ICIWRM – 2000, Proceedings of International Conference on Integrated Water Resources
Management for Sustainable Development, 19 – 21 December, 2000, New Delhi, India

Stream-aquifer interflow estimation - evaluation of common algorithms

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Abstract

A credible estimation of insitu stream-aquifer interflow is a prerequisite for modeling of contaminant transport in streams and groundwater aquifers. The interflow is commonly estimated by monitoring the stream stage and the water table elevation in an observation well in the vicinity of the stream. The measured difference between the two levels, distance of the well from the stream, stream-section, aquifer thickness and the hydraulic conductivity are employed to estimate the interflow. The estimation is mostly based upon Dupuit-Forchheimer's assumptions. It is believed that this solution is exact for fully penetrating streams. For partially penetrating rivers, the additional loss of head due to vertical velocities is accounted for by certain semi-empirical equations. In the present study these algorithms have been evaluated by two-dimensional steady state numerical modeling of the groundwater flow in the vicinity of the stream. The modeling permits simulation of the true stream-aquifer interflow, and the depth-averaged piezometric head representing the water table elevation. The algorithmic stream-aquifer interflow computed from this elevation is compared with the corresponding model-computed value. The comparison reveals that the commonly used algorithms based upon a single water table observation are quite unreliable and uncertain. This indicates the necessity of monitoring the piezometric head distribution in x-z plane by a nest of piezometers, and analyzing the flow net to estimate the interflow.

STREAM-AQUIFER INTERFLOW

A hydraulic connection between a stream and an aquifer permits an interflow between the aquifer and the stream. Direction of the interflow depends upon the relative levels of the water table and the stream free surface. If the water table level is lower then there will be an influent seepage from the stream to the aquifer. Otherwise there will be an effluent seepage from aquifer to the stream. Rate of the interflow depends upon the difference between the two levels, stream section and, aquifer geometry, parameters and the boundary conditions. This rate needs to be estimated for estimating the groundwater resource and the river flows. Further, this interflow also implies a transport of dissolved contaminants from river to aquifer or vice versa. As such the rate of interflow is required for projecting the solute concentration in groundwater and stream water.

The prevalent practice of monitoring the insitu stream-aquifer interflow essentially comprises of monitoring the stream stage and the water elevation in a well located close to the stream. The estimation of the interflow is mostly based upon either Dupuit Forchheimer (D-F) assumptions or upon certain semi empirical equations accounting for the additional head loss due to vertical velocities. All the equations describe the interflow rate in terms of the difference between the two levels, distance of the well from the stream, the stream section, the aquifer thickness and the hydraulic conductivity.

Present Study

The present study comprises simulation of the steady state spatial distribution of the piezometric head in a vertical plane. The plane is bounded by the following boundaries:

Water table at the top
An impervious boundary at the bottom
A water-divide at the upstream end
A stream at the downstream end

A uniform recharge is assigned at the water table. Since a water-divide is assigned at the upstream boundary, the entire recharge at steady state shall outflow to the stream. Thus, rate of outflow to the stream per unit stream length, shall be the product of recharge rate and flow domain length. Thus, the *true* interflow rate is known a priori. The spatial distribution of the piezometric head is employed to simulate the *well water level*. Using this simulated level and other data, the interflow rate is estimated by different semi empirical equations. The estimates are compared with the corresponding *true value*. The comparison has been carried out for varying stream and aquifer geometry, aquifer parameters, recharge etc. The simulation is conducted by modeling the two-dimensional steady state flow.

MODELING OF STREAM-AQUIFER INTERFLOW

A reported numerical model of two-dimensional transient saturated flow (Ahmad et al. 1991) has been used in the present study. The model simulates the spatial distribution of the unsteady state piezometric heads (h = h(x,z,t)) for an assigned pattern of vertical recharge. The model is based on a finite difference solution of the following differential equation governing two-dimensional (x-z plane) transient unconfined saturated flow in a heterogeneous and anisotropic porous medium:

$$\frac{\partial}{\partial x}(k_{xx}\frac{\partial h}{\partial x}) + (k_{zz}\frac{\partial h}{\partial z}) = S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where x(L) and z(L) are the coordinates alone principal permeability directions in a vertical plane (x in horizontal direction and z in vertical direction). Kxx(LT-1) and kzz(LT-1) are the hydraulic conductivities in x and z directions respectively, h(L) is the head above a datum. Ss(L-1) is the specific storage. The model accounts for the partial penetration of streams, flow above the initial drain level, vertical anisotropy, vertical flows, and associated head losses. The resulting solution comprises among others, unsteady state water table position at the chosen discrete times.

