A data-driven model to simulate groundwater levels - Application to an urban agglomeration in India

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1. Background

Groundwater contributes 85% of drinking water supply in India [1] . Due to variable surface water supply, urban areas are heavily dependent on groundwater. The rapid increase in urbanization impacts groundwater resources in the form of overexploitation, reduction of recharge zones, and deterioration of groundwater quality. Hence, it is important to quantify recharge and simulate groundwater levels for better sustainable water management.

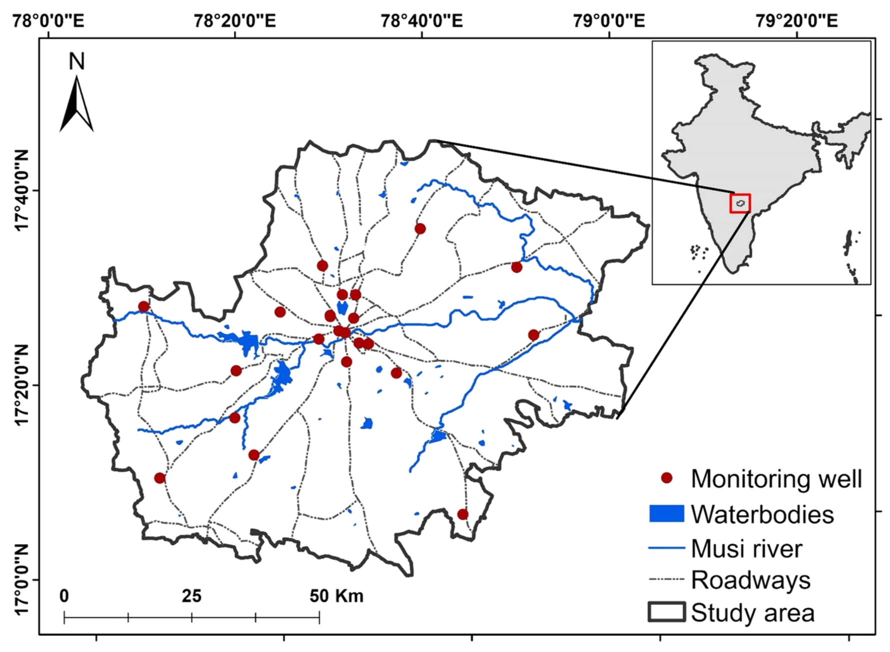


Figure 1: Location of the study area (Hyderabad metropolitan development authority region, India).

This study focuses on estimating recharge and simulating groundwater head in Hyderabad, one of the fastest growing mega cities in India, having heterogeneous sub-surface conditions (Figure 1). We calibrate a lumped parsimonious groundwater model using a multi-objective evolutionary algorithm. We also include uncertainty estimates in our groundwater head predictions using the Generalized Likelihood Uncertainty Estimation (GLUE) method.

2. Methods

We use a parsimonious conceptual groundwater model that is based on the following equation [3] :

$$h_i = h_{i-1} + \frac{r * P_i}{S_y} - \frac{Q_{p_i}}{S_y * A} + \frac{Q_{in_i} - Q_{out_i}}{S_y * A}$$

h_i : depth to water level in month i [m], h_{i-1} : depth to water level of previous month [m],
S_y : Specific yield [-] , P_i : input rainfall [mm/day],
r : recharge factor[-], Q_{in_i} : the lateral inflow [m³/s],
Q_{out_i} : the lateral outflow [m³/s], A : the area of study [Km²],
Q_{p_i} : f($Q_{p,max}$) [m³/s], where $Q_{p,max}$ is the maximum pumping rate and f is a step function (Figure 2).

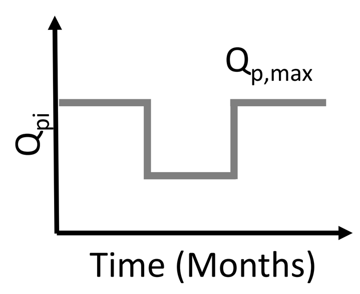


Figure 2: Pumping rate as a function of time(months). Pumping is assumed to be high during non-monsoon season and lesser in monsoon season.

