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An Investigation of Groundwater Recharge Utilizing Multiple Wells System

Hassan Ibrahim Mohamed

Department of Environmental Engineering and Civil, Majmaah University, Saudi Arabia

Abstract: The economic development in Saudi Arabia 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, soit 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 are usually installed. This group of recharge wells is located near each others, 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 researcher has investigated the optimum arrangement, spacing and number of that wells were investigated to achieve maximum possible recharge quantity.

Key words: Aquifer recharge · Wells interference · Storm water · Deep infiltration

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 the gulf region 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 is 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.

Artificial ground water recharge was the subject of many investigations, among of them [1-3]. The big advantage of underground storage is that there are no evaporation losses from the groundwater [4]. 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 do not grow in groundwater. Artificial recharge of wadi aquifers using treated waste water 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 [5].The effect of hydraulic and geotechnical parameters on the different groundwater recharge methods with reference to three methods frequently used in KSA (surface spreading, injection wells into Vadose zone and direct injection wells into the aquifer) were studied by [6]. It was found that geotechnical, hydraulic and geometrical parameters have large effect on all

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

Corresponding Author: Hassan Ibrahim Mohamed, Civil and Environmental Engineering Department, Majmaah University, Saudi Arabia. E-mail: h.mohamed@mu.edu.sa

methods. The using 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 [7]. 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 rechargeshaft, recharge cavity and recharge wells have proven to be effective recharge method [8-10] 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 and response of the aquifer to this recharge, which is determined by modeling, was investigated by [11]. 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 [12]. 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. 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 in row, 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.
- The different equations which can be used in estimating the recharge capacity for the different wells arrangement.

Theoretical Basis: [13] as cited from [14] 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: Q_1 and Q_2 are recharge of two wells in unconfined aquifer. The recharge equation for them can be written as

$$Q_1 = Q_2 = \frac{\pi K\left(h_w^2 - h^2\right)}{\ln \frac{R^2}{r_w b}} \tag{1}$$

Where h is the average water table head at the external boundary and h_w is the head at the wells as shown in Fig. 2.

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 is given by

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

The recharge through the middle well is given by

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

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 is given by

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

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 is given by

$$Q_1 = Q_2 = Q_3 = Q_4 = \frac{\pi K\left(h_w^2 - h^2\right)}{\ln \frac{R^4}{\sqrt{2} r_w b^3}} \tag{5}$$

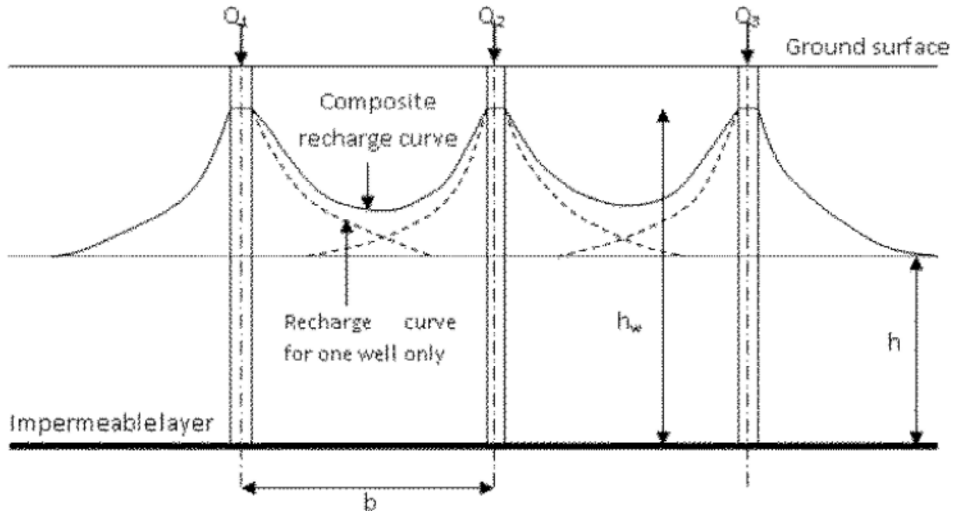

Fig. 2: Individual and composite mound curves for three wells in a line.

