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Groundwater Flow and Transport Modelling Around Gurupura Wetlands, Karnataka, India

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Abstract: *The water demand in the world is rapidly increasing due to population growth, extensive industrialization and agricultural practices. Groundwater plays an important role in the supplying of this ever increasing water demand. Therefore, accurate estimation of groundwater resources is a prerequisite for any sustainable water management especially in water scarce (semi – arid) areas. India has been blessed with a vast stretch of coastline. Many urban centres of the country are located on the coastal tract apart from thousands of villages and industrial settlements. Water resources in these coastal areas and wetlands take up a special significance since any developmental activity will largely depend upon availability of fresh water to meet domestic, industrial and agricultural requirements. Groundwater withdrawals in excess of safe yields and reduced recharges to groundwater due to rapidly changing land use pattern along the coasts have increased the incidences of seawater intrusions into the coastal aquifers. Groundwater modelling is an essential tool in the groundwater system in response to future stresses due to abstractions and land cover changes. Numerical groundwater flow models solve the distribution of hydraulic head and describe flow whereas numerical transport models solve the distribution of solute concentration due to advection, dispersion and chemical reactions. In the present study an attempt is made to formulate groundwater flow and transport modelling in and around wetlands of Gurupura basin in Karnataka state of India. The study intended to simulate the response of an unconfined, shallow, tropical coastal aquifer comprising of wetlands using SEAWAT. The numerical simulation of groundwater flow was carried out by building a MODFLOW model of the basin and the transport parameters are assigned to execute the MT3DMS model. Finally, the SEAWAT model which is a coupled version of MODFLOW and MT3DMS designed to simulate three dimensional, variability density groundwater flow and multi-species transport, is developed. The model is calibrated from August 2011 to August 2013 using observed groundwater heads and TDS data obtained from 27 observation wells. The data from VES (Vertical Electrical Sounding) and pumping tests conducted in the study area are used for aquifer characterization. The model is validated for 2013-2015. The model performance is encouraging except for monsoon months (June to September), while evaluating with three techniques R^2, RMSE and NSE. Overall the model performance is satisfactory with NSE≥0.5.The spatial distribution of simulated groundwater map shows presence of groundwater at a higher level in the areas around wetlands in the study area, even during peak summer months (April and May).The sensitivity analysis conducted shows that the aquifer is sensitive to specific yield, hydraulic conductivity and recharge rate. The simulation of solute transport model reveals the presence of TDS concentrations in and around the wetland regions during winter and summer seasons, but within safe range. The groundwater budget was estimated for the aquifer using groundwater mass balance simulation package 'ZONEBUDGET'. This analysis shows that during the period of maximum potential position (August), the component of groundwater contributing to wetland is 4.5% of total budget. During dry season with minimum potential head, the groundwater contribution to wetland is 1.4%. Hence, the presence of water in the wetland during the non-monsoon months is established by the contribution of only groundwater, in the study area.*

Keywords: *SEAWAT, MODFLOW, Solute transport, Groundwater modelling, Freshwater, Aquifer characterization.*

1. Introduction

1.1. Groundwater modelling

Although surface water is harnessed for domestic and industrial purposes, major thrust remains on the groundwater resources especially during the non-monsoon seasons. Excessive groundwater mining along the coast has resulted in the decline of the water table. This decline of fresh water reserves has resulted into encroachment of the sea water into the coastal aquifers both through surface and base flow. Hence it is essential to consider the effective and optimal utilization of coastal aquifers in the region for fresh water supply. The presence of wetlands serves to maintain the hydrologic balance of a region. The threat caused due to human intervention would lead to extinction of these natural water reserves. Hence understanding the phenomenon of water movement

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and contribution of groundwater to the wetlands is essential to preserve these natural habitats.

The groundwater models are handy tools for managing the groundwater resource. They can also be defined as a powerful management and prediction tool which combines the appropriate physical laws in a self-consistent mathematical model with the available hydrogeological data, to understand the response to externally applied stress and its behavior and properties of the system.

The application of a transient three-dimensional groundwater model to simulate water flux through a floodplain wetland, Narborough Bog, in Central England modelled by Bradley [1]. Three-layer groundwater model for the wetland was developed using MODFLOW considering some limitations. The accuracy of the model is then assessed by comparing daily model predictions of water-table response at specific monitoring points.

Two numerical modeling packages, MODFLOW and MT3D were used to quantify the degree of hyporheic interaction along an experimental reach of Red Canyon Creek, Wyoming by Laura K. Lautz and Donald I. Siegel [2].

The use of conceptual groundwater modelling approach of MODFLOW along with GIS was made to develope a groundwater model for the northern part of Mendha sub-basin in the semi-arid region of north-eastern Rajasthan by Rakesh K. Kushwaha et al (2009). The observed water level data from 1998 to 2003 were used for calibration and data during year 2003 to 2005 were used for model verification. The model generated groundwater scenario from 2006 to 2020 considering the existing rate of groundwater draft and recharge.

A groundwater model for Nankou area was developed by Feng Sun et al [3], using software OpenGeoSys (OGS). An independent nonlinear parameter estimation code PEST (parameter estimation system) was applied with OGS for parameter identification. The 3D hydrogeological solid model was created using GMS. Both GMS and PEST were integrated to OGS for creating the final model.

