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THE RECHARGE TRENCH AS A SUSTAINABLE SUPPLY SYSTEM

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The present day population of Indonesia is about 240 million. More than 30 percent live in urban areas under generally dense living conditions. Less than 50 percent of the urban population receives a drinking water supply for their domestic water needs. To get drinking water, most people withdraw shallow groundwater using dug wells. The storage of groundwater is decreasing due to over-exploitation. Also, infiltration of rainwater to replenish groundwater is also decreasing due to increased building density. One technique for water conservation and supply in urban areas is an infiltration system using recharge wells. In 1988 the author developed a computational formula to support this system. Similar formulas were also developed by the Public Works Department of the Government of Indonesia and the Bandung Institute of Technology. For areas with shallow groundwater, a recharge well is not highly efficient due to the small volume of storage available above a shallow water table. This paper proposes a more efficient horizontal recharge and supply system based on a recharge trench. A formula is developed analytically to calculate trench dimensions. A shape factor for the trench is proposed, based on previous shape factors of wells derived by the author. A system that combines recharge wells and recharge trenches can substitute for existing recharge well only supply systems. Due to their ability to conserve rainwater, these systems are true sustainable supply systems.

INTRODUCTION

People in Indonesia live in rural and urban areas and they use water from springs, swamps, lakes, rivers and shallow groundwater to fulfill their domestic water needs. The urban population is about 30 % of the total population, and less than 50 % have a drinking water supply. The rest of them withdraw shallow groundwater by dug wells. In the future a drastic increase in the use of groundwater in storage is predicted. Urbanization also creates an increase of impervious surface area, which in the end reduces the infiltration water to the ground. This situation will be worsened by deforestation. Rainwater will only become urban runoff, which will flow into the drainage network, rivers, and the sea with the consequence that groundwater storage will be further depleted.

Regarding this situation, Sunjoto (1989) developed a model to calculate the water balance between lost rainwater from existing drainage systems and domestic water demand for a city in Java, Indonesia, with a population of one million people, using real data as shown:

- Precipitation 2.580 mm/y
- Evapotranspiration 1.250 mm/y
- Domestic water demand 100 l/cpt/d
- Roof demand 30 m^2/cpt
- Runoff coefficient of roof 0.95
- Population 10^6 cpt (model)

a. Lost rain water from existing drainage systems.

$$\text{Volume} = 0.95 \times 30 \times (2.58-1.25) \times 10^6 = 37.9 \times 10^6 \text{ m}^3/\text{y}$$

b. Total domestic water demand.

$$\text{Volume} = 365 \times 0.10 \times 10^6 = 36.5 \times 10^6 \text{ m}^3/\text{y}$$

From the computation above, it can be concluded that a city on the island of Java, Indonesia, with a population of one million people will lose 37.9 x 10^6 m^3/y of fresh water from the existing drainage system. In the same period, the people will need as much as 36.5 x 10^6 m^3/y to provide their domestic water consumption. Based on these data, existing drainage systems should be modified by a system that allows infiltration of a volume of rainwater in the home yard by a recharge well and recharge trench as an effort for water conservation.

WATER CONSERVATION

There are two general methods of conservation. The first is by a vegetative cover like forest, jungle etc., and the second is by using an engineered structure. A recharge well is one of the engineering structure methods used to retain rainwater and recharge it to the subsurface, where it becomes groundwater in storage. There are three formulas or equations used to calculate the dimensions of a recharge well.