Present Application

In the present study the model was employed to simulate the steady state piezometric head distribution, and steady state water table position in a two-dimensional domain bounded by a rectangular stream on one end and a no-flow boundary on the other end. A uniform recharge rate was assigned over the entire domain. Steady state was simulated by neglecting the storage components (i.e. $S_s = 0$ and $S_y = 0$).

Boundary conditions: The solution domain was bounded by half stream section, drain center-line extending from drain bottom to the lower impervious layer, lower impervious layer extending from drain center-line to the upstream water-divide, and the water table extending from the upstream water-divide to the drain-aquifer interface. The following boundary conditions were assigned while simulating the piezometric head distribution (refer Fig 1):

Along the water table: $k_z.\partial h/\partial z = R$
Along the half-drain boundary: $h = D$
Along the drain center-line below the drain; and along the upstream water-divide $\partial h/\partial x=0$
Along the lower impervious layer $\partial h/\partial z = 0$

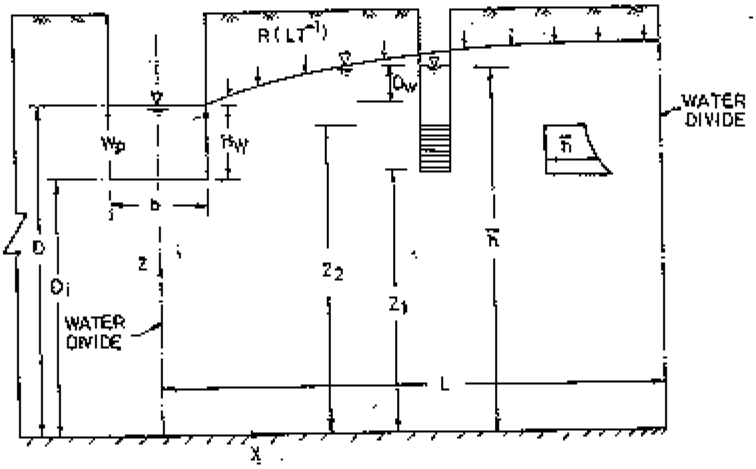

Figure 1. Monitoring of stream – aquifer interflow.

The simulated piezometric head distribution was employed to compute the following attributes of the system:

Stream aquifer interflow rate: This was computed by integrating the product of hydraulic conductivity and the hydraulic gradient (across the stream boundary outwards) all along the stream-aquifer boundary.

Water elevation in well: This elevation, conceptualized as the average piezometric head $\ddot{h}$ (x, z_1, z_2) along the well screen (refer fig. 1), is given by the following expression:

$$\bar{h}(x, z_1, z_2) = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} h(x, z) dz \qquad (2)$$

The integral was computed numerically employing the pre-simulated piezometric heads.

Adopted Dimensions/Characteristics

The present study has been conducted for the following dimensions/aquifer characteristics (refer Figure 1):

D	b	L	R.L	K_x	K_x/K_z	$\eta =$ $(D - D_i)/D$
25m	2,4,10,20 m	5,10 Km	0.5,2.5,5,10 m3/day/m	5 m/day	40,16.5,1.0	0.25,0.50, 0.75,1.0

Discretization of space

The flow model requires discretization of the flow domain by rows and columns. Closer spacings are required close to the stream to restrict the truncation errors. However, the spacings may be gradually increased away from the stream to restrict the computer time. In the present study the spacings were arrived at by a trial procedure. The adequacy of a given trial spacing pattern was ascertained by comparing the model computed stream aquifer interflow with corresponding assigned value (= R.L.). The spacings were sequentially reduced till the two matched within 5%.

ALGORITHMIC INTERFLOW RATE

Consider an observation well located at a distance x from the stream center and tapping the aquifer from vertical coordinate z_1 to z_2. The model-simulated *observed* water level in the *observation* well is employed to estimate the inter flow rate (f_i, i = 1, 2, 3, 4, 5) using the following five commonly used algorithms:

D-F solution for fully penetrating stream (Bouwer, 1965)

$$f1/Dw = 2k(Hw + 0.5Dw) / (x - 0.5b) \tag{3}$$

D-F solution for partially penetrating stream (Bouwer, 1969)

$$f2/Dw = 2k(Hw + Di + 0.5Dw) / (x - 0.5b) \tag{4}$$

D-F solution for partially penetrating stream - accounting for the vertical flow component

$$f3/Dw = 2k(Hw + Di + 0.5Dw) / (x + 0.5Di - 0.25b) \tag{5}$$

Bouwer's formula (Bouwer,1969)

$$f4 = \frac{k.D_w}{\frac{1}{\pi}\log_e[(D/W_p) + \frac{0.5x}{(D + 0.5D_w)}]} \tag{6}$$