A 3-D groundwater flow model to characterize the groundwater flow system and the groundwater levels in east-central Tunisia area, using coupling of MODFLOW and Geographic Information System (GIS) tools, was developed by Fethi Lachaal et al [4]. The model was calibrated and validated with datasets during the 1980–2007 period. The Tunisian Ministry of Agriculture provided the information about 73 water wells. The simulating period is divided in to two periods: 1980–2004 period is used to transient model calibration and the 2005–2007 period is used to model verification.

An attempt is made in the present study to develop a groundwater flow and transport model in and around wetlands of Gurupura basin in Karnataka state of India.The study intended to simulate the response of an unconfined, shallow, tropical coastal aquifer comprising of wetlands using SEAWAT.The numerical simulation of groundwater flow was carried out by building a MODFLOW model of the basin and the transport parameters are assigned to execute the MT3DMS model.

The studies conducted in geologically similar regions have confirmed agreeable results in terms managing the scarce groundwater resources (Vyshali, 2008 [5], Lathashri and Mahesha, 2016 [6]).

2. The study area and objectives of the study

The study area for the investigation is the coastal aquifer of Gurupura basin on west coast of India, with its southern boundary as Gurupura River, flowing from east to west. The area lies between longitude of 74°48'24.16"E to 74°56'23.08"E and latitude of 12°56'0.18"N to 12°59'31.97"N as shown in Figure 1. The areal extent of the region is about 57.73 km^2. Mangalore Refinery and Petrochemicals Limited (MRPL) and Mangalore International Airport is located in the region. In addition, other smaller units comprising of industrial estate, small scale industries also exist in the region. The wetland patches are present in the study area around south-west part of study area. The presence of water is observed among the wetlands, during peak summer months. The availability of surface water is scarce during January to May, in the region. Hence, greater thrust will be on the groundwater resources during these summer months.

The study area has a gradual westerly sloping low-lying terrain with elevation ranging from 2 to 151 m above mean sea level. The climate of the region is tropical humid type with moderate air temperatures of 36°C during May and 21°C during December. High levels of relative humidity ranging between 65% and 100% are observed in the region. The average annual rainfall of the region is about 3,500 mm. About 85% of the total annual precipitation occurs during the months of June through September on account of the southwest monsoon. The study area consists of laterite soils.

The objectives of the study are as follows:

1. to develop a representative three dimensional numerical groundwater flows and solute transport model using SEAWAT.
2. Sensitivity analysis of the hydrological stresses and aquifer parameters on groundwater model.
3. Estimation of groundwater budget for the aquifer.

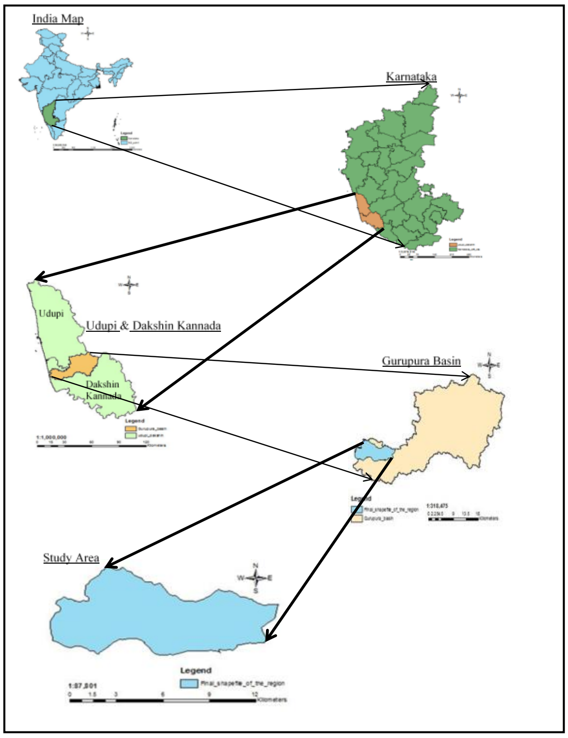


Figure 1. *The Study area*

3. Methodology

The topographic sheets, numbered 48L/13/NW, 48L/13/SW and 48L/13/SE with a scale 1:25,000 having a contour interval of 10m are procured from the Geological Survey of India. They are processed using ArcMap® (version 9.3) software to delineate the study area boundary. The Digital Elevation Model (DEM) was created and drainage network map was generated. The topographic sheets are geo-referenced and projected to UTM co-ordinate system. The meteorological, hydrological and hydro-geological data for the model are obtained from the government and private agencies. The aquifer characterization of the study area was carried out by Vertical Electrical Sounding (VES) survey and pumping tests.

The conceptual modelling approach is used in the present work for the simulation which simplifies the field problem and stacks the required field data for better understanding of the behaviour of the aquifer system of the study area. The conceptual model is introduced into SEAWAT. Initially, the MODFLOW is executed, and then the transport parameters are introduced to execute a MT3DMS model. These models are combined with additional input of density parameters to execute the SEAWAT model. Sensitivity analysis is performed to learn the parameter importance in the model calibration. Besides, the calibration is performed using the observed water level and water quality data. The aquifer parameters are revised within the appropriate range to obtain better calibration results. The model is then validated to assess the model performance evaluation.

4. The Flow Model

4.1. Data used

4.1.1 Groundwater Data

The groundwater data are collected from 27 wells in the study region on fortnightly basis. The duration of data collection is from 2011 to 2015.