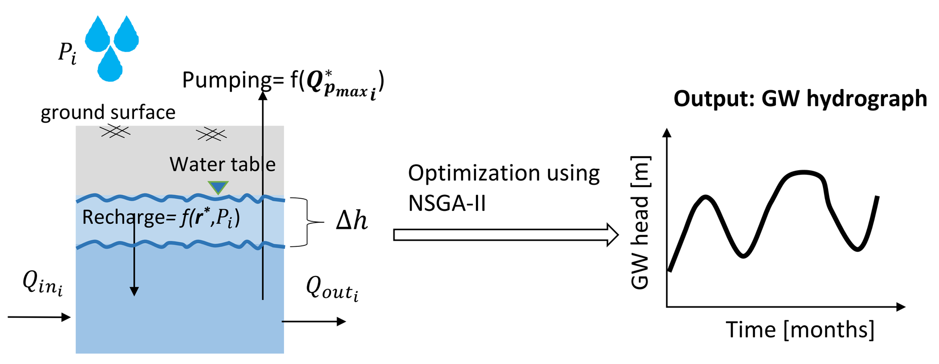


Figure 3: The conceptual model structure for simulating groundwater levels as a function of time.

A simple groundwater balance model based on the above equation along with storage, inflows, and outflows within the study area boundary is used (Figure 3). We simulate the model during 2004-2007 using non-dominated sorting genetic algorithm (NSGA-II) and validate its performance for the year 2008 [2]. Finally, GLUE method is used to understand the behaviour of the parameter used in the model [4].

3. Results: Calibration of the model

Model performance was evaluated using three objective functions: root mean squared error (RMSE), mean absolute error (MAE) and Nash-Sutcliffe model efficiency (NSE). Optimal values of the recharge factor, specific yield, and maximum pumping rate were estimated.

Three recharge scenarios are considered in the analysis:
(a) Case-1: constant recharge factor, r_1 for all the months.
(b) Case-2: two sets of recharge factors, r_1 for monsoon and r_2 for the non-monsoon season.
(c) Case-3: three sets of recharge factors, r_1 for the winter, r_2 for the summer, and r_3 for monsoon season.

The set of optimal solutions that account for the trade-off between the objective functions for three cases are selected for the further analysis (Figure 4).

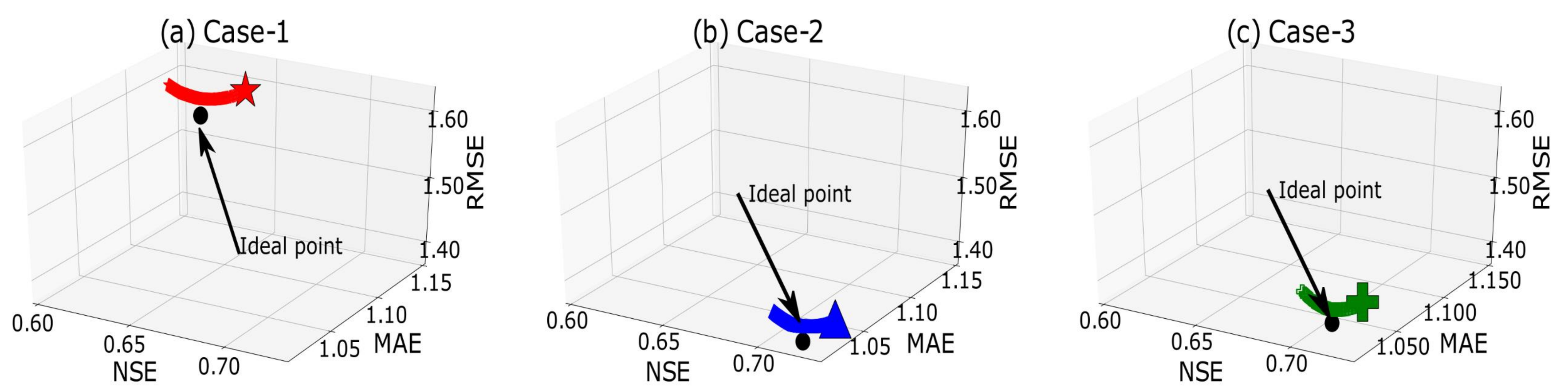
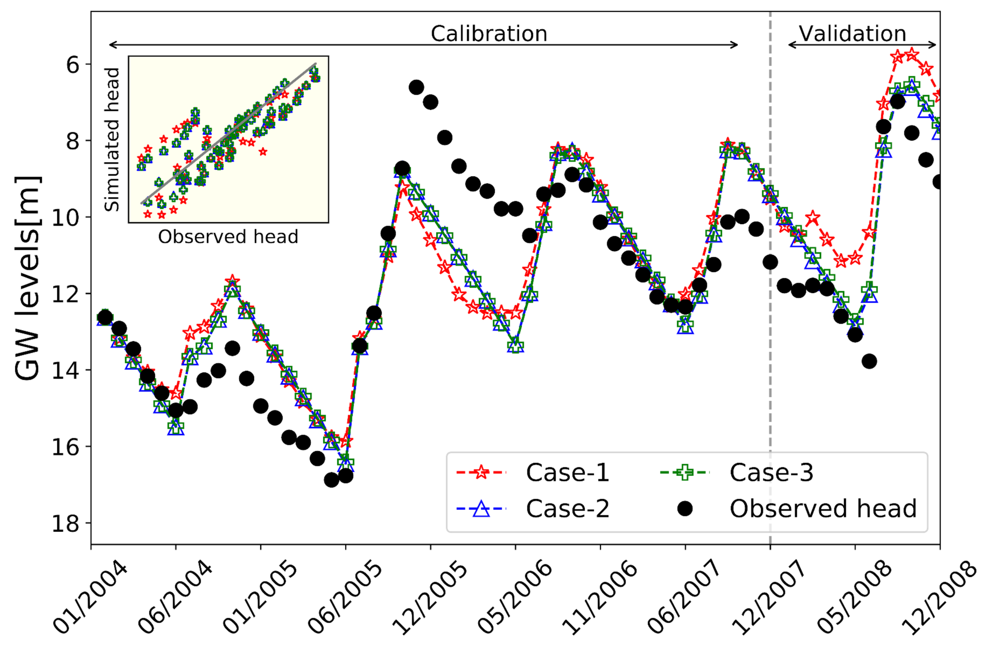


