Laboratory-Scale Investigation of Recharge Wells for Groundwater Storage

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ABSTRACT

Among several strategies proposed to increase groundwater recharge, the application of artificial recharges through wells is more applicable to Philippine setting. Laboratory-scale experiments were conducted to investigate the viability of artificial recharge by injection wells in a flow tank designed to model a confined aquifer system. Two sand aquifer thickness were simulated and the relevant hydrologic parameters were determined. Recharge was applied by injection and flow dynamics were observed to determine storage potential.

In each recharge application, the injected water gradually dispersed in an ellipsoidal shape until the entire porous medium is filled with the recharged water. The shape and behavior of the recharge plume are generally the same for all flow settings, except that the higher the injection rate, the faster it covers the whole aquifer. The rate of travel of injected water through the aquifer decreases with time. Increasing the aquifer thickness reduced the pore water pressure due to decreased confining layer thickness. The piezometric water levels increased during recharge and increases with injection rate implying storage in the aquifer.

Key Words: groundwater, confined aquifer, artificial recharge, recharge wells, laboratory-scale

INTRODUCTION

With the deteriorating quantity and quality of available surface water resources, the demand for fresh groundwater will increase dramatically. In agriculture, for example, the unreliability of water supply and the low efficiency of National (NIS) and Communal Irrigation Systems (CIS) has led many farmers to resort to shallow tubewells (STWs) for their irrigation water requirements. However, excessive groundwater abstraction to meet growing demands has led to large-scale lowering of groundwater tables, decreased seaward flow of freshwater and consequently, seawater intrusion into coastal aquifers.

One way to address this growing problem is to inject water into aquifers by some method of construction, spreading of water, or by artificially changing natural conditions and then recovering the stored water when needed, in what are known as Aquifer Storage and Recovery (ASR), or simply Artificial

Recharge (Asano, 1985; US EPA, 2005). Artificial recharge is applied in order to increase the sustainable yield, to control the groundwater level, to increase the volume of fresh groundwater available for emergencies, and/or as a barrier against inflow of saline groundwater and has the advantage of having zero evaporation (Sepúlveda and Spechler, 2004; Peters, 1998). Managed aquifer recharge (MAR) studies for groundwater storage have also been done (Bolster *et al*., 2007; Gaaloul, 2012; Masciopinto, 2013; Narayan *et al*., 2003).

Groundwater recharge studies have not been conducted in the Philippines due to the perceived inexhaustible water resources and the limited technology available. But excess rainfall stored in reservoir dams, small water impounding projects (SWIPs), small farm reservoirs (SFRs), as well as flood waters that would otherwise be lost to sea or cause flooding or soil erosion, can be stored and injected through wells to recharge aquifers. Shallow tubewells (STWs), estimated to be more than 500,000 units (David, 2003), may be converted into recharge wells by reversing the flow and injecting this excess water directly into the aquifer.

Groundwater investigations can be done through actual field studies, laboratory experiments and numerical simulations. However, large-scale groundwater flow investigations under actual field condition are very difficult, time-consuming and expensive to perform. Actual field studies require numerous observation wells and installation of sophisticated sensors at selected sites, depending on the coverage area. There is also a limited understanding of actual boundary conditions. Groundwater is practically invisible, and as such, studies of groundwater have relied on modeling techniques. Laboratory experiments and numerical simulation models provide a relatively convenient and inexpensive means to analyze groundwater flow dynamics. Numerical simulations are the current trend and state-of-the-art models that are powerful and accurate are already available. It can also be used to simulate laboratory-scale and field-scale groundwater flow conditions as well as both 2-D and 3-D scales. But these would require accurate lithologic and hydrologic data that are currently unavailable or limited.

Physical models, such as sand tanks, depend on building models in the laboratory to study specific problems of groundwater flow. These models can be used to demonstrate different hydrologic phenomena like the cone of depression or artesian flow, as well as contaminant transport and saltwater intrusion. Laboratory-scale flow tank experiments offer simple construction, easy manipulation in terms of various flow and boundary conditions, low starting cost and fast results. Several studies have been performed to analyze various groundwater flow conditions using laboratory-scale experimental setups with observable and reliable results [Ataie-Ashtiani *et al*. (1999), Zhang *et al*. (2001), Thorenz *et al*. (2002), Momii *et al*. (2005), Nakagawa *et al*. (2005), and Illangasekare *et al*. (2006), Goswami and Clement (2007) and Luyun *et al*. (2009, 2011)]. While they are useful and easy to setup, physical models cannot handle complicated real problems. They are also largely affected by scaling effects, and even minor inconsistencies in the homogeneity or compaction of the flow medium, affect the flow regime. As such, extreme care should be exercised in packing the flow medium and flow properties such as porosity and hydraulic conductivity must be determined. Nevertheless, flow tank experiments offer visual observation of actual behavior of the recharge plume, which will help understand the flow dynamics involve and facilitate analytical studies and numerical analysis.

The main objective of the study was to investigate the flow dynamics associated with the application of artificial recharge by injection wells using a laboratory-scale experimental setup. Specifically, the study aimed to: a) design, fabricate and test a laboratory-scale flow tank; b) simulate a confined aquifer system with a recharging well in a flow tank, and; c) determine the flow dynamics of recharge by injection in a confined aquifer.

MATERIALS AND METHODS

Flow Tank Setup

The setup consisted of a main flow tank, two overhead (supply) tanks, a recirculation system, and several piezometers (Figure 1). The main flow tank was designed to model a two-dimensional laboratory

-scale groundwater aquifer system. It was filled with sand of appropriate size to act as the porous medium or aquifer. The internal dimensions of the main flow tank were 60 cm length, 40 cm height, and 6 cm width. The size was designed for convenient and practical testing of most groundwater flow problems. It was neither too large as to require large amounts of sand and large quantity of water for circulation nor too small that flow dynamics would be very sensitive to even minor head gradients, yet head and flow conditions were limited. The design was adapted from the flow tank used by Luyun *et al*. (2011). The main flow tank was fabricated using 1-cm thick plexiglass so that flow dynamics could be visually observed and measured.

