INTERACTIONS AND IMPLICATIONS OF A COLLECTOR WELL WITH A RIVER IN AN UNCONFINED AQUIFER WITH REGIONAL BACKGROUND FLOW

A Thesis

by

WILLIAM DENIS DUGAT IV

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 2009

Major Subject: Geology

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Approved by:

Chair of Committee,	Hongbin Zhan
Committee Members,	Yuefeng Sun
	Ralph Wurbs
Head of Department,	Andreas Kronenberg

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ABSTRACT

Interactions and Implications of a Collector Well with a River in an Unconfined Aquifer
with Regional Background Flow. (August 2009)
William Denis Dugat IV, B.S., Texas A&M University
Chair of Advisory Committee: Dr. Hongbin Zhan

Ranney radial collector wells consist of an array of horizontal lateral wells arranged radially around and connected to the base of a vertical well. They offer numerous advantages over traditional vertical wells with application in both the petroleum industry and hydrologic sciences. This study improved the understanding of the interaction of collector wells and the aquifers/reservoirs they tap by numerically modeling flux exchanges between a collector well and a river in an unconfined aquifer with regional background flow. Modeling demonstrated that flux along each horizontal lateral increased with distance from the vertical well stem following a third order polynomial function. Ultimately these models demonstrated that in the collector well/aquifer/river system, the pumping rate of the collector well was the dominant factor in controlling flux between the river and aquifer under various conditions. This study can be used to project the maximum allowable pumping rate without causing an initially gaining river to become a losing river.

DEDICATION

This thesis is dedicated to my friends and family, who loved me and supported my passion for rocks for as long as I can remember; and to Susan Land for her companionship as we begin our life together.

ACKNOWLEDGEMENTS

I owe a debt of gratitude to the many people who supported the completion of this study, my interest in geology, and my education. I am especially grateful for the guidance of my advisor, Dr. Hongbin Zhan, who encouraged the exploration of my interests and then directed me in new research directions. Dr. Yuefeng Sun, a greatly appreciated committee member, offered valuable insights and taught me many lessons, not the least of which was the value of a concise, elegant argument. I am also thankful for the assistance of Dr. Ralph Wurbs, who encouraged me in my dealings with university bureaucracy and showed me that fluids are just as graceful above the surface of the earth as below.

I could never fully express my thanks to my friends, colleagues, and teachers in the Department of Geology and Geophysics, who made my time at Texas A&M both productive and happy. Thanks go to Chris Klug and Clayton Mack for friendship and thesis advice. Gwen Tennell, Debbie Schorm, Debra Stark, and Sandy Dunham made my education possible through their dedication to the details of administering financial aid, teaching assistantships, and student organizations. Thanks are also due to ConocoPhillips, Chevron/Texaco, Hess, and BP for their financial support of my education.

Finally, thanks to my family: Bill and Kathy Dugat, my parents, as well as my grandparents, Bill and Carline Gardner and Bill Jr. and Gwen Dugat, for their constant and unending support.

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1. INTRODUCTION

In November 1943, a group of oilmen gathered in Franklin, Pennsylvania around a new type of oil well designed by Leo Ranney that promised to dramatically increase the amount of oil recovered from declining petroleum reservoirs with diminishing reserves [*Oil Miner,* 1943]. Traditional oil wells vertically penetrate the reservoir with a narrow diameter borehole and induce flow through a comparetivly small screened interval. In Ranney's new method a central, reinforced caisson is sunk vertically into the reservoir and several lateral pipes are driven horizontally into the reservoir from the central borehole's base, radiating out like the spokes of a wheel. Ranney first successfully engaged this drilling method in groundwater collection and successfully provided water to London in 1934 when that city was facing a severe water shortage. Over the next two years he installed radial collector wells across Europe for public water supplies and, in 1936, he moved operations to the United States, installing 20 collector wells to provide water for industrial plants [*Oil Miner*, 1943]. After World War II Ranney's drilling methods found use in the petroleum industry; similar horizontal drilling practices are common in hydrocarbon recovery to this day. Ranney radial collector wells offer increased well efficiency over traditional vertical wells and remain in use both in the petroleum industry and hydrologic sciences.

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

2. BACKGROUND

A Ranney radial collector well is an array of horizontal lateral wells arranged around and connected to the base of a vertical well in which aquifer/reservoir fluids are collected and pumped to the surface [*Hantush and Papadopulos*, 1962]. Horizontal wells substantially increase the amount of contact area between the well and the aquifer/reservoir over traditional vertical wells and permit long perforated intervals in aquifers/reservoirs of small thickness [*Zhan and Zlotnik*, 2002]. *Parmentier and Klemovich* [1996] showed that one horizontal well has the same contact area to a groundwater reservoir as 10 vertical wells. Increased contact area and a large vertical component of flow due to the horizontal nature of the drill pipes provide collector wells improved control and recovery of reservoir fluids. This allows drilling and production in locations and rock types that traditional vertical wells could never reach [*Zhan and Zlotnik*, 2002]. The petroleum industry employs horizontal drilling technologies to tap unconventional hydrocarbon reservoirs, especially those of low permeability such as shale and tight sand plays. Horizontal, directional drilling techniques also allow penetration of several different prospects from one surface drilling platform, as exhibited in deep water drilling operations [*Joshi*, 1988; *Seines et al.*, 1994; *Maurer*, 1995; *Penmatcha et al.*, 1997]. The unique geometry of collector wells permits their use in areas where drilling operations directly above the reservoir prove physically impossible, such as near paved or highly populated areas [*Zhan and Zlotnik*, 2002]. Non-vertical wells are also used with success in groundwater collection and contaminant remediation [e.g., *Langseth*, 1990; *Morgan*, 1992; *Tarshish*, 1992; *Cleveland*, 1994; *Environmental Protection Agency (EPA)*, 1994; *Murdoch*, 1994; *Falta*, 1995; *Parmentier and Klemovich*, 1996; *Sawyer and Lieuallen-Dulam*, 1998; *Steward*, 1999; *Zhan*, 1999; *Zhan and Cao*, 2000]. These wells are often placed near or under rivers, where they collect water from both the surface and aquifer that is naturally filtered through low permeability riverbank sediments. *Seines et al.* [1994] demonstrated that one horizontal well has the same impact area as roughly four vertical wells. *Steward* [1999] explained how a horizontal well placed perpendicular to regional background flow and downstream of a contaminant source requires the smallest pumping rate to capture a contaminant plume.

Many studies have advanced the understanding of flow dynamics around horizontal wells. *Hantush and Papadopulos* [1962] provided the first comprehensive work in horizontal well drawdown and capture zone delineation. Assuming uniform flux along the length of a lateral, they presented an analytical solution projecting drawdown distribution around a collector well. *Hantush* [1964] later recommended the uniform flux assumption be altered to uniform head along the length of laterals, and later work by *Debrine* [1970] showed that the two assumptions are relatively interchangeable with only a small deviation. *Haitjema* [1985] used a steady-state model to demonstrate that uniform head along a lateral is a more realistic boundary condition and found flux along the length of laterals varied as a third order polynomial function. Subsequent studies used the constant flux assumption to derive analytical solutions for groundwater flow to a horizontal well under various conditions [*Schafer*, 1996; *Zhan*, 1999; *Steward*, 1999; *Zhan and Cao*, 2000; *Stewart and Jin*, 2001].

Radial collector wells are complex fluid collection systems that induce intricate flow dynamics as a result of their pumping because the interactions between different laterals. The designing of more efficient collector wells requires a better understanding of horizontal well hydraulics as well as the interactions between the horizontal laterals of the well. The need for improved collector well design leads to the following objectives.

3. OBJECTIVES

Although many studies have contributed drawdown and capture zone descriptions for specific scenarios involving horizontal and collector wells, more work is needed to generalize the interactions of collector wells, regional background flow, and various river conditions. The broad objective of this study is to better understand the interactions of a radial collector well with the surrounding groundwater reservoir through the numerical modeling of the flux exchanged between a collector well and river in an unconfined aquifer with regional background flow. To accomplish this, the following tasks must be completed:

- Creating a working model of a collector well
- Varying and comparing model parameters to induce different aquifer/reservoir and pumping conditions for sensitivity analysis
    - -pumping rate
    - -regional background flow
    - -river bed depth
    - -river stage
- Adding aquifer heterogeneities resembling natural features

4. METHODS AND MODEL PARAMETERS

This study will use Modflow-2000 Version 1.18.01 as the numerical engine to drive water modeling. Modflow, a three-dimensional, finite-difference groundwater model, was first published by the United States Geological Survey in 1984. It has a modular structure that allows easy modification to adapt the code for a particular application [*Harbaugh*, 2000]. Visual Modflow version 4.3.0.154 Pro from Schlumberger's Water Service division will be used as the graphical user interface to facilitate visual observation of the modeling results. Zone Budget, a program within Modflow used to calculate the sub-regional flux from one predetermined zone to another, will enable detailed observations of the interactions between the collector well, aquifer, and river.

In order to study the interactions of the collector well, aquifer, and river rather than the impact of various well configurations, this study adopted a single, consistent design for the Ranney radial collector well used in all modeling scenarios (Figure 1). The collector well used in this study had four, evenly spaced laterals 25 m in length and 0.15 m in diameter and screened for their entire length. Because Modflow does not inherently allow horizontal wells, grid cells of 0.15 m by 0.15 m were created to represent those laterals. Based the Hagen-Poiseuille Relationship:

$$\kappa = \frac{D^2}{32}, \qquad (1)$$

where κ is the intrinsic permeability (m^2) and D is the diameter of the lateral (m), the permeability of the lateral was determined to be7.03×10^{-4} m^2.

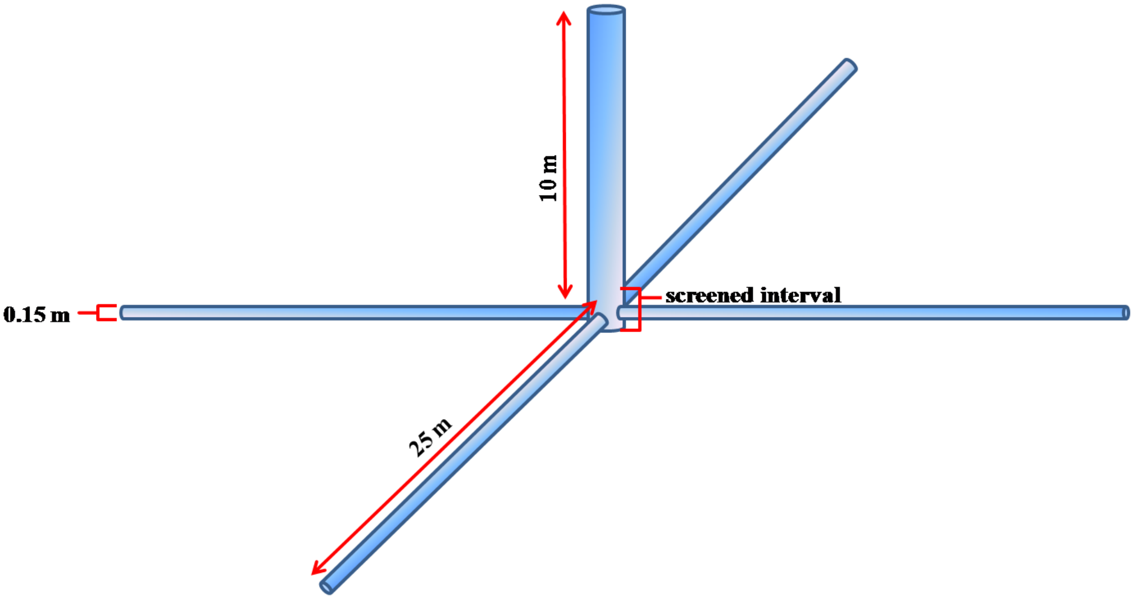

Figure 1: Standard Ranney radial collector well used for modeling (not to scale).

The corresponding hydraulic conductivity of a 0.15 m lateral, 6.81×10^7 m/day, was then calculated using:

$$K = \kappa \frac{\rho_w g}{\mu}, \qquad (2)$$

where K is the hydraulic conductivity (m/day), ρ_w is the density of water (kg/m^3), g is the acceleration of gravity (m/s^2), and μ is the dynamic viscosity of water (kg/ms). Modflow will not accept the true porosity value of a lateral, 1, so 0.999 was assigned to the cells representing the laterals as an appropriate approximation. The laterals were placed horizontally at a depth of 10 m, near the base of the vertical collector "stem." The vertical stem was screened for a total of 0.45 m, centered on the plane of the horizontal laterals. Screening above and below the lateral adjoining interval prevented the possible drying of cells when water in the horizontal laterals flowed too quickly out of the cells to the central stem and Modflow was unable to resupply water from the aquifer at such a high rate.