Figure 4: Pareto approximate solutions representing the trade-offs between the three objective functions. Shown are NSE on x-axis, MAE on y-axis, and RMSE on z-axis for three different recharge scenarios: (a) constant recharge throughout the year, (b) different recharge factors for monsoon and non-monsoon periods, and (c) three recharge factors for summer, monsoon and winter. The optimal solution is highlighted and is further used in validation.

4.Results: Validation of the model

The recharge factor (as a fraction of rainfall) is found to be 12% (case-1), 15% and 0% (case-2: monsoon and non-monsoon), and 29%, 0%, 5% (case-3: monsoon, summer and winter) during the calibration period (Jan 2004- Dec 2007). The model has reasonable performance in the validation period for the three recharge scenarios (Figure 5).



MAE: 1.15m,1.02m,1.04m
RMSE: 1.59m,1.39m,1.4m
NSE: 0.64,0.72,0.71

Figure 5: Validation of the optimal solutions from Jan 2008 to Dec 2008. The predicted groundwater head (y-axis) is plotted as a function of time (x-axis). Each colored line represents a simulation under a recharge scenario. Observations are shown as black dots.

5.Results: Uncertainty and Sensitivity analysis

The uncertainty bounds, along with the observed groundwater levels for the three recharge scenarios during calibration and validation period are shown in Figure 6. The result shows that most of the observed groundwater heads fall within the given 95% confidence interval during the validation period [2008]. A regional sensitivity analysis showed that specific yield and pumping rate are the most sensitive parameters for simulating groundwater head (Figure 7).