1. Sunjoto (1988)

Sunjoto (1988) has developed Equation (1) with a dynamic equilibrium analysis derived by integration solution as follows:

$$H = \frac{Q}{FK}\left\{1 - \exp\left(\frac{-FKT}{\pi R^2}\right)\right\} \tag{1}$$

where

H : depth of water on well (m)
F : shape factor of well (m)
K : coefficient of permeability (m/s)
T : dominant duration of precipitation (s)
R : radius of the well (m)
Q : discharge inflow (m^3/s) and $Q = CIA$
C : runoff coefficient of roof (-)
I : precipitation intensity (m/s)
A : area of the roof (m^2)

Equation (1) was derived analytically and it complies with the dimension analysis principle. When there is no rain ($I = 0$) or no house ($A = 0$), the depth of the water in the well will be equal to zero ($H = 0$), which means that it is in accordance with physical conditions.

2. Public Works Department, the Government of Indonesia (1990)

This formula was developed by using static equilibrium where the depth of water in the recharge well will be computed from the storage volume divided by the cross section area of the well. The storage volume is the inflow water in the well from the roof or any other surface minus the infiltrated water volume on the well. The equation follows:

1) Porous Cased Well.

$$H = \frac{AIT - A_s KT}{A_s + PKT} \tag{2}$$

2) Impervious Cased Well

$$H = \frac{AIT - A_s KT}{A_s} \tag{3}$$

where

H : depth of water on well (m)
T : duration of precipitation (s)
I : intensity of precipitation (m/s)
A : area of roof (m^2)
A_s : cross section area of the well (m^2)
P : cross section perimeter of well (m)

Equations (2) and (3) were derived analytically and they comply with the dimension analysis principle, but when there is no rain ($I = 0$) or no house ($A = 0$), the depth of water on the well will be different to zero ($H \neq 0$) meaning that it is not in accordance with the physical conditions.

3. Bandung Institute of Technology (1990)

The development of the equation used an empirical basis with the depth of water in the recharge well found from the storage volume divided by the cross section area of the well. The equation follows:

$$H = \frac{Ax0.7x0.9xR^{24j} - \{(\pi d^2/4)x(179/\sqrt{p})/6\}}{1000x\pi d^2/4} \tag{4}$$

where

H : depth of water on the well (m)
A : area of roof (m^2)
d : diameter of well (0,80 m to 1,40 m)
p : percolation coefficient (minute/cm)
R^{24j} : highest intensity in 24 hours (mm/d)
0.70 : runoff coefficient
0.90 : rain distribution factor
1/6 : conversion factor from 24 hours to 4 hours

Equation (4) was derived empirically and does not comply with the dimension analysis principle. When there is no rain ($I = 0$) or no house ($A = 0$), the depth of water on the well will be different to zero ($H \neq 0$), it means that it is not in accordance with physical conditions.

Recharge Trench

The recharge well is suitable for a region with the water table that is more than two meters below the ground surface. Where the area has a shallow water table, or the water table is just below the ground surface during the rainy season, the collection and recharge structure must be a horizontal trench due to the small capacity for vertical storage.

1. Forchheimer equation (1930)

The Forchheimer (1930) principle (Figure 1) was $Qo = FKh$ with the assumption that inflow discharge is equal to zero ($Q = 0$) and outflow discharge (Qo) is a shape factor (F) multiplied by a soil permeability coefficient (K) and multiplied by depth of water (h) on the casing, Equation (5). The outflow discharge is also equal to the cross section area of the well (A_s) multiplied by water thickness in a certain time, Equation 6. It follows that:

$$dQo = FKh \tag{5}$$

$$dQo = As\frac{dh}{dt} \tag{6}$$

where

Qo : outflow discharge
As : cross section area of casing
h : depth of water
t : duration of flow
F : shape factor of casing
K : coefficient of permeability

Inflow, Equation (5), equals outflow, Equation (6), so:

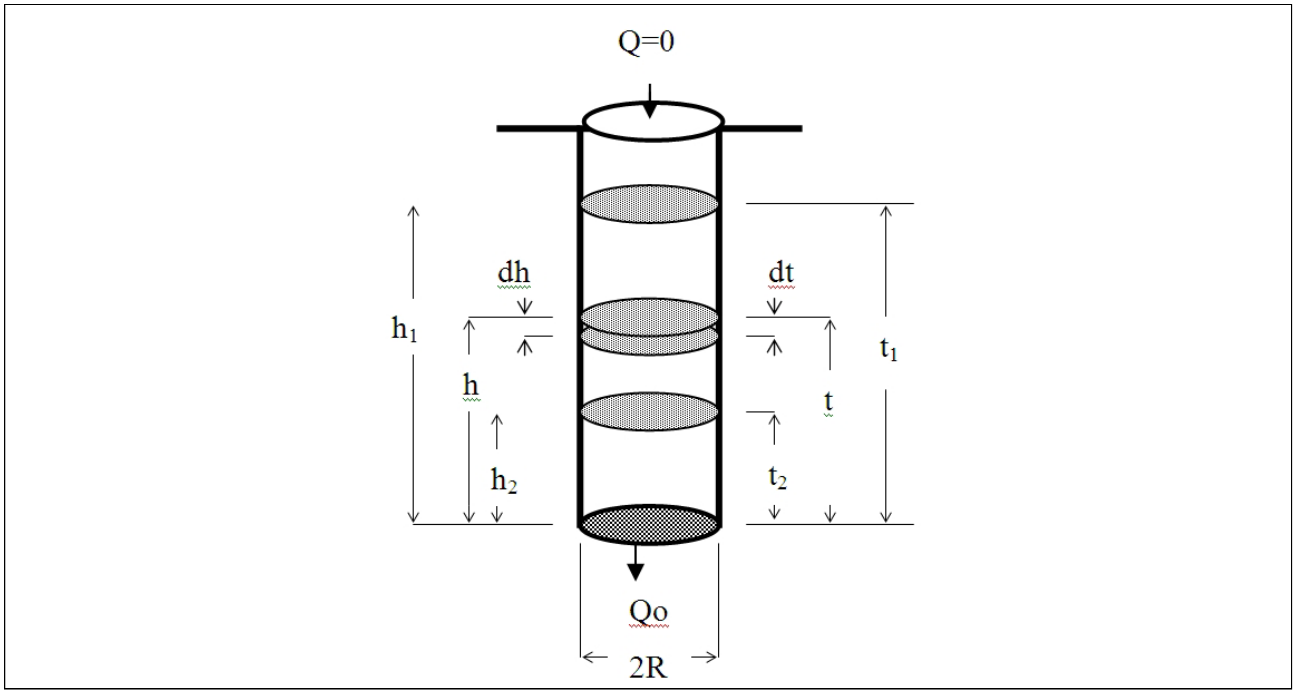


Figure 1. Sketch of water flow to the borehole (Forchheimer, 1930).

$$As\frac{dh}{dt} = FKh \Rightarrow As\int\frac{dh}{h} = FK\int dt$$

Note: $\int\frac{dx}{x} = \ln x$ and $\int dx = x$

$$As\ln h = FKT \Rightarrow As(\ln h2 - \ln h1) = FK(t2 - t1)$$

$As\ln\frac{h2}{h1} = FK(t2 - t1)$ when $A_s = \pi R^2$ so:

$$K = \frac{\pi R^2}{F(t2 - t1)}\ln\frac{h2}{h1} \tag{7}$$

where

K : coefficient of permeability (m/s)
R : radius of casing (m)
F : shape factor (m) (F = 4R (Forchheimer, 1930))
t_1 : starting time of measurement (s)
t_2 : final time of measurement (s)
h_1 : starting water depth of measurement (m)
h_2 : final water depth of measurement (m)

Proposed Equation

The proposed equation to calculate dimension of a recharge trench was developed using the principle of Forchheimer (1930). The assumption of this formula is based on the inflow discharge, which is different from zero (Q ≠ 0). Then water storage balance on the trench is as follows (Figure 2):

1). Storage volume is the difference between inflow and outflow discharge in a certain period, Equation (8).