To examine the dynamics around the collector well shown in Figure 1, a Modflow environment 1,000 m by 1,000 m by 20 m was created (Figure 2). The well was placed in the center of the model, sufficiently far from the lateral model boundaries to minimize any influence on the well. Initially, the model was homogenous and vertically anisotropic with K_x=K_y=0.2 K_z, where K_x and K_y are the horizontal hydraulic conductivities along the x and y axes, respectively, and K_z is the vertical hydraulic conductivity. Although the hydraulic conductivity of the aquifer varies in different test scenarios, the baseline K_x and K_y values are 8.64 m/day. The porosity of the aquifer was set to be 15% for all the scenarios. A constant head boundary representing a river was created parallel to the western model boundary and extending from the northern model boundary to the southern model boundary. It was placed 35 m laterally from the stem of the collector well. The distance from the upper model surface to the base of the river was varied, representing varied river bed depths. Similarly, the stage of the river was varied by altering the distance from the top of the constant head boundary representing the river to the base of the model. The river was 10 m wide. Conceptually, the river was modeled after one of the large meandering streams of the Texas Gulf Coast. A constant head boundary of 20 m was established on the western model boundary. Another constant head boundary of varied head value was created on the eastern model boundary to induce various regional background flows.

Using the Zone Budget Program included in Visual Modflow, a series of zones established around the pumping well and the river calculated the fluxes between the river, aquifer, and well under various conditions. Models ran under steady-state conditions to assess the long-term behavior of a collector well. The magnitude of regional background flow was varied by changing both the hydraulic conductivity of the

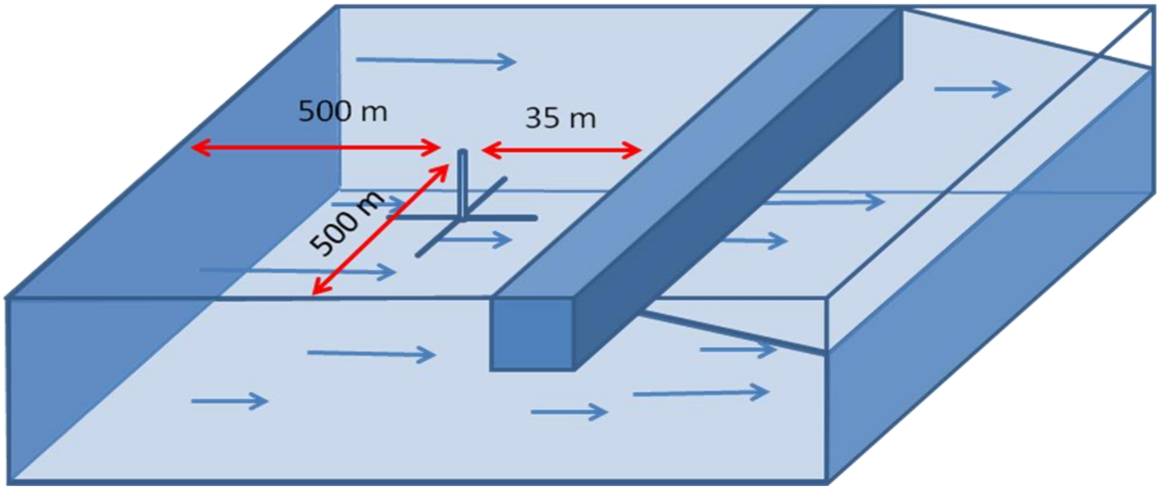

Figure 2: Model setup of the Modflow environment (not to scale).

aquifer and the difference hydraulic head between the western and eastern constant head boundaries. Pumping rate varied from no pumping to an upper limit defined by the rate at which the horizontal laterals dried up, causing the model to fail. This upper limit pumping rate varied with the specific scenarios of river stage, river bed depth, and regional background flow. Pumping rates used were representative of irrigation wells or water supply wells used by small communities. Three river bed depths were examined: 1 m, 5m, and 10 m from the upper model surface. Various river stages were studied at each of the scenarios of river bed depth. Head differences between the western and eastern boundaries, aquifer hydraulic conductivity, river bed depth, river stage, and pumping rate were varied simultaneously to test the impact of each parameter on the system. After establishing baseline river/well/aquifer interactions for homogenous aquifers, the addition of layers of different hydraulic conductivity resembling clay lenses, abandoned river channels, and other natural features conceptually improved the model toward a more realistic physical scenario. The geometry of the heterogeneous aquifer was based on the standard geometry of a meandering stream in a sandy fluvial system presented by *Walker and Cant* [1984].

5. RESULTS AND DISCUSSION

5.1 Dynamics Surrounding a Collector Well

Qualitative, visual examination of equal head lines and flow lines near a collector well illuminates several interesting points. The close spacing of the equal head lines around and conforming to the horizontal laterals suggests a constant head along the entire length of the lateral (Figure 3). This is expected since the hydraulic conductivity of the lateral is more than six orders of magnitude greater than that of the aquifer. Flow lines to the well demonstrate the uneven flux along the length of the laterals with a greater density of flow lines concentrating at the terminal ends of the laterals (Figure 4). This confirms the findings presented in *Haitjima* [1985]. Further inspection of the flow lines suggests the absence of stagnation zones directly around the horizontal lateral wells when there is no regional background flow. The pumping rate chosen in Figures 3-4 (500 m^3/day) is representative of irrigation wells or groundwater supply wells for small communities.

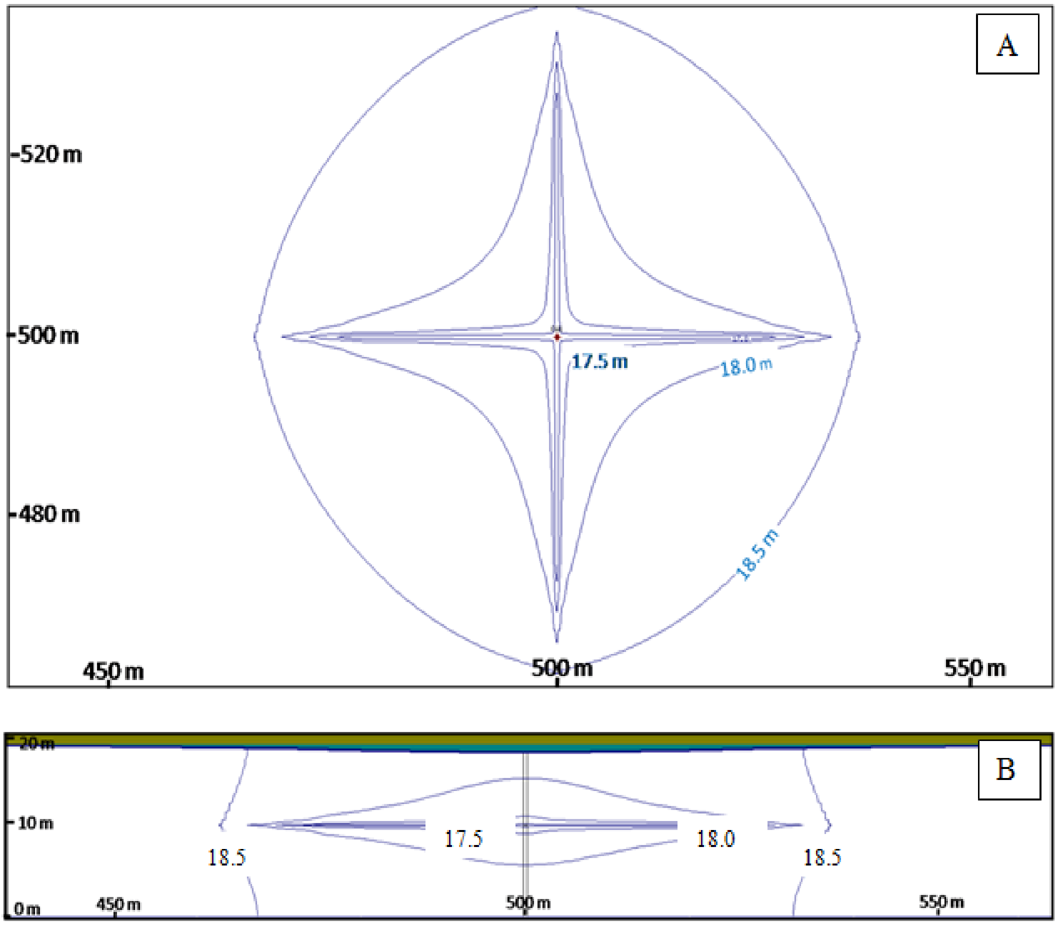

Figure 3: Equal head lines surrounding a collector well, 500 m^3/day pumping rate (planar view “A”, cross section view “B”).

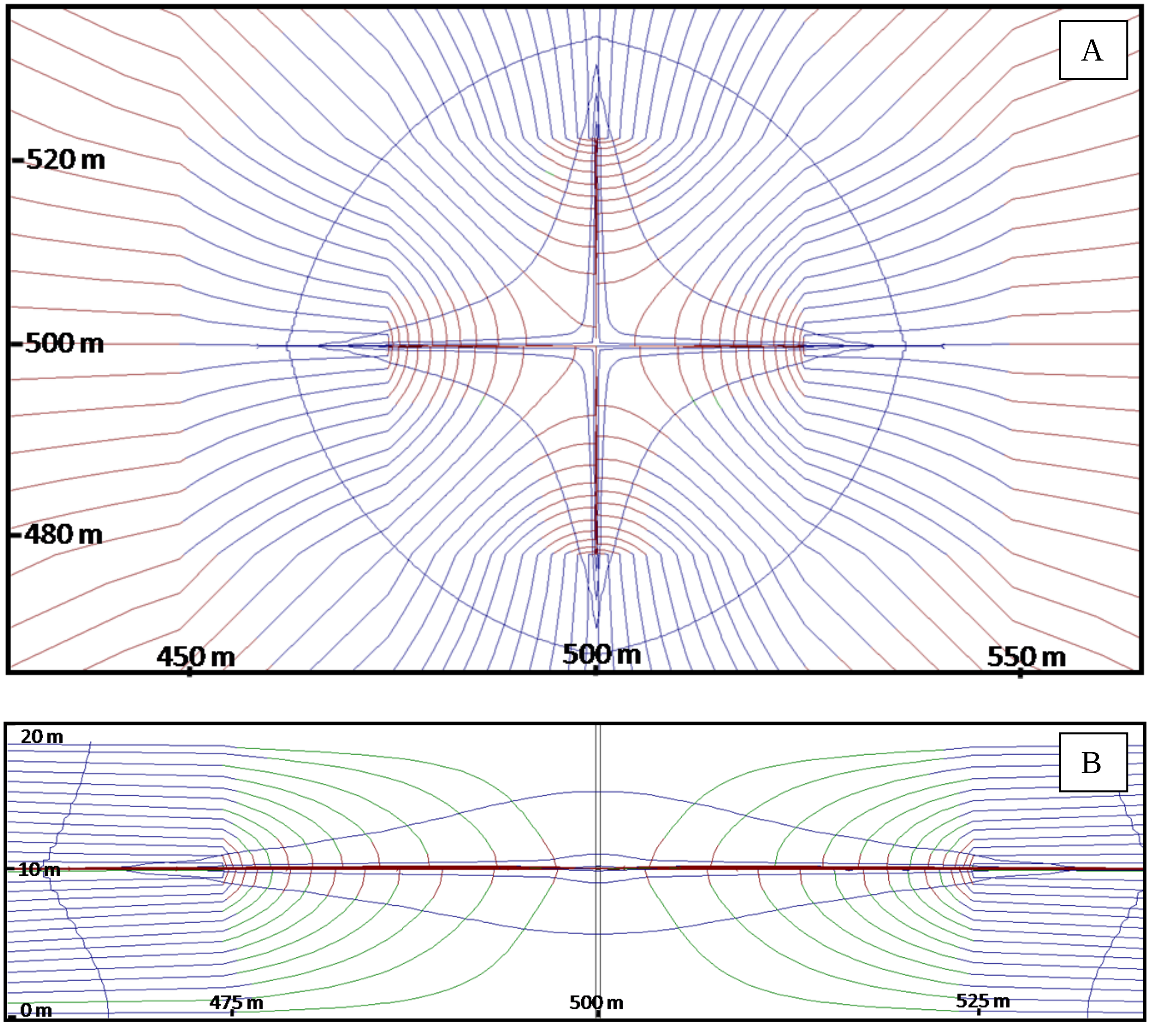

Figure 4: Flow path lines to a collector well, 500 m^3/day pumping rate (planar view “A”, cross section view “B”).

