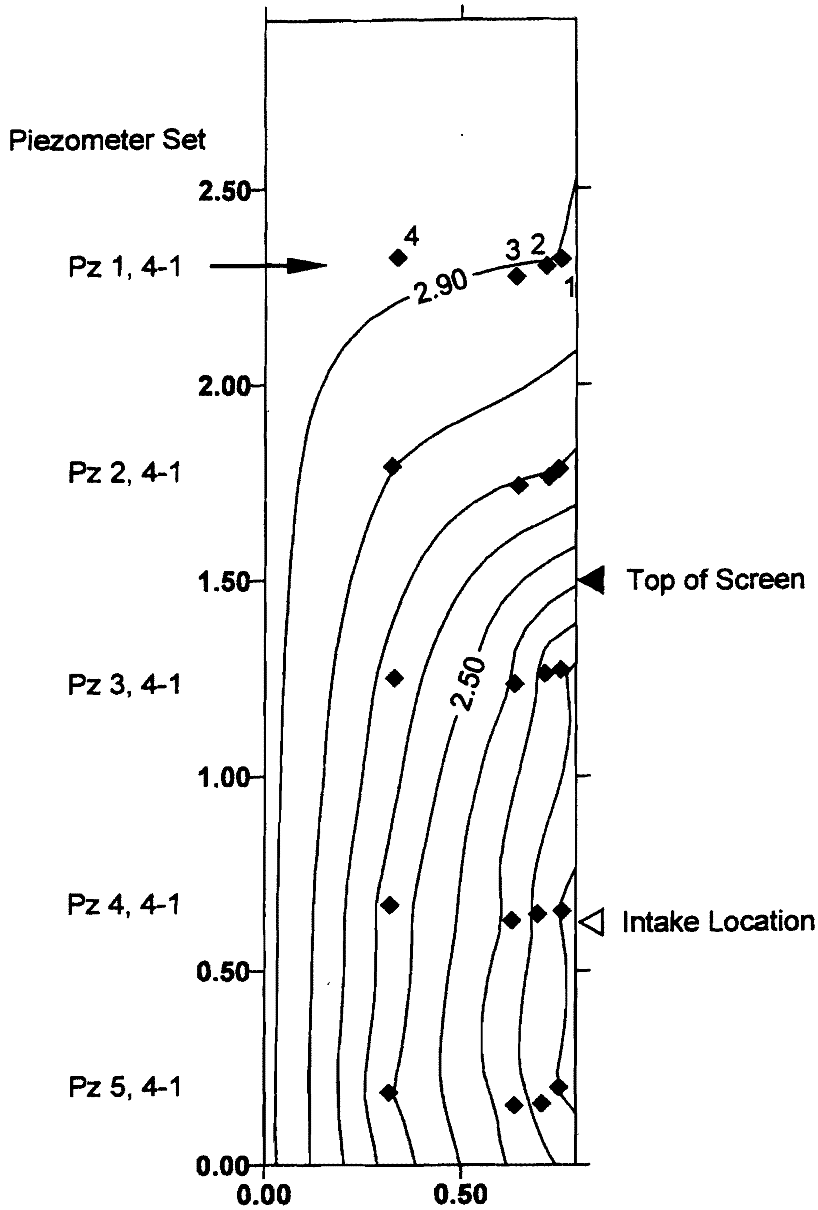

Figure 2. Plot of piezometer hydraulic heads during an experiment (0.63 m intake position, using 12-20 sand, Q at 15.8 L/s, and a 0.25 mm (010) slot size screen). Contour interval equal to 0.1 m. Well screen is to right and water reservoir is to left. Slight bowing of contour between piezometers is an artifact from gridding.

were compared. This is done by normalization with the model operating. Normalization with the model operating was termed dynamic normalization. When the experiments are running the model conditions, such as the relative volume of water in different parts of the model, change with respect to the head at the top of the tank and within the sand of the well model. To make sure that this was a hydraulic head difference independent of intake location, a piezometer in a relatively inactive area, one that had changed very little from when the model was started, was selected as a point of standardization. The differences between two separate data sets at this point were assumed to represent actual differences caused by intake location and not artifacts of operation. After this dynamic normalization has been applied, the differences between the two data sets were assumed to be due to the positions of the well intake. Figure 3 shows a before and after picture of two experimental data sets at similar conditions with respect to everything other than intake location except one has been dynamically normalized. Tables 2 and 3 contain the raw data used in the construction of Figure 3.

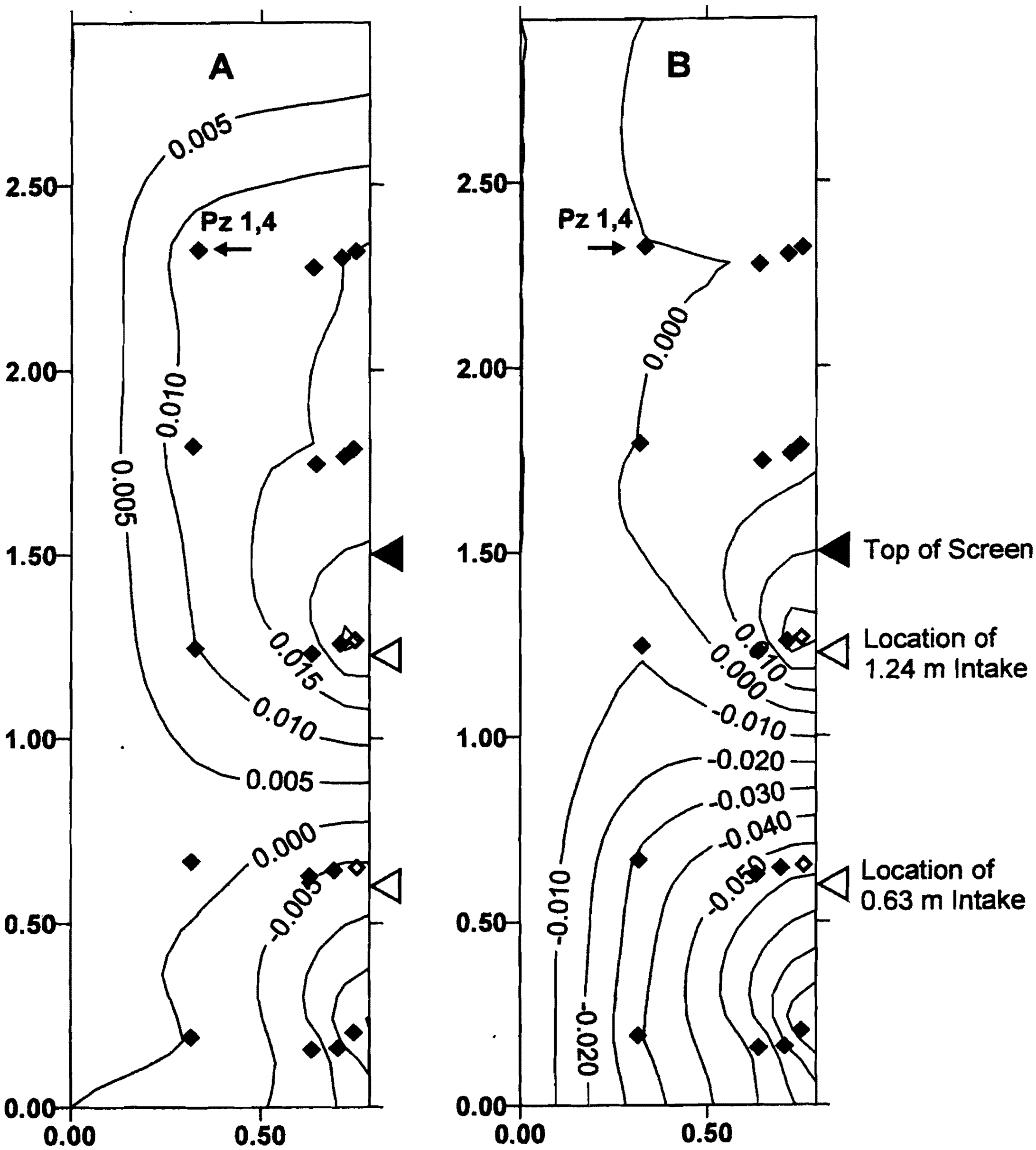

Figure 3. The effect of dynamic normalization. Plots A and B are of the same data sets. Plot A is the difference between two data sets representing two different intake locations, 0.63 m and 1.24 m. Plot B is the same as Plot A except that it has been normalized with respect to a piezometer, 1,4, within the piezometer plane in an area with little flow occuring. Plot B has undergone dynamic normalization. The conditions of these data sets are, 12-20 sand, 18.9 L/s Q, and a 0.25 mm slot size. The two piezometers that were not able to be recorded are represented by hollow diamonds.

Table 2. 1.24 m intake data used in the contouring of Figure 3.

Pumping rate 18.9 L/s, Water level in tank during pumping 2.938 m.

Piezometer Readings (Run I.D. No. 17 Korom et al., 2001 in review)

	Pz 1	Pz 2	Pz 3	Pz 4
Support 1	2.845	2.842	2.836	2.867
Support 2	2.609	2.605	2.598	2.734
Support 3	1.937	2.045	2.246	2.570
Support 4	1.905	2.043	2.165	2.462
Support 5	1.949	2.007	2.142	2.412

Table 3. 0.63 m intake data used in the contouring of Figure 3.

Pumping rate 18.9 L/s, Water level in tank during pumping 2.940 m.

Piezometer Readings (Run I.D. No. 22 Korom et al., 2001 in review)

	Pz 1	Pz 2	Pz 3	Pz 4
Support 1	2.893	2.888	2.877	2.908
Support 2	2.657	2.652	2.644	2.775
Support 3	Not Recorded	2.125	2.294	2.601
Support 4	Not Recorded	2.027	2.154	2.471
Support 5	1.886	1.975	2.122	2.414

Well Efficiencies

Well efficiency was defined by the Roscoe Moss Company in their Handbook of Ground Water Development, page 101, as:

> "In well hydraulics...well efficiency may be stated as the ratio of drawdown in the aquifer to the drawdown in the well."

Using the above as a guide, well efficiency was determined by measuring the maximum head level on the outside of the well, Hmax, which was measured just outside of the well casing in the tank, and comparing it to the level of water in the well, Hwell. The ratio of Hwell/Hmax was done for all of the separate experiments and plotted relative to intake location, sand characteristics, and flow rate (Q).

Reynolds' Number and Water Velocity

Both inertial and viscous forces influence the flow of ground water. Passing through sediment, ground water nearly always moves as laminar flow, in which viscous forces predominate. Near wells, high fluid velocities can cause the flow to become turbulent, in which inertial forces predominate. A dimensionless ratio, Reynolds' number, is used to determine the mode of flow.

The Reynolds' number (Re) is the ratio of the inertial force on the fluid per unit length of flow relative to the viscous force on the fluid.

Re = inertial forces / viscous forces = $\upsilon d/\nu$,

where

υ = velocity $[LT^{-1}]$,

d = mean grain diameter [L],

ν = kinematic viscosity $[L^2T^{-1}]$.

There is general consensus, according to the Roscoe Moss Company's Handbook of Ground Water Development (1990), that the laminar flow regime breaks down somewhere in the range of Reynolds' numbers of 1 to 10. When this occurs, Darcy's law is no longer applicable. That book also reports the following (page17):

> "In practice, Darcy's law may be applied to flow conditions that exist when the Reynolds number is equal to or less than 10. Between 10 and 600-700 a state of partial turbulent flow is considered to exist, whereas above 600-700 fully turbulent flow is found."

Reynolds' numbers for the different experimental runs were determined using the above equation and are listed in Table 6 in Appendix 3. The values were calculated using an area for the screen of 0.486 m^2 and the mean grain size and porosity given at the end of Chapter 2. The Reynolds' numbers range between 5.0 and 27.6, this is the region in which inertial forces predominate. Only in the lower flow rates, 6.3 L/s to 9.5 L/s, are the 16-30 sand with in the transition zone of Reynolds' numbers 1-10. Only the lowest flow rate for the 12-20 sand, 6.3 L/s, is a value with in this zone. The majority of experiments with the 12-20 sand and half the experiments using the 16-30 sand are in the region of Reynolds' number values in which inertial forces dominate flow in relation to viscous forces causing turbulent flow. This turbulent flow causes Darcy's Law to be invalid. The higher flow rates, and possibly all flow rates, as it is not known exactly which value of Reynolds number represents the transition in each particular case, are in transition from laminar to turbulent flow in which Darcy's Law is not valid.

The invalidity of Darcy's Law at these flow rates makes it inappropriate to draw flow nets using data such as shown on Figure 2. It has been suggested by Freeze and Cherry (1979) that a more general form of the porous media flow law might be:

$$\nu = - K (dL/dh)^m$$

If $m = 1$, the porous media flow law becomes Darcy's equation.

If $m \neq 1$, Darcy's equation is not valid and flow nets can not be used to estimate flow rates. However, it is still true that water flows in the direction of decreasing gradient. Flow direction can then be inferred from head data, knowing that water flows in the direction of decreasing head. The existence of doubt with regards to the validity of Darcy's law with respect to this case due to the confusion with as to what types of conditions, laminar or turbulent, prevail at a microscopic level are unanswerable with the model in which the experiments were conducted. What is known, however is that the results are reproducible to a level such that the data are of a quality that would indicate the model results are valid.

CHAPTER 4

RESULTS AND DISCUSSION

Experimental Reproducibility

My hypothesis is that the flow through a well screen in an unconfined homogeneous aquifer is concentrated near the pump intake. Establishing this fact is only possible if the experimental accuracy is shown to be great enough to eliminate the potential for background noise. Subtracting the results of individual experiments having identical model conditions tested the accuracy of the model results. This was done for a low flow and a high flow experiment to obtain an idea of the accuracy at the flow extremes and to assure the validity of the results between these extremes. Both of these checks indicate that the model results are sufficiently precis to check my hypothesis.

The low flow experimental reproducibility check was done at a flow rate of 6.3 L/s (100 gpm) with the finer 16-30 sand and the 0.25-mm (0.010-in.) slot size. These low flow conditions and location of the intake will give the maximum sensitivity that can be expected from the piezometers. The intake was located at a position 0.63 m above the well base.

The high flow experimental reproducibility check was done at a flow rate of 15.8 L/s (250-gpm) with the coarser 12-20 sand and the 0.25-mm (0.010-in.) screen. Even though this is not the highest flow rate encountered during this investigation it was the highest flow rate obtainable with the shorter intake, which, for reasons explained below gave the greatest concern for accuracy. The intake was located in the pipe above the screened section of the well, 1.85 m above well base. The runs used for the reproducibility were taken at different times, with the complete standardization procedure described below. The two 12-20 sand reproducibility experimental runs at 15.8 L/s were taken on separate days. The two 6.3 L/s 16-30 sand reproducibility experimental runs were done on the same day with the first in the early morning and the second later in the night, to ensure that any time dependent factors were accounted for. The high degree of reproducibility associated with the well efficiency gives confidence in the validity the efficiency results and that the model represents the effects of a pumping well in a homogenous aquifer with different intake locations. These two experiments are shown in Figure 4. The low flow 0.63-m reproducibility experiment accuracy was ±0.010 m. The accuracy of the high flow 1.85-m intake experiment was ±0.015 m.

