EVALUATION OF COLLECTOR WELL CONFIGURATIONS TO MODEL HYDRODYNAMICS IN RIVERBANK FILTRATION AND GROUNDWATER REMEDIATION

A Thesis

by

TIFFANY LUCINDA DE LEON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Geology

Evaluation of Collector Well Configurations to Model Hydrodynamics in Riverbank

Filtration and Groundwater Remediation

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Approved by:

Chair of Committee,	Hongbin Zhan
Committee Members,	John R. Giardino
	Bruce Herbert
Head of Department,	Andreas Kronenberg

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ABSTRACT

Evaluation of Collector Well Configurations to Model Hydrodynamics in Riverbank Filtration and Groundwater Remediation. (August 2010)

Tiffany Lucinda De Leon, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Hongbin Zhan

Collector well designs are necessary to maximize groundwater uptake and riverbank filtration without negatively impacting an aquifer. Unfortunately, there is a lack of information and research regarding the implementation of collector well design parameters. In the past, collector well installation was too costly, but recent advances in well technology have made collector wells more cost effective. This research will contribute a set of guidelines to optimize riverbank filtration and groundwater remediation. This study models the hydrodynamics surrounding collector well configurations in riverbank filtration and groundwater remediation. Visual Modflow® was utilized to run a variety of numerical models to test four areas: flux along the laterals of a collector well, collector well interactions with a river, collector well yield, and collector well remediation capability. The two design parameters investigated were lateral length (25 m, 50 m, and 100 m) and number of laterals (3 and 4).

The lateral flux tests confirm flux increases towards the terminal end of each lateral and pumping rate is the controlling factor in flux amount obtained along the laterals. The analysis of the flux-river interaction shows the main factor in determining flux amount is the initial river geometry, followed by the pumping rate, regional background flow, and collector well design, respectively. The models suggest that the 4-lateral collector well design is more effective than the 3-lateral design and in addition, 100 meter length laterals provide the highest amount of yield with the least amount of drawdown. The remediation tests investigate the application of vertical well equations to evaluate collector well designs in two areas: minimum pumping rate to capture line source of particles and first arrival time of particles. The remediation models show 100 meter length laterals provide both the lowest pumping rate and the highest residence time with the surrounding aquifer for maximum remediation. Ultimately, these models provide basic design guidelines and explain which designs are most effective, depending on the collector well purpose.

DEDICATION

This thesis is dedicated to my parents, Mario and Libby De Leon, who have always taught me the value of perseverance.

ACKNOWLEDGEMENTS

There have been so many individuals who have helped me achieve this dream and who have supported me during one of the hardest times of my life. I would like to thank my advisor and chair, Dr. Hongbin Zhan, for taking me on as his graduate student and providing not only the guidance of a professor, but also that of a friend. I would like to thank Dr. Rick Giardino, with his keen eye for perfection, who helped me stay organized and on track. Finally, I would like to thank Dr. Bruce Herbert for providing me with a great and quick method for writing my results and discussion section.

A million thanks to all of my friends and colleagues here at Texas A&M University who helped me embrace life and not get bogged down by it and its many hurdles. I would also like to thank the Department of Geology and Geophysics for providing me with a teaching assistantship for each semester I was here at Texas A&M University. Without this financial support I would not have been able to complete my Masters degree. Thanks to Ryan Young who helped me with my constant Visual Modflow® issues. Thanks to Brad Gamble for providing design parameters used in the field. And a huge thanks to Will Dugat, who provided so much help throughout the entire process.

And, of course, I would like to thank my parents: Mario and Libby De Leon. Thank you for always pushing me beyond my boundaries and believing in me, even when I did not believe in myself.

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1. INTRODUCTION

A collector well is a cluster of horizontal wells joined at the base of a central vertical caisson [*Hantush and Papadopulos*, 1962]. Collector wells are utilized to maximize the uptake of groundwater without negatively impacting an aquifer. Negative impacts to an aquifer range from lowering of the water table to contamination. Unfortunately, there are currently no guidelines about basic information and guidelines on designing and using a collector well system for the purpose of water supply. In addition, research [*Hunt et al.*, 2002; *Hiscock and Grischek,* 2002; *Dillon et al.,* 2002] shows collector well systems are utilized for remediation purposes and currently there are no guidelines for this purpose either. Therefore, this thesis will investigate various collector well designs to provide guidelines for water supply and remediation purposes.

Riverbank filtration involves the placement of wells in close proximity to a river (Figure 1), where the pumped water will invariably flow through the riverbed and aquifer materials, thus removing potential contaminants from the river water[*Ray et al.,* 2002]. Collector wells consist of a central, vertical caisson with several radiating laterals surrounding the bottom of the caisson (Figure 2) [*Bakker et al.,* 2005]. It has also been found that, by combining this filtration method with collector wells, contaminants can be removed, and a large amount of groundwater can be pumped without deleterious effects

This thesis follows the style of *Water Resources Research.*

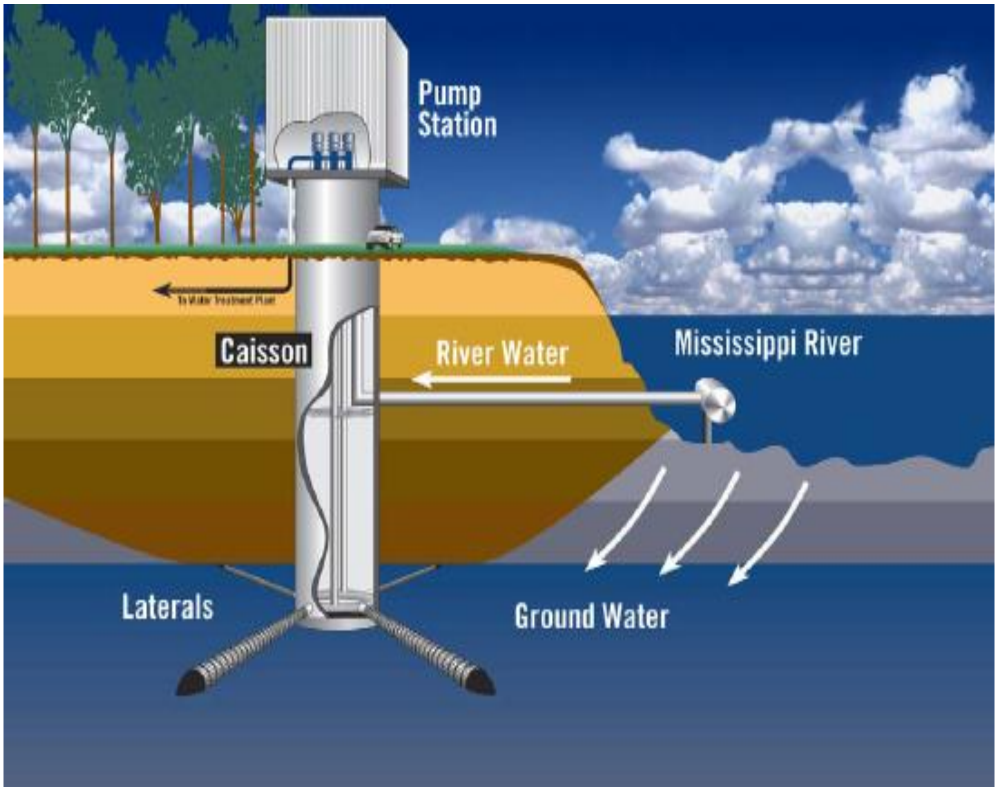


Figure 1: Illustration of induced riverbank filtration with collector well [*French*, 2010].

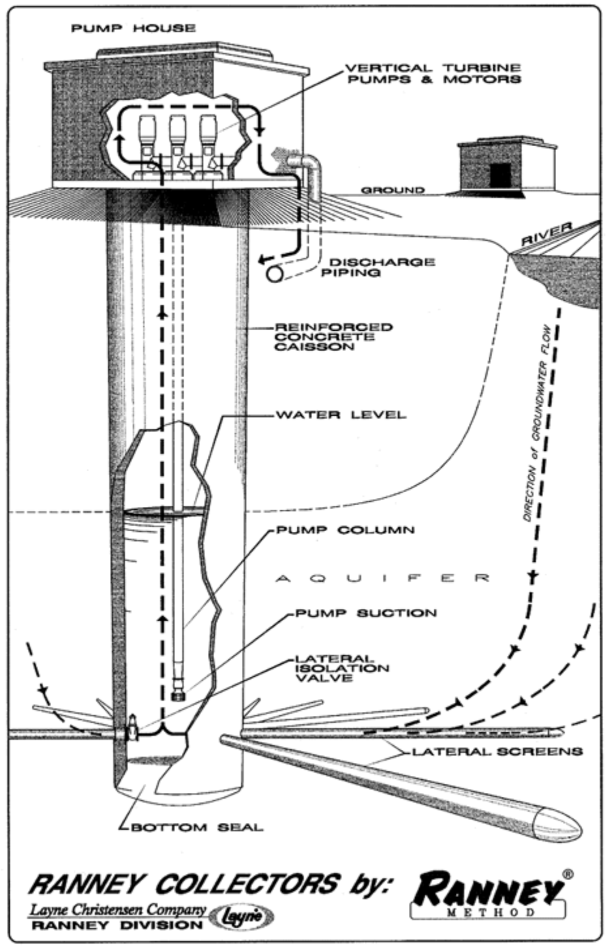


Figure 2: Diagram of general collector well configuration [*Ranney® Collector Wells*, 2010].

to the aquifer [*Patel et al,.* 2010]. These collector wells have been used throughout Europe since the 1930s, but they are gaining popularity within the United States as a method for groundwater extraction and/or remediation [*Hunt,* 2002]. However, there is a lack of published information on the practical application of various well configurations. This leads to the question: What are the collector well configurations to aid in riverbank filtration and groundwater remediation?

This thesis uses Visual Modflow®, numerical modeling software, to model different well configurations in a variety of river stages. A river stage refers to the water level of a river. The collector well designs are based on several parameters: lateral length, lateral orientation, and lateral number. The modeled river is varied based on three river stages: shallow, intermediate, and deep. The goal of this thesis is to gain insights on the hydrodynamics of collector wells and to provide guidelines for collector well designs in riverbank filtration and groundwater remediation.

2. BACKGROUND

2.1: Leo Ranney: Creator of the Collector Well

Collector wells are also called Ranney wells after their inventor Leo Ranney, a petroleum engineer in the United States, who designed them in the 1920s [*Hunt*, 2002]. A collector well consists of a vertical central cylindrical caisson with several horizontal wells, or laterals, surrounding it radially [*Bakker et al.,* 2005]. Ranney originally designed these wells, not for hydrological purposes, but for the petroleum industry.

During the 1920s, the price of oil was high and a large percentage of the oil was unattainable with conventional vertical wells. The standard form of drilling could only uptake about twenty percent of the oil within a formation [*Anonymous,* 1943]. Ranney made a simple suggestion: "Why not drill horizontally for oil, as miners dig coal?" [*Anonymous,* 1943, p.1]. Ranney's original collector well design involved a vertical concrete-lined shaft ending in a bottom circular chamber with twenty-four horizontal wells, each at 2,500 feet and radiating around the chamber like spokes of a wheel [*Anonymous*, 1943]. Ranney believed this well design could uptake 3,000 times more oil from a 20-foot oil-bearing layer, than a traditional vertical well design [*Anonymous,* 1943]. Ranney's first collector well was used in southern Ohio in 1927 for oil extraction [*Hunt,* 2003]. Reportedly, this allowed "more oil to be pumped from the formation using this single [collector] well over a six-month period, than a series of vertically-drilled wells had produced for a number of years" [*Hunt,* 2003, p.1].

However, in the 1930s the price of oil began to drop and Ranney's design, while efficient, was no longer cost-effective or necessary for oil miners [*Hunt et al.,* 2002]. In 1934, he traveled to London, England, during a water shortage and altered his collector well design for water supply purposes [*Hunt,* 2003]. Ranney continued to implement his well design throughout Europe, where its popularity grew. In the following years, several European companies improved the Ranney original method for installing collector well screens, which allowed for water to enter the lateral [*Hunt et al.,* 2002]. These improvements included an increase in the "available open area of the well screen to 40 percent or more" and allowed an artificial gravel-pack filter to be placed around the well screen [*Hunt,* 2003, p. 2]. Overall, Leo Ranney's innovative collector well design has impacted both the hydrogeologic and petroleum community. Its application has also broadened to address groundwater supply issues, and remediation involving riverbank filtration.

2.2: History of Riverbank Filtration

Riverbank filtration involves the placement of a well next to a river. This process can also be performed by installing collector wells underneath the river bed or within the river banks [*Dillion et al.,* 2000]. Riverbank filtration is often used to "induce recharge from the surface water" [*Bakker et al.,* 2005, p. 926]. Most collector wells are located in alluvial aquifers near riverbanks. As the water is pumped from the well, the surface water will percolate downward through the low-permeability riverbed sediments and through the porous aquifer media. As it moves through these materials, most chemical and biological contaminants are attenuated, filtered, and adsorbed onto the sediments

[*Ray et al.,* 2002]. The resulting pumped water is a mixture of surface and groundwater, therefore, its quality is higher than it was prior to pumping and the temperature is equilibrated [*Kim et al.,* 2008]. As a result, riverbank filtration is a good alternative for treating drinking water. Therefore, riverbank filtration decreases the need for additional chemicals in the water, which reduces both the cost and risk to human health [*Ray et al.,* 2002].

Since the 1800s, riverbank filtration has been utilized in Europe to facilitate clean drinking water [*Kim et al.,* 2008]. In 1810, the Glasgow Waterworks Company in the United Kingdom became the first known utility to use riverbank filtration for water-supply purposes [*Ray et al.,* 2002].

In recent years, riverbank filtration in the United States has gained interest because of technological advances and government incentives. The increasing application of horizontal wells in the United States can be attributed to advancements in drilling techniques over the past fifteen years [*Zhan and Zlotnik,* 2002]. The technology for horizontal wells has been available since the 1930s, but until these advances were made, it was not cost-effective to implement them for groundwater purposes. Lastly, the U.S. Environmental Protection Agency established the Long Term 2 Enhanced Surface Water Treatment Rule in 2006 which rewards additional *Cryptosporidium* filtration credits for treatment systems meeting certain design criteria [*Hiscock and Grischek*, 2002]. Depending on the site hydrogeology, pumping requirements, and available budget, a collector well design can be utilized instead of a vertical well [*U.S. EPA,* 2009]. Current and potential incentives are driving the need for more information on riverbank filtration systems and collector wells.

2.3: River Morphology

Knowledge of the grain-size distribution of riverbed sediments and morphology is critical in determining the site suitability for riverbank filtration [*Schubert*, 2002]. It is rare to locate a naturally straight river channel; most likely the river in question will be meandering [*Walker and Cant*, 1984]. A meandering river consists of bends, which are a result of varying rates of deposition and erosion. The outer bend of a meander is exposed to erosion, which results in the lateral accretion of sediments on the inside of the meander bend and the formation of a point bar [*Walker and* Cant, 1984]. Inside a meander bend, within a point bar, the highest volume of riverbank-filtered water is obtained, as a result of the dynamic nature of the riverbed [*Schubert*, 2002].

When a river channel forms, the river floor typically consists of gravel-sized sediments and clasts of partially consolidated mud [*Walker and Cant*, 1984]. In a meandering river, water flows in a spiraling pattern because of a combination of cross-channel and down-channel flows [*Walker and Cant*, 1984]. This flow pattern results in a fining-upwards of sediment within a point bar: coarse sand-sized, fine sand-sized, clay-sized, silt-sized particles, respectively. Movement away from the river channel and point bar, results in a coarsening of the sediments.

Overall, a meandering river is a dynamic system, and the flow patterns, in addition to the formation of point bars, can result in the development of a number of other features: oxbows, levees, ridges, splays, and abandoned channels [*Walker and Cant*, 1984].

Dugat [2009] tested the incorporation of realistic riverbed and riverbank heterogeneities in an original model similar to the modeled environment in this study. These heterogeneities included a low permeability layer representing riverbed sediments, high permeability zones representing flood plain or meander fairway boundaries, and high permeability zones representing abandoned river channels filled with well sorted alluvial sediments or point bar deposits of well sorted sand [*Dugat,* 2009]. *Dugat* [2009] concluded the addition of these heterogeneities altered the ease of flow, but had minimal impact on well-river interactions. As a result, this study will focus on a base, homogenous model without the addition of riverbed and riverbank heterogeneities.

2.4: Horizontal versus Vertical Wells

Horizontal wells are more expensive to install than conventional vertical wells, but they have a number of advantages [*Zhan et al*., 2001; *Zhan and Zlotnik,* 2002; *Zhan,* 1999]. The amount of surface area that a single horizontal well covers could be equivalent to ten vertical wells [*Zhan and Zlotnik*, 2002]. This well design helps lower drilling costs and eliminates the need for an excessive amount of hardware for groundwater extraction [*Anonymous,* 1993]. These wells also allow contaminants to be removed where surface structures could potentially block direct access to the site area. Some examples of this purpose include ponds, wetlands, and/or landfills [*Zhan and Zlotnik,* 2002]. Horizontal wells also work well in areas with a limited availability of land that cannot support numerous vertical wells [*Kim et al.,* 2008].

Dense-non-aqueous-phase-liquids (DNAPLs) are contaminants that are exceedingly difficult to remediate from aquifers, as they sink to the bottom of the aquifers [*Zhan et al.,* 2001]. However, horizontal wells can be installed near the bottom of the aquifer and interact with the DNAPL plume to quickly recover it [*Zhan and Cao,* 2000]. Another key advantage of horizontal wells is that their cone of depression is more subdued in comparison to vertical wells. This is especially beneficial for areas with thin aquifers. In addition, the velocities of groundwater entering the well screens are slower, which prevents the well screen from quickly becoming clogged and lessens the maintenance requirements [*Bakker et al.,* 2005]. Overall, the "larger contact zone between well and contaminated groundwater, vapor, or oil improves the effective recovery of fluids" [*Zhan et al.,* 2002, p. 1]. Conventional vertical wells have many established methods for estimating basic aquifer parameters, but this is not the case with horizontal wells applied towards groundwater [*Langseth et al.,* 2004].

2.5: Literature Review

Multiple studies [*Bakker et al.,* 2005; *Hantush and Papadopulous,* 1962; *Mohamed and Rushton,* 2006] have attempted to understand fluid flow and drawdown with associated horizontal and collector wells. However, fewer studies [*Kim et al.,* 2008*; Patel et al.,* 1998; *Patel et al.,* 2010] have been completed utilizing horizontal collector wells as a treatment process with riverbank filtration and maximizing groundwater remediation. *Hantush and Papadopulos* [1962] completed the first three-dimensional study to establish a "relationship between production rate and drawdown at collector wells" [*Kim et al.* 2008, p. 493]. The study involved the use of a series of jointed horizontal wells and provided "analytical solutions for the drawdown distribution around collector wells" [*Hantush and Papadopulos* 1962, p. 221]. *Tarshish* [1992] developed a mathematical model for steady-state flow in an aquifer for horizontal well use under a water reservoir. *Patel et al.* [1998] completed a study using Visual Modflow® to analyze the effects of tiers in collector well designs on discharge and the relationship between drawdown and the location of a recharge boundary. The study does note that there are theoretical equations, which can be used to compute the well yield for different collector well configurations; however, they may be inaccurate as they do not address the following: "recharge boundary effect of stream, thinning of aquifer toward bank, multiple tiers of radials, and uneven position and length of radial according to site feasibility" [*Patel et al.,* 1998, p. 98].

Zhan et al. [2001] developed a method to solve the boundary problem of flow to a horizontal well in an anisotropic confined aquifer where both the short and long-time approximations of drawdowns were provided in the paper. *Bakker et al.* [2005] used a multi-layer analytical element method (AEM) to model steady-state groundwater flow to a horizontal collector well, so that regional and local three-dimensional flow can be "simulated simultaneously and accurately in one regional model" (p. 926). Their study also addressed skin effect and internal friction losses as a result of flow in the laterals.

Mohamed and Rushton [2006] investigated horizontal wells in shallow aquifers and three different flow processes related to the wells: flow within the aquifer, flow from the aquifer into the horizontal well, and flow within the lateral. Previous papers addressed either one or two of these flow processes, but *Mohamed and Rushton* [2006] were the first to provide an analytical solution, which incorporated all three.

Kim et al. [2008] built a physical model aquifer with collector well laterals where the well water level, lateral length, diameter, and hydraulic conductivity of the sand were altered independently to investigate flow and head variations. Based on their experiment, a mathematical model was created to predict "axial flow velocity distribution and discharge intensity variation along the lateral using the head distribution" [*Kim et al.,* 2008, p. 493]. In terms of the lateral length, the results indicated that an increase in lateral length was related to an increasing production rate of the well.

Patel et al. [2010] developed a study using an AEM to simulate the discharge-drawdown relationship for a collector well in an unconfined aquifer. The goal of their study was to provide a method for quickly and effectively evaluating collector well designs, as numerical models, which use a finite difference method (FDM), require many trials, and are cumbersome to construct. *Patel et al.* [2010] successfully created methodology using AEM in two dimensions and a new empirical equation whose results were found comparable to current empirical equations and FDM models.

The literature covers a wide range of methods used to evaluate horizontal and collector wells. However, collector wells are not solely utilized for riverbank filtration, so few studies [*Kim et al.,* 2008*; Patel et al.,* 1998; *Patel et al.,* 2010] focus on the effectiveness of well design as a treatment process. Instead most studies [*Zhan and Park,* 2003; *Zhan et al.,* 2001; *Zhan and Zlotnik,* 2002] focus on the discharge-drawdown relationships and the creation of more accurate analytical models for a variety of scenarios.

3. OBJECTIVES

Collector wells are gaining popularity in the United States as a method for increasing groundwater yield and remediation. When coupled with riverbank filtration, a higher quantity and quality of groundwater can be obtained. Unfortunately, there is a lack of published information on the effective utilization of this technology. As, the essential goal of this thesis is to evaluate collector well configurations to model the hydrodynamics in riverbank filtration and groundwater remediation, several objectives have been established:

- Create a working model of a collector well using Visual Modflow®,
- Find the best configuration for a collector well by varying and comparing model design parameters, and
- Evaluate models based on the maximum well yield for water supply purposes and residence time for remediation purposes.

The following model parameters will not be investigated because the parameters were evaluated in *Dugat's* [2009] Master thesis:

- Variation in regional hydraulic conductivity, and
- Addition of aquifer heterogeneities.

Dugat's study focused on a collector well design of 4-laterals with 25 m long laterals. This study further investigates the effects of decreasing the number of laterals and increasing the lateral length and how it alters the net flux to a river, well yield, and remediation effectiveness.

4. METHODS AND MODEL PARAMETERS

4.1: Create a Working Model of a Collector Well

This study requires the use of Modflow-2000® Version 1.18.01, a modular finite-difference flow model, as the numerical engine to complete the groundwater modeling. Waterloo Hydrogeologic Software Visual Modflow® version 4.3.0.154 Pro from Schlumberger Water Service division was used as the graphical user interface to better visualize and understand the findings generated by the model.

The original model created in section 4.1 was designed by *Dugat* [2009]. Modifications to the original model are expanded upon in section 4.2. Figures 3-4 show the basic set-up of the original modeled Visual Modflow® environment is 1,000 m by 1,000 m by 20 m. The original model is homogenous and anisotropic with K_z=K_y=0.2K_z. The model includes two no-flow boundaries: the northern and southern boundaries. The northern boundary represents the ground surface or top of the aquifer and the southern boundary represents the bottom of the aquifer. The original model also includes three constant-head boundaries: a western, central, and eastern boundary. The western boundary maintains a constant head of 20 m. The eastern boundary has a varied head value: 20 m, 18 m, and 15 m, to initiate different regional background flows. The central constant head boundary represents the river and is parallel to the western and eastern model boundaries and extends from the northern model boundary to the southern model boundary. The river boundary has a varied head value to signify different river bed depths of 1 m, 5 m and 10 m with a river channel width of 10 m. The river is modeled

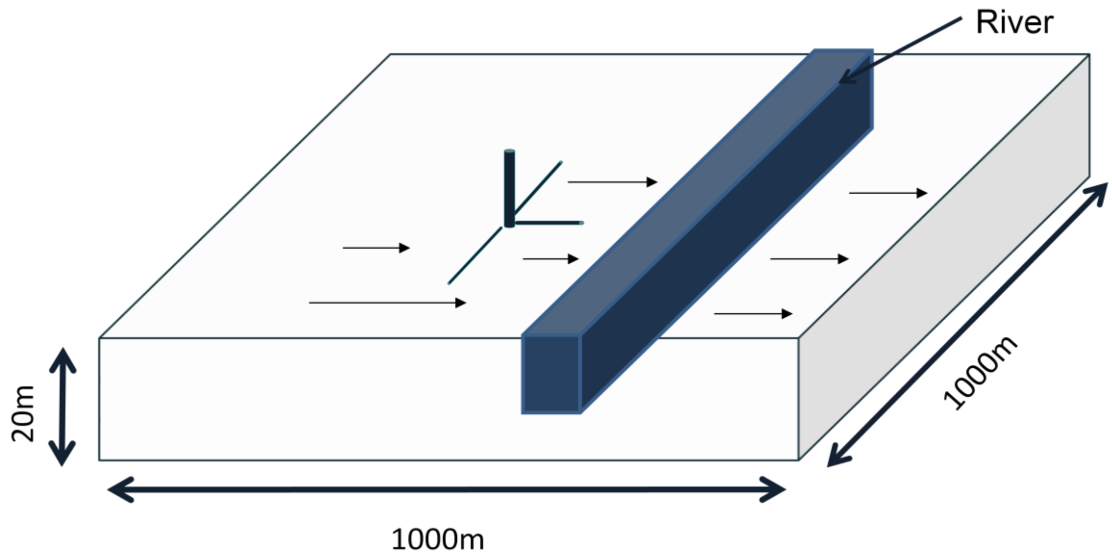


Figure 3: Model diagram of ModFlow® environment with a 3-lateral asymmetrical collector well. Arrows show direction of regional background flow (not to scale).

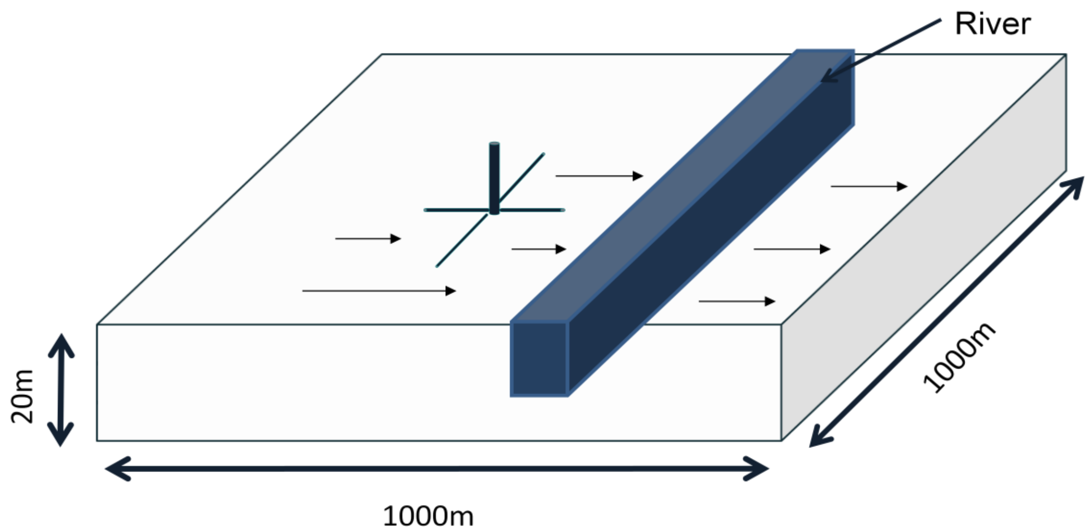


Figure 4: Model diagram of ModFlow® environment with a 4-lateral symmetrical collector well. Arrows show direction of regional background flow (not to scale).

after one of the large meandering streams in the Texas Gulf Coast [*Dugat,* 2009]. The vertical well, or central caisson, is placed directly in the center of the original modeled Visual Modflow® environment at 500 m and at a depth of 10 m below the northern boundary, also known as the ground surface. The laterals are placed around the base of the vertical well. The placement of the river, in relation to the well, is 35 m from the outside end of the eastern lateral of each collector well design. Further discussion of the well configuration is explained in section 4.2.

Visual Modflow® does not intrinsically allow for the creation of horizontal wells. *Dugat* [2009] handled this issue by altering the grid cells, which represent the laterals. The diameter of the laterals tested are 0.15 m. Therefore, the grid where the laterals are located is 0.15 m by 0.15 m. The cells were assigned a permeability of 7.03×10^{-4} m^2. *Dugat* [2009] determined the permeability with the Hagen-Poiseuille Relationship:

$$k = \frac{D^2}{32} \tag{1}$$

where k is the intrinsic permeability [m^2] and D is the diameter of the pipe [m]. The hydraulic conductivity for a 0.15 m lateral is 6.81×10^7 m/day. *Dugat* [2009] calculated a hydraulic conductivity value using the following equation:

$$K = k\left(\frac{\rho_w g}{\mu}\right) \tag{2}$$

where K is the hydraulic conductivity (m/day), ρ_w is the density of water [kg/m^3], g is the gravitational constant [m/s^2], and μ is the fluid viscosity of water [kg/ms]. Another issue which was addressed in the model creation is draining. Draining occurs when water in the laterals flows rapidly out of the cells and towards the vertical caisson [*Dugat,* 2009]. As a result, Visual Modflow® cannot provide the required amount of water from the aquifer to the caisson in an adequate amount of time. *Dugat* [2009] handled this issue by screening the vertical collector caisson 0.15 m above and below the attached laterals to prevent draining, which allowed for more accurate results.

4.2: Variation of Collector Well Design Parameters

There are several parameters in the well design, which can be altered: the number, length, direction, and diameter of the laterals, which are all key parameters in determining well yield [*Kim et al.,* 2008]. However, this study focuses on length, direction, and number. The diameter of 0.15 m is retained for all well configurations. The number of laterals investigated was three and four, respectively. Figures 5-6 show how the direction alters with the number of laterals. Originally, models containing two, four, and six symmetrical laterals were to be created, but *Gamble* [2009] explained that typically collector well designs consisting of three to six laterals are employed in the field. This discovery eliminated the need to run a two lateral model. Despite the fact that six laterals are utilized in the field, *Gamble* [2009] noted that the original study by *Hantush and Papadopolus* [1962] shows that a design with more than four symmetrical laterals has very little impact on overall well yield. Thus, a model with four symmetrical laterals would be the best base model for well yield, and a model consisting of six

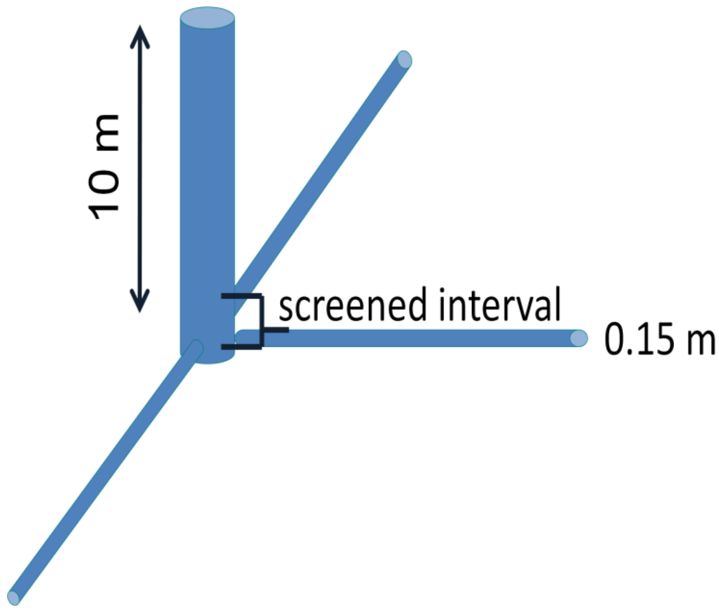


Figure 5: 3-lateral asymmetrical collector well configuration (not to scale).

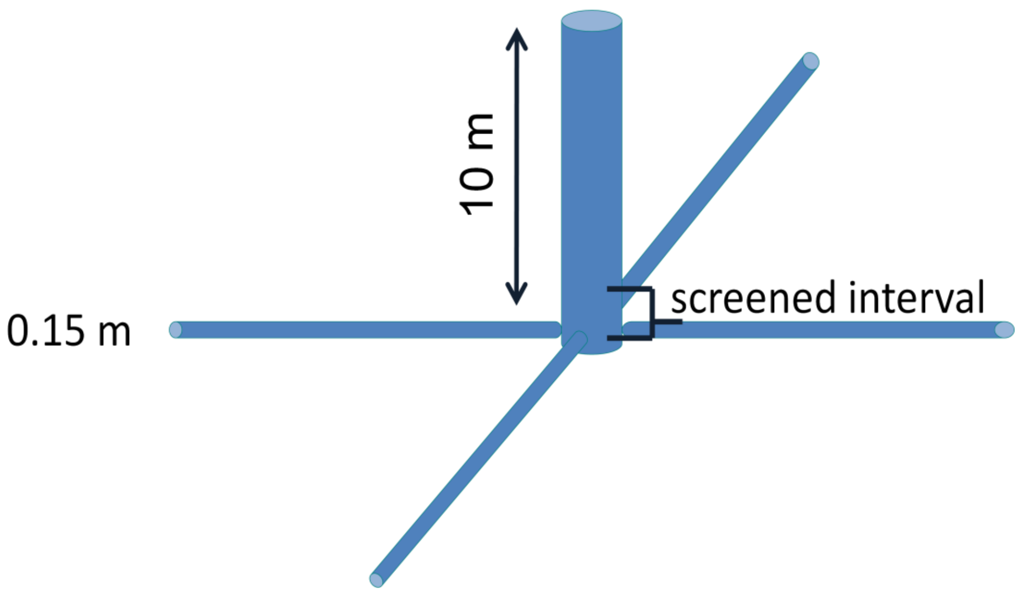


Figure 6: 4-lateral symmetrical collector well configuration (not to scale).

laterals would provide negligible results. The decision to run a three lateral asymmetrical model was two-fold: ease of design and lack of modeled information.

Visual Modflow® is a finite-difference model, which makes it difficult to create diagonal laterals. *Gamble* [2009] stated that little work has been published on utilizing asymmetrical lateral designs. He suggested a design of “three laterals 90 degrees apart with one projected toward the river and the other two projected parallel to the riverbank” [*Gamble,* 2009, p. 2]. For this reason, instead of running a two lateral model, an asymmetrical three lateral well design provided more beneficial results. The lengths utilized are 25 m, 50 m, and 100 m, respectively. These lateral lengths were selected based on research completed by *Zhan et al.* [2001]. *Gamble* [2009] stated that in the field roughly 75 m is considered to be an achievable total length for laterals and that rarely are laterals designed less than 30 m. However, *Gamble* [2009] stated that a length of 100 m would be a “good value for the maximum that can be installed using [their] methods” [*Gamble,* 2009, p. 1]. Therefore, these lengths provide a good range to determine the best length for collector wells. Lastly, the modeled is homogenous, but *Gamble* [2009] did note that boulders are a major limiting factor regarding the lateral length and depth of the vertical, caisson.

4.3: Evaluate Models for Water Supply and Remediation Purposes

One objective of this study is to evaluate the models for the best configuration to aid in riverbank filtration and groundwater remediation. Two programs within Visual Modflow® were used to analyze the models: Zone Budget® and ModPath®. Zone Budget® is a program that aids in computing sub-regional water budgets in different designated zones. The program helps clarify the interactions of each lateral in relation to one another and the modeled river. ModPath® is a program that acts as a particle-tracking postprocessor model. The program calculates particle paths and displays them graphically. ModPath® will assist in understanding how different collector well configurations work in removing contaminants from groundwater [*USGS,* 2009].

During the creation of the model and its laterals, 1 m zones were created along the length of each lateral, at the river, and at the river bed. After running each model the inflow and outflow values, of the zone budget, for the river zone, zone 107, were recorded. Next, the drawdown data for each collector well design were recorded to calculate the well yield (W). The following equation was used to calculate the well yield for each collector well design:

$$W = \frac{Q}{s} \tag{3}$$

where Q is the pumping rate (m^3/day), s is the maximum drawdown in the well (m), and W is the well yield (m^2/day). Well yield is represented by yield per unit of drawdown, which are typically gallons per minute per unit of drawdown (gpm/m). Eq. (3) is traditionally used to evaluate vertical wells. However, by incorporating another parameter, total screen length (T), the well yield for the collector wells' (W_h) unique configurations can be investigated:

$$W_h = \frac{W}{T} \tag{4}$$

where T is the total screen length (m) and W_h is the yield per unit of drawdown per total screen length (gpm/m/m). Once this step was completed the collector well designs were evaluated for water supply purposes.

Next, ModPath® was utilized to investigate the remediation capability of each collector well design. Currently, there are no equations to calculate the minimal pumping rate for a collector well to capture a finite line contamination source. *Zhan and Sun* [2007] developed an equation for a vertical well in an aquifer dominated by advection to calculate the minimal pumping rate to capture a line source:

$$Q_D > \frac{l_D}{\pi - \tan^{-1} l_D} \tag{5}$$

where Q_D is the dimensionless pumping rate:

$$Q_D = \frac{Q}{2\pi B x_0 q_0} \tag{6}$$

where Q is the pumping rate (m^3/day), B is the saturated thickness of the aquifer (m), x_0 is the distance of the line source to the extraction well (m), and q_0 is the regional background flow (m/day). And l_D is the dimensionless half length of the line source:

$$l_D = \frac{l}{x_0} \tag{7}$$

where l is the half length of the line source (m) and x_0 is the distance from the center of the line source to the extraction well (Figure 7). All the collector well designs have a central vertical well; therefore the assumption is that Eq. (5) can be applied towards the collector well designs. To test this assumption each of the collector well designs capability to capture a line source was evaluated with the ModPath® program. For all designs, a line source the length of 200 m and consisting of 50 particles was created at a set distance (x_0) from the vertical well, also referred to as the central vertical caisson. As a safety measure, the Q_D was increased by 10% to account for any dispersion that may occur. Once the Q_D is calculated, the Q (m^3/day) can be determined with the following equation:

$$Q = Q_D \times (2\pi x_0 q_0) \qquad (8)$$

Before testing the collector well designs, a vertical well was tested as a control in both regional background flow settings (0.017 m/day and 0.0432 m/day) to ensure Eq. (5) works. Such regional flow Darcian velocities are commonly seen in real applications. Next, each collector well design was tested to ensure that all particles are captured with the aid of Eqs. (5) and (8).