Aravin's formula (Aravin, 1965)

$$f5 = \frac{k(D_w + H_w)(D_w - H_w)}{x - \frac{b}{2}} + \frac{k(D_w - H_w)}{\frac{x}{2D_i} - \frac{1}{\pi}\log_e \sinh(\frac{\pi b}{4D_i})} \tag{7}$$

RESULTS

Recalling that the true interflow rate is (R.L), relative error (ε) in the algorithmic interflow rates ($f_{1,2,3,4,5}$) is defined as follows:

$$\varepsilon_{x,z_1,z_2} = 100 * \frac{f_{1,2,3,4,5} - RL}{RL} \qquad (8)$$

Where x is the distance of the observation well from the center of the stream and z_1 and z_2 are the vertical coordinates of lower and upper ends of its screen (refer Fig 1). The errors were estimated assigning water table elevation to z_2. The results are shown as variation of the computed error (ε) with x and z_1.

Fully penetrating streams

It is generally believed (Bowuer, 1965b) that the function f_1, representing a solution for stream aquifer interflow with Dupuit-Fochheimer assumptions, is an exact solution provided the stream is fully penetrating. However, the present study shows that there are some errors in this solution (refer Fig. 2) even if the stream is fully penetrating. These errors are on account of the vertical component of flow associated with the recharged water table, and hence increase as the vertical anisotropy increases. Thus, the errors for k_x/k_z = 16.5 are larger as compared to the errors for k_x/k_z = 1. (Dotted contours in the figure are for k_x/k_z = 1.)

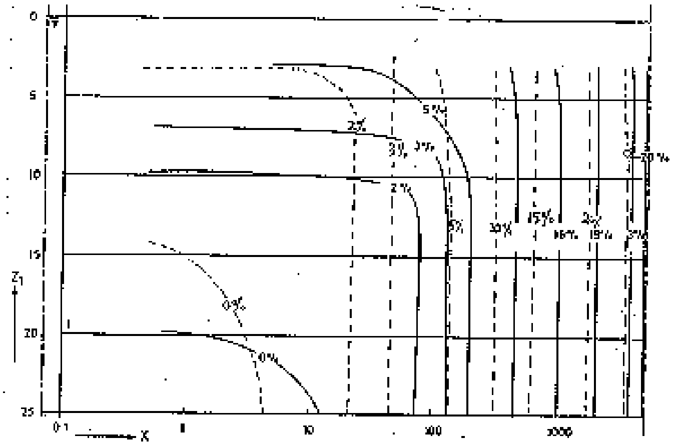

Figure 2. Interflow errors for a fully penetrating stream.

Partially penetrating streams

Figures 3, 4, 5 and 6 show the variation of the errors for a typical partially penetrating stream aquifer system (k_x/k_z = 16.5, b = 4m, η = 25%, R = 0.5 mm/day and L = 5 km) corresponding to the four formulae discussed earlier. It can be seen (refer Fig. 4) that the f_2 based upon the D-F solution leads to errors as large as 100%, close to the stream. However, these errors are smaller away from the stream. Further, it can be seen that more sophisticated formulation leads to a reduction in errors especially close to the stream. The error-patterns for f_3, f_4 and f_5 are quite similar i.e. if the observation well is located close to the stream and penetrates below the stream bed, the estimated interflow may be severely on the higher side. On the other hand, if a closely located well penetrates up to or above the river bed, the interflow may be underestimated with much smaller absolute errors. The effect of the well penetration reduces away from the stream with the interflow generally being overestimated, with decreasing absolute errors. Out of the three formulae, the Aravin's formula (f_5) has yielded the smallest errors.

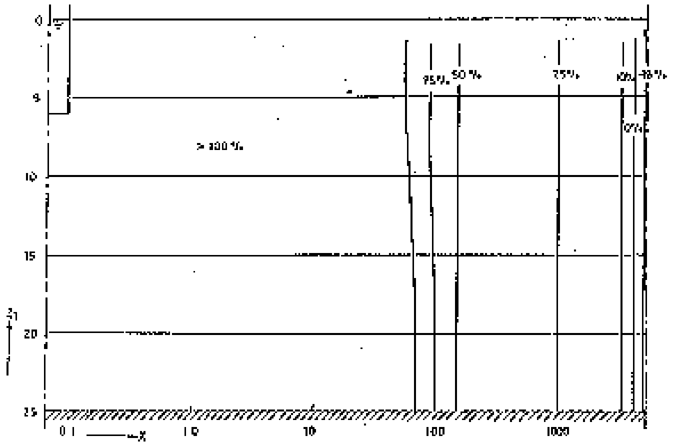

Figure 3. Interflow errors for a partially penetrating stream for D-F equation.