4.1.2 Discretization of the basin in the study area

The physical boundary of the basin is represented by river on its south and representative ridge line along rest of the part. Hence, the conceptual model in this study requires the design of aquifer system accordingly. The aquifer is defined as unconfined, with the vertical thickness based on the hydro-geological properties and geological stratigraphy of the basin, where the model elevations range between -30m to 151m. The model of the basin has two dimensional grids in the horizontal plane with an approximate cell dimension of 100×100m. The vertical section is represented by a single grid of varying dimension. The “time steps” play important role in analysing groundwater system. The length of time step depends on the dynamic character of the hydrologic process to be modelled. The aquifer system in the present study is modelled for transient state with daily time step. The steady state simulation is performed prior to transient run, in order to set up initial groundwater head for the transient simulation. The monthly data for the hydrologic stresses (Pumping rate and recharge rate) are assigned to the model as inputs.

4.1.3 Hydrologic sources and sinks

The concept involved in the development of the groundwater flow equation is the continuity equation, which states that, the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. The concept of “recharge coefficient” is used in the present numerical simulation. The recharge coefficient is defined as the ratio of the recharge to the precipitation. The recharge package (RCH), is used to simulate the aerially distributed recharge to the groundwater system. The recharge estimation for the present study is done based on the rainfall records observed at the meteorological station at the Meteorological Observatory at Mangalore Airport. The recharge is assigned on the uppermost active wet layer of the model for each vertical column of grid cell and is modified and refined within the specified range during the calibration stage. The WEL package in MODFLOW, is used to simulate the wells which withdraw water from the aquifer at a specified rate during a given stress period. The well discharge is handled in the WEL package by specifying the rate Q, at which, each individual well extracts water from the aquifer during each stress period.

4.2 The Governing Equation

The governing equation used in MODFLOW is the three dimensional movement of constant density groundwater through a porous media is described by the following parabolic partial differential equation, called groundwater flow equation (McDonald and Harbaugh [7])

$$\frac{\partial}{\partial x}\left\{Kxx\frac{\partial h}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{Kyy\frac{\partial h}{\partial y}\right\}+\frac{\partial}{\partial z}\left\{Kzz\frac{\partial h}{\partial z}\right\}-W=Ss\left\{\frac{\partial h}{\partial t}\right\} \tag{1}$$

Where, x, y, z = the cartesian coordinates aligned along the major axes of hydraulic conductivities Kxx, Kyy, and Kzz, h = potentiometric head (L), Ss=specific storage of the porous material (L^{-1}), t =time (T), W =volumetric flux per unit volume and represents sources and sinks of water (T^{-1}).

4.2.1 Boundary conditions

The Dirichlet boundary is also called as Type I boundary. The head or concentration value may vary from point to point or as a function of time and is treated as a known quantity in the solution of the equation. A Dirichlet boundary condition of constant head equal to 2 m above mean sea level is assigned to the southern boundary for the model, which corresponds to the Gurupura River, flowing from east to west. This is based on the stage observed in the river. The time variant specified head (CHD) package of MODFLOW is used to simulate the Dirichlet boundary condition.

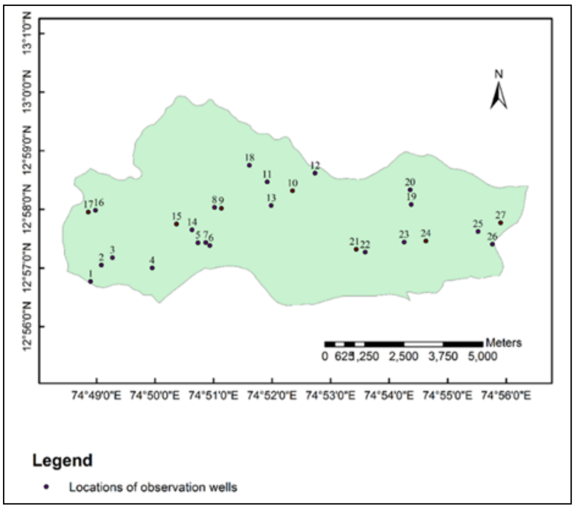


Figure 2 *Location and numbering of wells*

The Neumann boundary, also referred as Type II boundary represents the condition in which the gradient of the dependent variable is specified normal to the boundary.

In terms of groundwater flow, this boundary condition results in a specified flux of water into or out of the modelled area and in terms of solute transport, the concentration gradient is specified normal to the boundary. An impermeable boundary (commonly called a no-flow boundary) is simulated by specifying cells for which a flow equation is not solved. Except the southern boundary rest of the part is applied with Neumann boundary condition, the basin ridge line representing the no-flow boundary for the study area. The location of wells with numbering system of wells in the study area is shown in figure 2.

4.3 Steady State Calibration

Based on preliminary investigation, the aquifer system was found to be close to steady state condition during September 2010. Therefore the model was run and calibrated under steady state for this period and the calibrated hydraulic conductivity distribution and over all porosity values are obtained. The head obtained during the steady state calibration is assigned as the starting head for the transient simulation, for further modelling. Altogether, a total of 27 available observation well records are used in the steady state calibration process.

The values of statistical parameters obtained as an indication of model performance are; co-efficient of correlation (r) = 0.97, co-efficient of determination (R^2) = 0.96, and root mean square error (RMSE) = 0.98. A scatter plot of the simulated versus the observed heads is shown in figure 3. The plot reveals that the model fits the observed groundwater heads rather well.