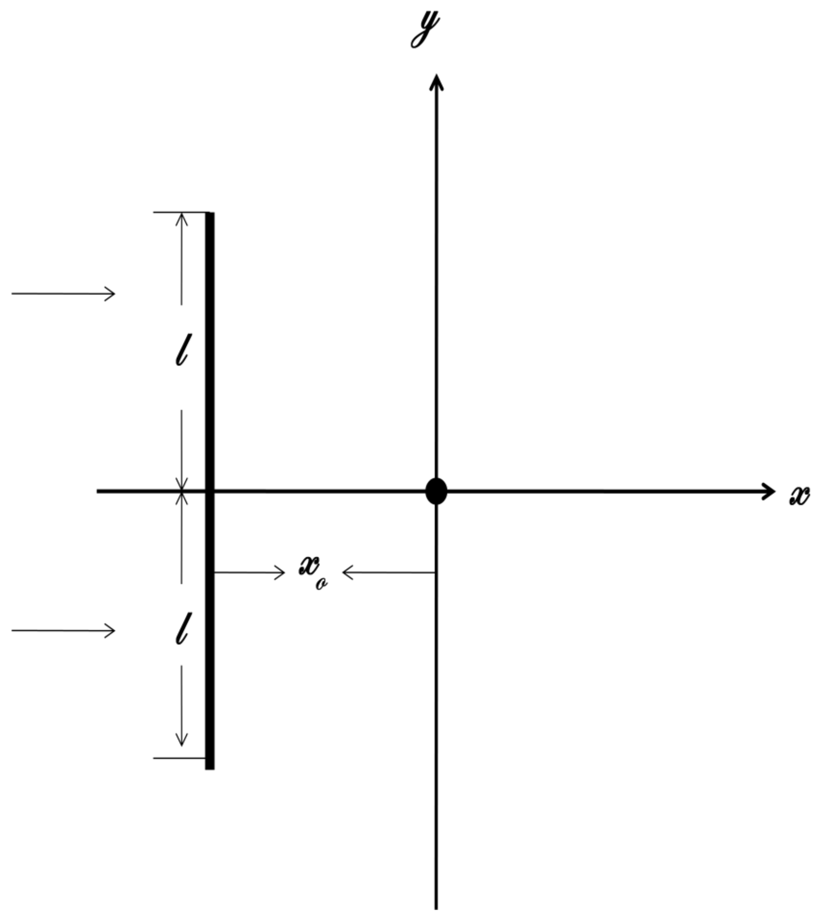


Figure 7: Schematic diagram of line source of particles. Line source is perpendicular to regional flow within a capture zone.

5. RESULTS AND DISCUSSION

5.1: Basic Well Hydraulics Surrounding the Collector Well

In past studies [*Hantush and Papadopulos*, 1962; *Rosa and Carvalho*, 1989; *Tarshish*, 1992], researchers have studied which boundary along the face of a lateral — uniform head or uniform flux— is more accurate for use in analytical studies. It is agreed that the most realistic boundary is the uniform head or infinite conductivity boundary [*Zhan et al.*, 2001]. The assumption of infinite conductivity, inside the wellbore, is equivalent to uniform head, along the laterals because there are zero "head losses in the well if the conductivity is infinite" [*Langseth et al.,*2004, p. 690]. Figures 8-13 illustrate equal head lines surrounding the different collector well designs at a 500 m^3/day pumping rate. Figures 8-10 focus on the 3-lateral collector well designs and Figures 10-12 focus on the 4-lateral designs. The close grouping of the equal head lines surrounding the laterals suggests uniform head along each lateral. These visual findings correspond to those by *Hantush and Papadopulous* [1962].

The uniform head boundary is difficult to incorporate in analytical studies, so the uniform flux, also called the discharge density, boundary is often used [*Zhan et al.,* 2001]. Figures 14-19 illustrate flow lines surrounding the various collector well designs at a 500 m^3/day pumping rate. Figures 14-16 focus on the 3-lateral collector well designs, whereas Figures 17-19 focus on the 4-lateral designs. The flow lines show uneven flux, as the number of flow lines gradually increases towards the end of each lateral. These visual results correspond to the findings of *Tarshish* [1992], which showed that the hydraulic head is at a minimum in the center of the well ,but increases towards the end of the laterals [*Langseth et al.*, 2004].

Figures 8-13 also provide a visual comparison of hydraulic head changes for each of the collector well parameters: lateral length and number of laterals. Figures 8-13 also show that with a constant number of laterals but increasing lateral length, there is an increase in hydraulic head. The 3-lateral design has a range of 16.5 m to 18.4 m (Figures 8-10). The 4-lateral design has a range of 17 m to 18.6 m (Figures 11-13). In terms of differences between the number of laterals of the same length the 4-lateral design has a higher hydraulic head than its 3-lateral counterpart. For the 25 and 50 m lengths, this value is 0.5 m greater than the 3-lateral values. However for the 100 m length lateral, there is only a 0.2 m increase compared to the 3-lateral design. These visual findings suggest that after a certain lateral length, the yields do not increase. This observation will be analyzed further throughout section 5.

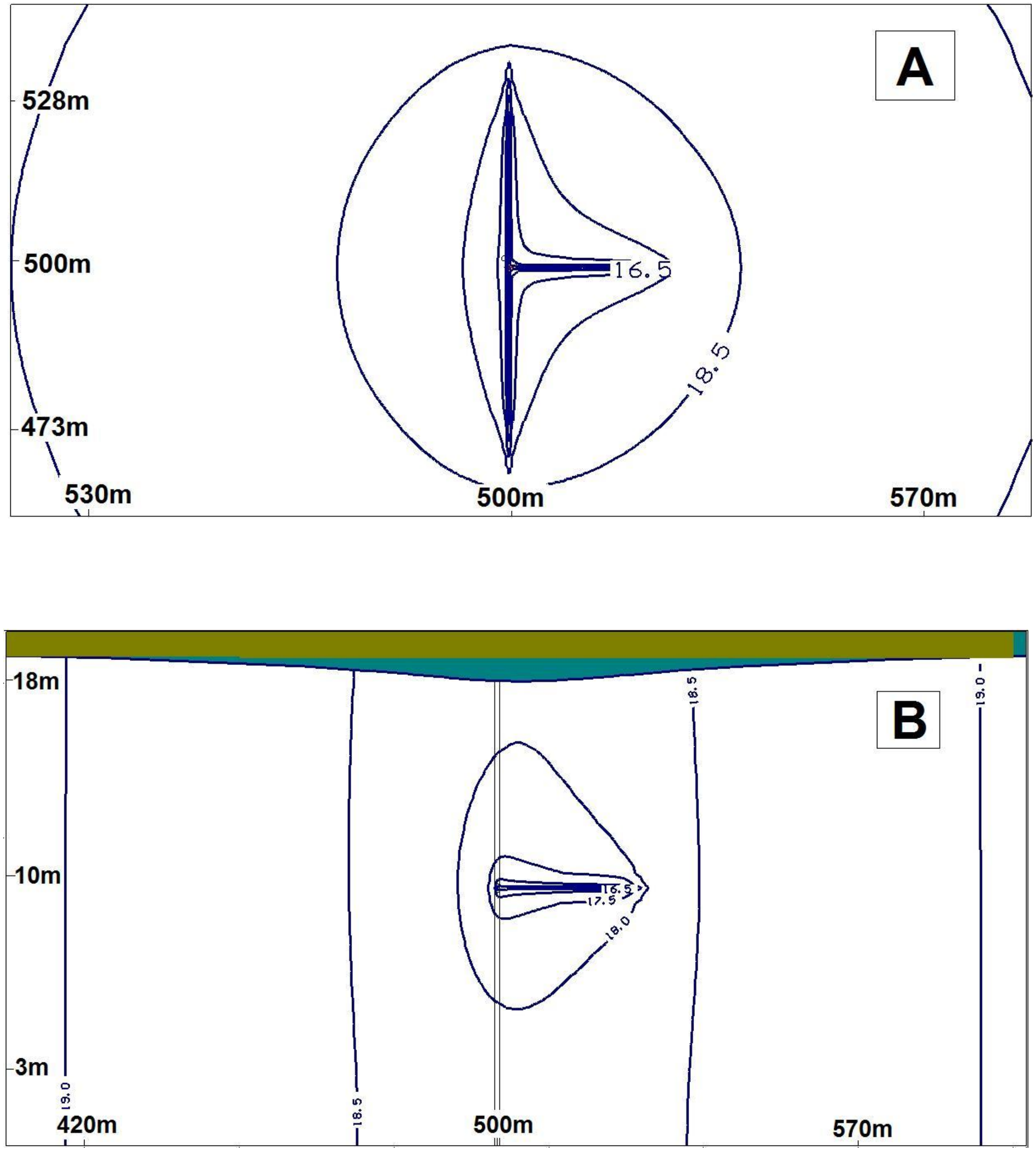
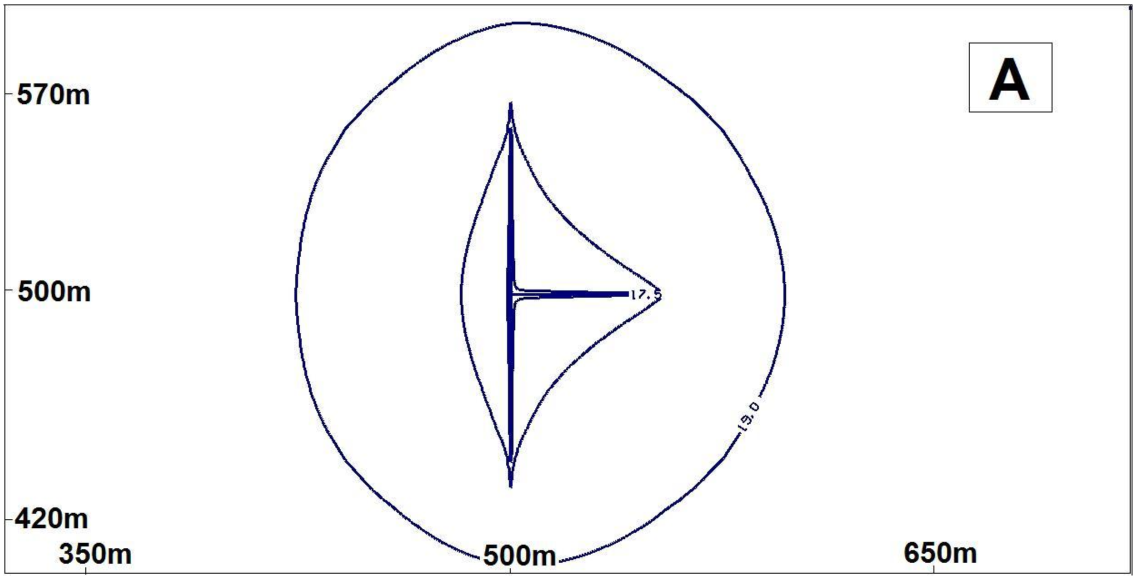


Figure 8: Equal head lines for 3-lateral, 25 m collector well configuration with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval. (a) Plan view, (b) Cross-section view with a vertical exaggeration of 5x.



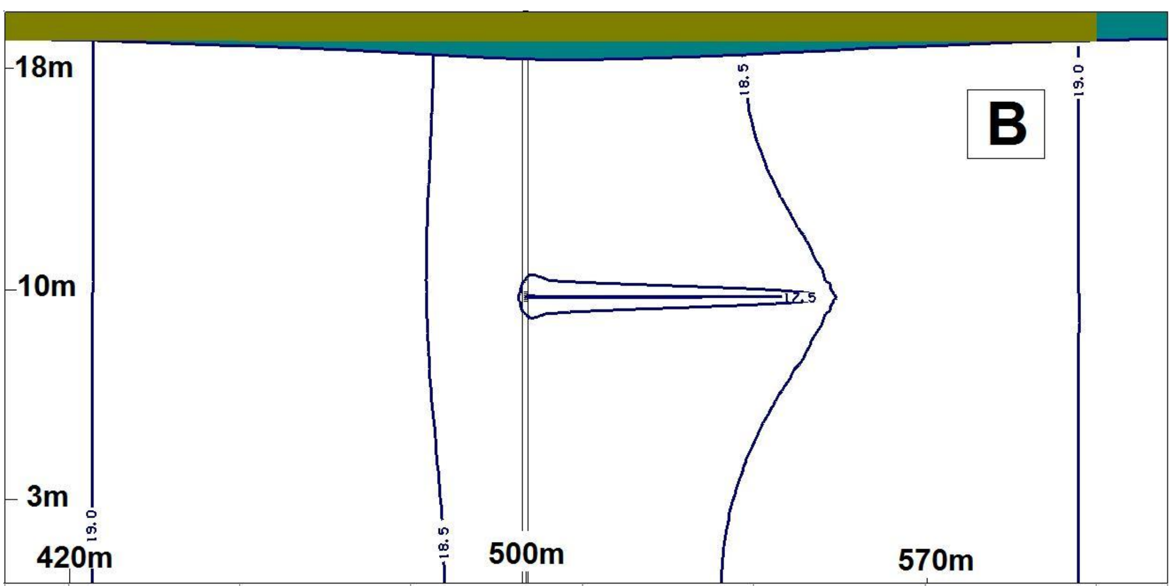


Figure 9: Equal head lines for 3-lateral, 50 m collector well configuration with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval. (a) Plan view, (b) Cross-section view with a vertical exaggeration of 5x.

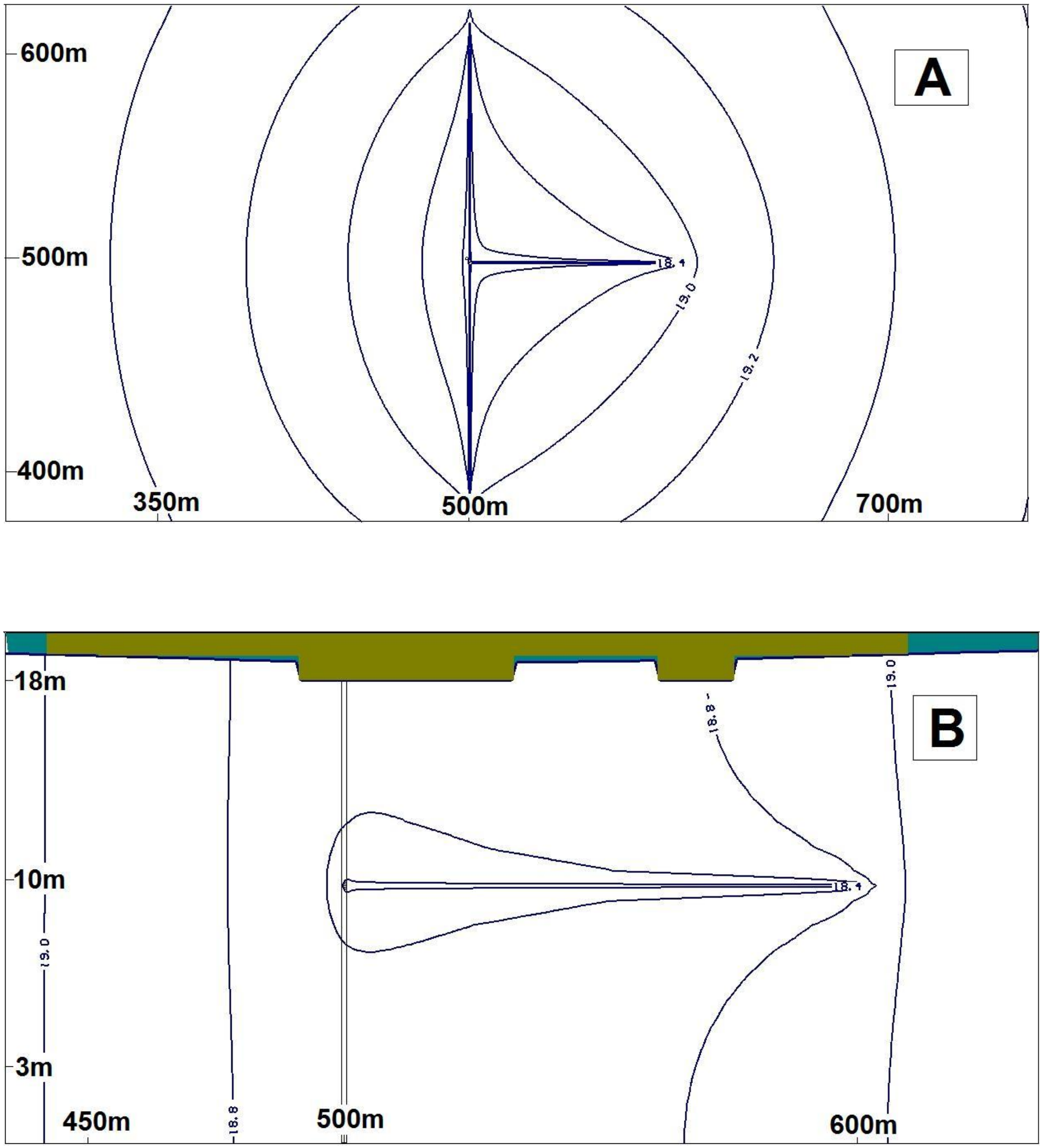


Figure 10: Equal head lines for 3-lateral, 100 m collector well configuration with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval. (a) Plan view, (b) Cross-section view with a vertical exaggeration of 5x.

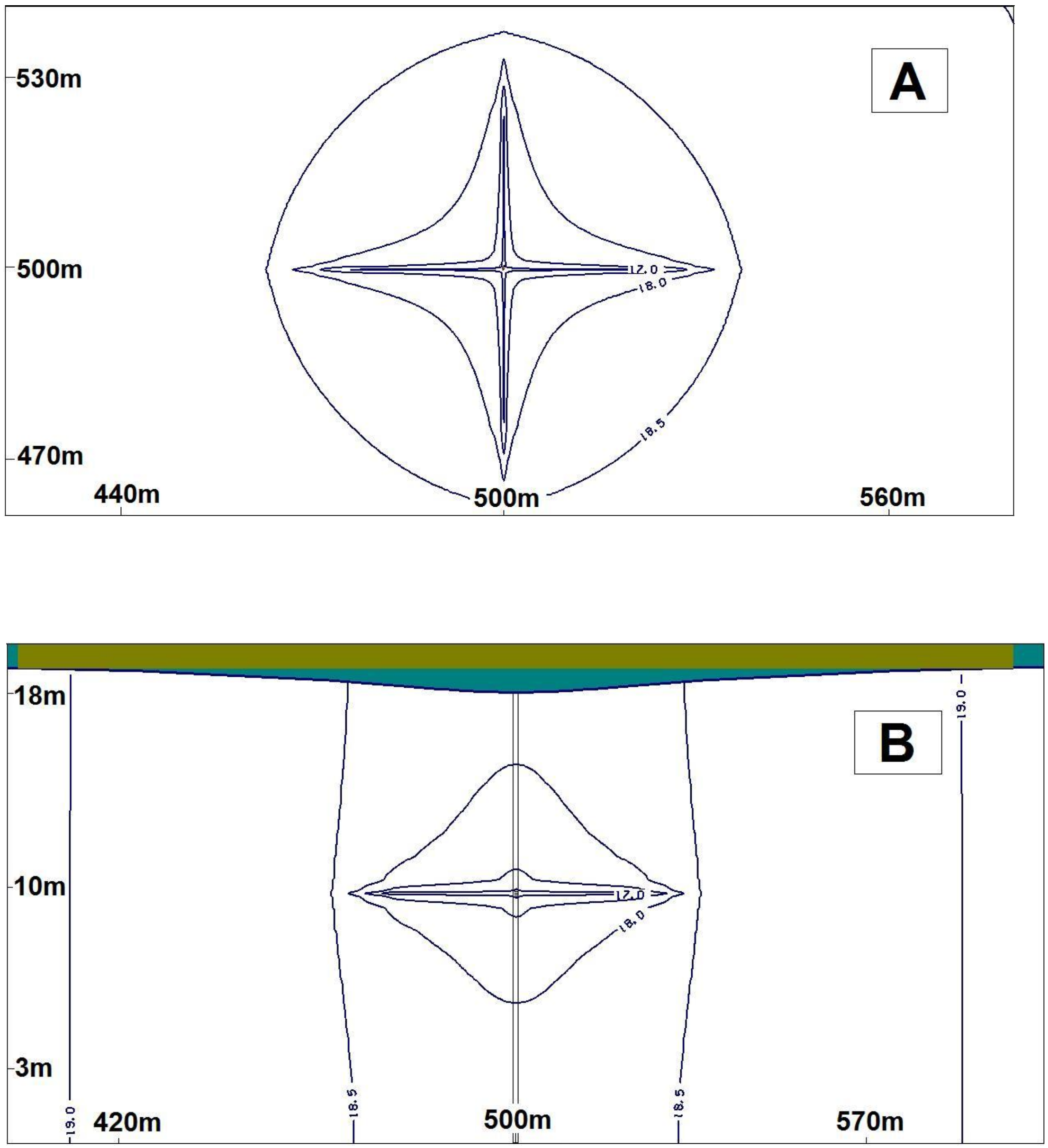
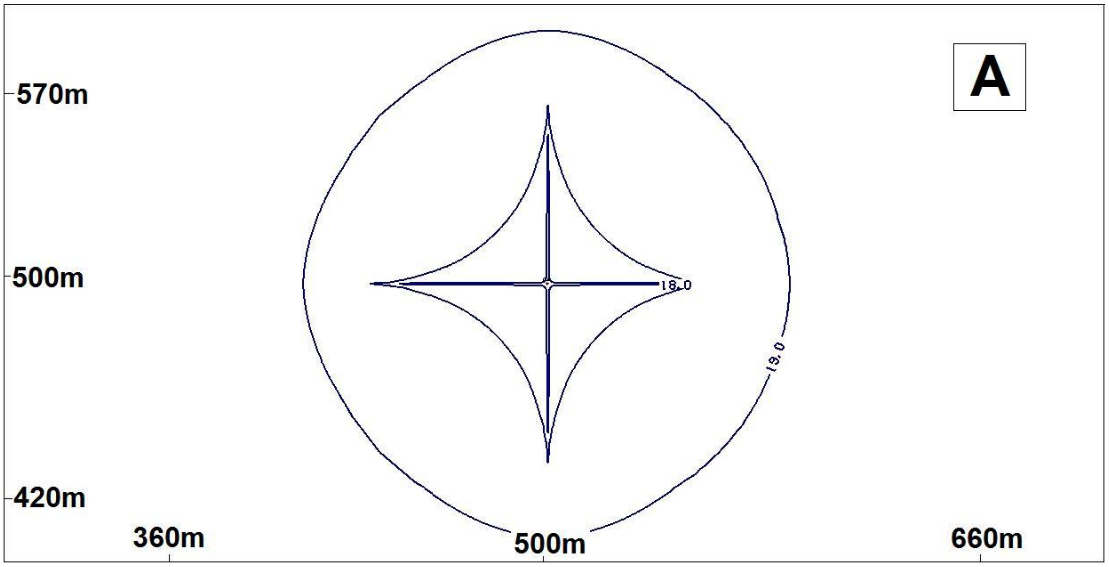


Figure 11: Equal head lines for 4-lateral, 25 m collector well configuration with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval. (a) Plan view, (b) Cross-section view with a vertical exaggeration of 5x.



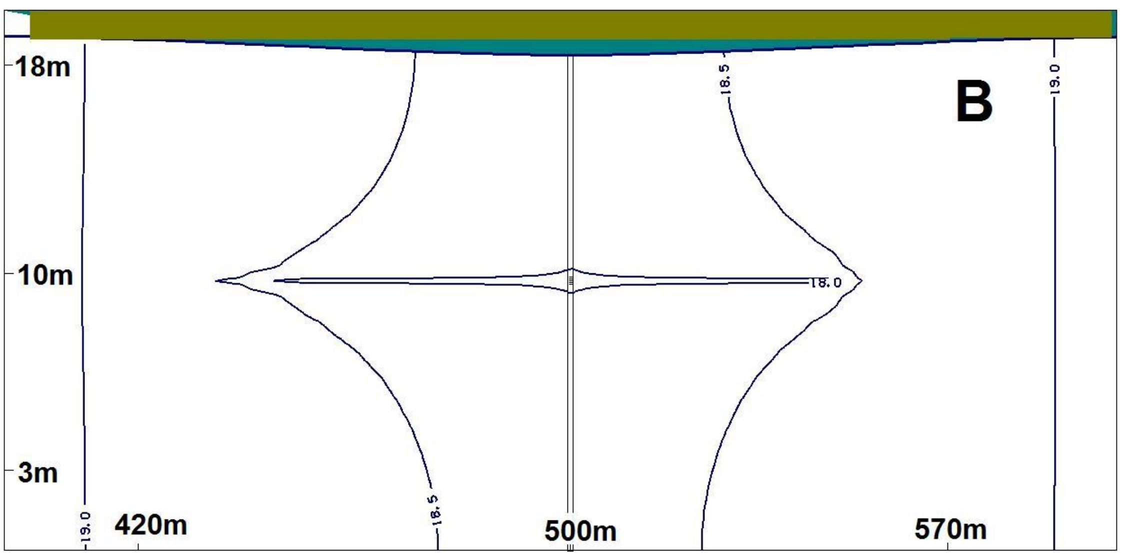


Figure 12: Equal head lines for 4-lateral, 50 m collector well configuration with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval. (a) Plan view, (b) Cross-section view with a vertical exaggeration of 5x.

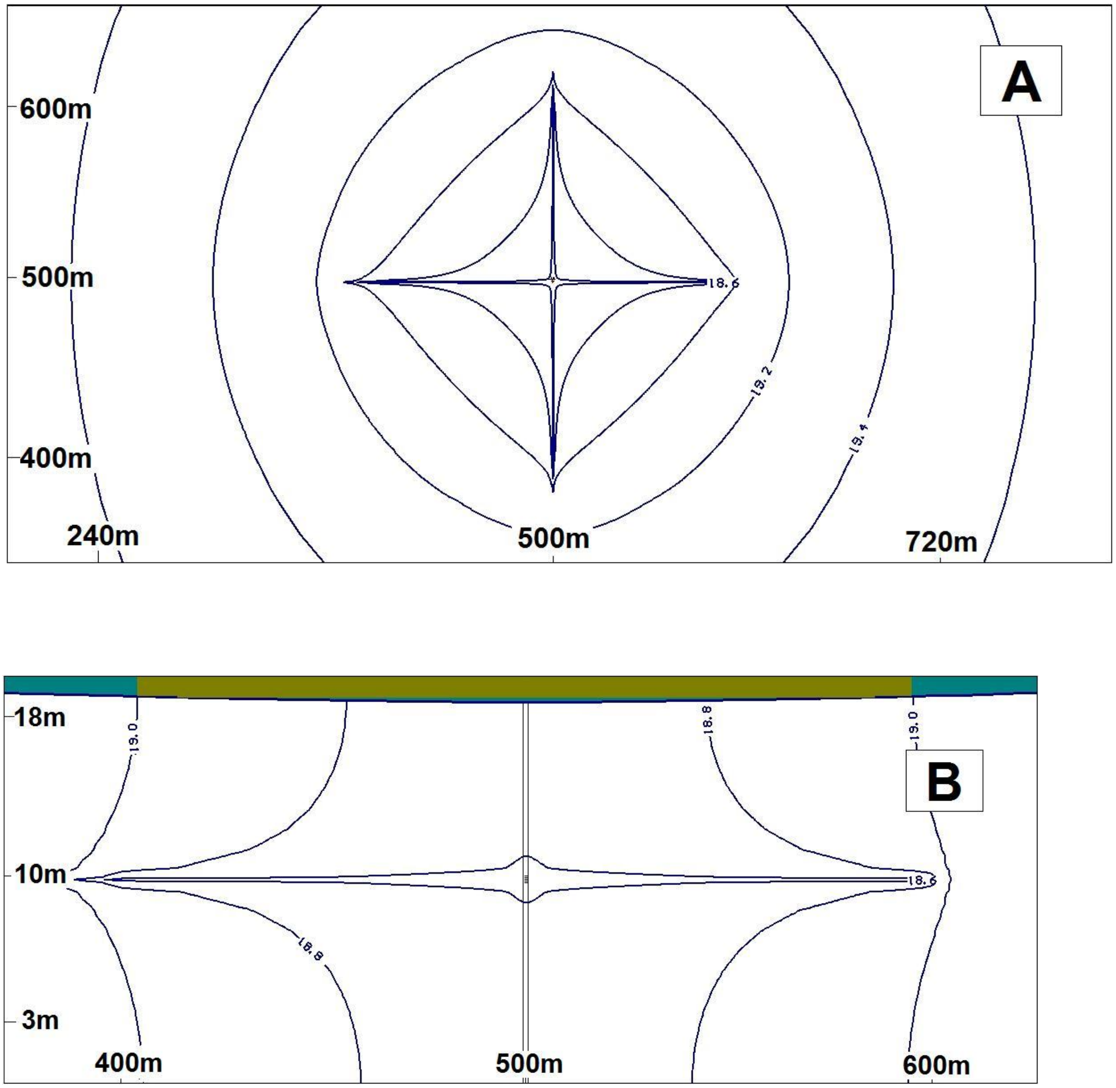


Figure 13: Equal head lines for 4-lateral, 100 m collector well configuration with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval. (a) Plan view, (b) Cross-section view with a vertical exaggeration of 5x.

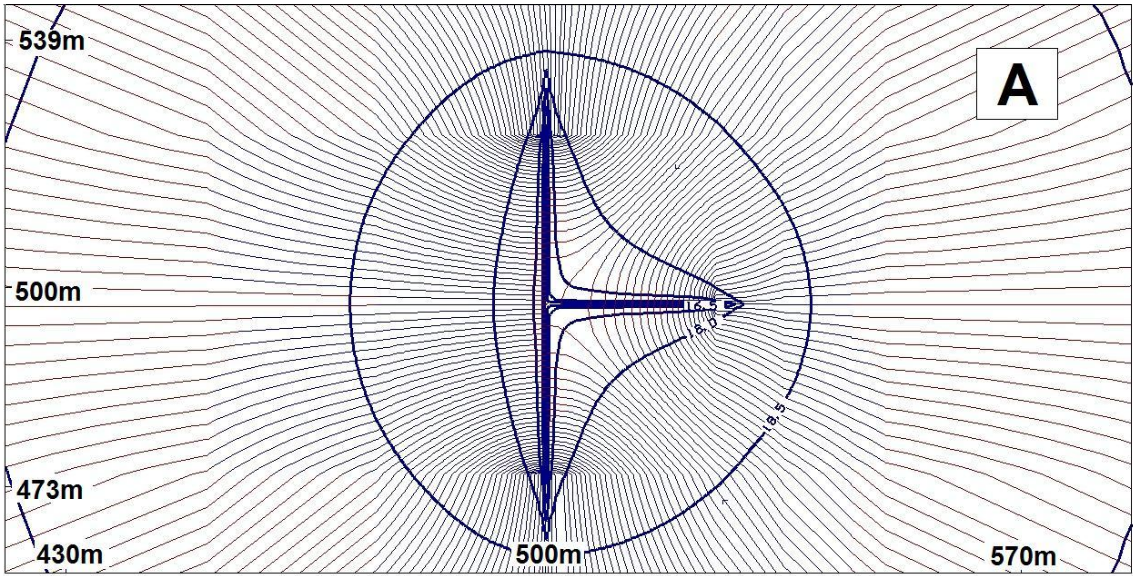


Figure 14: Plan view of flow path lines for a 3-lateral, 25 m collector well with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval.

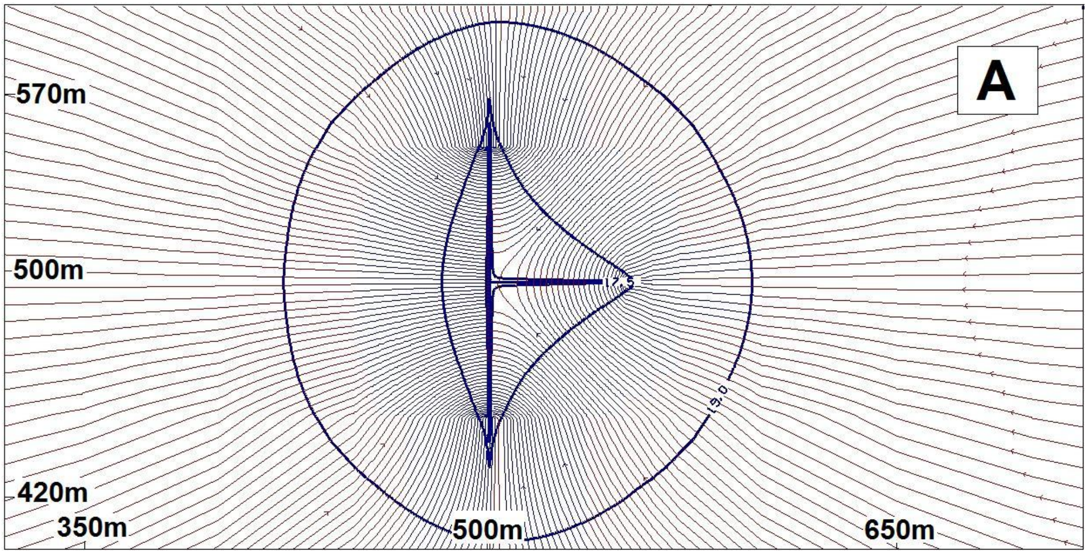


Figure 15: Plan view of flow path lines for a 3-lateral, 50 m collector well with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval.

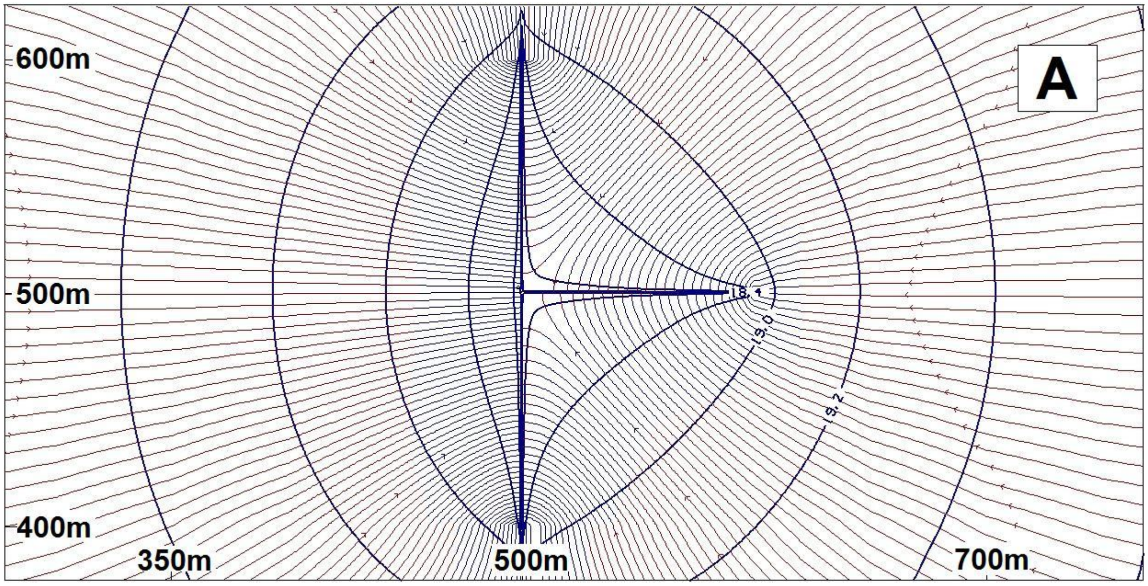


Figure 16: Plan view of flow path lines for a 3-lateral, 100 m collector well with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval.

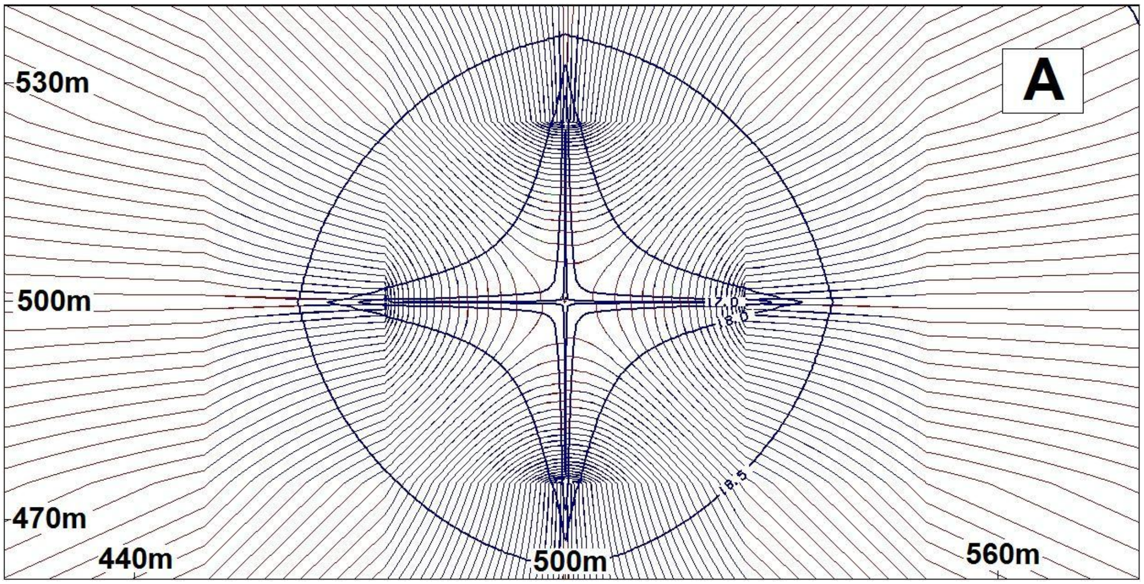


Figure 17: Plan view of flow path lines for a 4-lateral, 25 m collector well with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval.

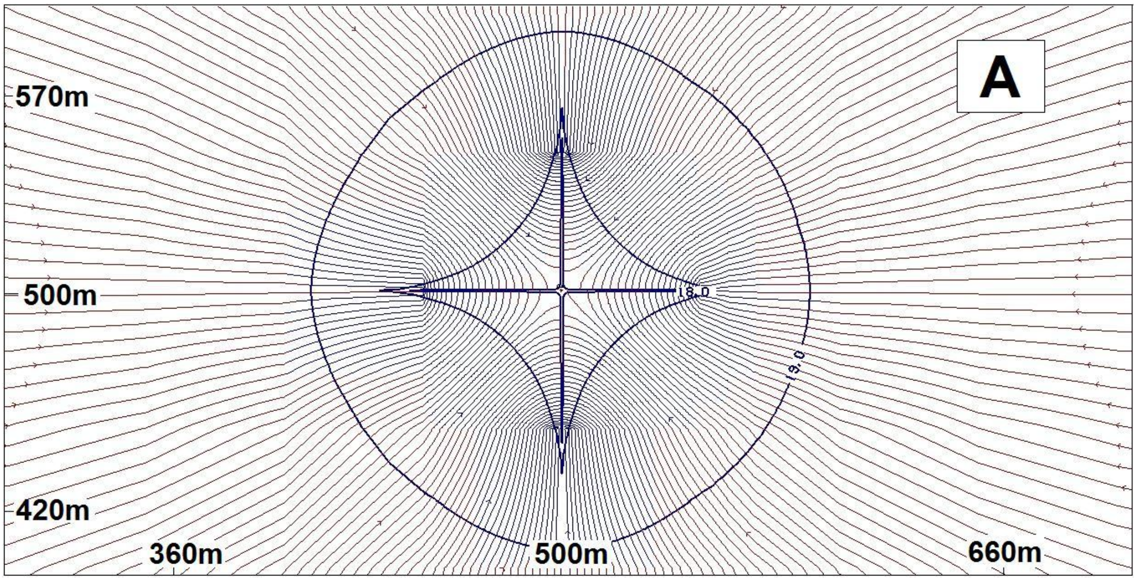


Figure 18: Plan view of flow path lines for a 4-lateral, 50 m collector well with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval.