Fifteen holes spaced evenly 10-cm apart were drilled at the back of the porous tank to be used for drawing out or injecting water to simulate pumping or recharging, respectively, at different locations in the flow field. The mechanism for conducting pumping or recharging is inserted in one of these holes. These can also be used to insert instruments to measure other flow properties (e.g. electrical conductivity). The holes were sealed with threaded plugs if not in use.

On both sides of the main porous tank were water reservoirs with internal dimensions of 10 cm × 40 cm × 10 cm to hold and control the water flowing through the porous medium. The width of the reservoir was set larger than that of the main tank to increase the surface area of water in the reservoir and reduce sensitivity of water level to changes in flow rate. Stainless steel mesh screen with clearance of 0.2 mm were installed to separate the main porous tank from the reservoirs. Cloth nets of finer mesh were then used to cover these stainless filters, as well as the piezometer ports at the bottom of the tank, to keep the sand grains within the porous tank. Standard steel rulers (cm and mm scales) were installed along the bottom and sides of the flow tanks to facilitate direct measurement of the freshwater levels and distances between observation points.

The heads in both reservoirs were controlled by adjustable 2-cm diameter PVC drainage pipes. Perforated 2-cm PVC pipes were also installed to serve as inlet pipes for water from the overhead tanks. These inlet pipes were equipped with gate valves to regulate water flow from the overhead tanks. Shutoff walls were inserted in slots between the main porous tank and the reservoirs to separate water supply from each chamber.

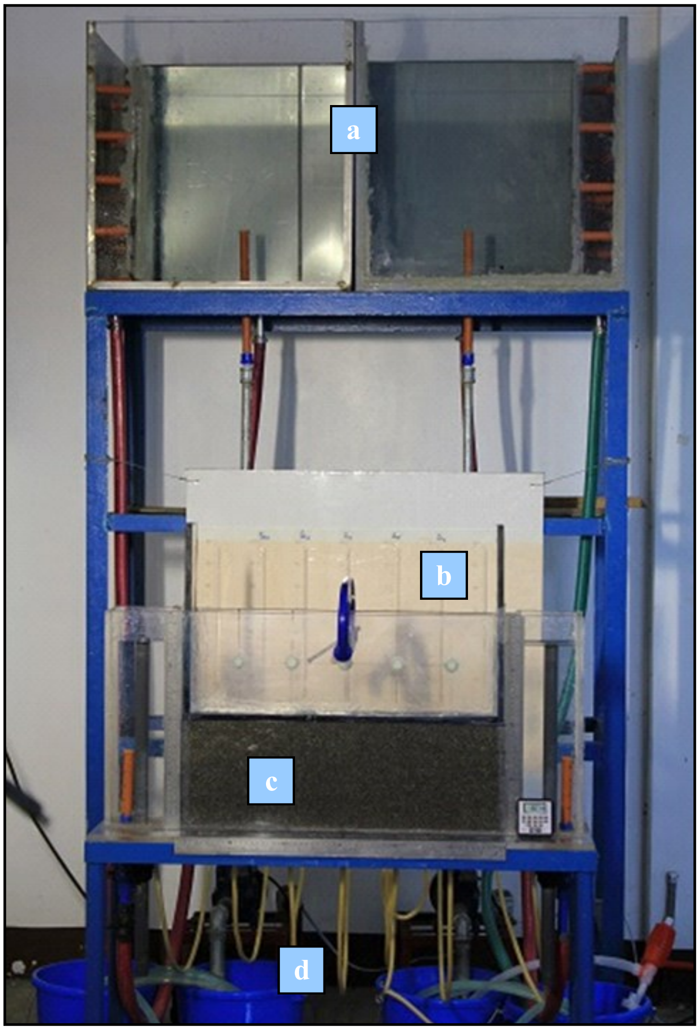


Figure 1. The laboratory-scale flow tank system - (a) Overhead tank; (b) Piezometers; (c) Main flow tank; (d) Recirculation system
(Source: Bumanglag. 2014)

Two large constant-head overhead tanks, one for each reservoir, were constructed to supply water into the system by gravitational flow. The front side of each tank was made of plexiglass for easier monitoring. Each overhead tank had an overflow weir to ensure constant head. Water that overflows from the weir and adjustable drainage pipe drain to separate containers connected by siphon hoses and the water was recirculated back to the overhead tank by a pump for each overhead tank. The pumps used were 370 W centrifugal water pumps with pumping rate of 40 liters per minute (lpm).

Tap water, stored in several 200-L containers to normalize the temperature and not directly from the tap, is used for the flow system. Piezometric water levels along the length of the flow tank were measured through manometers installed at the bottom of the tank. Drawdown and recharge curves were easily monitored through a calibrated graphing paper at the back of the manometer tubes.

Modeling the Confined Aquifer

This study was designed to simulate flows in confined aquifers with 15-cm and 20-cm thickness. Commercially available river sands were passed through No. 16 (1.18-mm) and No. 18 (1.00-mm) sieve and the sand grains retained in the No. 18- sieve were washed, cleared of impurities to be used as porous medium. The sands were packed in 5-cm layers under fully saturated condition to prevent formation of air packets. A mixing rod was used to carefully compress and homogenize each filled layer with those below to prevent any possible horizontal layering, including between the front and back face of the tank. This was repeated until the desired thickness was obtained. Careful packing was done near installed discharge/recharge pipe or instrument. A clamp was used to prevent expansion of the tank during packing and to ensure a constant width for the flow tank. Plexiglass cut into the width and length of the porous tank and fitted with rubber lining was used to press into the sand medium to form the confining layer. The sides of the main tank not filled with sand were also sealed with plexiglass and silicon sealant to ensure that water will flow only through the porous medium. The piezometric water level within the aquifer was determined by the water level on each reservoir. A leakage test was performed before each experiment. The schematic diagram of the 15-cm confined aquifer setup is presented on Figure 2.