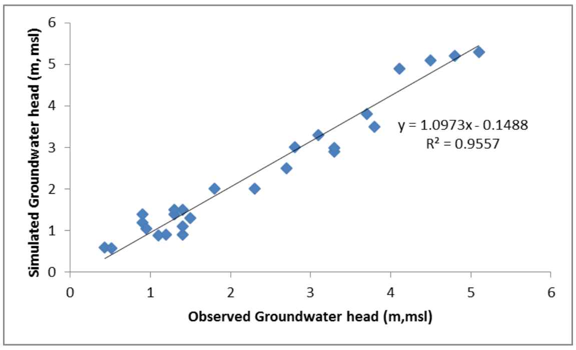


Figure 3*. Steady state calibration*

4.4 Transient Calibration

The period elapsing September 2011 to August 2013 is adopted for transient calibration. The simulation period of two years was divided into 24 stress periods. Daily time step was considered for the transient simulation applying all the hydro-geologic conditions existing during the same period. The spatial variability of the aquifer parameters and the seasonal performance of the model, were accounted for while carrying out calibration. Other than the aquifer parameters already calibrated in the steady state model namely, the hydraulic conductivity and porosity, the transient calibration requires the specification of the specific yield (S_y). After successful calibration, the values of horizontal hydraulic conductivity obtained for the unconfined aquifer was estimated to be in the range 2.54 m/day to

19.16 m/day and specific yield was estimated to be 0.007 to 0.089 respectively.
The values of R^2, RMSE and NSE for all months of the calibration period for the flow output are given in table 1. It is observed that the model performance is satisfactory as the parameters are well within the acceptable ranges. However, the model performance during the monsoon (June to Sept) is not convincing. All the three evaluation indicators showing deviation from the acceptable levels. The reasons for the deviation could be greater inter mixing of river water with seawater, additional later inflow/ outflow during monsoon months. This phenomenon is not well addressed by the model.

The model performance is tested with a graphical method and scatter plot of selected months in post-monsoon, monsoon and pre-monsoon, for are presented in figure 4. The scatter plot of the measured and simulated values of groundwater head for the pre-monsoon, monsoon and the post-monsoon seasons are exhibited. It is observed that the graphs show good agreement with the observed and simulated groundwater heads. It is also seen from the graph that, for the monsoon season, the model tends to under estimate the groundwater head; as few point appear below the 1:1 line.

Table 1. *Monthly model efficiency values for flow model during 2011-13.*

Month	R^2	RMSE	NSE
January	0.91	1.08	0.49
February	0.92	0.92	0.55
March	0.90	0.99	0.47
April	0.92	0.74	0.58
May	0.80	0.71	0.48
June	0.56	2.42	0.36
July	0.52	2.55	0.44
August	0.55	2.36	0.63
September	0.59	2.21	0.57
October	0.61	1.82	0.87
November	0.89	0.97	0.72
December	0.90	1.06	0.69

The reasons for this is again could be greater inter mixing of river water with seawater, additional later inflow/ outflow during monsoon months.

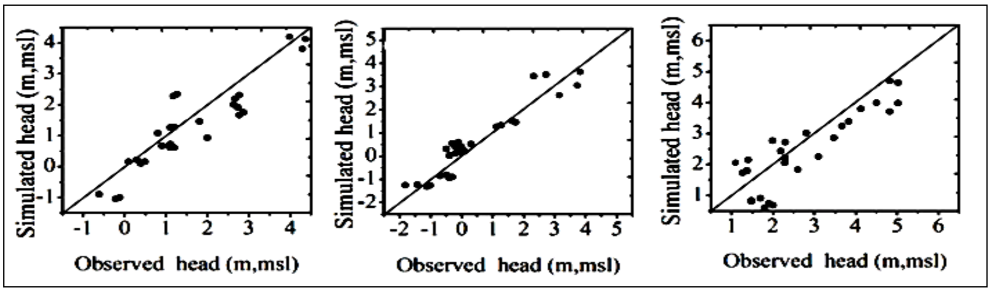
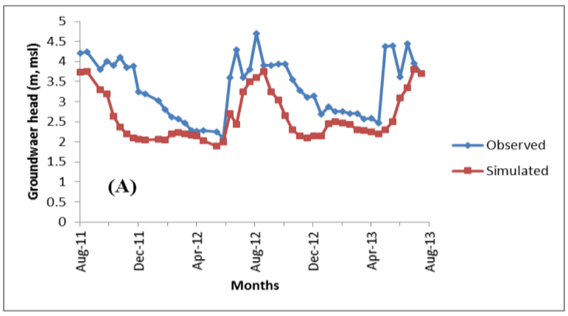


Figure 4. *Scatter plots of Simulated and observed groundwater heads (2011-13) for seasons Post-monsoon Pre-monsoon and Monsoon respectively*

The well numbers 3, 4 and 5 are located around the region where wetlands are present. The simulated results for these wells represents presence of groundwater at reasonably higher level even during peak summer, among these wells. Hence, this confirms that the wetland region is governed by presence of water during summer months, even though there are no other sources of water that can feed the wetland system in the study area. Figure 5 shows the simulated and observed groundwater heads during the calibration period (2011 – 2013) for well no.3 well no.4 and well no5 in the study area.