When a collector well pumping at a rate of 500 m^3/day is subjected to a regional background flow with a Darcian velocity of 0.0432 m/day, a stagnation zone develops approximately 110 m downstream of the collector well (Figure 5). The chosen regional flow is representative of those observed in natural alluvial aquifers. This stagnation zone is 16 m farther from the collector well than the stagnation point of a traditional vertical well pumping at the same location as the central stem with the same rate, as determined by the equation,

$$r_0 = \frac{Q}{2\pi q_0 B}, \qquad (3)$$

where r_0 is the distance to the stagnation point (m), Q is the pumping rate of the vertical well (m^3/day), q_0 is the regional background flow Darcian velocity (m/day), and B is the aquifer thickness (m).

5.2 Flux along Horizontal Laterals

After establishing a working radial collector well model, a series of tests examined the constant head/constant flux assumptions made by *Hantush and*

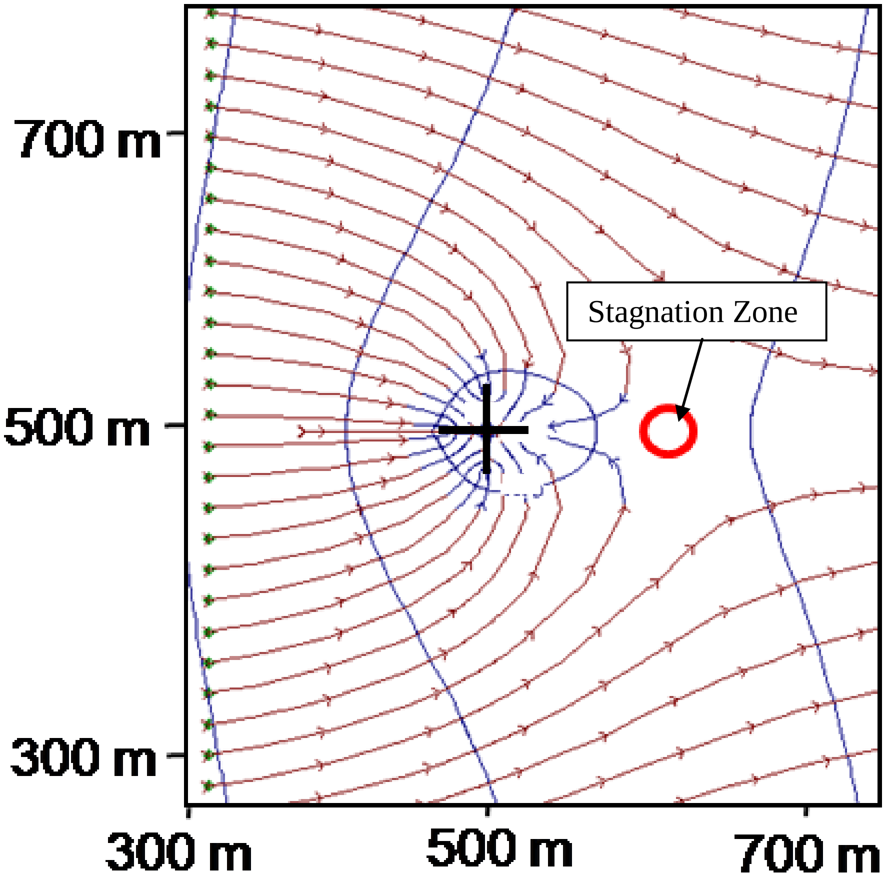

Figure 5: Stagnation zone of collector well pumping at a rate of 500 m^3/day with regional background flow of 0.0432 m/day.

Papadopuls [1962] and later revised by *Hantush* [1964] and *Haitjema* [1985]. The observed flux along the horizontal laterals confirms the result of *Haitjema* [1985] which stated that flux along the laterals' length increases with distance from the vertical collector stem as a third order polynomial function. This observation is understandable because with increasing distance away from the central stem, the distance between the horizontal laterals increases; and competition of those laterals for collecting water from the surrounding aquifer decreases. Figure 6 illustrates the flux along the horizontal laterals with a pumping rate of 500 m^3/day and no regional background flow. In the absence of regional background flow, flux to each lateral is virtually identical. It is interesting to note from Figure 6 that flux distribution along a lateral changes the most near the two ends and changes much less along the intermediate section of the lateral. Accordingly, a relatively long lateral will maintain uniform flux distribution in the central portion of the lateral.

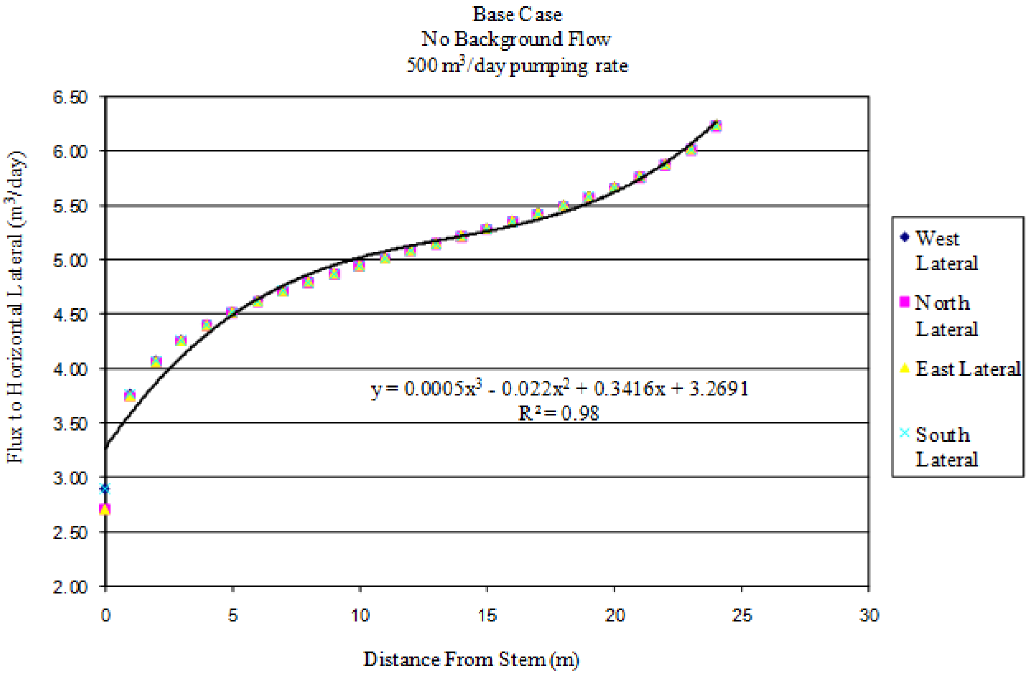

Figure 6: Flux along horizontal laterals, 500 m^3/day pumping rate, no regional background flow.

Increasing the pumping rate resulted in the expected increase of overall flux along the horizontal laterals, but had little impact on flux distribution along the length of the lateral wells, which still conformed to a similar third order function (Figure 7). In Figure 7, the flux distribution had only slight increases, even when the pumping rate doubled and quadrupled. Higher pumping rates compounded the impacts of lateral well competition and caused a greater difference in flux distribution along the laterals in the models with greater pumping rates. Notably, the greatest impact of pumping rate along the horizontal laterals occurred at the terminal ends of the laterals, farthest from the vertical stem.

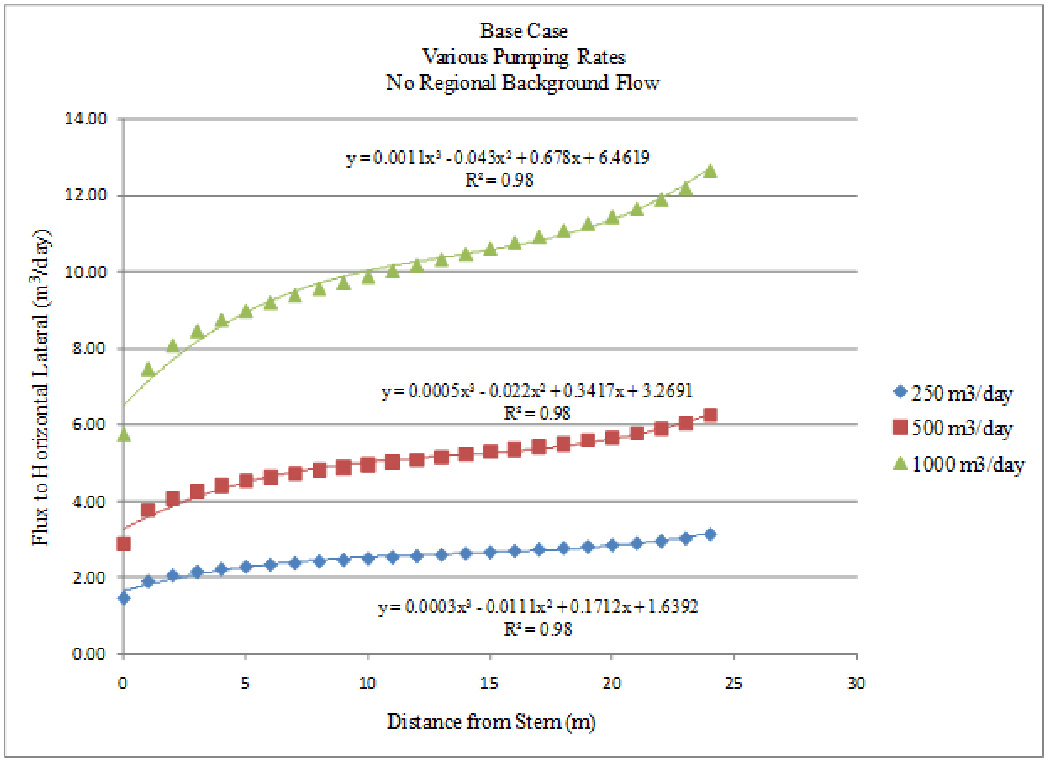

Figure 7: Flux along horizontal laterals with various pumping rates and no regional background flow.

After baseline confirmation of variable flux along the horizontal laterals, regional background flow was introduced flowing from west to east. As expected, the upstream, western lateral collected more water than the downstream, eastern lateral. The northern and southern laterals both had the same amount of flux, which was greater than the downstream lateral, and smaller than the upstream lateral (Figures 8 and 9). As regional background flow doubled, the difference between the upstream and downstream lateral fluxes also increases, but to a much smaller degree.