2). Storage volume is the cross section of the trench multiplied by the thickness of the water layer, Equation 9.

$$dV = (Q - Qo)dt = (Q - fKh)dt \tag{8}$$

$$dV = Asdh \tag{9}$$

where

Q : inflow discharge
Qo : outflow discharge
Vols : volume of storage
As : cross section area of trench
h : depth of water
t : duration of flow
f : shape factor of trench
K : coefficient of permeability

Equation (8) equals Equation (9) so:

$$Asdh = (Q - fKH)dt \Rightarrow dt = \frac{Asdh}{Q - fKh} \quad \div \frac{fK}{fK}$$

$$dt = \frac{\frac{Asdh}{fK}}{\frac{Q}{fK} - h} \quad \Rightarrow \quad dt = \frac{As}{fK} \times \frac{dh}{\frac{Q}{fK} - h}$$

Solved by integration solution *dC=0*.

$$\int dt = \frac{As}{fK} \int \frac{dh}{\frac{Q}{fK} - h} \Rightarrow \int dt = \frac{-As}{fK} \int \frac{d\left(\frac{Q}{fK} - h\right)}{\frac{Q}{fK} - h}$$

$$t2 - t1 = \frac{-As}{fK} \ln\left[\left(\frac{Q}{fK} - h\right)\right]_{h1}^{h2}$$

$$t2 - t1 = \frac{-As}{fK} \left\{\ln\left(\frac{Q}{fK} - h2\right) - \ln\left(\frac{Q}{fK} - h1\right)\right\}$$