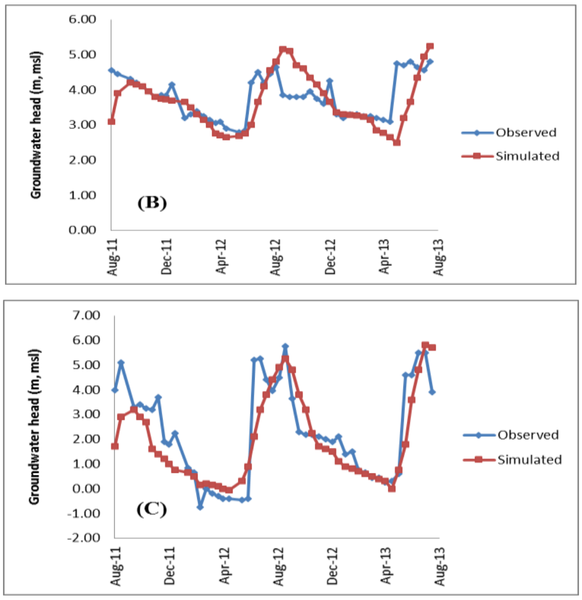


Figure 5. *Groundwater heads (2011 – 2013) for (A) well no.3 (B) well no.4 (C) well no.5*

The calibrated groundwater flow pattern for the month of May 2013 is presented in Figure 6. It can be clearly observed that the groundwater levels are higher level, around the regions of wetland even during the month of peak summer month, May (wells 3, 4, 5, 14 and 15). The flow patterns for the months June, July, August September and October are not simulated convincingly. This fact is well correlated to the performance statistics evaluation presented in table 1.

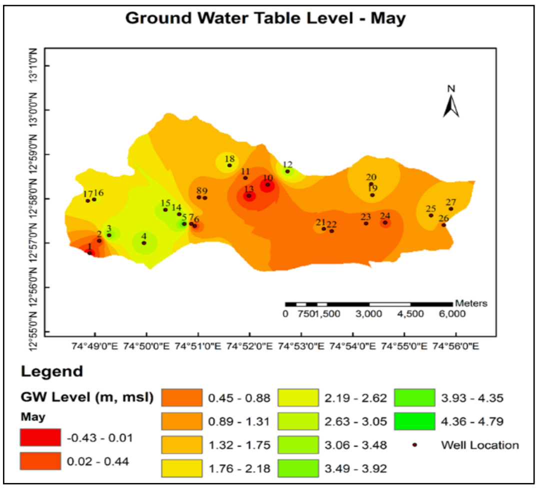


Figure 6. *Simulated groundwater levels for May 2013*

4.5 Validation of flow model

The validation is carried out for a period of two years during 2013-15 subsequent to the calibration run. The data of 27 wells monitored in the study area are used for validation purpose. The water level is converted to groundwater head in meters above mean sea level, using the grid elevation at the well location. The R^2, RMSE and NSE values obtained after analyzing the observed and calibrated groundwater head at various observation points is provided in table 2. The results are found to be consistent with that of the calibration results and therefore the model can be considered reliable for future predictions. To perceive the agreement between the observed and simulated groundwater head data during the validation period, combined scatter plot for two years is presented in figure 7. The trend observed from the scatter plot is convincing.

Table 2. *Validation results of flow dodel*

Season	R^2	RMSE	NSE
Pre Monsoon	0.90	0.85	0.51
Monsoon	0.57	2.38	0.52
Post Monsoon	0.84	1.21	0.68

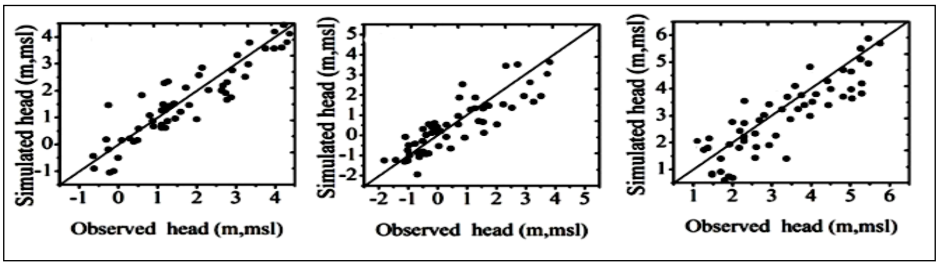


Figure 7. *Scatter plots of Simulated and observed groundwater heads (2013-15) for seasons Post-monsoon, Pre-monsoon and Monsoon respectively*

4.6 Groundwater budget

The results from the MODFLOW are used for running the groundwater mass balance simulation package, "ZONEBUDGET", which estimates the budget of volumetric flow rate of water in the whole aquifer system under consideration. The water budget of the model is presented schematically in figure 8. The rainfall recharge, contribution from the river, and storage due to aquifer properties form the inflow into the aquifer. The aquifer loses water due to pumping, discharge to the wetland system, river and drains. Table 3 presents the volumetric water budget during the monsoon (August) and summer (May). In both cases, the water movement into and out of the aquifer system can be considered dynamically stable, with the percentage discrepancy between the two being almost negligible. The figures in the table 3 confirms that more than 50% of available water is being discharged to the river during the wet season and during the dry season 82% of water is discharged through the southern boundary. During the dry periods, the volume of water flowing out of the aquifer is lesser than the flow into the aquifer indicating higher probability of contamination ingression from the river carrying salinity during high tides. Since the river is tidal in nature, the contribution of river saline water is considerable to the aquifer system during the non-monsoon months. It is also observed that the major input into the aquifer is through rainfall recharge, contributing to 74% of input.

