

Modelling contamination of a drinking water supply well in the Sabarmati river bed aquifer, Ahmedabad, India

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Abstract Drinking water supply wells in Ahmedabad city were constructed in the Sabarmati river bed aquifer using radial pipes and are known as French Collector wells. Groundwater contamination from one of the French wells near Sabarmati railway bridge was noticed during 1992. The suspected pollution sources are Duff-nala of Shahibaug and two other sources from slum dwellings on either side of Sabarmati River. A combined groundwater flow, pathlines and mass transport model was constructed covering an area of 9 km² to analyse the capture zone of the French well under two different scenarios. Dry river bed condition was simulated under Scenario I and controlled flow in the river bed was simulated under Scenario II. The groundwater velocity and migration of contaminant particles from sources was analysed in the pathline model. The computed pathlines and TDS concentration contours indicate likely migration of contaminant plume from pollutant sources to the French well during 365 days under both scenarios. The modelling study emphasized the necessity of controlled release of surface water from the Dharoi reservoir to the Sabarmati river bed throughout the year.

INTRODUCTION

French wells are radial collector wells with several horizontal radial infiltration pipes emanating from a central caisson (also called a jack well) and under favourable hydrogeological conditions are convenient means of groundwater recovery. Five such wells have been supplying drinking water from the Sabarmati river bed aquifer to Ahmedabad city water supply over the last decade. Each well has pumped groundwater at a rate of 4000 m³ day⁻¹. Bacterial and fungal contamination was detected in the French well water near the Sabarmati railway bridge during September, 1992 (Figs 1 and 2). The contamination problem could have been due to infiltration of the river water containing sewage effluent discharged in this reach of the Sabarmati River. Three types of investigations have been carried out:

- a tracer test designed to ascertain if there existed a rapid channel-type of flow between the sewage discharge points and any of the radials of the collector wells;
- a step draw-down pumping and recovery test to understand the process of the French well-river bed aquifer interaction; and
- physico-chemical and bacteriological analyses of the river bed to ascertain the extent of river bed contamination.

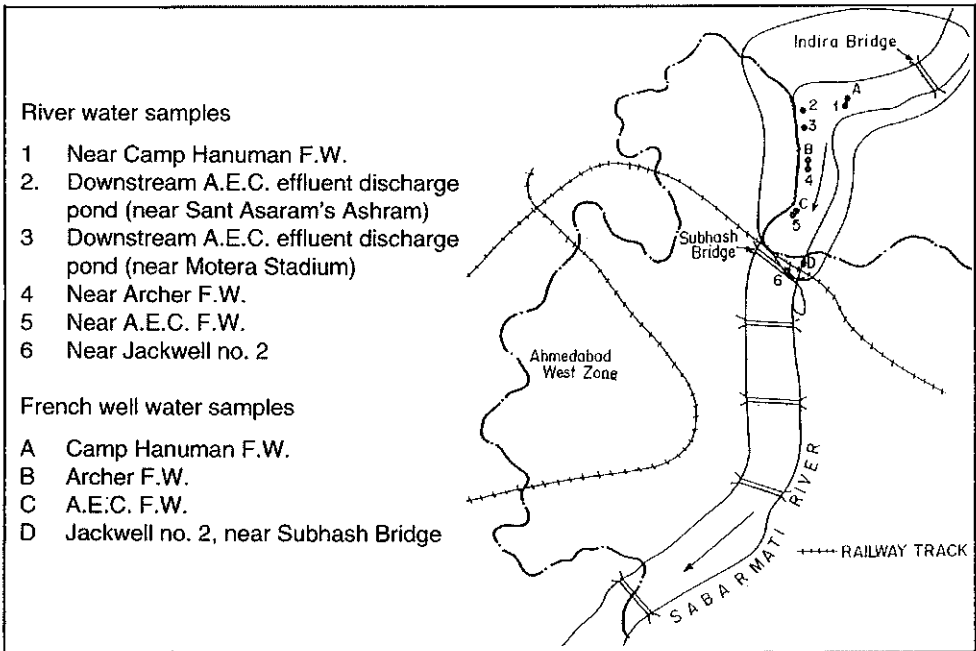


Fig. 1 Water quality monitoring stations in the Sabarmati River in Ahmedabad City.