General Results and Observations

During the course of the experimental runs the hypothesis that the flow was concentrated around the intake was confirmed. This was only pronounced for higher flow rates and can be clearly seen by subtracting data sets using dynamic normalization. Figure 5 shows the effect of gradual increase in flow rates in a coupled system with 1.24-m intake data sets subtracted from 0.63-m

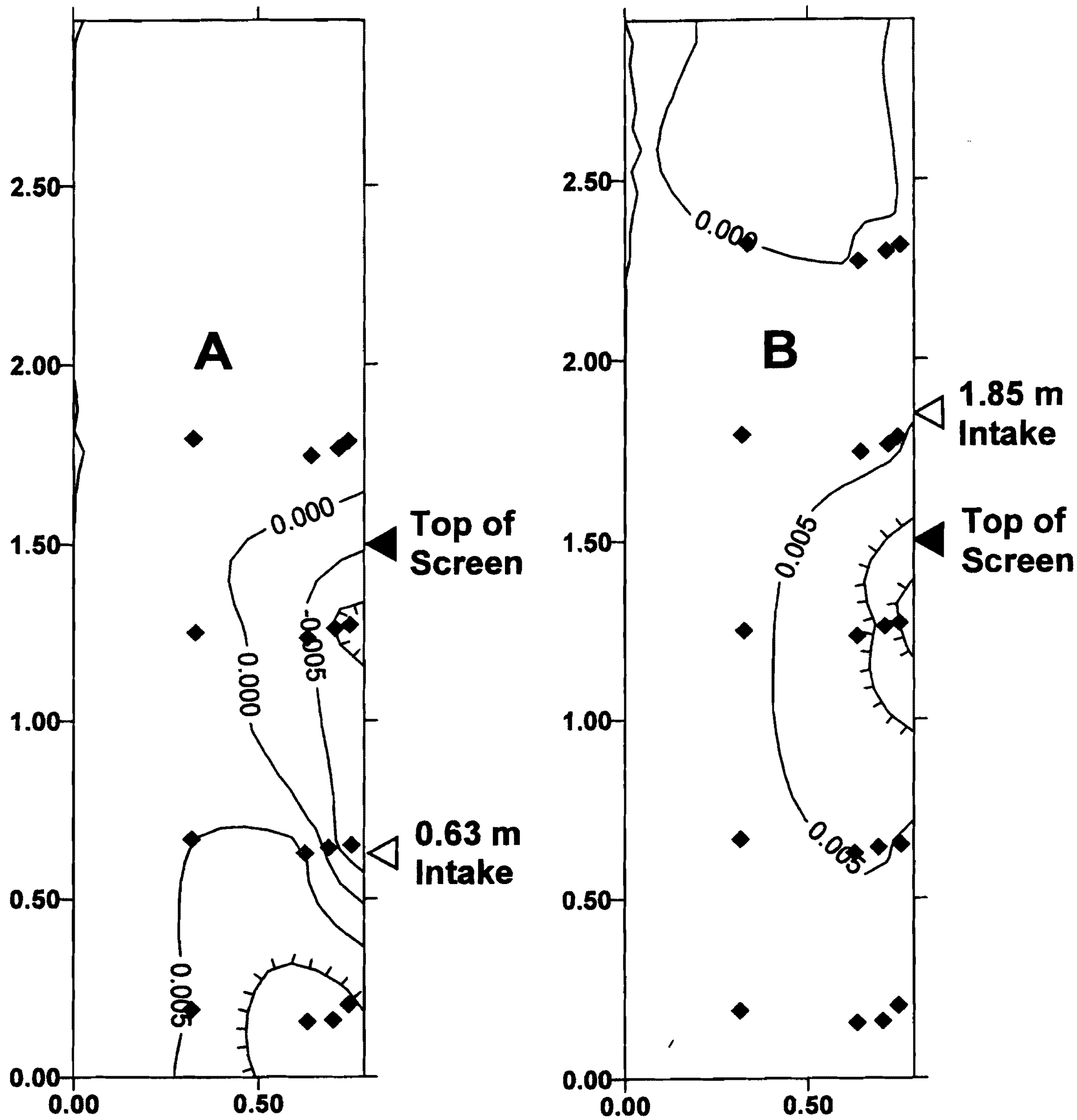

Figure 4. Results of reproducibility tests. A and B show the difference in data from duplicate runs, which show the noise that can be expected at these flow rates. "A" data sets taken at 6.3 L/s (100 gpm) using the 0.25 mm slot size (0.010 in.), the 16-30 sand, and the 0.63 m intake. "B" data sets taken at 15.8 L/s (250 gpm) using the 0.25 mm screen (0.010 in.), 12-20 sand, and the 1.85 m intake. Hachure points toward decreasing values.

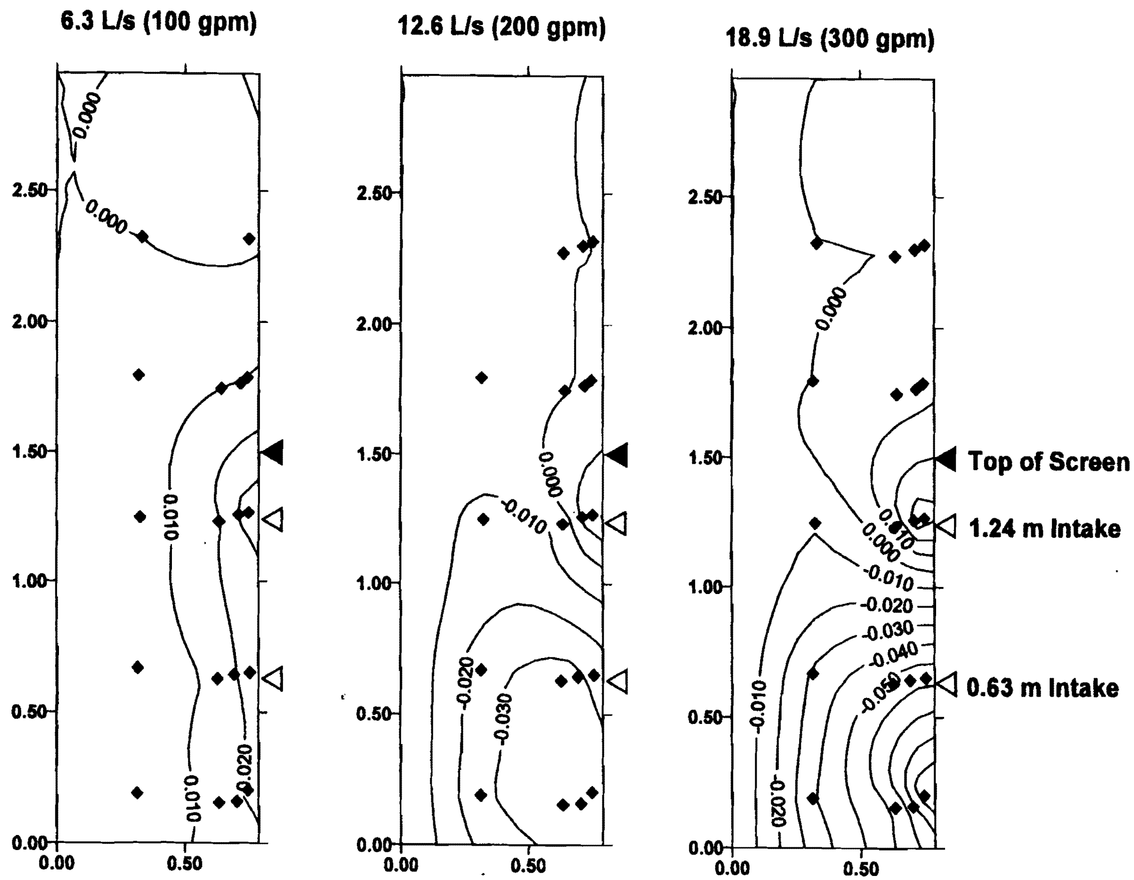

Figure 5. Progressively increasing importance of flow rate in causing non-horizontal flow conditions due to intake location for the 0.63m intake data set minus the 1.24 m data set for three flow rates, 6.3, 12.6, and 18.9 L/s using the 12-20 sand and 0.25mm slot size.

intake data sets. Other coupled systems show similar results (see Appendix 4 for additional Figures). Figure 5 provides graphical evidence that supports of my hypothesis. The results indicate that there is clearly not uniform horizontal flow through the well screen, although at low flows it approximates horizontal flow. This increased flow through the sections of well screen closest to the intake means that the sections of well screen closest to the intake contribute the most water to the well. This is true even when the intake is located above the well screen. Locating the intake above the well screen, however causes the greatest amount of water to flow through the well screen at its junction with the cased section of the well, as postulated by Von Hofe and Helweg (1998). This quite possibly creates the conditions that locating the intake in the casing of the well originally sought to avoid. Those conditions would be sand drive, causing a reduction in the hydraulic conductivity in the surrounding aquifer material, and sand pumping which destroys the pump itself.

Differences Between Intake Locations

The placement of the piezometer arrays has direct relationship to the quality of the data produced during experiments with different intake locations. Experiments with the 0.63 m and 1.24 m intake locations have data that provide much greater resolution than the 1.85 m intake experiments due to the positioning of the piezometer arrays close the actual intake. The 1.85 m intake, located 0.27 m above the screen, has its flow associated with the junction of the well screen with the non-screened upper section. This region lies between piezometer supports 2 and 3 (Figure 1) and zones of extreme heads may be missed. Information may be lacking with regard to the 1.24-m – 1.85-m plots given by the piezometer data, but the well efficiency results provide a indication that they are similar to that of the other intakes differences.

Discussion of Efficiency

Intake location was directly correlated to well efficiency. The efficiency differences between intake locations were more pronounced for the 0.63-m – 1.24-m runs, and the 0.63-m – 1.85-m runs than between the 1.24-m – 1.85-m runs. (Figures 6 – 9). (Appendix 5 provides tabulated results).

The efficiency is greater with screens having greater area. This can be seen in the figures noted above. This results from the fact that to deliver the same amount of water through smaller screen areas requires higher flow velocities, which result in greater friction losses and lower well efficiencies.

Lower flow rates resulted in greater efficiency for any given configuration of well model. This can be seen in (Figures 6 – 9). The greater efficiency is caused by the lower flow rates within the screen, resulting in less friction losses.

At any flow rate, the 0.63-m intake, the one farthest in the well screen, gives the greatest efficiency. The 0.63-m intake has the greatest well screen area in its immediate vicinity. Although the greatest flow comes from the area of the well screen closest to the intake, significant flow also comes from regions of

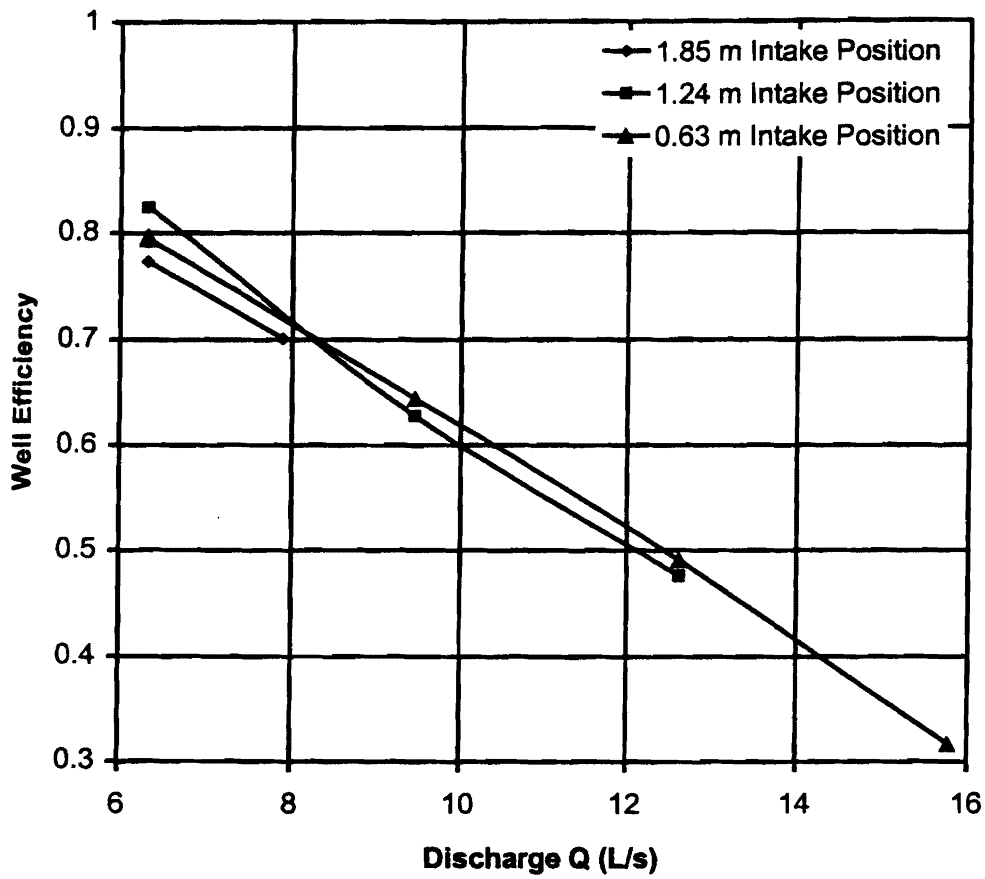

Figure 6. Well efficiencies for 16-30 sand and 0.25-mm slot size showing the relative efficiencies for different flow rates for the 1.85-m, 1.24-m, and 0.63-m intake positions.

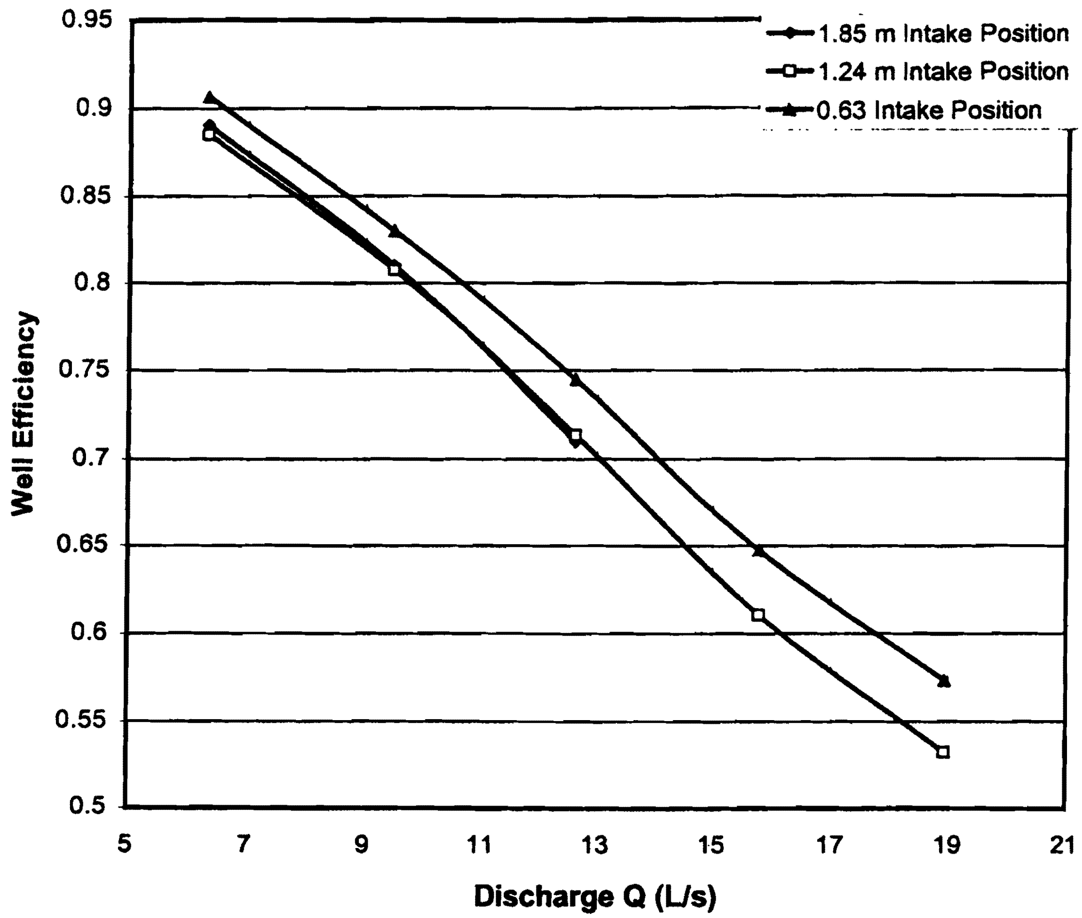

Figure 7. Well efficiencies for 12-20 sand and 0.25-mm slot size showing the relative efficiencies for different flow rates for the 1.85-m, 1.24-m, and 0.63-m intake positions.

