ARTIFICIAL RECHARGE OF CONFINED AND UNCONFINED AQUIFER UTILIZING MULTIPLE WELLS SYSTEM IN ARID AREAS

H. I. Mohamed

Civil Eng. Department, Assiut University, Assiut, Egypt,
E-mail: hassanmohamed_2000@yahoo.com

ABSTRACT

The economic development and the rapid growth rate in various development sectors are dependent on the availability of water resources. This will lead to stress on water resources, which is already scarce, so it must be managed within a context of integrated water resources management. More storage of water upstream of dams and especially in aquifers via artificial recharge is necessary to save water in times of water floods for use in times of droughts. To enhance ground water recharge upstream of dams, a group of injection wells is usually installed. This group of recharge wells is located near each other, their cone of recharge curves intersect with their radius of influence. Thus, the total capacity of recharge is decreased due to the interference. The wells arrangement may be in row or at the vertices of an equilateral triangle or at the vertices of a square shape. In this study, the optimum arrangement, spacing and number of that wells are investigated to achieve maximum possible recharge quantity for both confined and unconfined aquifer. Five different wells arrangement are studied. It was found from this study that the wells arrangement and spacing have a significant effect on the wells recharge capacity.

Keywords: aquifer recharge, wells interference, storm water, deep infiltration.

1 INTRODUCTION

In water scarce areas, where there is a low and erratic rainfall, there is an increased dependence on groundwater. Moreover, changes in the climatic condition have altered the rainfall frequency and intensity throughout the world. The impact of climate change is being significantly observed in many regions along the world with frequently high intensity rainfall as compared to past. There are various techniques to develop and manage groundwater artificially. In one of the methods, recharge wells are used, which admit water from the surface to fresh water aquifer through artificial recharging. In practice, recharge wells are positioned closer to each other as shown in Fig. 1. In such case, the wells will interface with each other and its capacity will be less than the individual well. To calculate the necessary number of wells, their recharge rate and their location, trial and error is used to estimate the number of wells and recharge rates. So, this situation needs to be examined and assume some general working hypotheses.

Fig. 1: A group of wells constructed upstream of El-Ghat dam, Saudi Arabia.

Artificial ground water recharge was the subject of many investigations, among of them Park et al. 2006; Singh et al. 2009; and Al-Othman 2011. The big advantage of underground storage is that there are no evaporation losses from the groundwater (Bouwer 2002). Groundwater recharge systems are sustainable, economical, and do not have the eco-environmental problems that dams have. In addition, algae, which may cause negative effect on water quality of the open stored water in reservoirs, does not grow in groundwater. Artificial recharge of wadi aquifers using treated wastewater would increase the availability of water within these sensitive systems and decrease the need to develop more capacity in desalination systems and accompanying conveyance infrastructure (Missimer et al. 2012). The effect of hydraulic and geotechnical parameters on the different groundwater recharge methods with reference to three methods frequently used in Saudi Arabia (surface spreading, injection wells into Vadose zone and direct injection wells into the aquifer) were studied by Mohamed and Ahmed (2013). It was found that geotechnical, hydraulic and geometrical parameters have large effect on all methods. The usage of vadose zone injection well method and deep injection well recharge method may be effective when the upper layer of soil has a low hydraulic conductivity. The effectiveness of dams on the recharge of shallow aquifer was studied by Sherif et al. (2011). They concluded that about 22% of the water storage in the ponding area of the dam has actually infiltrated through the unsaturated zone and reached the groundwater system. The rest (78%) of the water storage is either evaporated or stored in the unsaturated zone of the aquifer. Injection well-type recharge structures like vertical and horizontal recharge shaft, recharge cavity and recharge wells have proven to be effective recharge method (kumar et al. 2012; El Arabi 2012). Alrehaili and Hussein (2012) used remote sensing, (GIS) and groundwater monitoring to estimate artificial groundwater recharge. They showed that using of wells designed for artificial recharge reduces the losses of water by evaporation. Those wells help to make the harvested water reach the groundwater table rapidly. Also, they showed that the rate of recharge is a function of the presence of wells prepared for recharge. The impact of about 34 pumping wells and 6 recharge wells on groundwater recharge in Al-Qassim region (Saudi Arabia) and response of the aquifer to this recharge, which is determined by modeling, was investigated by Ghazaw et al. (2014). They showed that groundwater recharge using injection wells can reduce the aquifer drawdown by about 36% less than that without recharge. Also, recharge wells will help in prolonging the aquifer life by about 3%. Unsteady flow through recharge well in multiple leaky aquifers with accretion from unsteady ponding was analyzed by Singh and Shakya (2009). The analysis showed that the recharging in lower aquifer or both the aquifers is preferred for getting higher recharge rate.

