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Influence of Arrangement and Configuration of Extraction Wells to the Capture Zone in Pump and Treat System

Farzana Izzati Che Daud, Yusyalia Abdul Halim & Kuan Woei Keong*

Centre for Civil Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, Permatang Pauh Campus, 13500 Pulau Pinang, Malaysia

**Corresponding author: wkkuan@uitm.edu.my*

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ABSTRACT

Urbanization, industrial wastes, non-point sources from agricultural activities, and various types of wastes within a landfill system have posed major threats to groundwater quality in Malaysia. One of the common contaminated groundwater remediation techniques is pump and treat system. This work was conducted to investigate the influence of extraction wells in pump and treat system to remove the contaminant by evaluating the capture zone under different arrangements and configurations of well in an unconfined aquifer system. A conceptual model was developed using PMWIN software at pre-determined soil characteristics and boundary conditions. In the numerical simulation, 17 models were simulated to examine the influence of pumping rate of wells, distance between two wells, wells orientation and the number of wells to the width of capture zone under four study cases. The results show that the width of the capture zone corresponded linearly to the increment of pumping rate. In the two and four wells system, the width of the capture zone was reduced when the extraction wells were aligned parallelly to the flow direction and the distance between wells were increased. However, the capture zone was extended when the well orientation was aligned perpendicular to the flow direction. The simulation results show that the drawdown in the wells was reduced when the number of wells has increased due to the distribution of total pumping rate into two or four wells system. The finding indicated that the arrangement of extraction wells in pump and treat system has a major impact on the capture zone induced by the wells. The simulation results can help to improve the effectiveness of extraction well in pump and treat system by optimizing the extraction process and thus minimize the cost of groundwater remediation.

Keywords: Groundwater contamination; pump and treat system; extraction wells; capture zone

INTRODUCTION

Currently, groundwater has become an alternative source of raw water due to high demand of freshwater in Malaysia (Mohammed & Ghazali 2009). However, groundwater pollution has been a significant concern that is closely related to both environmental conservation and the need for water. Due to population growth, economic development, urbanization, and industrialization, the pollution of the groundwater has become worser (Narany et al. 2017). This is because the pollutant generated from various sources such as discarded solid materials from commercial, municipal, industrial, and agricultural activities has diffused into the environment and result in contamination of groundwater. All these contaminants are concealed from the view once they are in the ground. The contaminant will move slowly through the geological structure and eventually reach the groundwater system (Zaporezec, 1981; Brusseau, 2019). Significant amounts of dissolved organic substances, such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), xenobiotic organic compounds, inorganic salts, ammonia, heavy metals, and other toxicants produced from the waste can affect the environment and human health (Ashraf et al. 2013). As a result, when groundwater is contaminated, it could stay for decades, or maybe hundreds of years to clean up. It is also very difficult to restore the aquifer when they are polluted. In addition, the cost of monitoring the intensity of groundwater pollution is very high. Therefore, the selection of remediation approaches and contaminant sources control strategies are crucial to minimize the impact of groundwater contamination.

The application of pump and treat system has been widely used as an effective way to control groundwater flow and contaminant transport through porous medium and remediate contaminant plumes. Pump and treat system is a conventional and common method used for cleaning groundwater that is contaminated with chemicals such as fertilizers, industrial solvents and fuel oil. It is also used to contain the contaminant plume that keeps the contaminant from spreading by pumping contaminated water towards the wells. It involved with one or more extraction wells to extract the groundwater that is contaminated. The groundwater is either pumped to a treatment system or into a holding tank before pumped into the treatment section. After being treated above ground, the treated water was discharged into surface water or it was flowed back into the aquifer (Speight 2020; Reddy 2008; Christ & Goltz 2004).

Groundwater is withdrawn through extraction wells in the pump and treat system. The areas of water being extracted within the wells radius is named as capture zone. This study was conducted to demonstrate the influence of the arrangement and configuration of extraction wells to the capture zone in pump and treat system. The capture zone was selected as the key indicator to evaluate the efficiency of the extraction well in containing and withdrawing contaminant plume from the contaminated aquifer in this study.

METHODOLOGY

In this study, groundwater flow and transport simulation software, PMWIN (Chiang & Kinzelbach, 2006) was used to simulate a field scale unconfined aquifer system. The investigation was conducted by simulating a series of extraction wells at different withdraw rates and locations to evaluate the capture zone induced by pumping. The corresponded efficiency of the removal of contaminant was determined by the width of capture zone under different extraction scenarios. In PMWIN, MODFLOW module was used to simulate the hydrologic environment of the study area using finite difference modelling approach. The particle tracking model path, PMPATH module was used to delineate the groundwater paths and determine the width of the capture zone using semi-analytical particle tracking scheme.

