# Estimating the Yield of a Collector Well with Parallel Infiltration Galleries as Laterals

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**Abstract –** *In recent years, collector well with horizontal laterals is being used more often to tap groundwater resources. However, at the moment, majority if not all yield studies are focused on collector wells with radial orientation of laterals. In countries where trenchless technology is still uncommon, like in the Philippines, collector wells either have a single long lateral or parallel laterals. This paper presents applicable yield estimation techniques for collector wells with parallel laterals in the riverbed. The first method uses a source-sink pair model and image well theory, obtaining an approximate analytical solution. The second makes use of MODFLOW, a numerical approach to come up with a local groundwater model. The estimates from both are found to be in good agreement with actual yields measured in a study area. The developed equations can be used for rapid estimation of yield to other candidate sites. Although the MODFLOW model produced more accurate results than the approximate analytical method, it should also be used with caution as the estimates are usually greater than the actual, which can pose a problem for water supply development.*

*Keywords—collector well, infiltration gallery, horizontal well, water supply*

## I. INTRODUCTION

In recent years, collector well with horizontal laterals is being used more often to tap groundwater resources. This well can produce higher yield under the same drawdown level [1] and has less risk of saltwater intrusion in coastal areas [2] as compared to a conventional vertical well. It can also extract water from shallow but highly permeable aquifers [3]. For collector wells with laterals at or near riverbeds, well operation triggers riverbank filtration process which significantly improve the quality of pumped water in terms of turbidity and contaminant concentration [4, 5].

The amount of water that can be extracted, or the yield, is one the most important considerations for any water supply intake. For collector wells, several yield estimation methods had been developed through the years. One of the earliest ways is to assume that the whole assembly is equivalent to a hypothetical vertical well with effective radius that must be solved empirically [6]. Hantush and Papadopoulos [7] first described analytically the head and flow distribution around radial collector wells using boundary-value analysis in line-sink elements. The same general concept was used by Analytic Element Method (AEM) to represent horizontal wells [3, 8, 9]. Liongson [10, 11] provided a simple approach to develop a 2-dimensional steady-state flow equation of a single horizontal well using a source-sink pair under constant head. By direct use of analytic geometry of circles and algebraic manipulation of potential function, he obtained the same results as Kolymbas and Wagner [12].

 

Another method of estimating the yield is through numerical groundwater models. Numerical approach in groundwater works by dividing the system into smaller units and applying the basic groundwater equation with varying mathematical assumptions in discrete points. For instance, Finite Difference Method (FDM) approximates through simple difference equations the differential equations of groundwater flow. The most widely used model and considered a standard for numerical groundwater analysis is the FDM algorithm developed by United States Geological Survey (USGS), the MODFLOW. MODFLOW is used in research and engineering industry alike for numerous groundwater applications including but not limited to subsurface flow and pollution modeling [13]; estimation of aquifer parameters [14]; and simulation of salt/freshwater interfaces in coastal aquifers [15]. Similarly, MODFLOW can be used to model horizontal wells and estimate the yield through the flow budget. The drain package can be assigned to horizontal wells. With specified head or elevation, the head difference between the drain node and adjacent cells can be calculated and will be the basis for yield. A case study in Kelantan, Malaysia is an example of this application [5]. For MODFLOW models adapting the Dupuit-Forcheimer assumption, the yield in horizontal wells can be overestimated using the drain package [16]. This is because the resistances at the entrance of the gallery can't be properly described by simply discretizing. The converging flow near the wells must be considered, which can be done through Haitjema's [16] resistance formulation.

It is notable that at the moment, majority if not all yield studies are focused on collector wells with radial orientation of laterals. However, there are times when other configurations are better especially if the construction will be done by digging or trenching. For instance, maximum yield can be obtained by placing all laterals beneath the riverbed, and each lateral must be as far as possible with each other given a limited area. In this case, parallel laterals are better. In countries where trenchless technology is still uncommon, like in the Philippines, collector wells either have a single long lateral or parallel laterals. As there is no official standard with regards to hydraulic design of collector wells [17], yield predictions are usually based from crude estimations, resulting to poorly designed systems.

This paper aims to develop applicable yield estimation techniques for collector wells with parallel laterals in the riverbed. The first method uses a source-sink pair model and image well theory, obtaining an approximate analytical solution. The second method models a small portion of the aquifer using MODFLOW. Flow from actual collector well is compared to the estimates obtained to test the validity of both methods. This study can serve as a guidance for designing collector wells of similar configurations, and for detailed assessment of existing ones.

## II. METHODOLOGY

### *2.1 Study Area*

The study area is located in Calaca, Batangas, Philippines. The area has a distinct dry and wet season. The dry spell is from December to April when, in most cases, there is zero rainfall in two (2) to three (3) consecutive months. The rainy period is June to October, while May and November are seasonal transition months from dry to wet season and vice versa.

The collector well provides freshwater supply for a coal-fired thermal power plant. It has four (4) parallel 18-m long perforated pipes placed at approximately 4 m below the riverbed of Dacanlao River. These pipes are connected independently to solid pipes conveying water to the collector well. Each lateral is surrounded by gravels while the sands in the vicinity are enclosed in a series of geotextile bags. This setup enables maintenance or replacement of a lateral without affecting the others by building a cofferdam around it.