In view of the above, it will be of significant importance, if groundwater recharge using multiple wells system were studied in more details to arrive the best position of the wells and this is considered the first attempt to study artificial groundwater recharge using multiple system. Firstly, equations for various cases of wells arrangement will be derived. Secondly, a graphical solution and parametric study will be obtained for the following cases: two wells system, three wells system in row and at the vertices of equilateral triangle, four wells system and five wells system at the vertices and center of square. Where, the wells spacing, well diameter, aquifer hydraulic conductivity and mound rise above original groundwater level will be changed many times.

The objectives of the present study are as follows:

- Studying groundwater recharge using multiple recharge wells at different arrangement, i.e. row arrangement, at vertices of an equilateral triangle and at the vertices of square shape.
- Studying effect of groundwater recharge wells arrangement on recharge capacity.

2 THEORETICAL BASIS

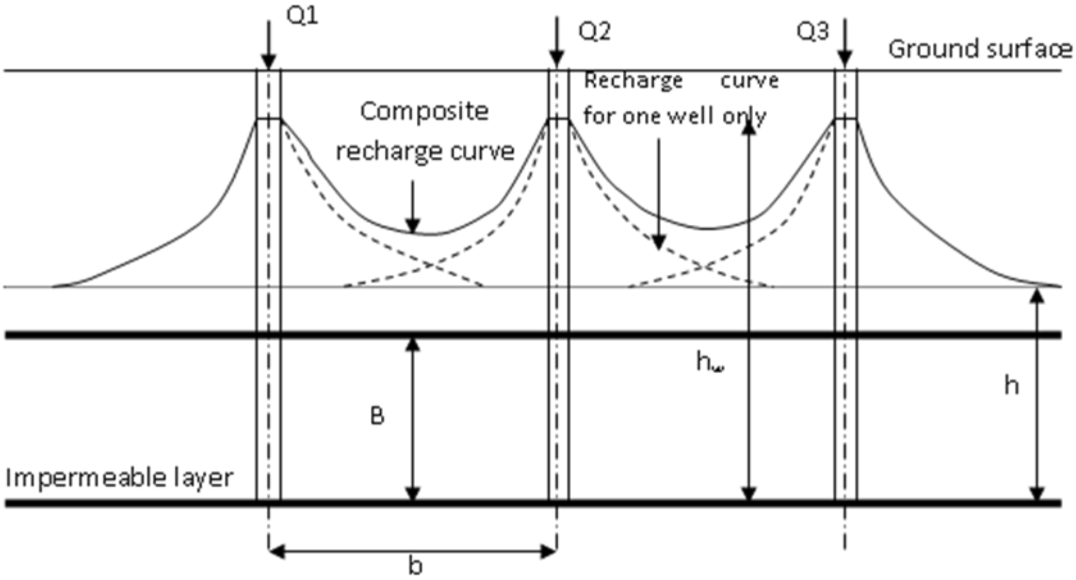
Mohamed (2014) and and Agrawal (2012) as cited from Muskt (1937) derived the relationships for computing well discharge under different arrangements of wells near the centre of wells field of radius R (equal to the radius of influence of each well). In a similar way these relationships can be rewritten for recharge wells as follows.

Case (a): Two wells Spaced b < R: Q1 and Q2 are recharge rate of two wells in aquifer. The recharge equation in confined and unconfined aquifer, respectively, for them can be written as:

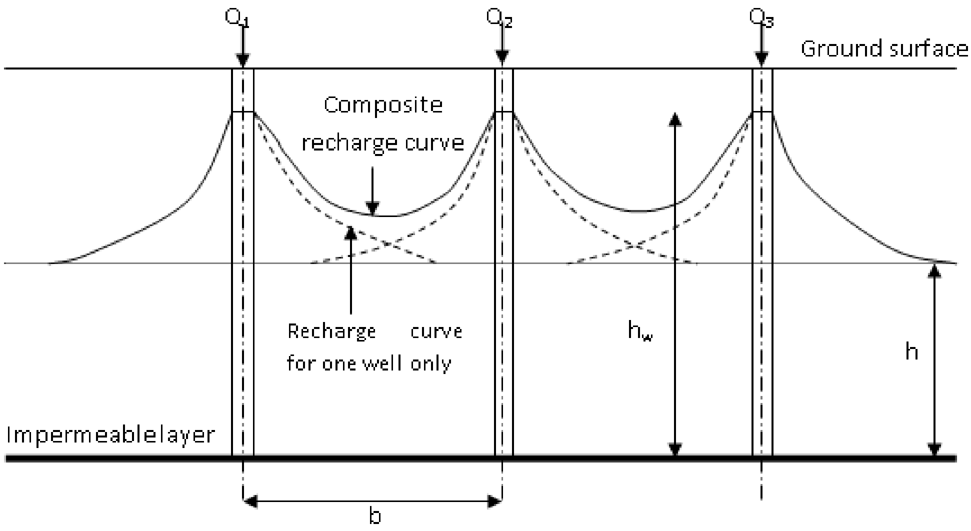
$$Q_1 = Q_2 = \frac{\pi K\, B(h_w - h\ \ )}{\ln\frac{R^2}{r_w b}} \quad (1)$$