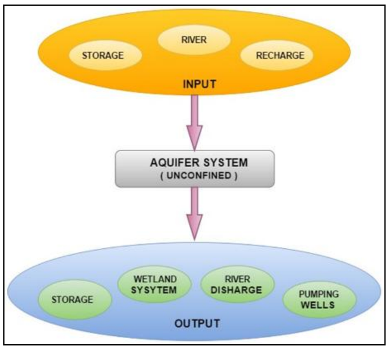


Figure 8. *Schematic representation of water budget of the aquifer in the study area*

During the period of maximum potential position (August), the component of groundwater contributing to wetland is 4.5%. During dry season with minimum potential head, the groundwater contribution to wetland is 1.4%. Hence, the presence of water in the wetland during the non-monsoon months is established by the contribution of only groundwater, in the study area.

Table 3. *Aquifer volumetric groundwater budget*

Water balance component (m^3/day)	Maximum potential position (August)		Minimum potential position (May)	
	In	**Out**	**In**	**Out**
Storage	0	153008	62173	0
Pumping wells	0	24493	0	28409
Wetland	0	17560	0	2489
River discharge	102270	195481	117192	148415
Recharge	288241	0	0	0
Total	390511	390542	179365	179313
In & Out	31		52	
% Discrepancy	0.008		0.028	

4.7 Sensitivity Analysis of flow model

The Sensitivity Analysis for the present study is carried out by using Sensitivity Index (SI) method. In this method, each of the specific yield, recharge rate and hydraulic conductivity values in the calibrated model, were given increments in terms of percentages of values ranging 25%, 50% and 75% and decrements of same ranges of percentages. The sensitivity is expressed by a dimensionless index namely Sensitivity Index (SI), which is the ratio of the relative (absolute) change of model output ($|\Delta y|/y_0$ and the relative change of an input parameter $\Delta x/x_0$, i.e. SI = $(|\Delta y|/y_0) / (\Delta x/x_0)$ (Lenhart et al. [8]), (Arlai et al. [9]). The calculated sensitivity indices are ranked into four classes, as shown in table 4.

Table 4. *Sensitivity Index (SI) and Nature of Class* (Lenhart et al. [10])

SI	Nature	Class
$0 \leq \|I\| \leq 0.05$	Small to Negligible	I
$0.05 \leq \|I\| \leq 0.20$	Medium	II
$0.20 \leq \|I\| \leq 1$	High	III
$\|I\| \geq 1$	Very High	IV

The sensitivity analysis is performed for 27 wells existing in the study area. The sensitivity analysis is conducted for the validation period 2013 - 2015. The hydraulic conductivity, recharge rate and specific yield are the parameters considered to be of prime importance in the study area. The parameter values are picked from the zonal values of parameters; those are obtained after simulations, towards the end of simulation period. The simulated values of parameters are picked from the look-out table. Since these values are zonal values of parameters, the same need to be assigned for specific well locations and the model is run for simulations again, for the entire calibration period in order to obtain the unique parameter value to be adopted for sensitivity analysis. This procedure is repeated for all the incremented parameter values and for all the wells in the study area. The values obtained after simulations are considered for the calculations of Sensitivity Index (SI).

4.7.1 Sensitivity Characteristics

The Sensitivity Index as a function of percentage change in Specific Yield, Hydraulic Conductivity and Recharge Rate are plotted and analyzed for their characteristics.

4.7.1.1 Specific Yield (Sy)

The well numbers which are falling under "small" and "medium" sensitivity range are 3, 4, 5, 14 and 15. This zone is represented by second lower region of specific yield values (0.007 and 0.013). The wetland is located in the same region of the study area. The observation from the sensitivity analysis is that the aquifer feeding to the wetland is having lower sensitivity to specific yield. Figure 9 shows the trend of variation of Sensitivity Index for well number 3.

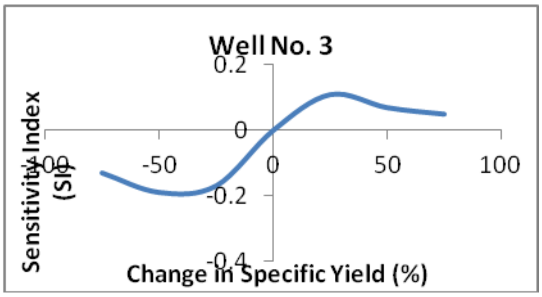


Figure 9. *Sensitivity Index for well number 3*

4.7.1.2 Hydraulic Conductivity (h)

The hydraulic conductivity is considered to be the important parameter when it comes to the sensitivity of the aquifer in the study area. It is observed that, a small percentage of change in hydraulic conductivity causes a considerable change in the hydraulic head all through the study area. figure 10 represents Sensitivity Index variation for well number 5.