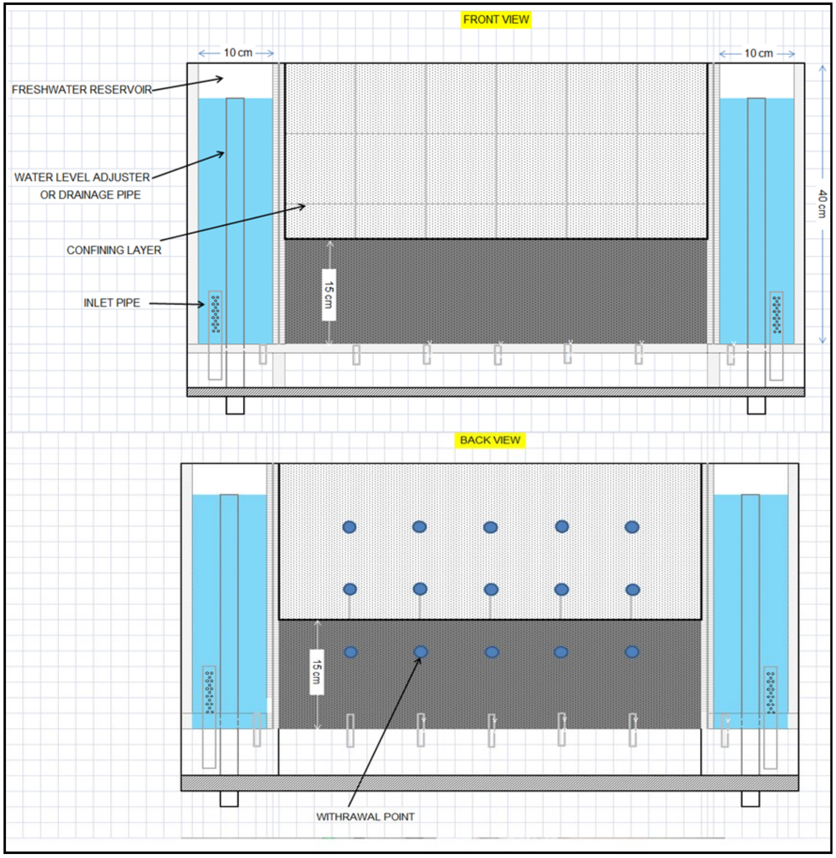


Figure 2. Schematic diagram of the 15-cm aquifer thickness setup

Determination of Hydrologic Properties

The porosity of the sand medium was determined using volumetric method while the average hydraulic conductivity of the porous medium was determined using the procedure followed by Luyun (2009, 2010). With only the right reservoir opened to supply water such that the flow was only from right to left, the hydraulic conductivity was determined at different head gradients by adjusting the drainage pipes in each reservoir. For each head gradient, flow was allowed to progress until hydrodynamic equilibrium condition was achieved and the corresponding discharge, Q on the left drainage pipe was measured using a graduated cylinder in at least three trials. The procedure was repeated using different combinations of heads on the left and right reservoirs having either 1.0 or 1.5 cm head gradients. Having constant length of flow path (60 cm) and cross-sectional area of flow: (15×6 cm^2 for the 15-cm thickness and 20×6 cm^2 for the 20 cm thickness), the hydraulic conductivity, k was computed using Darcy's equation.

$$Q = -kA\frac{\Delta h}{\Delta x}$$ *Equation 1*

where: $\boldsymbol{Q}$ = discharge;
$\boldsymbol{k}$ = hydraulic conductivity;
$\boldsymbol{A}$ = area perpendicular to flow;
$\Delta \boldsymbol{h}$ = change in hydraulic heads; and
$\Delta \boldsymbol{x}$ = length of the flow path.

A laboratory-scale pumping test was conducted to estimate the hydrologic parameters transmissivity and storage coefficient of the confined porous medium. In actual field condition, pumping test was conducted by pumping water from one well at a constant steady rate for certain time while carefully measuring the drawdowns in monitoring wells (Todd and Mays, 2005). In the lab-scale confined aquifer, an intake pipe made of 5-mm diameter copper tube spanning the entire width of the flow tank was used to model a pumping well. Small holes were drilled uniformly around the tube to ensure even inflow from all angles and covered with cloth net to prevent sand from entering. The tube for the model production well was inserted 20 cm from the right reservoir, 40 cm from the left reservoir and 10 cm from the bottom of the tank. The asymmetrical location of the well was intended to have maximum distance for water level measurement with minimum effects from the boundaries. To simulate pumping, the pipe was connected to a flexible hose with a screw-type hose clamp where the constriction can be adjusted to vary the discharge. After calibrating the desired discharge, the flow from the hose is stopped with a pinch clamp. The three piezometers at the left and one piezometer at the right of the model production well simulate the observation wells to monitor drawdown or recharge.

To simulate the pumping test in the experiment, the water level was first set at a constant depth in both reservoirs. Pumping was initiated by releasing the pinch clamp and drawdown was measured in each manometer (observation wells) at selected time intervals. Pumping was stopped when there were no more changes in the piezometric water levels indicating steady state condition had been reached.

In the 15-cm thickness, the well was pumped at three constant discharge rates equal to 20%, 40% and 50% of the total measured water discharge through the aquifer. These rates were arbitrary but should ensure that the water levels in the reservoirs are maintained. For the 20-cm thickness due to its larger storage capacity, the pumping rates were higher at 40%, 50%, and 74% of the total water discharge.

For each confined aquifer, the transmissivity $\boldsymbol{T}$, was estimated using three methods: (1) using its definition as the product of hydraulic conductivity and aquifer thickness, $\boldsymbol{T} = \boldsymbol{kb}$; (2) using steady state flow condition from the lab-scale pumping test and applying it to the Thiem equilibrium equation:

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln(r_2/r_1)}$$ (Equation 2)

where: $\boldsymbol{b}$ = aquifer thickness;
$\boldsymbol{h_1}$ = hydraulic head in observation well 1;
$\boldsymbol{h_2}$ = hydraulic head in observation well 2;
$\boldsymbol{r_1}$ = distance of well 1 from production well; and
$\boldsymbol{r_2}$ = distance of well 2 from production well

and (3) using the Theis method of superimposition based on pumping test data for unsteady state flow. Details of the procedure could be found in Kruseman and De Ridder (1990) and Todd and Mays (2005). For each aquifer thickness, the computed transmissivity values derived from each pumping test and for each observation wells, were averaged and compared with that computed using Thiem method.