$$Q_1 = Q_2 = \frac{\pi K\, (h_w^2 - h^2)}{\ln\frac{R^2}{r_w b}} \quad (2)$$

Where h is the average water table head at the external boundary, hw is the head at the wells, B is the thickness of the confined aquifer as shown in Fig. 2.



(a) Confined aquifer



(b) Unconfined aquifer

Fig. 2: Individual and composite mound curves for three wells in a line, (a) confined aquifer, (b) unconfined aquifer.

Case (b): Three Wells Spaced in Line b < R: If there are three identical wells in the same line having a spacing of b as shown in Fig. 3, the recharge through the two end wells for confined and unconfined aquifer, respectively, is given by

$$Q_1 = Q_3 = \frac{\pi K\, B\left(h_w - h\ \ \right)\ln\frac{b}{r_w}}{2\ln\frac{R}{b}\ln\frac{b}{r_w} + \ln\frac{b}{2r_w}\ln\frac{R}{r_w}} \quad (3)$$

$$Q_1 = Q_3 = \frac{\pi K \left(h_w^2 - h^2\right) \ln\frac{b}{r_w}}{2 \ln\frac{R}{b} \ln\frac{b}{r_w} + \ln\frac{b}{2r_w} \ln\frac{R}{r_w}} \tag{4}$$

The recharge through the middle well for confined and unconfined aquifer, respectively, is given by

$$Q_3 = \frac{\pi KB \left(h_w - h \quad\right) \ln\frac{b}{2r_w}}{2 \ln\frac{R}{b} \ln\frac{b}{r_w} + \ln\frac{b}{2r_w} \ln\frac{R}{r_w}} \tag{5}$$

$$Q_3 = \frac{\pi K \left(h_w^2 - h^2\right) \ln\frac{b}{2r_w}}{2 \ln\frac{R}{b} \ln\frac{b}{r_w} + \ln\frac{b}{2r_w} \ln\frac{R}{r_w}} \tag{6}$$

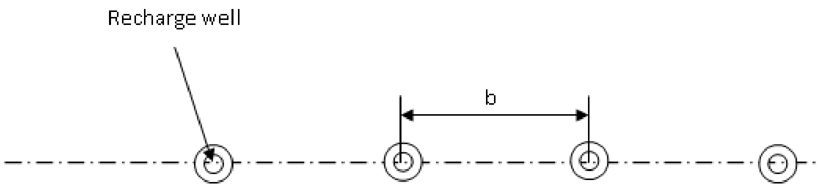


Fig. 3: Recharge wells arranged on a line at equal distance.

Case (c): Three Wells at the Vertices of an Equilateral Triangle with Side b: If there are three identical wells located at the apexes of an equilateral triangle with side b as shown in Fig. 4, the recharge from each well for confined and unconfined aquifer, respectively, is given by

$$Q_1 = Q_2 = Q_3 = \frac{\pi KB \left(h_w - h \quad\right)}{\ln\frac{R^3}{r_w b^2}} \tag{7}$$

$$Q_1 = Q_2 = Q_3 = \frac{\pi K \left(h_w^2 - h^2\right)}{\ln\frac{R^3}{r_w b^2}} \tag{8}$$

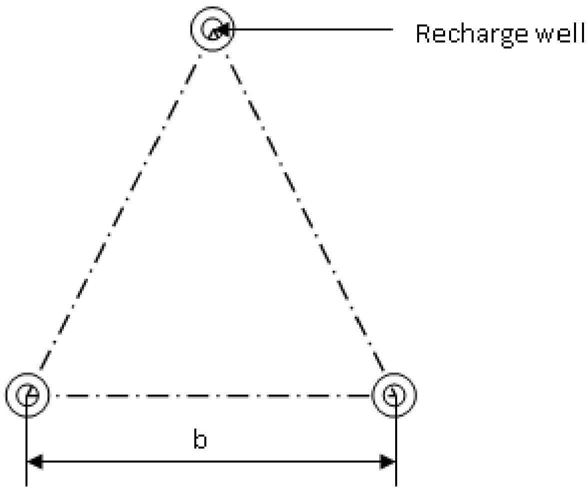


Fig. 4: Recharge wells arranged on the corners of an equilateral of triangle.