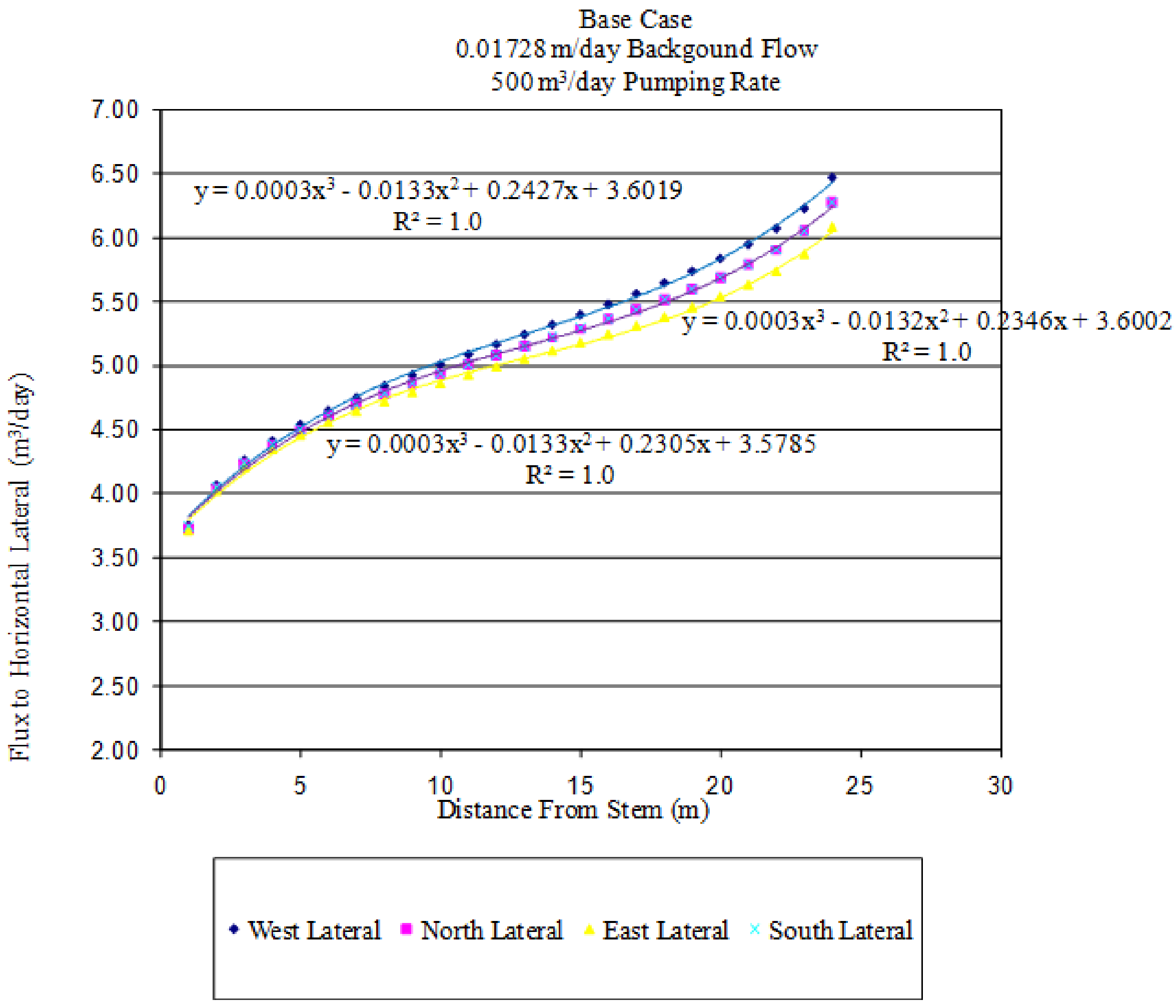

Figure 8: Flux along horizontal laterals, 500 m^3/day pumping rate, 0.0173 m/day regional background flow.

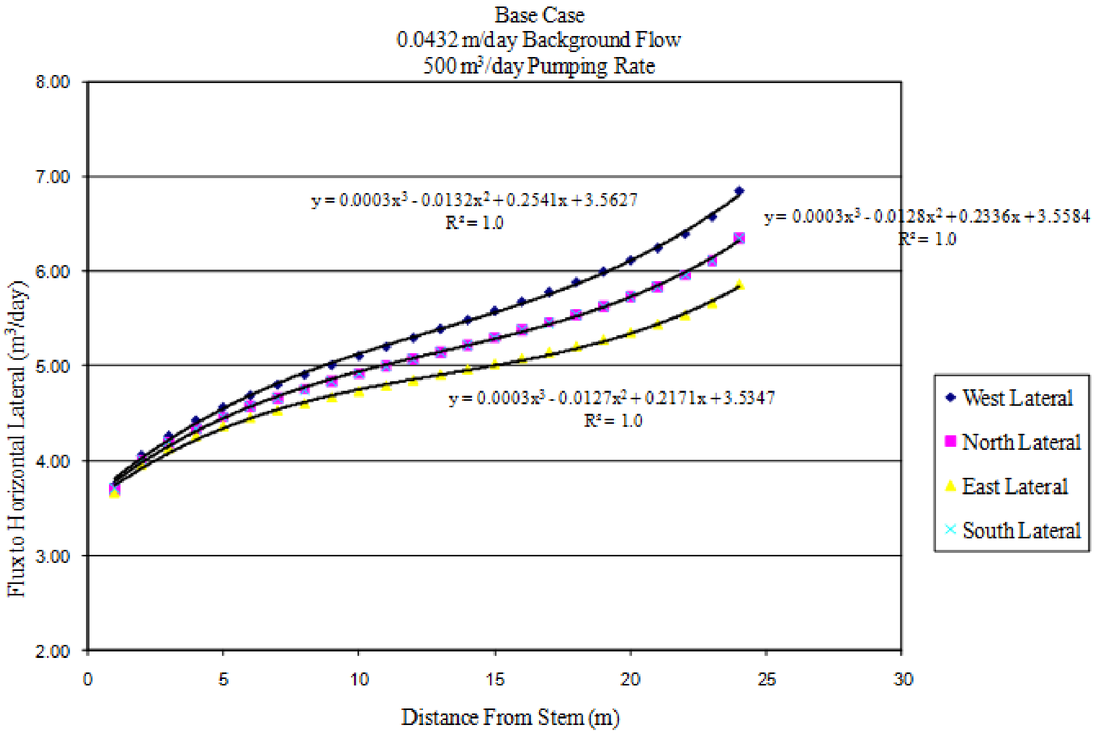

Figure 9: Flux along horizontal laterals, 500 m^3/day pumping rate, 0.0432 m/day regional background flow.

5.3 Net Flux to a River

To this end a series of tests were run to examine the interaction of a collector well and river in an unconfined aquifer with regional background flow. Figure 10 shows the gaining and losing components of flux to/from a river at 16 m stage in a 10 m deep river bed, where the river stage is measured from the bottom of the aquifer and the river depth is measured from the top of the model. A gaining portion of the river is characterized by flow from the aquifer to the river caused a higher hydraulic head in the adjacent aquifer than that in the river. Conversely, a losing portion of the river has flow from the river to the aquifer due to a higher river stage than the hydraulic head in the adjacent aquifer. Under certain circumstances, the gaining and losing portions of a river can coexist depending on the model parameters, as seen in Figure 10.

In Figure 10, the aquifer has a regional background flow of 0.043 m/day from west to east. Without pumping, the river begins as a gaining stream, but as the pumping rate of the collector well increases, the amount of water gained by the river decreases until, at a pumping rate of about 950 m^3/day, the river loses more water than it gains and becomes a losing stream. Flux observations of the river illustrated in Figure 10 are difficult to quantify beyond superficial observation or constrain to a projectable correlation. However, a meaningful, linear trend emerges when considering the net flux, the difference between the gaining and losing fluxes, with the pumping rate (Figure 11). By extrapolating from this linear trend, predictions can be made about the optimal pumping rate for a given river/well system in which the maximum amount of water is withdrawn from the aquifer while still maintaining a minimum flow to the river.

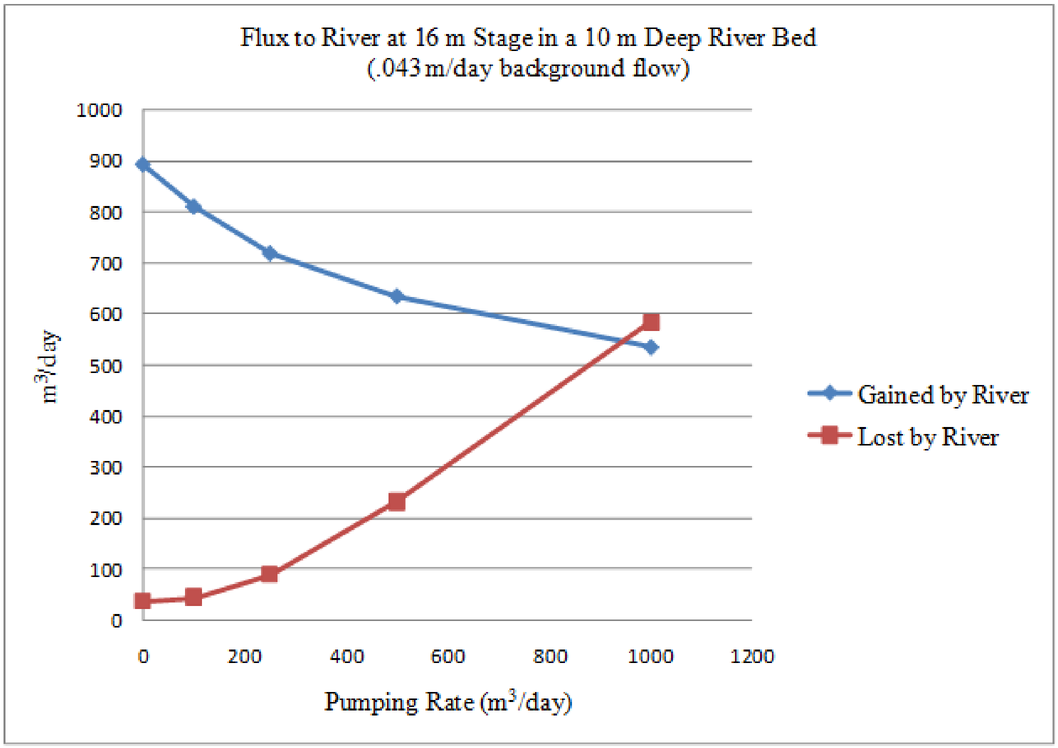

Figure 10: Gaining and losing components of flux to a river at 16 m river stage in a 10 m deep river bed.

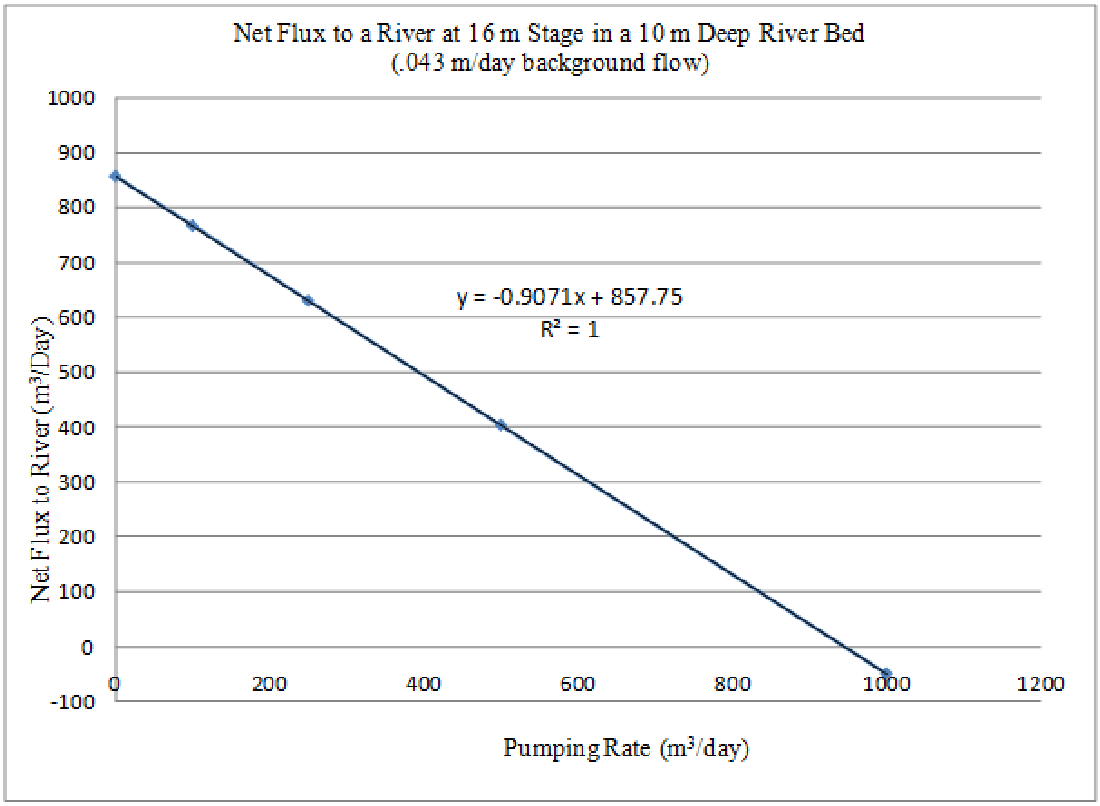

Figure 11: Net flux to a river at 16 m river stage in a 10 m deep river bed.

Although pumping rate is the primary mechanism controlling flux to the river observed in Figure 11, regional background flow also plays an important role. *Zhan and Sun* [2007] showed that for a vertical well, pumping rate, Q, and regional background flow, q_0, are inherently interrelated and can be presented as a single term, dimensionless pumping rate (Q_D):

$$Q_D = \frac{Q}{2\pi B x_0 q_0}, \qquad (4)$$

where B is the maximum saturated thickness of the aquifer before pumping (20 m) and x_0 is a reference distance defined as the distance between the vertical well and the river. This study hypothesizes that similar analysis can be made for the collector well system because pumping and regional background flow are two competitive mechanisms for groundwater and a collector well may be approximated as a large diameter vertical well under the steady-state conditions. If applying Eq. (4) to the collector well system here, x_0 is defined to be the shortest horizontal distance between the collector well stem and the river (35 m).