### *2.2 Hydrogeologic Investigation*

Batangas Province is dominated by quaternary volcanoes and their associated pyroclastic deposits. It occupies a generally floodplain environment belonging to the vast Batangas Plain. This plain is predominated by quaternary ash deposits named Taal Tuff, named after a local volcano. Deposits of Pleistocene Reef Limestone are confined along shorelines. Recent alluvium covers areas along the coast and floodplains of large streams. These quaternary alluvial deposits are characterized by

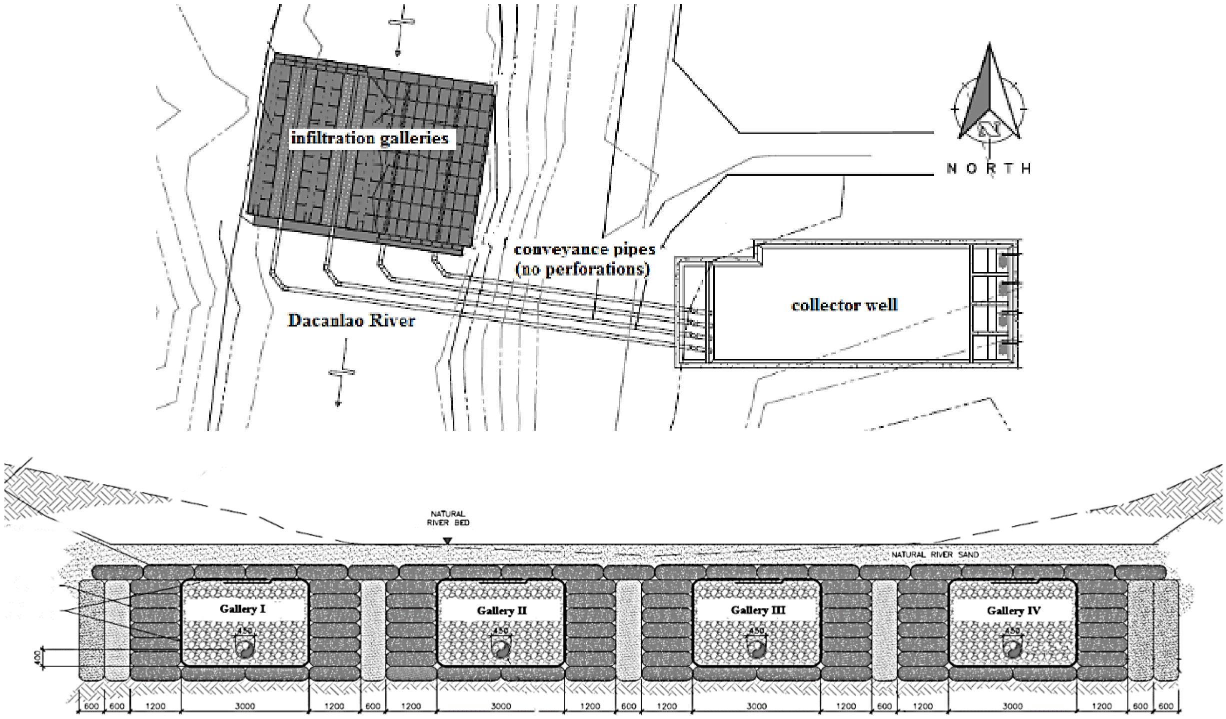


**Figure 1**. Plan view of study area showing the relative position of laterals and collector well (top); section view of the parallel laterals enclosed by gravel and geobags (bottom)

variability in density and consistency composed basically of unconsolidated to poorly consolidated gravels, sand, silt and clay. Dacanlao River's mouth is underlain by geologically recent alluvial materials consisting of silts and sands of loose to medium dense sands and silts.

Subsurface analysis was undertaken in the study area prior to construction. Boreholes advanced through wash boring drilling procedures and soil sampling by split-spoon and Standard Penetration Test (SPT) procedures provided basic description of the underlying geology of Dacanlao River and its vicinity. The samples were then tested in the laboratory for grain-size analysis and hydraulic conductivity testing.

*2.3 Development of Approximate Analytical Solution*

The analytical approach needed for parallel laterals is an extension of Liongson's [10] work and using image well theory. Figure 2 shows a single lateral and the variables affecting the yield. For lateral beneath the riverbed, the flow towards the gallery comes from induced river infiltration and from the aquifer. Assuming uniform flow for infiltration, the flow potentials (phi) of infiltration, source and sink are respectively expressed as,

$$\varphi_1 = Ky \tag{1}$$

$$\varphi_2 = \frac{q}{2\pi} ln\sqrt{x^2 + y^2} \tag{2}$$

$$\varphi_3 = -\frac{q}{2\pi} ln\sqrt{x^2 + y^2} \tag{3}$$

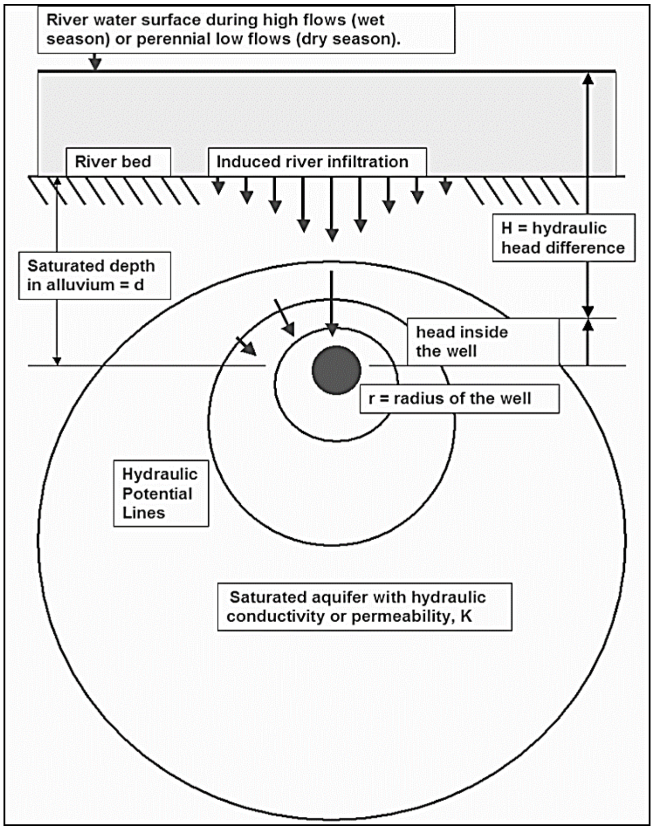


**Figure 2.** The following variables affect how much water from the river and surrounding aquifer can enter a lateral of the collector well: depth and radius of the gallery; head inside the collector well; head in the river; and hydraulic conductivity of the aquifer. (Source: Liongson, 2006)

in which x and y are the cartesian coordinates while q is the flow per unit length of the source and sink elements.