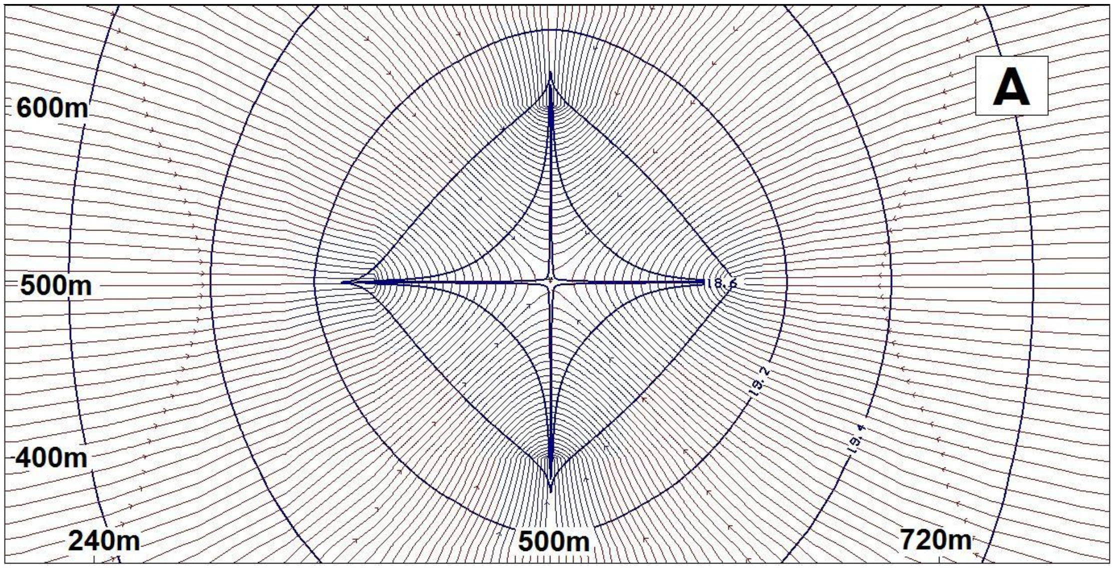


Figure 19: Plan view of flow path lines for a 4-lateral, 100 m collector well with a 500 m^3/day pumping rate. Equal head lines have a 0.5 m interval.

5.2 Water Flux along Laterals

Haitjema [1985] proposed that flux along a lateral increases as it moves away from the vertical, central caisson and towards the terminal ends of the laterals. *Dugat* [2009] confirmed these findings regarding a 4-lateral collector well design with 25 m laterals. This section will investigate how this trend changes with one less lateral and increasing lateral length. Figures 14-19 offer visual evidence of this uneven flux. Figures 20-21 illustrate the flux along each collector well designs lateral length at a 500 m^3/day pumping rate without any regional background flow. As there is negligible difference between the southern and northern lateral data, the northern lateral will be referred to as the northern/southern lateral.

Figures 20-22 show all collector well designs depict the trend of the flux increasing as it nears the terminal end of each lateral. Between the two designs, the 3-lateral collector well design has a higher flux than the 4-lateral design. This flux can be attributed to lack of an extra lateral and, possibly, the symmetrical lateral orientation of the 4-lateral design — a combination resulting in a higher amount of flux for the three remaining asymmetrical laterals to seize. In regards to lateral length, the 25 m laterals have a higher flux than the 50 m and 100 m laterals. Based on the previous observation, this flux is likely because the longer laterals are able to uptake the flux sooner and transport it over a longer period of time. *Zhan et al.* [2001] suggests this is a result of a longer lateral possessing “less pumping rate per unit screen length (*Q/L*) that determines early time drawdown” [*Zhan et al.,* 2001, p. 48]. Lastly, in both designs, the eastern lateral had the highest amount of flux. However, this trend is more visible in the 3-lateral collector well design. In these designs, the eastern lateral begins with a lower level of flux in comparison to the northern/southern lateral. Interestingly, towards the terminal end of the laterals, the eastern lateral overtakes the northern/southern lateral. This observation is possibly related to a lack of competition from the surrounding laterals as the flux in the eastern lateral moves farther from the vertical well. The same logic can be applied to the 4-lateral design but, with the presence of the western lateral, the difference in the amount of flux to the eastern lateral is not as significant.

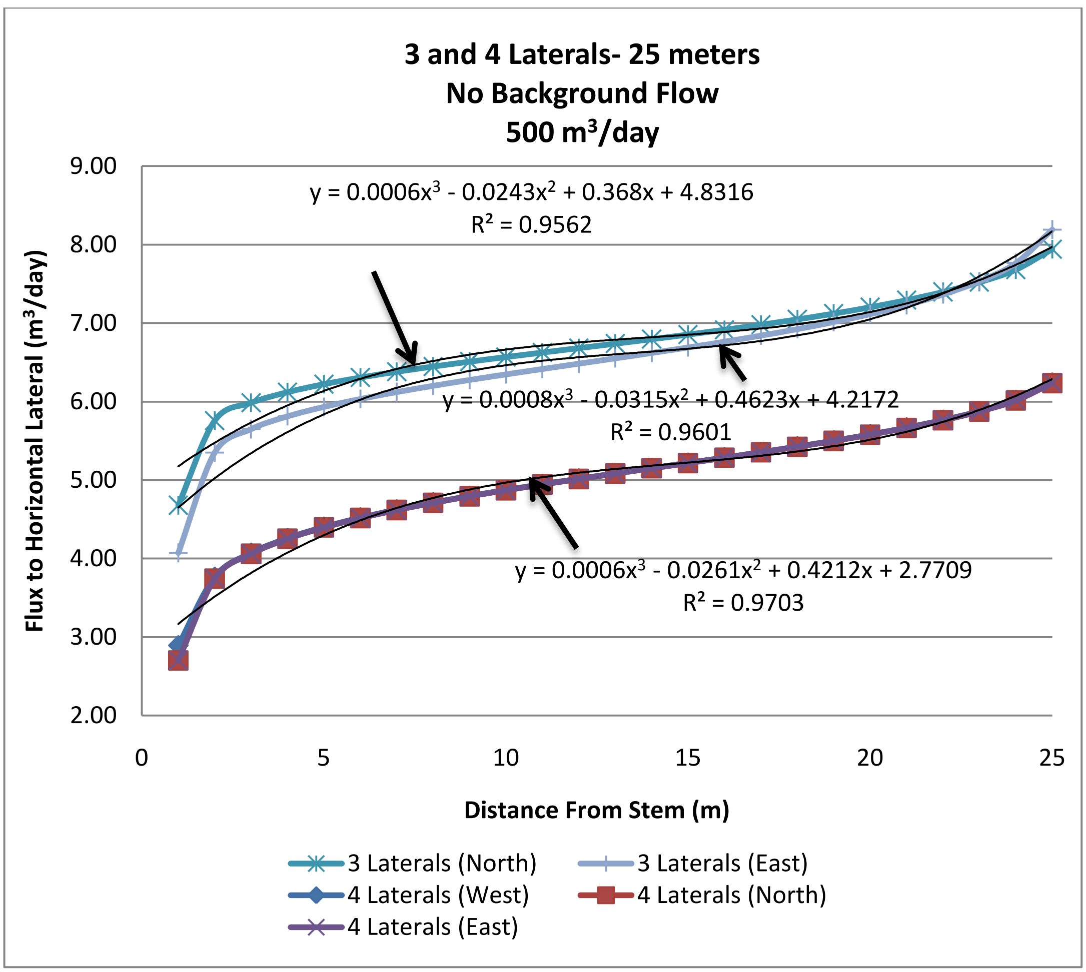


Figure 20: Flux along 3- and 4-laterals, 25 m in length with a 500 m^3/day pumping rate without regional background flow.

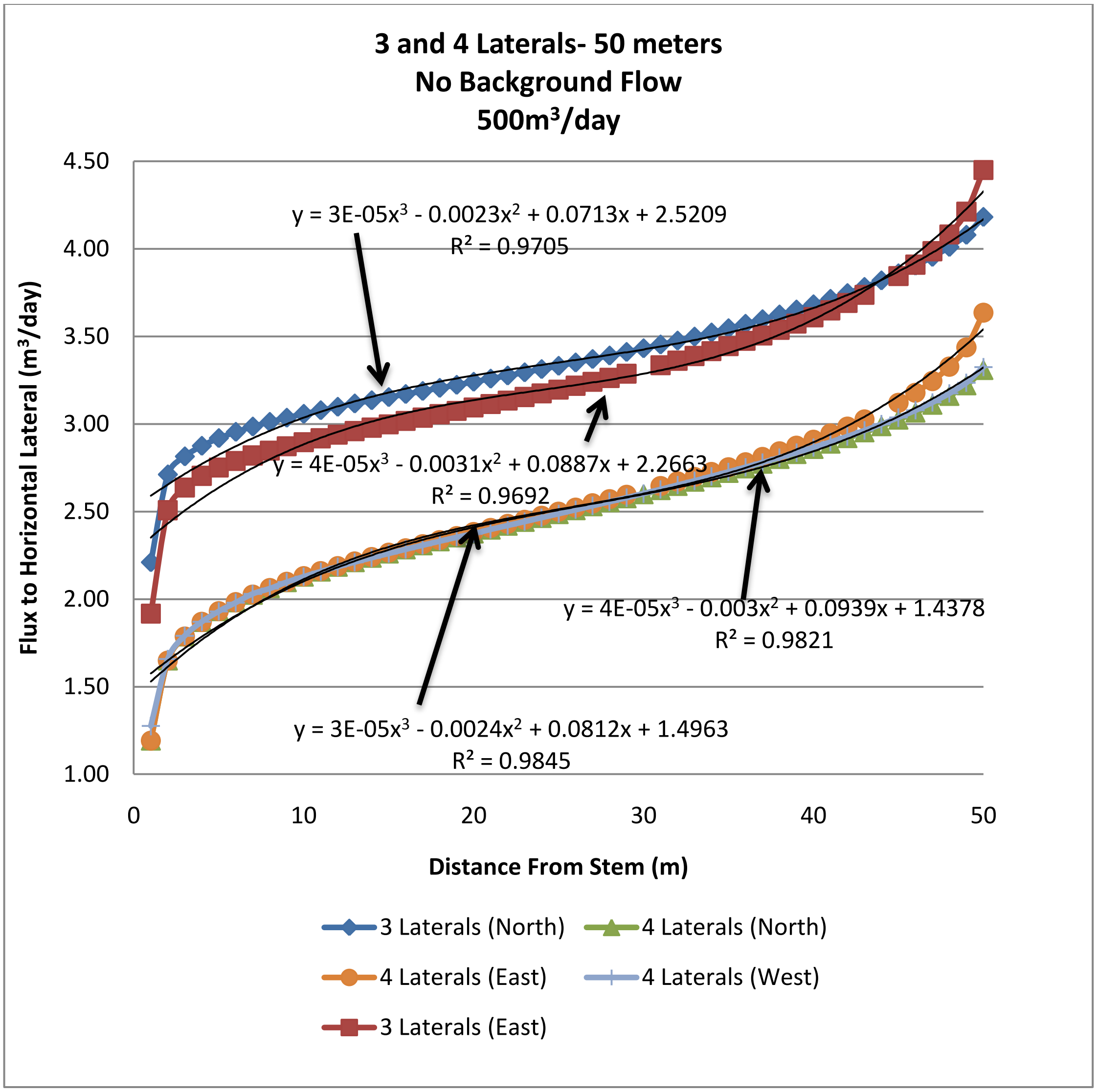


Figure 21: Flux along 3- and 4- laterals, 50 m in length with a 500 m^3/day pumping rate without regional background flow.

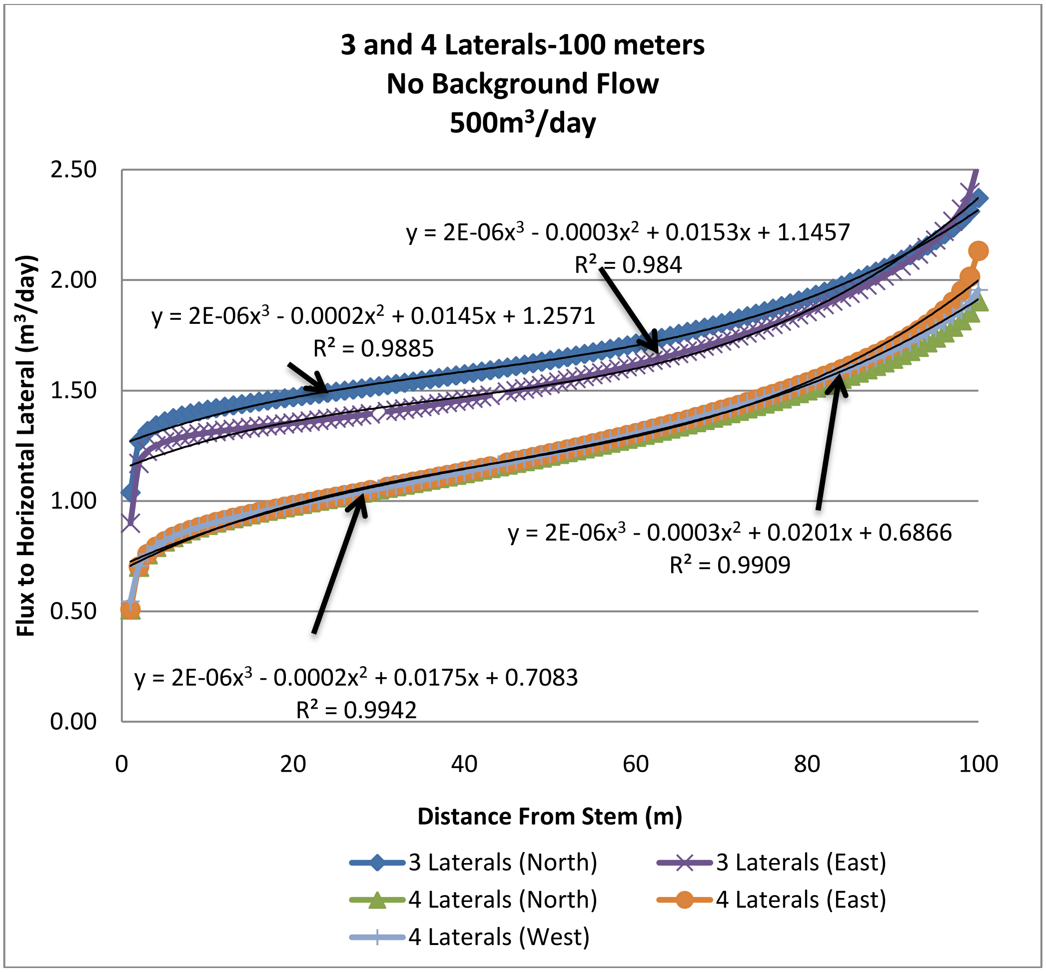


Figure 22: Flux along 3- and 4-laterals, 100 m in length with a 500 m^3/day pumping rate without regional background flow.

Dugat [2009] viewed the trend of increased pumping rate resulting in an increase in overall flux for a 4-lateral collector well design with 25 m laterals. Figures 23-25 display the effect of increased pumping rate without regional background flow on both a 3-lateral and 4-lateral design with 25 m, 50 m and 100 m long laterals. The following pumping rates are show in Figures 23-25: 250 m^3/day, 500 m^3/day, and 1,000 m^3/day. In order to obtain the overall flux to each collector well design, the average of the flux for each lateral was calculated. All figures show the expected increase in flux associated with an increase in pumping rate along the length of the laterals. Three similar trends, which were seen in Figures 20-22, were also seen in Figures 23-25. The 3-lateral designs have a higher amount of flux for all lateral lengths compared to the 4-lateral design. With increasing lateral length, the amount of flux intercepted for each collector well design decreases. Also, as the flux moves towards the terminal end of each collector well design, the flux increases. The differences between the 3-lateral design and the 4-lateral design can be attributed to the lack of an extra lateral. Without the extra lateral there is less competition for obtaining the flux, therefore the 3-lateral designs have a higher amount of flux compared to 4-lateral designs. This does not necessarily translate into 3-laterals providing a higher yield than 4-laterals.

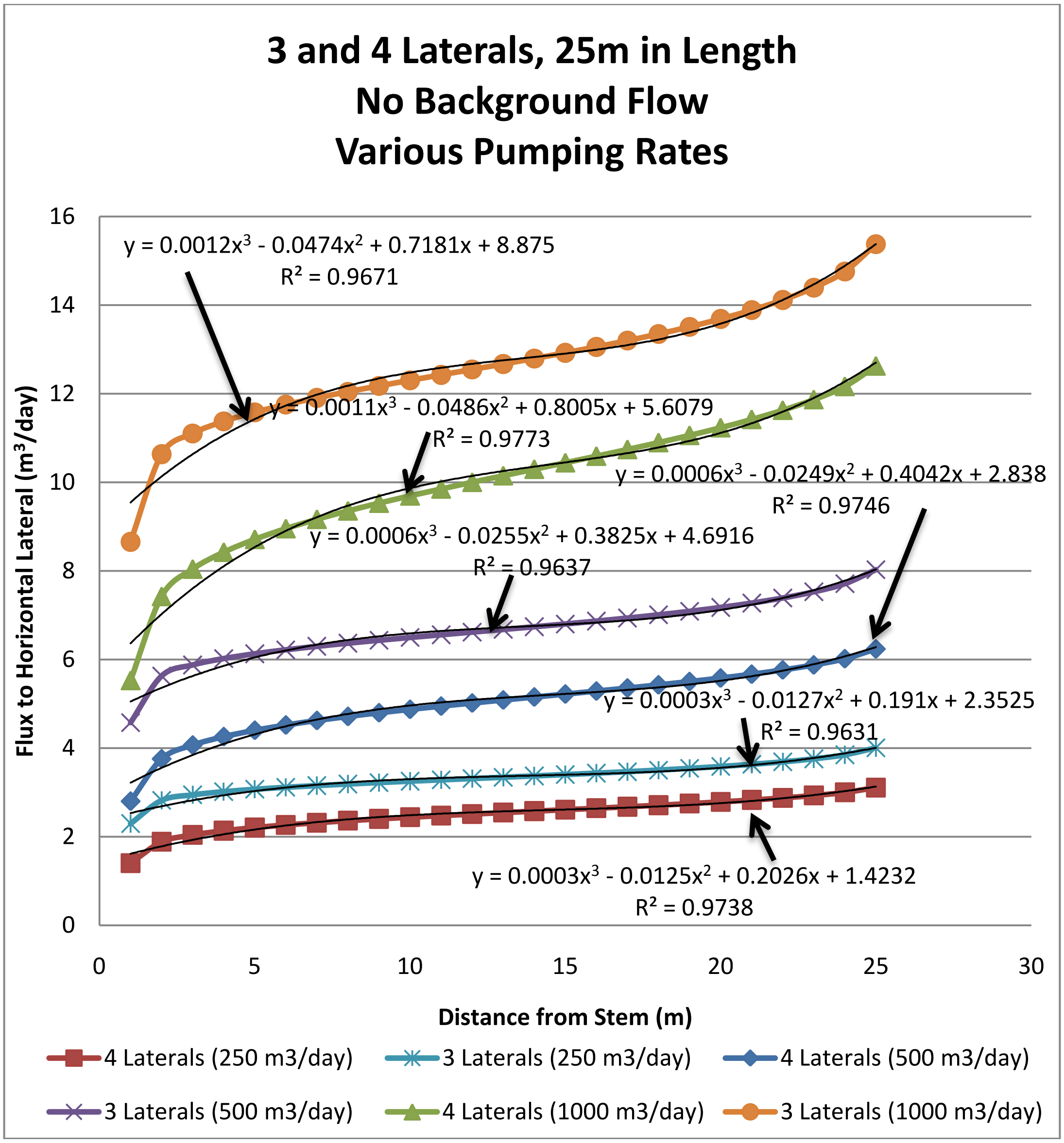


Figure 23: Flux along 3- and 4-laterals, 25 m in length with various pumping rates and no regional background flow.

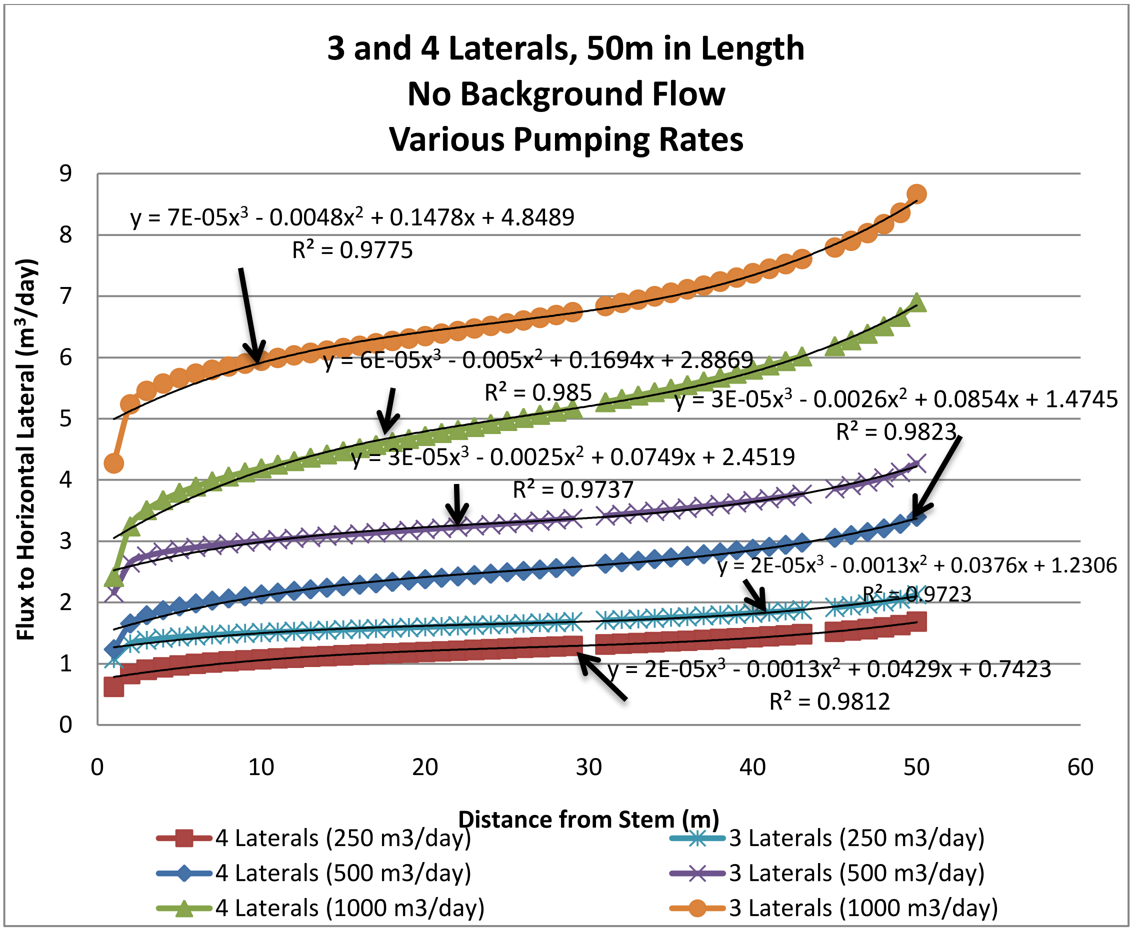


Figure 24: Flux along 3- and 4-laterals, 50 m in length with various pumping rates and no regional background flow.

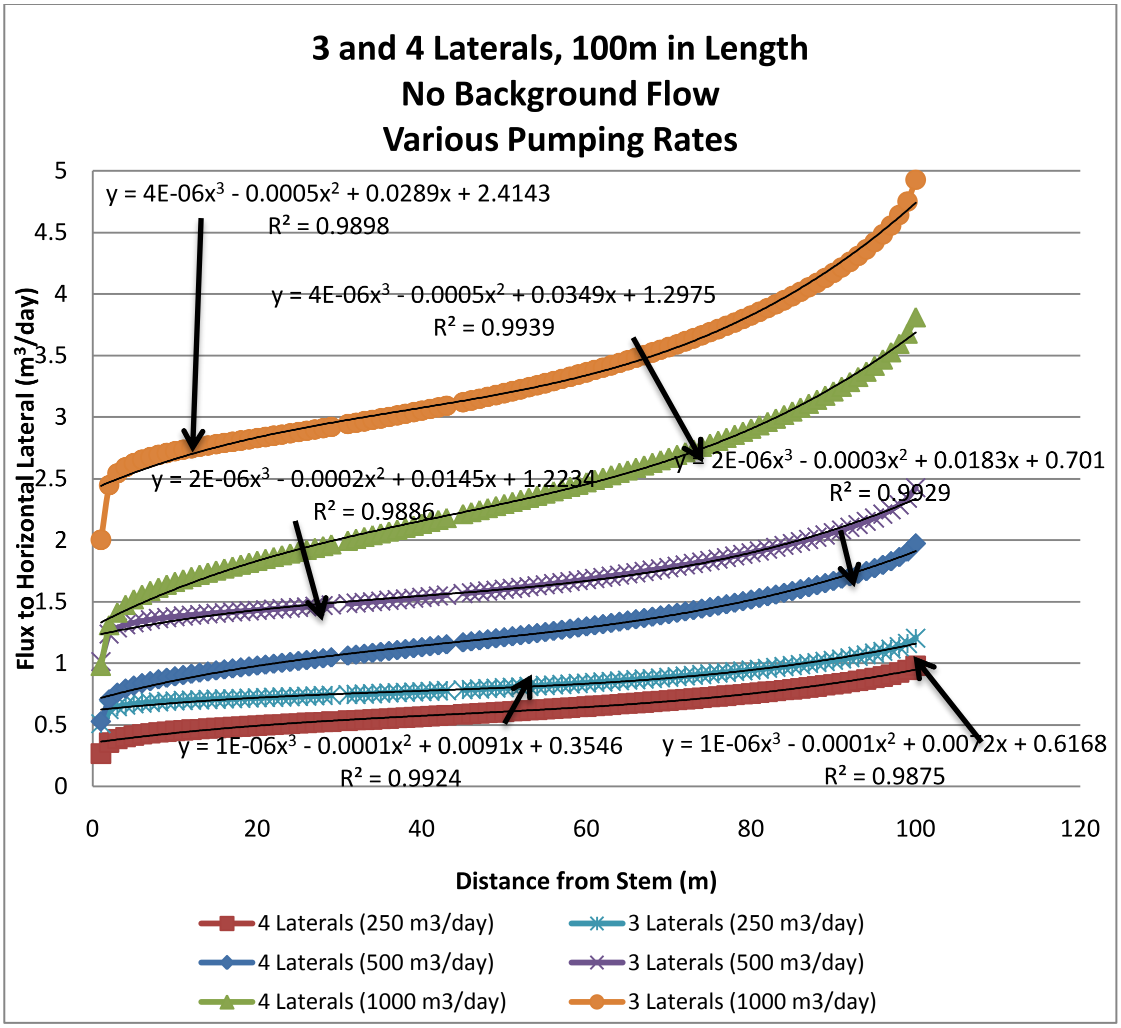


Figure 25: Flux along 3- and 4-laterals, 100 m in length with various pumping rates and no regional background flow.

Figures 26-28 illustrate the effect of increasing the regional background flow from zero to 1.73 x 10^{-2} m/day with various collector well configurations. Comparing Figures 26-28 to Figures 20-22, which have no regional background flow, allows the effects of increasing the regional flow to be easily visualized. *Dugat* [2009] showed that in a 4-lateral collector well design with 25 m long laterals the western lateral obtained the most flux, followed by the northern/southern lateral, and eastern lateral, respectively.

Figures 26-28 also support *Dugat's* [2009] findings. For each collector well design, the upstream or western lateral encountering the regional flow first has the highest amount of flux overall. The downstream or eastern lateral receives the least amount of flux. The northern/southern laterals are in-between the western and eastern laterals, in terms of amount of flux received. Tables 1- 2 display the amount of flux at the terminal end for each collector well design in the various regional background flow settings. Figures 26-28 show overall that the 3-lateral collector well design obtains the most amount of flux. In terms of lateral length, the amount of flux decreased with increasing lateral length.

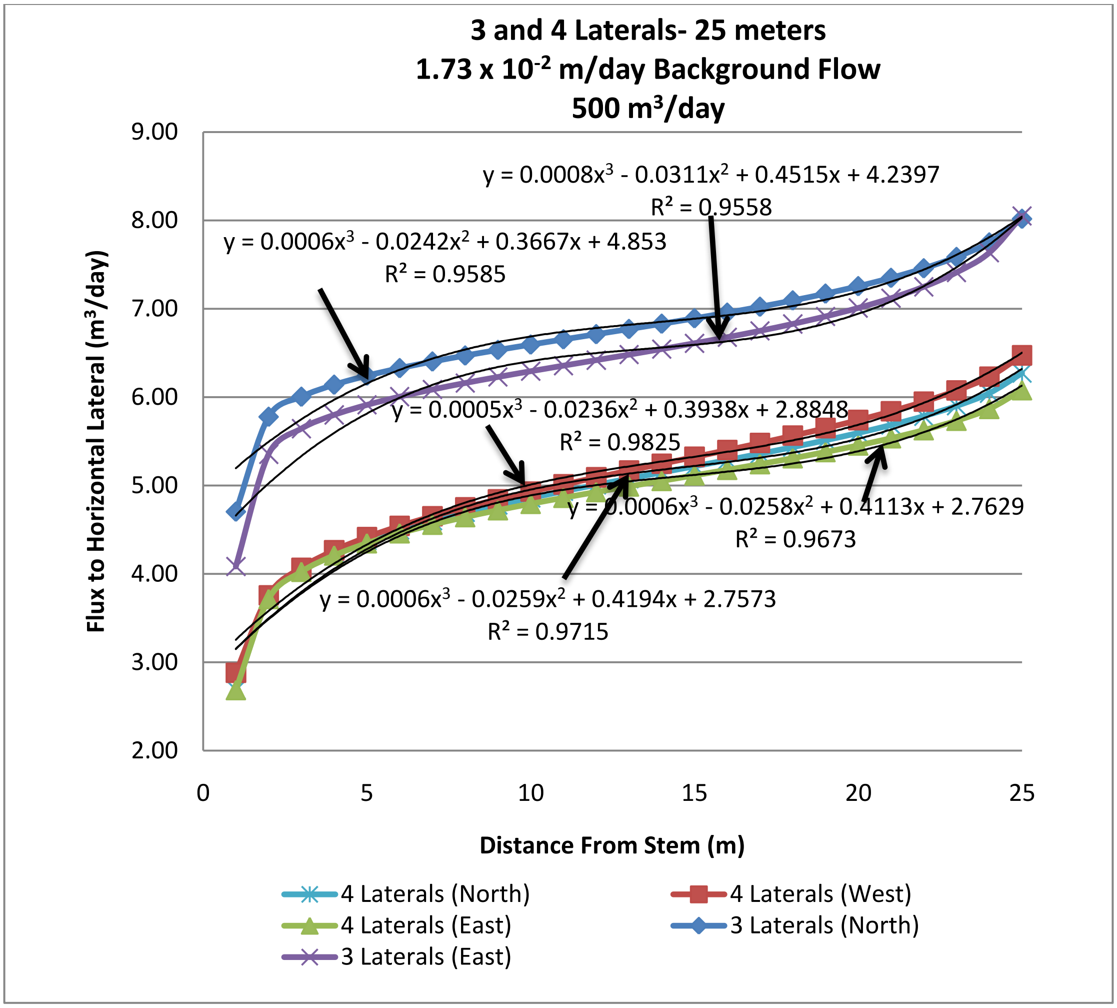


Figure 26: Flux along 3- and 4-laterals, 25 m in length with 500 m^3/day pumping rate with 1.73 x 10^{-2} m/day regional background flow.

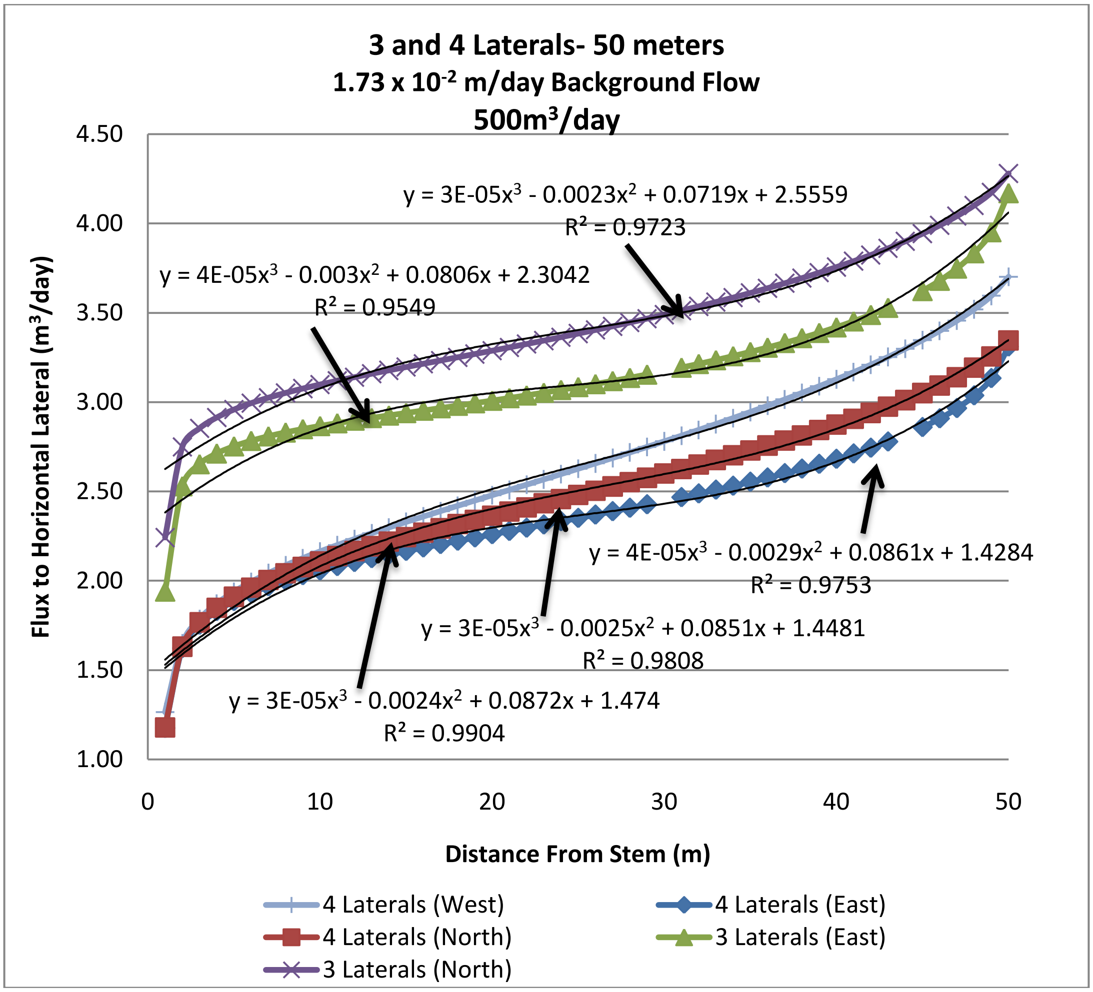


Figure 27: Flux along 3- and 4-laterals, 50 m in length with 500 m^3/day pumping rate with 1.73 x 10^{-2} m/day regional background flow.

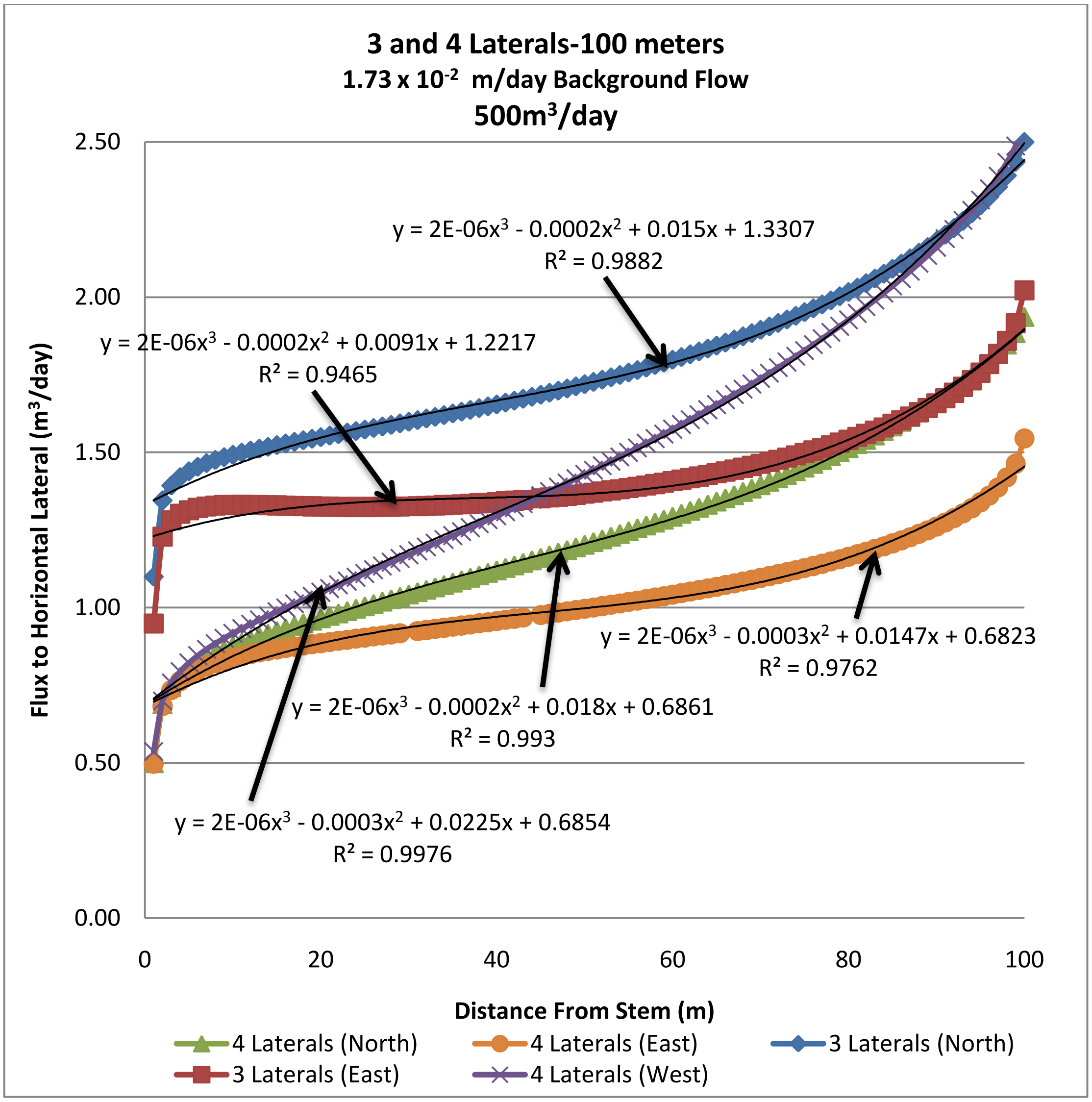


Figure 28: Flux along 3- and 4-laterals, 100 m in length with 500 m^3/day pumping rate with 1.73 x 10^{-2} m/day regional background flow.

Figures 29-31 further depict the effect of increased regional background flow on the collector well designs. Tables 1- 2 show the impact of increased regional background flow on the flux at the terminal end of each lateral. Overall, an increase in the regional background flow from 1.73 x 10^{-2} m/day to 4.32 x 10^{-2} m/day exacerbates the trends viewed in Figures 26-28. In both collector well designs, the northern/southern lateral experiences a slight increase in flux, whereas the eastern lateral encounters noticeably less flux. The western lateral receives a greater increase in flux, compared to the northern/southern lateral. However, there is one discrepancy to these trends. The 4-lateral design eastern lateral at 25 m in length shows an anomaly to the trend viewed in the other lateral lengths with an increase in regional background flow. Table 1 shows that the 25 m eastern lateral experiences an increase in flux, rather than the expected decrease. This may be attributed to a numerical error as this trend holds true for the other models.

Table 1: Flux at terminal end for 4-lateral collector well designs with increasing regional background flow.