The field scale model was simulated as homogeneous unconfined aquifer. The aquifer system has an area of 3920 m in length and 4000 m in width and thickness of 20 m. The area of the model was determined to eliminate the effects of the boundary to the capture zone induced by the pre-determined pumping rate within the simulated area. The aquifer domain was divided in 200 rows x 196 columns that generated a total of 117,600 nodes. The West and East sides of the aquifer were bounded by fixed water level at 19 m and 17 m respectively that produced hydraulic gradient of 0.0005. The horizontal hydraulic conductivity of the sand, K_x was assumed as 2 m/d similar to a course sand layer. The vertical hydraulic conductivity, K_z was assumed to be 10 percent of K_x. The effective porosity was assumed to be 0.25 for the aquifer layer. A series of extraction (pumping) wells were assigned to investigate the capture zone during simulation periods.

There are 4 study cases being evaluated in this study. In the first study case, the capture zone induced by different pumping rates (Model 1 of 50 m^3/day; Model 2 of 100 m^3/day; Model 3 of 150 m^3/day and Model 4 of 200 m^3/day) of a single well setup was evaluated. In the second study case, two extraction wells were simulated at a total pumping rate of 100 m^3/day and the distance between two wells was varied at 240 m (Model 5), 360 m (Model 6), 480 m (Model 7), 720 m (Model 8) and 960 m (Model 9) respectively. In the third study case, influence of well orientation of either parallel or perpendicular to the flow direction was evaluated. In Models 10 and 11, two extraction wells (separated at 120 m) with total pumping rate of 100 m^3/day was simulated perpendicular and parallel to the flow direction respectively. In Model 12 (perpendicular) and Model 13 (parallel), four extraction wells (separated at 120 m; total pumping rate of 100 m^3/day) of similar setup with Models 10 and 11 were simulated. In Model 14 (parallel) and Model 15 (perpendicular), a four extraction wells system (total pumping rate of 100 m^3/day) with shorter distance between wells of 60 m were simulated. In the fourth study case, the influence of the number of well was evaluated for single (Model 4), two-well (Model 16) and four-well (Model 17) system. The total pumping rates was fixed at 200 m^3/day and the wells were aligned parallelly to the direction of flow at a distance between the wells of 60 m.

RESULT AND DISCUSSION

In this study, the width of capture zone is defined as the width of a zone that contributed the groundwater being extracted by one or more wells. The capture zone was induced by the groundwater withdrawal from the extraction wells in the simulated area (Figure 1).

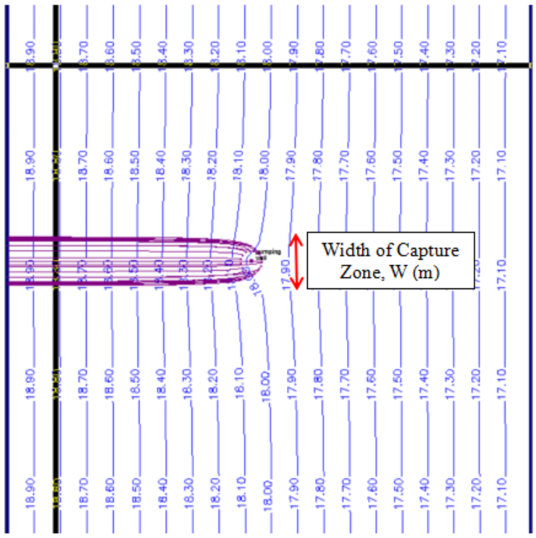
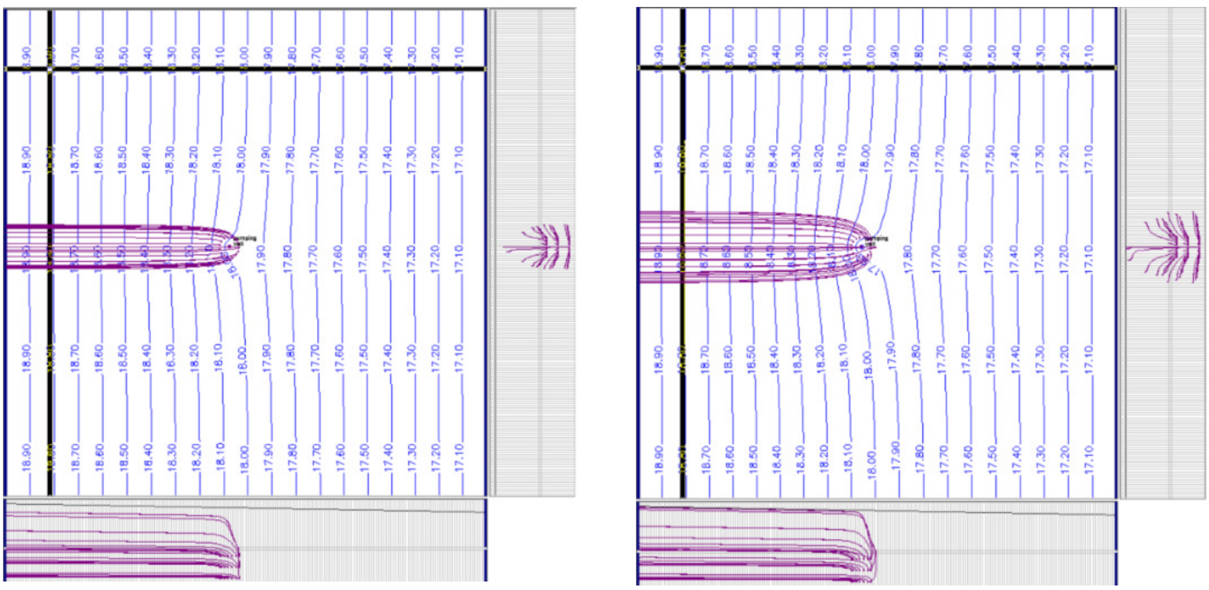