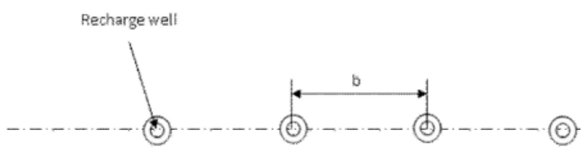

Fig. 3: Recharge wells arranged on a line at equal distance.

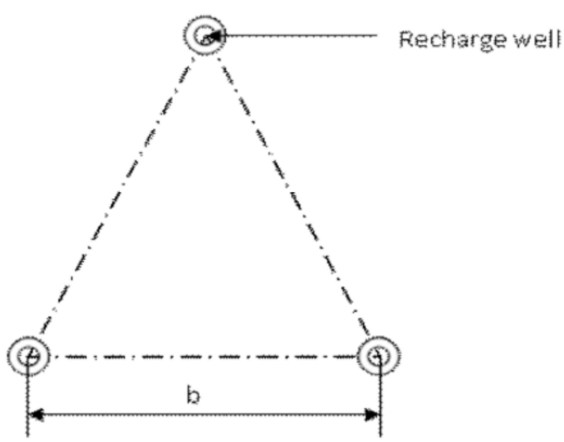

Fig. 4: Recharge wells arranged on the corners of an equilateral of triangle.

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

$$Q_1 = Q_2 = Q_3 = Q_4 = \frac{\pi K\,(h_w^2 - h^2)\ln\frac{b}{\sqrt{2}\,r_w}}{4\ln\frac{\sqrt{2}\,R}{b}\ln\frac{b}{\sqrt{2}\,r_w} + \ln\frac{b}{4\sqrt{2}\,r_w}\ln\frac{R}{r_w}} \quad (6)$$

$$Q_s = \frac{\pi K\,(h_w^2 - h^2)\ln\frac{b}{4\sqrt{2}\,r_w}}{4\ln\frac{\sqrt{2}\,R}{b}\ln\frac{b}{\sqrt{2}\,r_w} + \ln\frac{b}{4\sqrt{2}\,r_w}\ln\frac{R}{r_w}} \quad (7)$$

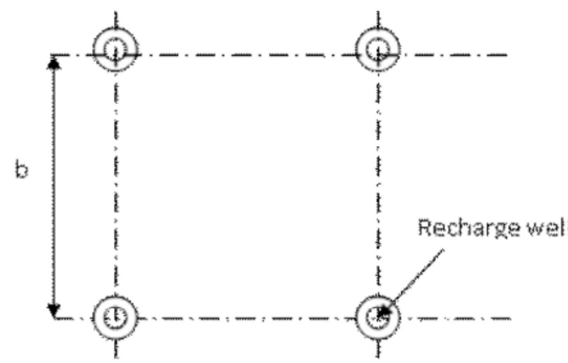

Fig. 5: Recharge wells arranged on the corners of square.

The previous analytical equations are used to investigate groundwater recharge utilizing multiple wells system with different configurations as shown in Figs. (3,4 and5). 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 (h_w-h) as shown in Fig. 2 is varied many times.

RESULTS AND DISCUSSION

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 (h_w-h) and hydraulic conductivity (K) equal to 0.2 m/day at two wells arranged at row. 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

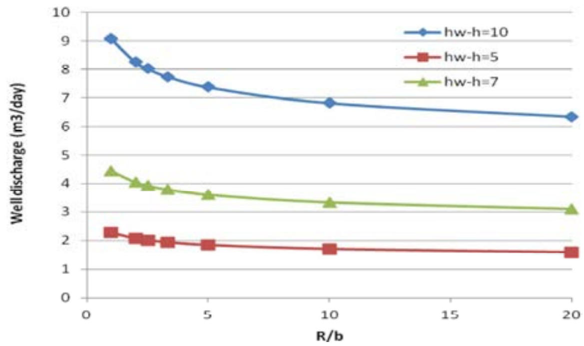

Fig. 6: Variation of well recharge rate with R/b ratio for different values of piezometric height at two wells arranged in line.