Provided that the aquifer thickness is much larger than the depth of galleries, flow potentials near them are circular [10]. All galleries can be treated individually, having different flow patterns and assumptions. For outer galleries, each can be thought of as a horizontal well near a vertical impermeable boundary below a horizontal recharge boundary in a semi-infinite aquifer. The impermeable boundary represents the influence of adjacent gallery. At any point, flow direction is towards the nearest gallery creating an imaginary "no flow" divide. As for inner galleries, each can be modeled as a horizontal well bounded to the left and right by impermeable boundaries below a horizontal recharge boundary. Figure 3 shows how the parallel galleries are separated in the analysis.

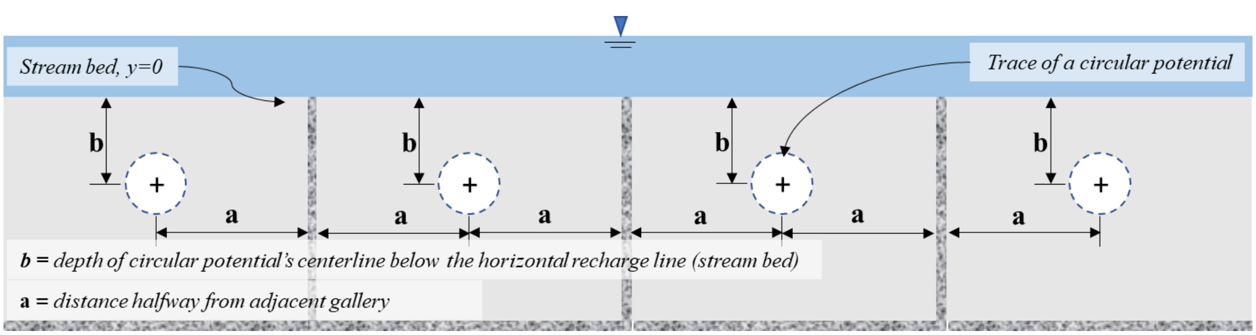


**Figure 3.** Individual treatment of the four galleries with Gallery I (leftmost) and Gallery IV (rightmost) assumed to have an impermeable boundary at one side while Galleries II and III (middle) can be represented individually by a horizontal well bounded by impermeable boundary on both sides.

***Case I - Outer Galleries***

Setting the origin at the intersection of riverbed and vertical axis of true sink, an outer gallery's flow can be approximated using the following potential functions:

Vertical Steady Seepage:

$$\varphi_1 = KH \tag{4}$$

Image Source at (-2a, b):

$$\varphi_2 = \frac{q}{2\pi} ln\sqrt{(x+2a)^2 + (y-b)^2} \tag{5}$$

Image Source at (0, b):

$$\varphi_3 = \frac{q}{2\pi} ln\sqrt{x^2 + (y-b)^2} \tag{6}$$

Image Sink at (-2a, -b):

$$\varphi_4 = -\frac{q}{2\pi} ln\sqrt{(x+2a)^2 + (y+b)^2} \tag{7}$$

True sink at (0, -b):

$$\varphi_5 = -\frac{q}{2\pi} ln\sqrt{x^2 + (y+b)^2} \tag{8}$$

By superposition and simplifying,

$$\varphi = -KH + \frac{q}{4\pi} \ln\left\{\frac{[(x+2a)^2+(y-b)^2][x^2+(y-b)^2]}{[(x+2a)^2+(y+b)^2][x^2+(y+b)^2]}\right\} \tag{9}$$

Equation 9 is the same as Liongson's [10] Equation 21, which represents the total potential induced by the constant recharge and source-sink pairs. The approximate potential exit ($\varphi$=0) is obtained by setting x=0 and y=-b near the true sink. Equation 9 then becomes

$$0 = -KH + \frac{q}{4\pi} \ln\left\{\frac{[4a^2+4b^2][x^2+(y-b)^2]}{[4a^2][x^2+(y+b)^2]}\right\} \tag{10}$$

which can be rearranged as

$$e^{\frac{4\pi KH}{q}} = \left[1 + \left(\frac{b}{a}\right)^2\right]\left[\frac{x^2+(y-b)^2}{x^2+(y+b)^2}\right] \tag{11}$$

Letting

$$F = \frac{e^{\frac{4\pi KH}{q}}}{1+\left(\frac{b}{a}\right)^2} \tag{12}$$

Equation 11 now becomes

$$F = \left[\frac{x^2+(y-b)^2}{x^2+(y+b)^2}\right] \tag{13}$$

which is an equation of a circle corresponding to the infiltration gallery's location. In standard form;

$$x^2 + \left(y + b\frac{F+1}{F-1}\right)^2 = \frac{4b^2F}{(F-1)^2} \tag{14}$$

Based from Equation 14, the depth of centerline, d from riverbed is:

$$d = b\frac{(F+1)}{F-1} \tag{15}$$

And the radius of the well must be:

$$r = \frac{2b\sqrt{F}}{F-1} \tag{16}$$

To solve for q, the ratio r/d can be evaluated hence getting an expression for F:

$$\frac{r}{d} = \frac{2\sqrt{F}}{F+1} \tag{17}$$

$$rF - 2d\sqrt{F} + r = 0 \tag{18}$$

Treating the equation as quadratic function and solving for the positive root of $\sqrt{F}$;

$$\sqrt{F} = \frac{d+\sqrt{d^2-r^2}}{r} \tag{19}$$

Using the equivalence of Equation 12 for F,

$$\sqrt{\frac{e^{\frac{4\pi KH}{q}}}{1+\left(\frac{b}{a}\right)^2}} = \frac{d+\sqrt{d^2-r^2}}{r} \tag{20}$$

