RADIAL COLLECTOR WELLS: SOME INSIGHT INTO FACTORS CONTROLLING YIELD AND CAPTURE ZONE

Nipun Kapur and S. K. Gupta
Earth Sciences Division, Physical Research Laboratory
Navrangpura, Ahmedabad 380 009, India

ABSTRACT

The pumping test data of three Radial Collector (RC) wells located at Rayka and Dodka in the Mahi and at Sabarmati in the Sabarmati riverbeds were analysed using anisotropic models with river infiltration effects. It was shown that ignoring aquifer anisotropy resulted in overestimation of design yield of these RC-wells. It was also found that maintaining some surface flow over the radials results in significantly higher yield and reduction of subsurface capture distance in comparison with the case when no surface water could be maintained. Hence, any strategy to increase RC-well yield, such as construction of Under Ground Check Dams (UGCD) by raising subsurface water level during the lean flow season (as is planned in case of Sabarmati at Ahmedabad) should be re-evaluated. We suggest that the height of the proposed UGCD be increased so as to maintain ~50 cm column of ponded water at the Sabarmati RC-well at Ahmedabad. Similar proposal should also be considered for increasing the yield of Rayka and Dodka RC-wells.

1.0 INTRODUCTION

Radial Collector (RC) wells dug near or within the riverbeds are becoming increasingly popular as a source of filtered water to sustain the needs of densely populated towns in India (Singhal and Gupta, 1999; Rao and Gupta, 1999). The standard practice in their design is to first choose the approximate locations of RC wells based on previous knowledge of hydrogeology and geography and then to conduct pump tests at the proposed sites. The observed drawdowns from the pump tests are then analysed to quantify the aquifer parameters and to estimate design yield and capture distance.

In the presence of permeability anisotropy, as in the case of riverbed aquifers (Bardley, 1996), homogeneous isotropic models and analytical techniques may not suffice to reliably estimate the aquifer parameters and the proportion of water derived from surface and subsurface sources. The ratio of vertical to horizontal permeability governs this proportion, which in turn defines the capture zone and the sustainable yield.

In the first part of the study, our objective was to identify the reasons for the observed low yield of the two RC wells of Rayka and Dodka (~50% of their design yield) in the Mahi riverbed near the city of Vadodara. Towards this end, drawdowns recorded in various observation wells during pumping tests carried out before the construction of the RC wells were simulated to re-estimate aquifer parameters. VMODFLOW (Finite Difference based groundwater-modelling package, Waterloo Hydrogeologic Inc., Ontario, Canada) was used for the purpose.

In the second part, we study yield and capture distance of a RC-well in the Sabarmati riverbed at Ahmedabad. This investigation was motivated by the knowledge that bacterial contamination was detected a few years ago (NEERI, 1994) in the pumped water from this RC-well. In addition, there is a proposal for construction of an Under Ground Check Dam (UGCD) across the riverbed to cut off subsurface flow thereby increasing subsurface water level during the lean flow season (GWRDC, 2000). These changes are likely to affect the yield and the capture zone of the Sabarmati RC-well.

2.0 THE MAHI RIVERBED AQUIFER AT VADODRA

For the purpose of model calibration, the available data comprised:

1. Detailed subsurface lithological investigation and pumping test data collected before construction of the RC-wells at Rayka and Dodka (M.K. Soil, 1989; KBM Engg, 1991)

2. An average lean season yield data of the two RC-wells with ponding around the jack well by diversion of the flow stream (VMC-Vadodara Municipal Corporation, files);

3. Approximate yield variation observed during different seasons with variation in river stage (VMC files).

2.1 Tube-well pump test simulations - reanalysis

The subsurface lithologic data indicated that the Mahi riverbed aquifer system comprised of two layers: (a) the upper sandy aquifer layer; and (b) the lower clayey aquiclude layer. At both locations, Rayka and Dodka, the top of aquiclude layer was saucer shaped. Because of the data limitations, a two step strategy of investigation was followed. This involved:

(1) Reanalysis of the available pump test data (M.K. Soil, 1989; KBM Engg, 1991) incorporating the actual saucer shape of aquifer bottom and the flow stream as river infiltration boundary.