FIGURE 1. Capture zone induced by extraction well (indicated by continuous lines parallel to the direction of flow) and its corresponded width

STUDY CASE 1: INFLUENCE OF PUMPING RATES

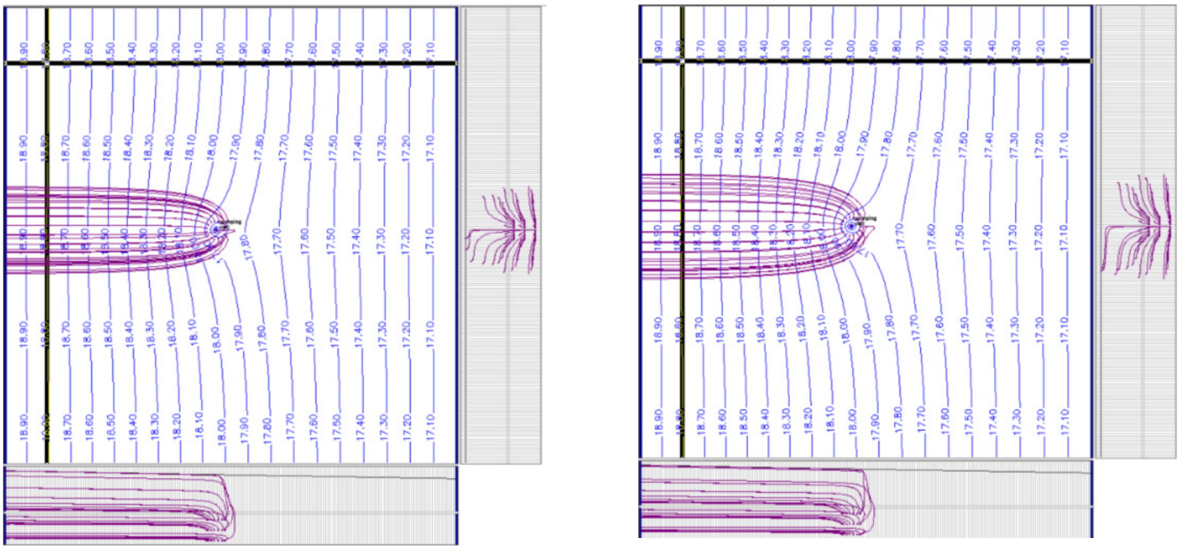
In study case 1, four models (Models 1 as base case, 2, 3 and 4) of a single extraction well system were developed to evaluate the capture zone under different pumping rates of 50 m^3/day, 100 m^3/day, 150 m^3/day and 200 m^3/day respectively. The simulation results indicated that the pumping rate has significantly affected the width of the capture zone and the drawdown in the pumping well.

The results show that the width of the capture zone has increased from 360 m at 50 m^3/day to 960 m at 200 m^3/day (Figure 2 and Table 1). When the pumping rate was doubled (100 m^3/day), tripled (150 m^3/day) and quadrupled (200 m^3/day) than the base case (Model 1) of 50 m^3/day, the increment of width was 1.6, 2.2 and 2.67 times the width of base case at pumping rate of 50 m^3/day. The increment of the width of capture zone was not equivalent to the increment of pumping rate. In the study of Bertone et al. (2020), higher pumping rates have also increased the width of capture zone.



(a) Model 1 : Pumping Rate = 50 m^3/day

(b) Model 2 : Pumping Rate = 100 m^3/day



(c) Model 3 : Pumping Rate = 150 m³/day

(d) Model 4 : Pumping Rate = 200 m³/day

FIGURE 2. Simulated Capture Zone in Study Case 1

TABLE 1. Width of capture zone under different pumping rates

Model	Pumping Rate (m³/day)	Width of Capture Zone (m)	Drawdown (m)
1	50	360	1.130
2	100	580	1.354
3	150	780	1.579
4	200	960	1.804

Similar results were indicated by the drawdown in the extraction well. The drawdown was 1.13 m under the pumping rate of 50 m³/day and increased to 1.80 m under the pumping rate of 200 m³/day (Table 1). The increment ratio of drawdown was found to be 1.2, 1.4 and 1.6 times higher than the base case when the pumping rates have increased to 100 m³/day, 150 m³/day and 200 m³/day. The simulation results indicated that drawdown and the width of capture zone was linearly related to pumping rates but the increment ratio was not equivalent to pumping rates (Figure 3). The rate of enlargement of the width of the capture zone was found to be higher than the rate of increment of drawdown when higher pumping rate was applied.