Storage coefficient was estimated as the product of a constant 3 x 10^{-6} and the aquifer thickness, $\boldsymbol{b}$, in meters (Lohman, 1972 as cited by Todd and Mays, 2005). These values were then compared with the average of the values derived using Theis method for each pumping test.

Recharge Well Experiments

A small electric (3W) submersible pump was used to facilitate the injection of water into the porous medium to model a recharging well in a confined aquifer. The pump has low, medium, and high flow settings, all of which were used in the recharging experiments. The water to be used for recharge was dyed with food color at a concentration of 5 grams of dye per liter of water, to facilitate visual observation. Two scenarios were simulated in this experiment, first with a constant water level and second with a fixed hydraulic gradient. These were performed in both aquifer thickness. For the first experiment, the drainage pipes on both reservoirs were adjusted to maintain constant head of 35 cm or zero hydraulic head ($\Delta h = 0$). For the second experiment, the left and right drainage pipes were adjusted to 35 cm and 36 cm, respectively, or a 1 cm hydraulic gradient ($\Delta h = 1$ cm). Prior to the start of each experiment, normal circulation of water was initiated and stabilized. For the constant head scenario, both left and right circulation pumps were used to maintain constant water level on both reservoirs. The discharge at each reservoir prior to recharging was measured. The recharge water was dyed with strawberry red food color for the 15 cm and blue food color for the 20 cm thickness. The pump discharges at 15 cm thickness for low, medium, and high setting were 1.32, 1.80, and 2.23 m^3/day, respectively. For the 20 cm thickness, the discharges were 1.38, 1.94, and 2.27 m^3/day.

Prior to each recharge simulation, the injection rate was measured and the initial piezometric levels were checked to be equal to the level corresponding to the flow setting. During recharging, the piezometric water levels were measured at different time intervals until no more changes were observed indicating that apparent steady state condition was achieved. Drainage discharges from the reservoirs were also measured at regular intervals to check for changes corresponding to pressure increases. A camera was used to take pictures of the porous medium at regular intervals during the injection process.

A separate experiment applying constant head recharge was also performed as an alternative to the constant recharge rate. A 500-ml Mariotte bottle was filled with dyed water and calibrated to the designed pressure head. For the experiment, the time to inject 500-ml of dyed water to the porous medium was measured for a given pressure head, h_m. Pressure heads of h_m = 38, 39 and 40 cm were used for recharge injection. The piezometric levels were recorded every minute and a camera was used to take pictures of the porous medium each time.

RESULTS AND DISCUSSIONS

Determination of Hydrologic Properties

Based on the particle size diameter of 1.0 mm, the sand is classified as coarse sand and the porosity was determined to be 0.49 ± 0.01 and falling under well-sorted sand (Meinzer, 1923 and Davis, 1969). The calculated average hydraulic conductivities of the 15-cm and 20-cm thick porous media were 0.66 and 0.73 cm/s, respectively. The discrepancy may be attributed to the different degree of packing in each model aquifer with the thicker aquifer being more difficult to compact. It should be noted that the model confined aquifer was assumed to be homogeneous and isotropic that at any point in the medium, the values of saturated hydraulic conductivity were independent of the direction of measurement. In the actual field, it is expected to be anisotropic in which the vertical component of the saturated hydraulic conductivity is usually higher (about one to two orders of magnitude) than the horizontal component (Chen, 2000).

Transmissivity is a measure of the potential discharge rate of wells penetrating a confined aquifer and its magnitude is an indication of the economic value of an aquifer as a source of water supply. Using the equation $T = kb$, the values of transmissivity for the 15-cm and 20-cm aquifer thickness were computed to be 85.1 and 126.14 m^2/day, respectively. Transmissivity values were also computed from the steady state pumping test data using Thiem equation. The final and constant drawdowns from the single observation well at the right (R1) and the second farthest observation well at the left (L2) of the production well were used. Table 1 summarizes the results showing an average T of 83.38 m^2/day with a standard deviation of 4.94 for the 15-cm thickness and 125.47 m^2/day and standard deviation of 6.19 for the 20-cm thickness. These were comparable to the values computed using the equation and both were computed with the assumption of steady state condition.

Using the Theis superimposition method on the transient data of the lab-scale pumping test, the computed values of and vary widely with distance of observation well and with percentage of flow. The values obtained using drawdown data from the

Table 1. Computed Transmissivity using Thiem equation

THICKNESS (CM)	OBSERVATION WELLS: R1-L2		T (m^2/day)
	Pumping Rate (% of Total Flow)	Q(cm^3/s)	
15	20%	4.63	88.34
	40%	17.49	83.35
	50%	20.59	78.46
		AVE	83.38
		SD	4.94
20	40%	9.68	122.98
	60%	13.90	132.52
	74%	19.03	120.92
		AVE	125.47
		SD	6.19

farthest observation well (piezometer 40 cm from production well) were observed to be very high indicating that the constant water level at the left reservoir acted as a positive boundary similar to a river bounding a well. The reservoir provided an effective line of recharge such that the cone of depression (drawdown curve) cannot spread beyond the reservoir. It is as if an imaginary recharging well is present. The same can be said for the results obtained from the single observation well at the right. The least affected were the results obtained from the nearest piezometer to the left, wherein the transmissivity values on both modeled aquifer thickness, were the only ones within 10% of the results from the steady state equations. The computed values were 76.35 and 112.92 m^2/day for the 15-cm and 20-cm thickness, respectively. Of course, a major factor here is the limited boundaries of the flow tank such that the assumption of extensive or infinite areal extent of the aquifer is not valid in this setup. Some other considerations include the sensitivity of the flow tank, the limited data points resulting to more subjectivity and possible human error in superimposition and finding the match point.