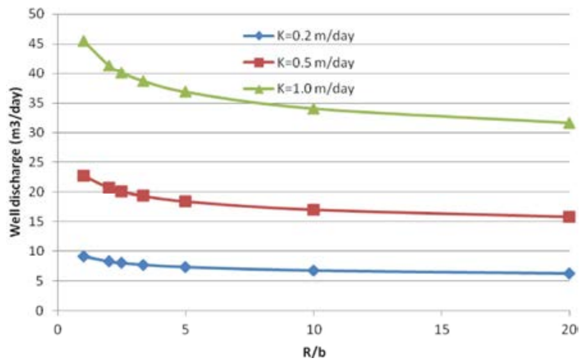

Fig. 7: Variation of well recharge rate with R/b for different values of hydraulic conductivity at two wells arranged in line.

agreement with [15] 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. 7 depicts the variation of recharge rate computed using Eqn. 1 with R/b values of two wells arranged in row at different values of hydraulic conductivity for height of mound cone (h_w-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.

To show percentage of reduction in recharge rate compared with single well recharge rate, in Fig. 8, ratio of well recharge rate to single well recharge rate Q/Q_{single} was

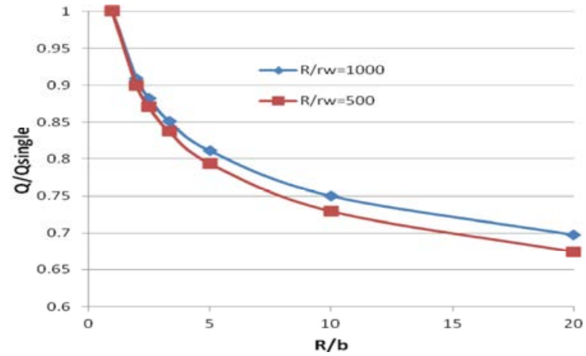

Fig. 8: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/r_w at two wells arranged in line.

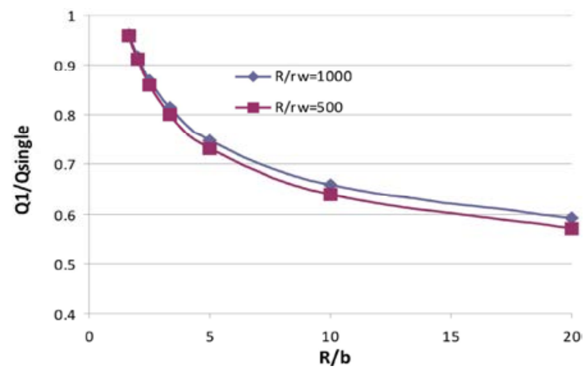

Fig. 9: Ratio of outer well recharge rate to single well recharge versus R/b ratio for two values R/r_w at three wells arranged in line.

plotted versus R/b ratio. It can be noticed from this figure that ratio of recharge rate for two wells system in line compared with single well recharge decreases as the distance between wells decreases to about 70% at R/b equal to 20 for R/r_w equals 1000 and reduces more than that if the well radius increases to R/r_w=500.

When three wells arranged in row, the recharge rate for outer wells is differ than that for inner well. Fig. 9 and 10 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 arranged in row.

When three wells forming an equilateral triangle, the recharge rate is the same for each well. Therefore, plots can be proposed between Q/Q_{single} and R/b ratio for

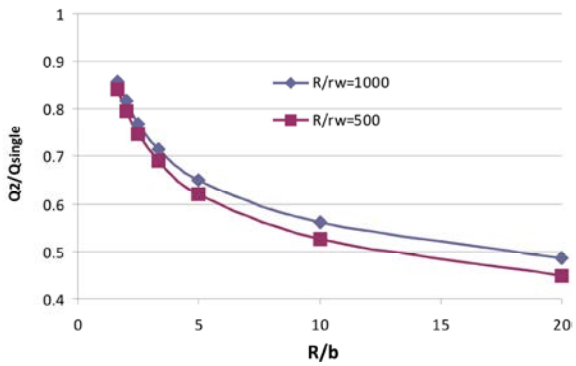

Fig. 10: Ratio of inner well recharge rate to single well recharge versus R/b ratio for two values R/r_w at three wells arranged in line.