Case (d): Four Wells form Square with Side b: If there are four identical wells located at the apexes of a square with side b as shown in Fig. 5, the recharge from each well for confined and unconfined aquifer, respectively, is given by

$$Q_1 = Q_2 = Q_3 = Q_4 = \frac{\pi KB \left(h_w - h \quad\right)}{\ln\frac{R^4}{\sqrt{2} r_w b^3}} \tag{9}$$

$$Q_1 = Q_2 = Q_3 = Q_4 = \frac{\pi K\left(h_w^2 - h^2\right)}{\ln\frac{R^4}{\sqrt{2}r_w b^3}} \tag{10}$$

If there is a fifth well at the center of the square, the corner wells yield and the center well recharge is given by

$$Q_1 = Q_2 = Q_3 = Q_4 = \frac{\pi K\, B\left(h_w - h\right)\ln\frac{b}{\sqrt{2}\, r_w}}{4\ln\frac{\sqrt{2}\,R}{b}\ln\frac{b}{\sqrt{2}r_w} + \ln\frac{b}{4\sqrt{2}\ r_w}\ln\frac{R}{r_w}} \tag{11}$$

$$Q_1 = Q_2 = Q_3 = Q_4 = \frac{\pi K\left(h_w^2 - h^2\right)\ln\frac{b}{\sqrt{2}\, r_w}}{4\ln\frac{\sqrt{2}\,R}{b}\ln\frac{b}{\sqrt{2}r_w} + \ln\frac{b}{4\sqrt{2}\ r_w}\ln\frac{R}{r_w}} \tag{12}$$

$$Q_5 = \frac{\pi KB\left(h_w - h\right)\ln\frac{b}{4\sqrt{2}r_w}}{4\ln\frac{\sqrt{2}\,R}{b}\ln\frac{b}{\sqrt{2}r_w} + \ln\frac{b}{4\sqrt{2}r_w}\ln\frac{R}{r_w}} \tag{13}$$

$$Q_5 = \frac{\pi K\left(h_w^2 - h^2\right)\ln\frac{b}{4\sqrt{2}r_w}}{4\ln\frac{\sqrt{2}\,R}{b}\ln\frac{b}{\sqrt{2}r_w} + \ln\frac{b}{4\sqrt{2}r_w}\ln\frac{R}{r_w}} \tag{14}$$

The previous analytical equations are used to investigate groundwater recharge utilizing multiple wells system with different configurations as shown in Figs. (3, 4, and 5). For each system pattern, the wells spacing (b) is changed in the range from 5 m to 50 m, hydraulic conductivity of the aquifer (K) is changed three times i.e. 0.2, 0.5 and 1.0 m/day and the recharge cone height (hw-h) as shown in Fig. 2 is varied many times. The thickness of confined aquifer (B) and original water before recharging of unconfined aquifer (h) are taken as a constant value equal to 10 m.

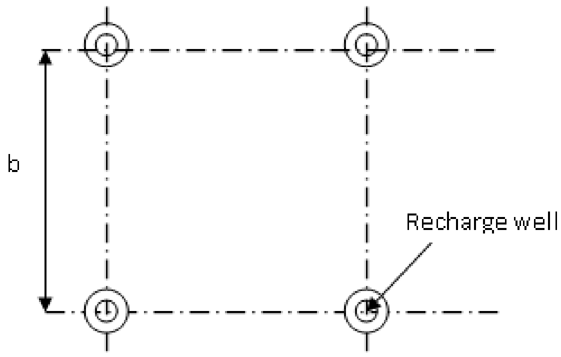


Fig. 5: Recharge wells arranged on the corners of square.

3 RESULTS AND DISCUSSIONS

Fig. 6 shows the variation of well recharge rate with R/b ratio, where R is the radius of influence of well and b is the distance between wells, for different heights of mound cone (hw-h) and hydraulic conductivity (K) equal to 0.2 m/day at two wells. It can be shown that the recharge rate decreases as R/b ratio increases or as the distance between wells decreases and this result in agreement with Scott and Aron (1967) who indicated that individual capacity increases with increased spacing because of reduced well interference, but total capacity per unit length of well row decreases. Also, the recharge rate decreases as the difference between water level in the well and original water level decreases.