Storage coefficient or storativity is a confined aquifer's water yielding capacity. It is defined as the volume of water released or added per unit area of aquifer per unit drop or rise in head or pressure. Storage coefficient normally varies with aquifer thickness and based on the rule-of-thumb relationship used by the U.S. Geological Survey (USGS) (Lohman, 1972 as cited by Todd and Mays, 2005), the computed values for the 15-cm and 20-cm aquifer thicknesses are 4.5×10^{-7} and 6×10^{-7}, respectively. These values are very small compared to actual field values which would range between 10^{-5} to 10^{-3} but this is due only to the laboratory scale condition applied in the study. The storage coefficient values obtained using drawdown data from the lab-scale pumping test, again reflect the same boundary effects as in the transmissivity values. Moreover, since the values are quite small given the thin layer used, the values are greatly amplified even by minor flow perturbations. Using only the values from the L1 piezometer (where the average transmissivity was also obtained), the average Sc were computed to be 2.15×10^{-7} and 6.63×10^{-7} for the 15- and 20-cm thickness, respectively. Using all computed values, the average is 2.86×10^{-7} for the 15-cm and 6.10×10^{-7} for the 20-cm thickness.

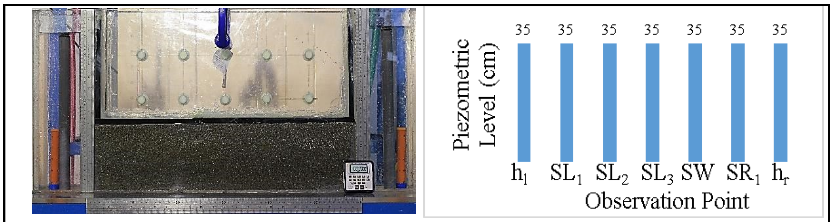
Effects of Aquifer Thickness

Figure 3 shows the initial flow condition, the behavior of the recharge plume at different time intervals for low recharge rate (Q = 1.32 m^3/day), and the piezometric water levels for the 15-cm thick aquifer with no flow gradient (Δh = 0). At the onset of recharge, the injected water initially radiated in a circular formation from the point of injection as the recharge flows in all direction around the recharge tube. The recharge plume gradually dispersed in an ellipsoidal shape, spreading progressively at a slower rate until the plume covered the entire porous medium after about 15 min. This dispersion phenomena constitutes a non-steady, irreversible mixing process with the surrounding water. When the recharge rate was increased to medium (Q = 1.80 m^3/day) and high flow setting (Q = 2.23 m^3/day), the recharge plume generally followed the same pattern and behavior but completely covered the tank in only 10 min.

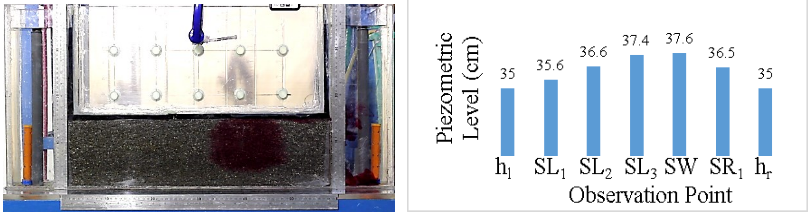
The induced recharge increased the pressure head at the point of injection as shown in the piezometer readings. Starting at a constant head of 35 cm, the piezometric levels increased reaching a maximum of 37.7 cm at the recharge well and gradually decreasing with distance from the injection point. For the medium and high recharge rates, the maximum water levels were 37.8 and 38.2 cm, respectively. An increase in piezometric water level indicates storage (Driscoll, 1986). Thus, as the recharge rate is increased, more water is stored in the aquifer. In actual field conditions, however, groundwater flows from high to low hydraulic pressure seeking the easiest way through the circumference of the well (Central Ground Water Board, 2007). This explains why the recharged water was observed to travel faster at the roof of the aquifer.

It was also observed during the high recharge setting that bubbles formed at the porous medium. In actual field condition, recharge water may carry large amounts of dissolved air, tending to reduce the permeability of the aquifer by air binding. Air binding is also caused by the cavitation of recharge water (Todd and Mays, 2005). This may explain the reduced spreading of the recharge plume with time. The reduction in permeability was confirmed when the computed hydraulic conductivity after each set of experiments were found to be less than the value at the start of the test. As such, extreme care must be observed to avoid over recharging as it may reduce the permeability, cause leakage through the confined aquifer and may even result in the collapse of the well.

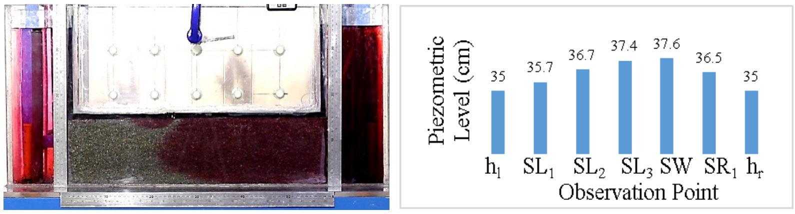
The results of the recharge experiment on the 15 cm aquifer with a hydraulic gradient of 1 cm showed that the general flow pattern and behavior of the recharge plume was the same as that with no gradient. The entire porous medium was covered in just 12 min in the low recharge rate which was faster than the results with zero gradient. The medium and high recharge rates, however, easily overcame the flow gradient and the recharge plume covered the porous medium in only 10-min, similar to the results in zero gradient for the same recharge rates. While it was also observed that piezometric water levels, and thus groundwater storage increased with increasing recharge, the storage capacities were limited compared to that with zero gradient. The maximum observed piezometric water levels at Δh = 1 cm for the three recharge rates, low, medium and high were 36.6, 37.2 and 37.7 cm, respectively.