(2) Determining the maximum sustainable yield of the RC-wells using the estimated aquifer parameters, in the process, adjusting the aquifer parameters to match the observed yield with the simulated ones (VMC files).

A model domain size 800 m x 1,600 m that included locations of Rayka and Dodka, was used (Fig. 1). The dimension of the coarsest Finite Difference (FD) grid cell was 50 m x 50 m close to the domain boundary and 0.5 m x 0.5 m close to the wells. Two layers, -1 and -2 were used to represent the upper sandy aquifer and lower clayey aquiclude with saucer shaped top. The relief between the deepest and the shallowest points of the saucer shape at Rayka is ~4.5 m and its a radius ~200 m. While for Dodka, the relief is ~1.5 m only and the radius ~150 m. The flow stream of river Mahi in the model area was included as a river boundary while the constant head boundaries were assigned at four sides of the model area far away from pumping wells (Fig. 1a).

2.2 RC-wells: simulation of maximum sustainable yields

The collectors/ Jack wells of the two RC wells have diameter ~ 6 m. The three tiers of laterals with an average length of 20 m, are situated between RL 1.25 m to 3.05 m for Rayka and RL 0.85 m to 2.65 m for Dodka.

In the model, the zone containing laterals was treated as a region of high average permeability (Fig. 1b). This approach in a way simulates the actual field condition wherein the region containing laterals effectively acts as a zone of higher conductance due to perforated horizontal pipes with hollow interiors. The concept of treating laterals as region of high permeability (K) is similar to the modelling of groundwater flow to Adits (horizontal tunnels). The Adits are assigned a larger value of hydraulic conductivity (Zhang and Lerner, 2000). Analytical expression by Hantush and Papadopulos, (1962) were used to test and validate the above strategy of representing the laterals and numerical routine. The errors in steady state distance drawdown variations for RC well using long time formulae of Hantush and Papadopulas (1962) was less than 10%.

We then incised infiltration ponds around the RC wells in the model (Fig 1). For this case the sustainable yields were calculated for the observed river stage RL of 6.5 m and the different possible permeability values. To estimate the sustainable yield, we gradually increase the steady state pumping rate in the simulations with VMODFLOW till any of the FD cells representing the laterals/ the jack well just goes dry due to increasing drawdown. Thus, we get the maximum likely sustainable yield of the RC-well for the used set of model parameters. Two models, one with saucer shape and other with flat top of clay layer, were used for the yield simulation analysis.

It was identified from the model simulation that when a pond was dug around the RC well, seepage of water from pond vertically downward to laterals, was the most dominating source of water to the RC well (Fig. 2a). As a result, the value of vertical permeability in the vicinity of radials primarily governs the drawdown distribution. On the other hand when there was no pond, as during the tube-well pump test, the main movement of water within the aquifer or from the primary source i.e. far off flow stream, was nearly horizontal (Fig. 2b). Therefore, we hypothesis that the permeability values determined from pump test analysis are essentially representative of horizontal values and hence will not give correct estimates of design yield of RC wells with infiltration ponds around them. In order to examine if permeability anisotropy could explain the