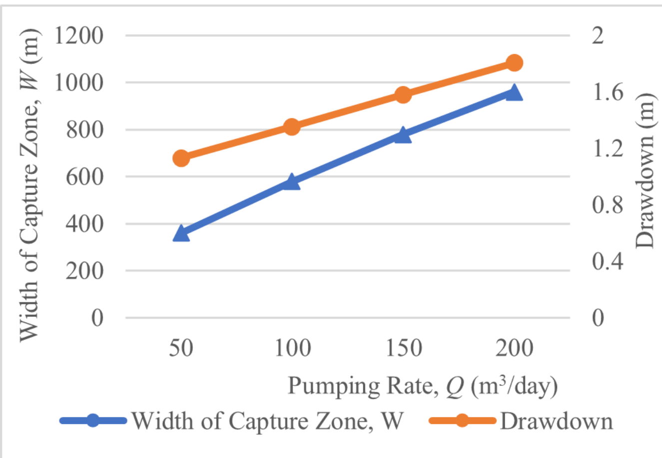
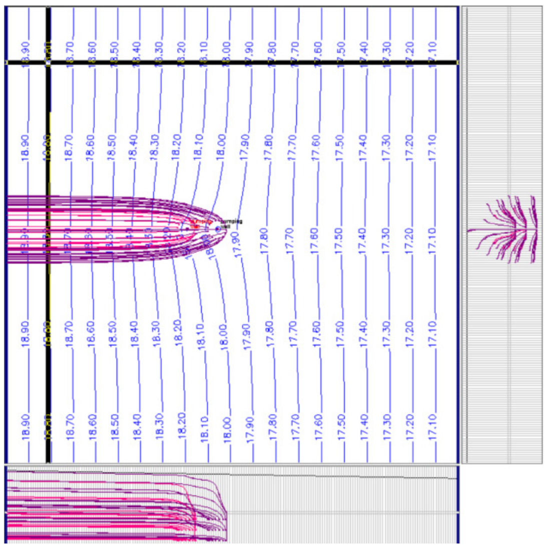


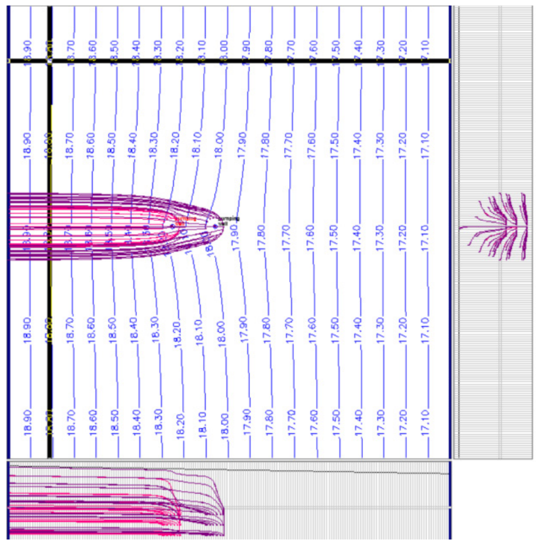
FIGURE 3. Width of capture zone, W and the drawdown of a single extraction well system under different pumping rates, Q

STUDY CASE 2: INFLUENCE OF THE DISTANCE BETWEEN TWO PUMPING WELLS

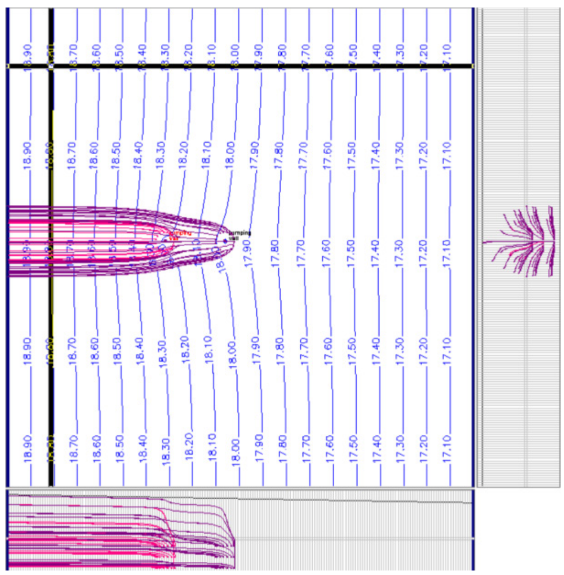
In the second study case, the distance between two pumping wells, *D* were varied at 240 m, 360 m, 480 m, 720 m and 960 m in Models 5, 6, 7, 8 and 9 respectively (Figure 4). A total pumping rate of 100 m^3/day was assigned in each model and was equally distributed into two pumping wells.