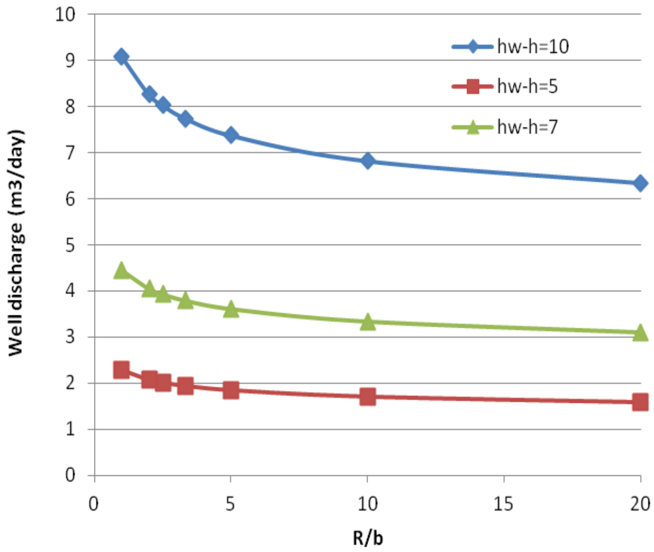


Fig. 6: Variation of well recharge rate with R/b ratio for different values of piezometric height at two wells.

Fig. 7 and 8 depict the variation of recharge rate computed using Eqn. 1 and 2 (confined and unconfined aquifer) with R/b values of two wells at different values of hydraulic conductivity for height of mound cone (hw-h) equal to 10 m. The hydraulic conductivity is changed three times, 0.2, 0.5 and 1.0 m/day, respectively. For each value of the hydraulic conductivity, the distance between wells is changed in the range from 5 m to 100 m. It is shown that the recharge rate decreases dramatically by decreasing the hydraulic conductivity. Also, it can be shown from this figure that the recharge rate decreases by decreasing the distance between wells.

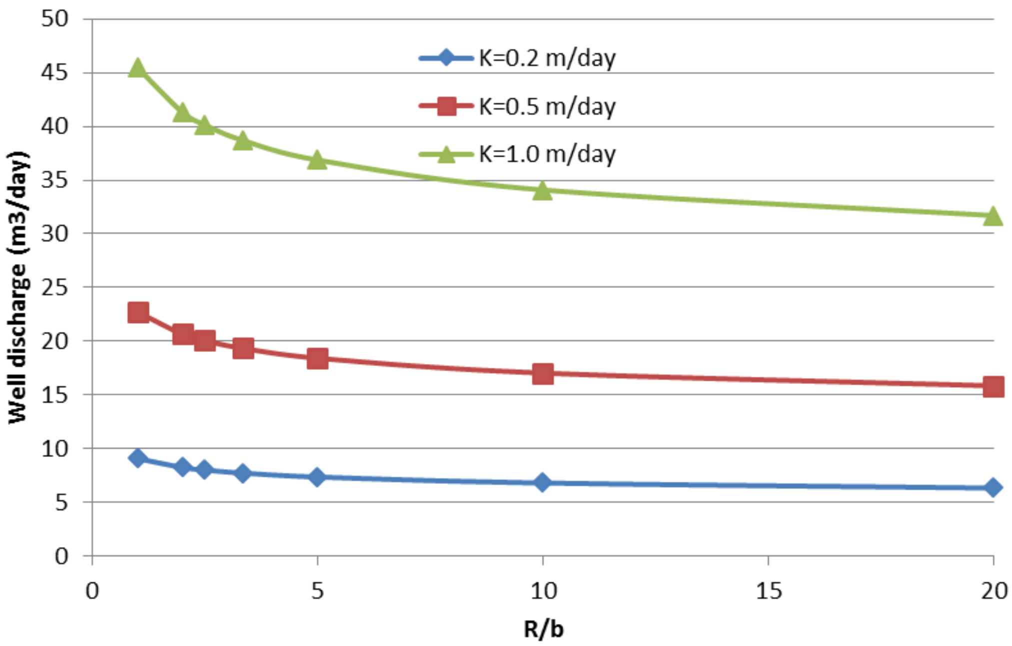


Fig. 7: Variation of well recharge rate with R/b for different values of hydraulic conductivity at two wells feeding confined aquifer.