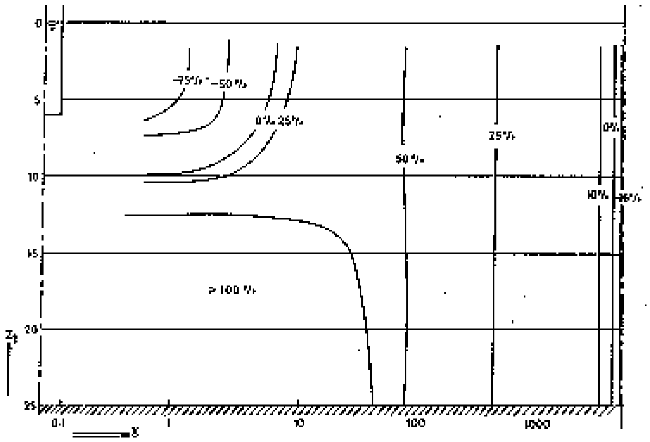

Figure 4. Interflow errors for a partially penetrating stream using modified D-F equation.

CONCLUSIONS

Contrary to the popular belief, the interflow estimated based upon the D-F assumption are not devoid or errors even if the stream is fully penetrating. These errors are on account of the vertical component of flow originating from the water table.

Out of the five solutions tested in the present study, Aravin's solution is found to be generally the least erroneous, and the D-F solution to be the most erroneous.

The errors in the estimates of the stream aquifer interflow based even upon the Aravin's solution may be quite high. The errors generally are larger for shallower and/or narrower streams, anisotropic, and/or larger aquifers and higher stream aquifer interaction.

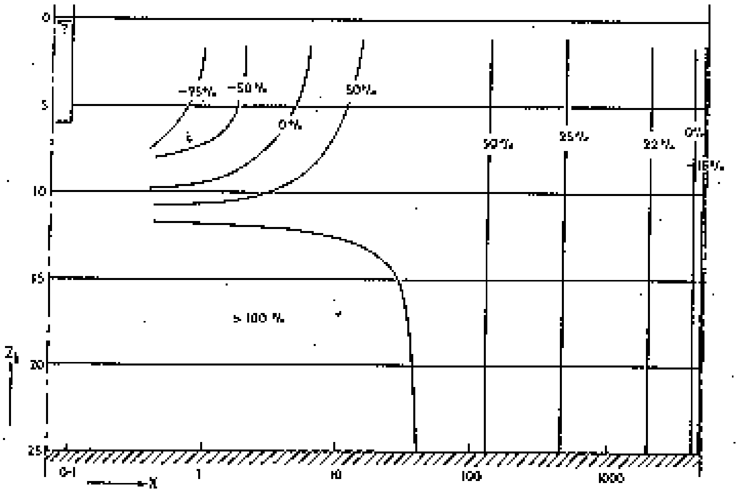

Figure 5. Interflow errors for a partially penetrating stream using Bouwer's formula.

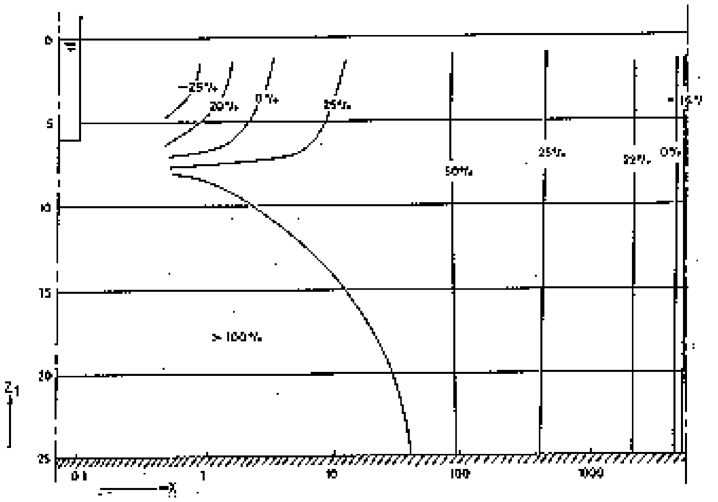

Figure 6. Interflow errors for a partially penetrating stream using Arvin's formula.

Based upon the present study no definite recommendation can be made regarding the optimal distance and the screen position of the observation well for minimizing the errors in the stream-aquifer interflow estimates. However, broadly it can be inferred that if the observation well is located close to the stream, the errors may not be very high provided the screen is located above the stream bed. An observation well located close to the stream should never have its screen below the stream bed, otherwise the errors may shoot up tremendously.

The prevalent procedure of estimating the stream-aquifer interflow, based upon the water level data from an observation well, seems to be quite unreliable and uncertain. A better procedure would be to monitor the piezometric head in x-z plane by a nest of piezometers. The piezometers head data so monitored can be used to draw flownet and hence the stream-aquifer interflow can be estimated reliably.

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