By combining the two competing terms of regional background flow and pumping rate, it becomes possible to co-vary two of the river flux controlling factors while still making meaningful observations. Figure 12 shows net flux to a river with the same geometry as the river in Figure 11 (at 16 m stage and in a 10 m deep river bed) but incorporates both pumping rate and regional background flow into Q_D. The trend remains linear and is very similar to that in Figure 11, verifying use of the dimensionless parameter.

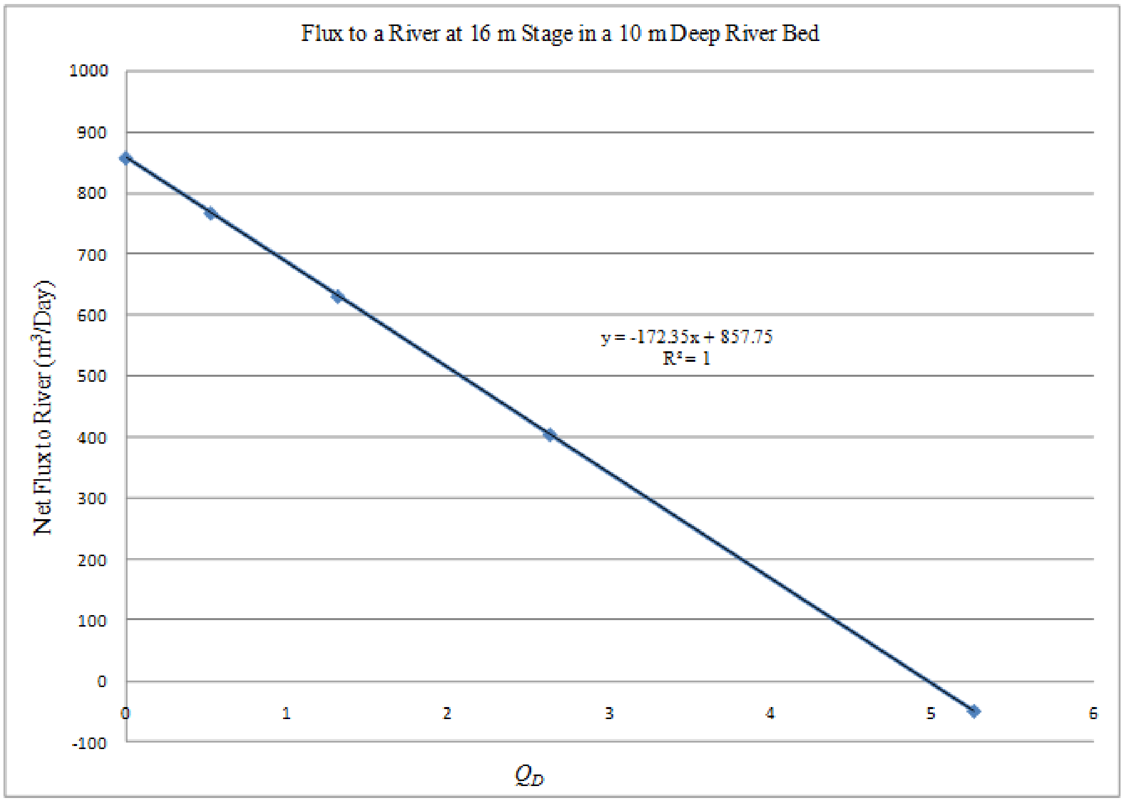

Figure 12: Net flux to a river at 16 m river stage in a 10 m deep river bed, varied by dimensionless pumping rate.

The impact of different regional background flows and various collector well pumping rates on net river flux in the river at 16 m stage in a 10 m deep river bed was tested. Figure 13 shows that the slope of the linear relationship between net flux to the river nearly doubled when the Darcian velocity of regional background flow doubled. This observation suggests that the net flux to the river is governed primarily by the collector pumping rate, and regional background flow plays only a minor role. This finding is different from that of *Zhan and Sun* [2007] which suggested that regional background flow and pumping rate play an equal role and, thus, the dimensionless pumping rate rather than the actual pumping rate is the primary controlling factor. This implies that the presence of the river, the primary difference between this study and that of *Zhan and Sun* [2007], significantly affected the flow dynamics.

Under the regional background flow with a smaller Darcian velocity, the river has a higher initial net gain from the aquifer and loses less to the aquifer at all pumping rates (Figure 13). In the case of regional background flow with a larger Darcian velocity, the impacts of increased pumping rate are more drastic and it requires a smaller collector well pumping rate to exact a larger loss from the river. Regardless of the magnitude of the Darcian velocity of the regional background flow and collector well pumping rate, the initial gaining nature of the river observed in Figure 13 was determined by the relationship between the water table and river stage.

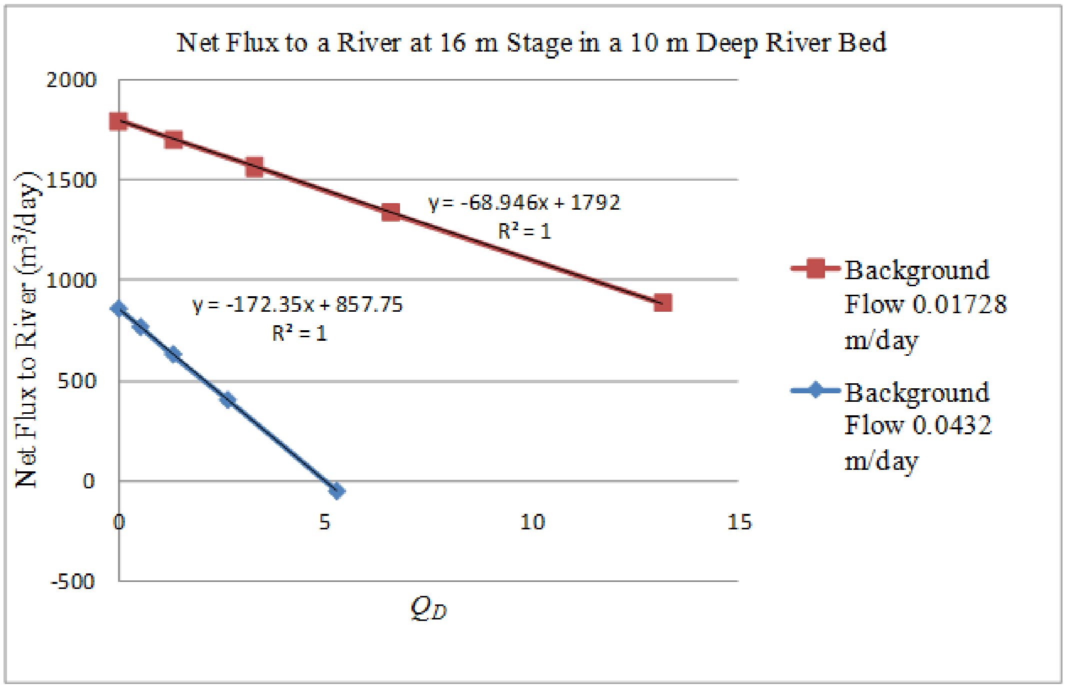

Figure 13: Net flux to a river at 16 m river stage in a 10 m deep river bed at various pumping rates and regional background flows.

5.4 Net Flux to a River under Various Circumstances

To confirm that pumping rate dominates regional background flow in altering net flux to the river, various river geometries, pumping rates, and regional background flows were examined (Figures 14-16). In each case 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 collector well pumping rate. In Figures 14-16 these relationships can be observed in the linear sets of data, which are naturally grouped by regional background flow. The slopes of lines in those figures are proportional to the magnitude of the Darcian velocity of regional background flow, while the net flux to the river is governed by the pumping rate. A larger Darcian velocity of regional background flow induce a larger net loss by the river. Additionally, pumping rate has a more drastic impact on flux to the river under stronger regional background flow.

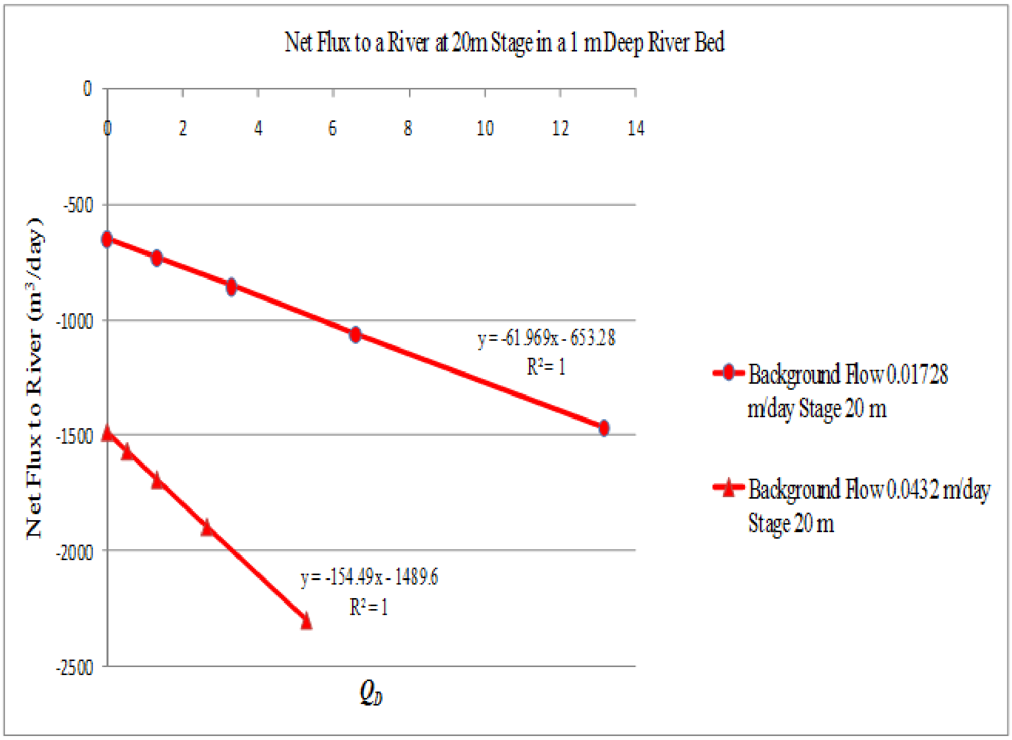

Figure 14: Net flux to a river at 20 m river stage in a 1 m deep river bed.