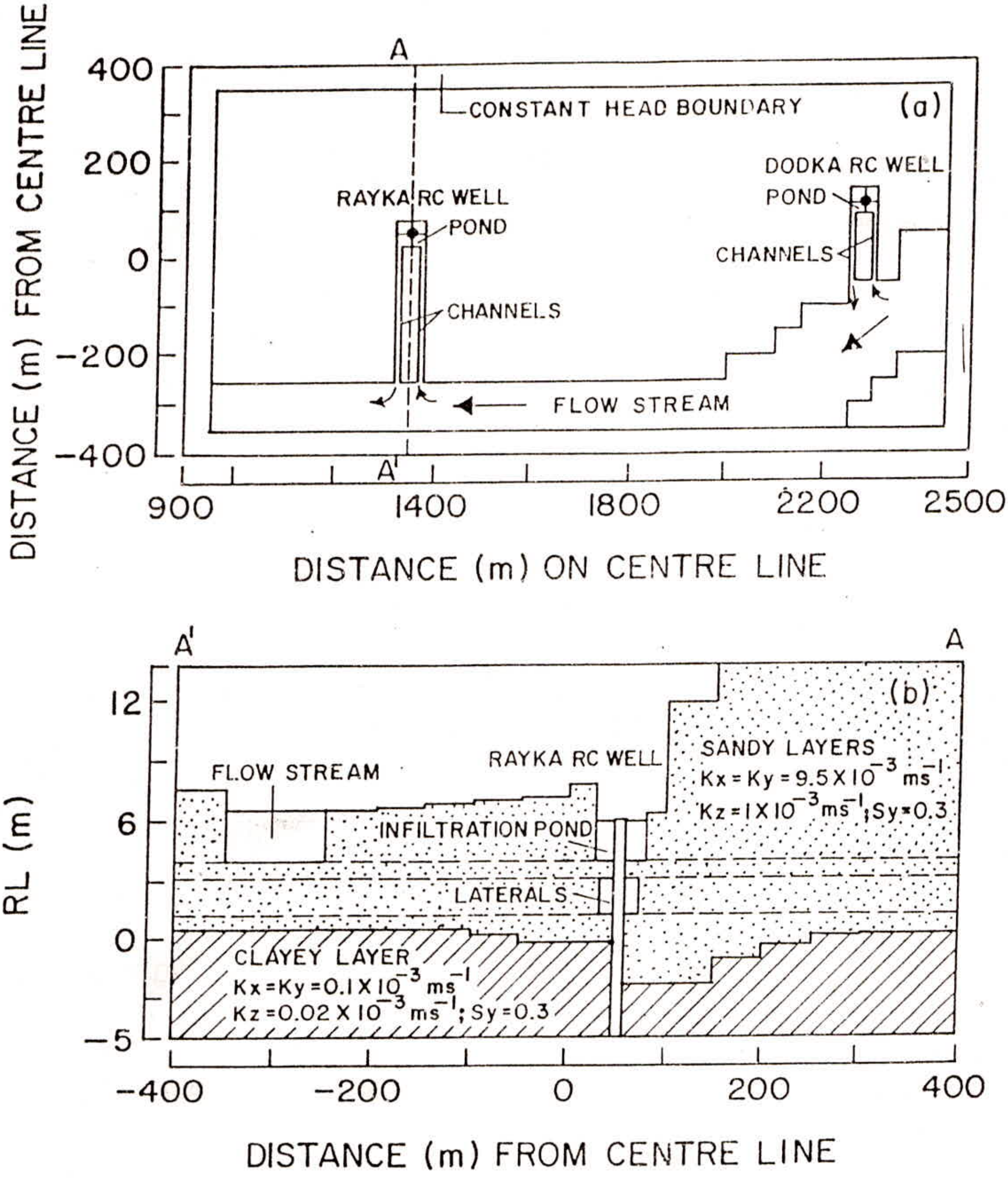

Fig. 1. (a) Plan and (b) cross section across the riverbed of the Finite Difference model used to simulate infiltration pond around the Rayka and Dodka RC wells and the saucer shaped top of the clayey aquiclude layer. Also note that the laterals of the RC-wells are defined as a zone of higher permeability.