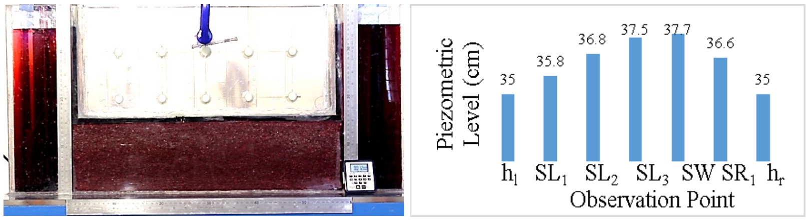
(a) Initial condition



(b) After 1 minute



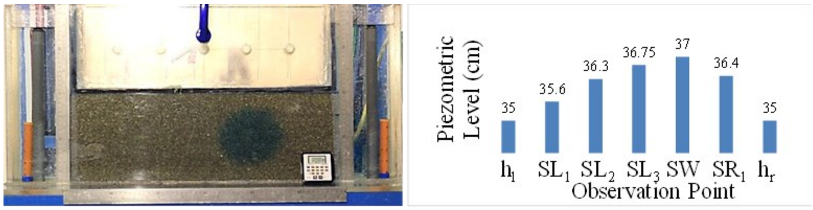
(c) After 5 minutes



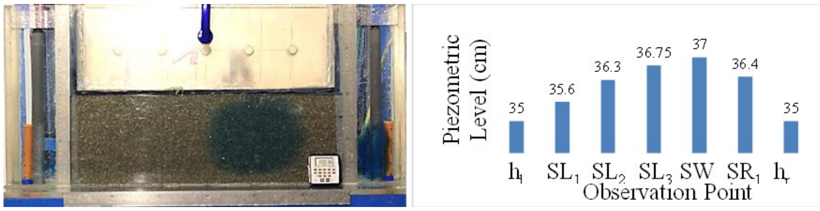
(d) Final condition

Figure 3. Behavior of recharge water at Q = 1.32 m^3/day, b = 15 cm and Δh= 0 cm, including corresponding piezometric water levels. (Source: Luna, 2014)

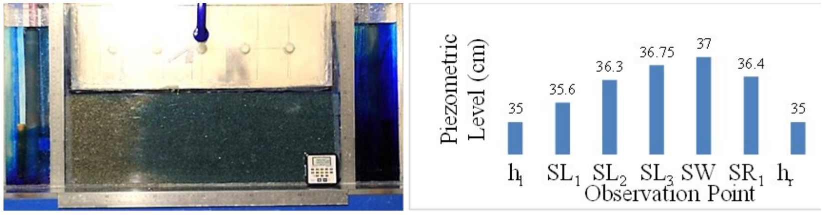
For the 20-cm thickness, the behavior of the recharge plume when recharge was applied at medium rate (Q = 1.38 m^3/day) with no flow gradient is shown in Figure 4. The injected recharge was dyed blue to distinguish it from the actual aquifer flow. In general, the behavior and pattern of flow of the recharge plume was the same as that in the 15 cm thickness for low, medium and high recharge rates. Since the injection point was effectively at the center of the aquifer, the circular pattern of dispersion was clearly visible. The times



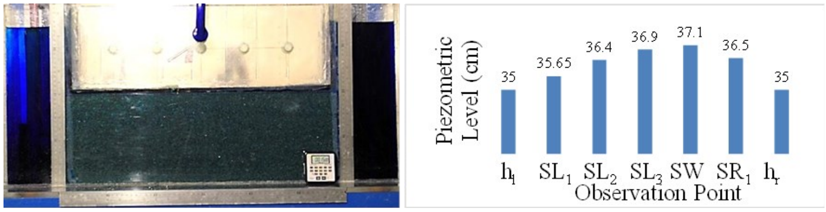
(a) After 30 seconds



(b) After 1 minute



(c) After 5 minutes



(c) After 5 minutes

Figure 4. Behavior of recharge water at Q =1.95 m^3/day with b = 20 cm and Δh = 0 cm.
(Source: Luna, 2014)

for the recharge plume to fully cover the aquifer for the three recharge settings were the same for both Δh = 0 and 1 cm. There were slight increases in the maximum piezometer readings in the 1-cm gradient for the low and medium recharge settings but they were practically the same for the high recharge rate.

Comparing the results from the 15- and 20-cm aquifer thickness at zero head gradient, it can be observed that higher piezometric water levels were observed for the 15 cm aquifer in all flow settings. There were no significant differences, however, with the 1-cm gradient. A greater aquifer thickness should have required more time to fill up the porous medium due to the increased storage space. But since the reservoir water level was the same for both, the piezometric water pressure at the upper layer of the 20-cm aquifer is less, effectively offering less resistance to flow. Moreover, the measured hydraulic conductivity in the 20-cm is greater than that in the 15-cm thick aquifer, which explains the faster spreading of the recharge plume to offset the larger aquifer space to cover.

In a confined aquifer, total storage is increased as pressure increases because the granular skeleton expands to create more void spaces. In contrast, if water is removed from the confined aquifer and the pressure decreases, so is the storage space as the granular skeleton compresses under its own weight. If water is removed from the confined aquifer, the hydraulic head decreases. This is observed during pumping test when the water level in manometers falls because of increasing amount of extracted water and storage space decreases. The amount of water that is absorbed or expelled from the aquifer is determined by the changes in water volume and porosity that resulted from the change in pressure.

Effect of Recharge Rates on Groundwater Storage

Groundwater in confined aquifers is under artesian pressure because of the confining layer on top. One problem in studying groundwater storage is the inability to directly measure the increase in the piezometric level in the aquifer. In this study, the piezometric level was measured through the manometers. Any increase in the piezometric levels indicates storage (Goulburn-Murray Water, 2003). If water is injected into a well, a cone of recharge will be formed that is similar in shape but is the reverse of a cone of depression surrounding a pumping well. This cone is referred to as cone of impression or the cone of recharge. The equation for the curve can be derived in a similar manner to that for a pumping well as shown in Thiem equation.

Using this equation and applying the constant recharge as well as various aquifer parameters derived from the same setup, a theoretical plot of the actual cone of impression was generated. This was done in all experiments at zero head gradient. The values of ***T*** used for the computation is 83.38 m^2/day and 125.47 m^2/day for the 15 and 20 cm thickness, respectively. The plot of the theoretical and actual cone of impression at various recharge rates for the 15 cm and 20 cm thickness are shown in Figure 5 and 6, respectively. The observation points are located at each of the seven piezometer tubes, one each on the left and right reservoir, and five equally spaced in the main flow tank.