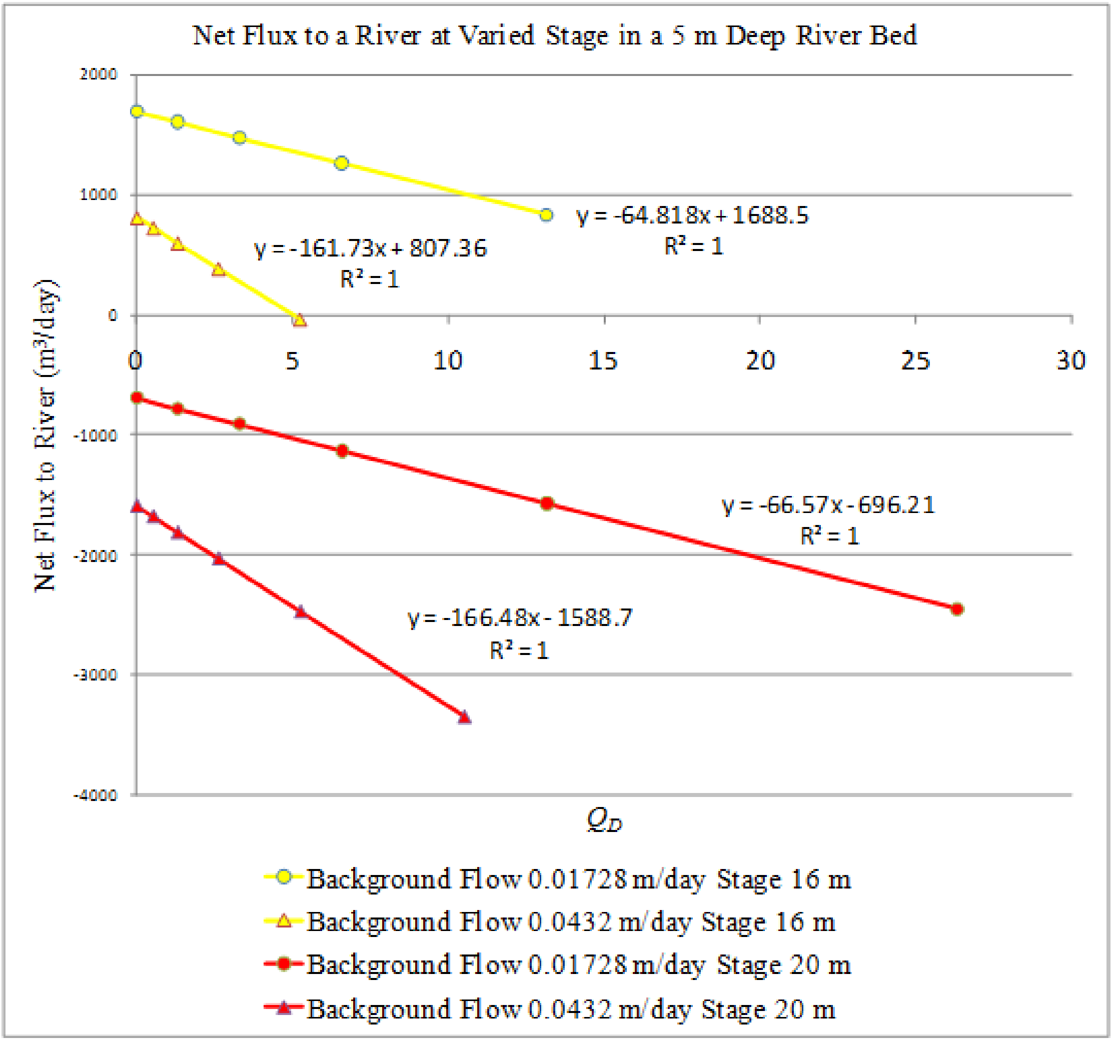

Figure 15: Net flux to a river at varied river stages in a 5 m deep river bed.

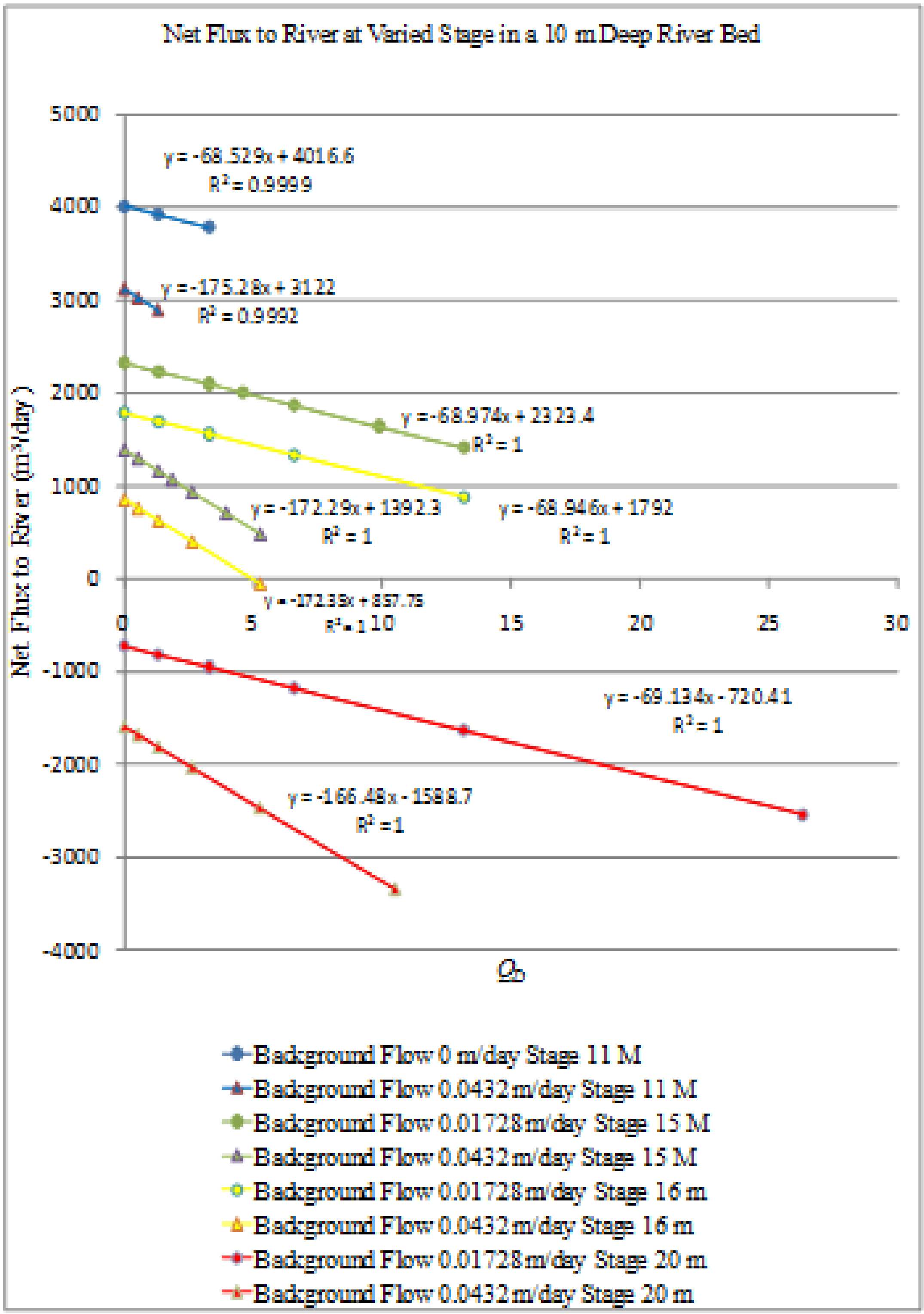

Figure 16: Net flux to a river at varied river stages in a 10 m deep river bed.

Figure 17 regroups the same data presented in Figures 14-16 to highlight the relationship between net flux to the river and river depth. Figure 17 shows a series of rivers at the same river stage but various river bed depth. Since the river stage (20 m) is higher than the hydraulic head in the aquifer, all the rivers examined in this figure are losing rivers. Furthermore and as previously observed in Figures 14-16, the stronger the regional background flow, the greater the slope of net loss by the river as a function of Q_D. Finally, at the given pumping rate and regional flow, the deeper river losses more water to the aquifer due to its increased surface area exposure to the aquifer.

Differences in regional head boundaries and hydraulic conductivity both influence the magnitude of regional background flow. In the models examined in Figures 14-17 regional background flow is varied by altering the models' constant head boundaries. Figure 18 shows the impact of varying regional background flow by increasing aquifer hydraulic conductivity from 8.64 m/day to 86.4 m/day.

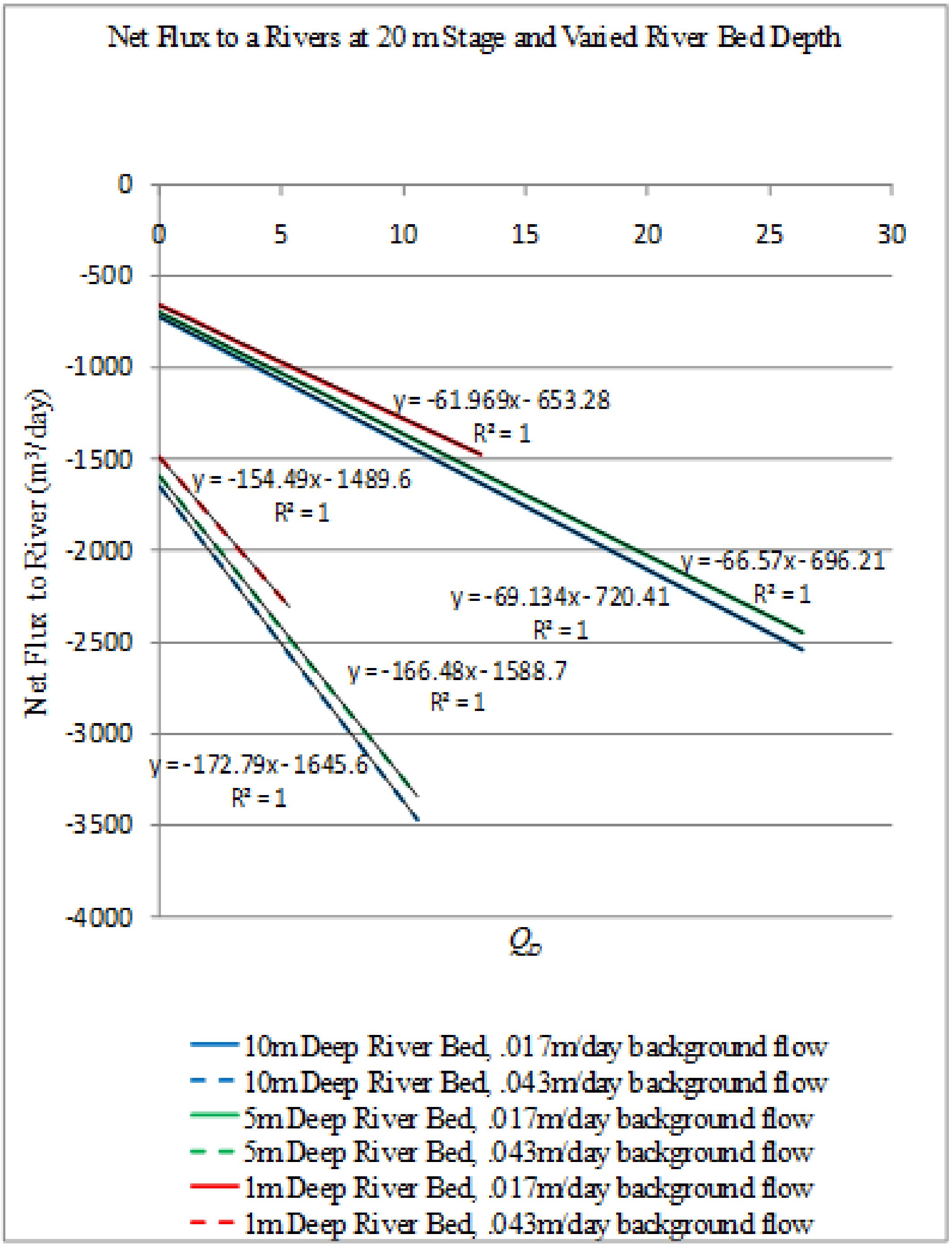

Figure 17: Net flux to a river at 20 m river stage with various river bed depths.

The associated regional background flow also increased by a factor of 10. Increasing aquifer hydraulic conductivity will also impact the well-river interactions. Conceptually, an increase in aquifer hydraulic conductivity increases the ease of flow between the well and river in the aquifer. Under conditions of higher hydraulic conductivity, collector well pumping rate remains the dominant factor in controlling net flux to the river. The general patterns observed in Figure 18 are consistent with those seen in Figures 14-17. The higher hydraulic conductivity results in a higher initial net flux to the river, but the impacts are minor and do not alter the losing/gaining nature of the stream.

Further investigation of the impacts of aquifer hydraulic conductivity on the interactions of the collector well and river confirms that the increase in regional background flow associated with increased aquifer hydraulic conductivity alters the initial gaining or losing condition of the river.