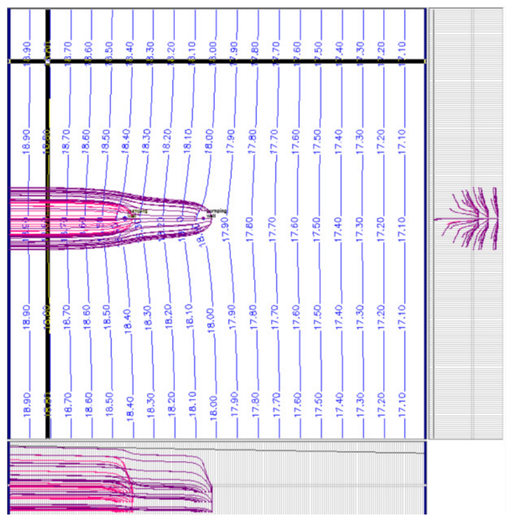
(a) Model 5: Distance, *D* = 240 m



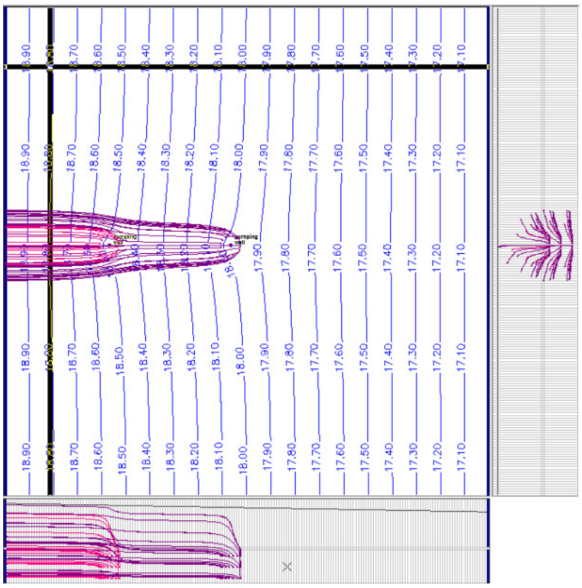
(b) Model 6: Distance, *D* = 360 m



(c) Model 7: Distance, *D* = 480 m



(d) Model 8: Distance, *D* = 720 m



(e) Model 9: Distance, D = 960 m

FIGURE 4. Simulated Capture zone in Study Case 2

TABLE 2. Width of capture zone under different distance between two wells

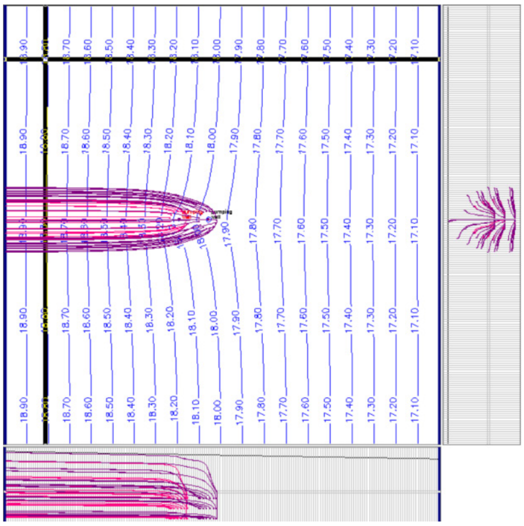
Model	Distance between two wells (m)	Width of Capture Zone (m)
2	-	580
5	240	620
6	360	610
7	480	590
8	720	585
9	960	580

The drawdown in a pumping well is always corresponded to the changes of pumping rate. Higher drawdown of groundwater head may lead to the reduction of water in the adjacent stream and lakes. In the second study case, the drawdown was controlled by distributing the withdrawal rate equally into two wells. The results denote that the width of the capture zone decreased when the distance between two wells was larger. The width of capture zone has reduced from 620 m to 580 m when the distance increased by four times (Models 8 and 9 in Table 2). Based on the simulated results, the distance between two wells has affected the extent of the capture zone. In the case of two extraction wells system, the results have indicated that by reducing the distance between two wells, the width of capture zone can be optimised.

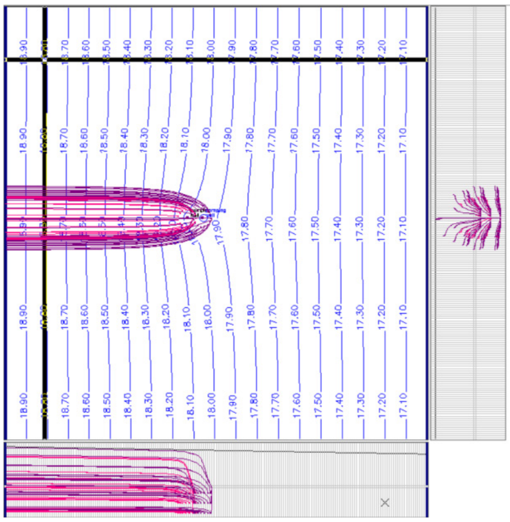
STUDY CASE 3: INFLUENCE OF WELL ARRANGEMENT