And lastly solving for q:

$$\boldsymbol{q} = \frac{2\pi KH}{\ln\left\{\left[1+\left(\frac{b}{a}\right)^2\right]^{\frac{1}{2}}\left[\frac{d+\sqrt{d^2-r^2}}{r}\right]\right\}} \tag{21}$$

***Case II - Inner Galleries***

An inner gallery can be regarded as a horizontal well bounded to the left and right by vertical impermeable boundaries and below a constant recharge in an aquifer with infinite thickness. In addition to the five (5) potential functions from Equations 4 to 8, two (2) more potentials must be superimposed to consider the effects of other gallery at the right side.

$$\varphi_6 = \frac{q}{2\pi} ln\sqrt{(x-2a)^2+(y-b)^2} \tag{22}$$

$$\varphi_7 = -\frac{q}{2\pi} ln\sqrt{(x-2a)^2+(y+b)^2} \tag{23}$$

Combining all potential functions, the composite flow potential is:

$$\varphi = -KH + \frac{q}{4\pi}\ln\left\{\frac{[(x+2a)^2+(y-b)^2][x^2+(y-b)^2][(x-2a)^2+(y-b)^2]}{[(x+2a)^2+(y+b)^2][x^2+(y+b)^2][(x-2a)^2+(y+b)^2]}\right\} \tag{24}$$

Similar to Case I, since the potential function is expected to be evaluated near the location of true sink at (0, -b), the (x,y) coordinates of image source and sink can be set to x≈0 and y≈-b to simplify the Equation 24, resulting to the following expression:

$$\varphi = -KH + \frac{q}{4\pi}\ln\left\{\frac{[4a^2+4b^2][x^2+(y-b)^2][4a^2+4b^2]}{[4a^2][x^2+(y+b)^2][4a^2]}\right\} \tag{25}$$

For the exit potential $\varphi$=0;

$$0 = -KH + \frac{q}{4\pi}\ln\left\{\frac{[4a^2+4b^2]^2[x^2+(y-b)^2]}{[4a^2]^2[x^2+(y+b)^2]}\right\} \tag{26}$$

$$e^{\frac{4\pi KH}{q}} = \left[\frac{4a^2+4b^2}{4a^2}\right]^2\left[\frac{x^2+(y-b)^2}{x^2+(y+b)^2}\right] \tag{27}$$

$$e^{\frac{4\pi KH}{q}} = \left[1+\left(\frac{b}{a}\right)^2\right]^2\left[\frac{x^2+(y-b)^2}{x^2+(y+b)^2}\right] \tag{28}$$

Letting

$$F = \frac{e^{\frac{4\pi KH}{q}}}{\left[1+\left(\frac{b}{a}\right)^2\right]^2} \tag{29}$$

Equation 28 then becomes:

$$F = \left[\frac{x^2+(y-b)^2}{x^2+(y+b)^2}\right] \tag{30}$$

Which is similar in form to Equation 13. Using the same sequence of operations as in Equation 14 to 19, the yield per unit length of inner gallery is

$$\boldsymbol{q} = \frac{2\pi KH}{\ln\left\{\left[1+\left(\frac{b}{a}\right)^2\right]\left[\frac{d+\sqrt{d^2-r^2}}{r}\right]\right\}} \tag{31}$$

Equations 21 and 31 are only applicable for homogenous aquifer. For heterogeneous soil media under non-linear flow direction as in the case study, there aren't any available full analytical methods yet. However, spatial averaging can be done following Desbarats' [18] geostatistical analysis. He developed a geostatistical model for conductivity such that several core samples in an area can estimate the average conductivity at a larger scale of the formation volume drained by a certain well. The resulting spatial averaging law for non-circular drainage region is given as:

$$K = \frac{1}{W}\int_o^V \frac{K(x)^w}{r^2(x)}dV \tag{32}$$

$$W = 2\pi p \ln\frac{0.956 r_e}{r_w} \tag{33}$$

where V is the drainage region, K(x) is the hydraulic conductivity at a radial distance r(x), W is a spatial averaging power in the range of -1 to 1, p is the length of drainage region, and $r_e$ is the external radius of drainage area with respect to well.

### *2.4 Numerical Approach*

MODFLOW through GMS™ was used to come up with a steady-state finite-difference model of the infiltration gallery. The conceptual model was limited within the vicinity of intake, with model domain spanning to 30mx38m area, enclosing the galleries and covering a short reach of Dacanlao River.

The local coordinate system was conveniently aligned to the galleries. The grid cell width was limited to 0.25m to properly capture the 0.5-m diameter of laterals. Six (6) layers were set in the model to capture the heterogeneity of the underlying soil, from the silty sand in the uppermost layers, then encased sand and gravel combinations in the next four (4) layers also including the galleries, and the natural geologic stratum up to the bottom of the unconfined aquifer. The laterals are represented as drains, getting a portion of flow from the aquifer depending in the head differences. Since the gallery is in a saturated unconfined aquifer, the external boundaries are assumed to follow the Dupuit assumption, having equal head to the river in the immediate vicinity. All four (4) sides then are set to be at a specified head equal also to the internal boundary head of Dacanlao River in the uppermost layer of the model. To account for flow disturbances due to the presence of infiltration galleries, the author adopted the method of Kelson [19] to calculate the resistance of the drains. The resistance to converging flow stems from two (2) sources: resistance to horizontal flow toward the lateral due to an aquifer zone of width s as shown in Figure 5, and vertical flow resistance conceptualized as line-sink.