Lateral	Western Lateral			Eastern Lateral			Northern/Southern Lateral		
Lateral Length (m)	*25 m*	*50 m*	*100 m*	*25 m*	*50 m*	*100 m*	*25 m*	*50 m*	*100 m*
Regional Background Flow (m/day)	*Flux m^3/day*			*Flux m^3/day*			*Flux m^3/day*		
0 m/day	6.24	3.32	1.96	6.24	3.64	2.13	6.23	3.31	1.90
1.73×10^{-2} m/day	6.47	3.70	2.56	6.08	3.31	1.54	6.27	3.35	1.94
4.32×10^{-2} m/day	6.83	4.27	3.44	6.15	2.83	0.68	6.33	3.41	1.99

Table 2: Flux at terminal end for 3-lateral collector well designs with increasing regional background flow.

Lateral	**Eastern Lateral**			**Northern/Southern Lateral**		
Lateral Length (m)	*25 m*	*50 m*	*100 m*	*25 m*	*50 m*	*100 m*
Regional Background Flow (m/day)	***Flux m^3/day***			***Flux m^3/day***		
0 m/day	8.19	4.45	2.53	7.94	4.18	2.37
1.73×10^{-2} m/day	8.05	4.28	2.02	8.02	4.28	2.50
4.32×10^{-2} m/day	7.85	3.76	1.27	8.15	4.44	2.70

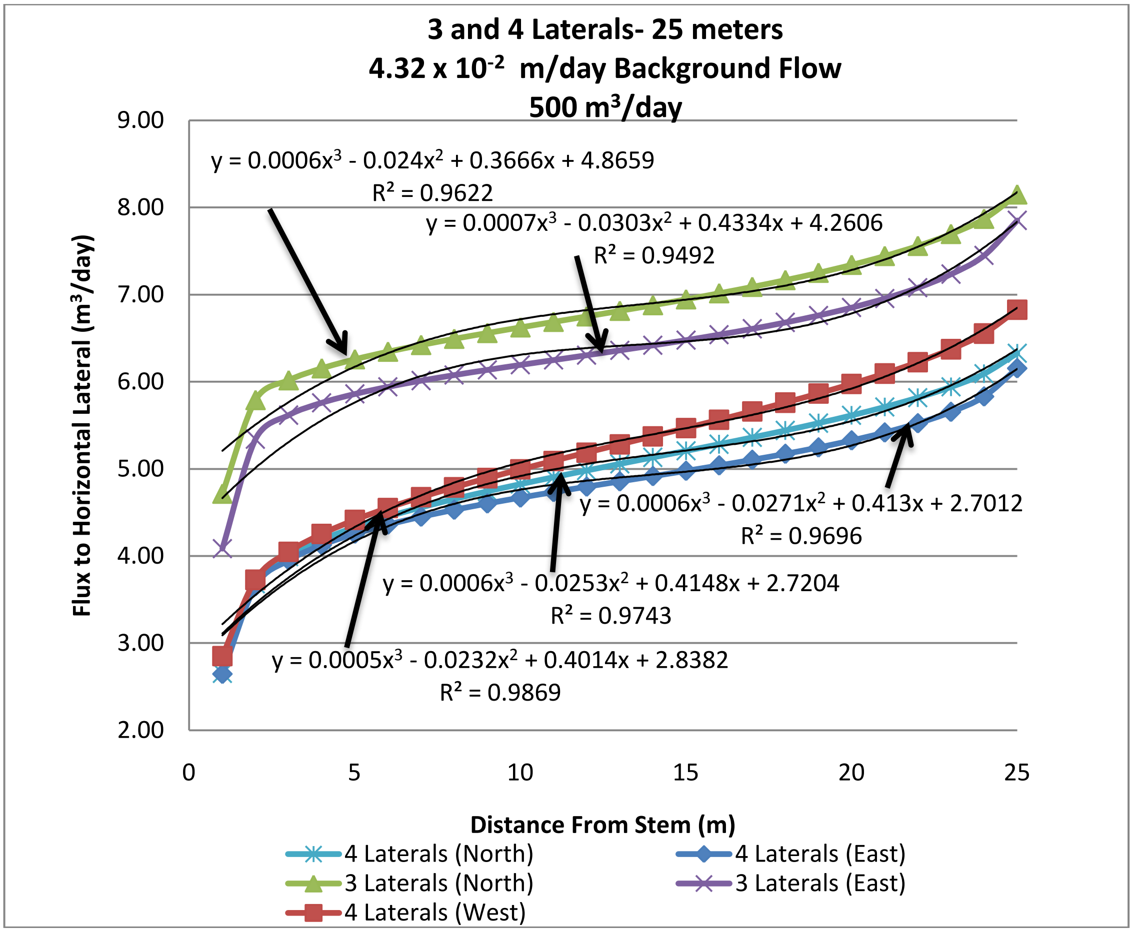


Figure 29: Flux along 3- and 4-laterals, 25 m in length with 500 m^3/day pumping rate with 4.32 x 10^{-2} m/day regional background flow.

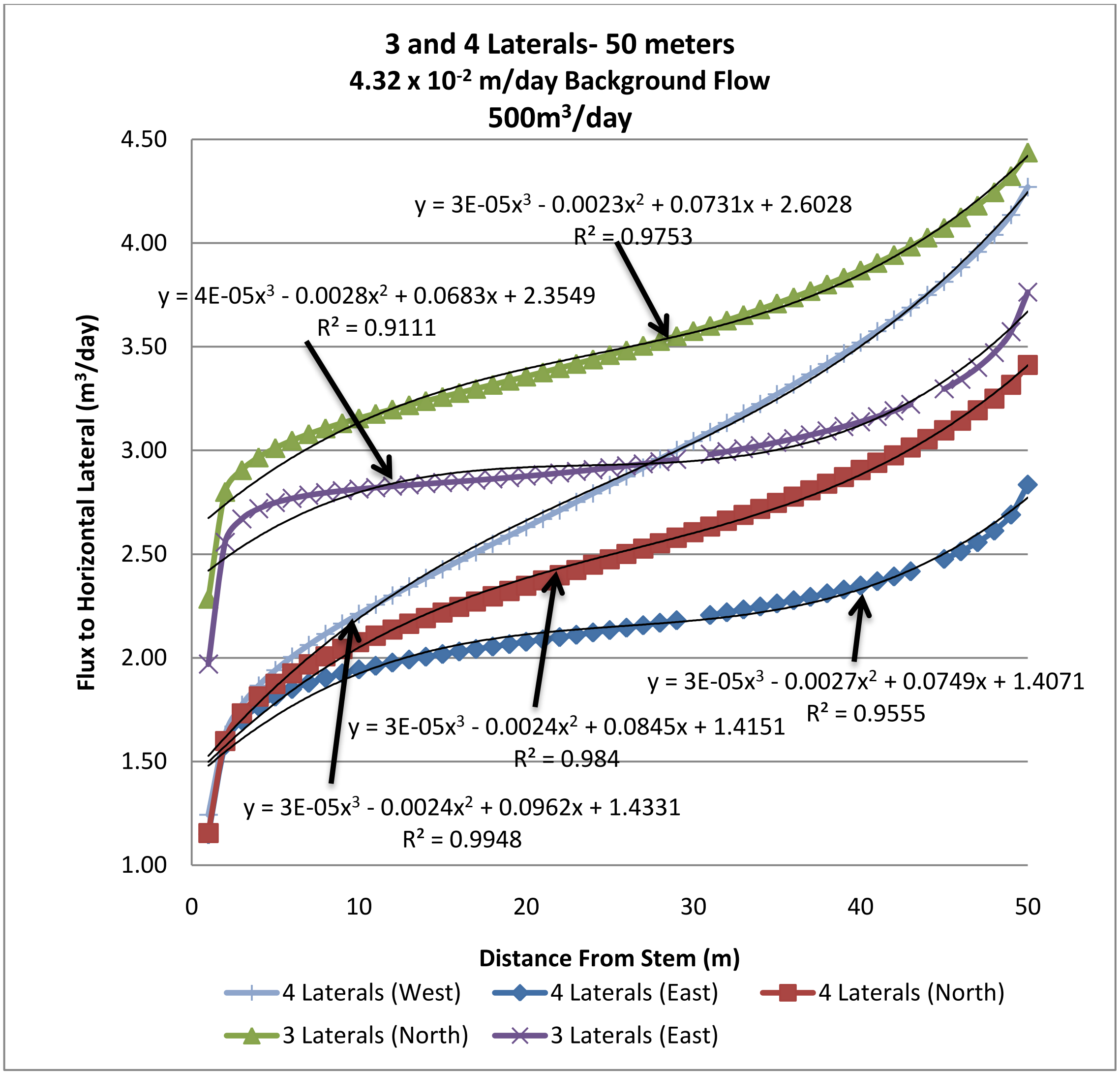


Figure 30: Flux along 3- and 4-laterals, 50 m in length with 500 m^3/day pumping rate with 4.32 x 10^{-2} m/day regional background flow.

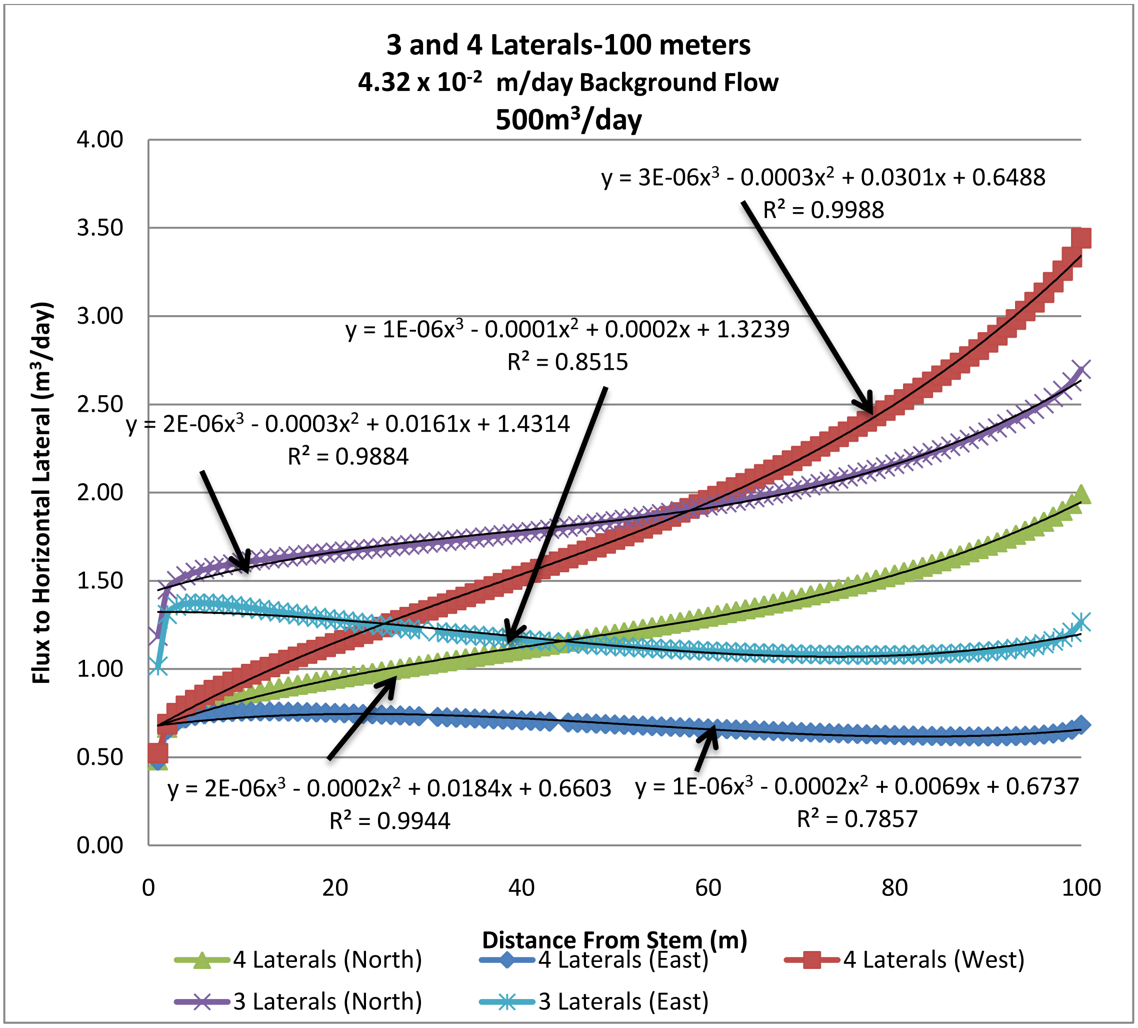


Figure 31: Flux along 3- and 4-laterals, 100 m in length with 500 m^3/day pumping rate with 4.32 x 10^{-2} m/day regional background flow.

5.3: Water Flux to River

5.3.1: Gaining and Losing Portions of River Investigation

After investigating the relationship of the flux along the laterals, the flux interaction between the collector well and the river was analyzed. To understand this relationship ZoneBudget® in Visual Modflow® was utilized to show the inflow and outflow for the modeled river. *Dugat* [2009] showed that the gaining and losing portions of the river could be plotted to illustrate when the pumping rate would have deleterious effects on the river and cause it to become a losing river. This section further demonstrates this finding on varied parameters of the collector well design.

Figures 32-34 show the gaining and losing portions of flux to and from a 16 m stage river in a 10 m deep riverbed with a 4.32 x 10^{-2} m/day regional background flow. All figures display the gaining and losing portions for the 3- and 4-lateral collector well designs. The losing portion of the river represents water lost to zone 106, the riverbed. Conversely, the gaining portion of the river represents water gained from the riverbed. All figures show that ultimately the gaining and losing portions of the river intersect at a point where the amount of water lost equals the amount of water gained. Figure 32 is the only figure that does not show these two lines intersecting. This is a result of an abnormal termination error received for the 1000 m^3/day pumping rate model. An abnormal termination error occurs because of non-convergence of a model. Non-convergence results when certain parameters in a model (i.e., dry cells) prevent a model from reaching a completed run. Figures 32-34 show that the maximum amount of flux for each collector well design is obtained at a 0 m^3/day pumping rate. As the pumping rate increases the amount of water lost from the river increases, and the amount of water gained from the river decreases. It is not until the amount of water lost from the river exceeds the amount of water gained from river that the river transforms from a gaining river to a losing one. As stated earlier, the lines do not intersect in Figure 33 as a result of non-convergence of the model. Figures 33-34 do display intersection for both collector well designs. Figure 33 illustrates convergence from the both designs at approximately the 900 m^3/day pumping rate. The 3-lateral design converges slightly sooner than the 4-lateral design. Figure 34 depicts intersection for the 3-lateral design roughly at 800 m^3/day, whereas the 4-lateral design meets at about the 950 m^3/day pumping rate. Overall, Figures 32-34 show that with increasing lateral length intersection occurs sooner and at a lower pumping rate. In regards to number of laterals, the 3-lateral designs have convergence sooner than the 4-lateral designs.

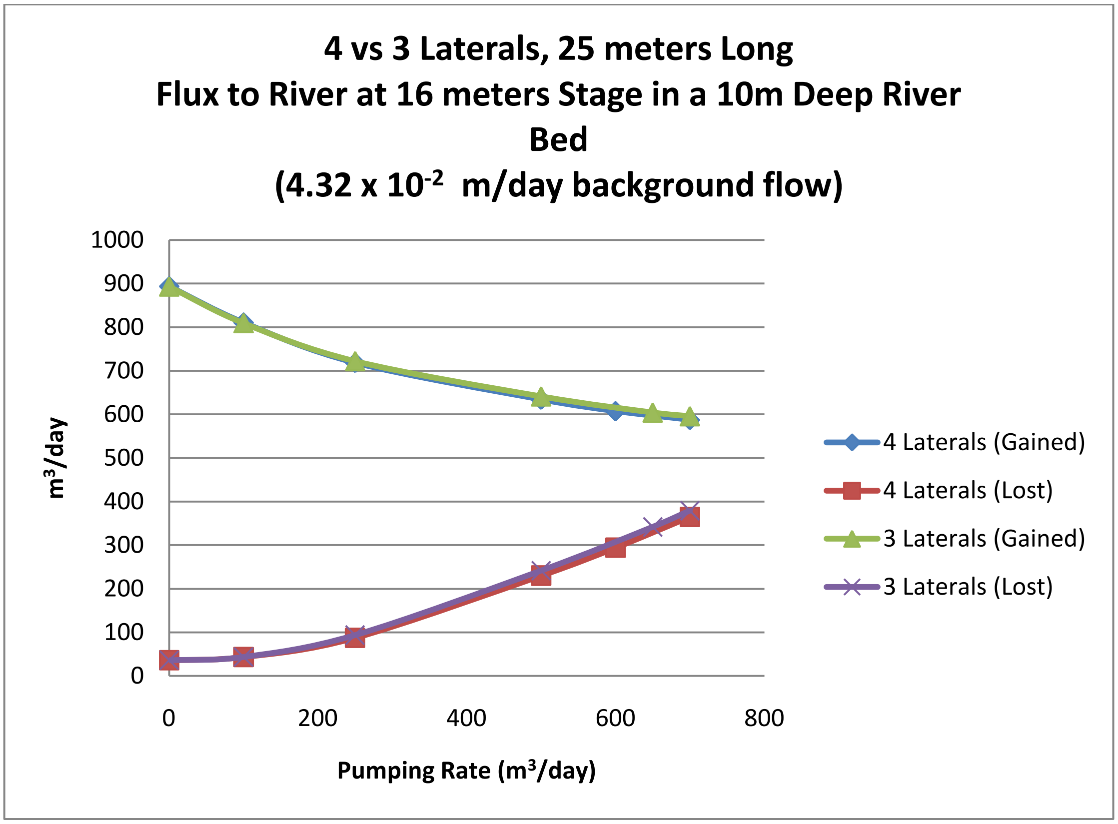


Figure 32: Flux to 16 m stage river in a 10 m deep river bed with 3- and 4-laterals at 25 m in length.

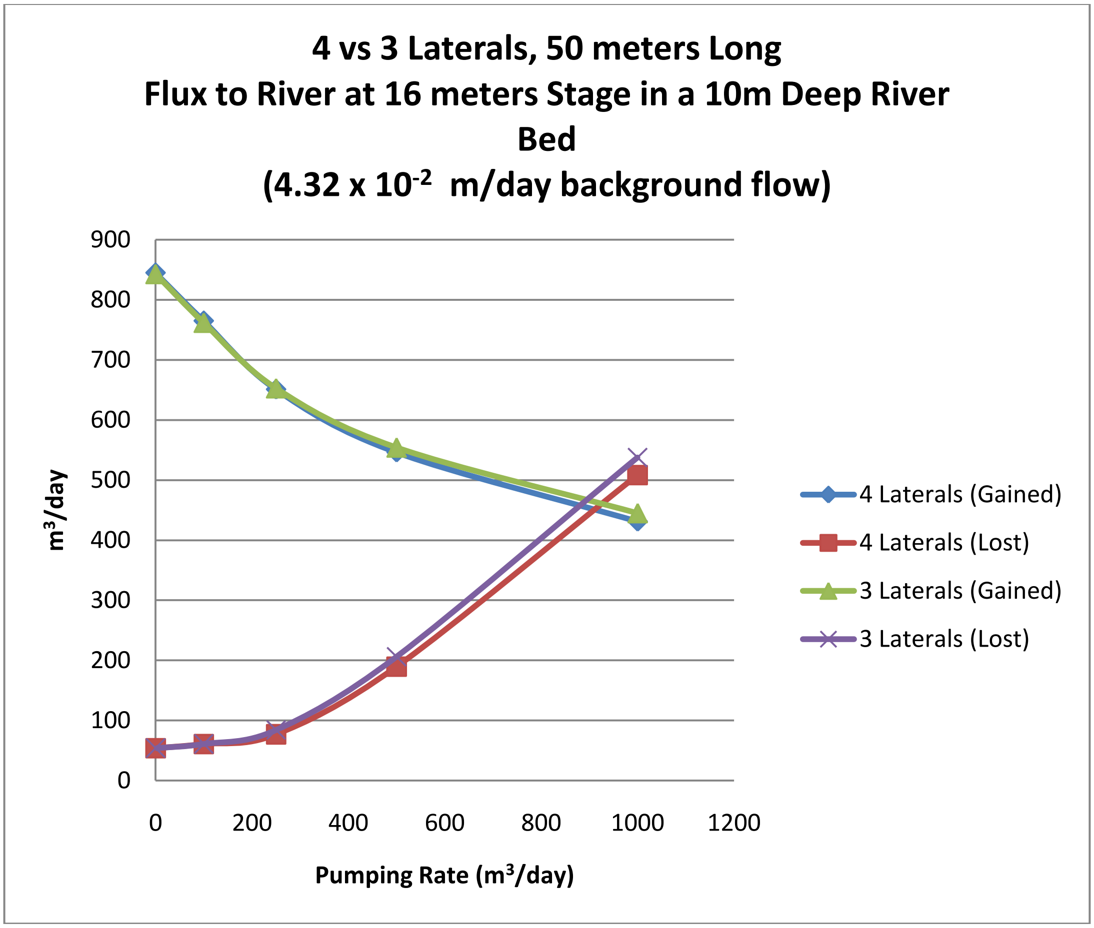


Figure 33: Flux to 16 m stage river in a 10 m deep river bed with 3- and 4-laterals at 50 m in length.

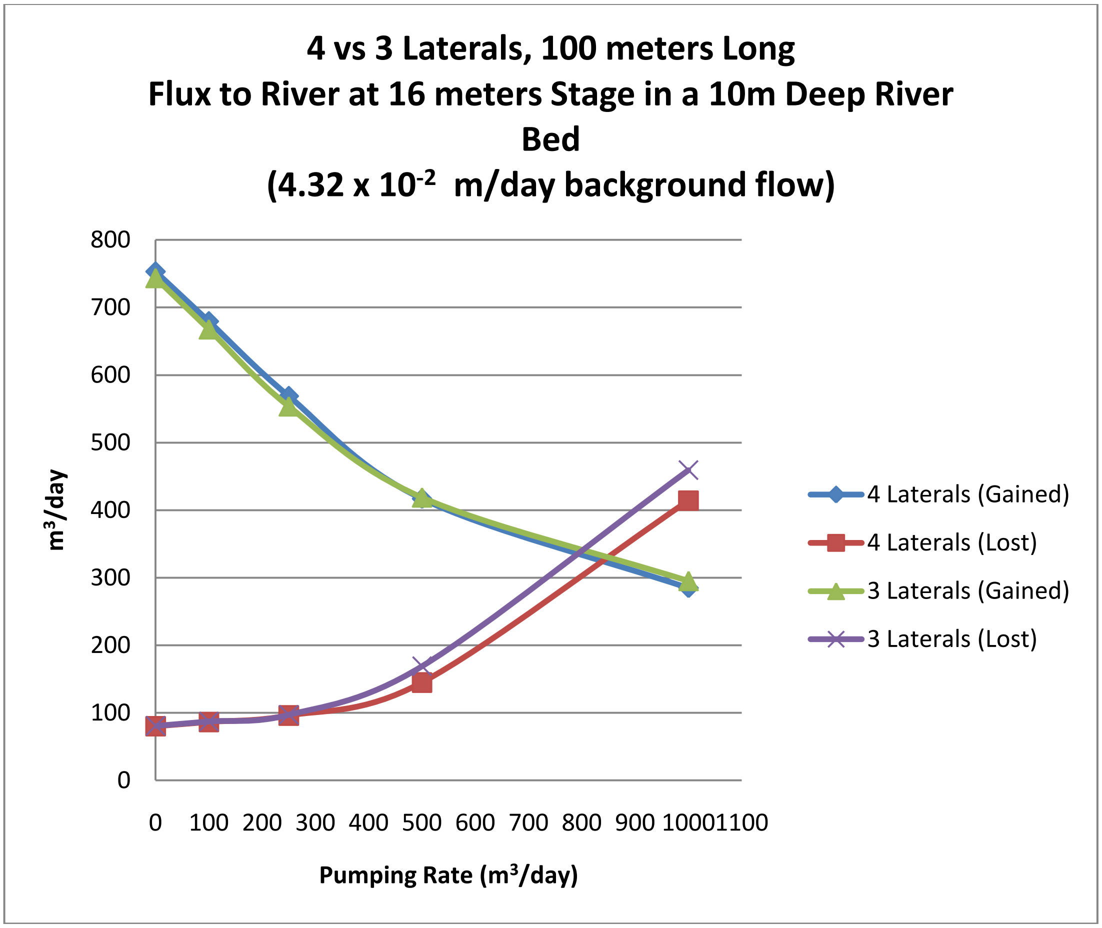


Figure 34: Flux to 16 m stage river in a 10 m deep river bed with 3- and 4-laterals at 100 m in length.

5.3.2: Net Flux Investigation

The data shown in Figures 32-34 provides a more significant trend when the net flux, the difference between the amount of inflow gained and the amount outflow lost, is plotted against its associated pumping rate. Figure 35 displays the linear trend for the net flux to a 16 m stage river in a 10 m deep riverbed with a 4.32 x 10^{-2} m/day regional background flow for all the collector well designs. This linear trend can be used to extrapolate projections regarding the optimal pumping rate for a collector well system without causing negative effects to the nearby river [*Dugat,* 2009].

Figure 35 shows that the 25 m length laterals provide the highest amount of flux, followed by the 50 m, and 100 m laterals ,respectively. In addition, the number of laterals does not appear to make a visible difference on flux until the laterals reach a length of 100 m, at which point the 4-lateral design provides slightly more flux than the 3-lateral design. Overall, Figure 35 shows shorter laterals require a higher pumping rate to cause deleterious effect on a river, compared to longer laterals. For example, a 100 m length 3-lateral design causes negative effects at approximately an 800 m^3/day pumping rate. However, a 50 m length design with the same number of laterals encounters negative effects at a 900 m^3/day pumping rate. In terms of number of laterals resulting in deleterious effects on the river, the 3-lateral design is a slightly better choice. For example, a 3-lateral, 100 m length design shows negative effects occurring at a 800 m^3/day pumping rate. With the addition of an extra lateral of the same length, the pumping rate changes to approximately 840 m^3/day.

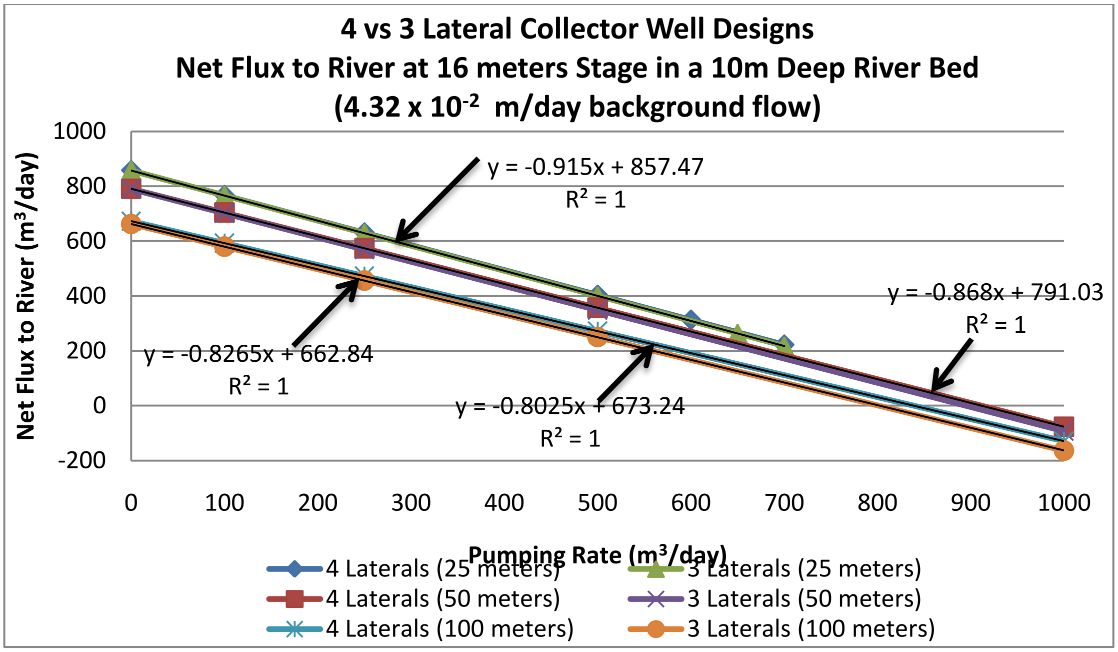


Figure 35: Net flux to 16 m stage river in 10 m deep river bed with 3- and 4- lateral collector well designs.

5.3.3: Dimensionless Pumping Rate

Figure 35 shows that two factors determine the amount of flux a river receives: the pumping rate and the lateral length. *Dugat* [2009] tested the effect that regional background flow had on the flux obtained by a river by utilizing an equation developed by *Zhan and Sun* [2007].

Zhan and Sun [2007] developed a dimensionless pumping rate term (Q_D) which incorporated regional background flow (q_0):

$$Q_D = \frac{Q}{2\pi B x_0 q_0} \tag{9}$$

where Q is the pumping rate (m^3/day), B is the saturated thickness of the aquifer (m), x_0 is the distance of the center of the collector well from the river (m), and q_0 is the regional background flow (m/day). This equation is similar to Eq. (6); however x_0 is defined differently in Eq. (9). *Zhan and Sun* [2007] utilized this term (Q_D) to investigate a vertical well in a confined aquifer. In the Visual Modflow® environment the collector well is designed to be a vertical well with zones of high permeability, representing the laterals surrounding it. Based on this design, Eq. (9) can be utilized to investigate the combined effect that regional background flow and pumping rate have on net flux to a river in a variety of river settings. Figure 36 utilizes the dimensionless pumping rate with the net flux for each collector well design to a 16 m stage river in a 10 m deep riverbed with a 4.32×10^{-2} m/day regional background flow. Figure 36 shows the same linear

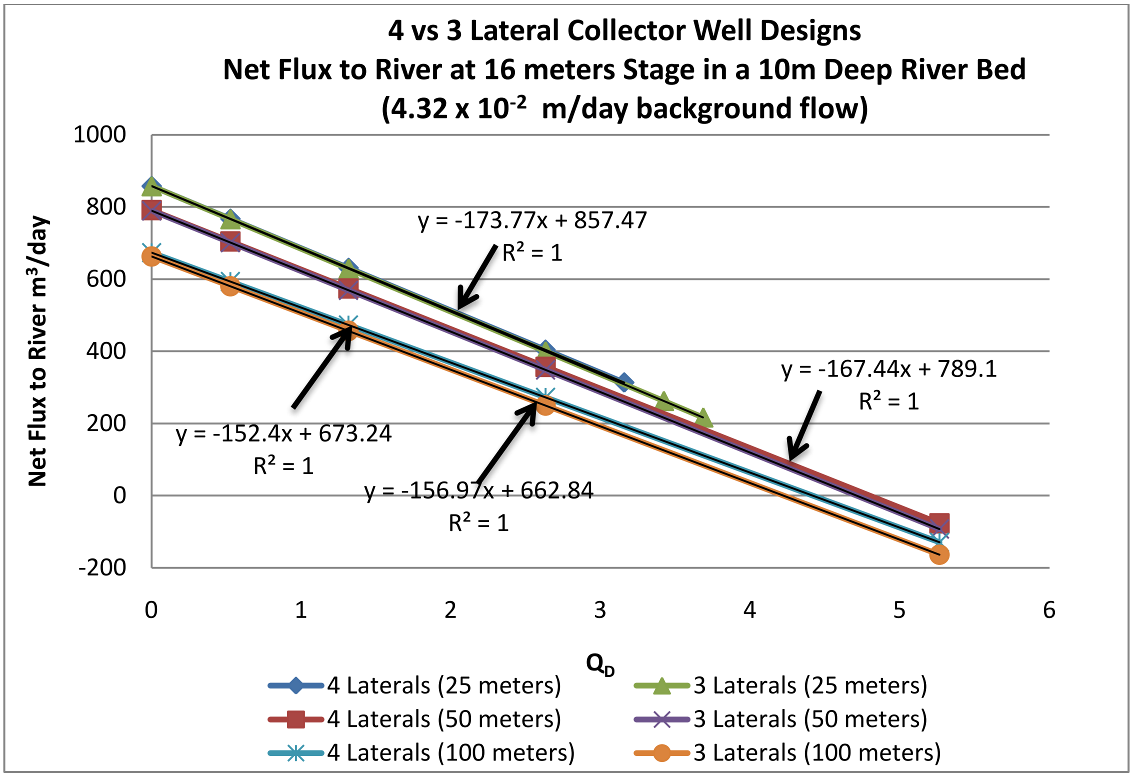


Figure 36: Net flux to 16 m stage river in 10 m deep river bed with 3- and 4- lateral collector well designs, varied by dimensionless pumping rate.

trend as Figure 35, thus confirming that incorporating regional background flow with the pumping rate does not result in drastic fluctuations.

Figures 37-39 display the collector well designs net flux to a 16 m stage river in a 10 m deep riverbed with varied pumping rates. When the regional background flow is doubled each collector well design undergoes a two-fold increase for the net flux to a river. This finding supports *Dugat's* [2009] observation that the net flux to the river is mainly controlled by the pumping rate and that the regional background flow only plays a slight role. Figures 37-39 conform to the same trend of Figure 36, where the number of laterals did not play a significant role. However, in terms of lateral length, there is a noticeable change in the amount of flux received with a 1.73×10^{-2} m/day regional background flow. With increasing lateral length the amount of net flux at 0 Q_D decreases. For example, a 25 m long lateral in the 4-lateral design has approximately 850 m^3/day net flux, compared to 673 m^3/day for 100 m laterals. Interestingly, this trend is not seen with a 4.32×10^{-2} m/day regional background flow, which encounters only a slight increase in flux with increasing lateral length.

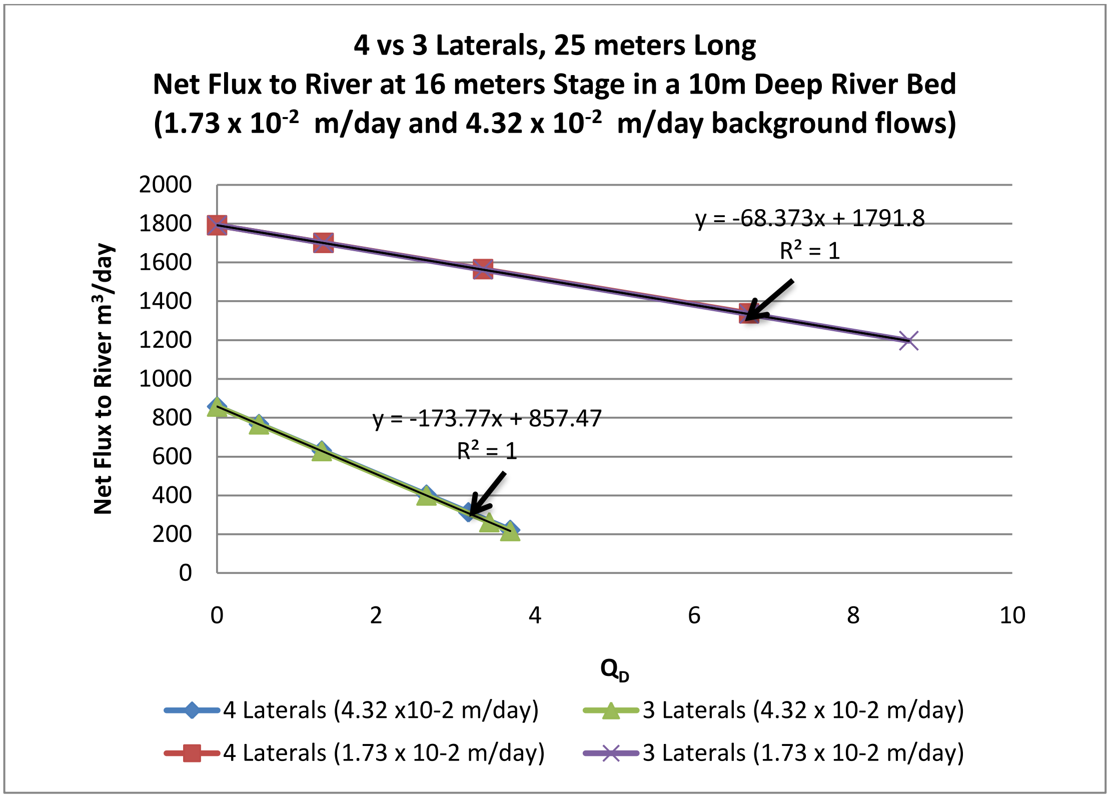


Figure 37: Net flux to 16 m stage river in 10 m deep river bed with 3- and 4-lateral collector well with 25 m long laterals at various pumping rates and regional background flows.

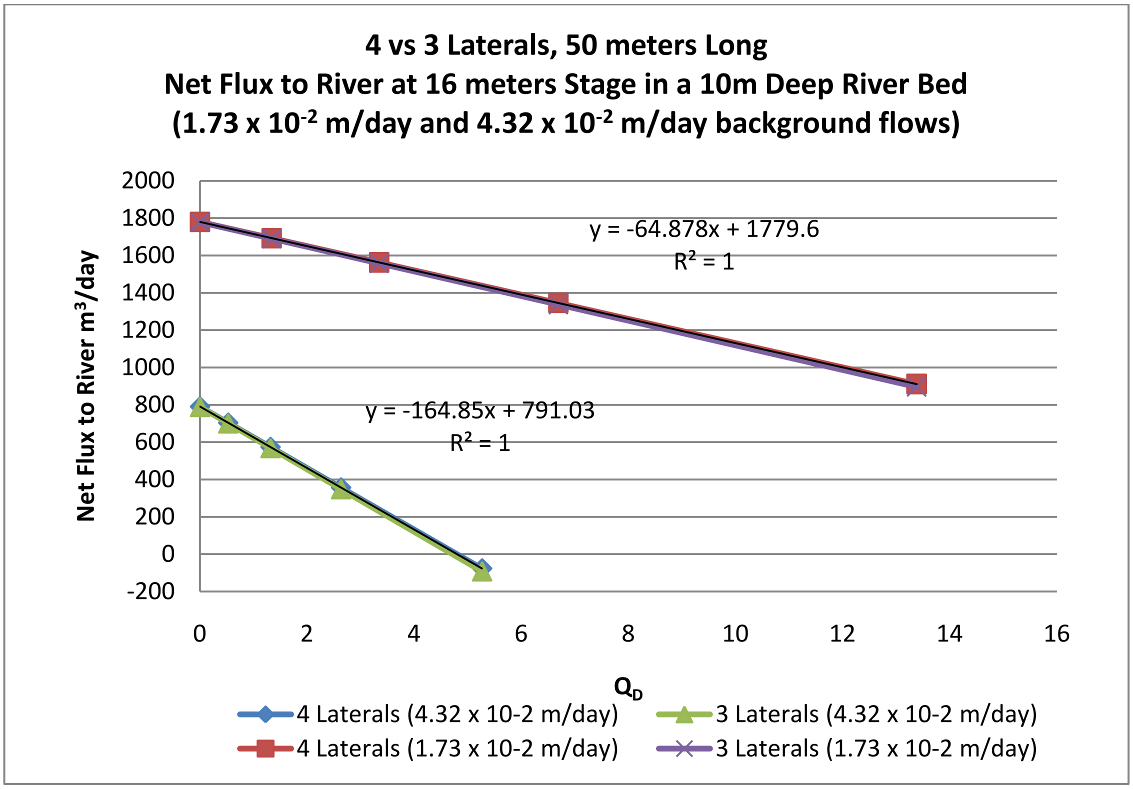


Figure 38: Net flux to 16 m stage river in10 m deep river bed with 3- and 4-lateral collector well with 50 m long laterals at various pumping rates and regional background flows.