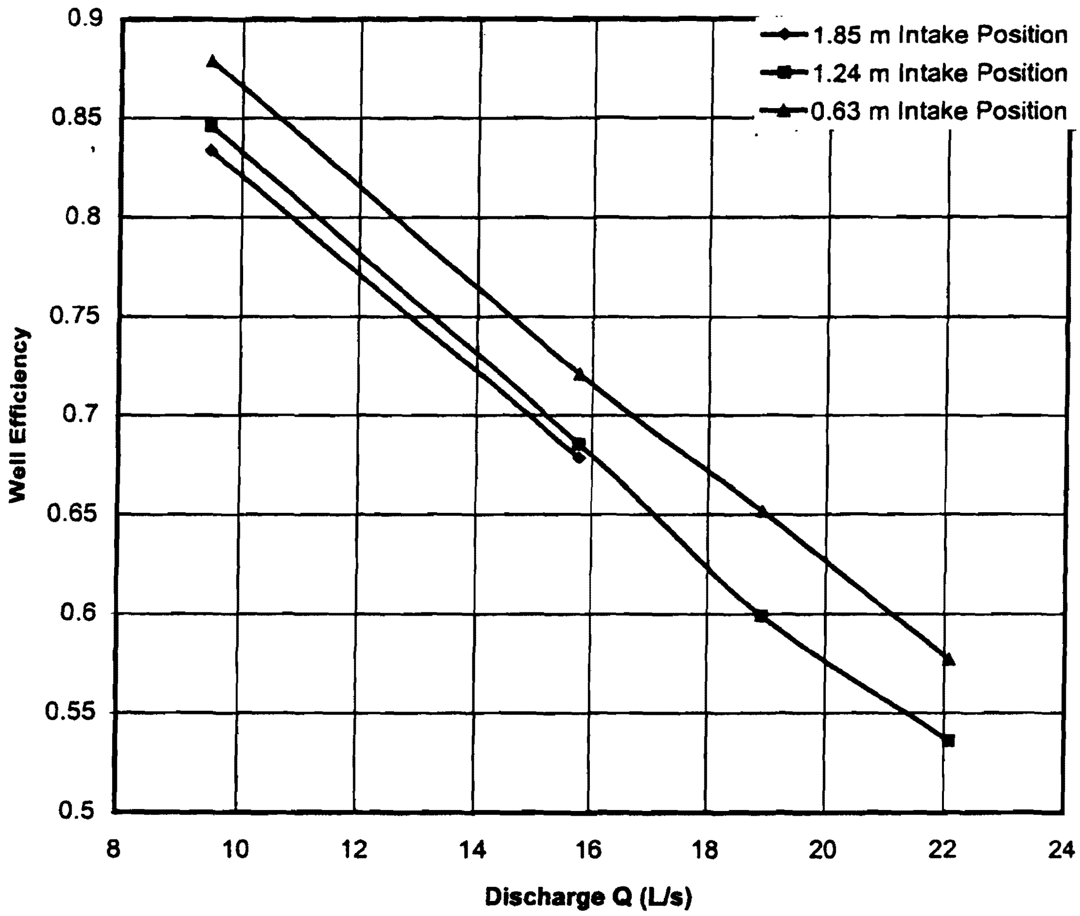

Figure 8. Well efficiencies for 12-20 sand and 0.51-mm slot size showing the relative efficiencies for different flow rates for the 1.85-m, 1.24-m, and 0.63-m intake positions.

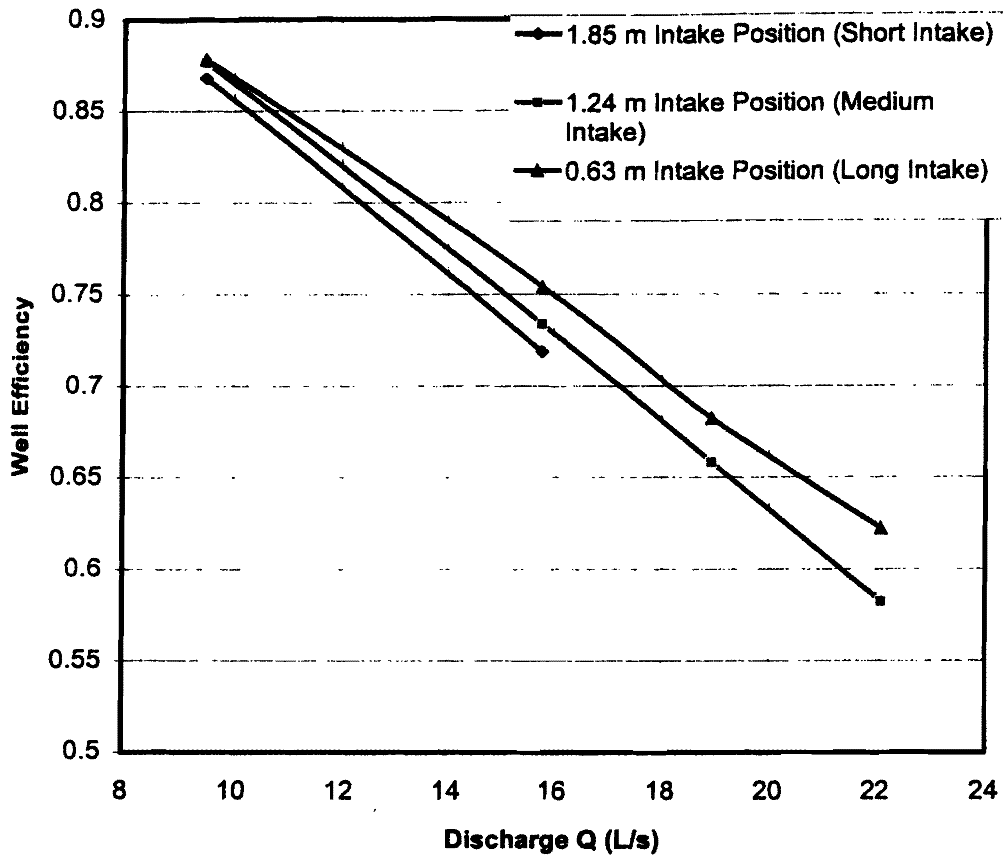

Figure 9. Well efficiencies for 12-20 sand and 0.76-mm slot size showing the relative efficiencies for different flow rates for the 1.85-m, 1.24-m, and 0.63-m intake positions.

the screen farther from the intake. This allows a lower average velocity for the screen and, more significantly, lower maximum velocity at the intake. This lower maximum velocity allows for greater efficiency relative to other positions. For any flow rate, the 1.85-m intake, the one above the well screen, is the least efficient. This apparently results from concentration of flow in the screen at the junction of the well screen and the cased section of the well. The maximum flow will be greater than for any other location of the intake (Von Hofe and Helweg 1998).

The efficiency of the 1.24-m intake which was in the well screen, but not far (-0.34 m) from its top, fell between the 1.85 m and the 0.63 m intakes. This held true for all flow rates and screen area sizes except for the lowest flow rate, the smallest screen, and finest sand. For this run the 1.24 m intake was slightly more efficient.

Differential Velocity

The differential velocity in separate sections of the well screen is the most likely cause of the direct near linear relationship between increased flow rates and lower efficiencies. At higher flow rates water is entering the well at high velocity near the pump intake, resulting in kinetic energy loss as the water enters the screen. The faster the water is moving into well screen the more energy has to be put into the system to move the water at that higher rate. Recall that it was not possible to measure velocity directly with the well model and that the velocity had to be inferred using the data from the models piezometers. It will not be possible to determine the true extent of the energy loss in production wells due to differential well screen velocity differences until the velocity can be measured directly at the small enough interval to determine the velocity profile. At this time the well efficiency results provide an excellent proxy for the magnitude of the energy losses.

CHAPTER 5

CONCLUSIONS

For the experiments done in this study, flow through well screens was concentrated around the pump intake. The assumption made in current well design of uniform entrance velocity along the length of a well screen is patently false.

Von Hofe and Helweg (1998) using a computer model were able to mathematically show the difference between locating the intake within the screen section and above it. This thesis confirms through physical experimentation the observations provide by VonHofe and Helwegs numeric modeling.

A critical aspect of well design is to reduce the entrance velocity of water into the well. The previous works hinting at non-uniform well screen entrance velocity suggests that some intake locations are superior to others. This is revealed in the higher efficiencies associated with some intake locations relative to others. Now that it is known that locating the intake above the screened section of the well maximizes the entrance velocity, wells can be designed to take that into account.

The magnitude of the preferential flow around the pump intake was directly correlated with the magnitude of the pumping rate. Higher pumping rates are less efficient than lower pumping rates regardless of screen, sand, and intake location. Pump intakes located farther within the well screen are more efficient than intakes, which are located inside the cased section of the well, or near the beginning of the casing. The larger the open area of a well screen open area, the more efficient flow will be through that well screen, but it would also be more susceptible to sand drive or sand pumping.

APPENDICES

APPENDIX 1

Part A

Piezometer Readings for Experimental Runs with 010 Slot Size and 12-20 Sand

Slot size 0.254 mm (.010 inches)   Intake location 1.85 m   Sand Size 12-20

Pumping rate 6.3 L/s (100 GPM)   Water level in tank during pumping 2.934 m

Piezometer Readings (Run I.D. No. 10 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	2.917, 0.994
2	2.846, 0.970	2.845, 0.970	2.843, 0.969	2.884, 0.983
3	2.684, 0.915	2.714, 0.925	2.761, 0.941	2.849, 0.971
4	2.681, 0.914	2.716, 0.926	2.747, 0.936	2.829, 0.964
5	2.689, 0.916	2.708, 0.923	2.743, 0.935	2.820, 0.961

Slot size 0.254 mm (.010 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.934 m

Piezometer Readings (Run I.D. No. 11 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	2.890, 0.985	Not Recorded
2	2.787, 0.950	2.784, 0.949	2.781, 0.948	2.845, 0.970
3	2.514, 0.857	2.566, 0.875	2.645, 0.901	2.785, 0.949
4	2.507, 0.854	2.567, 0.875	2.618, 0.892	2.750, 0.937
5	2.522, 0.860	2.553, 0.870	2.610, 0.890	2.731, 0.931

Slot size 0.254 mm (.010 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 12.6 L/s (200 GPM) Water level in tank during pumping 2.934 m

Piezometer Readings (Run I.D. No. 12 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.872, 0.979	2.870, 0.978	2.880, 0.982	2.887, 0.984
2	2.724, 0.928	2.721, 0.927	2.717, 0.926	2.805, 0.956
3	2.326, 0.793	2.406, 0.820	2.520, 0.859	2.715, 0.926
4	2.307, 0.786	2.399, 0.818	2.472, 0.843	2.657, 0.906
5	2.329, 0.794	2.375, 0.810	2.456, 0.837	2.627, 0.895

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 6.3 L/s (100 GPM) Water level in tank during pumping 2.937 m

Piezometer Readings (Run I.D. No. 13 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.915, 0.9925	Not Recorded	Not Recorded	2.923, 0.9952
2	2.844, 0.9683	2.842, 0.9677	2.841, 0.9673	2.884, 0.9820
3	2.670, 0.9091	2.702, 0.9200	2.750, 0.9363	2.845, 0.9687
4	2.661, 0.9060	2.697, 0.9183	2.730, 0.9295	2.823, 0.9612
5	2.669, 0.9088	2.691, 0.9162	2.726, 0.9282	2.812, 0.9574

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.937 m

Piezometer Readings (Run I.D. No. 14 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	Not Recorded
2	2.786, 0.949	2.783, 0.948	2.781, 0.947	2.847, 0.969
3	2.503, 0.852	2.553, 0.869	2.634, 0.897	2.780, 0.947
4	2.486, 0.846	2.546, 0.867	2.599, 0.885	2.741, 0.933
5	2.500, 0.851	2.533, 0.862	2.591, 0.882	2.723, 0.927

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 12.6 L/s (200 GPM) Water level in tank during pumping 2.938 m

Piezometer Readings (Run I.D. No. 15 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.882, 0.981	2.879, 0.980	2.876, 0.979	Not Recorded
2	2.727, 0.928	2.724, 0.927	2.719, 0.925	2.809, 0.956
3	2.321, 0.790	2.394, 0.815	2.510, 0.854	2.712, 0.923
4	2.288, 0.779	2.378, 0.809	2.454, 0.835	2.651, 0.902
5	2.307, 0.785	2.355, 0.802	2.440, 0.830	2.621, 0.892

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.938 m

Piezometer Readings (Run I.D. No. 16 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.862, 0.974	2.858, 0.973	2.853, 0.971	2.879, 0.980
2	2.658, 0.905	2.656, 0.904	2.648, 0.901	2.765, 0.941
3	2.089, 0.711	2.199, 0.749	2.360, 0.803	2.630, 0.895
4	2.062, 0.702	2.186, 0.744	2.288, 0.779	2.543, 0.866
5	2.087, 0.710	2.153, 0.733	2.268, 0.772	2.503, 0.852

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 18.9 L/s (300 GPM) Water level in tank during pumping 2.938 m

Piezometer Readings (Run I.D. No. 17 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.845, 0.968	2.842, 0.967	2.836, 0.965	2.867, 0.976
2	2.609, 0.888	2.605, 0.887	2.598, 0.884	2.734, 0.931
3	1.937, 0.659	2.045, 0.696	2.246, 0.764	2.570, 0.875
4	1.905, 0.648	2.043, 0.695	2.165, 0.737	2.462, 0.838
5	1.949, 0.663	2.007, 0.683	2.142, 0.729	2.412, 0.821

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 6.3 L/s (100 GPM) Water level in tank during pumping 2.929 m

Piezometer Readings (Run I.D. No. 18 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.941, 1.004	2.940, 1.004	2.939, 1.003	2.939, 1.008
2	2.882, 0.984	2.880, 0.983	2.879, 0.983	2.916, 0.996
3	2.735, 0.934	2.760, 0.942	2.796, 0.955	2.878, 0.983
4	2.714, 0.927	2.744, 0.937	2.770, 0.946	2.854, 0.974
5	2.719, 0.928	2.737, 0.934	2.766, 0.944	2.845, 0.971

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.934 m

Piezometer Readings (Run I.D. No. 19 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	Not Recorded
2	2.823, 0.962	2.820, 0.961	2.818, 0.960	2.879, 0.981
3	2.564, 0.874	2.607, 0.889	2.670, 0.910	2.807, 0.957
4	2.517, 0.858	2.567, 0.875	2.618, 0.892	2.760, 0.941
5	2.524, 0.860	2.555, 0.871	2.609, 0.889	2.741, 0.934

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 12.6 L/s (200 GPM) Water level in tank during pumping 2.924 m

Piezometer Readings (Run I.D. No. 20 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.915, 0.997	2.912, 0.996	2.908, 0.995	Not Recorded
2	2.761, 0.944	2.757, 0.943	2.752, 0.941	2.838, 0.971
3	2.376, 0.813	2.438, 0.834	2.535, 0.867	2.731, 0.934
4	2.296, 0.785	2.376, 0.813	2.452, 0.838	2.657, 0.908
5	2.308, 0.789	2.355, 0.805	2.437, 0.833	2.626, 0.898

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.935 m

Piezometer Readings (Run I.D. No. 21 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.902, 0.989	2.898, 0.987	2.893, 0.986	2.915, 0.993
2	2.702, 0.921	2.698, 0.919	2.691, 0.917	2.801, 0.954
3	2.182, 0.743	2.268, 0.773	2.402, 0.818	2.657, 0.905
4	2.066, 0.704	2.183, 0.744	2.285, 0.779	2.553, 0.870
5	2.083, 0.710	2.150, 0.733	2.261, 0.770	2.508, 0.855

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 18.9 L/s (300 GPM) Water level in tank during pumping 2.940 m

Piezometer Readings (Run I.D. No. 22 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.893, 0.984	2.888, 0.982	2.877, 0.979	2.908, 0.989
2	2.657, 0.904	2.652, 0.902	2.644, 0.899	2.775, 0.944
3	Not Recorded	2.125, 0.723	2.294, 0.780	2.601, 0.885
4	Not Recorded	2.027, 0.689	2.154, 0.733	2.471, 0.840
5	1.886, 0.641	1.975, 0.672	2.122, 0.722	2.414, 0.821