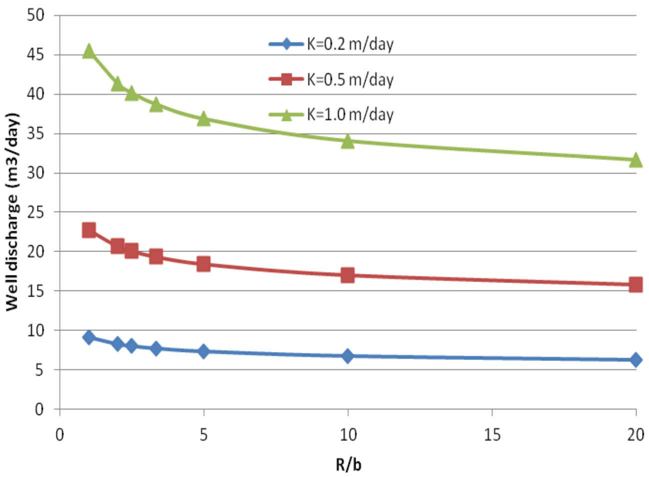


Fig. 8: Variation of well recharge rate with R/b for different values of hydraulic conductivity at two wells feeding unconfined aquifer.

To show percentage of reduction in recharge rate compared with single well recharge rate, in Fig. 9, ratio of well recharge rate to single well recharge rate Q/Qsingle was plotted versus R/b ratio. It can be noticed from this figure that ratio of recharge rate for two wells system compared with single well recharge decreases as the distance between wells decreases to about 70% at R/b equal to 20 for R/rw equals 1000 and reduces more than that if R/rw ratio decreases to 500.

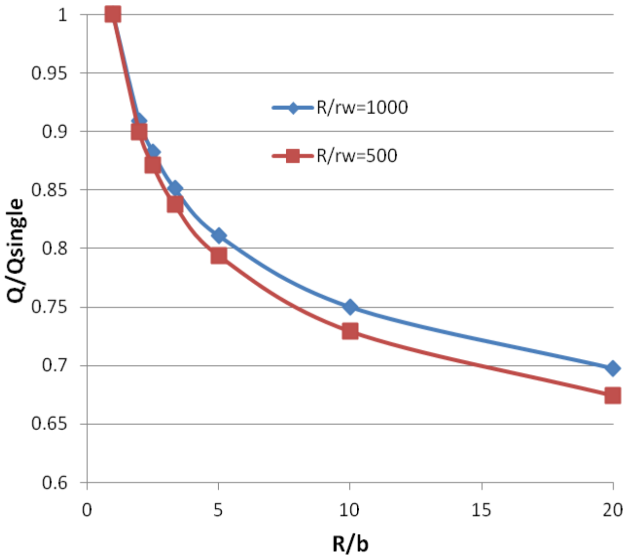


Fig. 9: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/rw at two wells.

When three wells arranged in row, the recharge rate for outer wells is differ than that for inner well. Figs. 10 and 11 show recharge rate as a percentage from single well recharge at case of three wells arranged in row for outer and inner well, respectively. In comparison between the two figures, it can be shown that the recharge of the outer well is higher than that of the inner well. The recharge rate of the outer well arrives to about less than 60% from that of a single well at R/b=20 and less than 50% for the inner well and these values for both wells is less than that for two wells.

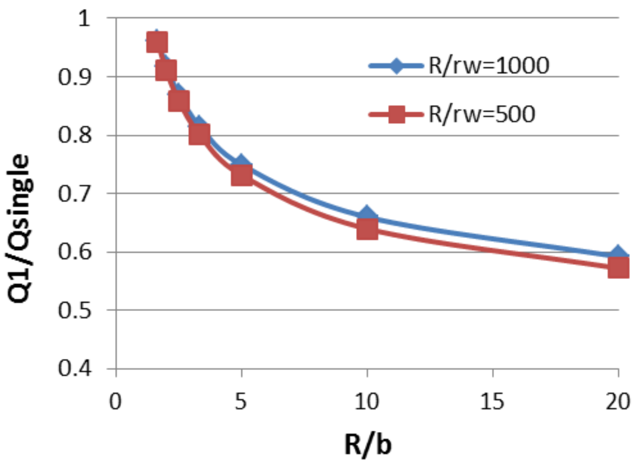


Fig. 10: Ratio of outer well recharge rate to single well recharge versus R/b ratio for two values R/r_w at three wells arranged in line.