The comparison of perpendicular and parallel wells configuration for two (Models 10 and 11) and four wells (Models 12-15) were evaluated in the study case 3. The distance, D between two extraction wells system was 120 m and the distance, D between four extraction wells system were varied at 120 m (Models 12 and 13) and 60 m (Models 14 and 15) (Figure 5). The results show that the width of capture zone induced by the extraction wells that arranged in perpendicular to the flow direction were higher than the arrangement of extraction wells parallel to the flow direction. The increment of the width of capture zone for perpendicular cases was 23%, 52% and 8% higher than the parallel cases (Table 3). The increment was more significant when the distance between wells has increased from 60 m to 120 m (85 to 52%). In the case of four wells aligned perpendicularly to the flow direction (Models 10 and 12), the width of capture zone increased from 540 m to 820 m when the distance between wells increased from 60 m to 120 m. In the parallel case, the increment was only 40 m between the two and four wells configuration (Table 3). Hence, the results indicated that the larger of distance, D between wells has contributed to the increment of the width of capture zone especially in perpendicular case.

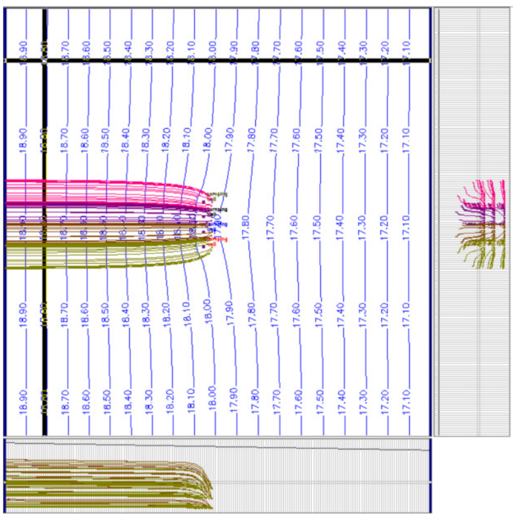
In the two and four wells orientation cases (Models 10 and 12, D = 120 m; Models 14 and 15, D = 60 m), the drawdown of wells in perpendicular orientation is relatively identical while in parallel orientation case, the drawdown was gradually increased toward upgradient of the flow direction (Figures 6 and 7). In both well orientation cases, the drawdown in the wells was lower than drawdown of 1.354 m in a single well system (Table 1, Figures 6 and 7). The results demonstrated that the parallel well orientation and the quantity of wells are able to further reduce the drawdown in the wells. Similar findings on the reduction of drawdown was also reported in the study of Christ & Goltz (2004)thereby preventing further migration of contaminated water down gradient. In this work, examining two-, three-, and four-well systems, we compare well configurations that are parallel and perpendicular to the regional groundwater flow direction. We show that orienting extraction wells co-linearly, parallel to regional flow, results in (1. Based on the results obtained, the orientation of the well and the number of well could affect the extent of the width of capture zone and drawdown in the wells.



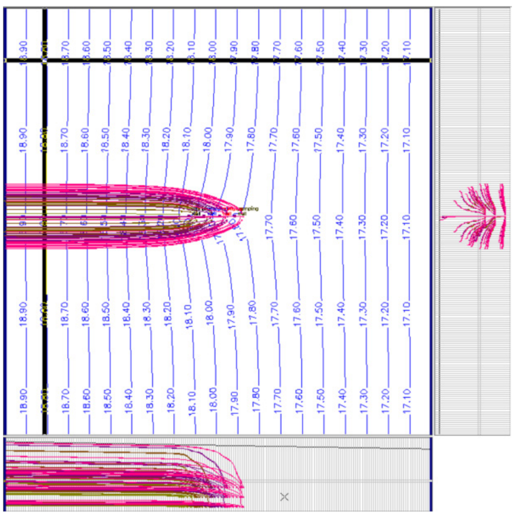
(a) Model 10: 2 Wells were aligned perpendicularly to flow direction (D = 120 m)



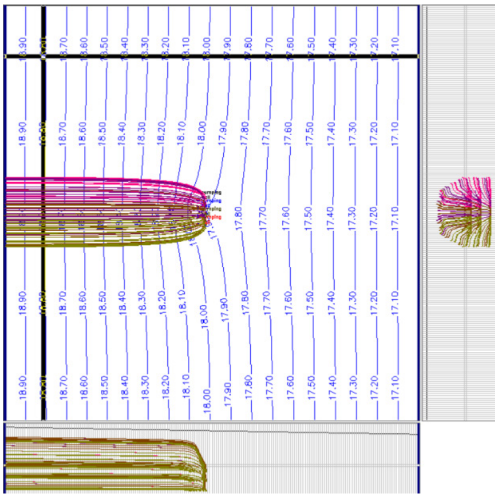
(b) Model 11: 2 Wells were aligned parallelly to flow direction (D = 120 m)