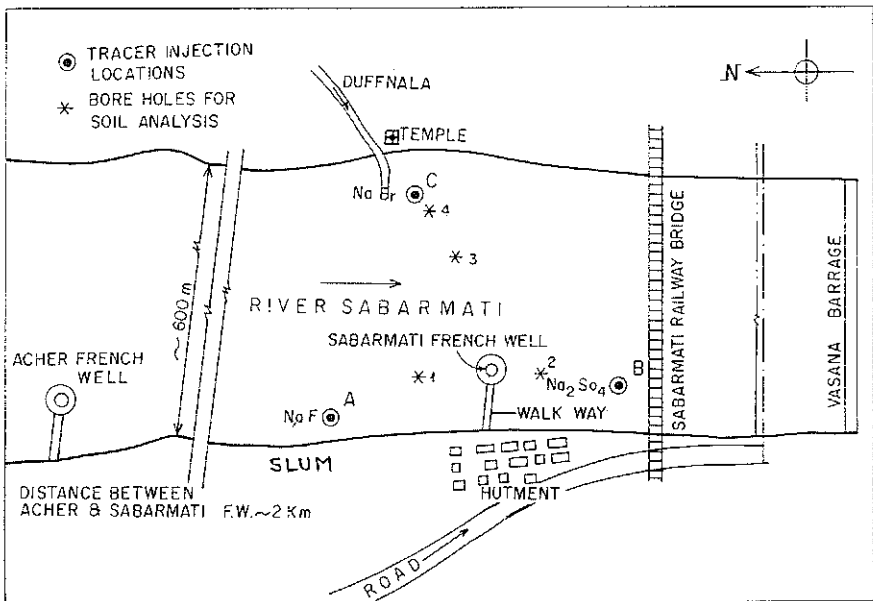


Fig. 2 Location of the Sabarmati French well near the railway bridge and three sewage (pollutant) sources.

It was reported that observed contamination of water pumped from the collector well was not caused by any channel-type of flow but may be due to slow and steady migration of contaminants through years of persistent sewage effluent discharge from river banks. The

groundwater flow, pathline and mass transport models were developed to analyse these reported concepts and to verify results of field experiments carried out by computing groundwater velocities and studying migration of contaminants from sources in the river bed aquifer. Predictions were made to determine the capture zone of the French well under two scenarios:

- when the river bed was dry with only lateral groundwater inflow/outflows across the river bed cross-section (Scenario I),
- under controlled release of surface water from the upstream Dharoi reservoir to keep a minimum water column of 0.2 m in the Sabarmati River (Scenario II).

The hydraulic head distribution of the aquifer was computed using visual MODFLOW (Guiger & Franz, 1996). The computed head distribution from the model was used to compute groundwater velocities using MODPATH (Pollock, 1989). The velocity field was utilized to compute the time dependent capture zone of the French wells under the two scenarios. A mass transport model (MT3D) was prepared for quantifying the contaminant migration pattern of Total Dissolved Solids (TDS) from three pollutant sources as a result of pumping from the collector well.

AQUIFER PARAMETERS

The permeability of the Sabarmati river bed aquifer was estimated by conducting a long duration pumping test. The permeability and aquifer thickness of the Sabarmati French well was estimated as 115 m day^{-1} and 18.3 m respectively (Kadiwala, 1973). The pumping test data was reinterpreted and results indicated that the river bed aquifer had high anisotropy with vertical permeability being only about 6% of the horizontal permeability (Table 1). Model simulation using the theory of groundwater flow to collector wells (Hantush & Papadopulos, 1962) estimated a higher permeability of 172 m day^{-1} around the French well (Table 1). The hydraulic gradient in the river bed aquifer was assumed as 0.5 m km^{-1} and porosity as 0.2. The permeability of formations on either side of the Sabarmati river course was assumed to be 20 m day^{-1} and the thickness of the first layer 18.3 m and the second layer as 10 m.