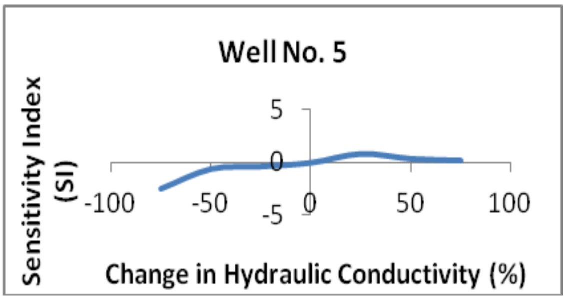


Figure 10. *Sensitivity Index for well number 5*

4.7.1.3 Recharge rate (r)

The aquifer sensitivity to the applied hydrological stresses, namely areal recharge rate is tested by conducting a similar process with increment and decrement of values with respect to the calibrated parameter values. The areal recharge due to

precipitation considered in the present study was found to be the most sensitive parameter. The recharge rate has a considerable effect on the system in areas with a shallow water table.
Figure 11 represents Sensitivity Index variation for well number 14.

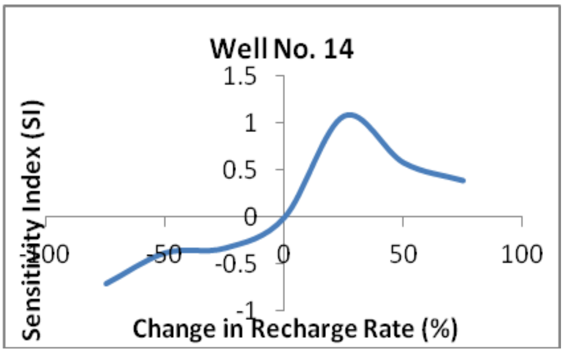


Figure 11. *Sensitivity Index for well number 14*

5. Solute Transport Modelling

5.1 General

The MODFLOW model is encompassed by the SEAWAT model, within its basic conceptual model structure. The SEAWAT model is developed by incorporating the density parameters to the originally developed groundwater flow model and transport parameters, through the MT3DMS model. Hence, the structure of both these models are learnt to be identical. Therefore, the SEAWAT model setup for the study area as executed in GMS (Groundwater Modelling System) software is directly relying on groundwater flow model (MODFLOW) set-up.

5.2. The Governing Equation

The governing equation for the variable density flow in terms of freshwater head as per the concept of equivalent freshwater head, is as follows:

$$\frac{\partial}{\partial\alpha}\left\{\rho K_{f\alpha}\left[\frac{\partial h_f}{\partial\alpha}+\frac{\rho-\rho_f}{\rho f}\frac{\partial Z}{\partial\alpha}\right]\right\}+\frac{\partial}{\partial\beta}\left\{\rho K_{f\beta}\left[\frac{\partial h_f}{\partial\beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\beta}\right]\right\}+\frac{\partial}{\partial\gamma}\left\{\rho K_{f\gamma}\left[\frac{\partial h_f}{\partial\gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\gamma}\right]\right\}$$
$$=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial\rho}{\partial t}\frac{\partial C}{\partial t}-\bar{\rho}q_s \quad (2)$$

where α,β,γ = orthogonal coordinate axes, aligned with the principal directions of permeability; $K_{f\alpha}$,$K_{f\beta}$,$K_{f\gamma}$ = equivalent freshwater hydraulic conductivities in the three coordinate directions, respectively [LT^{-1}]; ρ= fluid density [ML^{-3}]; ρf = density of freshwater [ML^{-3}]; h_f = equivalent freshwater head[L]; Z= elevation above datum of the centre of the model cell [L]; S_f = equivalent freshwater specific storage [L^{-1}] ;θ = effective porosity [dimensionless]; C = solute concentration [ML^{-3}]; ρ-= density of water entering from a source or leaving through a sink [ML^{-3}];qs= volumetric flow rate of sources or sinks per unit volume of aquifer [T^{-1}] and t = time [T]. The pre-conditioned conjugate-gradient (PCG2) package is used to solve the flow equation.

5.3 The Boundary Conditions

As it is observed during the field visits, due to the high tide in the sea, the seawater will have a backwater effect up to more than 15 km into the river. This phenomenon encourages applying the Neumann boundary condition to the stretch of river existing as a southern boundary of the study area. The Neumann boundary condition is assigned to the river with a TDS values of 35kg/m^3 during non-monsoon (October to May) months. The TDS value of 17.5 kg/m^3 is considered during monsoon (June to September) considering the quantum of mixing of freshwater and seawater as per the guidelines given by Lin et al. [10]. This value is assigned to account for the salinity carried by the backwater flow from the sea.

5.4 The Initial Conditions

The TDS is one of the indicators of salinity in solute transport model. The measured TDS in the observation wells during 2011-2013 is introduced to the sub-basin and using ArcGIS 9.3 the spatial distribution of TDS concentration is obtained. This is assigned to each cell as initial concentration for the transport model.

5.5 Density and Transport Parameters

For solving Solute Transport Equation 2, the solute transport parameter, namely the hydrodynamic dispersivity is essential. The values of hydrodynamic dispersivity are initially assigned as per available data which are adjusted by trial and error method during calibration of the model. The longitudinal dispersion is much larger than the transversal dispersion for transport simulations (Feseker [11]). Also, the horizontal transverse dispersivity of 1/10th of the longitudinal dispersivity is suggested by Cobaner et al. [12].

The diffusion coefficient used is $8.64\times10^{-5}m^2$/day. The molecular diffusion is an insensitive parameter and it can be ignored in the salinity calibration, as suggested by Langevin et al. [13].