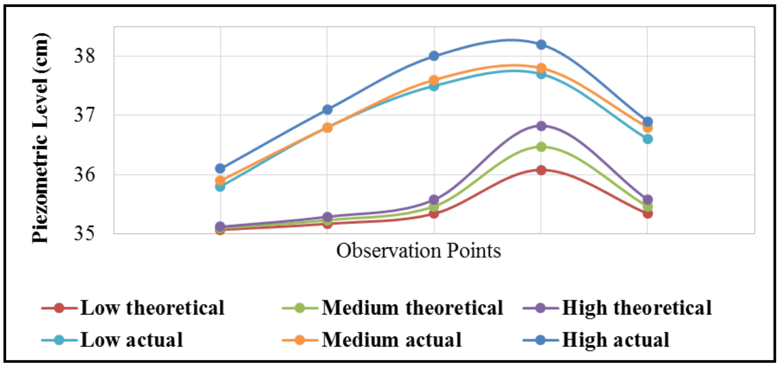


Figure 5. Theoretical and actual cone of recharge with b=15cm (Source: Luna, 2014)

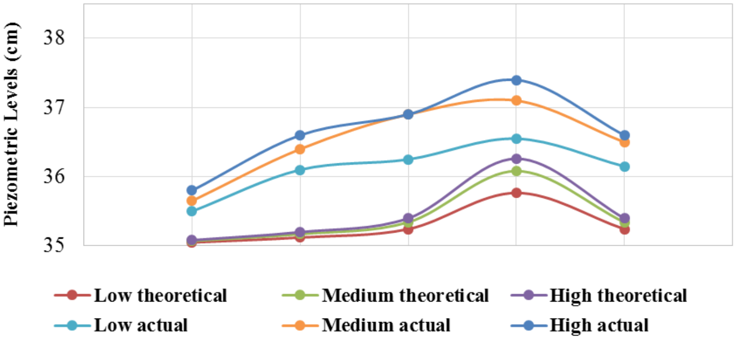


Figure 6. Theoretical and actual cone of recharge with b=20cm. (Source: Luna, 2014)

The plots show that the theoretical cones of recharge follow a definite pattern with a high recharge rate near the well that progressively decreased with distance from the recharging well as predicted by the Thiem equation, in reverse. The actual cones of recharge for both aquifer thicknesses are greater than the theoretically predicted patterns. Several factors can be attributed to this behavior but they can be summarized as due to the effect of limited boundaries. The equation used is based on radial flow in a pumping/recharge well. The assumption of infinite boundary does not apply to this setup. Though it was assumed that the porous medium was isotropic, change in hydraulic conductivity can result to increase in the discrepancy of actual values. Most common reason of change in hydraulic conductivity is that non-spherical sand particle is orienting their long axes in horizontal direction during the deposition (Vols, 2001).

Another possible reason is that the original equation assumed a fully penetrating well whereas recharge in this experiment was applied at a point, and this partial penetration contributed to the difference. Moreover, the reservoirs on both sides of the porous tank acted as a positive recharge boundary, contributing further recharge to the system.

A recharge well's flow is the reverse of a pumping well, but its construction may or may not be the same. Well recharging is practical where deep, confined aquifers must be recharged, or in urban areas, where the economy of space is an important consideration. However, excessive compression of aquifer materials by over pumping is mostly irreversible (Bouwer 1978, and references therein). By comparing the discharge equations for pumping and recharge wells, it can be anticipated that the recharge capacity would equal the pumping capacity of a well if the recharge cone has dimensions equivalent to the cone of depression. However, field results rarely support this reasoning, recharge rates seldom equal pumping rates (Todd and Mays, 2005).

Based on the theoretical equations for confined aquifers, head changes linearly with changing discharge. The piezometer level behaves linearly which can be related to the stabilization of pressure within the aquifer. At the onset of injection, there has been a change in pressure. The pressure inside the aquifer suddenly increased which induced higher velocity but as the pressure stabilizes, the rate of dispersion decreases. In areas where excess surface water is available during rainy season and the phreatic aquifers remain unsaturated, surface water can be pumped into the dug wells for augmentation of ground water resources. Wells with higher yields before getting dried up due to the desaturation of aquifers should be selected for recharge as they prove to be more suitable for ground water recharge when compared to low yielding wells (Central Ground Water Board, 2007).

Recharge by Differential Pressure Heads

In addition to specially designed injection wells, existing dug wells and shallow tube wells may be alternatively used as recharge wells particularly in areas where considerable de-saturation of aquifers has already taken place due to over-exploitation of ground water resources resulting in the drying up of dug wells and lowering of piezometric heads in tube wells.

This experiment was conducted in order to determine what pressure head maybe required to recharge a confined aquifer naturally or by gravity alone. The hydraulic condition on the left and right reservoirs were 35-cm and 36 cm, respectively; for a 1-cm head gradient. For each height setting of the Mariotte bottle, the test ended when 500 ml had been injected. The results show that no recharge was recorded at 36 and 37 cm pressure head setting, in both 15-cm and 20-cm aquifer thickness. Recharge started at 38 cm in both aquifers and increases in the piezometric water levels were recorded. Figures 7 and 8 show the final recharge cones after recharge injection at different pressure heads. Similar to Figures 5 and 6, the observation points are at the location of the piezometer tubes. The results showed that a sufficient pressure head is needed to be able to naturally inject water in an open hole or well and that the higher the pressure head, the higher the readings in the piezometers. The recharge head available in gravity recharge wells is the elevation difference between the surface water level in the feeder reservoir and the water table or piezometric head. The recharge rates in such cases are likely to be much less when compared to pressure injection and will also keep on reducing with build-up of the water table in the aquifer (Central Ground Water Board, 2007).

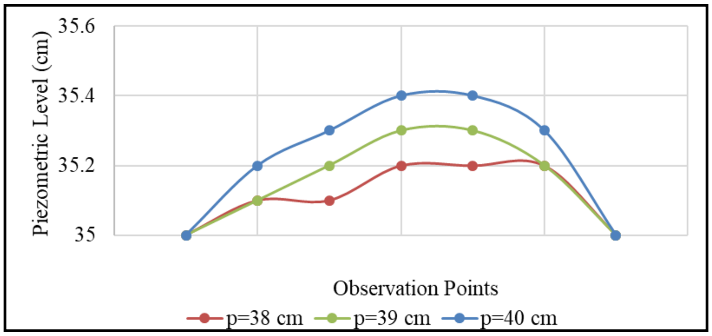


Figure 7. Piezometric levels at different observation points at different pressure heads with *b* = 15 cm and *Δh*= 1 cm.