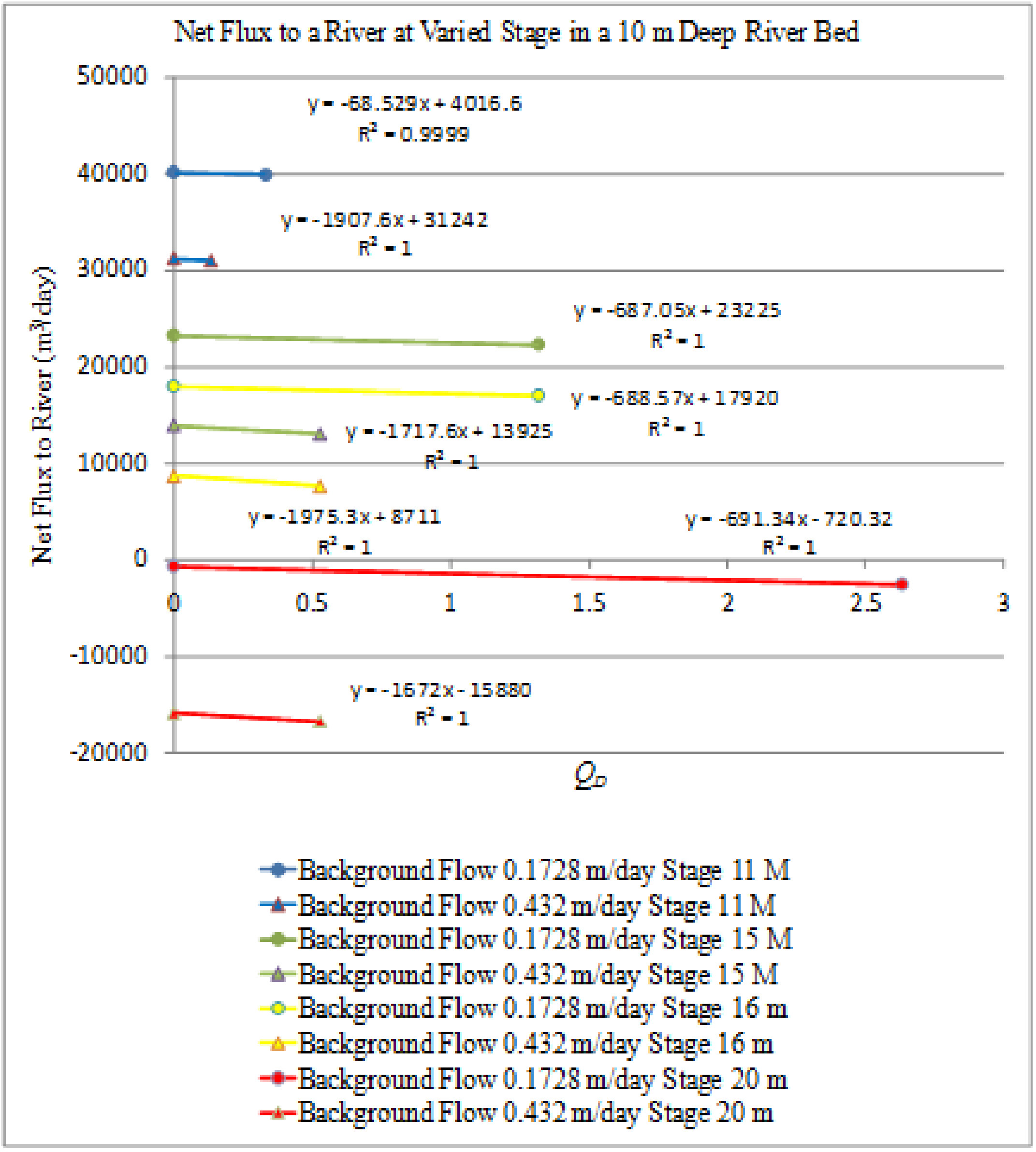

Figure 18: Net flux to a river at varied stage in a 10 m deep river bed with a higher hydraulic conductivity (86.4 m/day).

Figure 19 presents the impacts of varied aquifer hydraulic conductivity and associated regional background flow on a river under the same river conditions. Increased aquifer hydraulic conductivity magnified the already gaining nature of the river as well as the impacts of collector well pumping rate; however, collector well pumping rate remained the overriding factor in determining net flux to the river (Figure 19).

5.5 Net Flux to a River under Heterogeneous Aquifer Conditions

Under natural physical conditions, fluvial systems exist in environments marked with an abundance of heterogeneities such as over bank deposits, abandoned channels, flood plains, clay lenses, point bars, and oxbow lakes that alter both surface and subsurface flow. Complete understanding of the interactions of a collector well with regional background flow and river in an unconfined aquifer requires integration of these and other likely heterogeneities. Unfortunately, the Modflow environment can only practically represent simplified natural features and the Modflow numerical engines

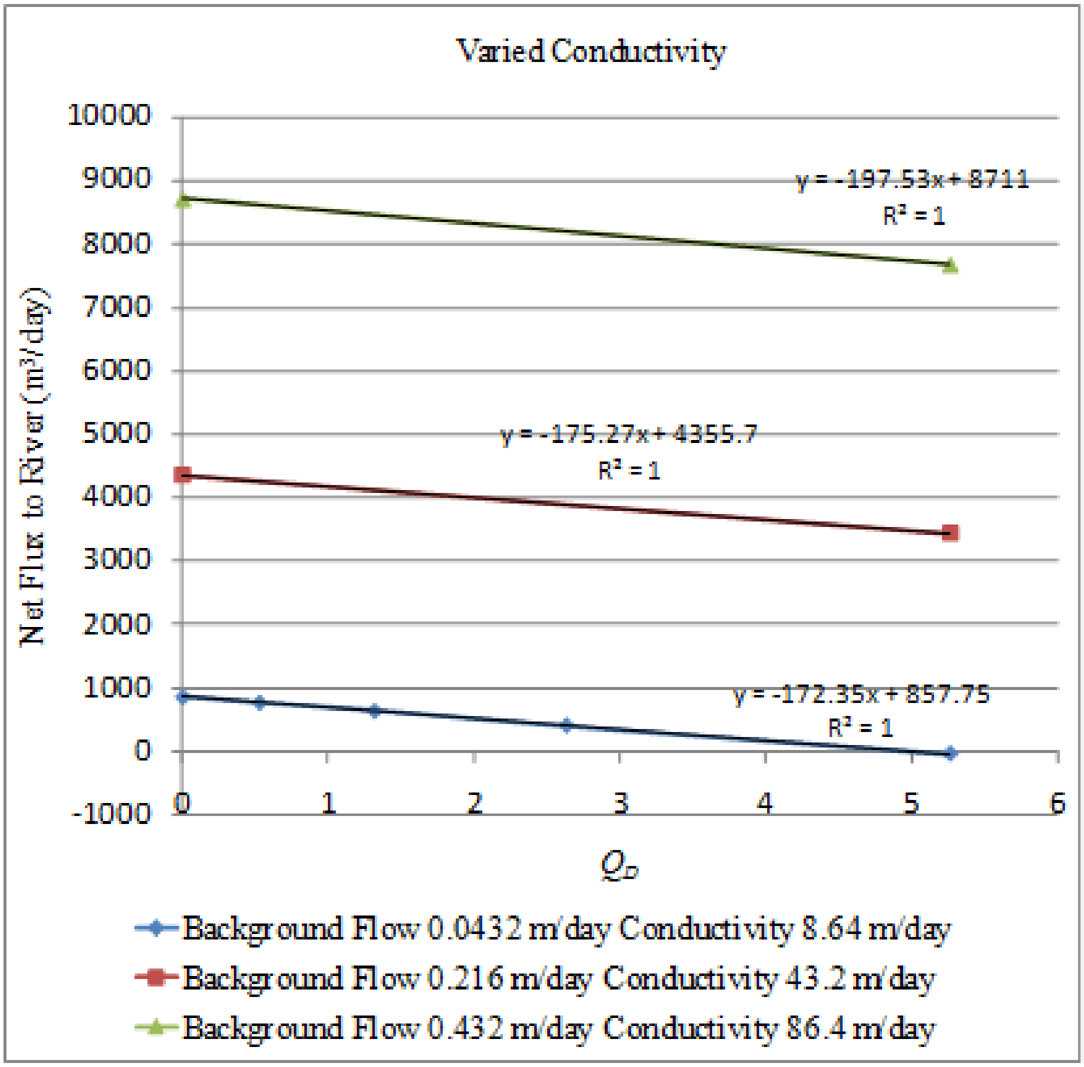

Figure 19: Impacts of varied regional background flow induced by varied aquifer hydraulic conductivity.

would require too much time to run models with realistic heterogeneities. Although a numerical model could never hope to capture the complexity of an actual river system, the addition of limited heterogeneities to the model allows the appreciation of their potential impact.

Based on the idealized stacking patterns of a sand rich, shallow graded, meandering stream presented by *Walker and Cant* [1984], four scenarios of increasing complexity were created (Figure 20) and explored at various pumping rates (Figure 21). The homogenous scenario provides confirmation of the viability of the model as well as a baseline against which to compare the impacts of heterogeneous additions. In heterogeneous Scenario 1, a 0.5 m thick low permeability boundary layer between the river and the groundwater aquifer was added. This layer had a permeability of 0.864 m/day which is representative of the low permeability sediment layer common in many natural streams. Heterogeneous Scenario 2 added high permeability zones near the eastern and western boundaries with hydraulic conductivity of 43.2 m/day, reminiscent of flood plain or meander fairway boundaries. Heterogeneous Scenario 3 is the most complex and includes the features of the previous two scenarios as well as additional high permeability beds at the base of the river. These high permeability beds had a hydraulic conductivity of 86.4 m/day and represent abandoned river channels filled with well sorted alluvial sediments or point bar deposits of well sorted sand. All of the heterogeneous additions represent features common to natural alluvial environments and move the model from an ideal system to a more realistic situation.

Regional background flow was maintained at a consistent level for all four scenarios and the results of modeling under different pumping rates indicate that, as with the homogenous scenarios, collector well pumping rate governed net flux to the river. It is also interesting to note that the relationship between collector well pumping rate and regional background flow remained largely unaffected by the addition of heterogeneities. The feature with the greatest impact was the 0.5 m thick low permeability bed that showed decreases in net flux to the river at all pumping rates tested. This confirms that natural low permeability sediments at the boundaries of stream beds inhibit flux between the stream and adjacent aquifer. In Scenarios 2 and 3 higher permeability beds increased the ease of water movement, which increased to amount of flux to the river to a small degree. This suggests that in complex natural systems the geometry of heterogeneous features and their specific permeabilities might impact the maximum pumping rate of a collector well but only to a small degree. Regardless of the additional heterogeneous features, all four scenarios confirm that the collector well pumping rate had the largest impact on net flux to the river and the heterogeneity has a minor impact in terms of net loss of the river.

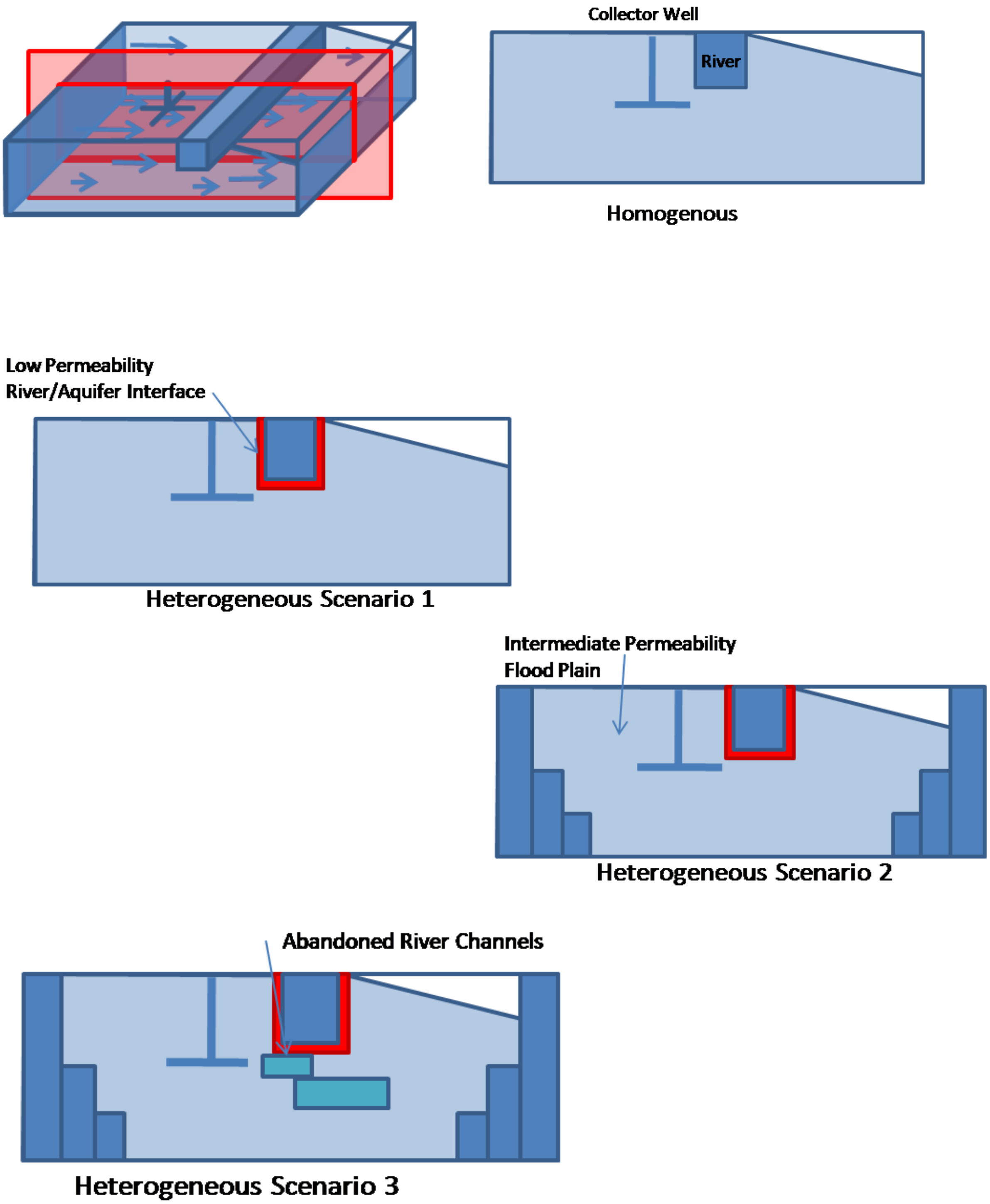

Figure 20: Representative cross sections of several homogenous and heterogeneous aquifer scenarios.