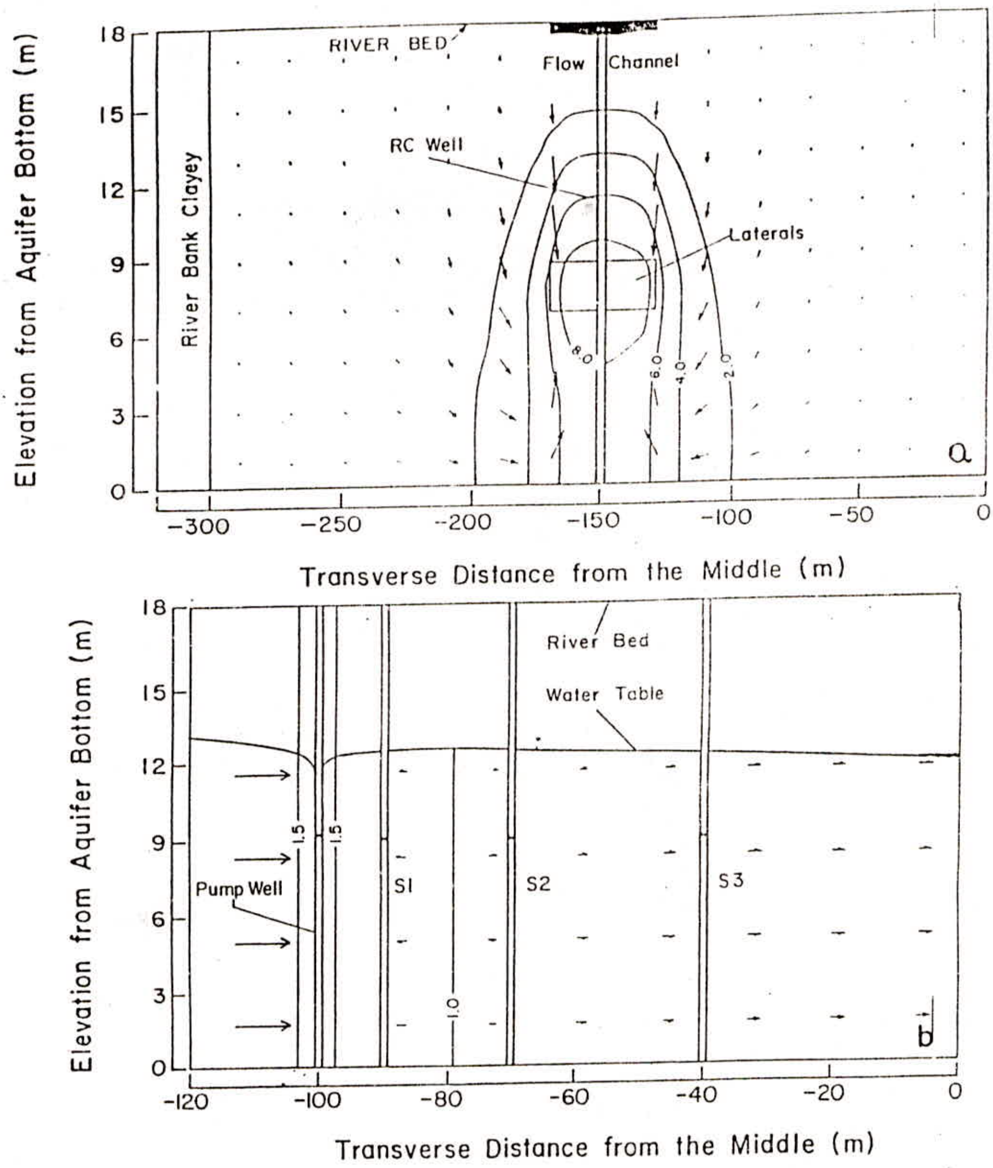

Fig. 2. Cross section across the riverbed showing drawdown contours (m) and relative groundwater velocity vectors for

(a) RC-well pump test with surface flow stream. Note that for RC-well with surface flow channel above the laterals the flow vectors are largely vertical. Whereas for normal tube-well pump test

(b) designed to estimate aquifer parameters the flow vectors are horizontal.

observed yields of the two RC wells at Rayka and Dodka, we incorporated permeability anisotropy in our model by giving different values for horizontal and vertical permeability. We were able to simulate observed yields of ~2.5 x 10^4 m^3d^{-1} of Rayka and ~2.7x10^4 m^3d^{-1} of Dodka for horizontal to vertical K value ratios of ~10:1 at Rayka and 16:1 at Dodka (Table 1). These ratios are in accordance with generally recognised observation that horizontal permeability is greater than vertical permeability in alluvial formations (Bardley, 1996).

