River Bank Filtration (RBF) Flow Processes Assessment using Particle tracking Technique nearby Varaha River, Andhra Pradesh, India

Y. R. Satyaji Rao¹, Y. Siva Prasad¹, Surjeet Singh² and T. Vijay¹
¹Deltaic Regional Centre, National Institute of Hydrology, Kakinada, A.P., India
²National Institute of Hydrology, Roorkee, India
*Corresponding author email: yrsrao@gmail.com

Abstract: Based on field lithologs, Electrical Resistivity Tomography (ERT) and Vertical Electrical Soundings (VES) at the bank filtration site, the two layer model having a top layer as clay mixed with sand (7 m thick) followed by the bottom layer as sand layer (10 m thick) is considered to carry out river bank filtrate flow modelling and particle tracking analysis. The model has been simulated using 10 observational wells during monsoon season for the year 2018. The particle-tracking technique is utilized in this paper to evaluate the movement of induced river water from the Varaha river. The filtration parameters, river bed conditions and other aquifer properties are acquired using ERT and VES surveys. The flow model has been simulated several times using MODFLOW and MODPATH for identifying the appropriate location of river bank filtration well. The modeling results indicated various pumping rates on flow paths, travel times of induced river particles, capture zones and proportion of bank filtrate-groundwater for 15 existing wells. Modeling results indicate that the travel time and migration of induced bank filtrate is dependent on pumping rates and the distance from the river to the pumping well. During simulations, most of the filtrate water arrives between the well locations PW-2 and PW-6 by the end of existing pumping period of 2 days at 700 m³/day. The capture zone, which has a connection to the river to surround aquifer, has been identified nearer to the PW-2. The proposed RBF well location nearer to the PW-2 well has the highest proportion of bank filtrate of 74% as compared to other pumping wells. The model has provided the confirmation of RBF well location on Varaha river reach to meet drinking water requirements.

Keywords: Groundwater; River bank filtration; Particle tracking

1. Introduction

The drinking water supply in India is facing specific challenges such as an increasing demand, water quality deterioration, and potential low-flow and increasing treatment costs. The high groundwater salinity problem especially in coastal areas has been increased over a period time. The need for safe drinking water supply would more persist where the groundwater is highly saline due to geogenic and anthropogenic sources in coastal areas. The induced Bank Infiltration (BI) to the aquifer is an alternative and natural water treatment method for maintaining the high water quality supplies (Essl et al., 2014; Ray et al., 2002). The BI system near rivers or any surface water bodies can be utilized to increase water quality to obtain safe drinking water supply from the river (Kühn and Müller, 2000). Most river–aquifer interaction studies have focused on the discharge losses in streams due to extraction of the groundwater by a pumping well (Hantush, 1965; Chen and Yin, 2001). The river bank filtration studies emphasizes on river-aquifer interaction by explaining the determination of the characteristics such as, the distance of pumping well from the river, the infiltrated river water travel into the aquifer during pumping...
period, the travel time from river–aquifer boundary to the pumping well, influence of pumping well to the surrounding aquifer, and the area of aquifer influenced by river water (Chen, 2001). An attempt is made to provide safe drinking water supply through RBF to the coastal rural populations, downstream of Varaha river of coastal Andhra Pradesh, India where many villages facing high salinity in groundwater. In the present study, numerical simulations are employed at study site on Varaha river reaches near Vommavaram village of S. Rayavaram mandal by utilizing groundwater flow model using MODFLOW to initiate particle-tracking simulations using MODPATH (Abdel-Fattah et al., 2008) for identification of exact location of installing the RBF well. Based on the modeling and particle tracking approach, the appropriate location of RBF well with good aquifer-river connection is successfully identified on the bank of Varaha river with high proportion of bank filtrate which is a reliable source for long term groundwater prospecting and also for potable water supply to the nearby coastal villages. The Electrical Resistivity Tomography (ERT) and Vertical Electrical Soundings (VES) survey have been conducted at the study site and have given river-aquifer interaction zones and also confirmed the location of proposed RBF well. However, to reconfirm the suitability of location of RBF well on Varaha riverbank, the groundwater flow modeling and particle tracking techniques are useful for identification of flow paths and migration of river water into surrounding aquifer zone. Based on lithologs obtained from the field, ERT and VES surveys, a two layer model is constructed to carry out river bank filtrate flow modeling and particle tracking analysis. The particle tracking model has provided the important information on appropriate location of proposed RBF well for implementing and operating the RBF system on Varaha river reaches.