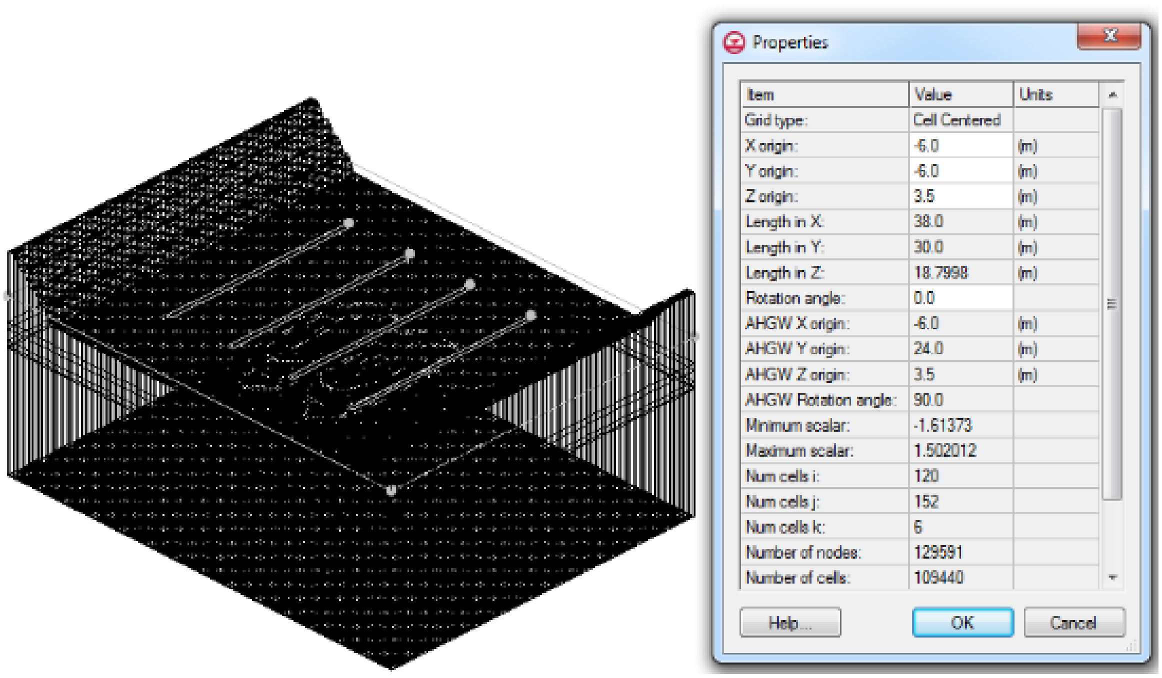


**Figure 3.** MODFLOW model discretization and cell properties as used in the study area.

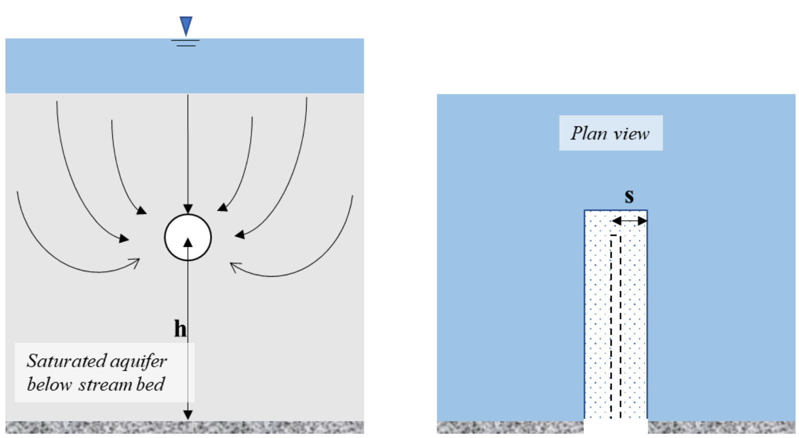


**Figure 5.** (a) Flow towards a gallery in an unconfined aquifer with constant head. (b) Dupuit conceptualization of representing the entrance resistance as having a stream boundary wrapped around the lateral (Source: Haitjema, 2006)

Detailed description of resistances and equivalent Dupuit models are thoroughly discussed by Haitjema [16]. The required resistance, c is:

$$c = c_{tot} - \frac{sw}{2kB} \tag{34}$$

$$c_{tot} = -\frac{w}{2\pi k} \ln\left\{ tan\left(\frac{\pi}{4}\frac{r_w}{B}\right) tan\left(\frac{\pi}{2}\frac{h+0.5r_w}{B}\right)\right\} \tag{35}$$

where
- c – total resistance [L]
- $c_{tot}$ – vertical resistance [L]
- s – width of superimposed aquifer zone [L]
- w – arbitrary width of line-sink element [L]
- k – hydraulic conductivity [L/T]
- B – aquifer thickness [L]
- $r_w$ – radius of gallery [L]
- h – distance of the gallery from aquifer base [L]

The resistance equations are derived on a basis of conformal mapping with two source-sink pairs.

*2.5 Evaluation*

To assess the validity of the estimation methods, the actual yield was measured in a monthly basis. The measurement was carried out for three (3) consecutive dry months, where aquifer recharge is negligible and the field condition is closest to steady-state. As described in Figure 6, the difference in water stages between the river and collector well is the effective head that drives the flow towards the galleries. To determine the yield, the volume change in the collector well was monitored for a period of time. The results were then compared to the values given by the approximate analytical solution and numerical model.