Table 1 : Final model permeability values and corresponding sustainable yields obtained through numerical simulations of Rayka and Dodka RC wells.

Permeability x 10^{-3} ($m\ s^{-1}$)				Maximum Sustainable Yield x 10^3 ($m^3\ d^{-1}$)
Sandy aquifer		Clayey aquiclude		
Kx = Ky	Kz	Kx = Ky	Kz	
Rayka RC Well				
9.5	1.0	0.1	0.02	25
Dodka RC Well				
4.0	0.25	0.4	0.03	28

Kx and Ky are horizontal permeabilities along stream flow and transverse directions and Kz denotes vertical permeability.

We also studied the variation in maximum sustainable yield of the two RC-wells with different water levels in the river flow stream and also for situations when water table is below the riverbed level. As a result of increase in river stage level, the width of the flow channel also increases which was also taken into account during simulations. These calculations were also used to calibrate the model by comparing with the approximate seasonal yield data of the two RC wells. A sharp increase in the yield was observed when the condition changes from no surface water to the one with some surface water as is shown for the case of Sabarmati river discussed subsequently (Fig. 3). Although, it is a common knowledge that the presence of surface water increases the yield, we emphasise the presence of a break in the curve at zero water level. Our analysis shows that this break results from a sudden change in flow pattern of groundwater from largely horizontal to vertical when some surface water is maintained above the laterals (Fig. 2).

The values of maximum sustainable yields were calculated for different river stages for both saucer and flat shape top of the aquiclude layer. It was observed that for any given set of aquifer parameters and initial/boundary conditions, lower yields were obtained for saucer shape bottom (Kapur and Gupta, a, communicated).