2. Study Area and Methods

The study area, near Vommavaram village of S. Rayavaram mandal in the downstream of Varaha river basin is located in the Visakhapatnam district of Andhra Pradesh State and extends between latitude 17° 21’ 00” N and 17° 28’ 10” N and longitude 82° 46’ 40” E and 82° 47’ 30” E, covering an area of 7 km² (Fig.1). Most of the lithology consists of a thick river alluvium and silty clay as top soil (5-10 m) underlain by sandy aquifer, followed by khondalitic rocks as basement rock. The regional conceptual model for groundwater aquifer has been developed based on lithologs (for aquifer layers) collected during drilling of bore wells in the study region. The boundary conditions are extended to both sides of Varaha river to study the regional effect of proposed RBF well on riverbank. The groundwater flow model is created based on measured water levels (amsl) during monsoon season (September) in the year 2018. A two layer model is constructed for the aquifer system at bank filtrate site. The model represents the less saturated clay formation as top aquifer layer and saturated sandy layer (permeable) is considered as second aquifer layer (Fig.2). The top layer is defined as 3-7 m clayey silt followed by 4-10 m thick sandy layer (coarse sand) up to the maximum depth of 16 m from ground surface. In the model, the thickness of coarse sand layer (second aquifer) is reduced gradually as going farther to the river.
Fig. 1: Location of modeled area on Varaha river bank near Vommavaram village of S. Rayavaram mandal, A.P., India

Fig. 2: Cross sectional view of layers in the model

Organized by Indian Institute of Technology Roorkee and National Institute of Hydrology, Roorkee during February 26-28, 2020
In order to analyze the impact of the river water on the groundwater regime, data of groundwater level and river water level during monsoon in the month of September 2018 is collected and evaluated. Groundwater level is monitored in ten observation wells and fourteen existing pumping wells located along the river with varying distances are considered in the model. In the study area, the influence of precipitation to the groundwater recharge is less due to low permeable thick silty clay presence on first layer. The groundwater aquifer nearer to the river are dominated by river influence since the change in groundwater levels concurrent with the Varaha river water level which is noted in the observation wells. This indicates a strong hydraulic connection between surface water and groundwater. The total recharge of 8 percent of total precipitation is considered in the model calibration. For initial estimation of hydraulic properties to the model, the hydraulic conductivities of the model layers were calculated from the aquifer thickness and transmissivity values estimated from the pumping tests of the region. Left branch of Varaha river is considered as river boundary condition which allows water to enter the wells through gravity flow. The river bed material is assumed to be the same as the aquifer material (Shamsuddin et al., 2014). The model setup for the bank filtration and existing pumping wells are shown in Fig.3.

Fig 3 Distribution of pumping wells near Varaha bank filtration site
In several calibration runs, the input parameters are refined and a specific conductivity values ensured to give best match between the observed and calculated head values. In the model, three zones of different horizontal hydraulic conductivity (K) values ranging from 3.8 m/day to 36 m/day are assigned. One uniform conductivity zone across the entire first layer of model region with a value of 3.8 m/day in the x, y direction as it is considered as less permeable. Since second layer is more saturated and permeable than first layer, the conductivity value of 36 m/day is set to calibrated for second aquifer layer (sand layer which is hydraulically connected with the river). Based on the river conditions, the river bed zone in the second layer is well calibrated with the conductivity value of 9 m/day.

3. Results and Discussion

The data used for calibration were based on the monitoring data collected in the month of September 2018 from ten observation wells to simulate the groundwater flow and transport pathogens and particles in Varaha river bank filtration system. The relation between measured and simulated heads at the calibration wells is shown in Fig.4. For this model, the estimated the RMS error is 0.1 m, and the normalized root mean square error (NRMS) is 8.3%, which indicate a well-calibrated model.

![Calculated vs. Observed Head: Steady state](image)

**Fig.4** Computed and Observed head for steady state condition (September 2018)
Particle Tracking Analysis

To show the migration process of infiltrated river water into the first and second aquifers, forward particle tracking was performed by using MODPATH (Pollock, 1989). For each zone a sub-regional water budget is also calculated for every pumping well during one day pumping using ZONEBUDGET. Particles were placed along the interface between the river and aquifer in a model (Fig.5). In Fig.5, the maroon arrows represent the river water pathlines that terminate at each pumping wells in the model domain. For establishing new RBF well, three different scenarios are established in particle tracking with varying pumping rates to the wells.

![River water pathlines in model domain](image)

**Scenario-1: In the case of no RBF well**

To establish flow paths from the river, the particle tracking technique is used initially to all the existing pumping wells PW1-PW13 with the minimum pumping rate of 30m$^3$/day. It is identified that, out of fourteen pumping wells, PW-2, PW-3, PW-8, PW-9 are only the wells which are extracting river water with more particles and path lines with higher flow velocities (Fig.6). The path lines that are terminating from river are reaching to PW-2 well in 57 days and 40 days for the first and second aquifers respectively with the velocity of 0.75 m/day. For the remaining

Organized by Indian Institute of Technology Roorkee and National Institute of Hydrology,
Roorkee during February 26-28, 2020
wells, most of the extracted water is from groundwater. For PW-3 well, particles are reaching from layer-2 in 146 days with the velocity of 1.1 m/day. In this case, more than 365 days is needed to reach the particles to PW-8 and PW-9. Hence, it is established that, the appropriate location for installing the new RBF well could be nearer to PW-2 and PW-3.