Table 1 Hydrogeological parameters of the Sabarmati river bed aquifer estimated from different pumping test interpretations (DFR, 1994).

Location	Sabarmati French wells:		Acher French well:
	A	B	C
Saturated aquifer thickness (m)	18.3	20.0	17.0
Permeability (m day^{-1})	115	172	90
Ratio of vertical to horizontal permeability (K_z/K_x)	0.06	–	–
Storage coefficient (S)	0.2	0.2	0.2

A: using pump test data of Kadiwala (1973) and considering theory of unconfined aquifers with vertical movement; B and C: obtained from pumping test interpretation model with no vertical movement.

BOUNDARY CONDITION AND STRESSES

The model area covers about $3000 \text{ m} \times 3000 \text{ m}$ and the Sabarmati River flows from north to south through the centre. The width of river is about 500 m around the French

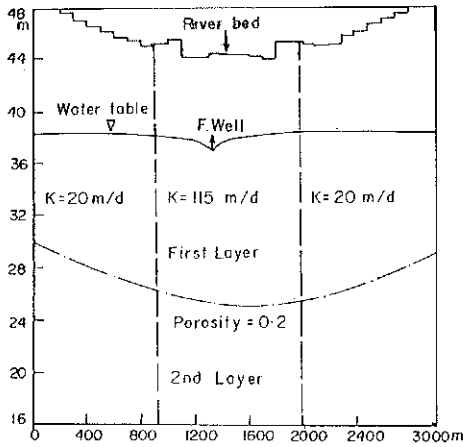


Fig. 3 Vertical cross-section of the Sabarmati River simulated in the model.

well near the Sabarmati railway bridge, Ahmedabad. Three point sources include:

- Duff-nala stream of Shahibaug on the eastern periphery of the river,
- sewage discharge from a slum pocket on the western periphery, and
- another sewage discharge from hutments to the south of the French well.

A finite difference grid was used for modelling of groundwater flow, pathlines and mass transport. The simulated vertical cross section has two layers (Fig. 3). No flow boundary has been assumed to the east and west. Some lateral inflow enters from the north and leaves to the south mostly across the river bed. The inflow and outflow at the river nodes were simulated as constant head boundary conditions. The collector well is fitted with 16 radial infiltration pipes of lengths varying from 3 to 50 m at a depth of 10–11 m below the river bed (Fig. 4). Groundwater pumping of $4000 \text{ m}^3 \text{ day}^{-1}$ from the French well was simulated in the model throughout the year. The Duff-nala stream was located about 600 m from the French well and average sewage discharge was about $300 \text{ m}^3 \text{ day}^{-1}$. About $100 \text{ m}^3 \text{ day}^{-1}$ was assumed as seepage to the groundwater regime and was simulated as a quantum of input through an injection well in the model. The sewage effluent discharge from slum pocket and hutment sources was about $30 \text{ m}^3 \text{ day}^{-1}$ each. The seepage from these sources was assumed as $10 \text{ m}^3 \text{ day}^{-1}$ each to the groundwater regime and accordingly simulated as input to the model through two injection wells. Local pumping and areal recharge was assumed equal. Thus no areal input/output was simulated in the model.

MODEL

Groundwater heads were computed in the model from visual MODFLOW software (Guiger & Franz, 1996; McDonald & Harbaugh, 1988). The computed heads were used to calculate groundwater velocities using porosity values in the MODPATH program (Pollock, 1989). The groundwater velocity field was coupled to the mass transport model using MT3D software (Zheng, 1990). Sewage effluent TDS concentration was in the range of $800\text{--}1000 \text{ mg l}^{-1}$ and at these sources the