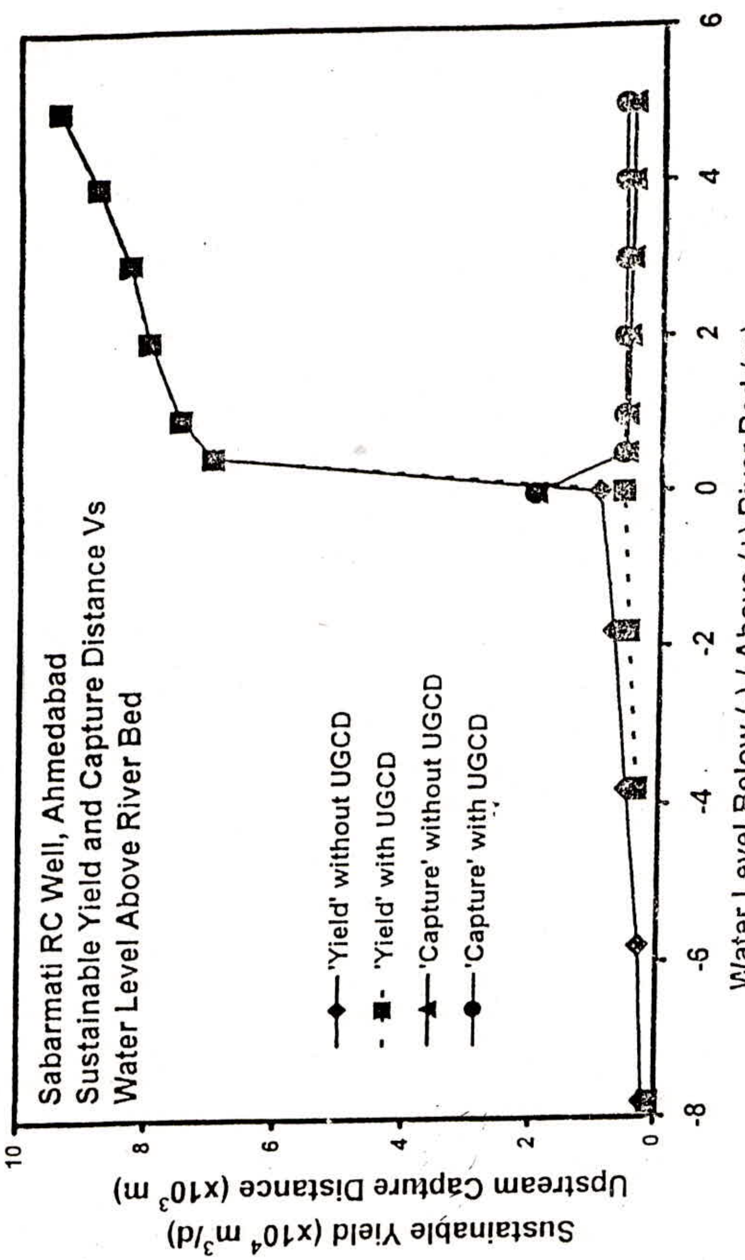

Fig. 3. Curves showing the maximum sustainable yield and capture distance variation for different water levels above (surface water present) and below (surface water absent) the riverbed. A sharp change in 'yield' and capture distance is observed at zero water table depth below the riverbed level.

3.0 THE SABARMATI RIVER BED AQUIFER AT AHMEDABAD

For the purpose of model calibration, the available data comprised:

1. Pump test data (Kadiwala, 1973) from the location of the Sabarmati RC-well at Ahmedabad.

2. A step drawdown test (NEERI, 1994) of the RC well. In all five pumps were run each starting at a different time in the RC-well test.

3.1 Pump test simulations-reanalysis

A domain of 2,000 m x 2,000 m was used for the reanalysis of the pump test data (Kadiwala, 1973). The FD model consisted of 62 rows, 63 columns and 1 layer. The thickness of the domain was taken as 18.3 m in line with the riverbed level. The flow stream having a gradient of 1:5000, ~50 m width and ~100 m from the pump well, was also incorporated into the model. The sandy Sabarmati riverbed and the adjoining clayey banks were assigned different permeability values in the model. The constant head boundary condition was assigned using observed distribution of the head values before the start of the pump test. The time drawdown curves were simulated at the six observation wells.

Starting with horizontal permeability Kx=Ky=115 md^{-1}, and vertical permeability Kz=6.9 md^{-1}, and the specific yield Sy=0.15 for the sandy riverbed aquifer following NEERI (1994), and Kx=Ky=Kz=20 md^{-1} and Sy=0.15 for the clayey banks (Rao and Gupta, 1999), final accepted values of 160 md^{-1}, 70 md^{-1} and 6.9 md^{-1} were obtained for Kx, Ky and Kz using the pump test data of Kadiwala (1973) for the sandy riverbed aquifer (Kapur and Gupta, b, communicated).

3.2 The RC-well pump test simulations

The laterals of the RC-well lie between depths of 9.5 to 11.5 m. The domain used was 1,000 m wide and 4,000 m long representing the Sabarmati riverbed and adjoining clayey banks. As observed in the field at the time of the RC-well test, the flow stream was ~50 m wide with ~1 m deep water column and passed directly around the jack-well running diagonally across the domain. The Finite Difference (FD) grid laid over the domain consisted of 90 columns, 30 rows and 3 layer. As in case of wells at Rayka and Dodka, the middle layer was added to simulate laterals in the form of a high permeability zone of limited extent that includes the laterals.