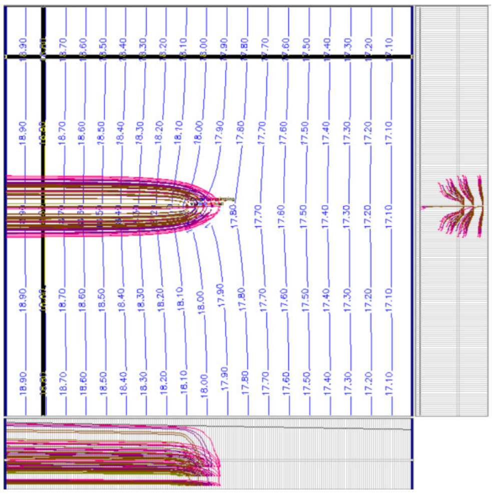
(c) Model 12: 4 Wells were aligned perpendicularly to flow direction (D = 120 m)



(d) Model 13: 4 Wells were aligned parallelly to flow direction (D = 120 m)



(e) Model 14: 4 Wells were aligned perpendicularly to flow direction (D = 60 m)



(f) Model 15: 4 Wells were aligned parallelly to flow direction (D = 60 m)

FIGURE 5. Simulated Capture Zone in Study Case 3

TABLE 3. Width of capture zone under different well orientation

Model	Distance between wells (m)	Width of Capture Zone (m)
10*#	120	640
11+#	120	520
12*	120	820
13+	120	540
14*	60	540
15+	60	500

*Indicate well arrangement in perpendicular to flow direction.
+Indicate well arrangement in parallel to flow direction.
#Indicate two-well system

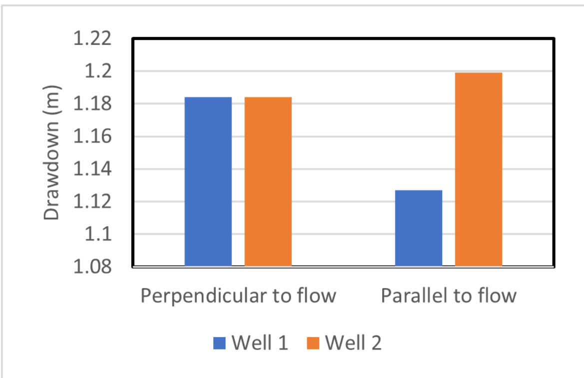


FIGURE 6. The drawdown of wells in two extraction wells system. The distance between the well, D = 120 m

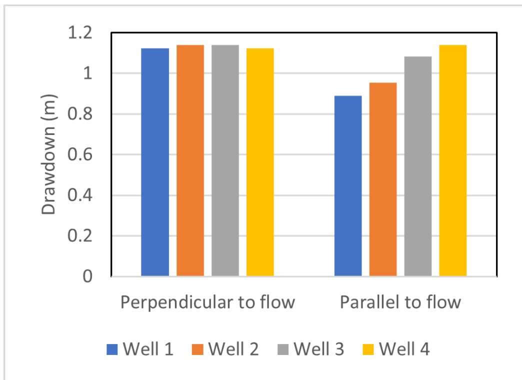


FIGURE 7. The drawdown of wells in four extraction wells system. The distance between the well, D = 60 m

STUDY CASE 4: INFLUENCE OF THE NUMBER OF WELL

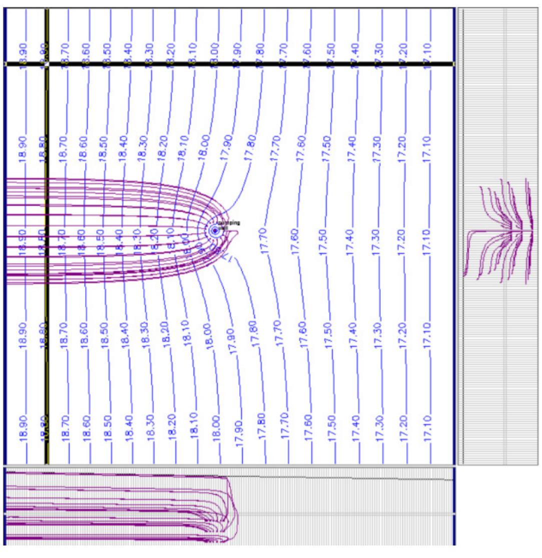
In this study case, three models were simulated to evaluate the effect of the number of well to the width of capture zone (Figure 8). The number of well is varied but the total pumping rate of the wells were fixed at 200 m^3/day. In the cases of two and four wells configuration, the distance between the wells, D was set at 60 m. When the total pumping rate of 200 m^3/day was distributed in two wells and four wells configuration, the width of capture zone was reduced due to the lower pumping rate in the individual well (Table 4). Similar results was shown in the cases at a pumping rate of 100 m^3/day when the wells was separated by 120 m in Models 11 and 13 when compared with Model 2 (Table 4). The width of capture zone has reduced from 580 m (single well) to 520 m and 540 m for two and four wells system respectively. Unlike the orientation of well perpendicularly to the direction of flow, the width of capture zone was increased when the number of well has increased from a single to double and four wells system (Table 4). However, the drawdown was found to reduce in both orientation under multiple wells system when the pumping rates were equally distributed in two and four wells respectively. The results shows that the distribution of pumping rate was able to reduce the drawdown, however the width of capture zone was reduced in the case of multiple wells aligned parallelly to the flow direction. The results indicated that in the application of multiple wells configuration, the orientation of wells have a great impact on the control of width of capture zone in the aquifer. Similar to the findings of Bear et al. (1998)because of uncertainties associated with the system. The changes in concentrations in reality may differ significantly from predicted ones. Instead, a multi-stage decision process is formulated and solved as a two-level hierarchical optimization model. Cost serves as the objective function, while contaminant concentration and total cleanup time are constraints. The entire cleanup time is divided into several stages. The number of wells for both pumping and injection is treated as a decision variable in each design stage. At the basic level, well locations and pumping/injection rates are sought so as to maximize mass removal of contaminants. At the upper level, the number of wells for pumping and injection is optimized, so as to minimize the cost, taking maximum contaminant level (MCL, by optimizing the number of wells, the pump and treat system can achieve a maximum removal rate of contaminants.