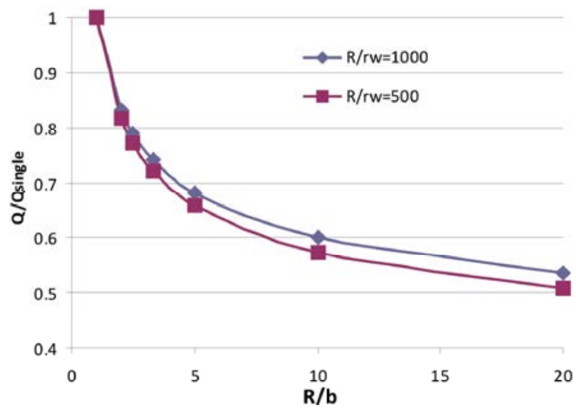

Fig. 11: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/r_w at three wells system arranged at the vertices of triangle.

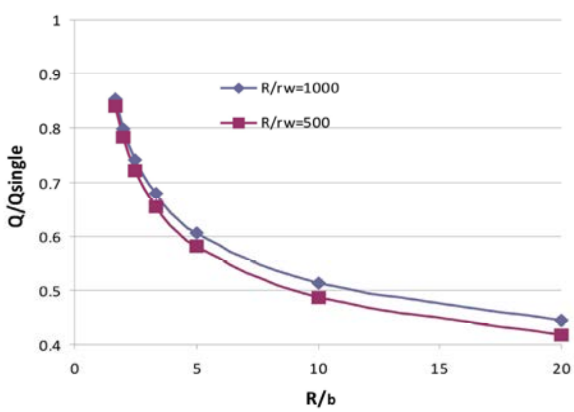

Fig. 12: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/r_w at four wells system arranged at the vertices of square.

various values of h_w-h and for given R/r_w, K and b as shown in Fig. 11. Theses graphs can be used for computing the recharge rate of wells for known R/b ratio.

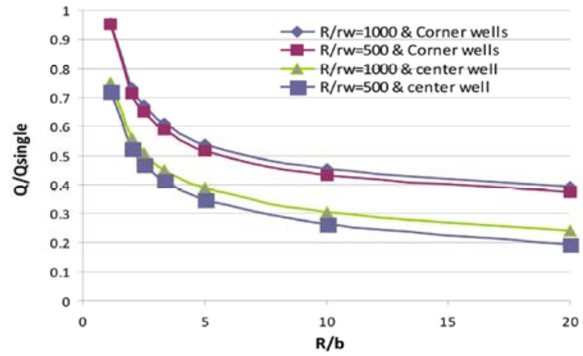

Fig. 13: Ratio of well recharge rate to single well recharge versus R/b ratio for two values R/r_w at four wells system arranged at the vertices of square and one well at the center of square.

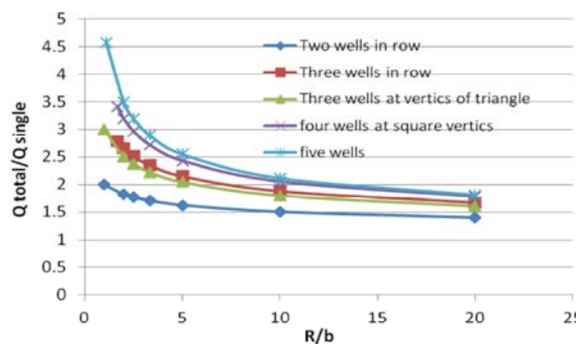

Fig. 14: Variation of total recharge rate for different wells arrangement with R/b ratio at R/r_w=1000.

For four wells forming a square, the recharge rate is the same through each of the wells. Fig. 12 shows the relation between Q/Q_{single} and R/b for two values of R/r_w. 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. 13. Also, recharge rate of the central well is less than that of corners wells.

Fig. 14 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 [3].

CONCLUSIONS

Groundwater recharge using multiple wells system is studied in this paper. Five types of wells configuration is used, i.e. two wells in line, 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:

- Arrangement method of multiple recharge wells has significant effect on recharge capacity of the system.
- The recharge rate of well operated in multiple wells system is less than that of single for all different cases of configuration.
- The recharge rate of well operated in multiple system decreases as the distance between wells decreases and as the well radius increases.
- 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 and mound height (h_w-h).
- Construction of three wells in raw gives more recharge than that of three wells at the vertices of triangle.
- Five wells at the corners and center of square gives slight increase in the recharge rate than four wells only at the corners.

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