In this simulation exercise, we accepted the horizontal permeablities as determined from our simulations of the pump test data of Kadiwala (1973). Only permeability value in the vertical direction, was varied to get a match between observed and computed drawdowns at different times (Fig. 4). The finally accepted model permeabilites are Kx=160 md^{-1}, Ky=70 md^{-1} and Kz=12 md^{-1} for the sandy riverbed aquifer.

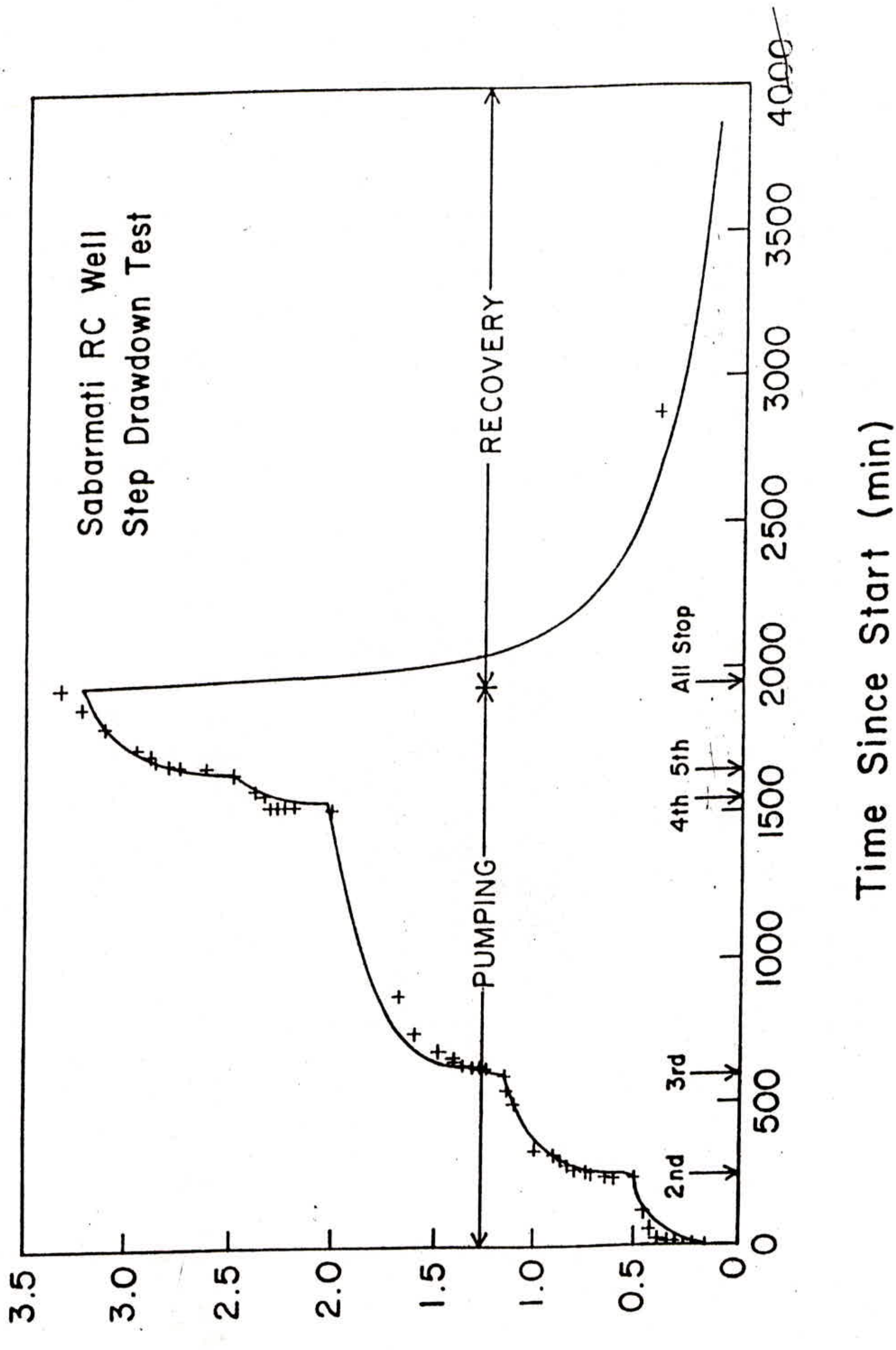

Fig. 4. Observed (marked as +) and simulated (smooth curve) drawdowns at various times for Sabarmati RC-well step drawdown and recovery test.