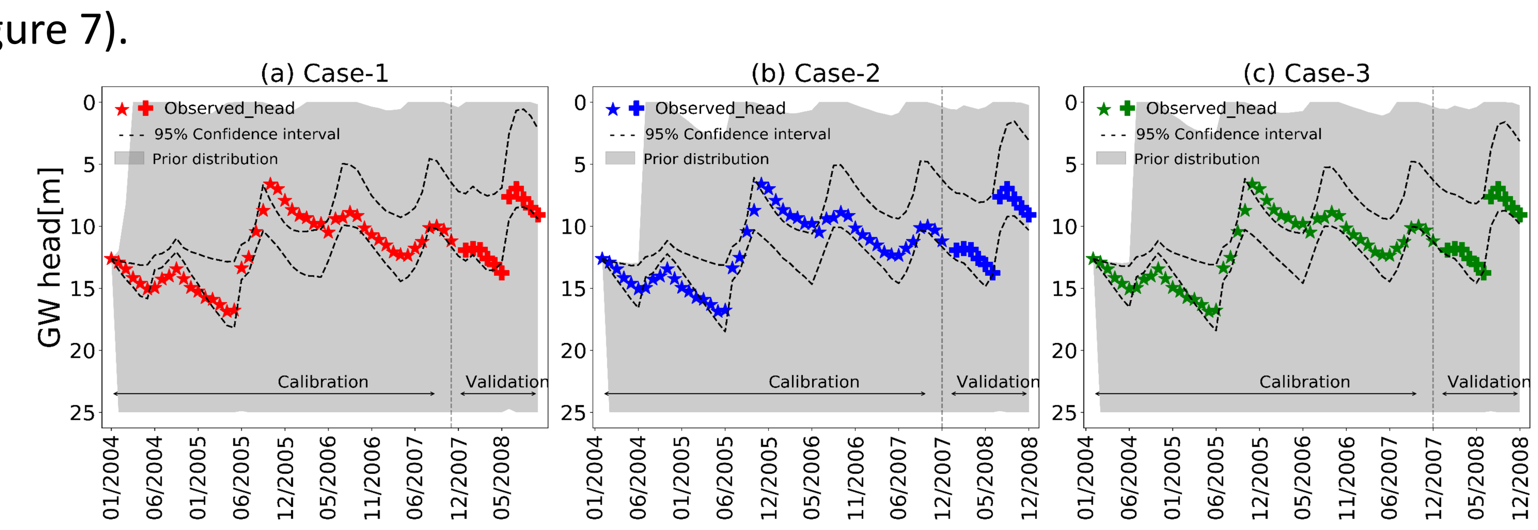


Figure 6: 95% prediction intervals as obtained from the three optimal parameter sets for each recharge scenario.

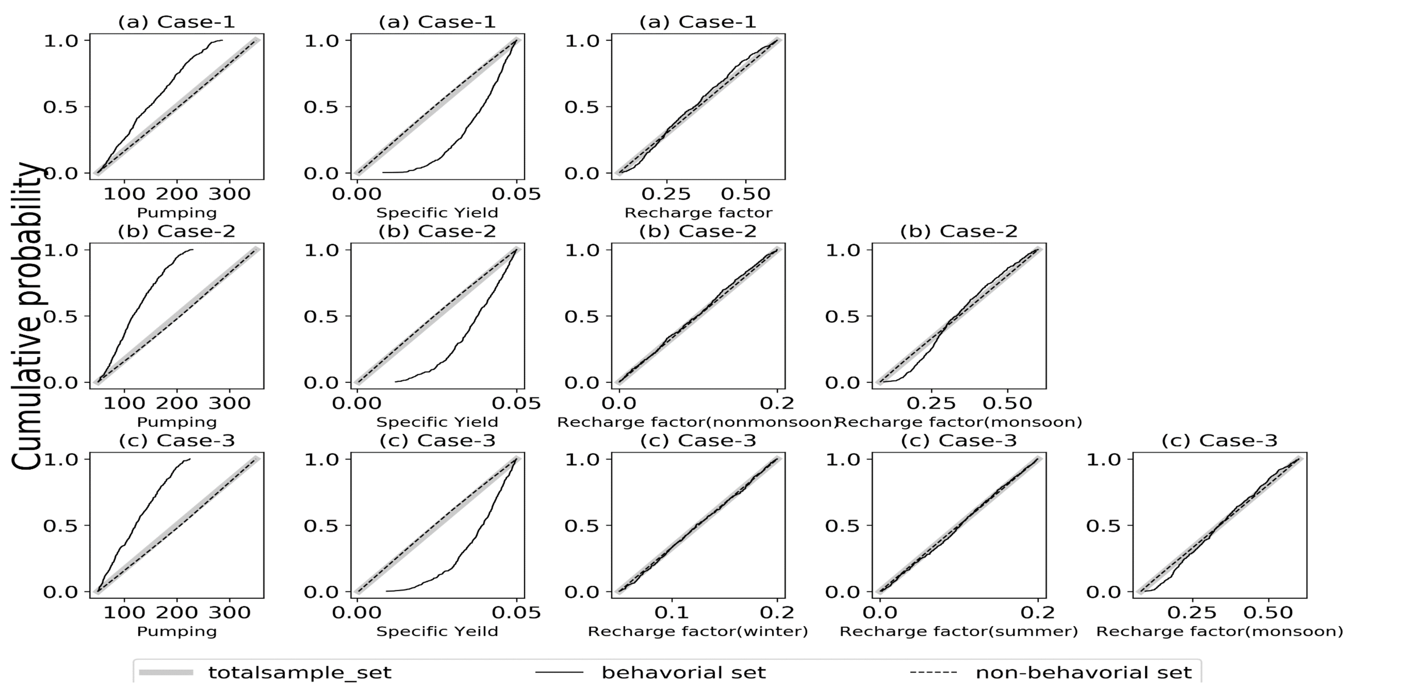


Figure 7: Cumulative distribution functions of behavioural (solid black), non-behavioural (solid dashed), and prior distribution (grey solid) for each parameter.

Conclusions

We develop an open source software, REGSim (Recharge estimation and groundwater simulation for urban aquifers) to provide a platform for modelers to apply these methods to various other urban regions. The software includes all the methods discussed here. Additionally, it can also compute lateral fluxes within a GIS framework [5].

This model framework can be used as an appropriate tool for estimating simple groundwater budget, and further work aims to develop future management scenarios for integrated water management framework.

Acknowledgements

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