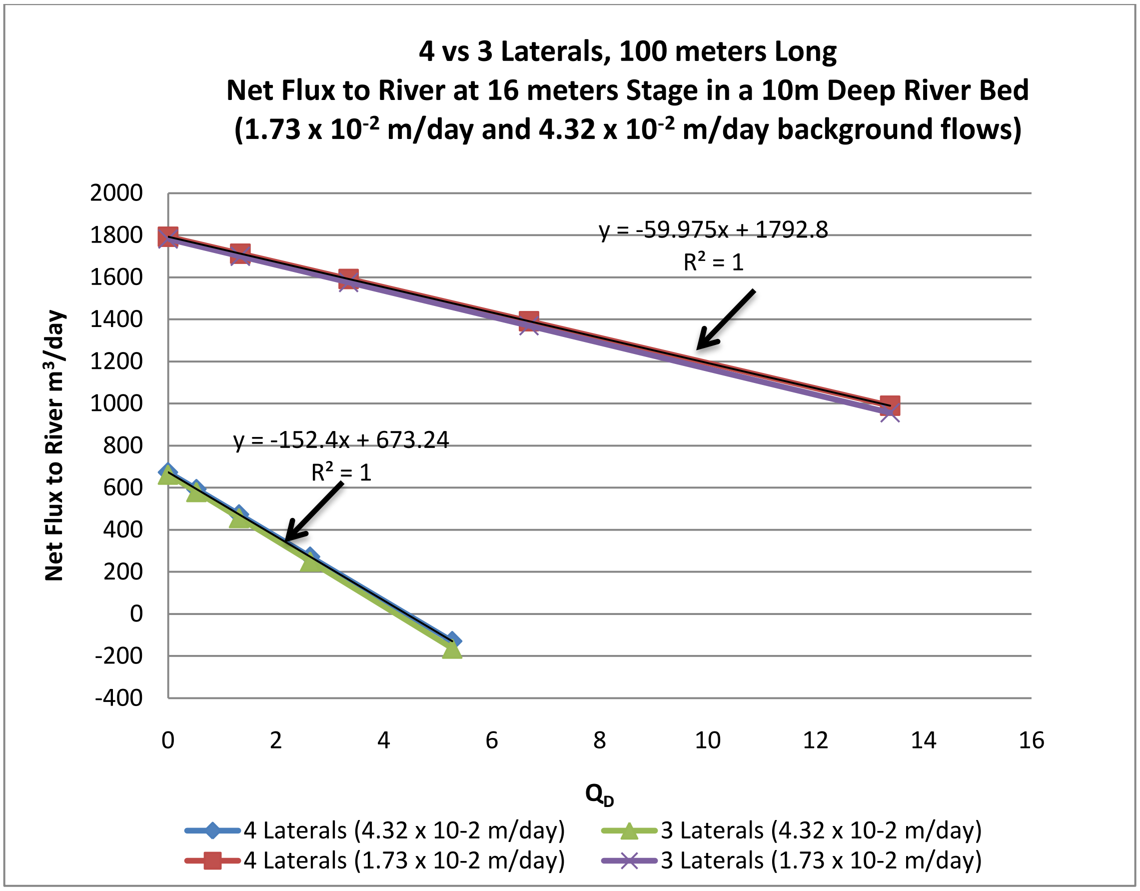


Figure 39: Net flux to 16 m stage river in 10 m deep river bed with 3- and 4-lateral collector well with 100 m long laterals at various pumping rates and regional background flows.

5.3.4: Flux Investigation to Various River Stages

Figures 40-51 investigate the effect of various collector well designs in different river settings on the net flux to a river. Figures 40-42 highlight the net flux to a 20 m stage river in a 1 m deep riverbed. For all designs, the river is a losing river, as it has a higher hydraulic head then the surrounding aquifer. Figure 40 shows that, when the laterals are 25 m long, each design has a distinct amount of flux and the number of laterals impacting the flux. However, Figure 42 shows that when laterals reach a length of 100 m, the number of laterals result in considerable gains. Instead with longer laterals, the 3-lateral design eventually equals the same amount of net flux as a 4-lateral collector well design. For this river setting, a design of 3-laterals with 25 m length laterals would be best for the least amount of flux lost from the river.

Figures 43-45 emphasize the net flux to rivers at 20 and 16 m stages, respectively in a 5 m deep riverbed. In each river setting, the number and length of the laterals do not impact the amount of net flux to the river. Instead, it is the river stage and riverbed depth that control the flux amount. This relationship differs from the trend viewed in Figures 40-42, where the lateral length played an important role in the flux amount. Comparisons to Figures 40-42 illustrate the effect a deeper riverbed has on a 20 m river stage. A deeper river bed results in a slight increase in net flux to a river, approximately 40 m^3/day compared to a 1 m deep riverbed.

Figures 46-51 illustrate the net flux to rivers at 20, 16, 15, and 11 m stages in a 10 m deep riverbed. Figures 46-48 show the same trends viewed in Figures 43-45. Figures 47-49 show that the 11 m stage river obtains the most amount of flux in a 10 m deep riverbed. This is an expected trend given that this river stage is the lowest and will receive more water from the surrounding aquifer given the hydraulic gradient. This finding suggests that the river geometry determines the amount of net flux to a river. The next factor that determines the amount of flux is the pumping rate. Figures 47-49 confirm that the number of laterals and lateral length do not make significant changes in the amount of net flux.

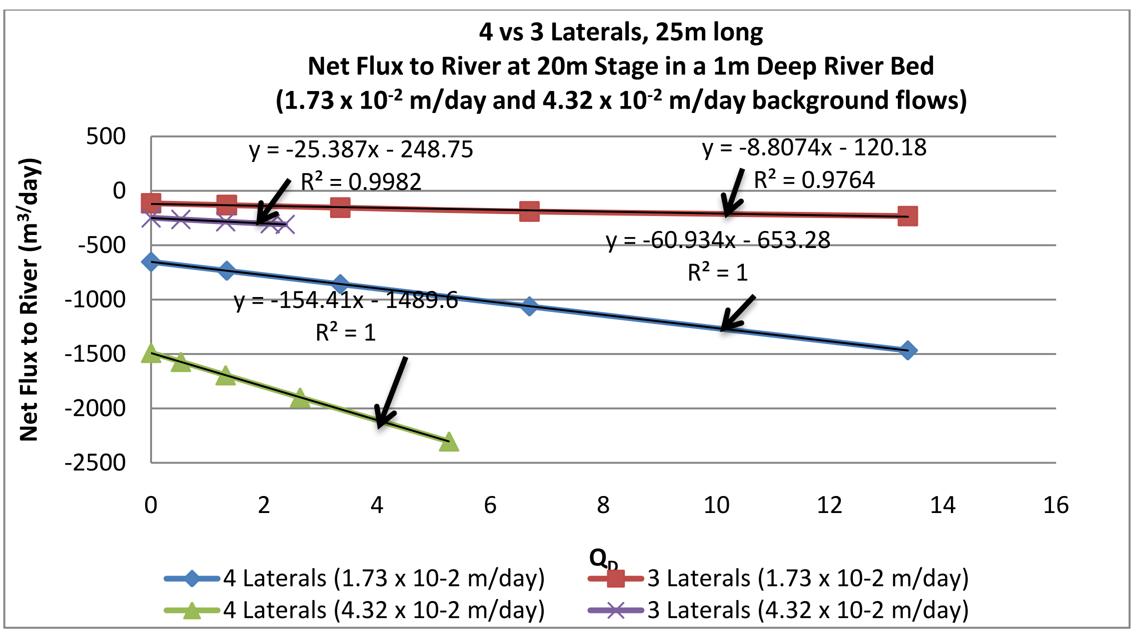


Figure 40: Net flux to 20 m stage river in 1 m deep river bed with 3- and 4-lateral collector well with 25 m long laterals with varied pumping rates and regional background flows.

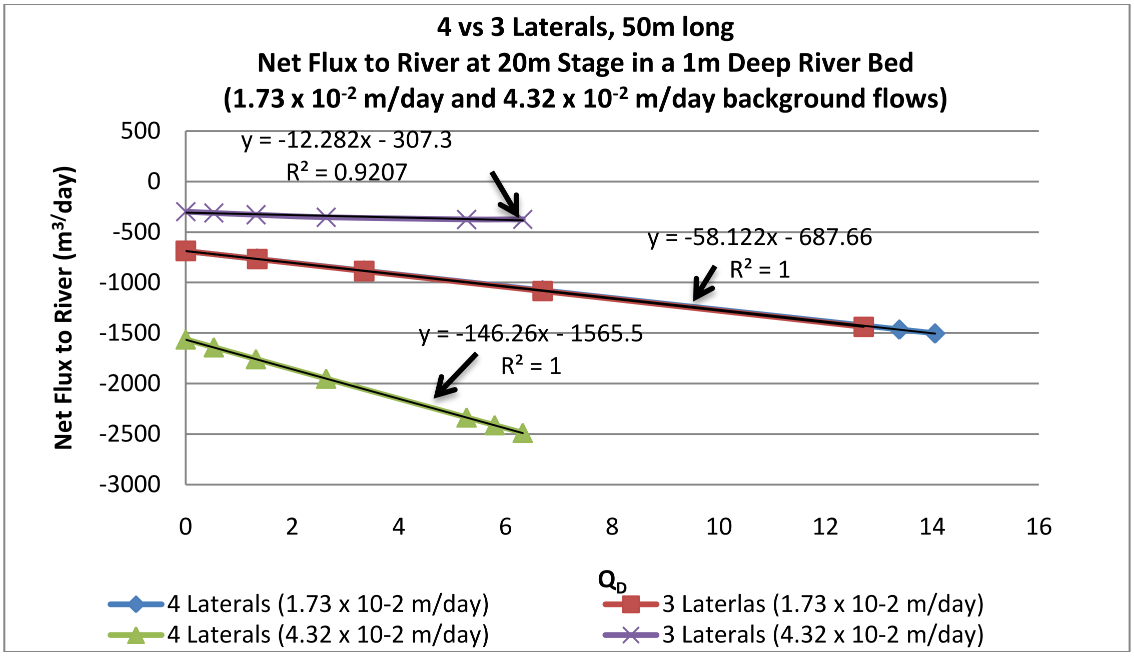


Figure 41: Net flux to 20 m stage river in 1 m deep river bed with 3- and 4-lateral collector well with 50 m long laterals with varied pumping rates and regional background flows.

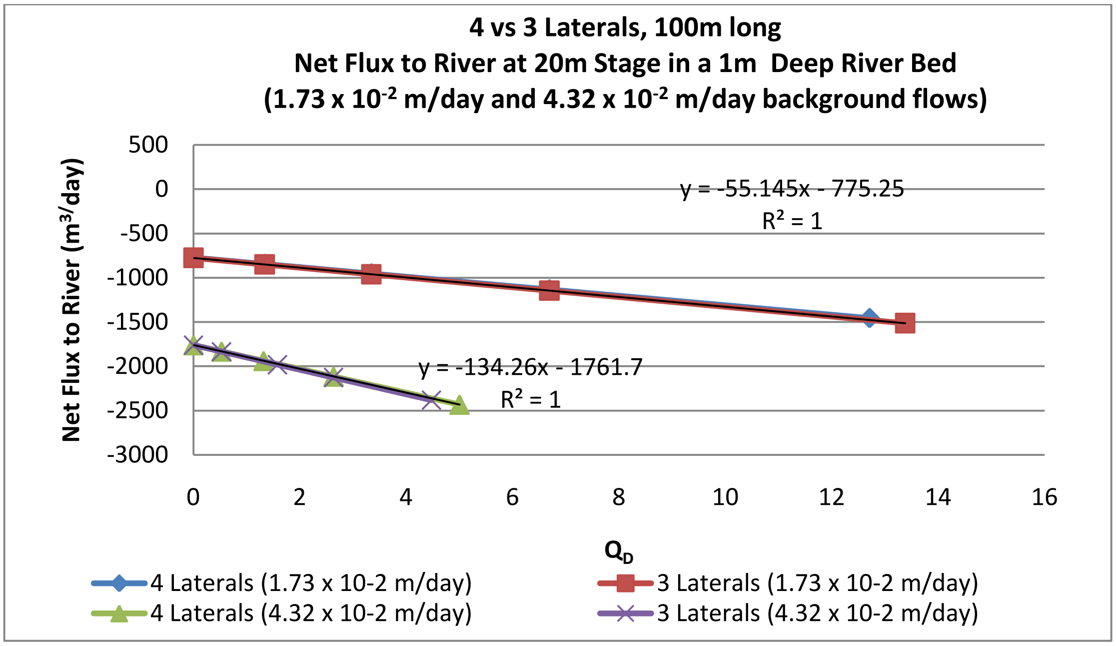


Figure 42: Net flux to 20 m stage river in 1 m deep river bed with 3- and 4-lateral collector well with 100 m long laterals with varied pumping rates and regional background flows.

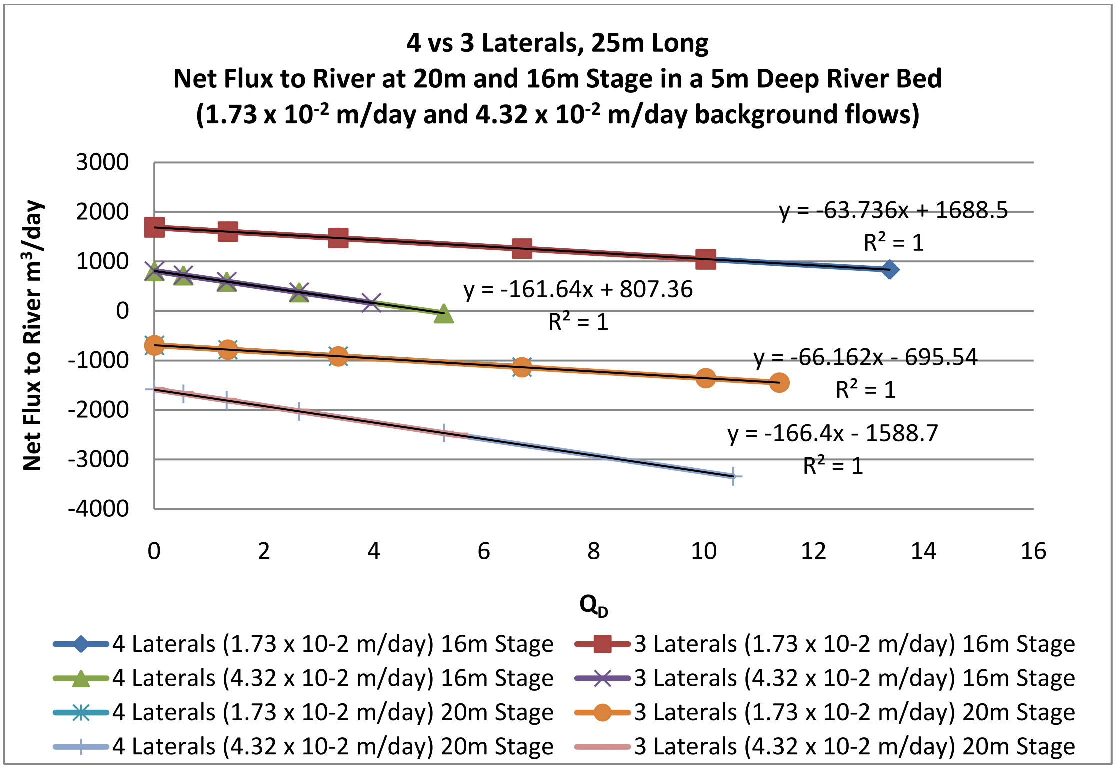


Figure 43: Net flux to 16 m and 20 m stage rivers in 5 m deep river bed with 3- and 4-lateral collector well with 25 m long laterals at various pumping rates and regional background flows.

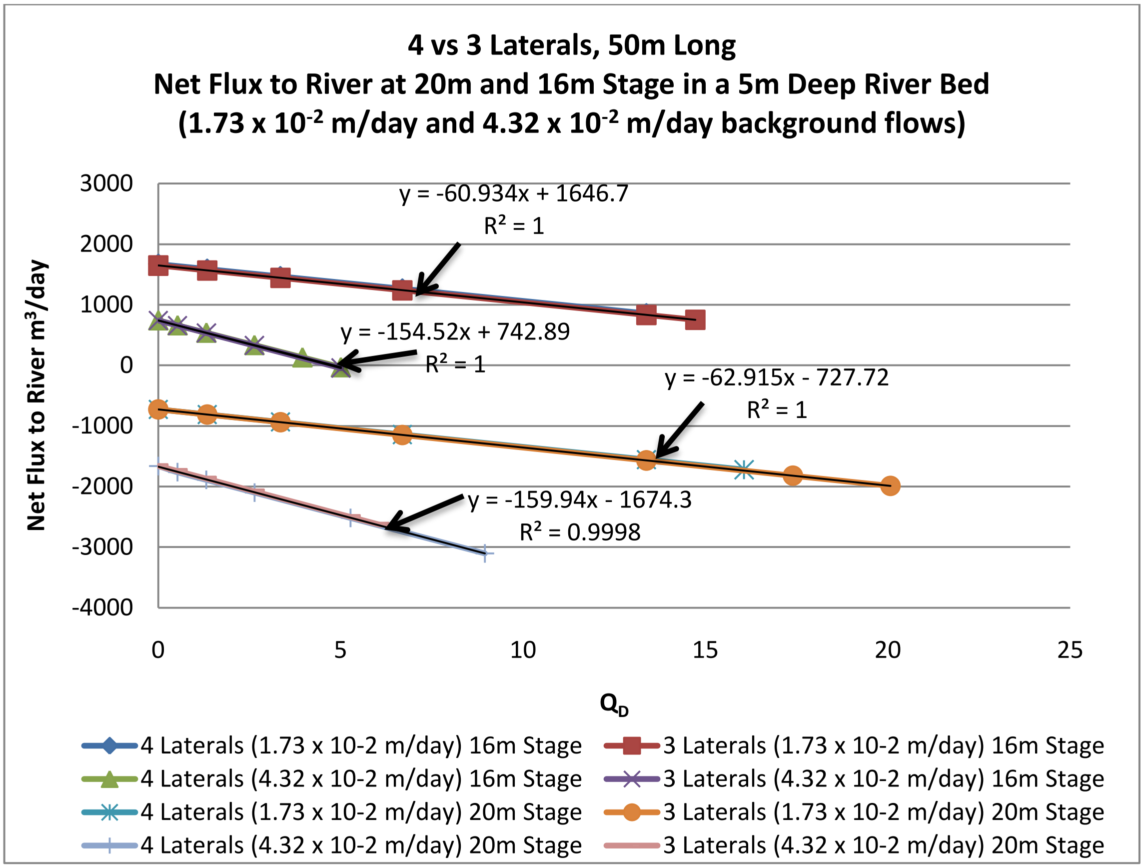


Figure 44: Net flux to 16 m and 20 m stage rivers in 5 m deep river bed with 3- and 4-lateral collector well with 50 m long laterals at various pumping rates and regional background flows.

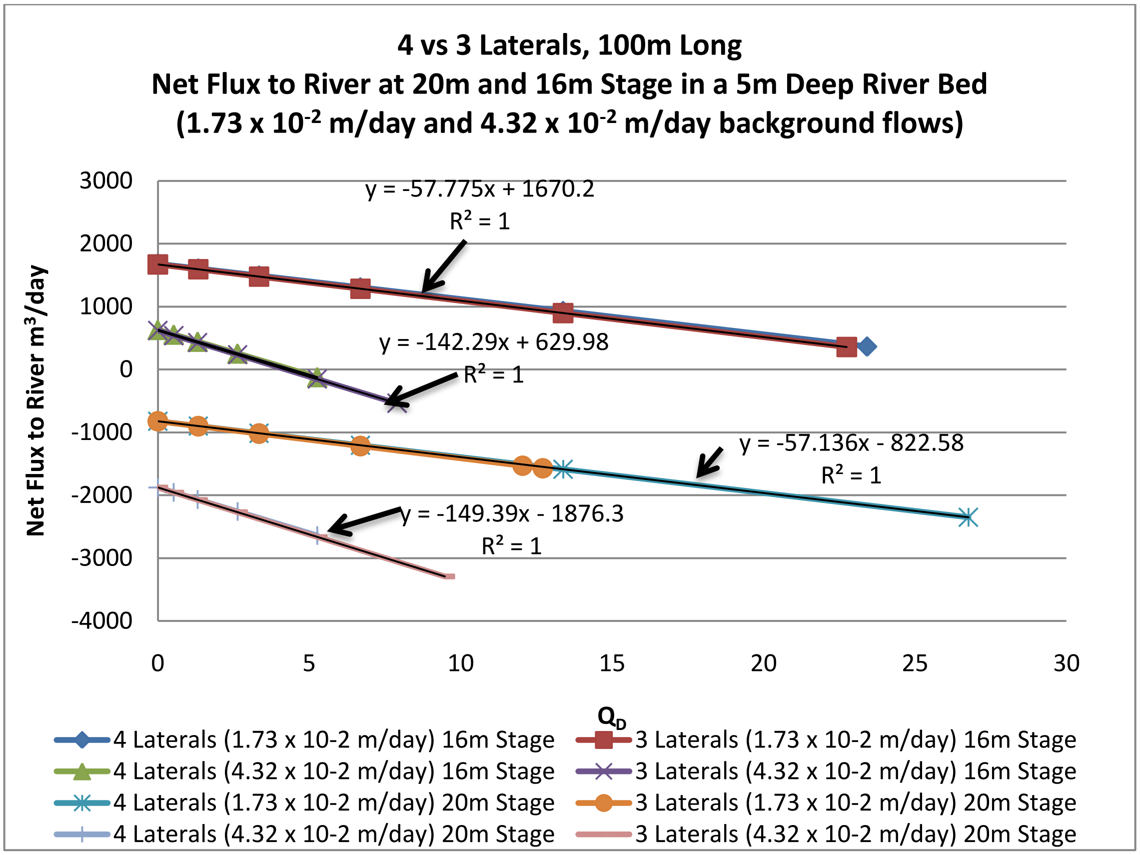


Figure 45: Net flux to 16 m and 20 m stage rivers in 5 m deep river bed with 3- and 4-lateral collector well with 100 m long laterals at various pumping rates and regional background flows.

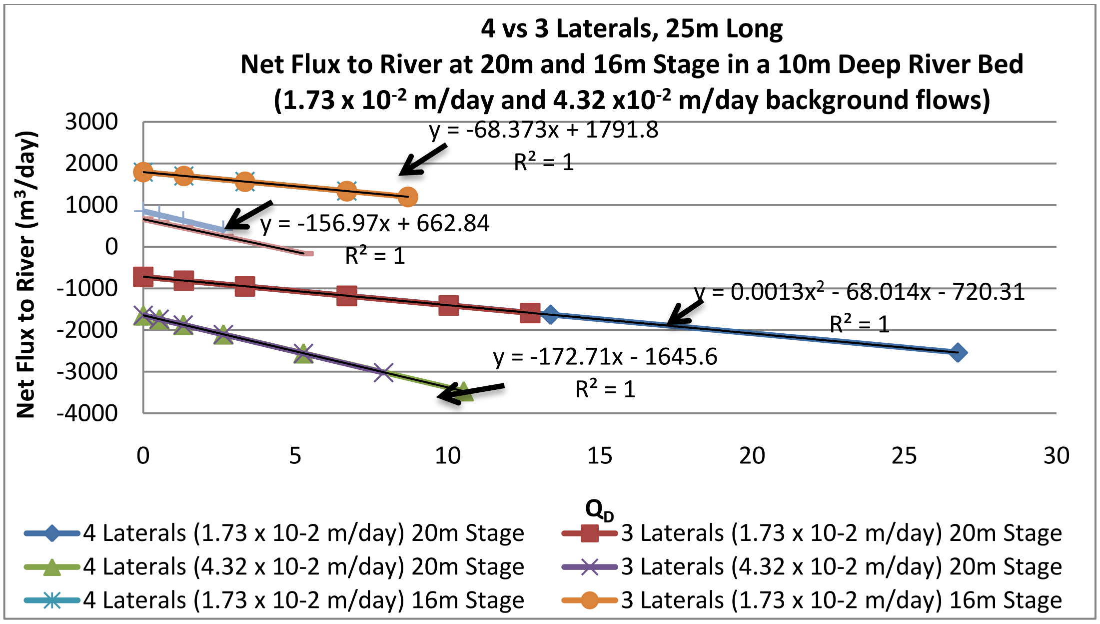


Figure 46: Net flux to 16 m and 20 m stage rivers in 10 m deep river bed with 3- and 4-lateral collector well with 25 m long laterals at various pumping rates and regional background flows.

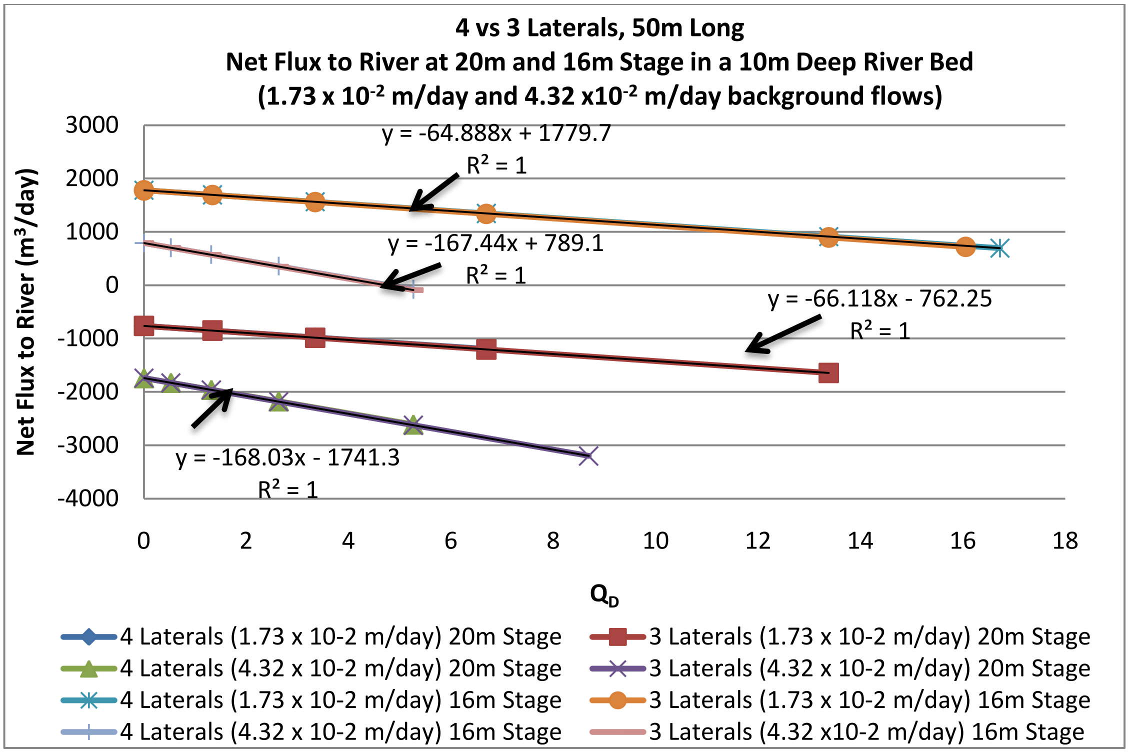


Figure 47: Net flux to 16 m and 20 m stage rivers in 10 m deep river bed with 3- and 4-lateral collector well with 50 m long laterals at various pumping rates and regional background flows.

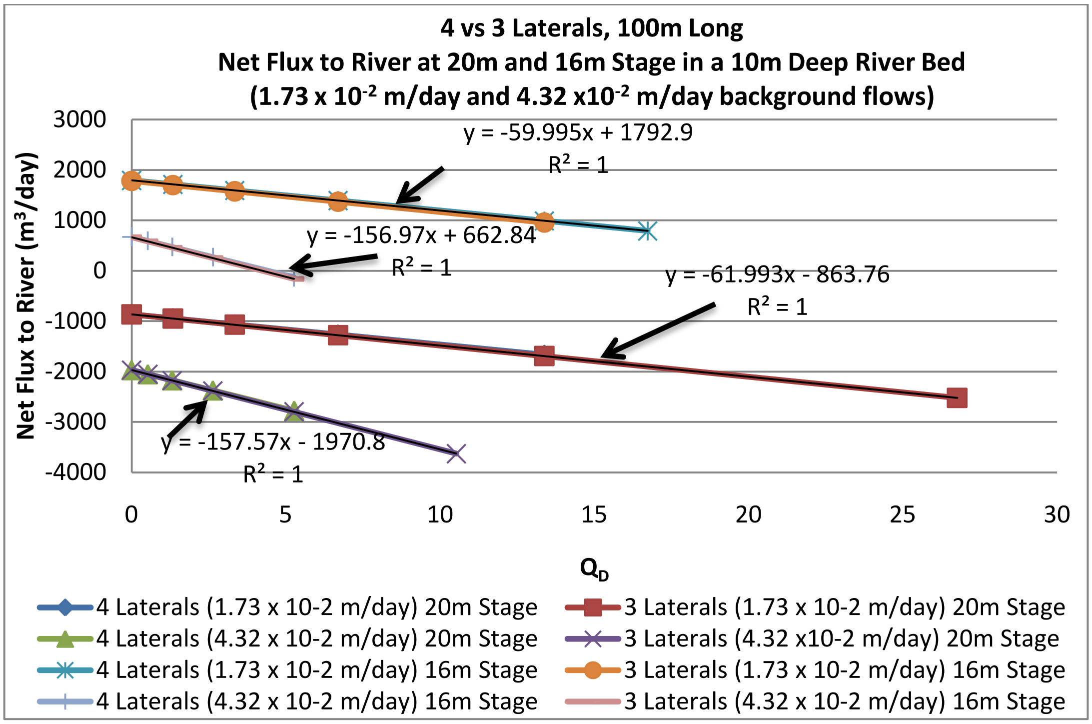


Figure 48: Net flux to 16 m and 20 m stage rivers in 10 m deep river bed with 3- and 4-lateral collector well with 100 m long laterals at various pumping rates and regional background flows.

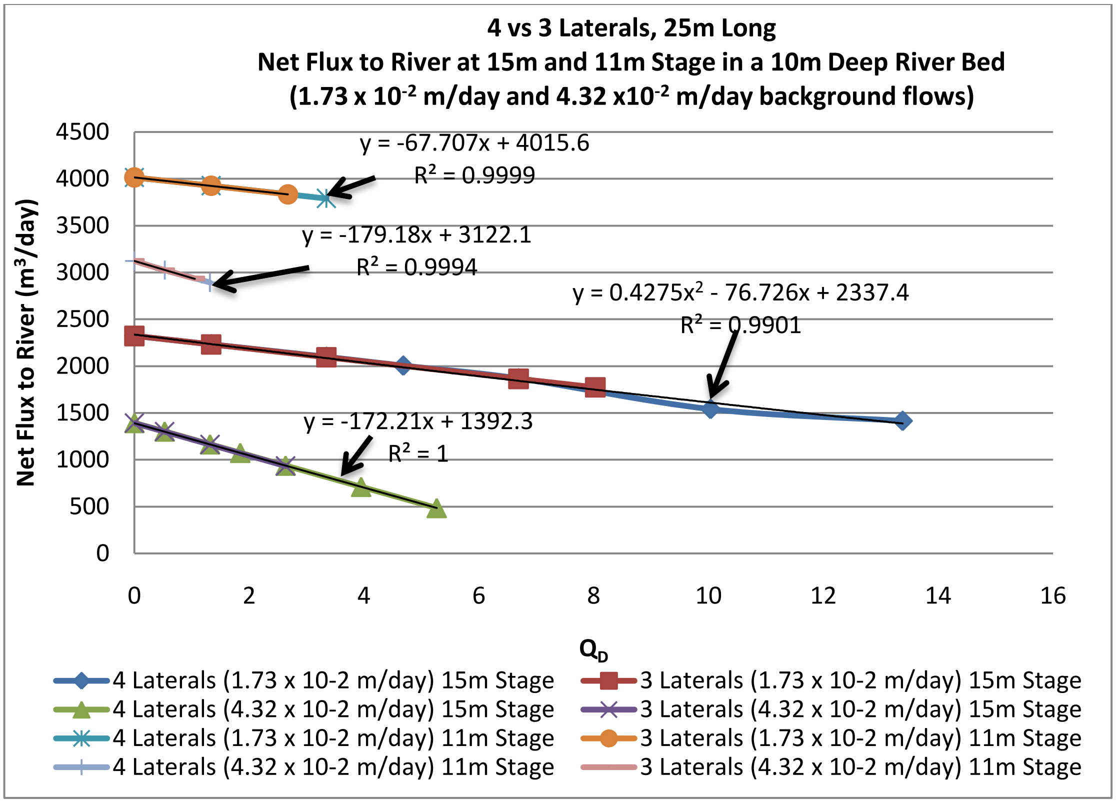


Figure 49: Net flux to a 15 and 11 m stage rivers in a 10 m deep river bed with a 3- and 4-lateral collector well with 25 m long laterals at various pumping rates and regional background flows.

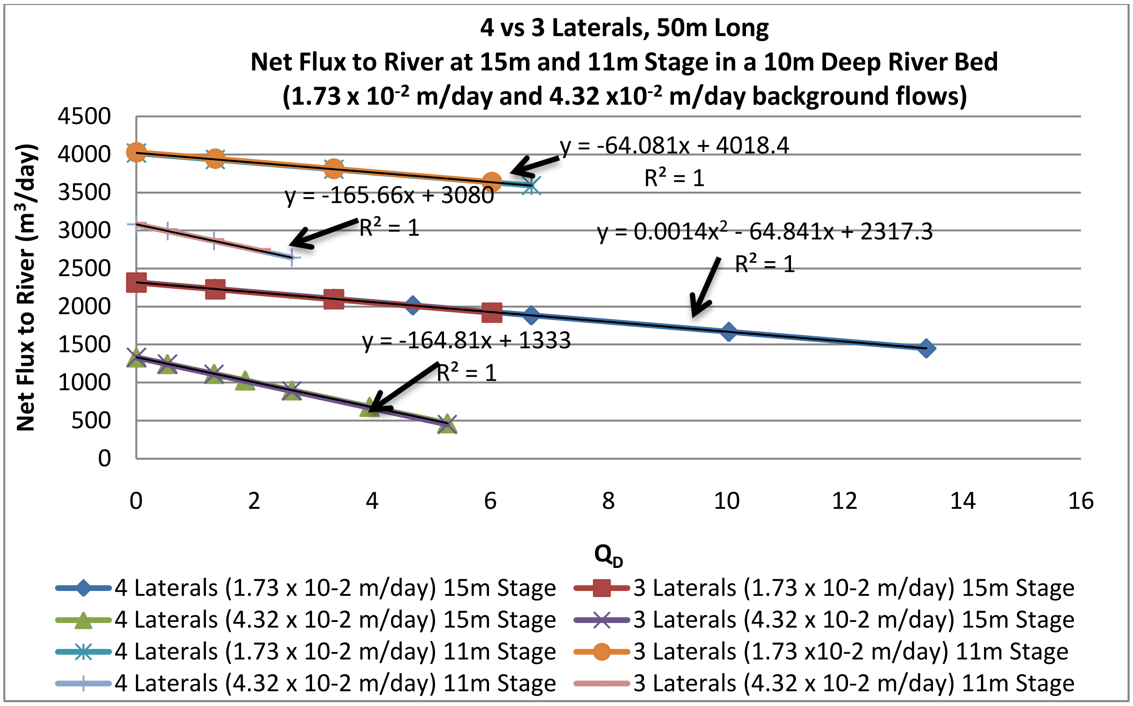


Figure 50: Net flux to a 15 and 11 m stage rivers in a 10 m deep river bed with a 3- and 4-lateral collector well with 50 m long laterals at various pumping rates and regional background flows.

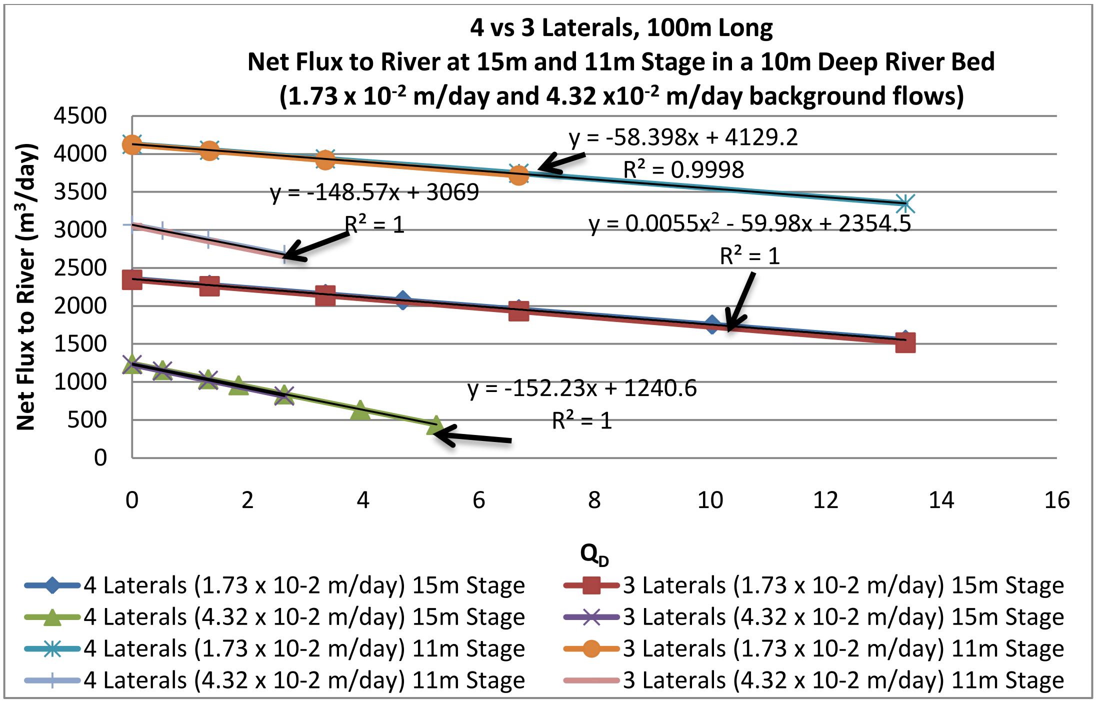


Figure 51: Net flux to a 15 and 11 m stage rivers in a 10 m deep river bed with a 3- and 4-lateral collector well with 100 m long laterals at various pumping rates and regional background flows.

Figures 52-54 highlight a 20 m river stage in all three riverbed depths. As stated earlier, all rivers at a 20 m river stage will be losing rivers given the higher hydraulic head of the river stage. Figures 52-54 show that a deeper river bed depth will result in more net flux lost from the river. This is expected as a deeper river bed will have more surface area exposed to the surrounding aquifer [*Dugat,* 2009]. Figure 52 shows a similar trend viewed in Figure 40 regarding the 3-lateral collector well design in a 1 m deep riverbed. Surprisingly, in a 1 m deep river bed, the collector well design does have an impact on the net flux to a river, but this is only if 25 m laterals are selected. If not, then the collector well design does not result in significant gains. Figures 52-54 show that with increasing lateral length (50-100 m), the number and length of the laterals is not a major contributing factor in net flux. Instead, the river bed depth is the most significant factor as the 1 m deep bed has the highest amount of flux, followed by the 5 m and 10 m deep beds, respectively.