APPENDIX 1

Part B

Piezometer Readings for Experimental Runs with 010 Slot Size and 16-30 Sand

Slot size 0.254 mm (.010 inches) Intake location 1.85 m Sand Size 16-30

Pumping rate 6.3 L/s (100 GPM) Water level in tank during pumping 2.942 m

Piezometer Readings (Run I.D. No. 1 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.878, 0.978	2.875, 0.977	2.873, 0.977	2.885, 0.981
2	2.746, 0.933	2.751, 0.935	2.746, 0.933	2.818, 0.958
3	2.414, 0.821	2.478, 0.842	2.568, 0.873	2.744, 0.933
4	2.374, 0.807	2.482, 0.844	2.554, 0.868	2.730, 0.928
5	2.439, 0.829	2.475, 0.841	2.547, 0.866	2.709, 0.921

Slot size 0.254 mm (.010 inches) Intake location 1.85 m Sand Size 16-30

Pumping rate 7.9 L/s (125 GPM) Water level in tank during pumping 2.945 m

Piezometer Readings (Run I.D. No. 2 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.867, 0.974	2.865, 0.973	2.862, 0.972	2.857, 0.970
2	2.707, 0.919	2.713, 0.921	2.707, 0.919	2.796, 0.949
3	2.283, 0.775	2.370, 0.805	2.485, 0.844	2.704, 0.918
4	2.223, 0.755	2.369, 0.804	2.459, 0.835	2.680, 0.910
5	2.302, 0.782	2.348, 0.797	2.442, 0.829	2.648, 0.899

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 16-30

Pumping rate 6.3 L/s (100 GPM) Water level in tank during pumping 2.942 m

Piezometer Readings (Run I.D. No. 3 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.881, 0.979	2.879, 0.979	2.878, 0.978	Not Recorded
2	2.729, 0.928	2.736, 0.930	2.730, 0.928	2.817, 0.958
3	2.393, 0.813	2.453, 0.834	2.531, 0.860	2.724, 0.926
4	2.349, 0.798	2.443, 0.830	2.507, 0.852	2.697, 0.917
5	2.406, 0.818	2.439, 0.829	2.509, 0.853	2.679, 0.911

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 16-30

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.945 m

Piezometer Readings (Run I.D. No. 4 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.848, 0.967	2.845, 0.966	2.841, 0.965	2.868, 0.974
2	2.618, 0.889	2.627, 0.892	2.618, 0.889	2.748, 0.933
3	2.093, 0.711	2.184, 0.742	2.309, 0.784	2.603, 0.884
4	2.010, 0.683	2.157, 0.732	2.255, 0.766	2.547, 0.865
5	2.096, 0.712	2.147, 0.729	2.253, 0.765	2.513, 0.853

Slot size 0.254 mm (.010 inches) Intake location 1.24 m Sand Size 16-30

Pumping rate 12.6 L/s (200 GPM) Water level in tank during pumping 2.954m

Piezometer Readings (Run I.D. No. 5 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.815, 0.953	2.809, 0.951	2.805, 0.949	2.843, 0.962
2	2.513, 0.851	2.525, 0.855	2.512, 0.850	2.682, 0.908
3	1.746, 0.591	1.889, 0.639	2.074, 0.702	2.483, 0.840
4	1.626, 0.550	1.854, 0.628	1.973, 0.668	2.423, 0.820
5	1.772, 0.600	1.835, 0.621	Not Recorded	2.323, 0.786

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 16-30

Pumping rate 6.3 L/s (100 GPM [b]) Water level in tank during pumping 2.945 m

Piezometer Readings (Run I.D. No. 6* Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.877, 0.977	2.876, 0.977	2.873, 0.976	Not Recorded
2	2.758, 0.937	2.763, 0.938	2.758, 0.937	2.827, 0.960
3	2.470, 0.839	2.526, 0.858	2.597, 0.882	2.756, 0.936
4	2.423, 0.823	2.512, 0.853	2.569, 0.872	2.737, 0.929
5	2.464, 0.837	2.494, 0.847	2.555, 0.868	2.718, 0.923

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 16-30

Pumping rate 6.3 L/s (100 GPM [a]) Water level in tank during pumping 2.967 m

Piezometer Readings (Run I.D. No. 6* Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	Not Recorded
2	2.773, 0.934	2.777, 0.936	2.772, 0.934	2.837, 0.956
3	2.468, 0.832	2.524, 0.851	2.605, 0.878	2.767, 0.933
4	2.423, 0.817	2.520, 0.849	2.586, 0.872	2.752, 0.928
5	2.485, 0.838	2.516, 0.848	2.580, 0.870	2.733, 0.921

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 16-30

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.945 m

Piezometer Readings (Run I.D. No. 7 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.846, 0.966	2.842, 0.965	2.839, 0.964	2.864, 0.973
2	2.640, 0.897	2.649, 0.899	2.641, 0.897	2.754, 0.935
3	2.139, 0.726	2.238, 0.760	2.362, 0.802	2.628, 0.892
4	2.035, 0.691	2.196, 0.746	2.234, 0.779	2.574, 0.874
5	2.109, 0.716	2.161, 0.734	2.273, 0.772	2.531, 0.860

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 16-30

Pumping rate 12.6 L/s (200 GPM) Water level in tank during pumping 2.954 m

Piezometer Readings (Run I.D. No. 8 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.816, 0.953	2.810, 0.951	2.807, 0.950	2.843, 0.962
2	2.537, 0.859	2.549, 0.863	2.537, 0.859	2.690, 0.910
3	1.791, 0.606	1.915, 0.648	2.123, 0.719	2.506, 0.848
4	1.638, 0.555	1.873, 0.634	2.021, 0.684	2.404, 0.814
5	1.765, 0.598	1.838, 0.622	1.989, 0.673	2.340, 0.792

Slot size 0.254 mm (.010 inches) Intake location 0.63 m Sand Size 16-30

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.953 m

Piezometer Readings (Run I.D. No. 9 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.810, 0.952	2.804, 0.950	2.801, 0.949	2.840, 0.962
2	2.515, 0.852	2.527, 0.856	2.514, 0.851	2.671, 0.904
3	1.645, 0.557	1.797, 0.609	2.001, 0.678	2.440, 0.826
4	1.238, 0.419	1.556, 0.527	1.781, 0.603	2.308, 0.782
5	1.457, 0.494	1.530, 0.518	1.740, 0.589	2.163, 0.733

APPENDIX 1

Part C

Piezometer Readings for Experimental Runs with 020 Slot Size and 12-20 Sand

Slot size 0.508 mm (.020 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.946 m

Piezometer Readings (Run I.D. No. 23 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	Not Recorded
2	2.808, 0.953	2.807, 0.953	2.801, 0.951	2.863, 0.972
3	2.582, 0.876	2.611, 0.886	2.676, 0.908	2.807, 0.953
4	2.570, 0.872	2.615, 0.887	2.657, 0.902	2.777, 0.943
5	2.581, 0.876	2.610, 0.886	2.656, 0.901	2.765, 0.938

Slot size 0.508 mm (.020 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM[a]) Water level in tank during pumping 2.840 m

Piezometer Readings (Run I.D. No. 24* Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.813, 0.990	2.810, 0.990	2.806, 0.988	2.829, 0.996
2	2.658, 0.936	2.654, 0.935	2.647, 0.932	2.747, 0.967
3	2.262, 0.796	2.306, 0.812	2.426, 0.854	2.643, 0.930
4	2.215, 0.780	2.302, 0.811	2.380, 0.838	2.583, 0.909
5	2.235, 0.787	2.284, 0.804	2.367, 0.833	2.554, 0.899

Slot size 0.508 mm (.020 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM[b]) Water level in tank during pumping 2.946 m

Piezometer Readings (Run I.D. No. 24* Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.867, 0.973	2.863, 0.972	2.860, 0.971	2.883, 0.978
2	2.707, 0.919	2.704, 0.918	2.697, 0.915	2.798, 0.950
3	2.295, 0.779	2.352, 0.798	2.471, 0.838	2.693, 0.914
4	2.266, 0.769	2.349, 0.797	2.429, 0.824	2.633, 0.894
5	2.285, 0.776	2.336, 0.793	2.418, 0.821	2.604, 0.884

Slot size 0.508 mm (.020 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.896 m

Piezometer Readings (Run I.D. No. 25 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	Not Recorded
2	2.763, 0.954	2.761, 0.953	2.756, 0.952	2.819, 0.973
3	2.520, 0.870	2.547, 0.879	2.613, 0.902	2.754, 0.951
4	2.499, 0.863	2.545, 0.879	2.590, 0.894	2.721, 0.940
5	2.513, 0.868	2.542, 0.878	2.593, 0.895	2.709, 0.935

Slot size 0.508 mm (.020 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.897 m

Piezometer Readings (Run I.D. No. 26 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.833, 0.978	2.829, 0.977	2.825, 0.975	2.850, 0.984
2	2.664, 0.920	2.660, 0.918	2.651, 0.915	2.759, 0.952
3	2.218, 0.766	2.268, 0.783	2.391, 0.825	2.637, 0.910
4	2.176, 0.751	2.262, 0.781	2.344, 0.809	2.570, 0.887
5	2.203, 0.760	2.256, 0.779	2.343, 0.809	2.541, 0.877

Slot size 0.508 mm (.020 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 18.9 L/s (300 GPM) Water level in tank during pumping 2.899m

Piezometer Readings (Run I.D. No. 27 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.815, 0.971	2.809, 0.969	2.806, 0.968	2.833, 0.977
2	2.606, 0.899	2.602, 0.898	2.592, 0.894	2.722, 0.939
3	2.039, 0.703	2.108, 0.727	2.265, 0.781	2.571, 0.887
4	1.994, 0.688	2.102, 0.725	2.204, 0.760	2.481, 0.856
5	2.028, 0.700	2.093, 0.722	2.201, 0.759	2.443, 0.843

Slot size 0.508 mm (.020 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 22.1 L/s (350 GPM) Water level in tank during pumping 2.902 m

Piezometer Readings (Run I.D. No. 28 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.803, 0.966	2.798, 0.964	2.793, 0.962	2.824, 0.973
2	2.568, 0.885	2.563, 0.883	2.551, 0.879	2.698, 0.930
3	1.915, 0.660	1.995, 0.687	2.182, 0.752	2.524, 0.870
4	1.872, 0.645	1.989, 0.685	2.110, 0.727	2.422, 0.835
5	1.910, 0.658	1.980, 0.682	2.103, 0.725	2.375, 0.818

Slot size 0.508 mm (.020 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.883 m

Piezometer Readings (Run I.D. No. 29 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	Not Recorded
2	2.782, 0.965	2.780, 0.964	2.777, 0.963	2.826, 0.980
3	2.581, 0.895	2.605, 0.904	2.656, 0.921	2.769, 0.960
4	2.537, 0.880	2.579, 0.895	2.617, 0.908	2.732, 0.948
5	2.547, 0.883	2.570, 0.891	2.612, 0.906	2.715, 0.942

Slot size 0.508 mm (.020 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.883 m

Piezometer Readings (Run I.D. No. 30 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.831, 0.982	2.827, 0.981	2.825, 0.980	2.842, 0.986
2	2.682, 0.930	2.680, 0.930	2.671, 0.926	2.763, 0.958
3	2.286, 0.793	2.332, 0.809	2.435, 0.845	2.646, 0.918
4	2.179, 0.756	2.267, 0.786	2.344, 0.813	2.564, 0.889
5	2.197, 0.762	2.246, 0.779	2.329, 0.808	2.527, 0.877

Slot size 0.508 mm (.020 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 18.9 L/s (300 GPM) Water level in tank during pumping 2.884 m

Piezometer Readings (Run I.D. No. 31 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.813, 0.975	2.808, 0.974	2.805, 0.973	2.829, 0.981
2	2.628, 0.911	2.625, 0.910	2.614, 0.906	2.727, 0.946
3	2.128, 0.738	2.187, 0.758	2.318, 0.804	2.581, 0.895
4	1.990, 0.690	2.105, 0.730	2.204, 0.764	2.474, 0.858
5	2.013, 0.698	2.112, 0.732	2.183, 0.757	2.425, 0.841

Slot size 0.54 mm (.020 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 22.1 L/s (350 GPM) Water level in tank during pumping 2.892 m

Piezometer Readings (Run I.D. No. 32 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.781, 0.962	2.776, 0.960	2.769, 0.957	2.771, 0.958
2	2.564, 0.887	2.559, 0.885	2.548, 0.881	2.678, 0.926
3	1.967, 0.680	2.045, 0.707	2.275, 0.787	2.508, 0.867
4	1.837, 0.635	1.951, 0.675	2.074, 0.717	2.384, 0.824
5	1.861, 0.643	1.937, 0.670	2.046, 0.707	2.325, 0.804

APPENDIX 1

Part D

Piezometer Readings for Experimental Runs with 030 Slot Size and 12-20 Sand

Slot size 0.762 mm (.030 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.869 m

Piezometer Readings (Run I.D. No. 33 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	Not Recorded	Not Recorded	Not Recorded	2.843, 0.991
2	2.766, 0.964	2.765, 0.964	2.765, 0.964	2.806, 0.978
3	2.602, 0.907	2.634, 0.918	2.682, 0.935	2.768, 0.965
4	2.582, 0.900	2.625, 0.915	2.657, 0.926	2.740, 0.955
5	2.584, 0.901	2.608, 0.909	2.647, 0.923	2.727, 0.951

Slot size 0.762 mm (.030 inches) Intake location 1.85 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.869 m

Piezometer Readings (Run I.D. No. 34 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.806, 0.978	2.803, 0.977	2.799, 0.976	2.819, 0.983
2	2.667, 0.930	2.664, 0.929	2.664, 0.929	2.739, 0.955
3	2.328, 0.811	2.394, 0.834	2.494, 0.869	2.653, 0.925
4	2.276, 0.793	2.366, 0.825	2.432, 0.848	2.592, 0.904
5	2.281, 0.795	2.331, 0.813	2.409, 0.840	2.563, 0.894

Slot size 0.762 mm (.030 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.875 m

Piezometer Readings (Run I.D. No. 35 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.864, 0.996	2.862, 0.995	2.857, 0.994	2.875, 1.000
2	2.791, 0.971	2.790, 0.970	2.789, 0.970	2.833, 0.985
3	2.616, 0.910	2.645, 0.920	2.693, 0.937	2.788, 0.970
4	2.599, 0.904	2.639, 0.918	2.672, 0.929	2.759, 0.960
5	2.607, 0.907	2.632, 0.915	2.668, 0.928	2.748, 0.956

Slot size 0.762 mm (.030 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.875 m

Piezometer Readings (Run I.D. No. 36 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.834, 0.986	2.832, 0.985	2.829, 0.984	Not Recorded
2	2.687, 0.935	2.683, 0.933	2.682, 0.933	2.762, 0.961
3	2.324, 0.808	2.384, 0.829	2.484, 0.864	2.666, 0.927
4	2.277, 0.792	2.363, 0.822	2.431, 0.846	2.603, 0.905
5	2.294, 0.798	2.345, 0.816	2.420, 0.842	2.576, 0.896

Slot size 0.762 mm (.030 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 18.9 L/s (300 GPM) Water level in tank during pumping 2.877 m

Piezometer Readings (Run I.D. No. 37 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.815, 0.978	2.813, 0.978	2.808, 0.976	2.831, 0.984
2	2.634, 0.916	2.629, 0.914	2.629, 0.914	2.727, 0.948
3	2.175, 0.756	2.253, 0.783	2.379, 0.827	2.602, 0.904
4	2.109, 0.733	2.219, 0.771	2.305, 0.801	2.516, 0.875
5	2.126, 0.739	2.191, 0.762	2.288, 0.795	2.480, 0.862

Slot size 0.762 mm (.030 inches) Intake location 1.24 m Sand Size 12-20

Pumping rate 22.1 L/s (350 GPM) Water level in tank during pumping 2.878 m

Piezometer Readings (Run I.D. No. 38 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.798, 0.972	2.794, 0.971	2.789, 0.969	2.818, 0.979
2	2.584, 0.898	2.578, 0.896	2.578, 0.896	2.693, 0.936
3	2.013, 0.699	2.115, 0.735	2.274, 0.790	2.539, 0.882
4	1.945, 0.676	2.080, 0.723	2.184, 0.759	2.433, 0.845
5	1.965, 0.683	2.044, 0.710	2.159, 0.750	2.387, 0.829