![Fig.6 Path lines for pumping wells PW-2, PW-8, PW-9, PW-13 are active with the minimum pumping rate of 30 m$^3$/day](image)

**Scenario-2: When RBF well installed on Varaha river bank**
The pathlines of proposed RBF well is examined by putting it in between PW-2 and PW-8 as shown in Fig.7. The pumping wells PW-2, PW-8, PW-9, PW-13 and RBF well are activated with higher pumping rates. The path lines that are terminating from river are reaching to PW-2 well in 26 days from second aquifer with the velocity of 1.1 m/day. The particles could not reach to PW-8 and PW-13 wells and no particles entering from layer 1 and layer 2 to these two wells. The particles taking 260 days to reach PW-9 well from layer-2 having velocity of 0.96 m/day. Whereas, particles has been reached to RBF well within 19 days from layer-2 with a velocity of 1.4 m/day.

**Scenario-3: When all pumping wells and RBF well are active with higher pumping rates**
When all wells are active with the pumping rate of 100 m$^3$/day, the RBF well extract water from river within 3 days. It is identified that, the RBF well extracts water from river less than one day when pumping rate of RBF well are increased to the maximum yield of 500 m$^3$/day. It is also identified that, except PW-2, RBF well, PW-8 and PW-9, none of the river water path lines are converged (Fig.8) at the other pumping wells within 5 days. It is also identified that, unlike RBF
well, none of the pumping wells extracting the river water path lines within one day. Except these four wells, the remaining wells extracting the bank filtrate in more than 50 days time (Fig.5).

**Fig.7** Pathlines of pumping wells PW-2, PW-8, PW-9, PW-13 and proposed RBF well are active
Fig. 8 River pathlines in 50 days travel time when all pumping wells are activated with 100 m$^3$/day

*Backward tracking of particles: Capture zone analysis*
The backward tracking in MODPATH is used to delineate capture zones for the pumping wells for given time period (Fig.9) shows water contributed from the river is mixing with water contributed from the surrounding aquifer to the pumping wells in bank filtration zone. The capture zones after five days of pumping with the pumping rate of 300 m$^3$/day for the pumping wells PW-2, PW-3, PW-5, PW-6, PW-7, PW-8, and RBF well (Fig.9). The Fig.9 illustrates that the pathlines intersect the area covered by the river which indicates that, a good connection between the river and the production wells PW-2 and proposed RBF well is existed during the pumping period. Hence it is clear from capture zone analysis that, PW-2 and RBF wells have more river water influenced zones around these two wells than other pumping wells.

**Mixture of river water and groundwater at different pumping wells**

In Bank filtrate zone, the pumping wells will produce a mixture of river water and groundwater. The particle tracking model has been demonstrated that, travel time and proportion of river water is depend on distance and location of pumping well from the river. For the wells located farther from the river, the pathlines will take longer time to reach the well. To determine the percentage of river water at the pumping well, zone budgeting option is used. Fig.10 shows the portion of the pumped water at different wells of model domain. For monsoon conditions, PW-6, PW-10, PW-13 and PW-15 are capturing higher percentage of groundwater extraction of more than 50% and also taking very long travel time to receive the river water. Out of all pumping wells, the existing pumping well PW-2 is receiving 71% of bank filtrate with lesser travel time of 2 days.
and the proposed RBF well is receiving 74% of bank filtrate with further lesser travel time of less than 1 day from Varaha river during monsoon season.

![Fig.10](image) portion of pumped water in the existing pumping wells and RBF well

Modeling results indicate that the travel time and migration of induced bank filtrate is depending on pumping rates and the distance from river to the pumping well. Hence it is recommended from particle tracking analysis that, the River Bank Filtration (RBF) well is to be proposed in the vicinity of PW-2 to extract higher percentage of river water from Varaha river.

5. Conclusions

The particle-tracking technique is used at a river bank filtration (RBF) location site near Vommavaram village to establish new RBF well on riverbank. From particle tracking analysis, most of the filtrate water arrives between the well locations PW-2 and PW-8. From the analysis of zone budget analysis, out of total extracted water, nearly 74% of river water could be extracted from proposed RBF site. From capture zone analysis, a good connection between the river and the production wells PW-2 and proposed RBF well is existed during the pumping period. Hence it is recommended from particle tracking analysis that, the River Bank Filtration (RBF) well is to be proposed in the vicinity of PW-2 to extract higher percentage of river water from Varaha river and for implementing and operating the future RBF practices on Varaha river reaches.

Acknowledgements

The authors are thankful to the Department of Water Resources, RD & GR, Ministry of Jal Shakti, Govt., of India for proving funds for project and also to Dr.N.C Ghosh who has provided
technical guidance for the project. Dr. S. K. Jain, Director, National Institute of Hydrology, Roorkee is duly acknowledged for his support and encouragement to initiate field based study.

References