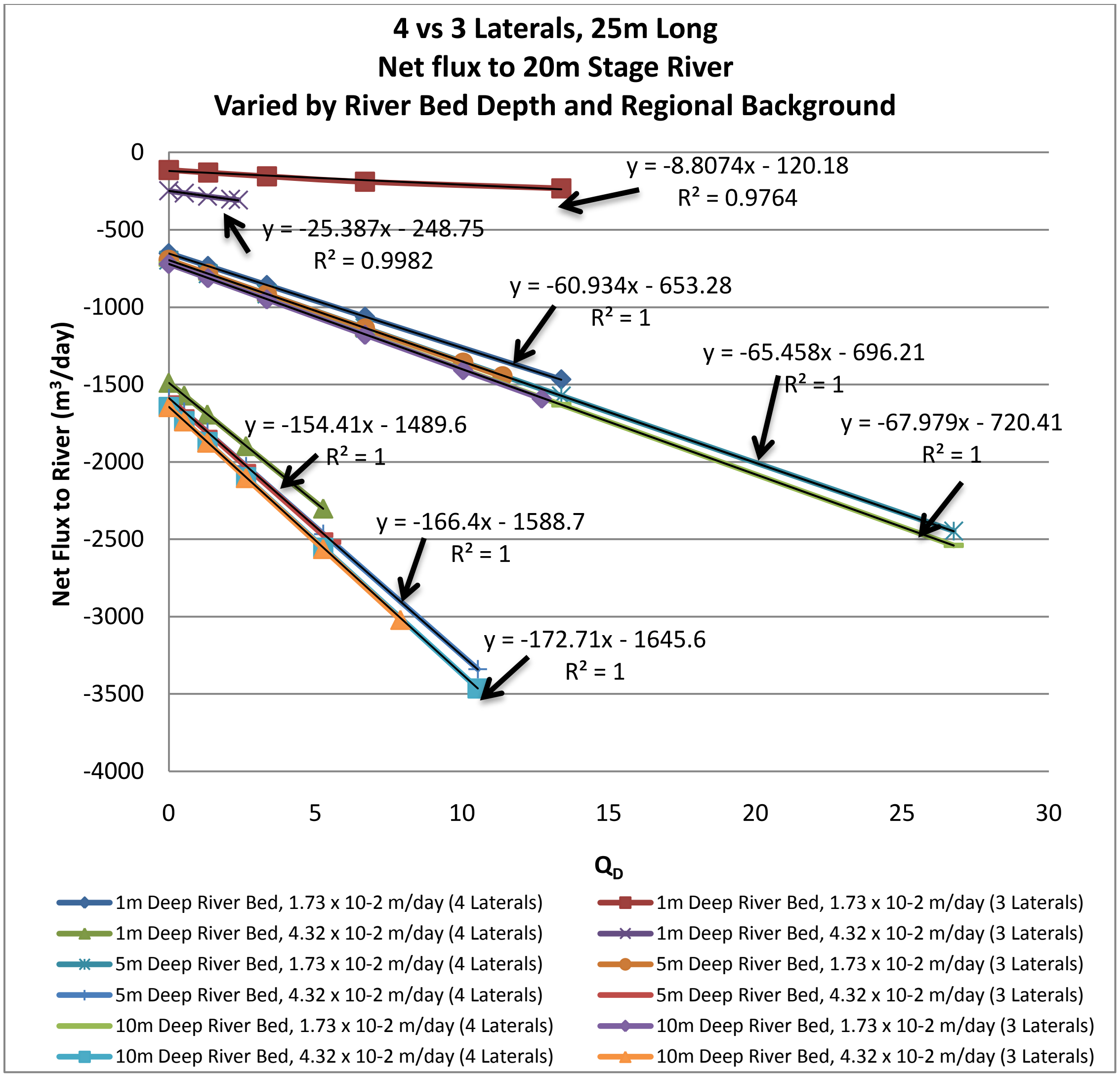


Figure 52: Net flux to 20 m stage river in 1, 5, and 10 m deep river bed with 3- and 4-lateral collector wells with 25 m long laterals varied with pumping rates and regional background flows.

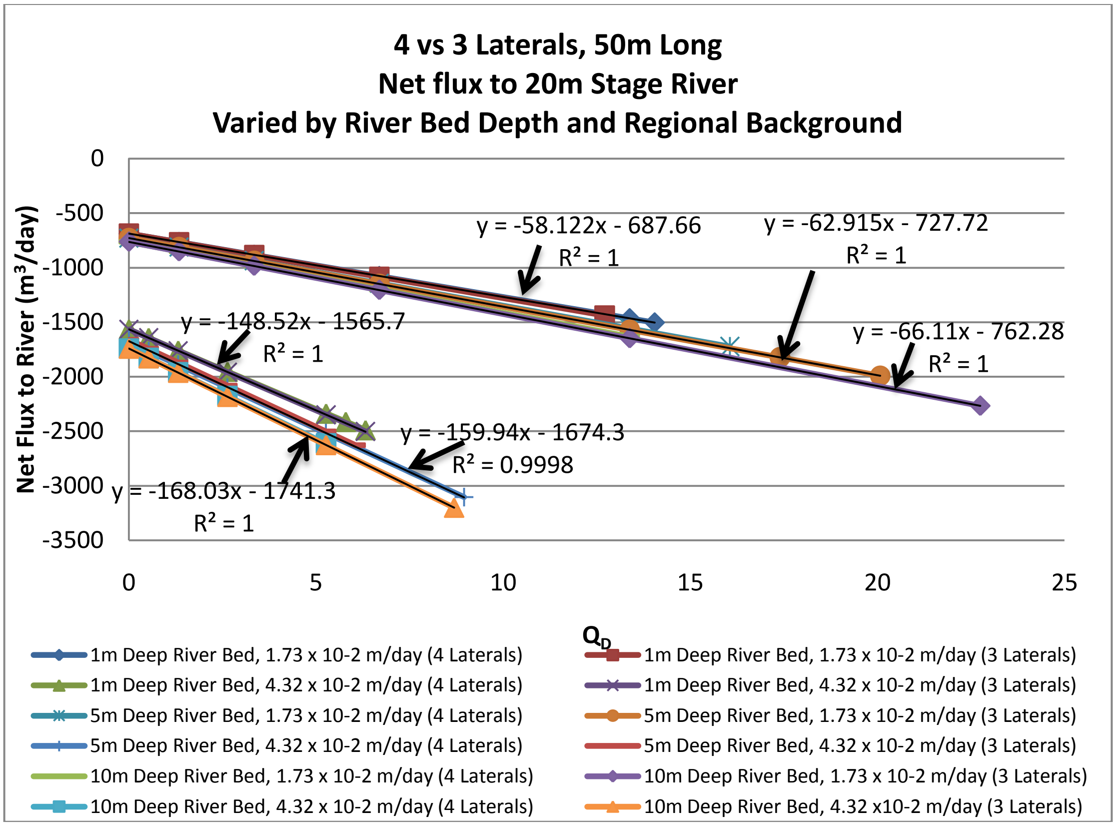


Figure 53: Net flux to 20 m stage river in 1, 5, and 10 m deep river bed with 3- and 4-lateral collector wells with 50 m long laterals varied with pumping rates and regional background flows.

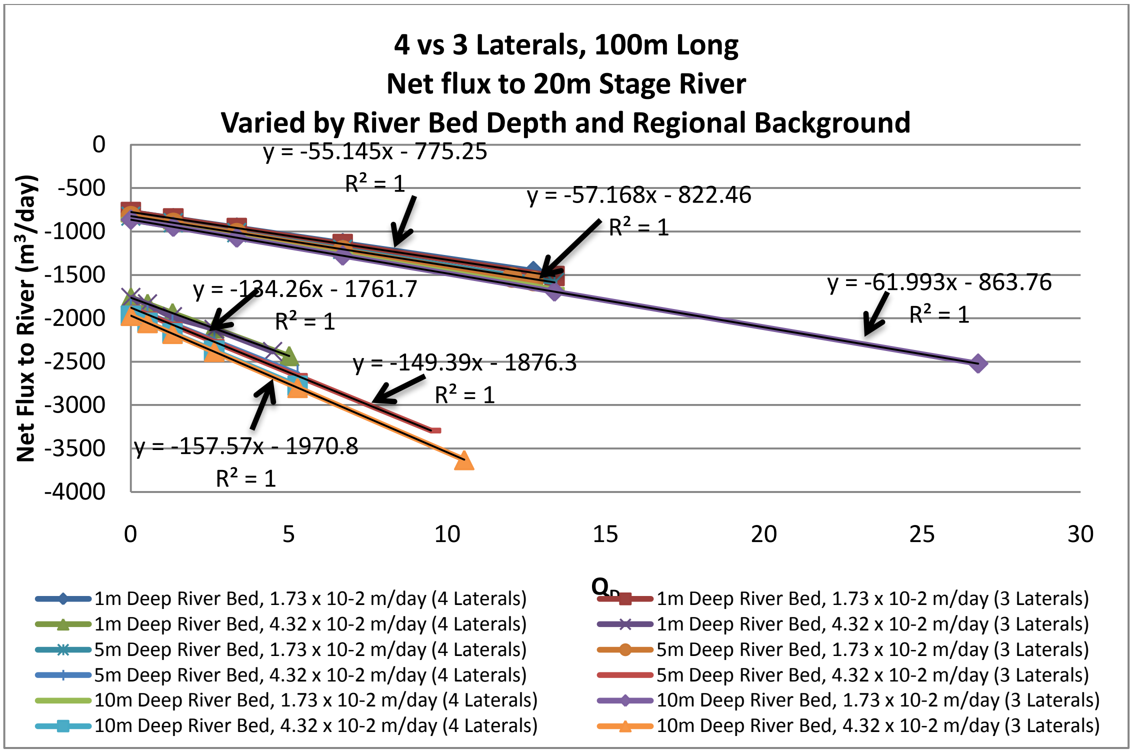


Figure 54: Net flux to 20 m stage river in 1, 5, and 10 m deep river bed with 3- and 4-lateral collector wells with 100 m long laterals varied with pumping rates and regional background flows.

5.4 : Water Supply Evaluation

5.4.1 : Drawdown Investigation

The next area that was investigated was the water supply evaluation for each collector well design. The first step is to analyze the maximum drawdown (Figures 54-61) for each design. *Hantush* [1964] derived an equation to calculate the maximum drawdown (s_i) "induced by the *i*th of a group of laterals of a collector well" [*Hantush,* 1964, p. 401]:

$$s_i = [(Q_i/l_i)/4\pi Kb]\Bigg\{\alpha W[(\alpha^2+\beta^2)/4vt] - \delta W[(\delta^2-\beta^2)/4vt]$$

$$- 2\beta[\tan^{-1}(\alpha/\beta) - \tan^{-1}(\delta/\beta)] + 2l_i$$

$$+ (4b/\pi)\sum_{n=1}^{\infty}(1/n)[L(n\pi\alpha/b, n\pi\beta/b) - L(n\pi\delta/b, n\pi\beta/b)]$$

$$\cdot \cos(n\pi z/b)\cos(n\pi z_i/b)\Bigg\} \tag{10}$$

in which

$$\propto = r\cos(\theta-\theta_i) - r_c, \qquad \beta = r\sin(\theta-\theta_i)$$

$$\delta = r\cos(\theta-\theta_i) - l', \qquad l^i = r_c + l_i$$

$$r^2 = x^2 + y^2, \qquad v = Kb/\in$$

where Q_i is the discharge of the *i*th lateral (m^3/day), L is the length of each of a symmetrically located group of laterals (m), K is the hydraulic conductivity of an aquifer (m/day), b is the initial depth of saturation in a water-table aquifer or uniform thickness of an artesian aquifer (m), t is the time since pumping began (days), l_i is the length of the ith lateral of a collector well (m), and z_i is the vertical position of the ith lateral in a collector well.

Given the complexity of Eq. (10), numerical modeling with Visual Modflow® was utilized to determine the maximum drawdown for each collector well design in each river settings. Figures 55-56 display the maximum drawdown for each of the associated pumping rates for each collector well design in a 1 m deep riverbed with a 20 m stage river. Figures 55-56 show that the number of laterals and the lateral length play a key role in drawdown. As expected, 3 laterals have more drawdown than 4 laterals. And the shortest lateral length of 25 m has the most drawdown, followed by 50 and 100 m, respectively. Figure 54 shows that doubling the regional background flow (4.32×10^{-2} m/day) decrease the drawdown by approximately 50%. Figures 57-58 show the maximum drawdown for each of the associated pumping rates for each collector well design in a 5 m deep riverbed with 20 and 16 m stage rivers. The same trend viewed in Figures 55-56, regarding the relationship between the number of laterals and lateral length with the maximum drawdown is seen in Figures 57-58. In addition, with a lower river stage of 16 m there is even more drawdown than the 20 m river stage. Figures 59-60 display the maximum drawdown for each of the associated pumping rates for each collector well design in a 10 m deep riverbed with 20 and 16 m stage rivers. The change in the riverbed depth to 10 m only has a slight impact, about a 1 m decrease, on the drawdown. The same pattern seen with the increase in regional background flow is maintained as seen in Figures 59-60. Figures 61-62 illustrate the maximum drawdown for each of the associated pumping rates for each collector well design in a 10 m deep riverbed with 15 and 11 m stage rivers. The only difference in the trends is that the 11 m stage experiences more drawdown than the 15 m stage.

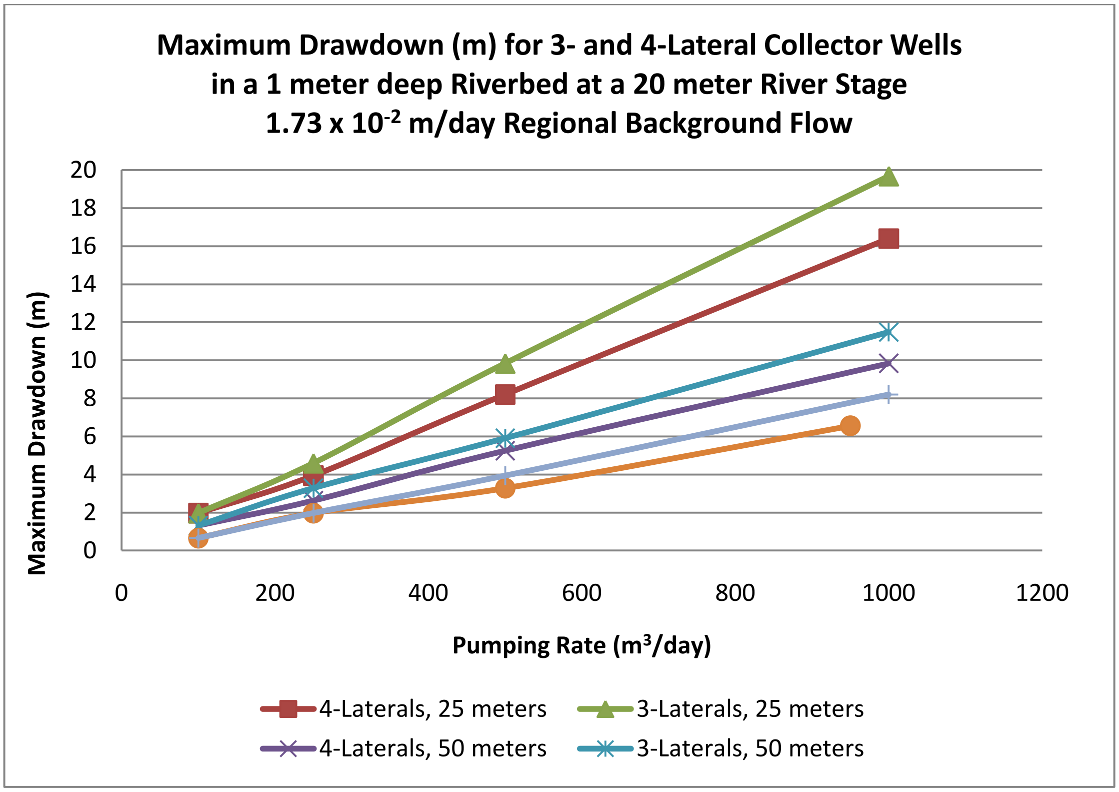


Figure 55: Maximum drawdown for 3- and 4-lateral collector well designs in 20 m stage river in 1 m deep river bed with 1.73 x 10^{-2} m/day regional background flow.

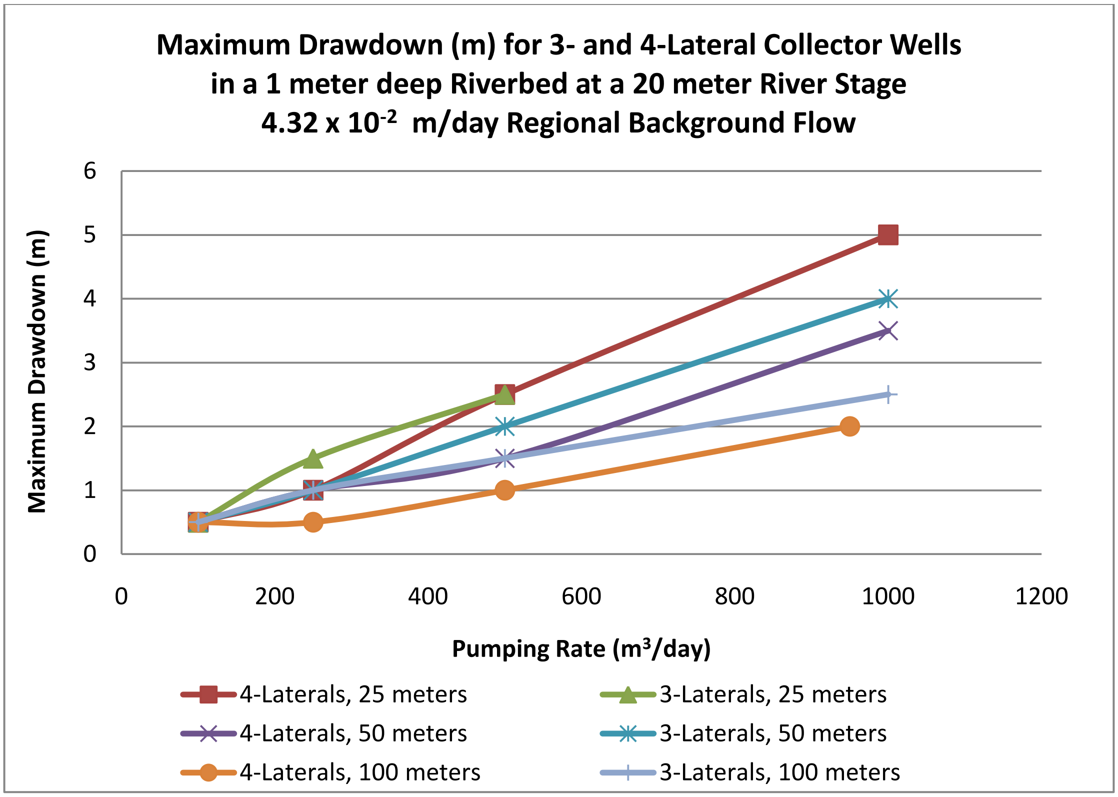


Figure 56: Maximum drawdown for 3- and 4-lateral collector well designs in 20 m stage river in 1 m deep river bed with 4.32 x 10^{-2} m/day regional background flow.

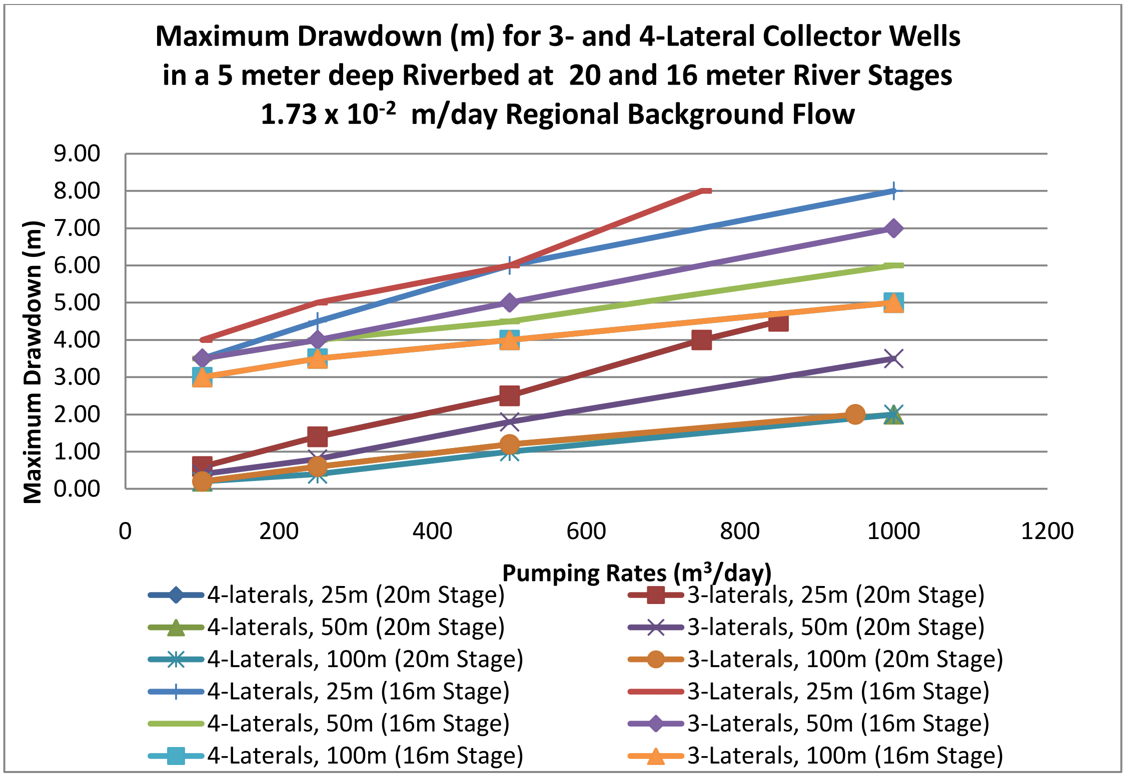


Figure 57: Maximum drawdown for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 5 m deep river bed with 1.73 x 10^{-2} m/day regional background flow.

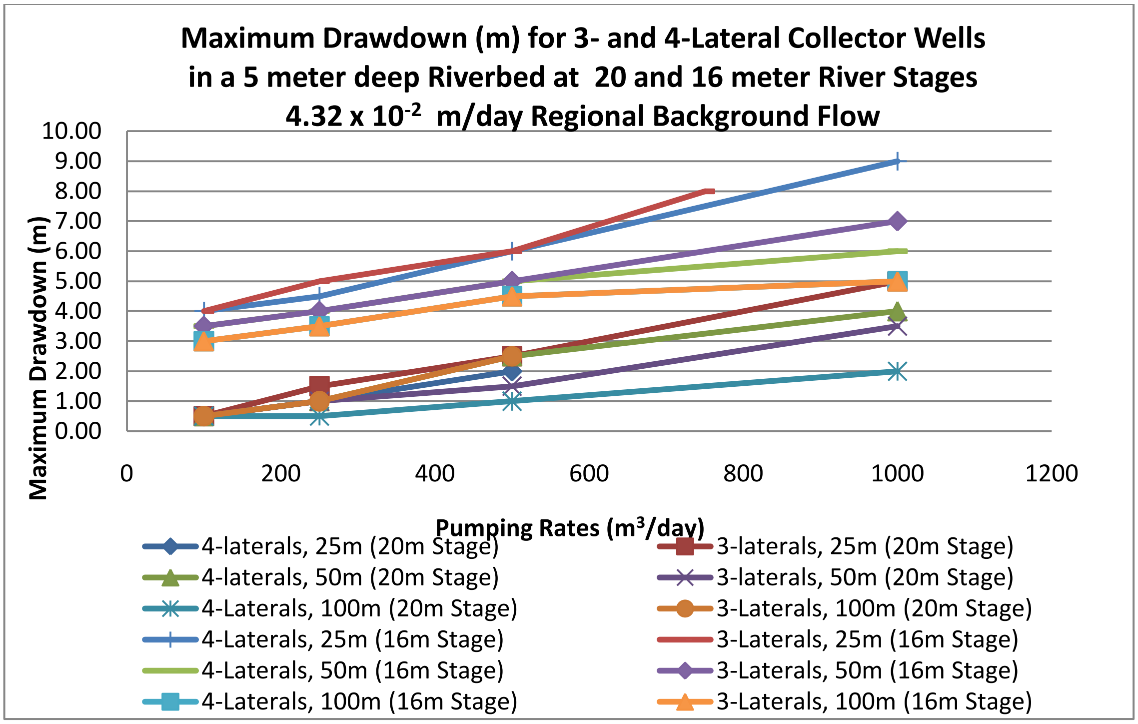


Figure 58: Maximum drawdown for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 5 m deep river bed with 4.32 x 10^{-2} m/day regional background flow.

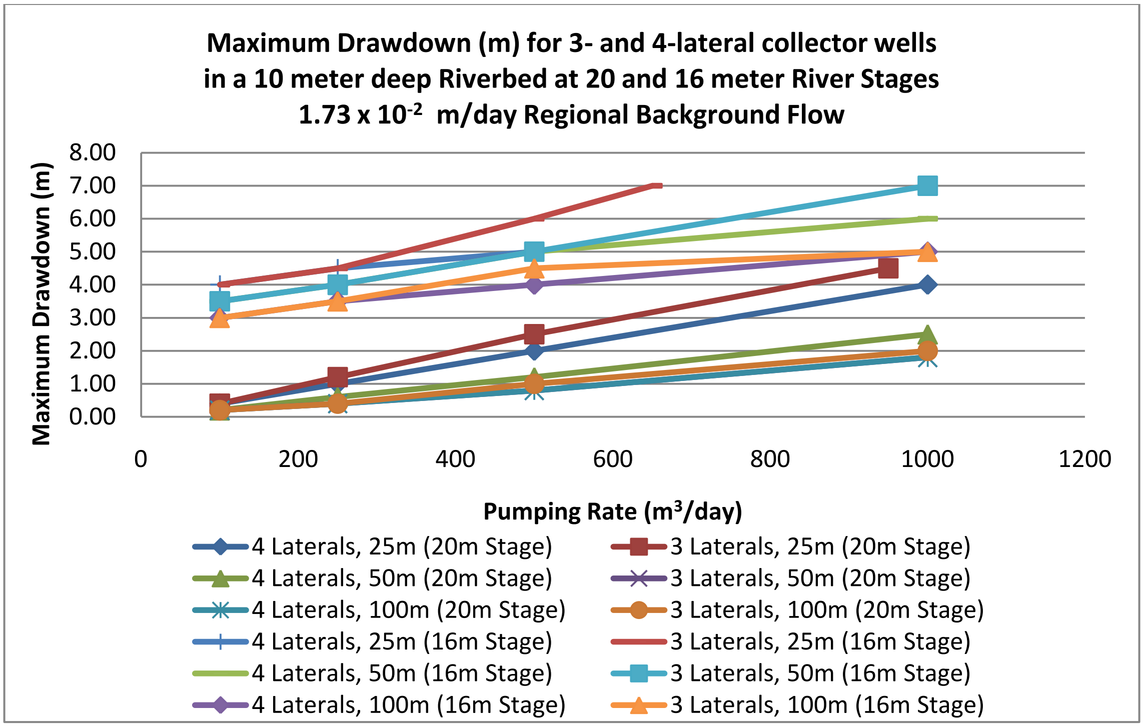


Figure 59: Maximum drawdown for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 10 m deep river bed with 1.73 x 10^{-2} m/day regional background flow.

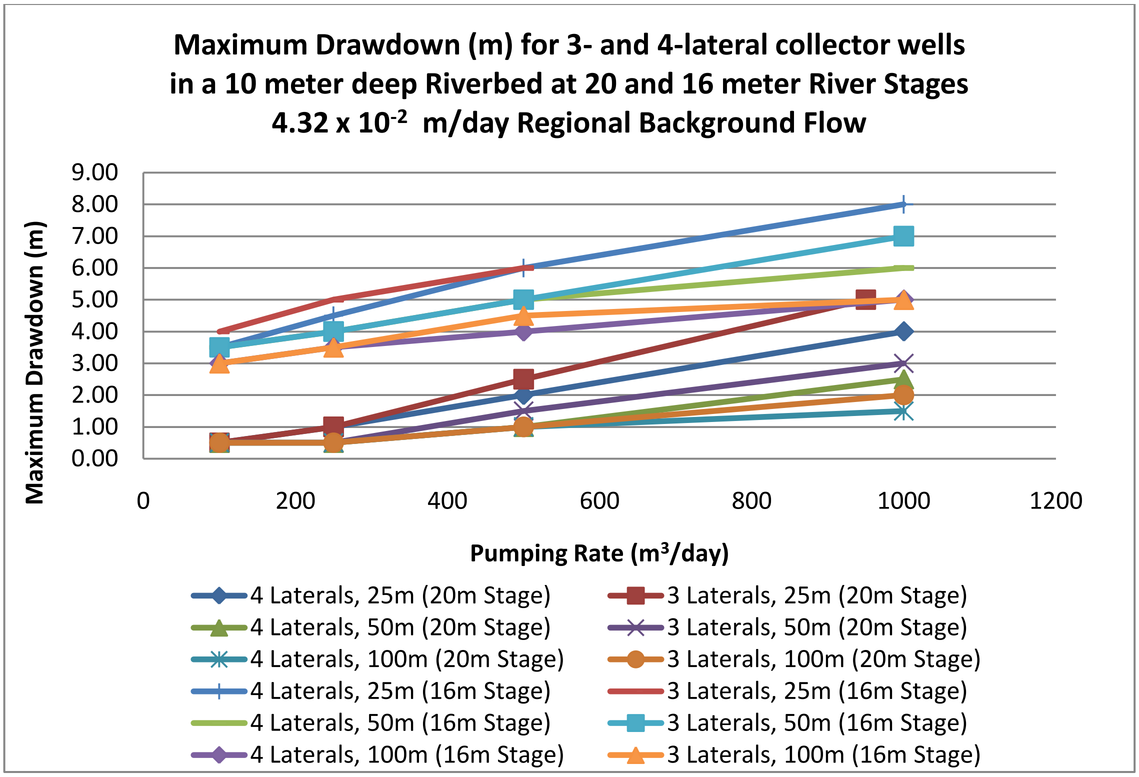


Figure 60: Maximum drawdown for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 10 m deep river bed with 4.32 x 10^{-2} m/day regional background flow.

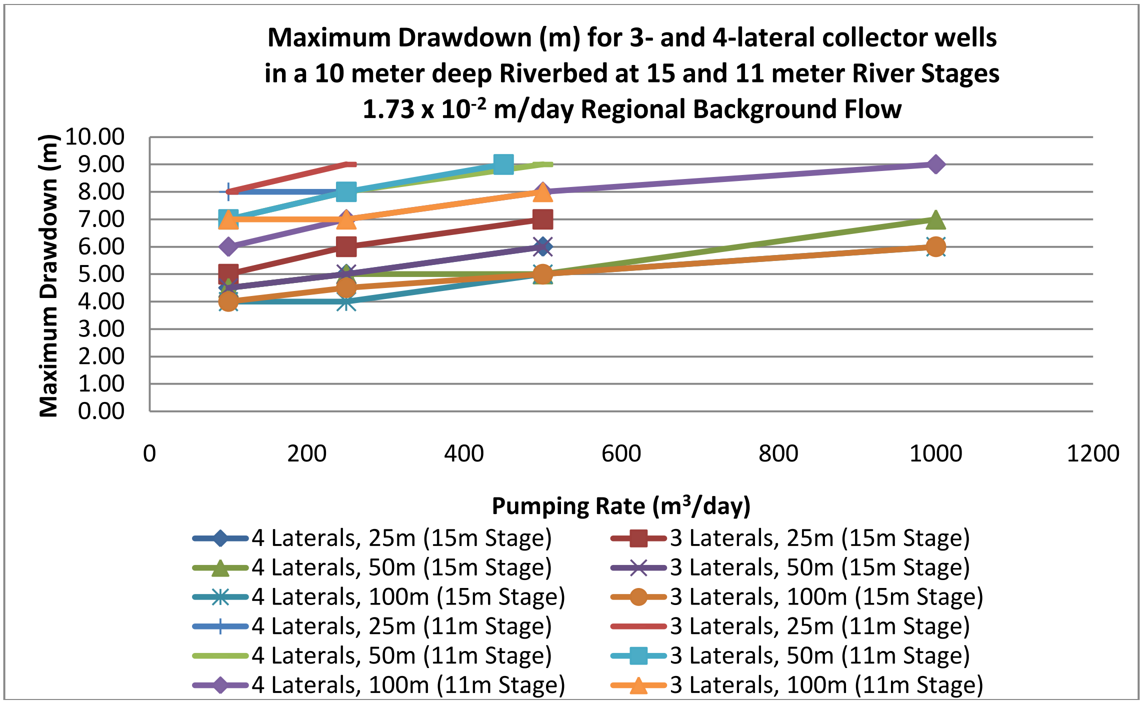


Figure 61: Maximum drawdown for 3- and 4-lateral collector well designs in 15 m and 11 m stage rivers in 10 m deep river bed with 1.73×10^{-2} m/day regional background flow.

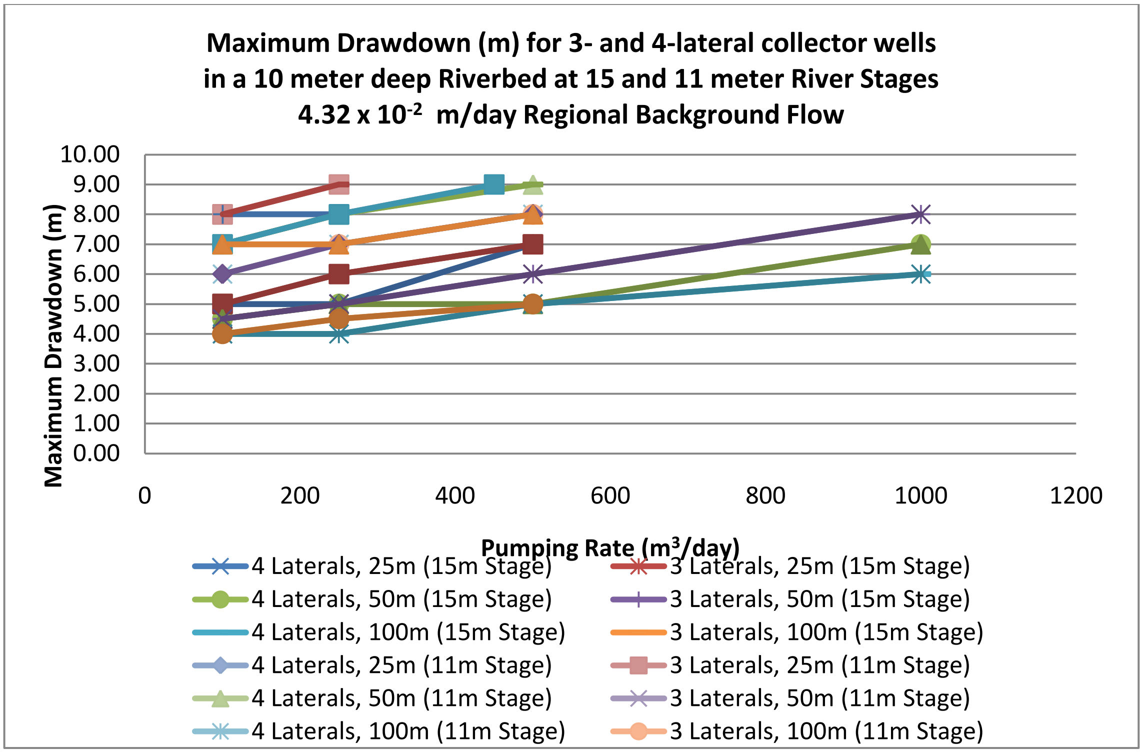


Figure 62: Maximum drawdown for 3- and 4-lateral collector well designs in 15 m and 11 m stage rivers in 10 m deep river bed with 4.32×10^{-2} m/day regional background flow.

5.4.2: Well Yield

Figures 63-70 show how the well yield changes with increasing lateral length and the number of laterals in different river stages and regional background flows (1.73×10^{-2} and 4.32×10^{-2} m/day). Eq. (3) is used to calculate the well yield. Based on the linear relationship between maximum drawdown (m) and pumping rate (Figures 55-62), the well yield should form a straight line. However, Figures 63-70 do not display straight lines. Instead, the well yields level off past the 500 m^3/day mark. Most likely this is a result of numerical errors in the model. Figures 63-64 show the well yield for the collector well designs in a 1 m deep riverbed at a 20 m river stage. With increasing lateral length and number of laterals the well yield increases. For example, a design with 4-laterals and 100 m long laterals will provide the highest well yield. In addition, based on Figures 55-62 this design will also have the least amount of drawdown. Therefore, more drawdown (m) does not equal better yield (gpm/m). Increasing the regional background flow to 4.32×10^{-2} m/day does not result in doubling the well yield as seen in Figure 56. The only design in Figure 64 that drastically changes well yield is the 3-lateral design with 100 m laterals with a loss in well yield. Figures 65-66 show the well yield for the collector well designs in a 5 m deep riverbed at 20 and 16 m river stages. Despite the increase in the riverbed depth, the well yield for a 20 m river stage stays the roughly the same as the yield for a 1 m deep riverbed. For a 16 m river stage, the well yield does display the same trend as seen for a 20 m river stage, but the well yield gains are not as vast. The well yield also does not ever seem to reach a point where it is leveling off; instead it appears to increase with an increase in pumping rate. Figures 67-

70 show the well yield for the collector well designs in a 10 m deep riverbed at 20, 16, 15, and 11 m river stages. Both the 20 m and 16 m river stages show the same trends viewed in Figures 63-66. Figures 69-70 show an interesting trend where both 3- and 4-lateral designs produced the same yield. The trend of increasing length obtaining better yield is maintained. Lastly, a 15 m river stage only produces slightly more well yield than a 11 m river stage.

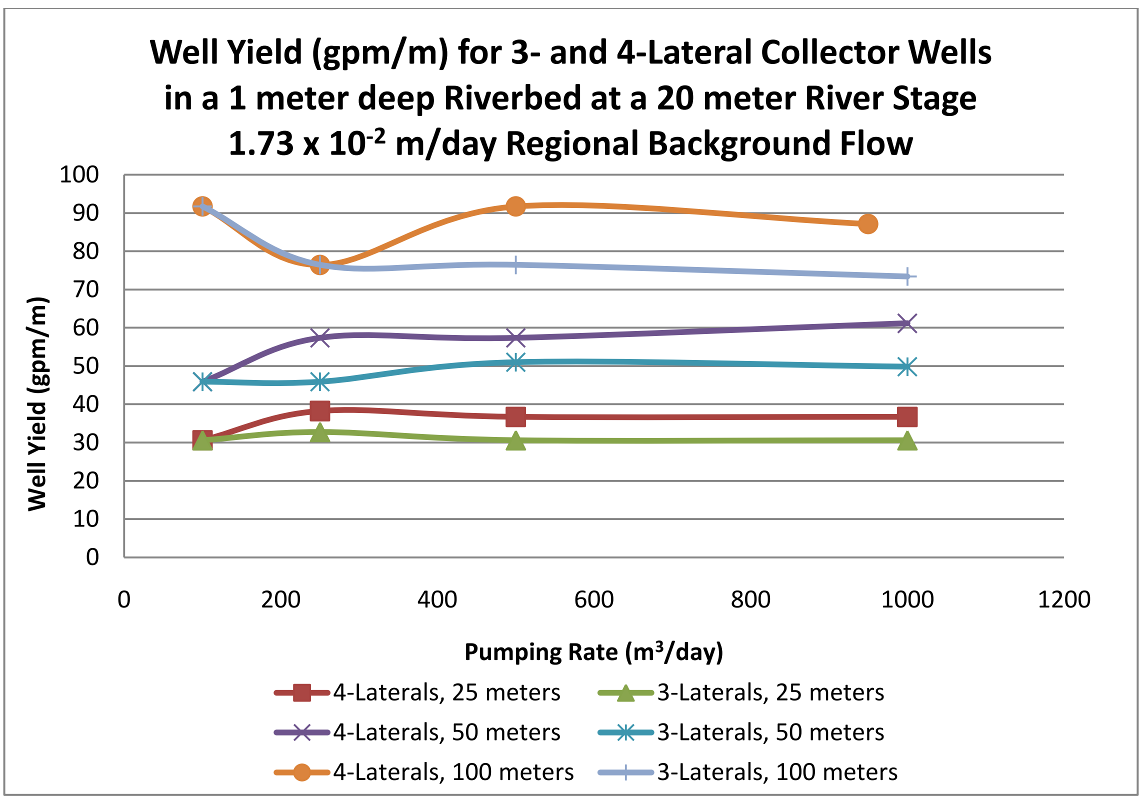


Figure 63: Well yield for 3- and 4-lateral collector well designs in 20 m stage river in 1 m deep riverbed with a 1.73 x 10^{-2} m/day regional background flow.