Slot size 0.762 mm (.030 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 9.5 L/s (150 GPM) Water level in tank during pumping 2.875 m

Piezometer Readings (Run I.D. No. 39 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.840, 0.988	2.837, 0.987	2.835, 0.986	2.852, 0.992
2	2.769, 0.963	2.767, 0.962	2.767, 0.962	2.808, 0.977
3	2.598, 0.904	2.630, 0.915	2.677, 0.931	2.766, 0.962
4	2.565, 0.892	2.609, 0.907	2.644, 0.920	2.735, 0.951
5	2.568, 0.893	2.594, 0.902	2.636, 0.917	2.736, 0.952

Slot size 0.762 mm (.030 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 15.8 L/s (250 GPM) Water level in tank during pumping 2.875 m

Piezometer Readings (Run I.D. No. 40 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.807, 0.976	2.805, 0.976	2.802, 0.975	Not Recorded
2	2.675, 0.930	2.671, 0.929	2.672, 0.929	2.731, 0.950
3	2.354, 0.819	2.411, 0.839	2.499, 0.869	2.654, 0.923
4	2.259, 0.786	2.350, 0.817	2.419, 0.841	2.588, 0.900
5	2.262, 0.787	2.315, 0.805	2.395, 0.833	2.555, 0.889

Slot size 0.762 mm (.030 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 18.9 L/s (300 GPM) Water level in tank during pumping 2.877 m

Piezometer Readings (Run I.D. No. 41 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.786, 0.968	2.784, 0.968	2.780, 0.966	2.802, 0.974
2	2.622, 0.911	2.618, 0.910	2.618, 0.910	2.706, 0.941
3	2.213, 0.769	2.286, 0.795	2.398, 0.834	2.589, 0.900
4	2.078, 0.722	2.198, 0.764	2.284, 0.794	2.495, 0.867
5	2.077, 0.722	2.146, 0.746	2.250, 0.782	2.450, 0.852

Slot size 0.762 mm (.030 inches) Intake location 0.63 m Sand Size 12-20

Pumping rate 22.1 L/s (350 GPM) Water level in tank during pumping 2.878 m

Piezometer Readings (Run I.D. No. 42 Korom et al., 2001 in review)

(Original in meters, Normalized to tank level)

Support	Piezometer 1	Piezometer 2	Piezometer 3	Piezometer 4
1	2.770, 0.962	2.767, 0.962	2.762, 0.960	2.790, 0.969
2	2.581, 0.897	2.576, 0.895	2.576, 0.895	2.682, 0.932
3	2.083, 0.724	2.177, 0.756	2.313, 0.804	2.536, 0.881
4	1.932, 0.671	2.075, 0.721	2.178, 0.757	2.422, 0.841
5	1.930, 0.671	2.012, 0.699	2.134, 0.741	2.366, 0.822

APPENDIX 2

Sand Sieve Analyses

Table 4. Sand Sieve Analysis for 16-30 Sand. (Colorado Silica Sand, Inc. 1996)

US SIEVE	Opening (inches)	Opening (mm)	Cumulative Wt. % Passing	Cumulative Wt. % Retained	Individual Wt. % Retained
16	0.0465	1.18	90-100	0-10	0-10
20	0.0335	0.85	23-66	24-77	34-67
25	0.0280	0.71	9-25	75-91	14-41
30	0.0236	0.60	0-10	90-100	9-15
35	0.0197	0.50	0-2	98-100	0-8
Pan	Pan				

Table 5. Sand Sieve Analysis for 12-20 Sand. (Colorado Silica Sand, Inc. 1996)

US SIEVE	Opening (inches)	Opening (mm)	Cumulative Wt. % Passing	Cumulative Wt. % Retained	Individual Wt. % Retained
12	0.0669	1.70	95-100	0-5	0-5
16	0.0465	1.18	13-45	55-87	55-82
18	0.0394	1.00	1-20	1-20	12-25
20	0.0335	0.85	0-5	0-5	1-15
30	0.0236	0.60	0-1	0-1	0-4
Pan	Pan				

Appendix 3

Parameters of Experimental Runs

Table 6. Parameters of experiments (runs) conducted, a and b denote multiple experiments at same model configuration. The data generated from these runs are in Appendix 1. Reynolds' numbers are in parenthesis next to the flow rate (Q) values.

Sand Size	Screen Slot Size	Intake Position	Q L/s (Re #)
16-30	0.25 mm	1.85 m	6.3 (5.0)
16-30	0.25 mm	1.85 m	7.9 (6.2)
16-30	0.25 mm	1.24 m	6.3 (5.0)
16-30	0.25 mm	1.24 m	9.5 (7.5)
16-30	0.25 mm	1.24 m	12.6 (9.9)
16-30a	0.25 mm	0.63 m	6.3 (5.0)
16-30b	0.25 mm	0.63 m	6.3 (5.0)
16-30	0.25 mm	0.63 m	9.5 (7.5)
16-30	0.25 mm	0.63 m	12.6 (9.9)
16-30	0.25 mm	0.63 m	15.8 (12.4)
12-20	0.25 mm	1.85 m	6.3 (7.9)
12-20	0.25 mm	1.85 m	9.5 (11.8)
12-20	0.25 mm	1.85 m	12.6 (15.7)
12-20	0.25 mm	1.24 m	6.3 (7.9)
12-20	0.25 mm	1.24 m	9.5 (11.8)
12-20	0.25 mm	1.24 m	12.6 (15.7)
12-20	0.25 mm	1.24 m	15.8 (19.7)
12-20	0.25 mm	1.24 m	18.9 (23.6)
12-20	0.25 mm	0.63 m	6.3 (7.9)
12-20	0.25 mm	0.63 m	9.5 (11.8)
12-20	0.25 mm	0.63 m	12.6 (15.7)
12-20	0.25 mm	0.63 m	15.8 (19.7)

12-20	0.25 mm	0.63 m	18.9 (23.6)
12-20	0.51 mm	1.85 m	9.5 (11.8)
12-20a	0.51 mm	1.85 m	15.8 (19.7)
12-20b	0.51 mm	1.85 m	15.8 (18.7)
12-20	0.51 mm	1.24 m	9.5 (11.8)
12-20	0.51 mm	1.24 m	15.8 (19.7)
12-20	0.51 mm	1.24 m	18.9 (23.6)
12-20	0.51 mm	1.24 m	22.1 (27.6)
12-20	0.51 mm	0.63 m	9.5 (11.8)
12-20	0.51 mm	0.63 m	15.8 (19.7)
12-20	0.51 mm	0.63 m	18.9 (23.6)
12-20	0.51 mm	0.63 m	22.1 (27.6)
12-20	0.76 mm	1.85 m	9.5 (11.8)
12-20	0.76 mm	1.85 m	15.8 (19.7)
12-20	0.76 mm	1.24 m	9.5 (11.8)
12-20	0.76 mm	1.24 m	15.8 (19.7)
12-20	0.76 mm	1.24 m	18.9 (23.6)
12-20	0.76 mm	1.24 m	22.1 (27.6)
12-20	0.76 mm	0.63 m	9.5 (11.8)
12-20	0.76 mm	0.63 m	15.8 (19.7)
12-20	0.76 mm	0.63 m	18.9 (23.6)
12-20	0.76 mm	0.63 m	22.1 (27.6)

Appendix 4

Plots of Piezometer Results

Notes

All contours are in meters, and set at 0.01 m. When needed hachures are used and point downslope. Appendix 4 contains all plots not included in the body of the text. If pz 1,4 is absent the pz 2,4 is used.

Figure 10. 0.25 mm Slot Size, 16-30 Sand, 1.85 m Intake - 1.24 m Intake at 6.3 L/s.

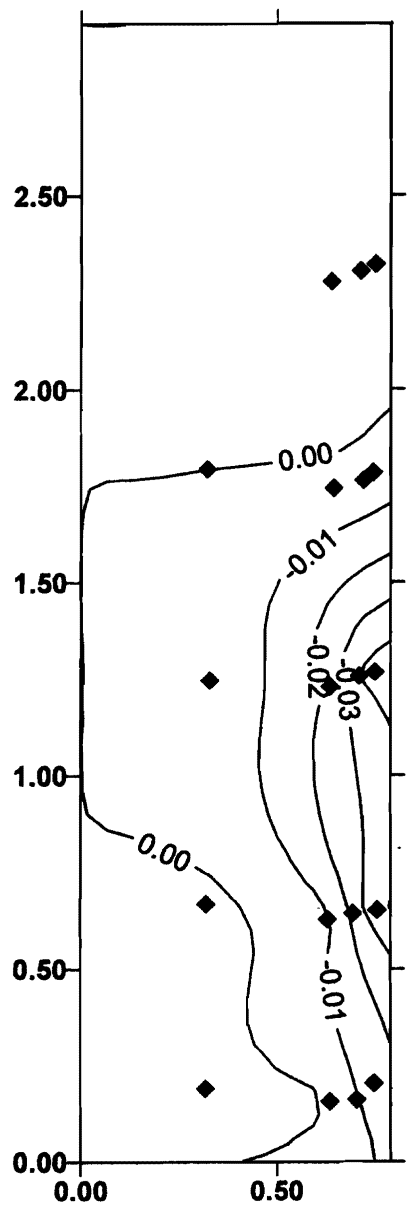

Figure 11. 0.25 mm Slot Size, 16-30 Sand, 1.85 m Intake - 0.63 m Intake at 6.3 L/s.

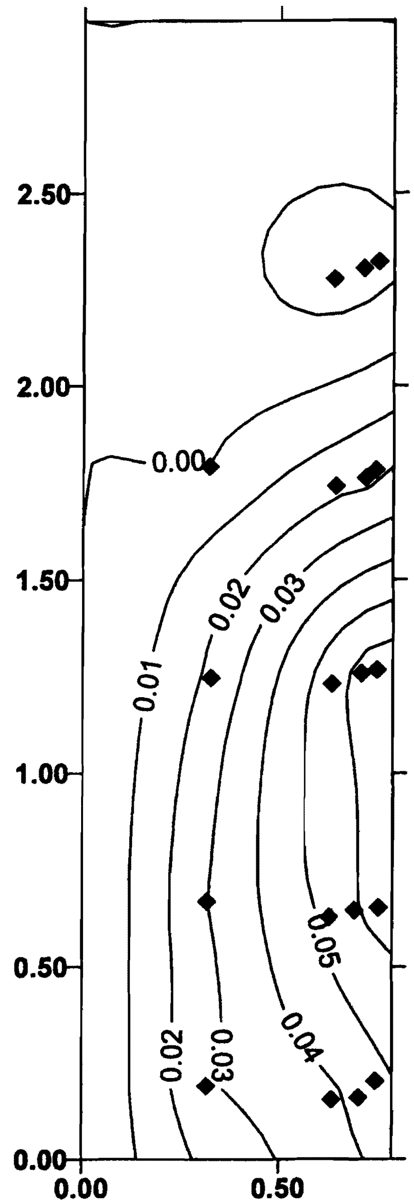

Figure 12. 025 mm Slot Size, 16-30 Sand, 0.63 m Intake - 1.24 m Intake at 6.3 L/s.

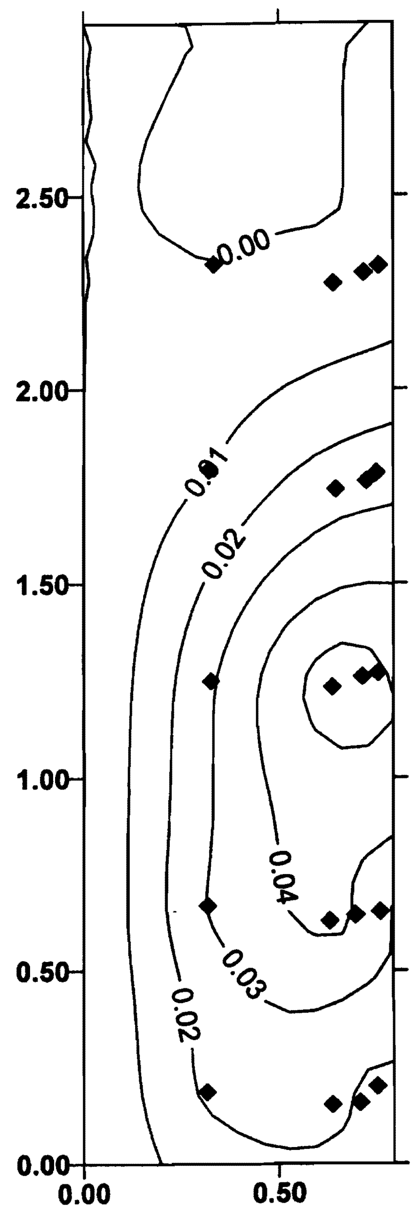

Figure 13. 0.25 mm Slot Size, 16-30 Sand, 0.63 m Intake - 1.24 m Intake at 9.5 L/s.

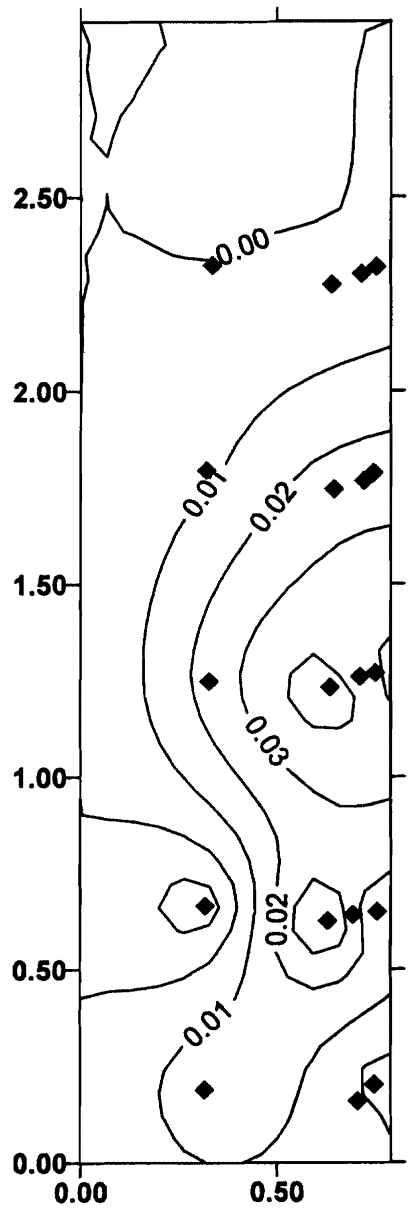

Figure 14. 0.25 mm Slot Size, 16-30 Sand, 0.63 m Intake - 1.24 m Intake at 12.6 L/s.

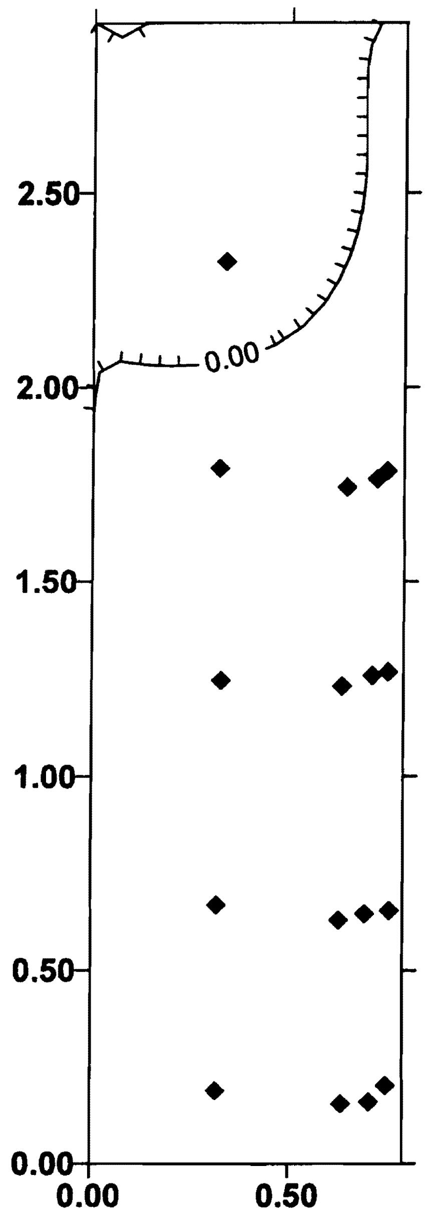

Figure 15. 0.25 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 6.3 L/s.