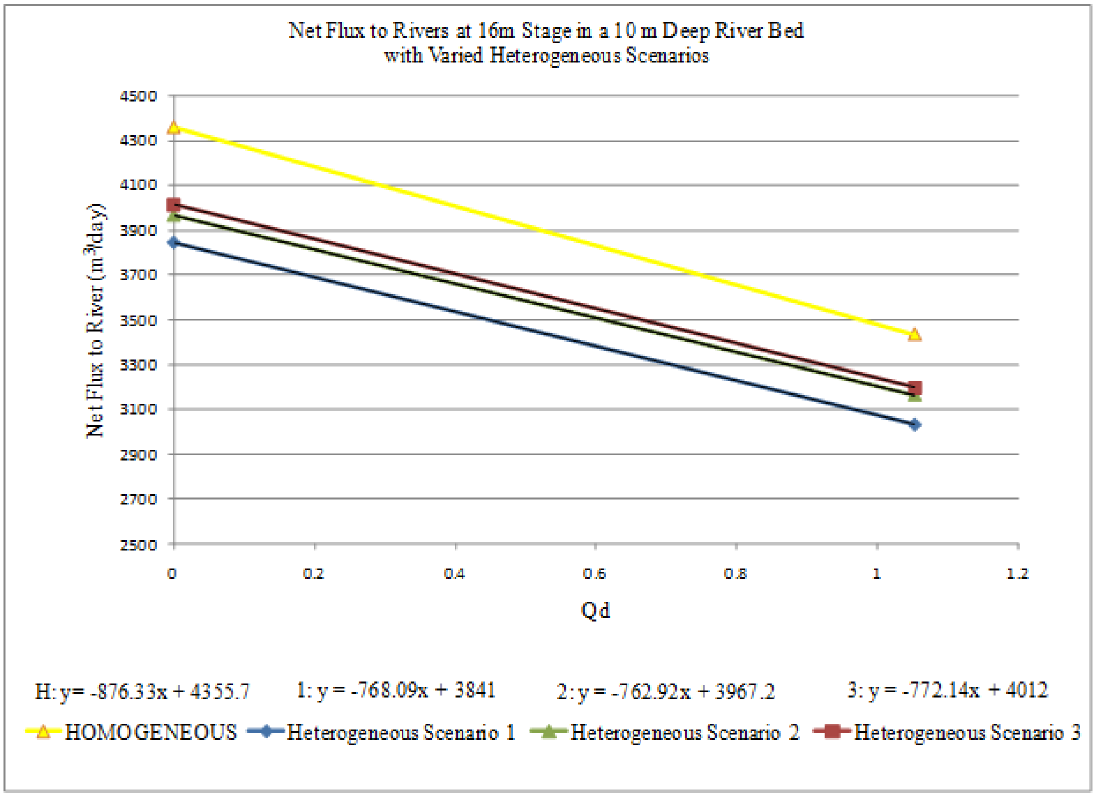

Figure 21: Net flux to a river under varied heterogeneous aquifer conditions.

6. CONCLUSIONS AND RECOMMENDATIONS

This study established a working model of a Ranney radial collector well, examined flow characteristics around the well, and investigated interactions of collector well pumping rate, regional background flow, and river in homogenous and heterogeneous circumstances. Flux along the laterals of a collector well increased as a third order polynomial function with increasing distance from the vertical stem. The greatest pumping rate along the length of the lateral is at the terminal end, farthest from the vertical stem. This suggests that when installing a collector well, the longer the horizontal laterals, the greater the flux at the terminal end; however, at some length, flux will reach a point of diminishing returns and become asymptotic. Furthermore, there are drilling challenges that present physical limitations and financial restrictions that make extremely long laterals unrealistic. Future studies should address the optimum length of horizontal laterals in collector well design.

Visual inspection of the dynamics of flow directly around the collector well shows that for a collector well with four evenly spaced laterals hydraulic head is evenly distributed along the length of the lateral. No stagnation points exist with no regional background flow; however, when subject to regional background flow, a stagnation point develops only slightly further downstream than the stagnation point caused by a vertical well with the same pumping rate at the same location with the central stem. This is important when visualizing flux to the well because the horizontal laterals can be approached as a “disk” of flux rather than individual line sinks. Their impressive flux capacity makes collector wells very attractive in contaminant remediation, groundwater collection, and hydrocarbon recovery.

Net flux to a river consistently demonstrated a linear relationship when varied by dimensionless pumping rate. This counters the findings of *Zhan and Sun* [2007] but validates the use of dimensionless pumping rate as a model variable that is useful in simultaneously comparing the impacts of two parameters. Using dimensionless pumping observations, the present study concludes that, for a collector well placed relatively close to a river in an unconfined aquifer, collector well pumping rate dominates regional background flow in determining the amount of water gained or lost by that river. Regional background flow moderates the impacts of the pumping rate of the collector well. As regional background flow increases, the impact of collector well pumping rate becomes more drastic. The direct linear relationship repeatedly observed between dimensionless pumping rate and net flux to river allows for precise river loss predictions. By establishing the initial gaining or losing nature of the river, magnitude of the Darcian velocity of regional background flow, collector well pumping rate, and collector well placement in relation to the river, the point at which the river begins to demonstrate a net loss due to the influence of the collector well can be projected. For example, in a relatively simple system of a river at 16 m stage in a 10 m deep river bed in an unconfined aquifer with a regional background flow of 0.0432 m/day, the collector well pumping rate should not exceed approximately 950 m^3/day to avoid a net loss by the river. If regional background flow decreases, larger pumping rates can be sustained without a net loss of water by the river. In many small communities around the world where collector wells similar to the one modeled in this study are installed, knowledge of this maximum pumping rate can allow well operators to optimize water production without causing surface water losses.

Heterogeneities resembling natural features found in sandy alluvial systems were added to the model in an attempt to make the model more realistic. A low permeability layer at the interface between the river and aquifer representing low permeability river sediments at the base of the river bed had the largest impact on flux between the river and aquifer. The addition of this low permeability layer cased more water loss from the river. Addition of further high permeability zones decreased the amount of water lost by the river, but their impact was minimal. The overall effect of additional complexities was the alteration of the ease and geometry of flow, but this had minimal impact on well-river interactions. Even with the addition of heterogeneities, the amount of water gained or lost by the river was determined by pumping rate primarily and regional background flow only modified the impacts of pumping rate to a small degree. This can be observed in the identical rates of river net loss with increased pumping rate under different heterogeneous scenarios as regional background flow remained consistent. The complexities of natural systems alter the initial gaining or losing character of the river, but are of little importance in determining net flux to a river when compared to the impacts of a collector well pumping rate.

Collector wells offer numerous advantages over traditional vertical wells, require further investigation to fully understand their complex flow dynamics, and merit application in the hydrologic sciences and petroleum industry. This study demonstrates the impact of a radial collector well on the exchange of water between the river and aquifer and the overwhelming control of the collector well over fluid dynamics in the groundwater reservoir.

REFERENCES

Cleveland, T.G., Recovery performance for vertical and horizontal wells using semianalytical simulation, *Ground Water, 32*(1), 103-107, 1004.

Debrine, B.E., Electrolytic model study for collector wells under riverbeds. *Water Resour. Res., 6*(3), 971-978, 1970.

Evironmental Protection Agency (EPA), Manual alternative methods for fluid recovery, *EPA/625/R-94/003*, Washington, D.C., 1994.

Falta, R.W., Analytical solutions for gas-flow due to gas injection and extraction from horizontal wells, *Ground Water, 33*(2), 235-246, 1995.

Haitjema, H.M., Modeling three dimensional flow in confined aquifers by superposition of both two- and three-dimensional analytic functions, *Water Resour. Res., 21*(10), 1557-1566, 1985.

Hantush, M.S., Hydraulics of wells, in *Advances in Hydroscience*, edited by V.T. Chow, pp. 57-88, Academic, San Diego, Calif., 1964.

Hantush, M.S. and I.S. Papadopulos, Flow of groundwater to collector wells, *J. Hydraul. Div. Proc. Am. Civ. Eng., HY5*, 221-244, 1962.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process: *U.S. Geological Survey Open-File Report 00-92*, 121 p. 2000

Joshi, S.D., Augmentation of well productivity with slant and horizontal wells, *JPT*, 729-739, 1988.

Langseth, D.E., Hydraulic performance of horizontal wells, paper presented at HMCRI's 11th Annual National Conference and Exhibition, Hazard. Mater. Control Res. Inst., Washington, D.C., Nov. 1990.

Maurer, W.C., Recent advances in horizontal drilling, *Journal of Canadian Petroleum Technology*, *34*, 25-33, 1995.

Morgan, J.H., Horizontal drilling applications of petroleum technologies for environmental purposes, *Ground Water Monit. Rev., 12*(2), 98-102, 1992.

Murdoch, L.C. , Transient analyses of an interceptor trench, *Water Resour. Res.,30*(11), 3023-3031, 1994.

"Oil Miner." *Time*, December 6, 1943.

Parmentier, P.P. and R.M. Klemovich, A new direction in remediation, *Civil Eng., 66,* 55-57, 1996.

Penmatcha, V.R., S. Arbabi, and K. Aziz, Effect of pressure drop in horizontal wells and optimum well length, paper presented at 1997 SPE Production Operations Symposium, Society of Petroleum Engineers, Oklahoma City, Oklahoma, March 1997.

Sawyer, C.S. and K.K. Lieuallen-Dulam, Productivity comparisons of horizontal and vertical ground water remediation well scenarios, *Ground Water*, *36*(1), 98-103, 1998.

Schafer, D.C., Determining 3D capture zones in homogenous, anisotropic aquifers, *Ground Water, 34*(4), 628-639, 1996

Seines, K., S.C. Lieu, and B.T. Haung, Troll horizontal well tests demonstrate large production potential from thin oil zones, *Society of Petroleum Engineers Reservoir Engineering, 9*(2), 133-139, 1994.

Steward, D.R., Three dimensional analysis of the capture of contaminated leachate by fully penetrating, partially penetrating, and horizontal wells, *Water Resour. Res., 35*(2), 461-468, 1999.

Steward, D.R. and W. Jin, Gaining and losing sections of horizontal wells, *Water Resour. Res., 37*(11), 2677-2685, 2001.

Tarshish, M., Combined mathematical model of flow in an aquifer-horizontal well system, *Ground Water, 30*(6), 931-935, 1992.

Walker, R.G. and D.J. Cant, Sandy fluvial systems, in *Facies Models,* pp. 48-64, ed. R.G. Walker, Geological Assn. of Canada, Toronto, 1984.

Zhan, H., Analytical study of capture time to a horizontal well, *Water Resour. Res., 217* (4), 46-54, 1999.

Zhan, H., and J. Cao, Analytical and semi-analytical solutions of horizontal well capture times under no-flow and constant-head boundaries, *Adv. Water Resour., 23*(8), 835-848, 2000.

Zhan, H., and D. Sun, Travel-time distribution from a finite line contamination source to an extraction well with regional flow. *Adv. in Water Resour. 30* (2), 389–398, 2007.

Zhan, H. and V. Zlotnik, Groundwater flow to a horizontal or slanted well in an unconfined aquifer, *Water Resour Res.*, *38* (7), 1108-1121, 2002.

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