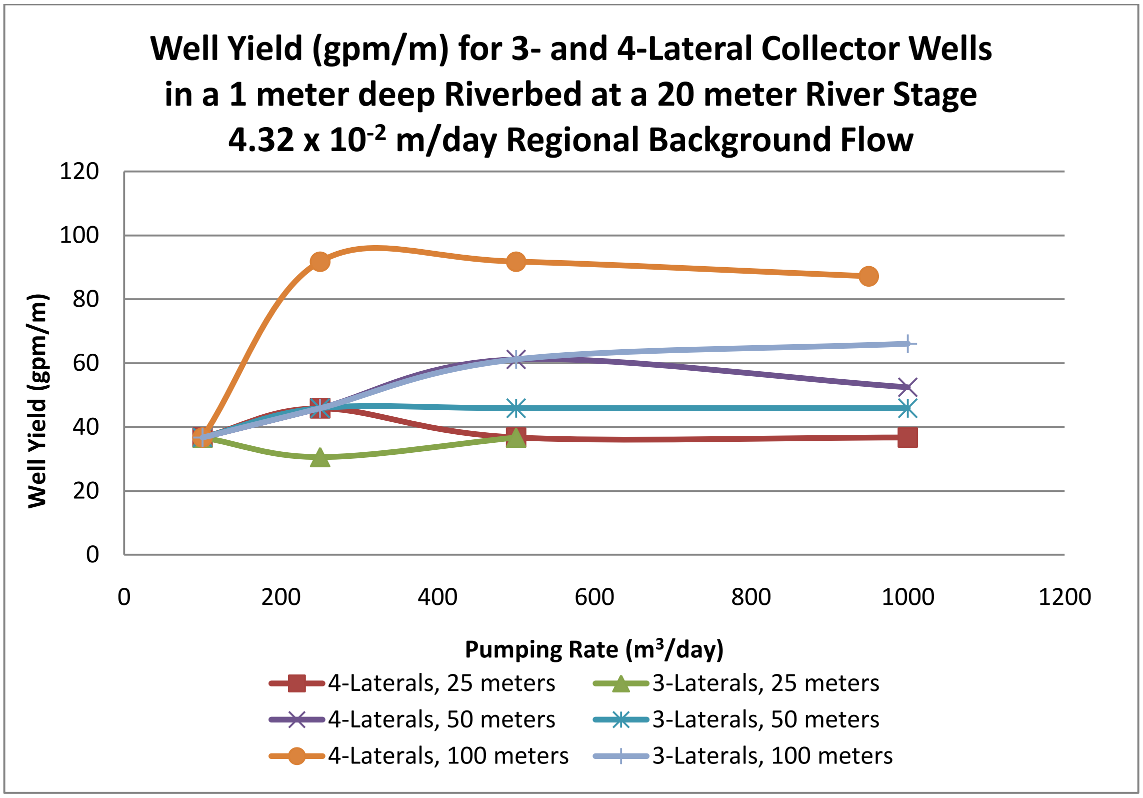


Figure 64: Well yield for 3- and 4-lateral collector well designs in 20 m stage river in 1 m deep riverbed with 4.32 x 10^{-2}m/day regional background flow.

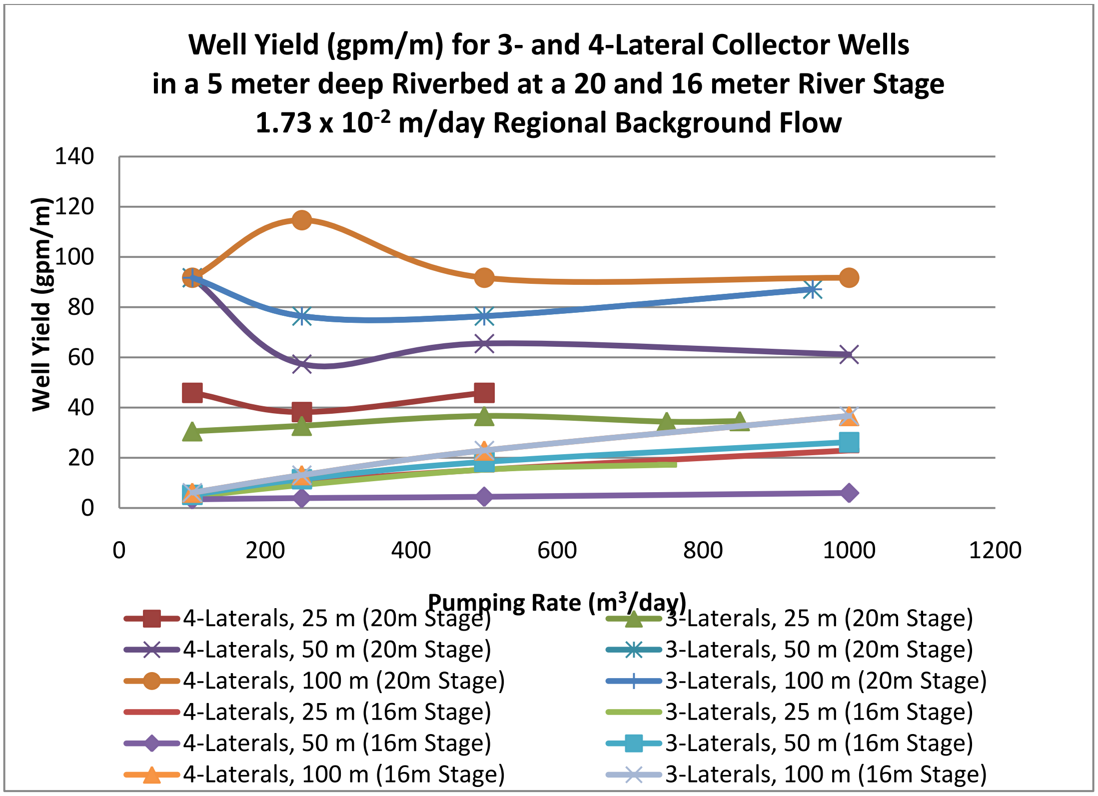


Figure 65: Well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 5 m deep riverbed with 1.73 x 10^{-2} m/day regional background flow.

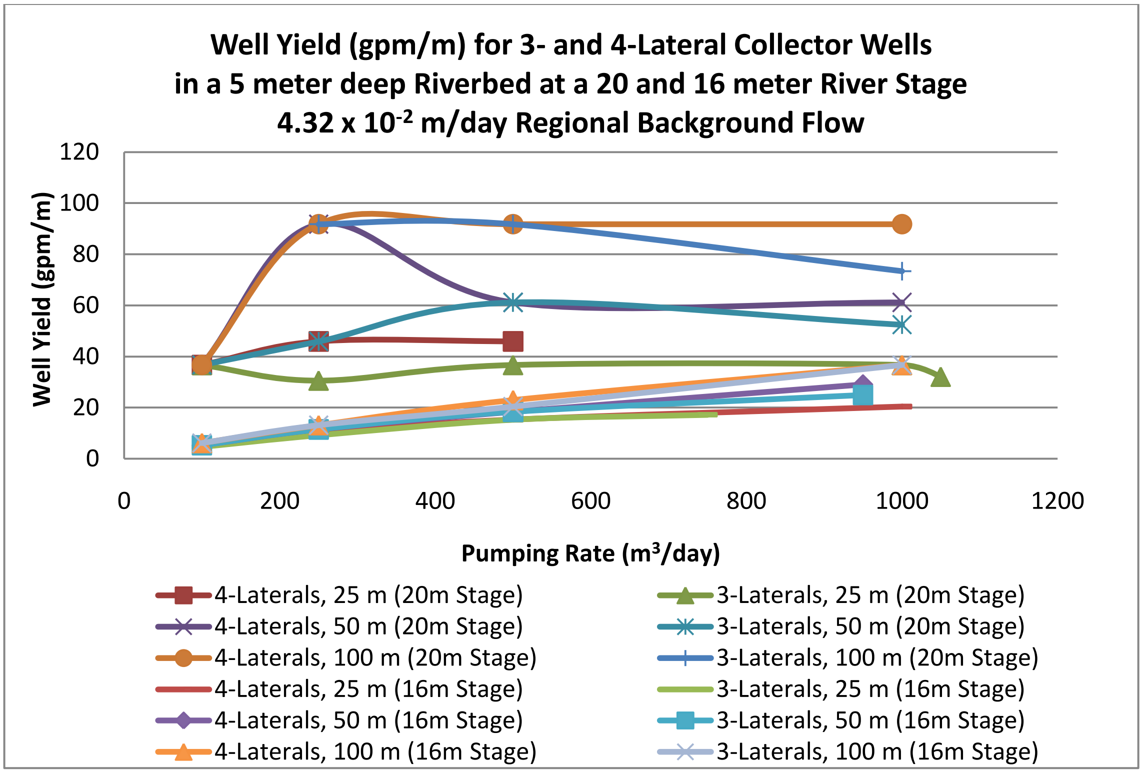


Figure 66: Well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 5 m deep riverbed with 4.32 x 10^{-2} m/day regional background flow.

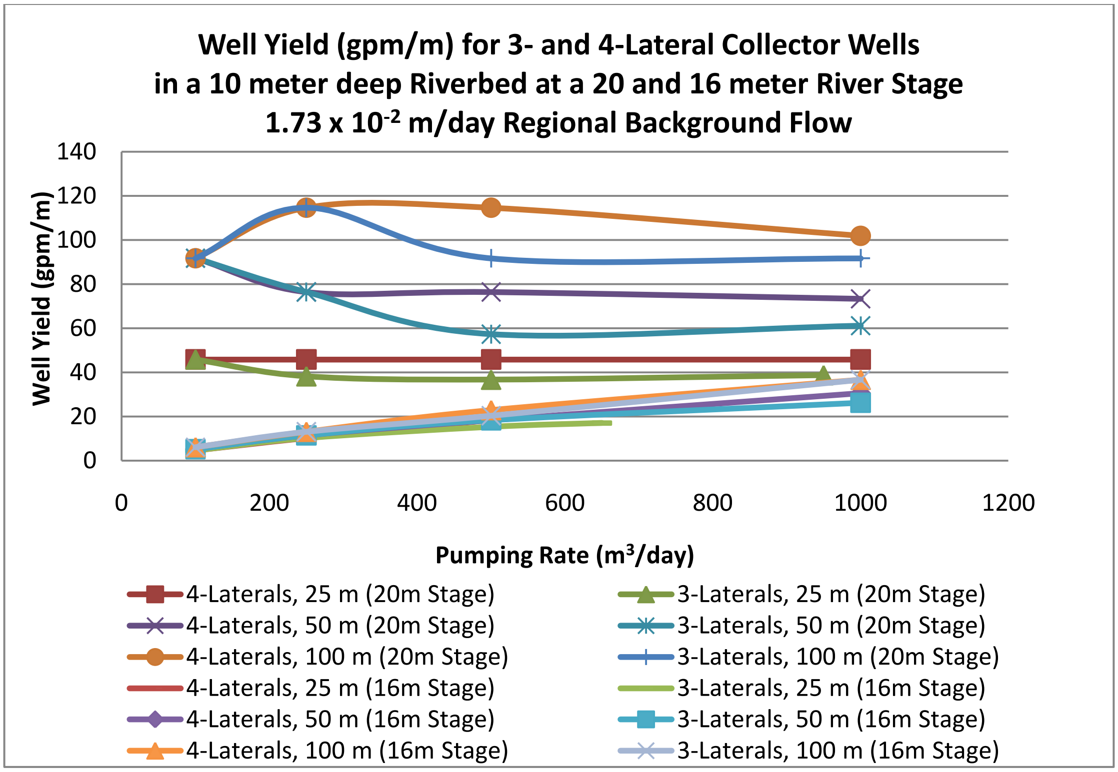


Figure 67: Well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 10 m deep riverbed with 1.73 x 10^{-2} m/day regional background flow.

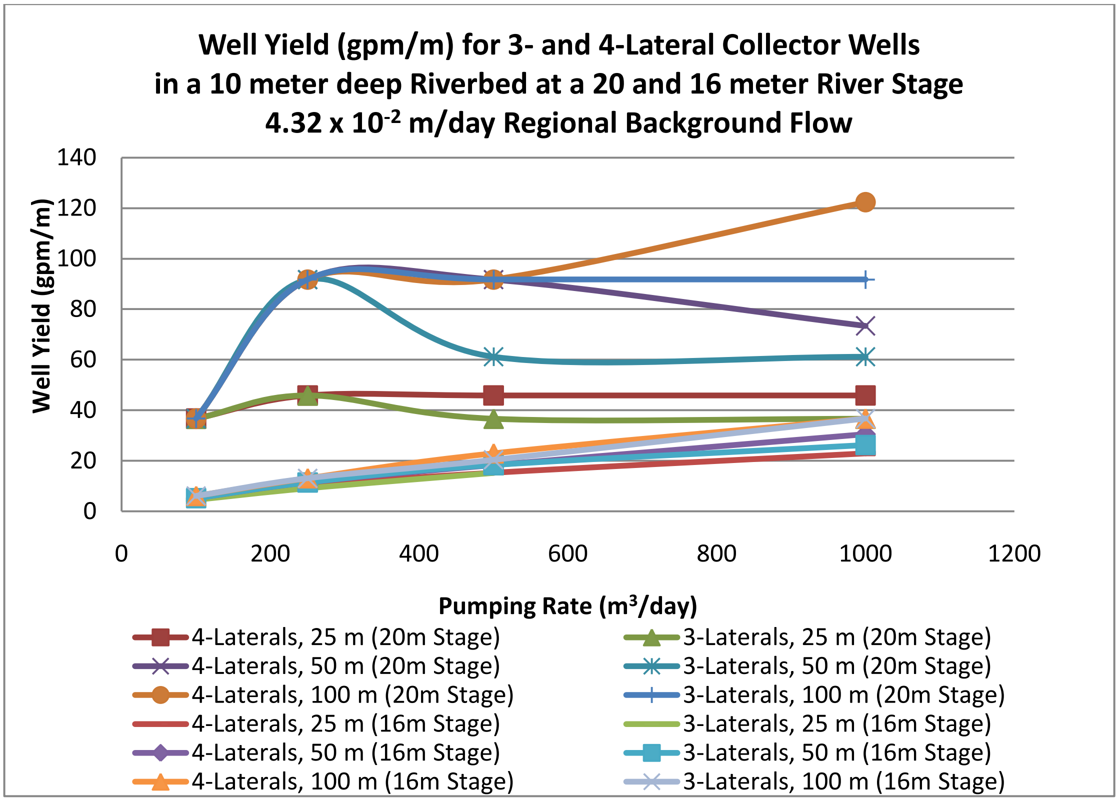


Figure 68: Well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 10 m deep riverbed with 4.32×10^{-2} m/day regional background flow.

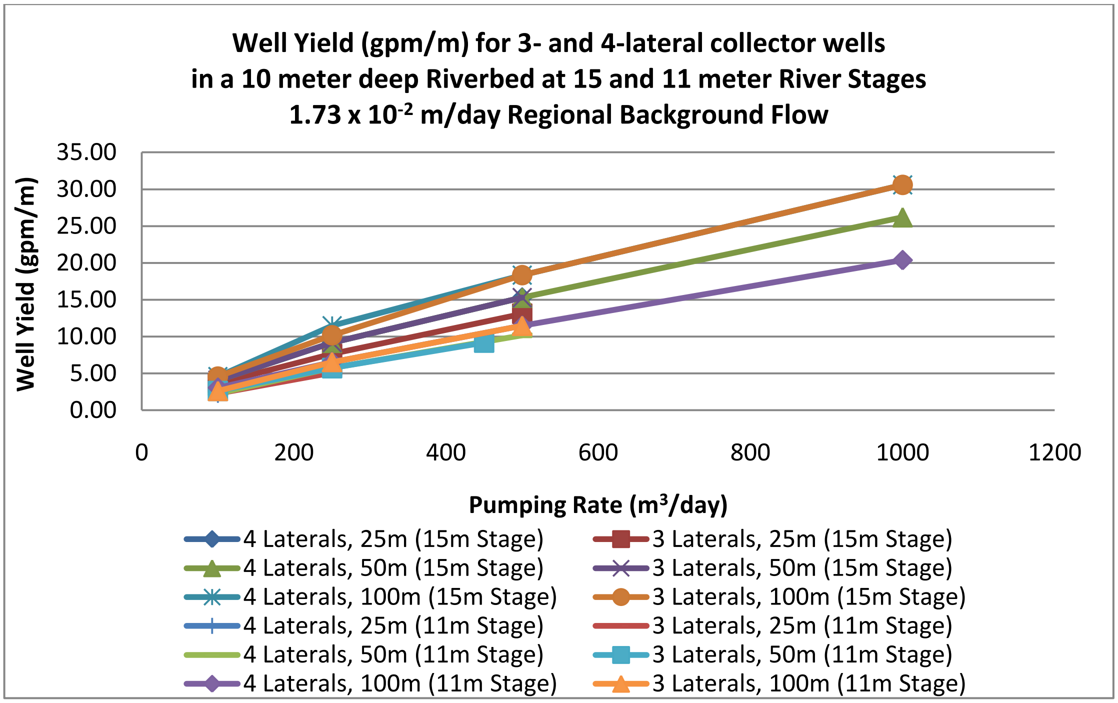


Figure 69: Well yield for 3- and 4-lateral collector well designs in 15 m and 11 m stage rivers in 10 m deep riverbed with 1.73 x 10^{-2} m/day regional background flow.

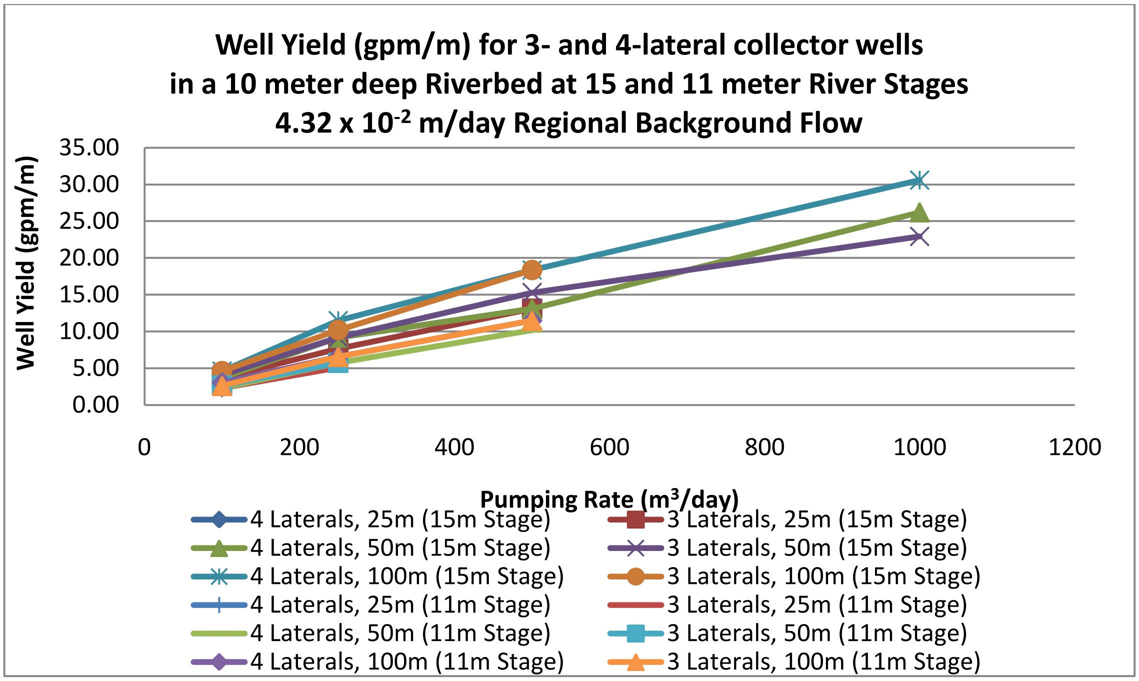


Figure 70: Well yield for 3- and 4-lateral collector well designs in 15 m and 11 m stage rivers in 10 m deep riverbed with 4.32×10^{-2} m/day regional background flow.

5.4.3: Modified Well Yield for Collector Wells

Eq. (4) calculates the modified well yield. Figures 71-78 show the modified well yield for each collector well design in each river setting. The modified well yield shows the same trend viewed in the Figures 63-70 with two major differences. With the modified well yield, the 3-lateral design appears to produce the most yield, in comparison to the 4-lateral design. Because it is divided by the total screen length the overall yield is also lower.

Overall, the trends viewed for Figures 55-78 demonstrate that if a design with the least amount of drawdown is desired then the 4-lateral, 100 m length lateral design is necessary. More laterals with a longer length will result in less impact on the aquifer and nearby river. In terms of well yield, the design to select depends on the river stage. For a 20 m stage river the 4-lateral, 100 m length laterals results in the highest well yield. For a 16 m stage river, the lateral length, not the number of laterals is more important. The 4-lateral design does not result in a significant increase in yield, but longer laterals do. Lastly, for 15 and 11 m stage rivers, only the lateral length is important. In both river stages, the 4- and 3-lateral designs produce the same amount of yield.

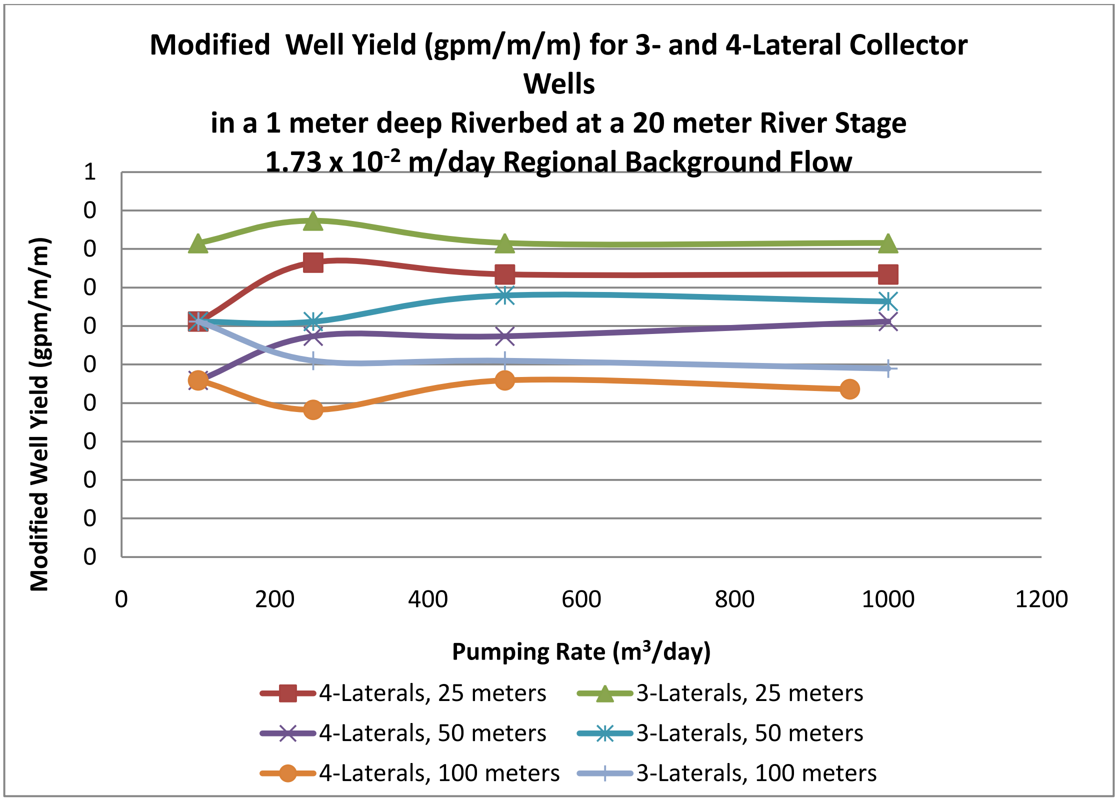


Figure 71: Modified well yield for 3- and 4-lateral collector well designs in 20 m stage river in 1 m deep riverbed with 1.73 x 10^{-2} m/day regional background flow.

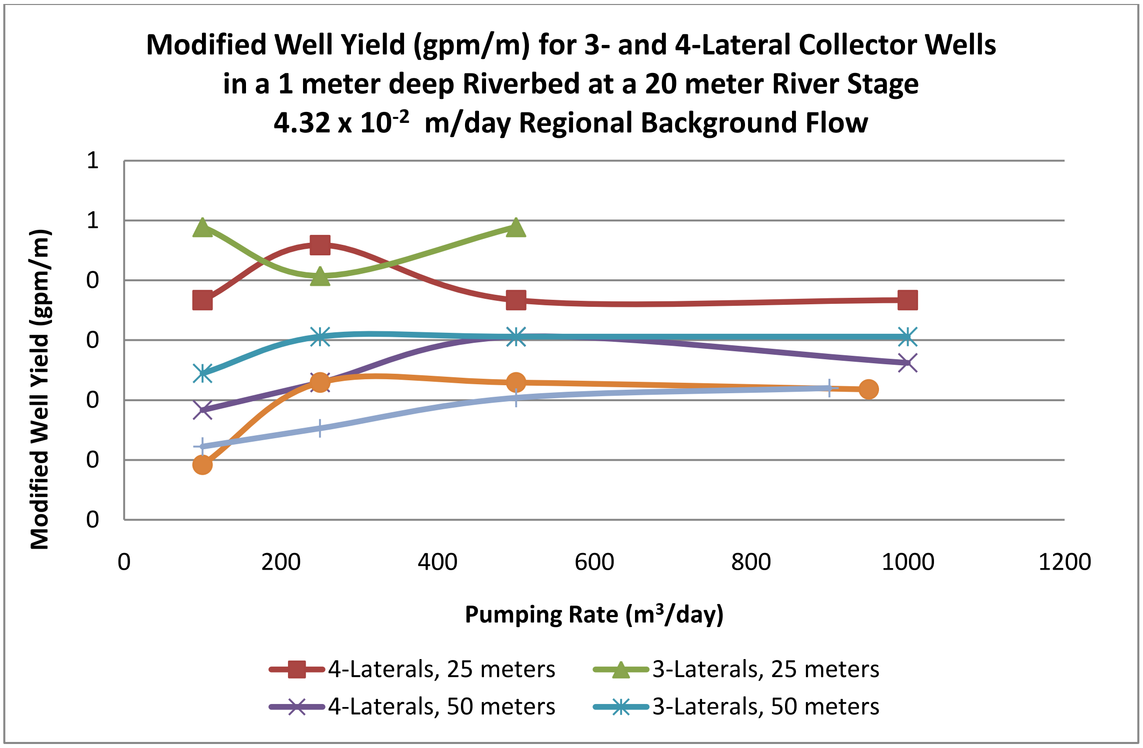


Figure 72: Modified well yield for 3- and 4-lateral collector well designs in 20 m stage river in 1 m deep riverbed with 4.32 x 10^{-2} m/day regional background flow.

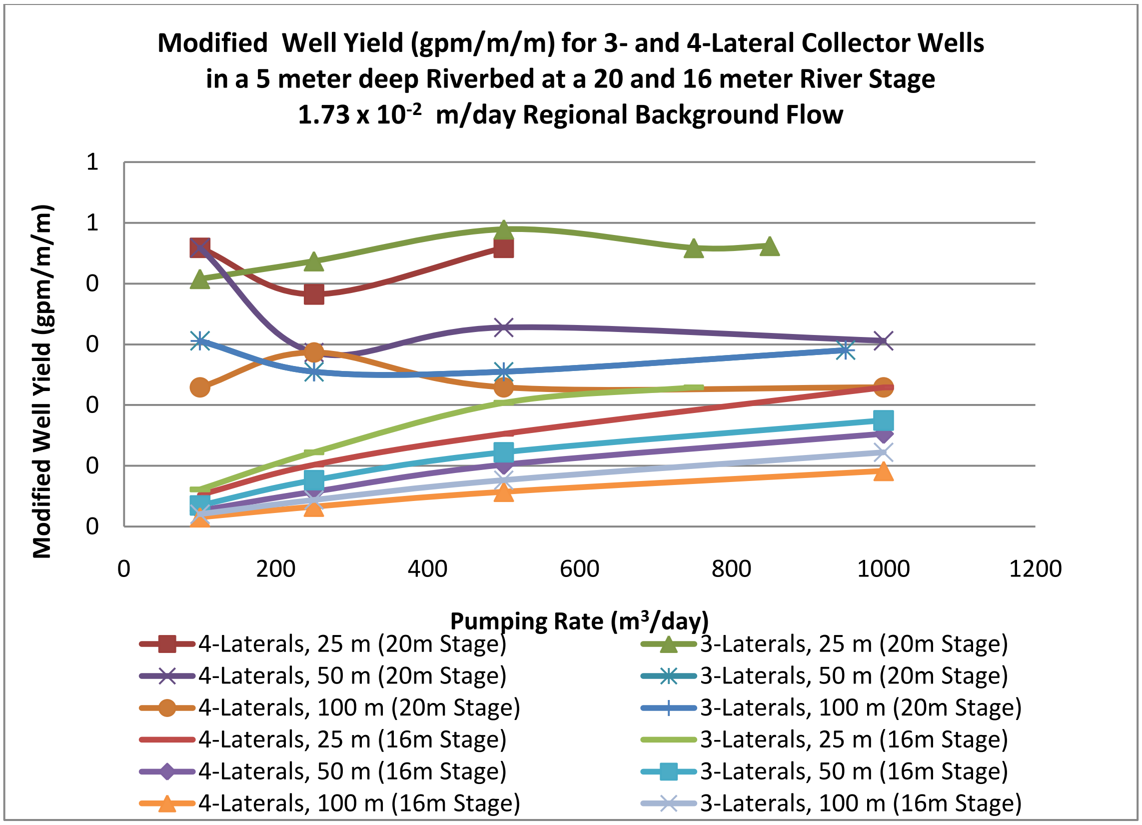


Figure 73: Modified well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 5 m deep riverbed with 1.73 x 10^{-2} m/day regional background flow.

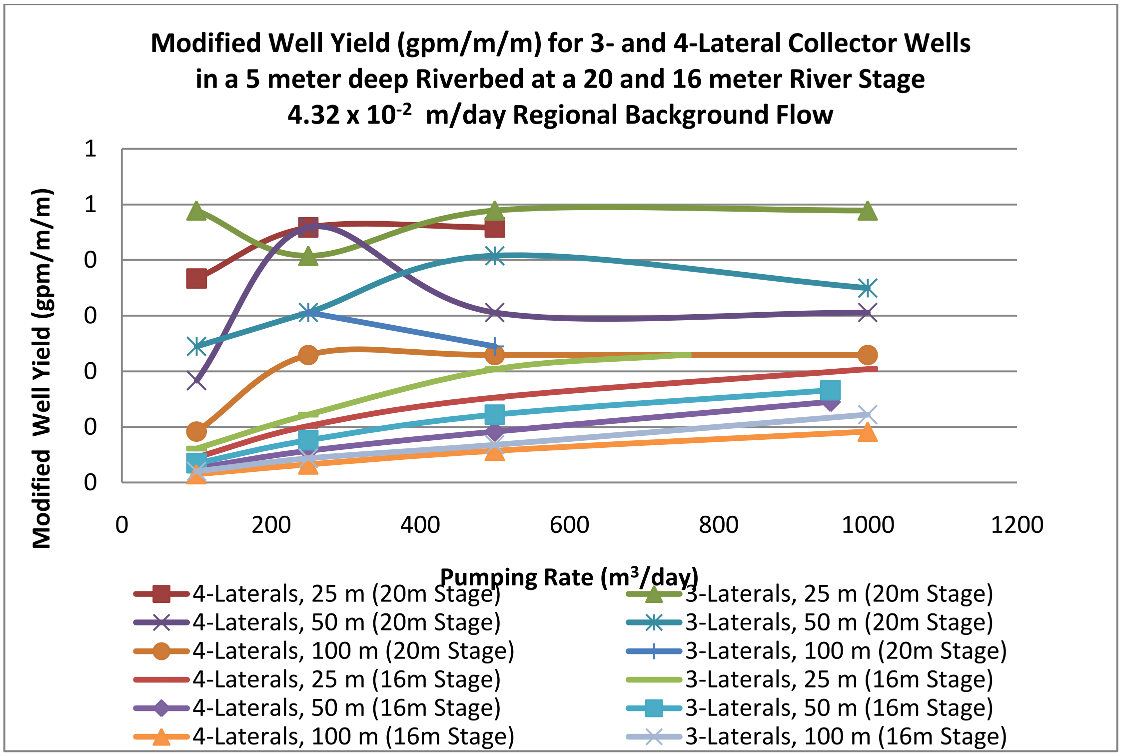


Figure 74: Modified well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 5 m deep riverbed with 4.32 x 10^{-2} m/day regional background flow.

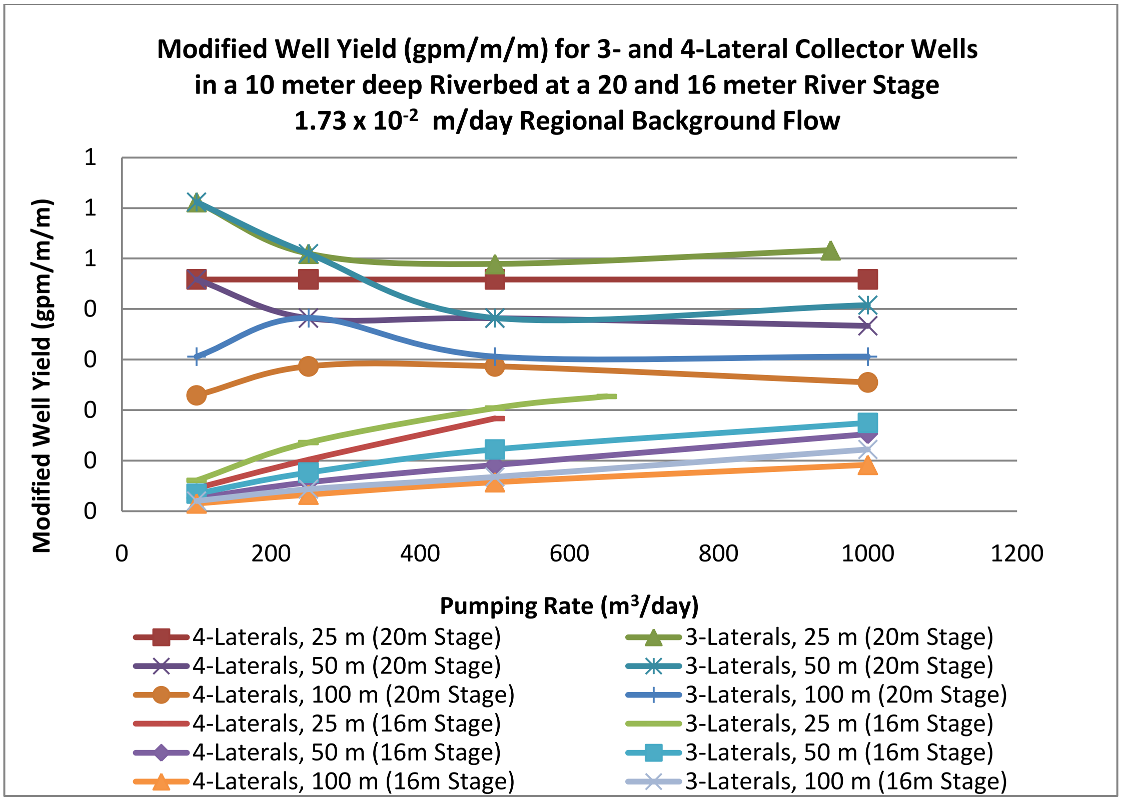


Figure 75: Modified well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 10 m deep riverbed with 1.73 x 10^{-2} m/day regional background flow.

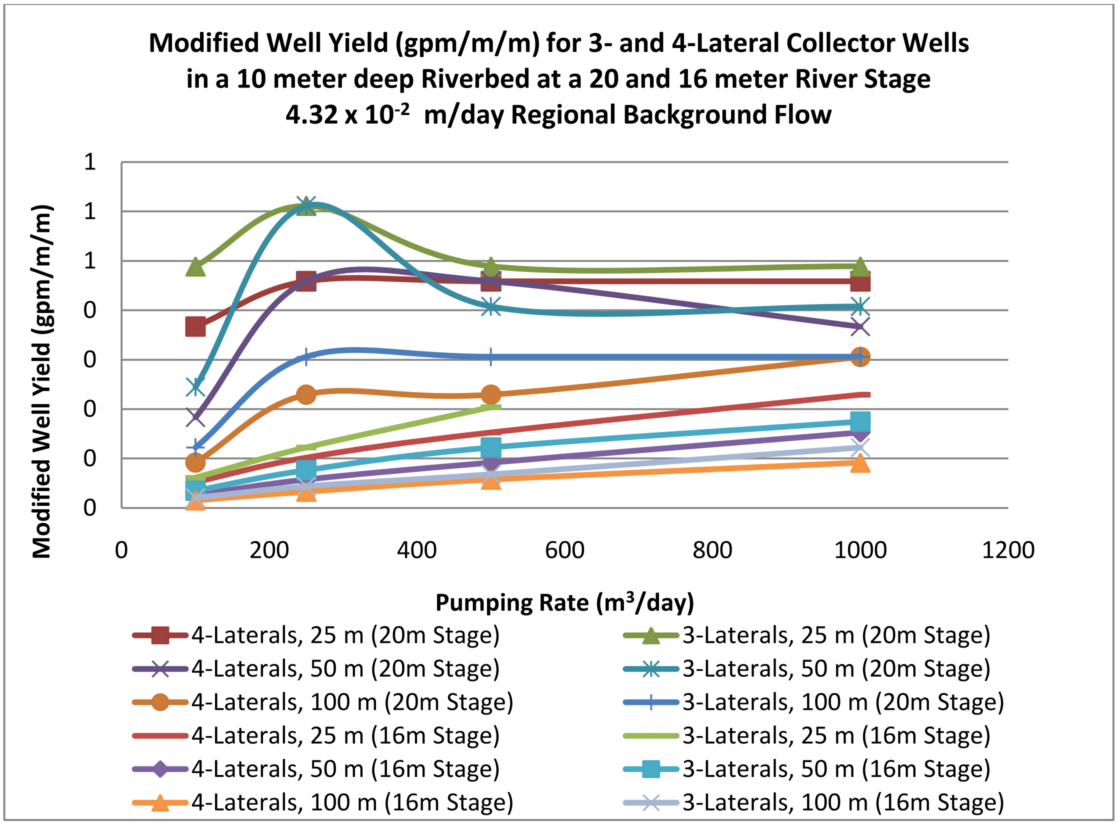


Figure 76: Modified well yield for 3- and 4-lateral collector well designs in 20 m and 16 m stage rivers in 10 m deep riverbed with 4.32 x 10^{-2} m/day regional background flow.