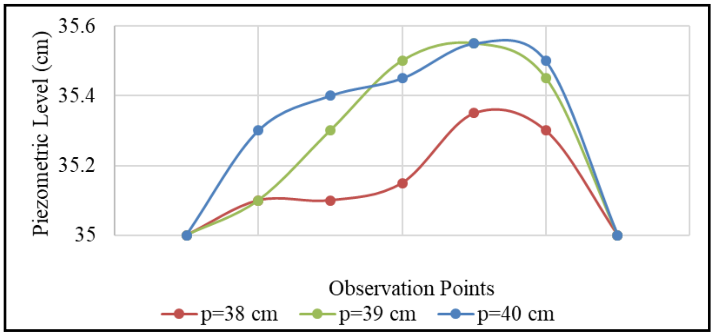


Figure 8. Piezometric levels at different observation points at different pressure heads with *b* = 20 cm and *Δh*= 1 cm.

Theoretically, the pressure head due to the weight of the injected water must overcome the piezometric pressure of the aquifer. For a laboratory-scale experiment, a small diameter injection pipe and hose may have large effect due to capillarity and surface tension effects. In actual field conditions, it can be said that naturally recharging dug wells would be more effective than using tube wells.

Many problems accompany the injection of water into an aquifer. The thickness of confining layer over pervious formation limits recharge methods applicable in an area. Simple spreading may be used where the aquifer is exposed at the surface (unconfined aquifer). Trenches or variously shaped pits may be used when the aquifer is found at a relatively shallow depth. Tube wells are necessary, however, where the depth of the impermeable cover makes the pit or trench method impractical or too costly. Pressure injection wells have been most commonly used for these deep formations. This type of well has an advantage in that it may be used as a production well and as a recharge well. Factors that tend to reduce the effectiveness of pressure injection wells are: the "air binding" of the aquifer, which results from gases released from the injected water; the restructuring of the aquifer due to the pressure and velocities inherent in the system; and the penetrating of solids deep into the aquifer that reduce the permeability of the formation. Other problems associated with recharge systems are biological clogging and movement of chemical and bacterial pollution. Problems such as these must be evaluated through continuing research in the laboratory and in full-scale field experiments (Skodje, 1971).

CONCLUSION

A flow tank was designed and fabricated to be used for laboratory-scale groundwater flow analysis. The laboratory setup included a main flow tank, two overhead supply tanks, a water circulation system, and piezometers. The main flow tank was designed to model a quasi-2-dimensional cutaway view of a confined aquifer flow systems. The setup was used to investigate the flow of injected recharge water through a confined aquifer. Two aquifer thicknesses were modeled using sand with a nominal diameter of 1.0 mm as the porous medium. For each aquifer thickness, flow conditions with a constant piezometric water level and with a head gradient of 1-cm were simulated. Aquifer hydrologic constants such as porosity, hydraulic conductivity, transmissivity and storage coefficients, were effectively determined and checked with theoretical values. Recharge was applied by injection using a small pump at different flow settings. For each recharge injection, the flow dynamics were observed and the piezometric water levels were recorded to determine the storage potential.

Simulation of a confined aquifer with a recharge well was made possible through the lab-scale setup facilitating the study of the flow dynamics of artificial recharge. In each recharge application, the injected water initially radiated in a circular formation from the point of injection, then gradually dispersed in an ellipsoidal shape until the entire porous medium was filled with the recharged water. Generally, the behavior of the injected water and its shape are the same for different flow settings: low, medium and high differing only in the time to completely cover the porous medium. The higher the injection recharge rate, the faster it covers the whole aquifer. Increasing the aquifer thickness effectively increases the storage capacity but the general pattern and behavior of the injected water and the time to cover the entire aquifer were the same.

Increases in the piezometric water levels were observed during injection and as recharge increases, the piezometric water levels also increase. This implies that groundwater is stored throughout the aquifer. There were however observed decrease in piezometric water levels in the experiments with head gradient. But this should not be translated to decrease storage potential but that the injected water are being carried by the increased velocity of flow caused by the hydraulic gradient.

It can also be observed that the rate of travel of injected water decreases with time and bubbles accumulate at the porous medium, especially after injection at large recharge rates. This is similar to air binding in actual field condition, which tends to reduce the aquifer permeability. The reduction in permeability was confirmed by the decrease in computed hydraulic conductivity after experiment.

In recharging by gravity, a sufficient pressure head is needed to inject and store water in confined aquifers. Theoretically, the weight of the injected water must be greater than the piezometric pressure of the aquifer to effect natural recharge and storage.

Another important observation was that the injected water was observed to spread faster at the roof of the aquifer already seeping to the reservoirs even if the recharge plume had not yet spread through to the end of the porous medium. In actual field conditions, groundwater flows from high to low hydraulic pressure thus it seeks its easiest way through the circumference of the well. While it was observed that groundwater storage increases with increasing recharge, this will be limited to the storage capacity of the aquifer. Thus, extreme care must be taken in applying high recharge rates in confined aquifers because it may destroy the well, cause leakage through the confined aquifer and result in well collapse.

RECOMMENDATIONS

The following recommendations were made based on the results of the study:

1. For better visual presentation of the dispersion of injected water, the porous medium must be made of white sand grains or glass beads.
2. The pump to be used for injection must have adjustable discharge rates to be able to control the injection rates.
3. A longer experimental setup may be needed to reduce the effect of limited boundary and positive recharge from the reservoirs. Numerical simulation is a recommended alternative (e.g. MODFLOW).
4. Follow-up studies on unconfined, leaky and other non-idealized conditions may be conducted.

ACKNOWLEDGEMENT

The authors would like to thank the Center for Agri-fisheries and Biosystems Mechanization (BIOMECH), College of Engineering and Agro-Industrial Technology (CEAT), University of the Philippines Los Baños (UPLB) for funding this faculty-based project.

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