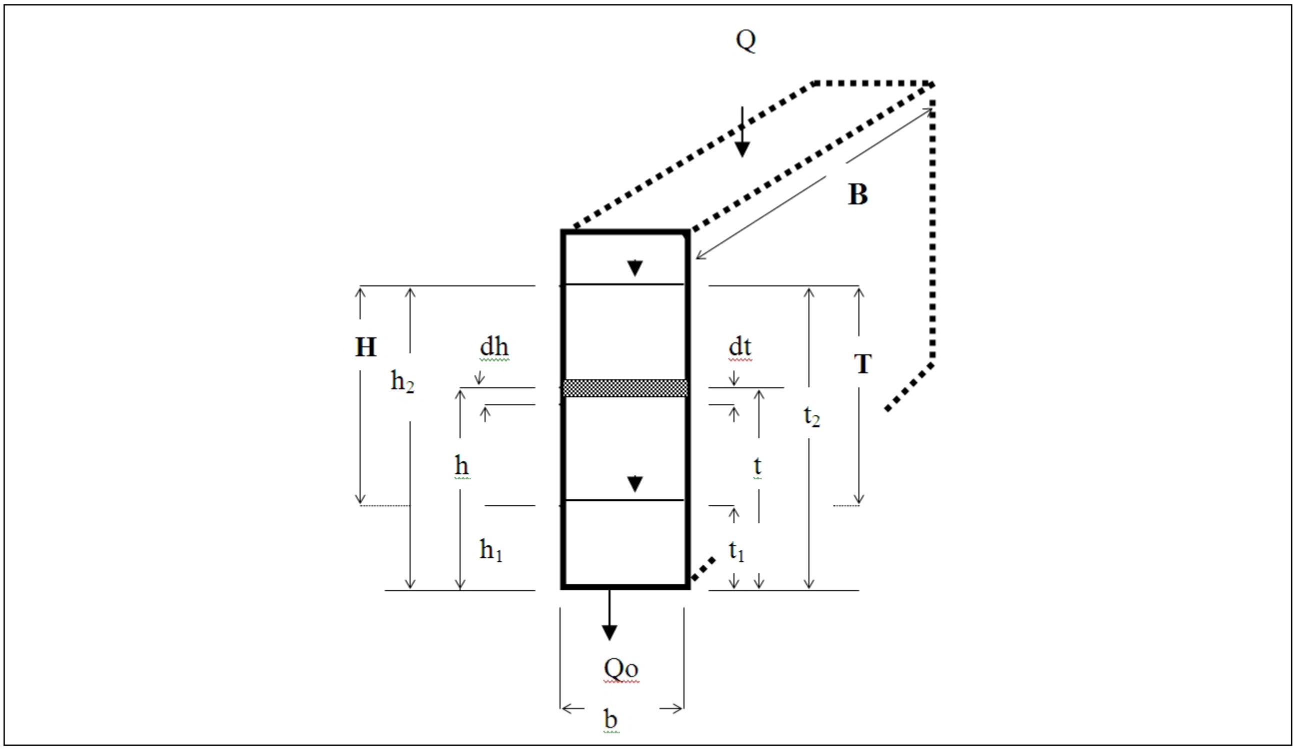


Figure 2. Sketch of water balance for the trench.

$$\frac{-fK(t2-t1)}{As}=\ln\left(\frac{\frac{Q}{fK}-h2}{\frac{Q}{fK}-h1}\right)$$

In the beginning of flow, there is no water in the base of trench, which means that $t_1 = 0$, $h_1 = 0$, and when $t_2 - t_1 = T$, $h_2 - h_1 = H$, the equation becomes:

$$\frac{-fKT}{As}=\ln\left(\frac{\frac{Q}{fK}-H}{\frac{Q}{fK}}\right) \Rightarrow \frac{-fKT}{As}=\ln\left(1-\frac{fKH}{Q}\right)$$

Note: $As = Bb$, so the length of trench:

$$B=\frac{-fKT}{b\left\{\ln\left(1-\frac{fKH}{Q}\right)\right\}} \qquad (10)$$

where

B : length of trench (m)
b : width of trench (m)
f : shape factor of trench (m)
K : coefficient of permeability (m/s)
H : depth of water on trench (m)

T : dominant duration of precipitation (s)
Q : inflow discharge (m^3/s) and $Q = CIA$
C : runoff coefficient of roof (-)
I : precipitation intensity (m/s)
A : area of the roof (m^2)

Equation (10) was derived analytically and it complies with the dimension analysis principle. When there is no rain ($I = 0$) or no house ($A = 0$), the length of the trench will be equal to zero ($B = 0$), it means that it is in accordance with physical condition.

Shape factor of trench

The value of the shape factor of the trench is represented by the length and width of the trench and defined by the soil characteristic where the trench is constructed, the form of the base of the trench, and a characteristic wall of the trench. The well shape factor has been widely developed by various researchers as curves or equations. On the contrary, the shape factor for the trench has never been developed. This paper proposes a shape factor for a trench derived from the shape factor of a well as follows:

1) The shape factor of the well multiplied by a 'shape coefficient' is the shape factor of the trench.

2) The 'shape coefficient' is a 'perimeter coefficient' multiplied by an 'area coefficient', when $b = 2R$ where R is the radius of a circle and b is side of a square or width of rectangle and B is the length of the rectangle.

3) The 'perimeter coefficient' from a circle form to a square form, is square perimeter ($4b$) divided by circle perimeter ($2\pi R$) and is equal to $4b/(2\pi R)$.

4) The 'area coefficient' from a square form to a rectangular form, is a root of the rectangle area divided by square area and is equal to $\sqrt{(bB)/b^2}$.

5) Finally, the value of the 'shape coefficient' from a circle form to a rectangular form, is equal to $4b/(2\pi R)\times\sqrt{(bB)/b^2} = 2\sqrt{(bB)}/(\pi R)$.

The shape factor of the trench is the shape factor of the well multiplied by the 'shape coefficient', $\{2\sqrt{(bB)}/(\pi R)\}$. Using shape factor values of a well (F) for each condition from Table 1, multiplied by 'shape coefficient', the shape factor values of a trench (f) can be found for the same condition and are tabulated in Table 2.