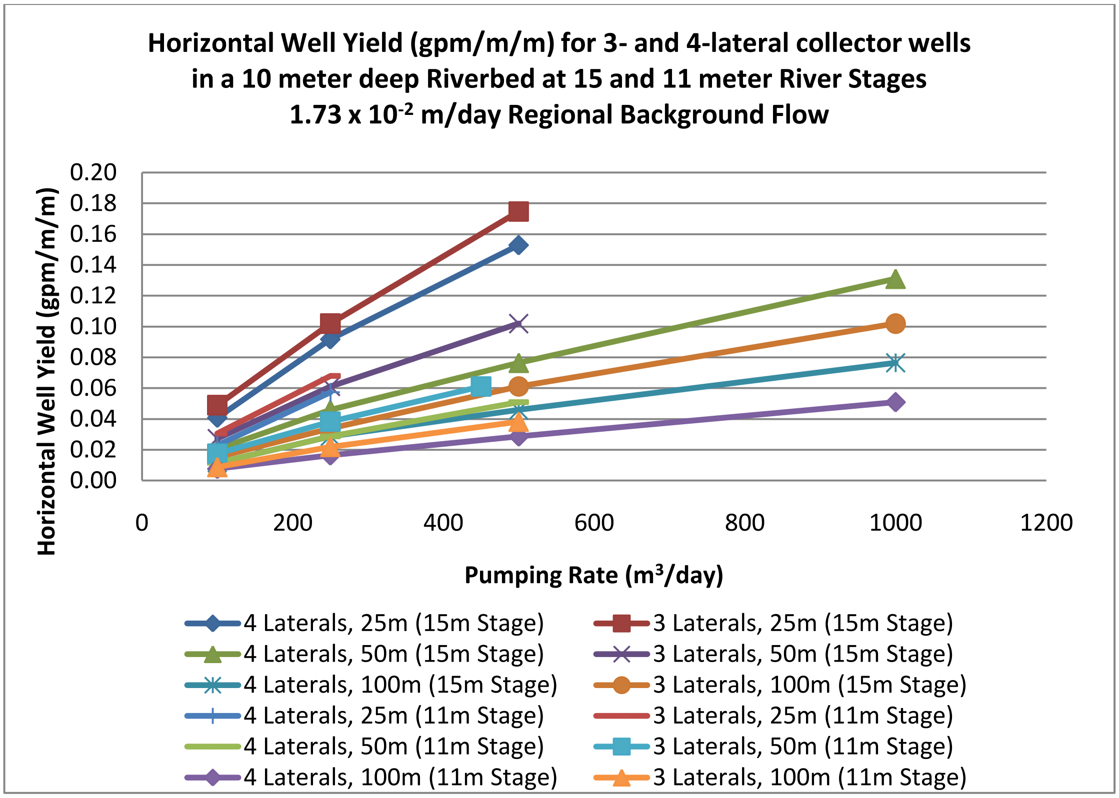


Figure 77: Modified well yield for 3- and 4-lateral collector well designs in 15 m and 11 m stage rivers in 10 m deep riverbed with 1.73×10^{-2} m/day regional background flow.

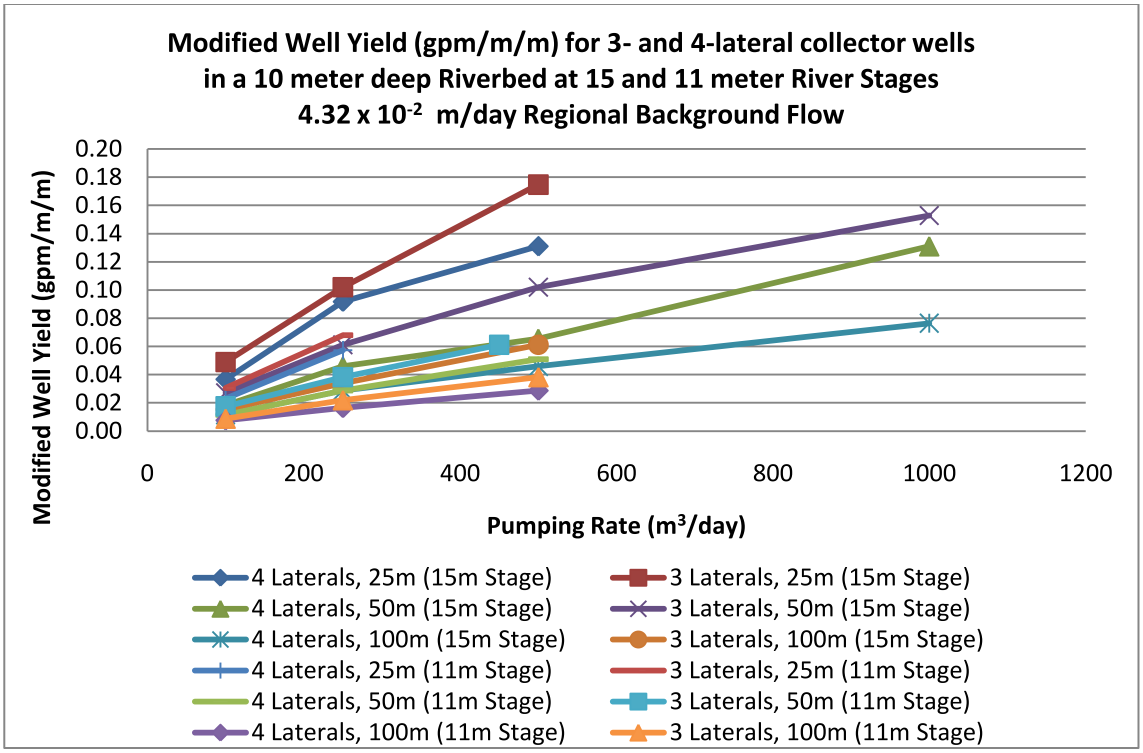


Figure 78: Modified well yield for 3- and 4-lateral collector well designs in 15 m and 11 m stage rivers in 10 m deep riverbed with 4.32×10^{-2} m/day regional background flow.

5.5 :Remediation Evaluation

5.5.1: Investigation of Minimal Pumping Rate

This section will investigate each collector well designs ability for remediation with the utilization of *Zhan and Sun* [2007] equation (Eq. (5)) for calculating the minimal pumping rate to capture a line source. Eq. (5) was originally created for a vertical well; therefore, the viability of Eq. (5) will be tested on a vertical well in both regional background settings: 1.73 x 10^{-2} m/day and 4.32 x 10^{-2} m/day, respectively. Figure 79 illustrates the capture zone of particles to a vertical well and confirms the capability of Eq. (5) to calculate the minimal pumping rate. Figures 80-82 visually validate that Eq. (5) can be utilized to calculate a minimal pumping rate to capture a line source for all three variations of the 4-lateral collector well designs. Table 3 shows the calculated pumping rates used and tested for both the vertical and 3- and 4- lateral collector well designs.

Next, the 3-lateral designs were investigated, but because of the lack of a western lateral, the distance x_0 used for the vertical well could be utilized for all of the 3-lateral designs. All of the variations for the 3-lateral designs were investigated with the same pumping rates used for the vertical wells (Table 3) in both regional background flow settings. These pumping rates did work to completely capture the particles, however, it was visually clear that the pumping rate utilized could be lower (Figure 83). To test this premise, the regional background flow direction was altered to enter from the right side of the model. This would allow the regional flow to interact with the eastern lateral of the 3-lateral design and determine whether the presence of a fourth lateral was imperative to the capture all the particles. The same distances for the 4-laterals were used for the 3-lateral designs. Figures 84-86 visually show that the calculated pumping rates (Table 3) can be used to capture a line of particles for all of the 3-lateral collector well designs.

Table 3 also shows another interesting finding regarding the differences between vertical and collector wells. All collector well designs were able to capture the same line source of particles as the vertical well, but with a lower pumping rate. In addition with increasing lateral length, the pumping rate decreased. Table 3 also shows that there is not a difference in selecting a 3- or 4-lateral collector well design as both designs were able to capture the same amount of particles with the same pumping rate. The only factor to consider if remediation is the main purpose of using a collector well design would be the lateral length as it does alter the pumping rate needed to fully capture the line source.

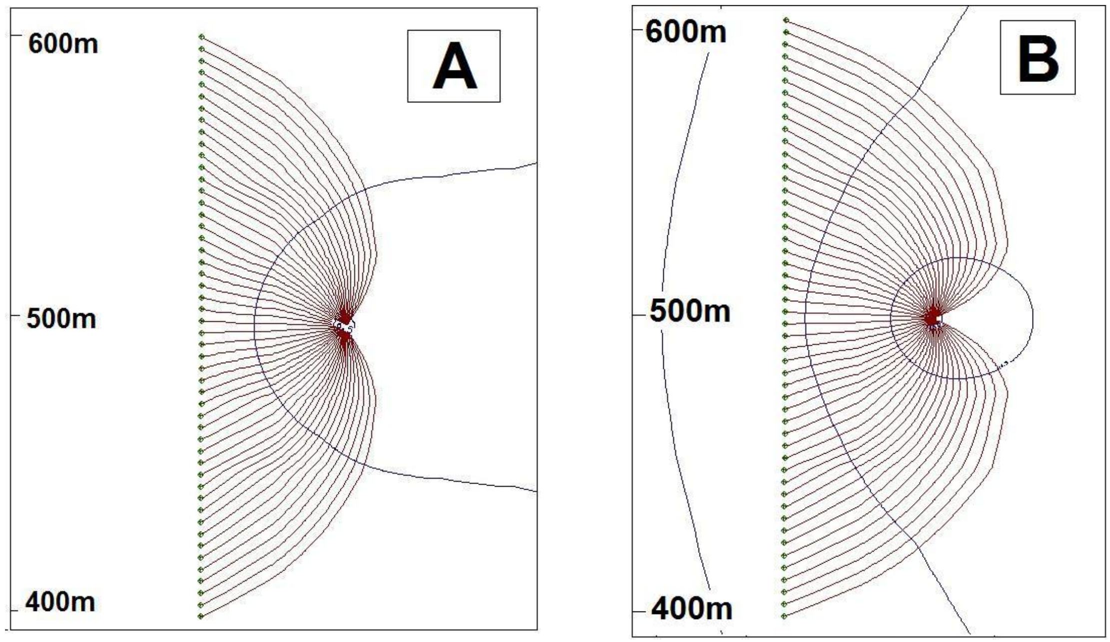
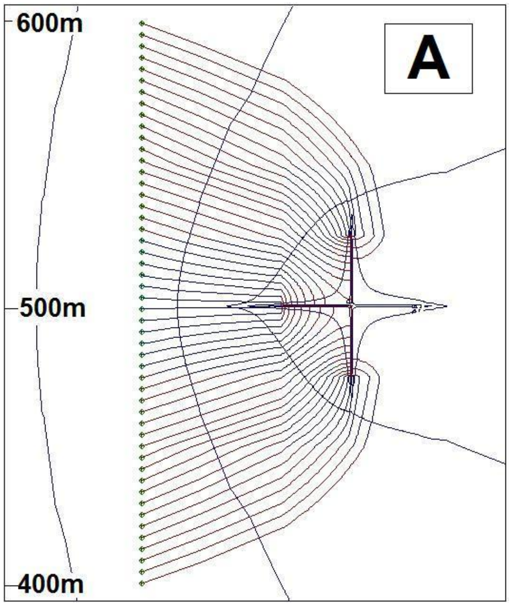


Figure 79: Plan view of capture zone for vertical well with different regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.



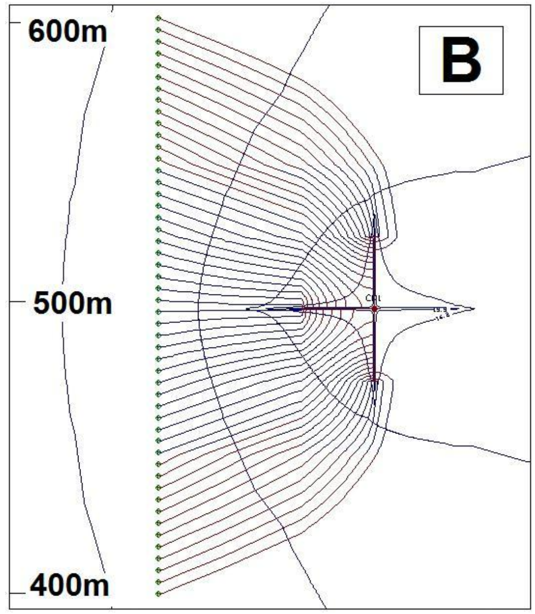


Figure 80: Plan view of capture zone for 4-lateral collector well design with 25 m long laterals with different regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.

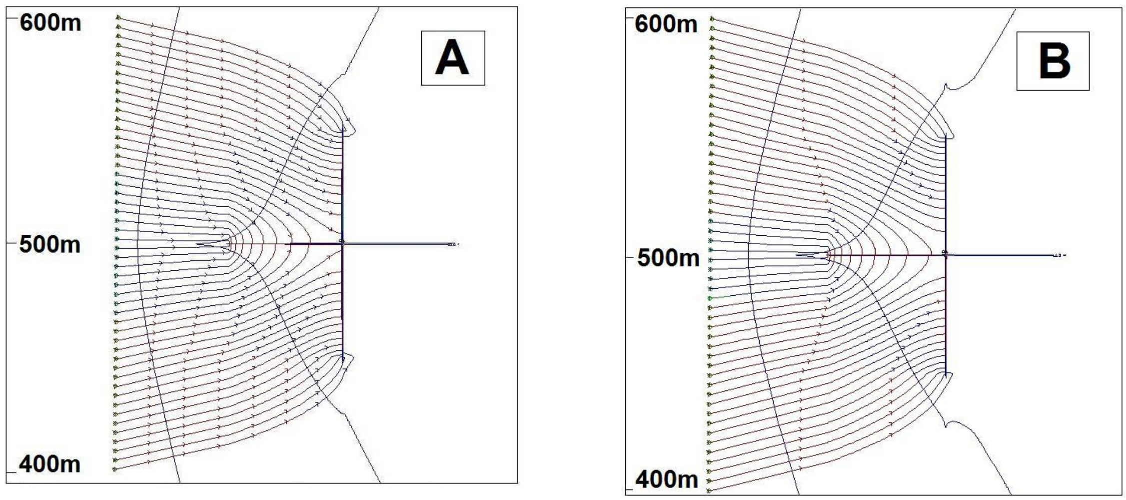


Figure 81: Plan view of capture zone for 4-lateral collector well design with 50 m long laterals with different regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.

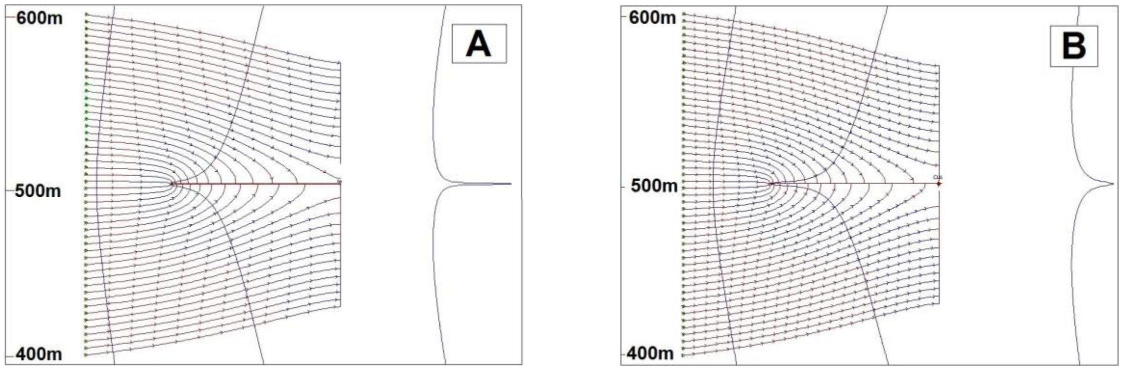


Figure 82: Plan view of capture zone for 4-lateral collector well design with 100 m long laterals with different regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.

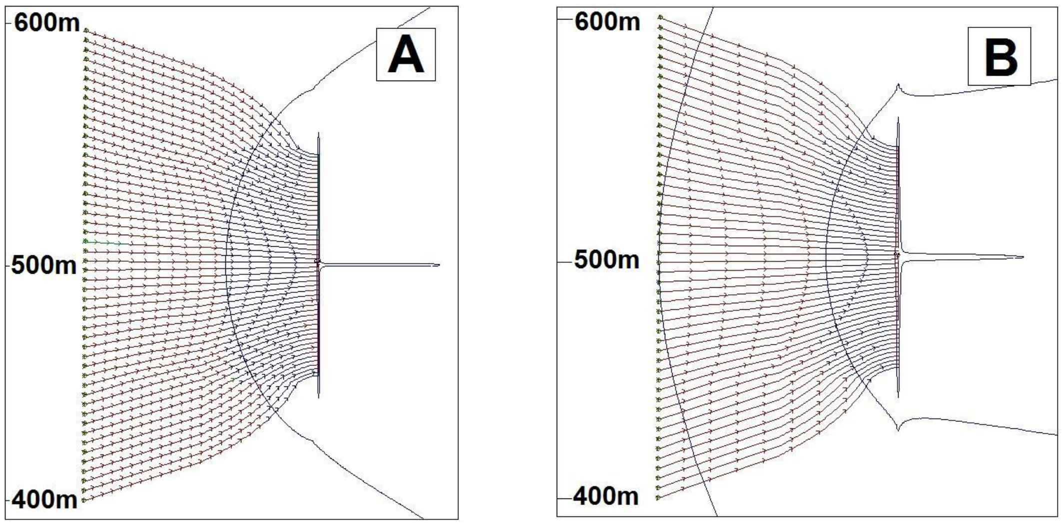


Figure 83: Plan view of capture zone for 3-lateral collector well design with 50 m long laterals with different regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.

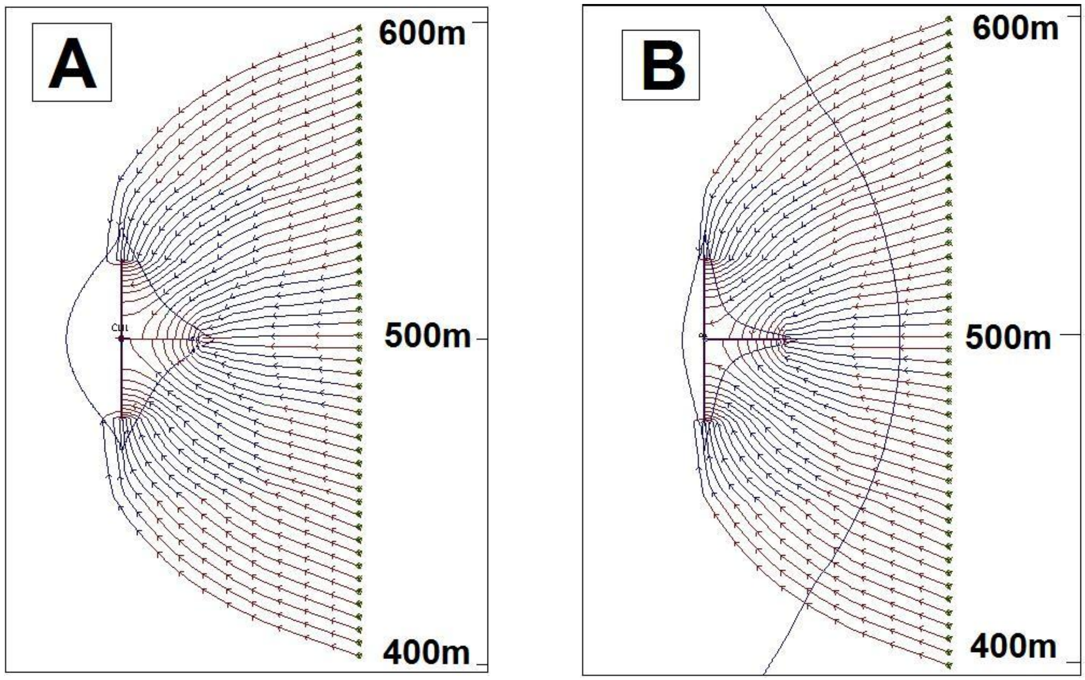


Figure 84: Plan view of capture zone for 3-lateral collector well design with 25 m long laterals with reversed regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day

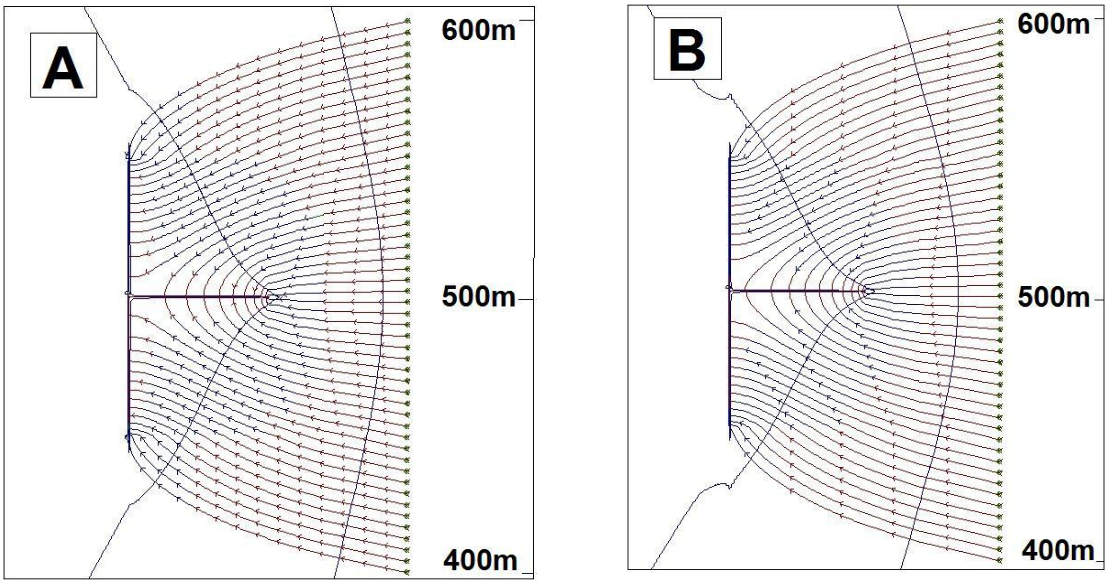


Figure 85: Plan view of capture zone for 3-lateral collector well design with 50 m long laterals with reversed regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.

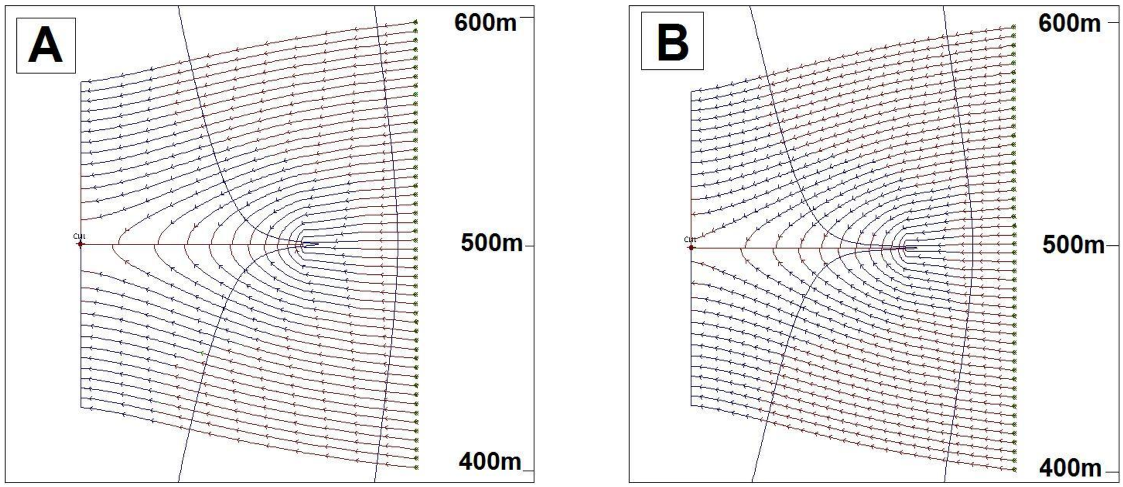


Figure 86: Plan view of capture zone for 3-lateral collector well design with 100 m long laterals with reversed regional background flows: a) 1.73 x 10^{-2} m/day and b) 4.32 x 10^{-2} m/day.

Table 3: Minimum pumping rates for each collector well design.

Collector Well Design	Minimum Pumping Rate (m^3/day) with a 1.73 x 10^{-2} m/day Regional Background Flow	Minimum Pumping Rate (m^3/day) with a 4.32 x 10^{-2} m/day Regional Background Flow
Vertical Well	232	588
4-Lateral Well with 25m Laterals	142	360
4-Lateral Well with 50m Laterals	100	254
4-Lateral Well with 100m Laterals	62	156
3-Lateral Well with 25m Laterals	142	142
3-Lateral Well with 50m Laterals	100	100
3-Lateral Well with 100m Laterals	62	156

5.5.2: Investigation of First Arrival Time

Upon completion of the Modpath® program, a report listing the minimum, maximum ,and average travel times for the particles tested is displayed. To effectively remove pathogens and contaminants, the residence time, the amount of interaction time between the surface water and the vertical caisson, should be maximized [*U.S. EPA*, 2009]. *Zhan and Sun* [2007] also created an equation to calculate the dimensionless first arrival time for a vertical well in a confined aquifer:

$$t_{0D} = 1 - Q_D ln\left(1 + \frac{1}{Q_D}\right) \tag{10}$$

where t_{0D} is the dimensionless first arrival time and Q_D is the dimensionless pumping rate.

$$t_0 = \frac{q_0}{t_{0D} n_e x_0} \tag{11}$$

where t_0 is the first arrival time (1/day), t_{0D} is the dimensionless first arrival time, n_e is the effective porosity, x_0 is the distance from the center of the line source to the extraction well (m), and q_0 is the uniform regional flow from Darcy velocity, along the negative x-axis (m/day).

Tables 4-5 show both the modeled and calculated first arrival times for the vertical and collector well designs. To calculate these values Eqs. (10) and (11) were utilized. Based on the data shown in Tables 4-5, Eq. (10) cannot be applied towards collector wells, as it drastically overestimates the first arrival time. In fact, with increasing lateral length the error regarding the arrival time increases. For the modeled data, the expected trend of the first-arrival time increasing with increasing lateral length is pictured in Tables 4-5. Figures 87-89 graphically show the distribution of the first-arrival times for both modeled and calculated data. Figures 87-88 illustrate that collector well design is important regarding the first-arrival time. This is an unexpected result as the models utilized for the 3-lateral designs involved the regional background flow entering from the right side of the model. Therefore, the x_0 distance was the same for both the 3- and 4-lateral collector well designs. The trend expected was that the number of laterals would not affect the first arrival times. With 25 and 50 m length laterals, the 4-lateral collector well design had the lowest first arrival times. Surprisingly, when the laterals reach a length of 100 m, the 3-lateral design offers the fastest first arrival time in both regional background flow settings. This unexpected observation highlights that after reaching a certain lateral length, the effectiveness of utilizing more laterals diminishes. Consequently, the length of the laterals is more important than the number of laterals as it allows for more interaction between the contaminants and surface water.

Table 4: Modeled versus calculated first arrival times of particles in all collector well designs with 1.73 x 10^{-2} m/day regional background flow.

Collector Well Design	Pumping Rate (m^3/day)	Modeled First Arrival Time (days)	Calculated First Arrival Time (days)
Vertical Well	232	82.40	128.89
4-Lateral Well with 25m Laterals	142	100.00	258.92
4-Lateral Well with 50m Laterals	100	178.00	413.57
4-Lateral Well with 100m Laterals	62	265.00	750.67
3-Lateral Well with 25m Laterals	142	141.00	258.92
3-Lateral Well with 50m Laterals	100	205.00	413.57
3-Lateral Well with 100m Laterals	62	243.00	750.67

Table 5: Modeled versus calculated first arrival times of particles in all collector well designs with 4.32 x 10^{-2} m/day regional background flow.

Collector Well Design	Pumping Rate (m^3/day)	Modeled First Arrival Time (days)	Calculated First Arrival Time (days)
Vertical Well	588	42.10	50.72
4-Lateral Well with 25m Laterals	360	38.10	101.89
4-Lateral Well with 50m Laterals	254	68.70	162.75
4-Lateral Well with 100m Laterals	156	105.00	295.40
3-Lateral Well with 25m Laterals	360	52.40	101.89
3-Lateral Well with 50m Laterals	254	78.80	162.75
3-Lateral Well with 100m Laterals	156	96.70	295.40

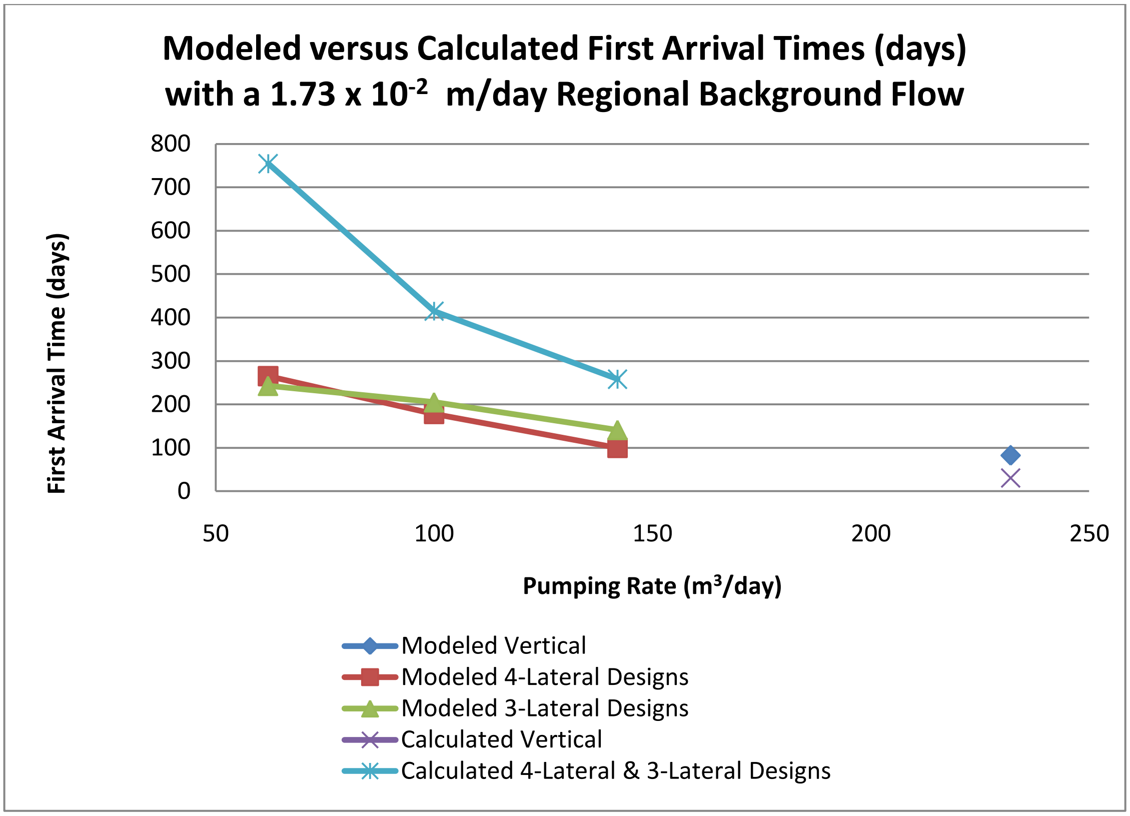


Figure 87: Modeled versus calculated arrival times for vertical and collector well designs with 1.73 x 10^{-2} m/day regional background flow.

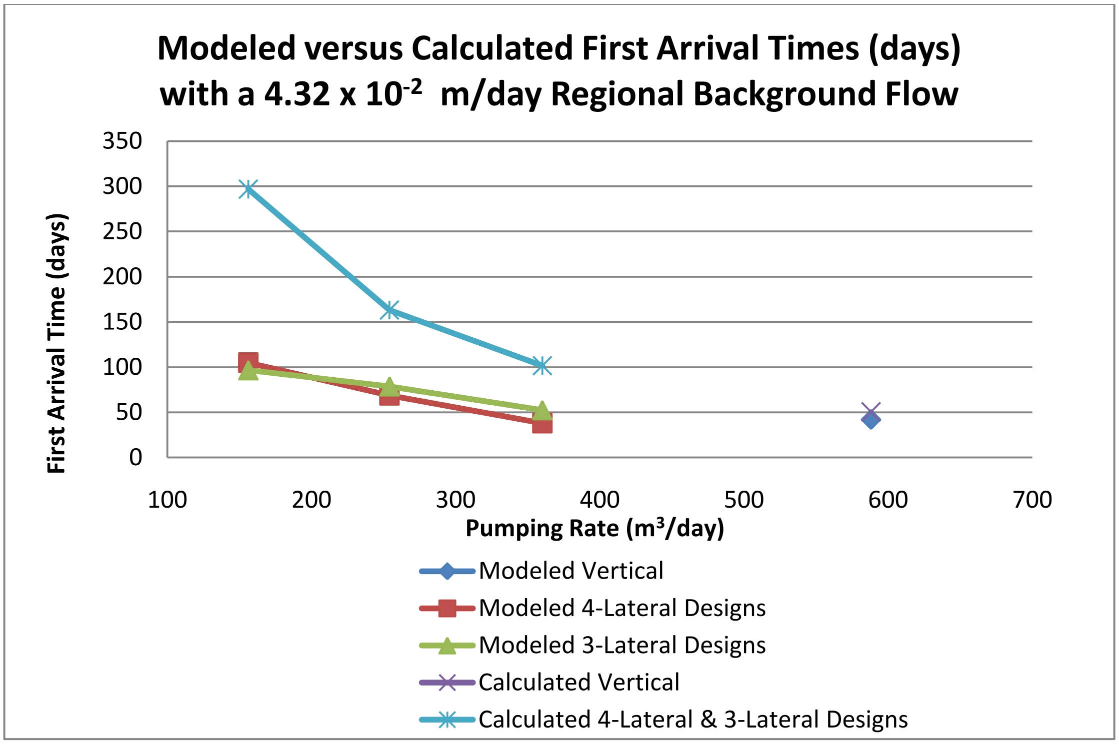


Figure 88: Modeled versus calculated arrival times for vertical and collector well designs with 4.32 x 10^{-2} m/day regional background flow.

6. CONCLUSIONS AND RECOMMENDATIONS

The primary goal of this Masters thesis was to evaluate collector well configurations to model hydrodynamics in riverbank filtration and groundwater remediation. The parameters investigated were lateral length, number of laterals, riverbed depth, and river stage. To determine the optimal configurations for collector wells four areas were explored: flux along the laterals of a collector well, collector well interactions with a river, collector well yield, and collector well remediation capability.

Analysis of flux along the laterals of a collector well and collector well interactions with a river were first studied by *Dugat* [2009] with one basic collector well configuration: 4-laterals at 25 m in length. *Dugat* [2009] suggested that "flux will reach a point of diminishing returns and become asymptotic" regarding flux along the laterals of a collector well (p. 45). Investigation of flux along the laterals with increasing lateral lengths shows that the amount of flux does not increase. Based on this observation, it would appear that Dugat's above statement is correct. However the data also show that a 3-lateral collector well design intercepts more flux than a 4-lateral design. This finding highlights that whereas the amount of flux does increase towards the terminal end of each lateral, collector well design does not impact the amount of flux obtained. Instead, the amount of flux obtained in each design is the same. However, depending on the amount of surface area exposed in each collector well design, it appears that certain configurations uptake more flux. The factor that does determine the amount of flux received is the pumping rate, not the collector well design.

Dugat [2009] showed “the relationship between river stage and water table position established the initial losing or gaining condition of the river, collector well pumping rate determined net flux to river, and regional background dampened or intensified the impact of a collector well pumping rate” (p. 31). Variation of collector well design did little to alter the pre-existing conditions already determined by the river geometry and regional background flow. *Dugat* [2009] further demonstrated that the linear relationship between net flux to a river and dimensionless pumping rate could be used to project which pumping rate would cause deleterious effects to a nearby river. Additional investigation of this relationship with different lateral lengths shows that negative effects towards a river occur at lower pumping rates with longer laterals. In regards to the number of laterals, the 4-lateral design is a marginally better choice as harmful effects to a river occur at a higher pumping rate than a 3-lateral design. These findings show that between lateral length and number of laterals, lateral length is of more importance in design.

Collector wells are often utilized for groundwater supply purposes. Therefore, selecting a design which maximizes well yield without negatively impacting the water table is of key importance. As viewed earlier, the river stage, riverbed depth, regional background flow, and pumping rate determines the amount of water available for uptake with any collector well design. As expected, a 4-lateral collector well design with 100 m length laterals produces less drawdown than a 3-lateral design with the same number of laterals. In all river settings, a 4-lateral collector well design provided slightly better yield than a 3-lateral design. Increasing lateral length also provided better yield. The increase in well yield obtained when upgrading from 50 m to 100 m laterals was not as great as when switching from 25 m to 50 m laterals. For example, a 4-lateral collector well design— situated in a 10 m deep river bed at a 20 m river stage—that experienced an increase in lateral length from 25 m to 50 m resulted in an average 68.4% increase in well yield. However, an increase in lateral length from 50 m to 100 m only resulted in a 16.7% increase in well yield. Based on these findings, it would be more effective to utilize a 4-lateral collector well design with 50 m length laterals for maximum groundwater yield.

Riverbank filtration is another basis for selecting a collector well design over a traditional vertical well. For this purpose, additional understanding of a collector well's capability for remediation is necessary. Currently, there are no equations to calculate the minimal pumping rate to capture a line source for collector wells. *Zhan and Sun* [2007] equation for a vertical well in a confined aquifer was able to calculate a minimal pumping rate for a variety of collector well designs. When compared to the test vertical well data, all collector well designs show that in order to capture the same line source of particles, a lower pumping rate is needed. With increasing lateral length for each collector well design, the pumping rate further decreased. Based on the equation, no data showed that the number of laterals factored into the minimal pumping rate. Further investigation of particle first arrival time did highlight a different perspective. *Zhan and Sun* [2007] vertical well equation for calculating particle first arrival time could not be applied towards a collector well design. The modeled data, however, did show trends regarding the lateral length and number of laterals. Following an increase in the lateral length the expected trend, resulted in an increase in particle first arrival time. In terms of number of laterals, the 3-laterals resulted in a longer first arrival time in all designs except the 100 m length laterals. Surprisingly, 100 m length laterals in a 3-lateral collector well have a faster arrival time than their 4-lateral design counterparts. These findings show that for mximum remediation, a 4-lateral design with 100 m length laterals is needed.

Overall, this study provides a set of guidelines regarding which design parameters should be selected to maximize riverbank filtration and groundwater remediation. Further studies regarding collector well parameters should focus on lateral diameter and more laterals, which is capable with a finite element model. In terms of remediation effectiveness, various concentration levels and types of contaminants should be tested. This model was based on a homogenous aquifer which does not represent a realistic setting. The incorporation of different lithologies and pore types should be added into the models. Lastly, confirmation of model viability by comparison to collector well field data is needed to determine the accuracy of these modeled guidelines.

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VITA

Name: Tiffany Lucinda De Leon

Address: Texas A&M University, Department of Geology & Geophysics, MS 3115,
College Station, TX 77843-3115

Email Address: tdeleon@tamu.edu

Education: B.S., Bioenvironmental Science, Texas A&M University, 2005
M.S., Geology, Texas A&M University, 2010