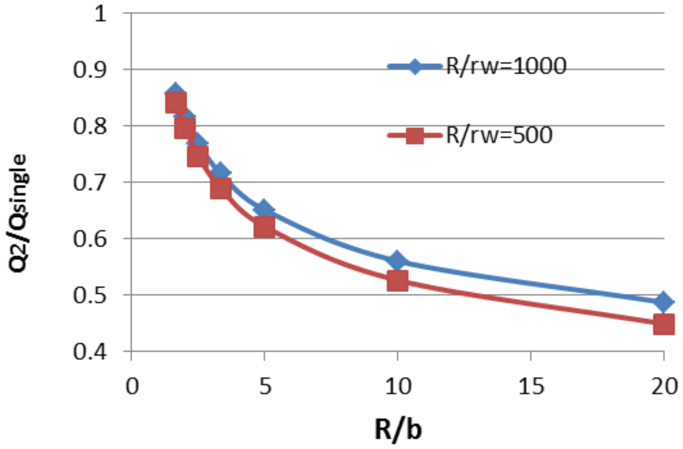


Fig. 11: Ratio of inner well recharge rate to single well recharge versus R/b ratio for two values R/r_w at three wells arranged in line.

When three wells forming an equilateral triangle, the recharge rate is the same for each well. Therefore, plots can be proposed between Q/Qsingle and R/b ratio for various values of hw-h and for given R/rw, K and b as shown in Fig. 12. Theses graphs can be used for computing the recharge rate of wells for known R/b ratio.

For four wells forming a square, the recharge rate is the same through each of the wells. Fig. 13 shows the relation between Q/Qsingle and R/b for two values of R/rw. It can be shown that percentage of well recharge arrives to a value less than 0.5 at R/b equal to 20. If a fifth well is placed at the center of square, it is noticeable that the recharge rate of wells at corners is less than those without well in the center as shown in Fig. 14. Also, recharge rate of the central well is less than that of corners wells.

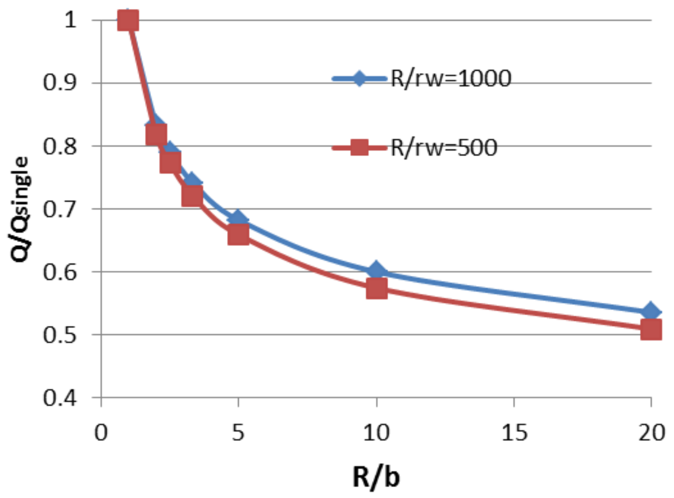


Fig. 12: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/r_w at three wells system arranged at the vertices of triangle.

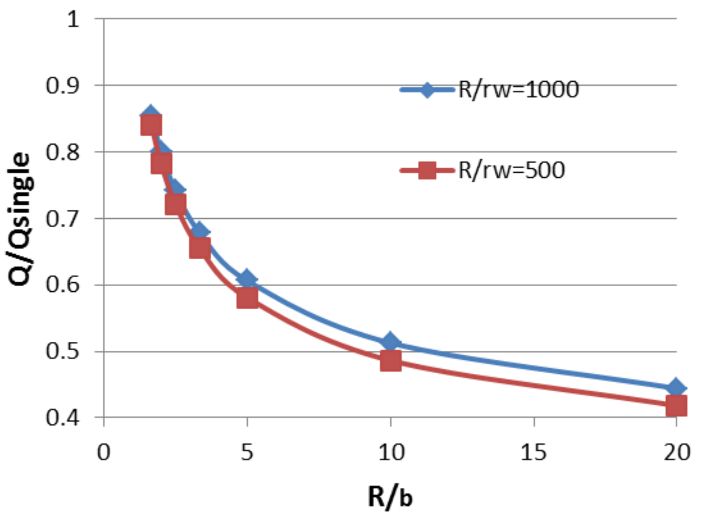


Fig. 13: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/rw at four wells system arranged at the vertices of square.