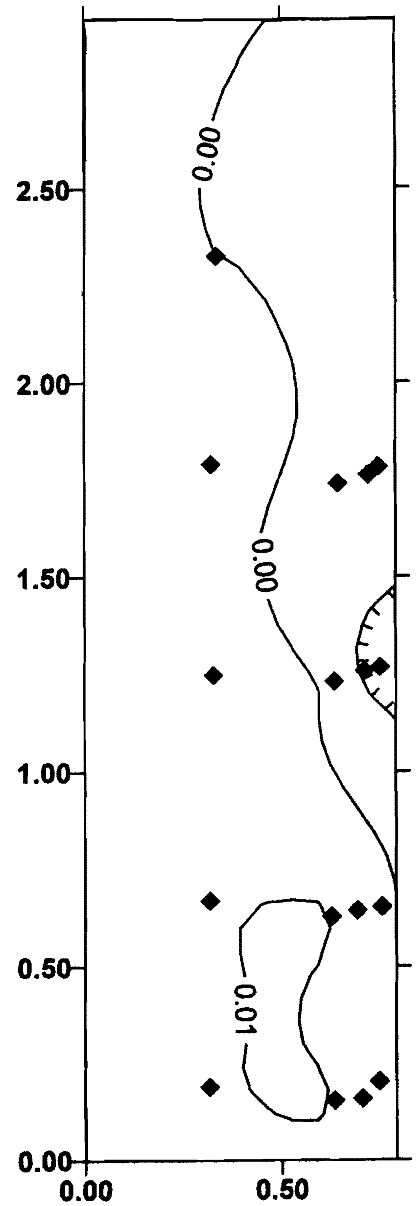

Figure 16. 0.25 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 6.3 L/s.

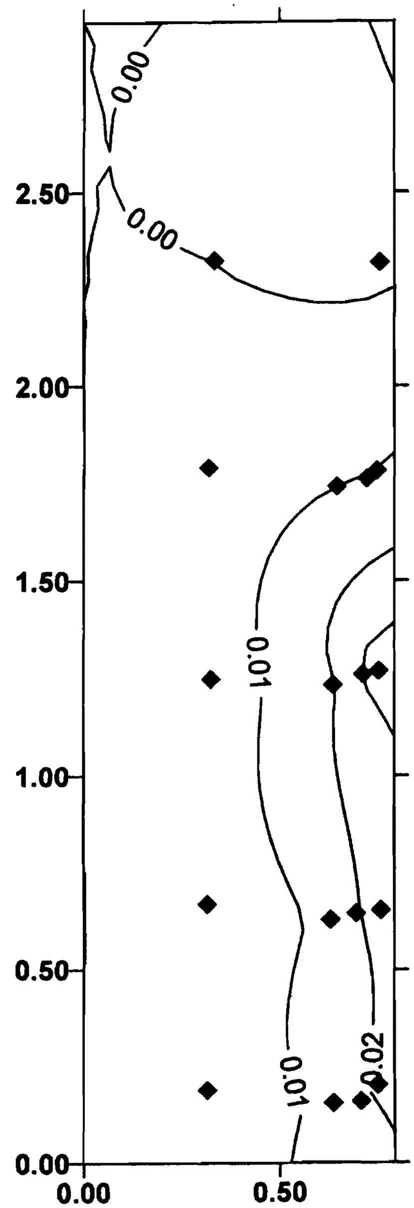

Figure 17. 0.25 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 6.3 L/s.

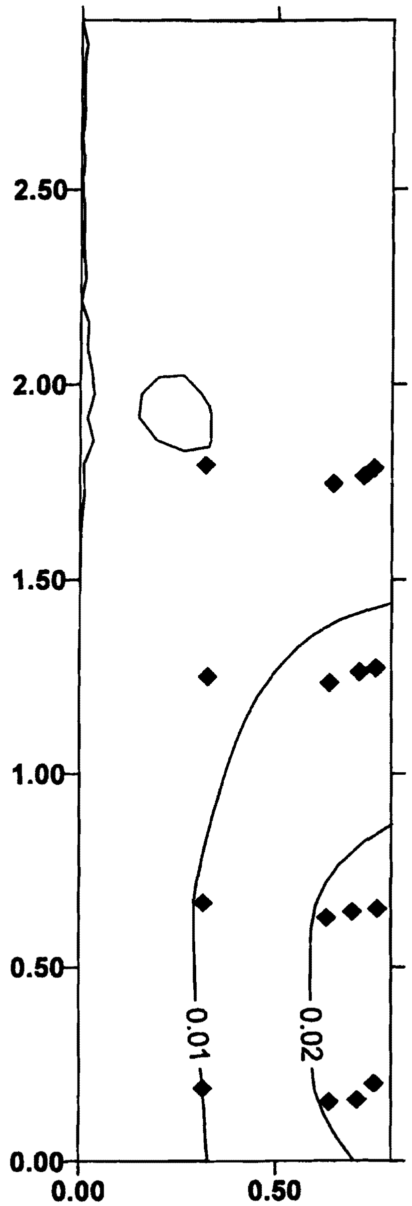

Figure 18. 0.25 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 9.5 L/s.

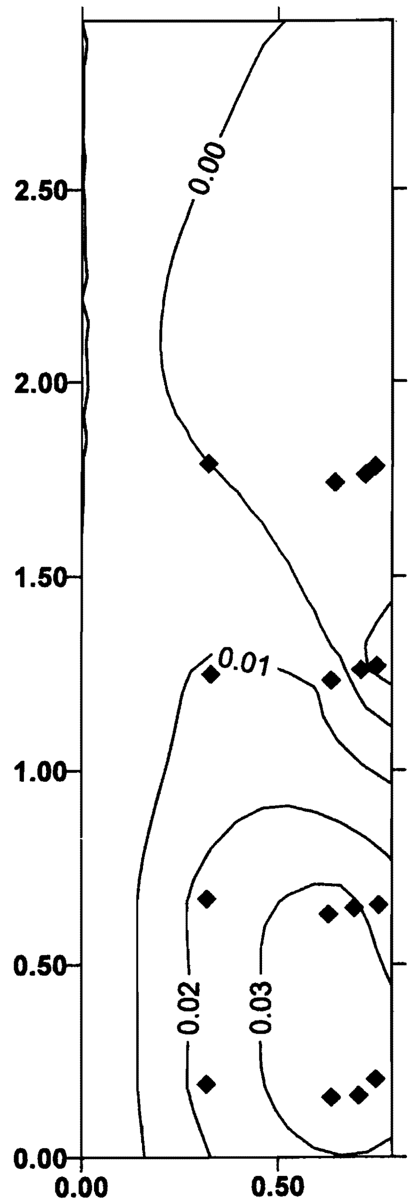

Figure 19. 0.25 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 9.5 L/s.

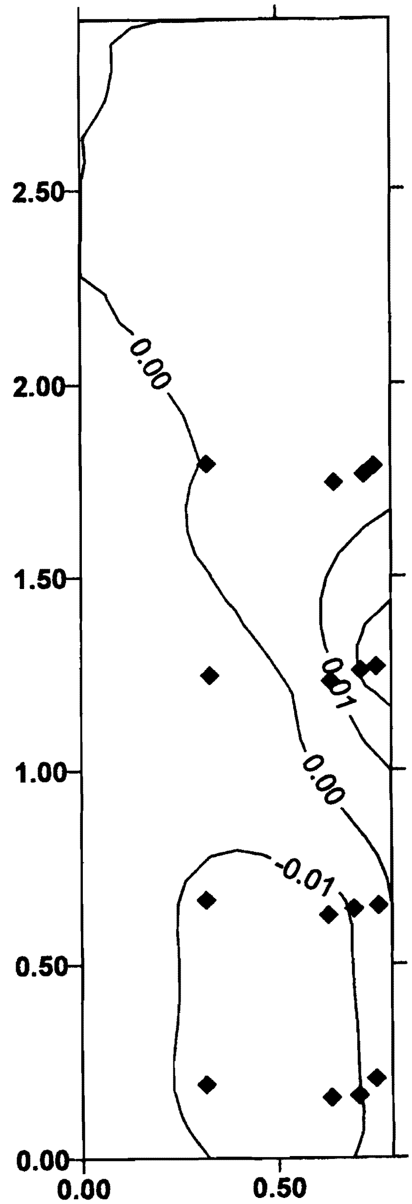

Figure 20. 0.25 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 9.5 L/s.

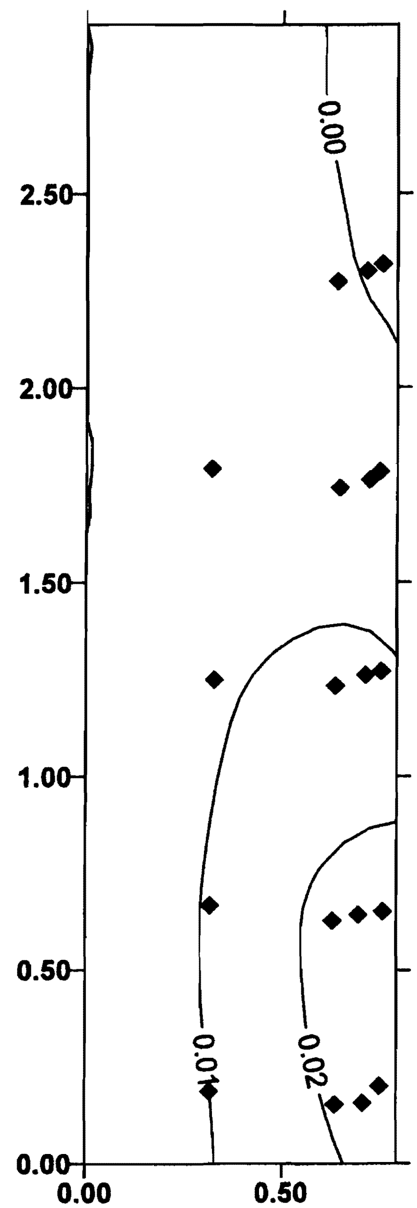

Figure 21. 0.25 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 12.6 L/s.

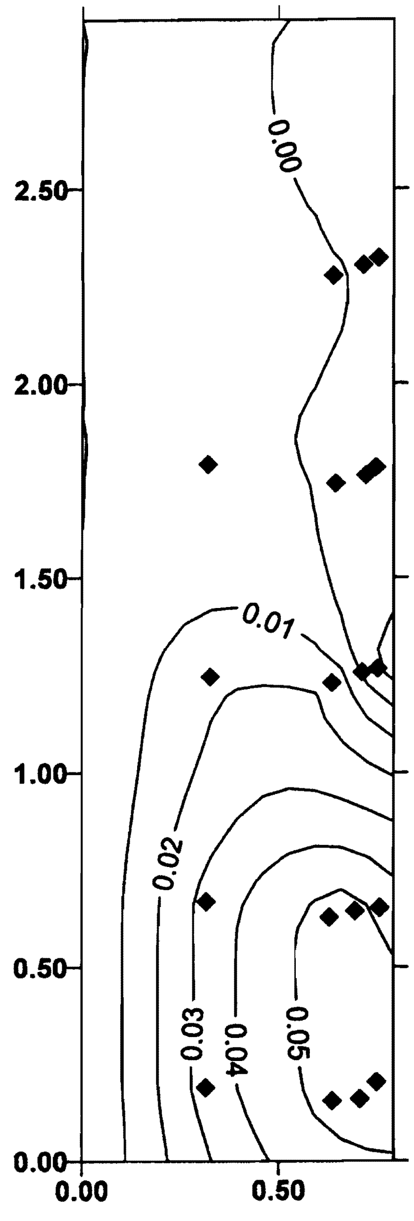

Figure 22. 0.25 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 12.6 L/s.

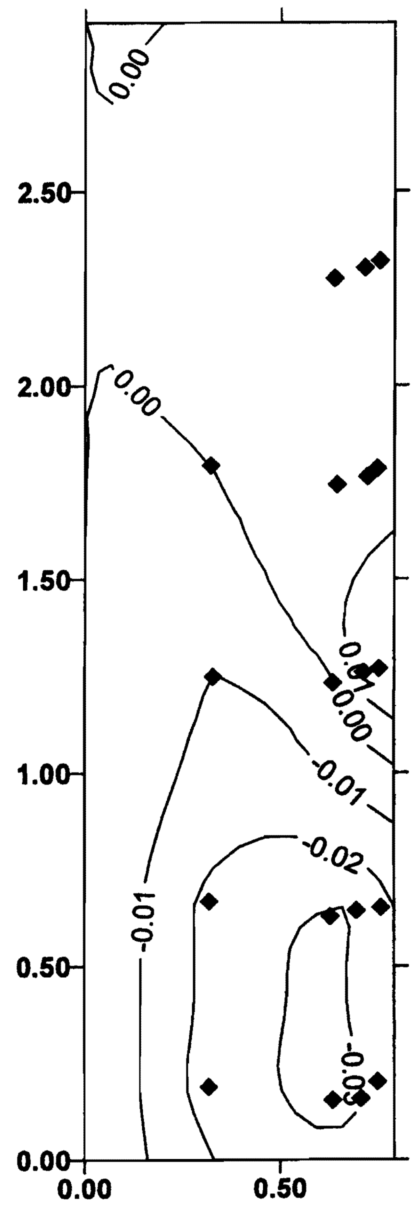

Figure 23. 0.25 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 12.6 L/s.

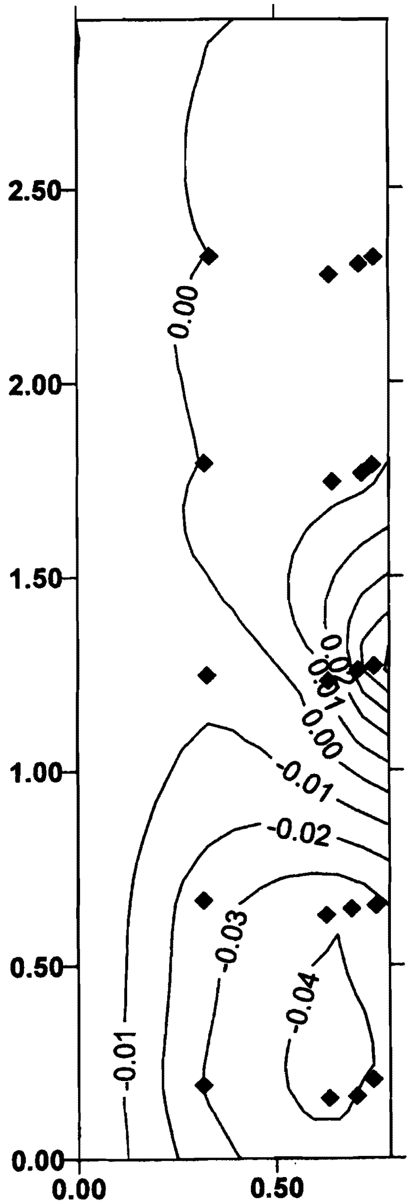

Figure 24. 0.25 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 15.8 L/s.