3.3 Simulation of maximum sustainable yield and capture distance

As was the case with RC-wells in the Mahi river, it was observed that the quantity of water that can be pumped is significantly larger if some surface flow around the jack well over the radials is maintained. As explained earlier, the reason for this break in sustainable yield curve is that surface flow provides a continuous source of water that infiltrates vertically downwards to the laterals. It is for this reason that groundwater capture zone is relatively small when some surface water is available in the flow stream around the RC-well. The groundwater capture zone in this study is identified as zone within which all groundwater flows towards the RC-well pumping at maximum sustainable yield in steady state. Outside the capture zone the groundwater flow is in the opposite direction. In the present case the groundwater capture zone is estimated to be ~550 m when some surface water is sustained around the RC-well and >2000 m when no surface water is available (Fig. 3). This is because in the latter case nearly all the pumped water must then come from horizontal flow from within the aquifer, hence relatively very large dimension of the groundwater capture zone.

So from the point of view of subsurface contaminant transport to the RC-well, some contaminant free surface water must be maintained to limit the groundwater capture zone. This is being emphasised because, at present significant quantity of effluent discharges are released on to the dry bed of the Sabarmati river. The implication of the Fig.3 is that even if the flow channel containing contaminant free water is segregated from the effluent channel on the riverbed, the possibility of contamination reaching the RC-well via the subsurface route can not be ignored.

Lastly, we comment on the Under Ground Check Dam (UGCD) proposed at a distance of approximately 1 km downstream of the Sabarmati RC-well. It has been surmised that by cutting off the subsurface flow in the downstream direction through the riverbed aquifer, the groundwater level during the dry season will rise substantially. This is then expected to increase the dry season sustainable yield of Sabarmati and few other RC-wells in the upstream direction. To examine the influence of the UGCD downstream of the Sabarmati RC-well on the yield and the capture zone, we incorporate the same in our model. In keeping with the design parameters, we take it to be 0.6 m thick and 18.3 m deep (i.e. up to aquifer bottom) and spanning the entire width of the riverbed. The permeability value is assumed to be a very small ($\sim10^{-8}$ md^{-1}) so as to make it essentially a no flow boundary. In Fig. 3 we see that even if the groundwater table rises by as much as 8 m to fully saturate the riverbed aquifer there is no substantial increase in maximum sustainable yield until a pool of water is maintained above the riverbed level.

The above analysis suggest that if the height of the proposed UGCD (GWRDC, 2000), could be increased even marginally so as to ensure some amount of ponding (~50cm) in the u/s direction the recoverable water from the RC-wells will significantly increase. The danger of contamination would however increase due blocking off the subsurface flow in the downstream direction. It is, therefore, strongly recommended that measures to prevent the discharge of sewage effluents into the river be undertaken prior to the construction of UGCD.

4.0 CONCLUSIONS

(1) As riverbed aquifers are inherently anisotropic and permeability estimates are strongly groundwater flow path dependent use of homogeneous isotropic models may result in large errors in estimation of yield and capture distance of a RC-well particularly with surface water above the radials. Under such circumstances, use of controlled flow path pump tests along with use of numerical tools can provide efficient means of groundwater flow analysis.

(2) A sharp fall in the maximum sustainable yield and increase in subsurface capture distance of RC-wells occurs when the surface water pond above the radials can not be maintained. Therefore, construction of UGCD to increase subsurface water levels only may not result in desired/optimal increase in RC well yield if it does not help in maintaining a surface water ponding over the radials.

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