Fig. 15 shows the total recharge rate for the different wells configurations as number of times of single well recharge rate. It is noticeable in general that the total recharge rate increases by increasing the number of wells. When three wells arranged in row gives more recharge than three wells arranged at vertices of triangle. Five wells arranged at the corner and center of square gives slight increase in the recharge rate than four wells arranged only at the corner of square but this increase does not balance the increase in cost due the construction of fifth well. Although number of wells influences the recharge rate, it is subject to the economic feasibility (Al-Othman 2011).

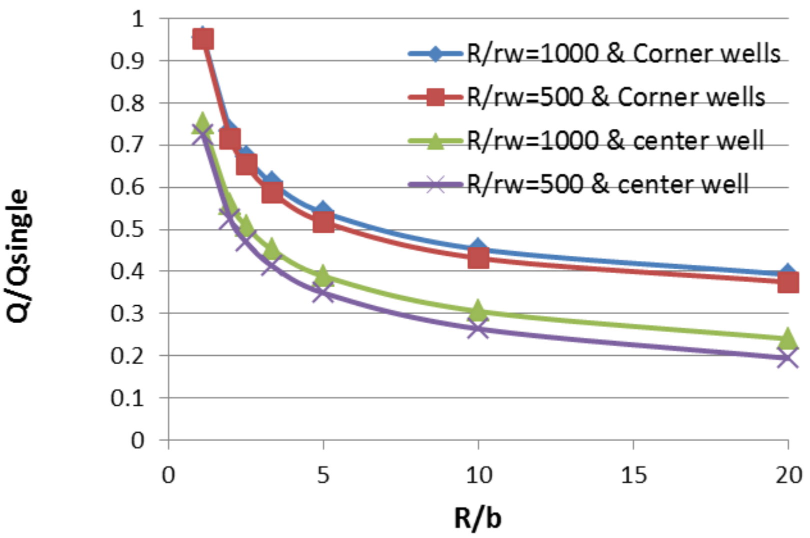


Fig. 14: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/r_w at four wells system arranged at the vertices of square and one well at the center of square.

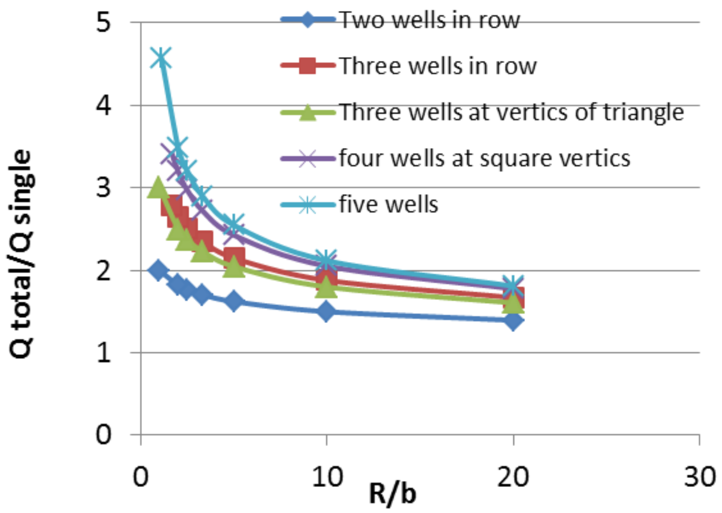


Fig. 15: Variation of total recharge rate for different wells arrangement with R/b ratio at R/r_w=1000.

4 CONCLUSIONS

Groundwater recharge using multiple wells system is studied in this manuscript. Five types of wells configuration is used, i.e. two wells, three wells in line, three wells at the vertices of equilateral triangle, four wells at the vertices of square and the previous case with one well in the center of the square. It was found from this study that:

1. Arrangement method of multiple recharge wells has significant effect on recharge capacity of the system.
2. The recharge rate of well operated in multiple wells system is less than that of single well for all different cases of configuration.
3. The recharge rate of well operated in multiple system decreases as the distance between wells decreases.
4. The recharge rate of well in different arrangement can be computed as a percentage of single well recharge as a function of R/b and it independent on hydraulic conductivity, mound height (hw-h) and confined aquifer thickness.

5. Construction of three wells in raw gives more recharge than that of three wells at the vertices of triangle.
6. Five wells at the corners and center of square gives slight increase in the recharge rate than four wells only at the corners.

ABBREVIATIONS

The following symbols are used in this paper:
b = wells spacing;
h = the original water table height measured from impermeable layer;
h_w = water level height in the well measured from impermeable layer;
K = hydraulic conductivity;
Q = well recharge rate for multiple recharge well system;
Q_{single} = recharge rate for single well;
R = radius of influence of well;
r_w = radius of well.

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