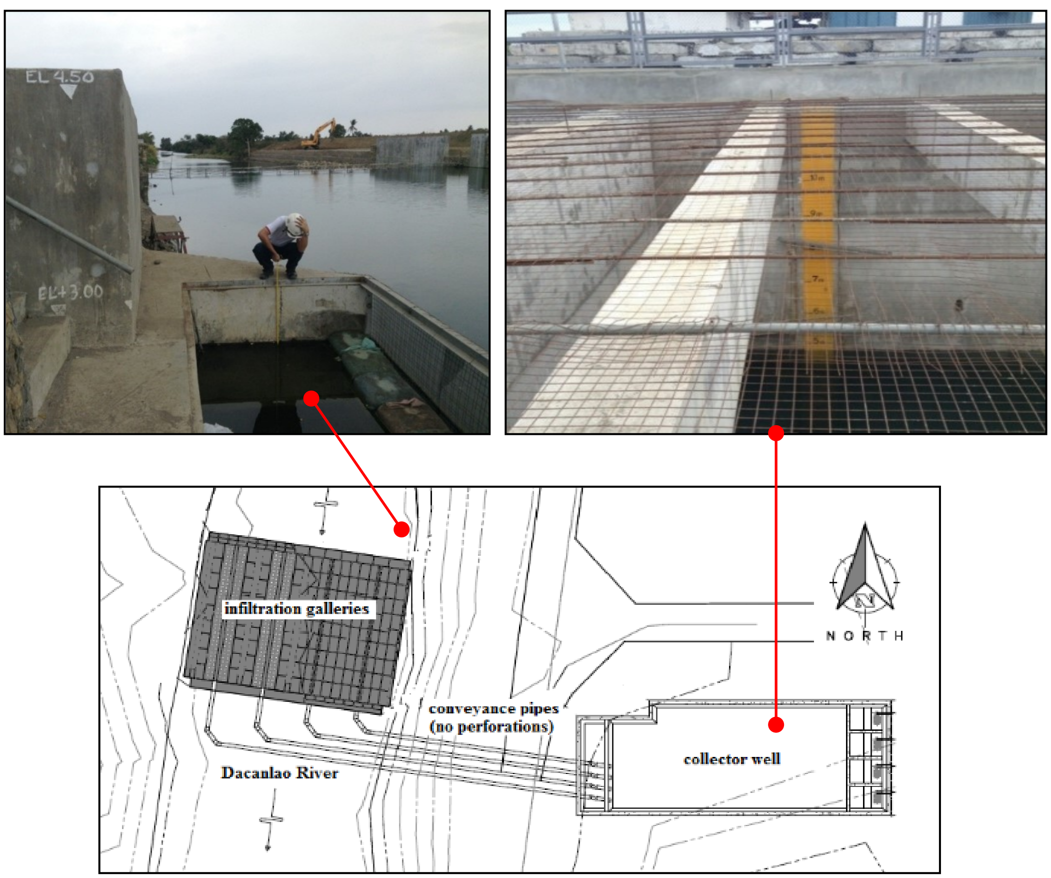


**Figure 6.** Locations where water stages are measured to determine the actual head that drives the flow towards the collector well

## III. RESULTS AND DISCUSSION

### *3.1 Hydrogeologic Characterization*

The underlying geology of the study area is primarily sand of differing density and consistency, typical of a downstream portion of catchment areas in the Philippines. Figure 7 shows the interpolated subsurface geology of Dacanlao River prior to construction of galleries. The uppermost layer is silty sand, then sands of increasing density as one move deeper. Table 1 displays the hydraulic conductivities of the formation in the infiltration galleries based from geotechnical investigation.

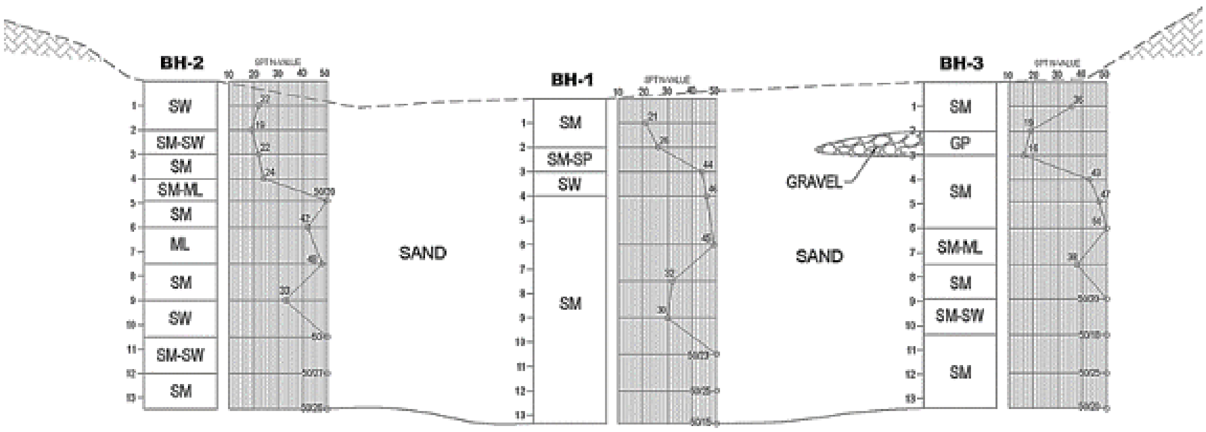


**Figure 7.** Borehole (BH) data based from Standard Penetration Test (SPT) indicates that the riverbed and unconfined aquifer underneath are composed of sand of almost homogenous nature. Soil acronyms indicated is according to Unified Soil Classification System (USCS).

**Table 1.** Soil properties around the laterals

| Layer | Hydraulic Conductivity (m/s) |
|---|---|
| Silty Sand | 3.40E-05 |
| Sand | 1.48E-03 |
| Gravel | 2.75E-02 |

The water table in the general vicinity is very shallow, nearing 0.2 metre – 1.5 metre below the natural ground elevation. The riverbed is at elevation -0.7 metres above mean sea level (msl) while the bottom of the unconfined aquifer is at -15 msl. Dacanlao River is perennial as opposed to majority of streams in the province which are either intermittent or ephemeral. This fact suggests that the baseflow can sustain the streamflow for the half-year dry period. It also implies that the river has good hydraulic connection with the aquifer.

### 3.2 Yield Estimates

The yield is a direct function of head inside the galleries. Figure 6 shows the comparison between the yield estimates and the actual yield. The approximate analytical solutions developed in this study shows linear relationship between the two (2) variables. For the numerical model, aside from the effect of head in the groundwater flow equation, the conductance of galleries is also head dependent. However, sensitivity analysis also indicated an almost linear relationship between head and yield. The linearity was also observed by Patel [3] using AEM for radial collector wells. The same trend was observed in the field measurement, however, there are only three (3) observation points preventing the study to have exhaustive correlation analysis.