DISCUSSION

Equation (10) is not an explicit equation, so the length of trench (B) cannot be calculated directly due to the fact that the right hand side of the equation contains the shape factor (f) which consist of the parameters width of trench (b) and length of the trench (B). A trial and error method must be used to calculate Equation (10).

All values of the shape factor of a well with parameters $R = 1$, $H = 0$, $L = 0$ will be equal to the values of the shape factor of a trench when $b = B = \pi/2$, $H = 0$ and $L = 0$ except for the condition 2b. This condition, the shape factor of well, has the same values as the shape factor of the trench

Table 1. Shape factor of well.

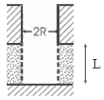
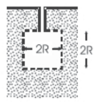
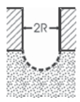
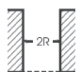
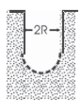
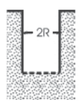
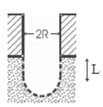
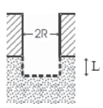
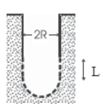
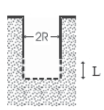
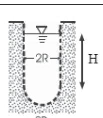
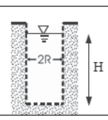
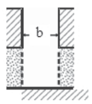
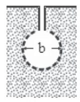
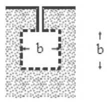
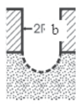
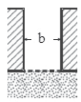
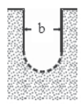
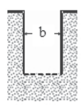
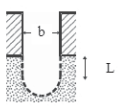
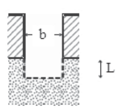
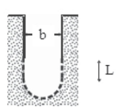
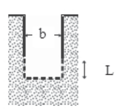
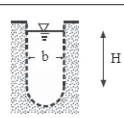
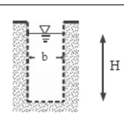
No	Condition	Shape Factor of Well (F)	Value of F when R=1; H=0, L=0 except for F_1, L=1	References
1		$\frac{2\pi L}{\ln\left(2\left(L+2R\right)/R+\sqrt{\left(2L/R\right)^2+1}\right)}$	2.980	Sunjoto, S. (1989)
2a		$4\pi R$	12.566	Samsioe, A.F. (1931) Dachler, R. (1936) Aravin, V.E. (1965)
2b		$18R$	18.000	Sunjoto, S. (2002)
3a		$2\pi R$	6.283	Samsioe, A.F. (1931) Dachler, R. (1936) Aravin, V.E. (1965)
3b		$4R$	4.000	Forchheimer, P. (1930) Dachler, R. (1936) Aravin, V.E. (1965)
4a		$\pi^2 R$	9.870	Sunjoto, S. (2002)
4b		$2\pi R$	6.283	Sunjoto, S. (2002)
5a		$\frac{2\pi L+\pi^2 R\ln 2}{\ln\left(\left(L+2R\right)/R+\sqrt{\left(L/R\right)^2+1}\right)}$	6.227	Sunjoto, S. (2002)
5b		$\frac{2\pi L}{\ln\left(L/R+\sqrt{\left(L/R\right)^2+1}\right)}$	0/0	Dachler, R. (1936)
		$\frac{2\pi L+2\pi R\ln 2}{\ln\left(\left(L+2R\right)/R+\sqrt{\left(L/R\right)^2+1}\right)}$	3.964	Sunjoto, S. (2002)
6a		$\frac{2\pi L+\pi^2 R\ln 2}{\ln\left(\left(L+2R\right)/2R+\sqrt{\left(L/2R\right)^2+1}\right)}$	9.870	Sunjoto, S. (2002)
6b		$\frac{2\pi L}{\ln\left(L/2R+\sqrt{\left(L/2R\right)^2+1}\right)}$	0/0	Dachler, R. (1936)
		$\frac{2\pi L+2\pi R\ln 2}{\ln\left(\left(L+2R\right)/2R+\sqrt{\left(L/2R\right)^2+1}\right)}$	6.283	Sunjoto, S. (2002)
7a		$\frac{2\pi H+\pi^2 R\ln 2}{\ln\left(\left(H+2R\right)/3R+\sqrt{\left(H/3R\right)^2+1}\right)}$	13.392	Sunjoto, S. (2002)
7b		$\frac{2\pi H+2\pi R\ln 2}{\ln\left(\left(H+2R\right)/3R+\sqrt{\left(H/3R\right)^2+1}\right)}$	8.525	Sunjoto, S. (2002)