5.6 Model Calibration

5.6.1 Calibration of flow parameters

The calibrated aquifer parameters obtained from the MODFLOW model are adopted directly in the SEAWAT. Hence, it is essential to validate the SEAWAT model through calibration, once again. This step is inevitable to gain acceptance in the variable-density flow and transport model results. This is achieved by comparing the groundwater head values obtained by the constant density model with that of the variable density model. It was found that the SEAWAT simulates the aquifer system with nearly the same accuracy as that of the MODLFOW.

The groundwater head contours of the both the simulations have an almost identical pattern with very slight variation. Hence, no further refinement is carried to validate the SEAWAT model.

5.6.2 Calibration of Transport Parameters

The calibration of transport parameters is performed similar to that of the flow parameters. The observation well data of 27 wells are measured for TDS values, on fortnightly basis during 2011-2013, are used to calibrate the model. The calibration in steady state is not carried out in the present study due to non-availability of quality data. The accuracy of the seasonal performance of the solute transport model is tested using the four model evaluation techniques used for evaluation of the flow model. Apart from the aquifer parameters calibrated in the MODFLOW, the dispersivity parameter is calibrated in the SEAWAT model by varying the values within the range by trial and error method. The calibration results obtained are satisfactory.

5.6.3 Transient Calibration

The transient calibration has been done successfully and the solute transport parameters are obtained. The monthly RMSE, R^2 and NSE values obtained are listed in table 3.

Table 3. *Monthly SEAWAT Efficiency Values during 2013-2015*

Month	RMSE	R^2	NSE
January	0.05	0.78	0.75
February	0.10	0.70	0.70
March	0.06	0.78	0.78
April	0.05	0.66	0.54
May	0.06	0.79	0.78
June	0.08	0.77	0.68
July	0.05	0.76	0.13
August	0.05	0.72	0.21
September	0.06	0.72	0.46
October	0.05	0.72	0.51
November	0.05	0.65	0.54
December	0.05	0.78	0.77

As observed in table 3, the model performance is satisfactory, as the values are well within the acceptable ranges. The model performance during the monsoon (June to Sept) is not very convincing when compared to rest of the months. Also, the observed TDS data of wells that are very close to the river, do not match well with the simulated results. This could be because of the complex river-aquifer interaction which is not well addressed by the model. The scarcity of the data may be the reason behind this discrepancy.

The distribution of TDS in the study area based on the simulations carried is presented in figure 12 for the summer season. The TDS trend during summer months from April to June is found to be around 400 mg/lt to 719 mg/lt, for wells nearby wetland. Around well number 24, the summer TDS values are highest observed among all seasons, that is 1192 mg/lt. Apart from these, well numbers12 and 11 shows highest TDS values in the range of 1200 mg/lt to 1500 mg/lt. The groundwater around the region, though are of higher in terms of TDS concentration, is safe from contamination ingression.

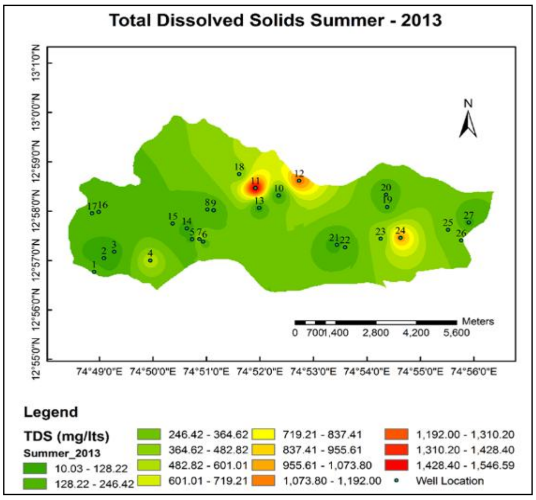


Figure 12 *TDS distribution for Year 2013 (April – June)*

5.7 Validation of Solute Transport Model

For the purpose of application of the calibrated solute transport model for future contamination scenario, validation of the model is carried out for a period during 2013-15. The validation of the model is carried out for one year period, 2014-2105. Monthly stress periods are provided for obtaining the results of validation in terms of TDS values. The observed values of TDS during calibration period are in tune with the trends followed during the simulation period (2011-2013), except for summer 2015, wherein the model results are slightly under estimated.

6. Summary and conclusions

The present study focused on flow and transport modelling around wetland region in Gurupura baisn, by taking up the simulation of the shallow, tropical coastal aquifer. The numerical simulation was carried out using SEAWAT. The results obtained from the investigation may be useful for scientific assessment of freshwater resources under similar conditions. The major conclusions drawn from the investigation are presented below:

1.The NSE ≥ 0.5 (except during the monsoon months) demonstrates the ability of the model to simulate the monthly groundwater table with reasonable accuracy both during the calibration and validation process.

2. The simulations of flow model confirms presence of groundwater at higher levels during peak summer months in the study area around the regions of wetlands. This is verified through the field data obtained during the field visits.

3. During the summer months, the component of groundwater contributing to wetland is 4.5%. During dry season with minimum potential head, the groundwater contribution to wetland is 1.4%. Hence, the presence of water in the wetland during the non-monsoon months is established by the contribution of only groundwater, in the study area.

4. The sensitivity analysis carried out indicates that the specific yield is having medium sensitivity to the aquifer in the regions of wetlands. The hydraulic conductivity and recharge rate are showing medium to high sensitivity in the study area.

5. The simulations carried out through Solute Transport Modelling confirm that the quality of the groundwater in the study area is safe against contamination caused due to salinity carried by the river during high tides.

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