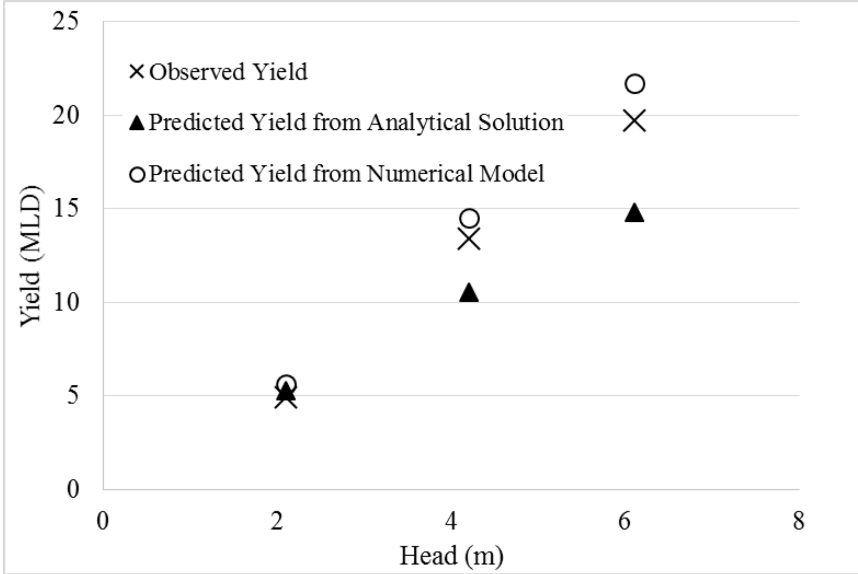


**Figure 8.** Estimated and actual yields as compared to the head inside the laterals

It can be deducted from Figure 8 that as the head increases, the discrepancy between the estimates becomes larger. The MODFLOW model always returns larger value than the analytical solution. As the developed approximate analytical solution is closely related to the AEM approach used by other researchers, comparisons with regards to the results can be made. Kelson [19] also obtained the same result for radial collector wells, that FDM estimates are generally higher than AEM, but Patel [3] suggested otherwise, though the deviations in his work is only within 6%. The FDM considers that as the head changes, aside from the increased riverbed infiltration and aquifer flow, the conductance of the galleries are also increased.

Table 2 shows the deviations of estimates to the observed values. Because of operational constraints, there are only limited observation points. However, in the absence of any other basis of evaluation, these data are valuable for the subsequent assessment. The estimate from analytical approach has a root mean square error (rmse) of 26%. This is significantly better than Banerjee [20], where an observed yield is more than double of the estimate using image-theory, a semi-analytic approach for radial collector wells. The better accuracy in this research is primarily because the hydraulics of flow in parallel laterals is simpler than radial laterals and can be captured more precisely by established methods. More spatial variations are present in the case of a radial collector well and estimating its yield needs a full AEM approach rather than a simple application of potential flow theory used in this study.

**Table 2.** Deviations of the estimates from actual values

| Head (m) | Observed Yield (MLD) | % Deviation | |
|---|---|---|---|
| | | Analytical | Numerical |
| 6.1 | 19.73 | (-)25 | (+)10 |
| 4.2 | 13.43 | (-)21 | (+)8 |
| 2.1 | 4.96 | (+)6 | (+)13 |

Similar with the behavior against FDM model, the analytical method's deviation becomes larger as the head increases. It means that there are some processes and variables that wasn't directly incorporated by the estimation technique. For instance, the effect of adjacent gallery was represented by an impermeable boundary at the mid-distance while in truth, their areas of influence are not equal but also a function of flow. As the head increases, the outer galleries will have more flow and will exert larger influence in the surrounding aquifer as compared to the inner galleries. The errors could also stem from the radial averaging of hydraulic conductivity, since the method is particularly suited for homogenous aquifers only.

The developed approximate analytical approach can be a valuable tool for future yield predictions especially during preliminary stages of water resources exploration where rapid yield estimates are necessary. Two (2) out of three (3) data points underestimates the actual yield, which is on the conservative side of water supply studies.

The FDM model results overestimates the yield by 10.5%. This study employed the method to incorporate flow resistance around horizontal wells in FDM models under Dupuit models as proposed by Kelson [19]. Typically, the Dupuit model overpredicts well yields because of its underlying limitations. The formulation of conductance values based from AEM models tried to resolve this issue and was proven to be acceptable by the same study. Similarly, the parallel laterals are easier to model numerically than the radial orientation, thus making Equations 34 and 35 to be implemented directly in this research. Rather than the conductance formulation, the error in estimation can be attributed to the representation of the laterals. It is impossible to capture the circular section of the well in finite difference approach and making the grid sizes very small to try to capture this information is not practical. The head losses due to convergence in the perforations and pipe friction cannot be directly incorporated in the model, making the heads larger than the actual values. Although previous studies [3, 14] claim that the frictional loss inside a lateral is negligible, for an error of 10.5%, it could affect the accuracy.

Though more cumbersome to setup, the results of MODFLOW simulation is in better agreement from the observed values as compared to the approximate analytical solution. However, the apparent overestimation must also be considered especially in the design phase of water supply systems to ensure that the actual yield can satisfy the demand.

*3.3 Comparison of Analytical and Numerical Methods*

Based from the application of approximate analytical and numerical models in estimating the yield of collector well in the study area, detailed comparison is summarized in Table 3.