Table 2. Shape factor of trench (proposed).

No	Condition	Shape Factor of Trench (f)	Value of f, when	
			b = B = π/2, H = 0, L = 0 except for f_1, L = 1	b = B = 2, H = 0, L = 0 except for f_1, L = 1
1		$\frac{4L}{\ln\left(\left(L+4\sqrt{bB}\right)/2\sqrt{bB}+\sqrt{\left(L/2\sqrt{bB}\right)^2+1}\right)}$	2.980	3.367
2a		$8\sqrt{bB}$	12.566	16.000
2b		$9\sqrt{bB}$	14.137	18.000
3a		$4\sqrt{bB}$	6.283	8,000
3b		$8/\pi.\sqrt{bB}$	4.000	5.093
4a		$2\pi\sqrt{bB}$	9.870	12.566
4b		$4\sqrt{bB}$	6.283	8.000
5a		$\frac{4L+2\pi\sqrt{bB}\ln 2}{\ln\left(\left(L+4\sqrt{bB}\right)/2\sqrt{bB}+\sqrt{\left(L/2\sqrt{bB}\right)^2+1}\right)}$	6.227	7.928
5b		$\frac{4L+4\sqrt{bB}\ln 2}{\ln\left(\left(L+4\sqrt{bB}\right)/2\sqrt{bB}+\sqrt{\left(L/2\sqrt{bB}\right)^2+1}\right)}$	3.964	5.048
6a		$\frac{4L+2\pi\sqrt{bB}\ln 2}{\ln\left(\left(L+4\sqrt{bB}\right)/4\sqrt{bB}+\sqrt{\left(L/4\sqrt{bB}\right)^2+1}\right)}$	9.870	12.566
6b		$\frac{4L+4\sqrt{bB}\ln 2}{\ln\left(\left(L+4\sqrt{bB}\right)/4\sqrt{bB}+\sqrt{\left(L/4\sqrt{bB}\right)^2+1}\right)}$	6.283	8.000
7a		$\frac{4H+2\pi\sqrt{bB}\ln 2}{\ln\left(\left(H+4\sqrt{bB}\right)/6\sqrt{bB}+\sqrt{\left(H/6\sqrt{bB}\right)^2+1}\right)}$	13.392	17.050
7b		$\frac{4H+4\sqrt{bB}\ln 2}{\ln\left(\left(H+4\sqrt{bB}\right)/6\sqrt{bB}+\sqrt{\left(H/6\sqrt{bB}\right)^2+1}\right)}$	8.525	10.856

when $b = B = 2, H = 0$ and $L = 0$, due to the fact that both have the same cross section of rectangular form. All of the values of the shape factor of a well (F) and the shape factor of a trench (f) from 'condition 1' to 'condition 7' are presented in Tables 1 and 2.

CONCLUSIONS

A recharge well is suitable for implementation in areas with a deep water table, but for an area which has a shallow water table, a recharge trench is the appropriate solution. Use of a recharge well and recharge trench together will improve recharge systems and can replace existing supply systems based only on a recharge well. This recharge system is appropriate for urban areas especially were the water table is shallow. It can become a potential water conservation method as well. Due to the fact that existing supply systems do not reflect an environmental perspective, the application of those combined recharge systems of a recharge well and trench can be seen as a 'sustainable supply system'.

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