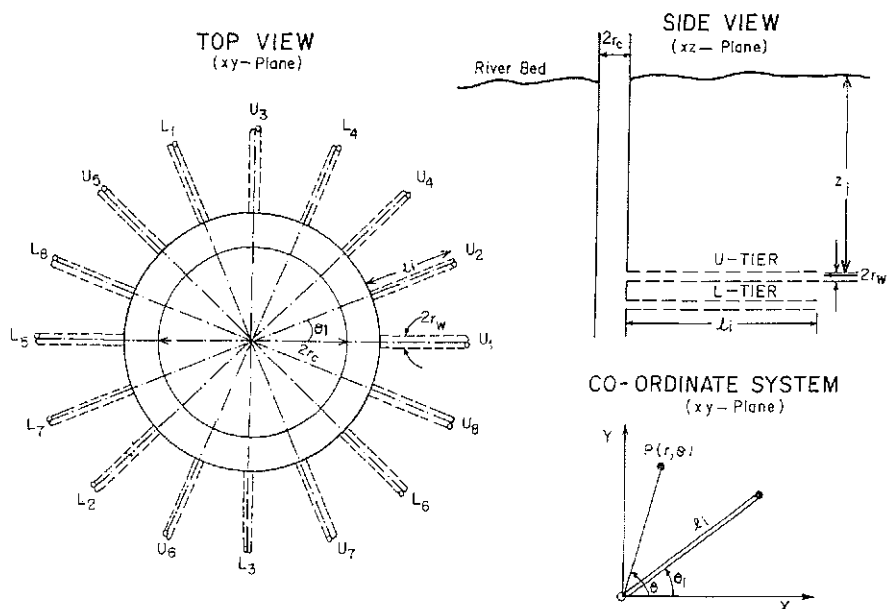


Fig. 4 Schematic diagram of the Sabarmati French collector well.

groundwater TDS concentration was reached at about 500 mg l^{-1} . Thus the groundwater TDS concentration at the source nodes was kept constant at 500 mg l^{-1} throughout the mass transport model simulation period. The longitudinal dispersion coefficient of 30 m and a horizontal transverse dispersion coefficient of 10 m were assumed for accounting dispersion processes in mass transport. The model used a daily time step for 365 days. Time dependent pathlines and iso-TDS concentration contours were computed under the two different scenarios; they determined the capture zone and contaminant migration from sources towards the French well.

SCENARIO I: DRY RIVER BED CONDITION

The steady state water level and drawdown at the French well were computed. A maximum drawdown of 3 m was compared with observed drawdown and a close match was obtained. The groundwater velocity vectors indicate a predominant groundwater flow towards the French well. The predicted pathlines assuming conservative contaminant migration with a retardation factor ($R = 1$), indicates the capture zone of the French well for 365 days. The capture zone had a radius of about 350–400 m (Fig. 5). The migration of contaminant in groundwater for the same period was predicted in the mass transport model. The computed iso-concentration contours of TDS indicate the migration of contaminant from pollutant sources entering the capture zone of the French well (Fig. 5).

SCENARIO II: CONTROLLED FLOW IN RIVER

The boundary conditions of river nodes were modified to incorporate river-aquifer interaction assuming controlled release of surface water flow from the upstream

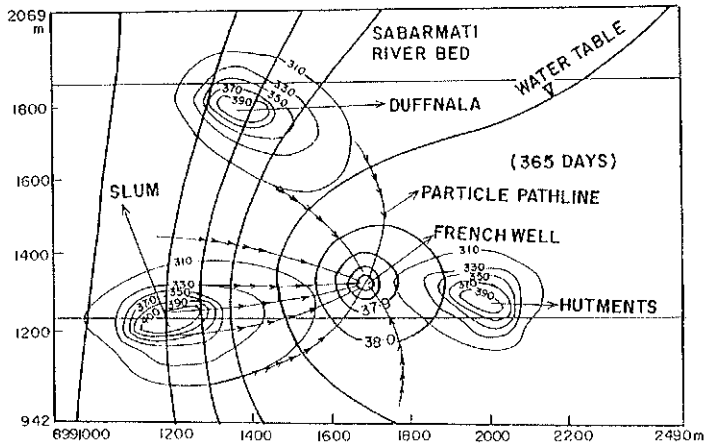


Fig. 5 Predicted contaminant migration from sewage sources and capture zone of the French well under Scenario I: dry river bed.