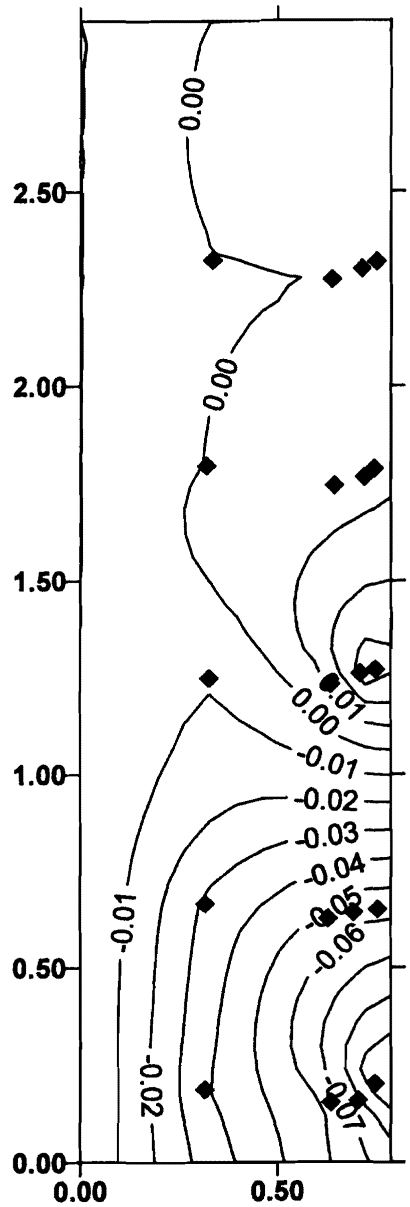

Figure 25. 0.25 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 18.9 L/s.

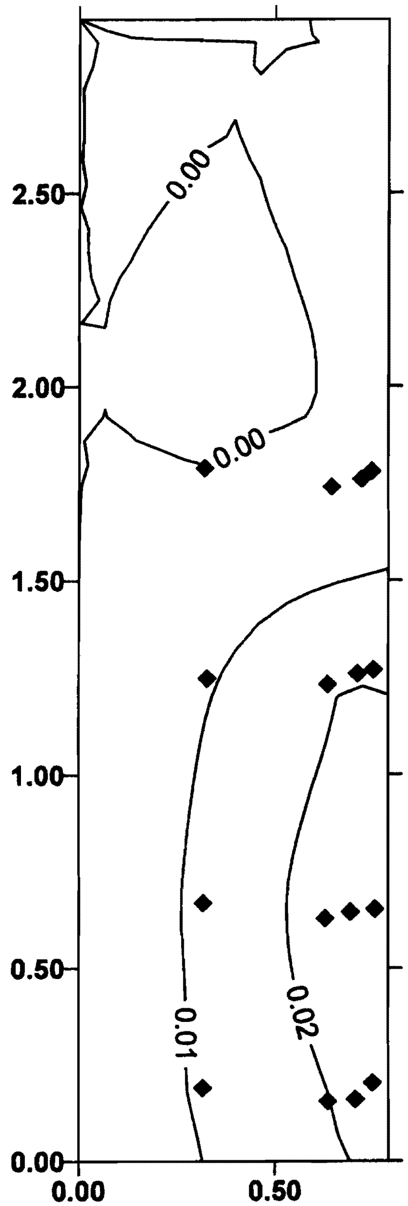

Figure 26. 0.51 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 9.5 L/s.

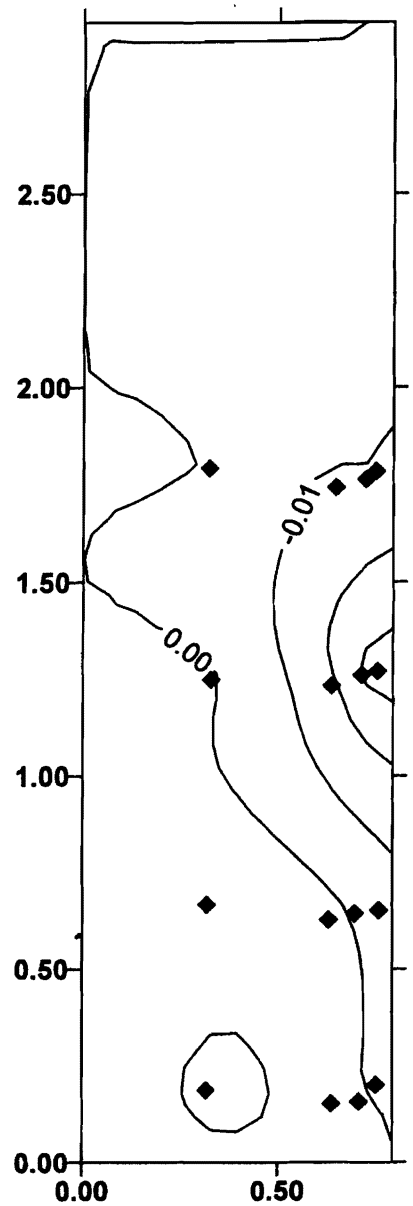

Figure 27. 0.51 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 9.5 L/s.

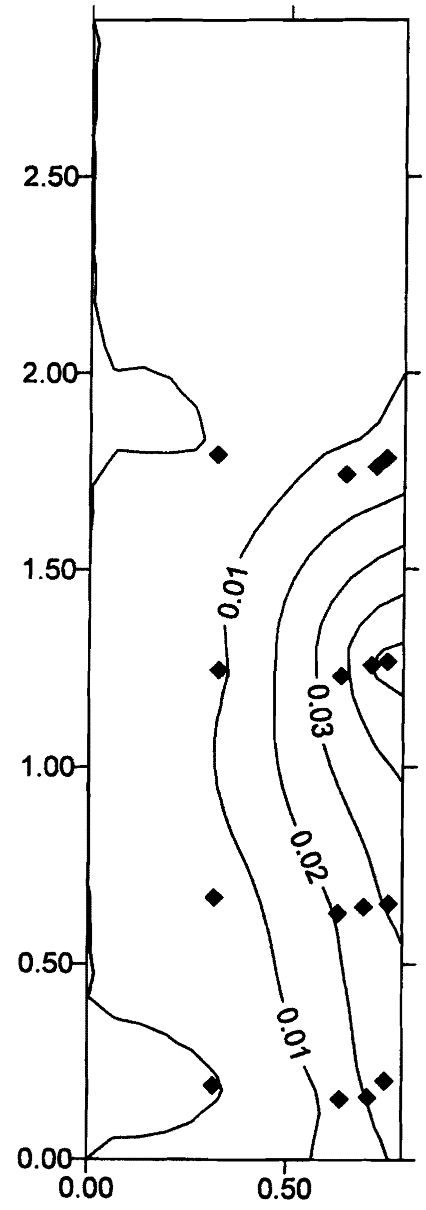

Figure 28. 0.51 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 9.5 L/s.

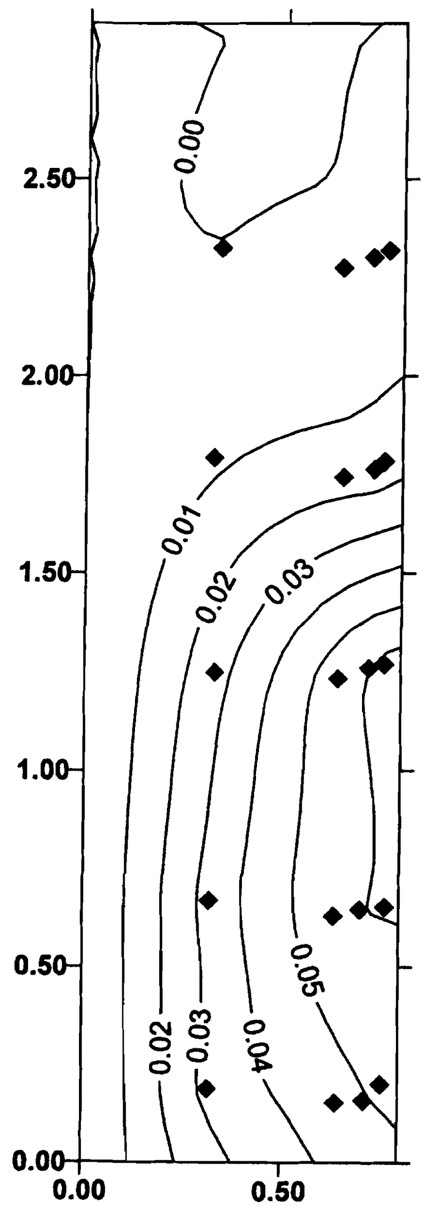

Figure 29. 0.51 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 15.8 L/s using the a data set for the 1.85 m Intake.

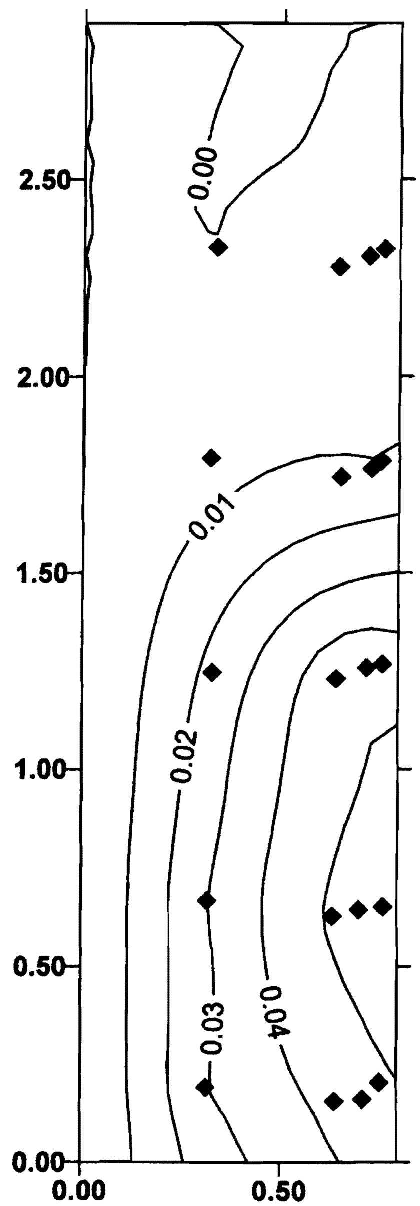

Figure 30. 0.51 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 15.8 L/s using the b data set for the 1.85 m Intake.

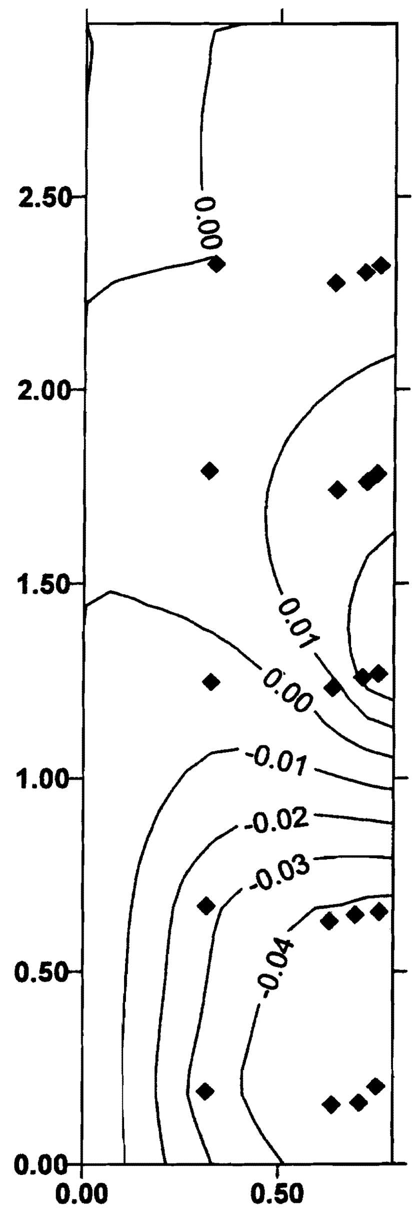

Figure 31. 0.51 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 15.8 L/s using the b data set for the 1.85 m Intake.

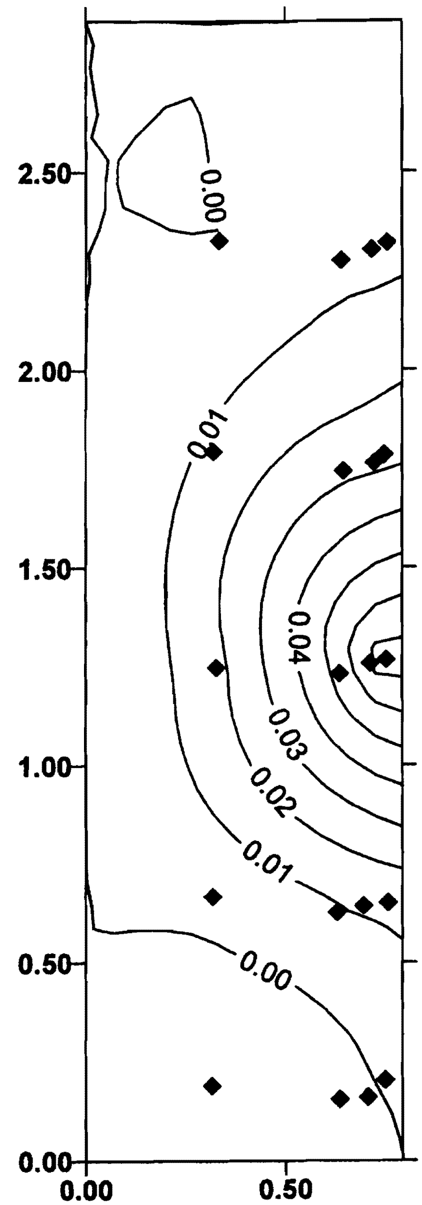

Figure 32. 0.51 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 15.8 L/s.

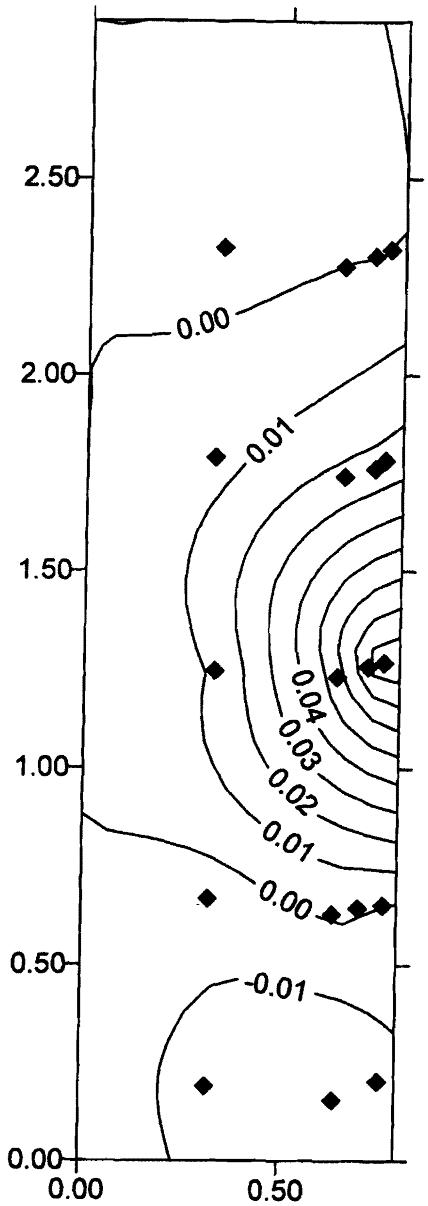

Figure 33. 0.51 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 18.9 L/s.

Figure 34. 0.76 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 9.5 L/s.

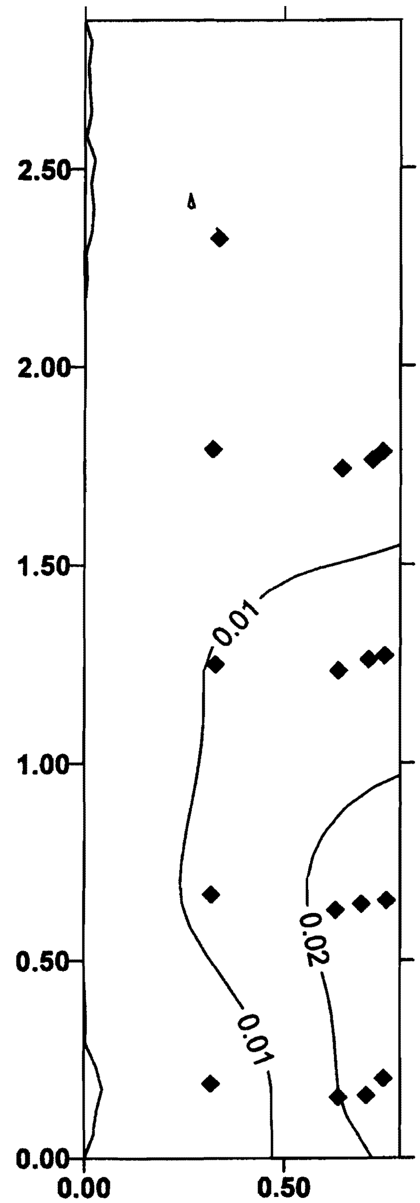

Figure 35. 0.76 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 9.5 L/s.