**Table 3.** Detailed Comparison Between Analytical and Numerical Models

| Feature | Analytical Model | Numerical Model |
|---|---|---|
| Basic Equation | Potential Flow of Source-Sink Elements with hydraulic approximations | General Groundwater Flow Equation |
| Way of Solution | Direct, but with approximation of potential exit | with mathematical approximations due to discretization |
| Consideration of nearby hydrologic/hydrogeologic elements | either through image well theory or direct representation by employing full AEM | through boundary conditions |
| Description of Aquifer Heterogeneity | Indirect, through Spatial Averaging | Direct, by applying attributes to each cell |
| Description of Anisotropy | Indirect, through Spatial Averaging | Direct, by applying attributes to each cell |
| Description of Unsteady Flow | not yet fully developed | Simple |
| boundaries of the area of interest | no fixed outer boundaries | needs fixed outer boundaries |
| subdivision of the area of interest | based on hydraulic considerations | geometric, by grid |
| coordinate system | standard | local coordinate system is useful |
| aquifer representation | through K and aquifer extent | through K and aquifer extent |
| surface water interaction | through constant head | can handle constant or transient heads |

## IV. CONCLUSION

Collector wells with horizontal laterals can be an effective water supply intake. Aside from the more common radial orientation, the laterals can also be constructed in parallel, as what had been done in the Philippines. Although these types are generally more difficult to construct, maintenance is more convenient. A modular setup as in the study area in this research can be done to allow continuous operation of collector well while doing maintenance works at a lateral. This study shows that yield estimations for parallel horizontal wells both by analytical and numerical methods are easier as compared to radial collector wells. In fact, approximate analytical yield equations were derived and the resulting total yield estimate is in good agreement with the observed values. The developed equations can be used for rapid estimation of yield to other candidate sites. Meanwhile, the FDM model using MODFLOW produced more accurate results than the analytical method. However, it should also be used with caution as the estimates are usually greater than the actual yields, which can pose a problem for water supply development. It must be noted that limited observation points were used to evaluate the results. It is recommended that the developed equations and methodologies be applied to other candidate sites for further validation.

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**REFERENCES**

[1] Adjei, E.K., Shu L., Adjei, K.A., Lu C., Deng, M., “ Interpretation of Pumping Test with Radial Collector Well Using a Reservoir Model”, ASCE Journal of Hydrologic Engineering, Vol 17, No. 12, pp.1397-1407, 2012.

[2] Yeh, H.D., Chang, Y.C., “Recent Advances in Modeling Well Hydraulics”, Advances in Water Resources Vol. 51, pp. 27-51, 2013.

[3] Patel, H.M., et. al., “Simulation of Radial Collector Well in Shallow Alluvial Riverbed Aquifer Using Analytic Element Method”, ASCE Journal of Irrigation and Drainage Engineering, Vol. 136, No. 2, 2010.

[4] Camacho, A., “Evaluation of the Existing Performance of Infiltration Galleries in Alluvial Deposits of the Parapeti River, La Paz, Bolivia”, Bolivian Association of Sanitary Engineers Casilla, 2005.

[5] Ismail, W.M.Z.W., Yusoff, I. & Rahim, B.E.A., “Simulation of Horizontal Well Performance Using Visual MODFLOW”, Environmental Earth Sciences, Volume 68, Issue 4, pp 1119–1126, 2013.

[6] Mikels, F.C. & Klaer, F.H., “Application of Ground Water Hydraulics to the Development of Water Supplies by Induced Infiltration”, Symposia Darcy, Pub No. 41, pp. 232-242, 1956.

[7] Hantush, M. S. & Papadopulos I. S., “Flow of Groundwater to Collector Wells”, J. Hydraul. Div. Proc. Am. Soc. Civ. Eng., HY5, 221–244, 1962.

[8] Kompani-Zare, M & Zhan, H., “Steady Flow to a Horizontal Drain in an Unconfined Aquifer with Variable Thickness”, Journal of Hydrology, Vol. 327, Issues 1-2 pp. 174-185, 2006.

[9] Csoma, R., “The Analytic Element Method for Groundwater Modeling”, Periodica Polytechnica Ser. Civ. Eng., Vol. 45, No. 1, pp. 43–62, 2001.

[10] Liongson, L.Q., “Exact and Approximate Analytical Solutions for Steady Seepage Inflows to Horizontal Wells”, Proceedings of the International Symposium on Managing Water Supply for Growing Demand, UNESCO-IHP Technical Document in Hydrology No. 6, 2006.

[11] Castro, P.M., “Theoretical and Practical Aspects of Infiltration Gallery Planning and Design”, COE-NEC Technical Bulletin Vol. 2 No. 1, 2006.

[12] Kolymbas, D. & Wagner, P., “Groundwater Ingress to Tunnels”, Institute of Geotechnical and Tunnel Engineering, University of Innsbruck, Austria, 2006.

[13] Singha, S. & Verma, M.K., “Application of GIS and MODFLOW to Groundwater Hydrology – A Review”, International Journal of Engineering Research and Applications, Vol. 6, Iss.1, pp. 36-42, 2016.

[14] Moharir, K., Pande, C. & Patil, S., "Inverse Modelling of Aquifer Parameters in Basaltic Rock with the Help of Pumping Test Method using MODFLOW Software", Geoscience Frontiers, Vol. 8, Iss. 6, pp. 1385-1395, 2017.

[15] Szymkiewicz, A., Gumula-Kawecka, A., Simunek, J., et. al., "Simulations of Freshwater Lens Recharge and Salt/Freshwater Interfaces Using the HYDRUS and SWI2 Packages for MODFLOW", Journal of Hydrology and Hydromechanics, Vol. 66, Iss. 2, pp. 246-256, 2018.

[16] Haitjema, H.M., "Accounting for Resistance to 3-D Flow Near Horizontal Wells or Galleries in a Dupuit-Forccheimer Model", Academic Press, Inc., 2006.

[17] Moore, R., Kelson, V., Wittman, J., Rash, V., "A Modeling Framework for the Design of Collector Wells", Ground Water, Vol. 50, No. 3, pp. 355-366, 2012.

[18] Desbarats, A.J., "Spatial Averaging of Hydraulic Conductivity Under Radial Flow Conditions", Journal of Mathematical Geology, Vol. 26, No. 1, 1994.

[19] Kelson, V., "Predicting Collector Well Yields with MODFLOW", Journal of Hydrology, Vol. 50 Is. 6, Wiley Online

[20] Banerjee, G., "Groundwater abstraction through river-bed collector well: A case study based on geophysical and hydrological investigation", Clean Technologies and Environmental Policy. 14. 10.1007/s10098-011-0417-6, 2011.