Dharoi reservoir. The surface water level was assumed to be about 0.2 m above the stream bed level along the entire river course. The hydraulic gradient of river water level was considered while assigning surface water level at the river nodes. The scenario could be implemented by arranging a controlled release of surface water from Dharoi reservoir throughout the year. The leakage factor from the stream bed to the aquifer was assumed as 0.03 l day^{-1} . The output from the model, i.e. pumping from the French well and pollutant load from three sources on the Sabarmati River were kept the same as in Scenario I.

The computed maximum draw-down around the French well under the second scenario was 0.9 m. About 85% of pumped water from the French well was replenished through river-aquifer interaction. The predicted capture zone of the French well for 365 days under the scenario was small (Fig. 6). The computed iso-concentration of TDS from the mass transport model indicates decreased levels

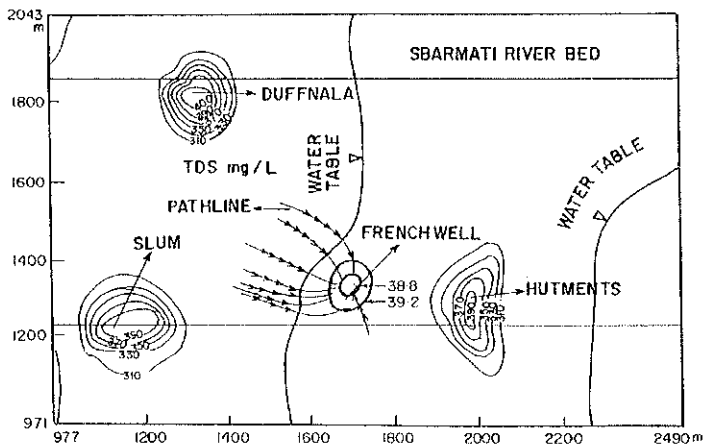


Fig. 6 Predicted contaminant migration from sewage sources and capture zone of the French well under Scenario II: flow in river.

confined to a small region. In this case, there is no possibility of pollutant particles migrating from sources to the French well capture zone over a period of one year. The length and width of the contaminant plume from the three pollutant sources was relatively small (Fig. 6).

Comparison of pathlines and iso-concentration contours of TDS under both scenarios indicate that the capture zone of the French well under Scenario II was much less than under Scenario I. Scenario II clearly indicated the necessity of controlled release of surface water from the Dharoi reservoir to maintain a minimum level of 0.2 m surface water flow in the river bed around the French well. The scenario could be implemented through an appropriate planning of controlled release of surface water from the Dharoi reservoir. The significant role of river-aquifer interaction controlling pollutant migration from the sewage sources was evident in this scenario. The flow modelling study obtained a radius of influence of pumping from the French well as 150–200 m when there is flow of surface water in the river; confirming the pumping test results (DFR, 1994). The annual flood flows also dilute surface water contamination and it may take more than one year for the contaminant in groundwater to reach the French well, as reported from the tracer experiment results (DFR, 1994).

SENSITIVITY ANALYSIS

Variation in permeability and porosity values of the river bed aquifer was made to assess the importance of each parameter in controlling the migration of contaminants from sources to the French well using sensitivity analysis. The permeability value of 172 m day^{-1} (DFR, 1994) was used, keeping the same aquifer thickness, and the capture zone for the French well over 365 days was computed. A lower permeability value of 90 m day^{-1} was also simulated in the model and a corresponding capture zone for the French well over 365 days was also computed. Comparisons with the calibrated model capture zone revealed that there was no appreciable variation in the size of capture zone for changes in permeability values. Even if river bank aquifer permeability was modified from 20 m day^{-1} to 100 m day^{-1} and keeping thickness unaltered in the model, there still was no appreciable change noticed in the capture zone. The second parameter varied in the sensitivity analysis was a leakage factor between river and aquifer. This leakage factor was varied from 0.06 to 0.015 l day^{-1} in order to assess its influence on the capture zone. The contaminant migration moved closer towards the French well, but the capture zone remained almost the same size.