TABLE 4. Width of capture zone under single, two, and four wells configuration

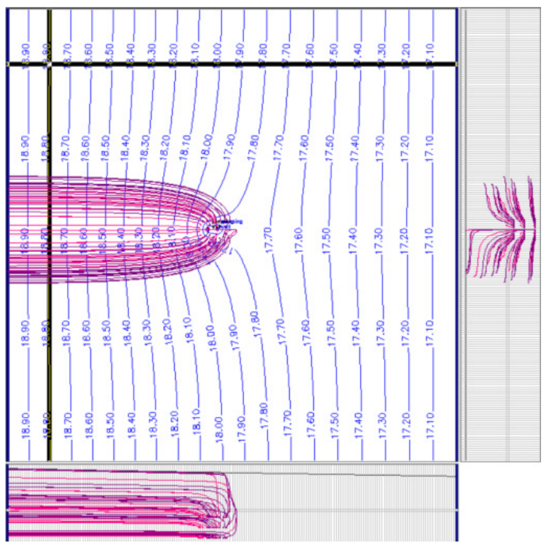
Model	Number of well	Width of Capture Zone (m)	Pumping rate (m^3/day)
4	1	960	200
16$^+$	2	740	200
17$^+$	4	760	200
2	1	580	100
11$^+$	2	520	100
13$^+$	4	540	100
2	1	580	100
11*	2	640	100
13*	4	820	100

*Indicate well arrangement in perpendicular to flow direction.

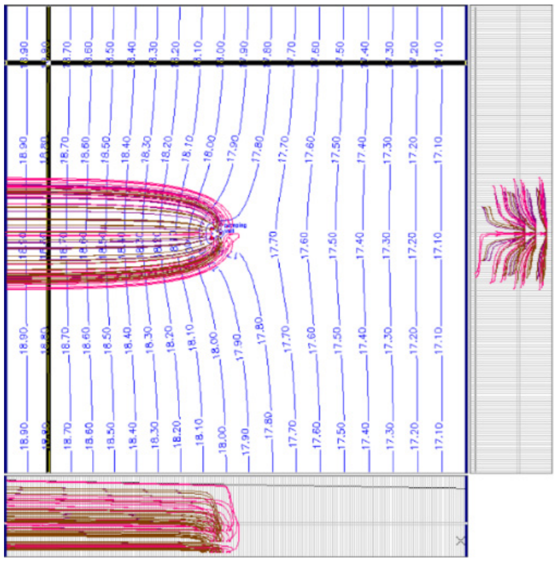
$^+$Indicate well arrangement in parallel to flow direction.



(a) Model 4: Single well



(b) Model 16 - two wells aligned parallelly to the direction of flow.



(c) Model 17 - four wells aligned parallelly to the direction of flow.

FIGURE 8. Simulated Capture Zone in Study Case 4

CONCLUSION

This study has demonstrated the influence of arrangement and configuration of extraction wells to the width of capture zone in the pump and treat system using numerical model. The result shows that the width of capture zone was increased corresponding to the increment of total pumping rates in the single well study cases. However, the increment of the width of capture zone was not equivalent to the increment of pumping rate. In the two-well system that were installed parallel to the flow direction, the results demonstrated that the width of capture zone has decreased when the distance between two wells, was enlarged. When the orientation of multiple wells system was varied to the flow direction, the width of capture zone was higher in the case of wells arranged perpendicularly to the flow direction. The findings of this study can help to enhance the performance of extraction well in pump and treat system and reduce the cost of groundwater remediation by optimizing the extraction process.

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DECLARATION OF COMPETING INTEREST

None

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