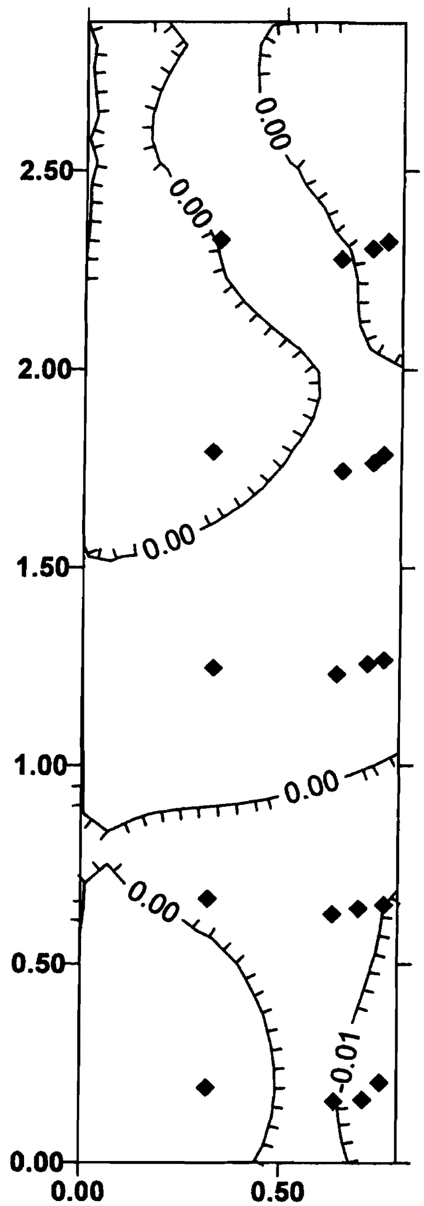

Figure 36. 0.76 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 9.5 L/s.

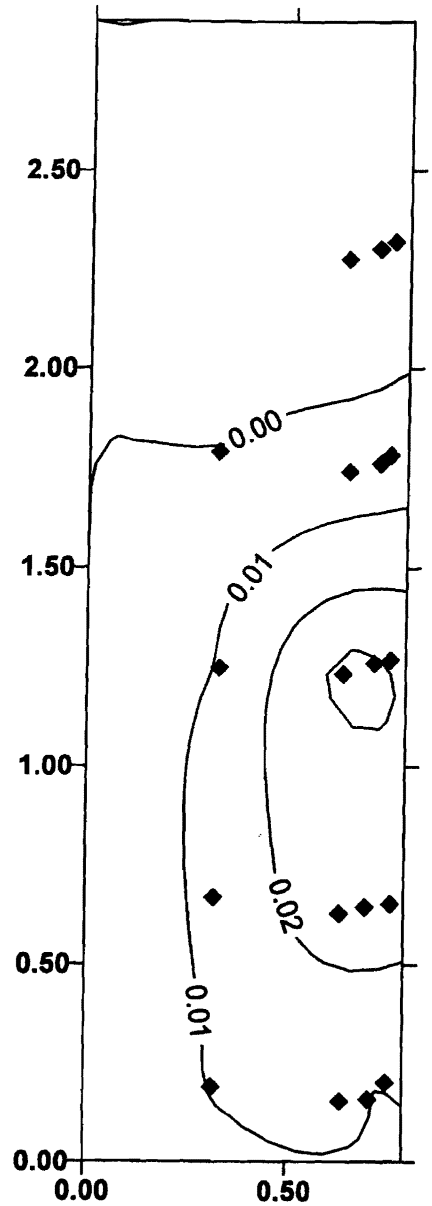

Figure 37. 0.76 mm Slot Size, 12-20 Sand, 1.85 m Intake - 1.24 m Intake at 15.8 L/s

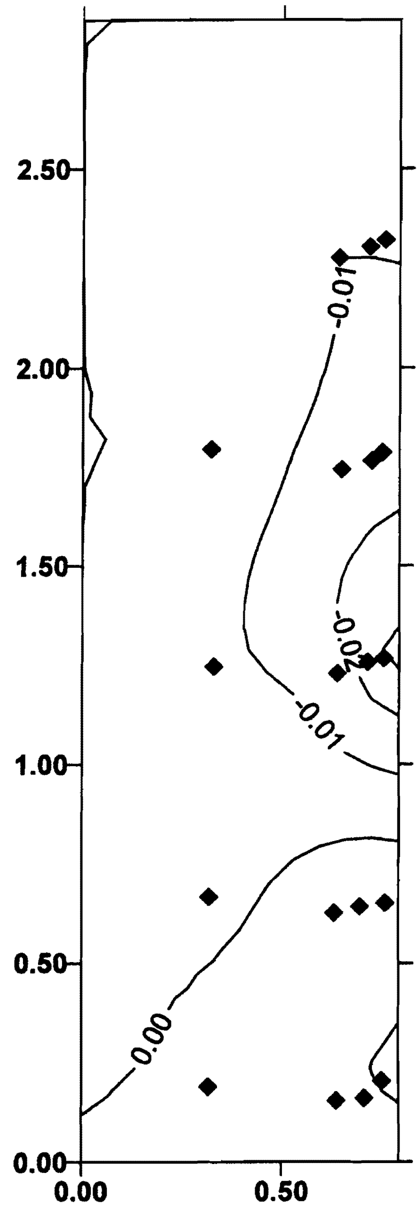

Figure 38. 0.76 mm Slot Size, 12-20 Sand, 1.85 m Intake - 0.63 m Intake at 15.8 L/s.

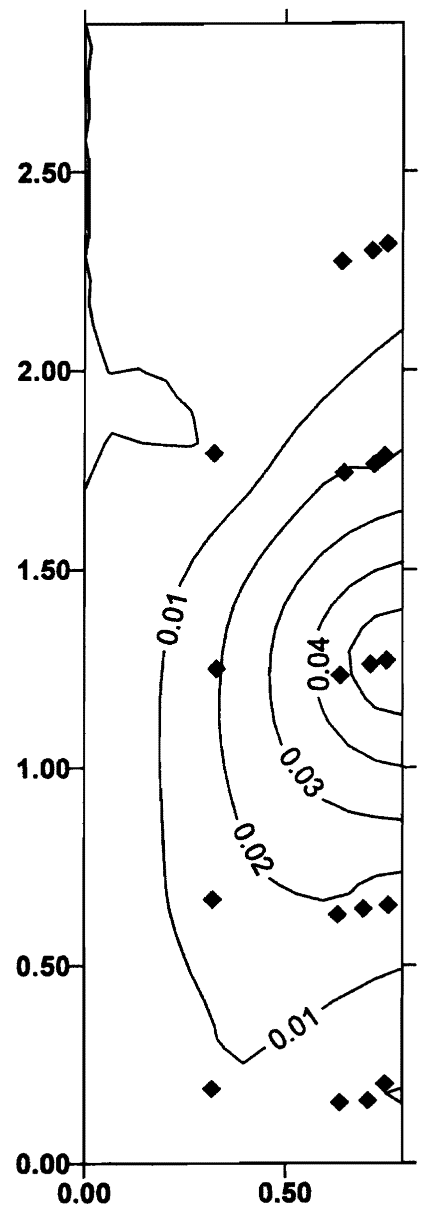

Figure 39. 0.76 mm Slot Size, 12-20 Sand, 0.63 m Intake - 1.24 m Intake at 15.8 L/s.

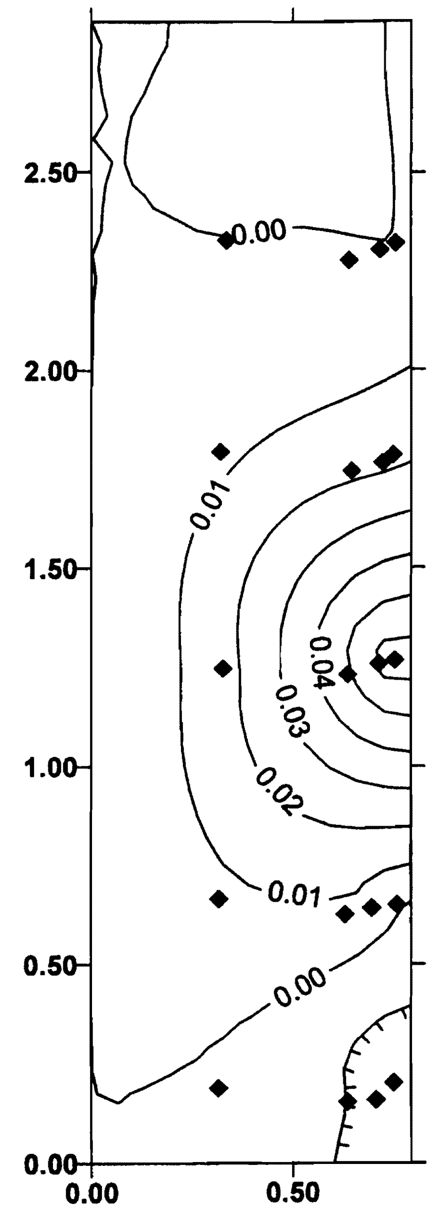

Figure 40. 0.76 mm Slot Size, 12-20 Sand, 0.63 Intake - 1.24 Intake at 18.9 L/s.

APPENDIX 5

WELL EFFICIENCY RESULTS

Table 7. Well efficiency results relative to intake location, sand size, flow rate (Q), and screen slot size.

Sand Size	*Slot Size*	*Intake Length*	*Q L/s (gpm)*	*H max meters*	*H well meters*	*Efficiency Hmax/Hwell*
1630	0.25 mm (010)	1.22 m (4 ft)	6.3 (100)	2.942	2.273	0.773
	0.25 mm (010)	1.22 m (4 ft)	7.9 (125)	2.945	2.064	0.701
1630	0.25 mm (010)	1.83 m (6 ft)	6.3 (100)	2.942	2.426	0.825
	0.25 mm (010)	1.83 m (6 ft)	9.5 (150)	2.945	1.848	0.627
	0.25 mm (010)	1.83 m (6 ft)	12.6 (200)	2.972	1.416	0.476
1630	0.25 mm (010)	2.44 m (8 ft)	6.3 (100)	2.945	2.346	0.797
	0.25 mm (010)	2.44 m (8 ft)	6.3 (100)	2.967	2.356	0.794
	0.25 mm (010)	2.44 m (8 ft)	9.5 (150)	2.948	1.899	0.644
	0.25 mm (010)	2.44 m (8 ft)	12.6 (200)	2.954	1.451	0.491
	0.25 mm (010)	2.44 m (8 ft)	15.8 (250)	3.010	0.953	0.316
1220	0.25 mm (010)	1.22 m (4 ft)	6.3 (100)	2.934	2.613	0.891
	0.25 mm (010)	1.22 m (4 ft)	9.5 (150)	2.934	2.376	0.810
	0.25 mm (010)	1.22 m (4 ft)	12.6 (200)	2.934	2.083	0.710
1220	0.25 mm (010)	1.83 m (6 ft)	6.3 (100)	2.937	2.600	0.885
	0.25 mm (010)	1.83 m (6 ft)	9.5 (150)	2.937	2.372	0.808
	0.25 mm (010)	1.83 m (6 ft)	12.6 (200)	2.938	2.097	0.714
	0.25 mm (010)	1.83 m (6 ft)	15.8 (250)	2.938	1.794	0.610
	0.25 mm (010)	1.83 m (6 ft)	18.9 (300)	2.938	1.565	0.533
1220	0.25 mm (010)	2.44 m (8 ft)	6.3 (100)	2.929	2.655	0.907
	0.25 mm (010)	2.44 m (8 ft)	9.5 (150)	2.931	2.432	0.830
	0.25 mm (010)	2.44 m (8 ft)	12.6 (200)	2.924	2.178	0.745
	0.25 mm (010)	2.44 m (8 ft)	15.8 (250)	2.935	1.900	0.647
	0.25 mm (010)	2.44 m (8 ft)	18.9 (300)	2.940	1.686	0.573
1220	0.51 mm (020)	1.22 m (4 ft)	9.5 (150)	2.946	2.456	0.834
	0.51 mm (020)	1.22 m (4 ft)	15.8 (250)	2.840	1.905	0.671
	0.51 mm (020)	1.22 m (4 ft)	15.8 (250)	2.946	2.022	0.686
1220	0.51 mm (020)	1.83 m (6 ft)	9.5 (150)	2.896	2.450	0.846
	0.51 mm (020)	1.83 m (6 ft)	15.8 (250)	2.897	1.986	0.685
	0.51 mm (020)	1.83 m (6 ft)	18.9 (300)	2.899	1.737	0.599
	0.51 mm (020)	1.83 m (6 ft)	22.1 (350)	2.902	1.556	0.536
1220	0.51 mm (020)	2.44 m (8 ft)	9.5 (150)	2.883	2.534	0.879
	0.51 mm (020)	2.44 m (8 ft)	15.8 (250)	2.883	2.078	0.721
	0.51 mm (020)	2.44 m (8 ft)	18.9 (300)	2.884	1.880	0.652
	0.51 mm (020)	2.44 m (8 ft)	22.1 (350)	2.892	1.668	0.577
1220	0.76 mm (030)	1.22 m (4 ft)	9.5 (150)	2.867	2.489	0.868
	0.76 mm (030)	1.22 m (4 ft)	15.8 (250)	2.869	2.062	0.719
1220	0.76 mm (030)	1.83 m (6 ft)	9.5 (150)	2.875	2.521	0.877
	0.76 mm (030)	1.83 m (6 ft)	15.8 (250)	2.875	2.110	0.734
	0.76 mm (030)	1.83 m (6 ft)	18.9 (300)	2.877	1.892	0.658
	0.76 mm (030)	1.83 m (6 ft)	22.1 (350)	2.878	1.676	0.582
1220	0.76 mm (030)	2.44 m (8 ft)	9.5 (150)	2.875	2.526	0.879
	0.76 mm (030)	2.44 m (8 ft)	15.8 (250)	2.875	2.169	0.754
	0.76 mm (030)	2.44 m (8 ft)	18.9 (300)	2.877	1.962	0.682
	0.76 mm (030)	2.44 m (8 ft)	22.1 (350)	2.878	1.791	0.622

REFERENCES

Colorado Silica Sand, Inc. January, 1996 Technical Bulletin, Colorado Silica Sand, Inc. Colorado Springs, Colorado.

Cooley, R. L., and A. B., Cunningham. 1979. Consideration of total energy loss in theory of flow to wells. Journal of Hydrology, 43, 161-184.

Driscoll, F. G. 1986. Groundwater and Wells. St. Paul, Minnesota: Johnson Division.

Freeze, R. A., and J. A., Cherry. 1979. Ground Water. Englewood Cliffs, New Jersey. Prentice Hall.

Garg, S. P., and J., Lal. 1971. Rational design of well screens. Journal of the Irrigation and Drainage Division, ASCE, 97(IR1), 131-147.

Kaleris, V. 1989. Inflow into monitoring wells with long screens. Proceedings of the International Symposium on Contaminant Transport in Ground-Water, Stuttgart, FRG, April 4-6.

Korom, S. F., K. Bekker, and O. J. Helweg, 1999. Using physical models in well design and operation: An example with pump intake location. Proceedings of the 1999 International Water Resources Engineering Conference, ASCE, Seattle, Washington.

Korom, S. F., K. F. Bekker, O. J. Helweg, 2001. Influence of Pump Intake Location on Well Efficiency. In Review, Journal of Hydrologic Enginerring.

Roscoe Moss Company. 1990. Handbook of Ground Water Development. New York: John Wiley & Sons.

Von Hofe, F. P., and O. J. Helweg, 1998. Modeling Well Hydrodynamics. Journal of Hydraulic Engineering 124, no.12: 1198-1202.