RESULTS AND DISCUSSION

The model computations were made with a uniform permeability of 115 m day^{-1} for the river bed aquifer. The extent of the computed capture zone of the French well was not appreciably changed even for permeability values which varied between 172 m day^{-1} and 90 m day^{-1} . The computed maximum draw-down around the French well for different permeability values is presented in Table 2. The change in average groundwater velocity was found to be very small under different permeability values. This might be due to minor variations that could have resulted in a hydraulic gradient

Table 2 Comparison of computed draw-down (in m) at the French collector well for different permeability values of river bed aquifer.

River bed aquifer permeability (m day ⁻¹)	Scenario I	Scenario II
172	2.0	0.6
115	2.5	0.9
90	2.6	1.0

for changes in the permeability values. The permeability of the river bank does not have much influence on the river bed aquifer. This feature clearly illustrated that drawdown due to pumping from the French well was mainly confined to a 500 m width of the river bed aquifer only. However, it was noticed that significant changes in the velocity field would occur for variations in the porosity value, which controls the migration of contaminant and also the capture zone of the French well. Thus it seems important to estimate the porosity value more precisely in the river bed aquifer.

CONCLUSION

A well head protection area that was delineated by using a time-of-travel criterion was equivalent to a time-related capture zone. The time-related capture zone was smaller for sorbing solutes than for conservative ones. The assumption of conservative solute transport leads to a conservative estimate for computation of the size of any required well head protection area. The predicted capture zone around the French well will be somewhat larger in the present case. If the sorption property of the contaminant is known, an appropriate retardation factor can be used to account for the adsorbing properties of the aquifer material for computation of the actual capture zone. The predicted capture zone of the French well under controlled release of surface water from the Dharoi reservoir was small compared to the capture zone under dry river bed conditions. The average groundwater velocity of the river bed aquifer under both conditions ranged from 50–145 m year⁻¹. If surface water flow is allowed around the French well, continuous pumping at a rate of 4000 m³ day⁻¹ will be sustained. The capture zone of the French well under dry river bed conditions has a radius of about 300 m. There were no preferred pathways in the river bed aquifer for contaminant migration from three sewage sources on the river banks. The required travel time for the contaminant to reach the capture zone of the collector well from pollutant sources was more than a year. As such, there seems to be some self-purifying mechanism operating in the river bed aquifer during the annual monsoon flood. The contaminant migration may be considerably retarded due to filtration, adsorption and decay mechanisms. However, persistent pollution of the Sabarmati river bed around the French well could be avoided and there is a need to implement controlled releases of surface water from the Dharoi reservoir to arrest the depleting water levels in the river bed aquifer due to pumping from the French well, as well as to control migration of contaminant from the three known pollutant sources around the French well.

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REFERENCES

- DFR (Draft Final Report) (1994) Investigation into Contamination of the French Well at Ahmedabad. Study undertaken jointly by National Environmental Engineering Research Institute, Nagpur, and Physical Research Laboratory, Ahmedabad, India.
- Guiger, N. & Franz, T. (1996) *Visual MODFLOW Version 2.0*. Waterloo Hydrogeologic Software, Ontario, Canada.
- Hantush, M. S. & Papadopoulos, I. S. (1962) Flow of groundwater to collector wells. *J. Hydraul. Div. ASCE* **88**(HY5), 221–244.
- Kadiwala, A. D. (1973) Permeability characteristics of Sabarmati aquifer. MEng Thesis, Department of Civil Engineering, Gujarat University, Ahmedabad, India.
- McDonald, M. G. & Harbaugh, A. W. (1988) *A Modular Three Dimensional Finite Difference Groundwater Flow Model*. Techniques in Water Resources Investigations, 06-A1, USGS.
- Pollock, D. W. (1989) Documentation of computer programs to compute and display pathlines using results of the USGS. Modular three dimensional finite difference groundwater model. *USGS Open File Report 89-391*.
- Zheng, C. (1990) MT3D – A modular three dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. S. S. Papadopoulos & Associates Inc., Environmental and Water Resource consultants, Maryland 20814, USA.