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Analysis of Groundwater Flow for Saltwater Interaction Range Using Visual Modflow: A Case Study of Coastal Belt in Srikakulam District of Andhra Pradesh, India

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Abstract: Groundwater flow modeling is one of the important tools to know the direction and magnitude of groundwater flow along the coastal aquifer. A study carried out in the coastal belt of Srikakulam showed a region where there is a probable mixing of ground water with the sea water. In the present investigation, the ground water flow and velocity are determined by using ModFlow Software. The entire study area has been divided into small grids. The wells are identified and located in eight lines perpendicular to the coastal belt. In this investigation, 97 existing wells are selected for carrying out the study. The distribution of the hydraulic head was estimated through a 20-year simulation. The observed results indicate that a considerable advance in seawater intrusion can be expected in the coastal aquifer of the study area. It is concluded that the average velocity of ground water in the Srikakulam coastal belt is 1.1 m/day. The results help to determine the groundwater flow channels and also help to explain the ground water recharge and flow areas in the aquifer.

Key words: Groundwater modeling, visual modflow, steady-state, hydraulic heads, ground water flow, velocity.

Introduction

Computation of groundwater velocities is an important component of modeling contaminant transport in the subsurface. Groundwater withdrawals in excess of safe yields and reduced recharge to groundwater due to rapidly changing land use patterns along the coasts have increased the incidences of seawater intrusions into the coastal aquifers (Varghese, 2018). With the development of groundwater investigations, it is important to understand the development of comprehensive conceptual models and analytical solutions or numerical methods of groundwater modeling. The management of groundwater resources in coastal aquifers requires special attention to minimise the extension of seawater intrusion into aquifers and the upcoming seawater near pumping stations (Bear, 2011). The extent of intrusion depends on a number of factors including aquifer geometry and properties (hydraulic conductivity, anisotropy, porosity and dispersivity), abstraction rates and depth, recharge rate, and distance of pumping wells from the coastline (Werner & Simmons, 2009). Our present work deals with the flow and velocity of ground water. This flow will help us to know the rate of speed and direction of sea water that is entering into the ground water. The obtained velocity of ground water is useful in the design of wells. A pumping out test is carried out to determine the coefficient of permeability of soil strata of the coastal aquifer which is based on potential theory by maintaining the constant

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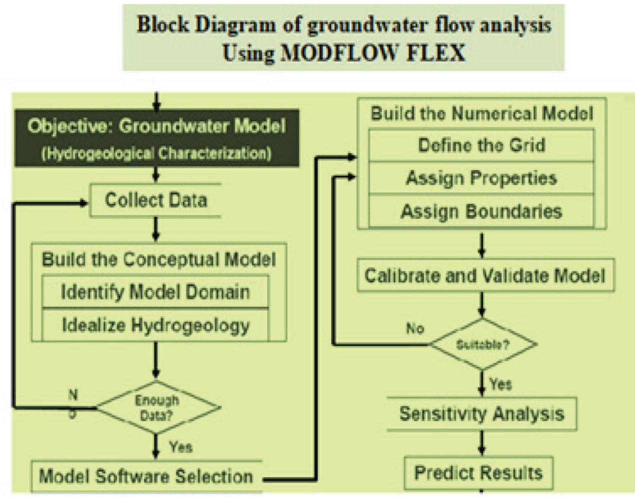
discharge (Igboekwe et al., 2008). Flow and velocity of ground water are obtained by giving the values of hydraulic properties, vertical electrical soundings and well locations in MODFLOW2010.1. The spatial properties of the velocity distributions are described; of particular interest is the occurrence of a transient upward velocity component during the recharge process. The groundwater flow modeling for an unconfined coastal aquifer surrounded by saline water bodies plays a significant role in providing information on the direction and magnitude of groundwater flow with respect to seasons and location (Kuan et al., 2012). Modeling the groundwater flow system provides insight into the areal distribution of recharge to and discharge from the aquifer system (Rojas & Dassargues, 2006). The study also attempts to delineate the recharge and discharge areas from the model outputs and also discusses the performance of the aquifer model based on statistical techniques. The ability to predict the flow of groundwater is of paramount importance in planning and implementing development projects in the groundwater under the growing demand for freshwater resources. Groundwater flow modeling has been used extensively worldwide with varying degrees of success. The ability to predict the groundwater flow is critical in planning and implementing groundwater development projects under increasing demand for fresh water resources. First, a preliminary visit was carried out to all those regions around the coastal belts of the Srikakulam district. Interaction with the local people of each area helped us in finding out the regions which are much affected by saltwater intrusion. Some of the wells in each area were identified using the help of the local people. In total, six wells were chosen in the study area. All the wells which are chosen for the study purpose are identified and labeled with appropriate numbers. At each of the identified wells, the latitude and longitude of the location are found using a GPS instrument of that particular well where the sample is collected and wells in the study area as shown in Figure 1.

Groundwater Flow Analysis Using Visual Modflow

Visual MODFLOW is the most complete and easy-to-use graphical modeling environment for professional 3-D groundwater flow and contaminant transport simulations. This seamless package allows the user to graphically assign all necessary flow and transport parameters, run the simulation, calibrate the model and visualise the results. Both the input and output can be visualised in plan view or full-screen cross-sections at any time. For practical applications in three-dimensional



groundwater flow and contaminant transport modeling, MODFLOW is a very useful software.

A large amount of information and a complete description of the flow system is required to make the most efficient use of MODFLOW. In situations where only rough estimates of the flow system are needed, the input requirements of MODFLOW may not justify its use. To use MODFLOW, the region to be simulated must be divided into cells with a rectilinear grid resulting in layers, rows and columns. Files must then be prepared that contain hydraulic parameters (hydraulic conductivity, evapotranspiration), boundary conditions (location of impermeable boundaries and constant heads), and stresses (pumping wells, recharge from precipitation, rivers, drains, etc.).

Study Area

To investigate the groundwater storage zones, the availability of the groundwater resources is quite imperfect because of a number of constraints, therefore, in order to address local scale groundwater issues, the present study investigated the Srikakulam coastal belt using mathematical modeling techniques (using MODFLOW). Srikakulam district is one of the important districts of Andhra Pradesh flanked by Orissa on the north east side and Bay of Bengal on the east. This district has the longest coast line, about 193 kms, in the state of Andhra Pradesh (AP.Gov.in, 2020). Nagavali and Vamsadhara are the major rivers in the Srikakulam district. These two river basins together constitute about 5% of the area. The selected area of the study comprised of a large number of bore wells and open wells based spread all over the area.

Garamandal is located in the Srikakulam district of Andhra Pradesh, India. It is located in the geographical

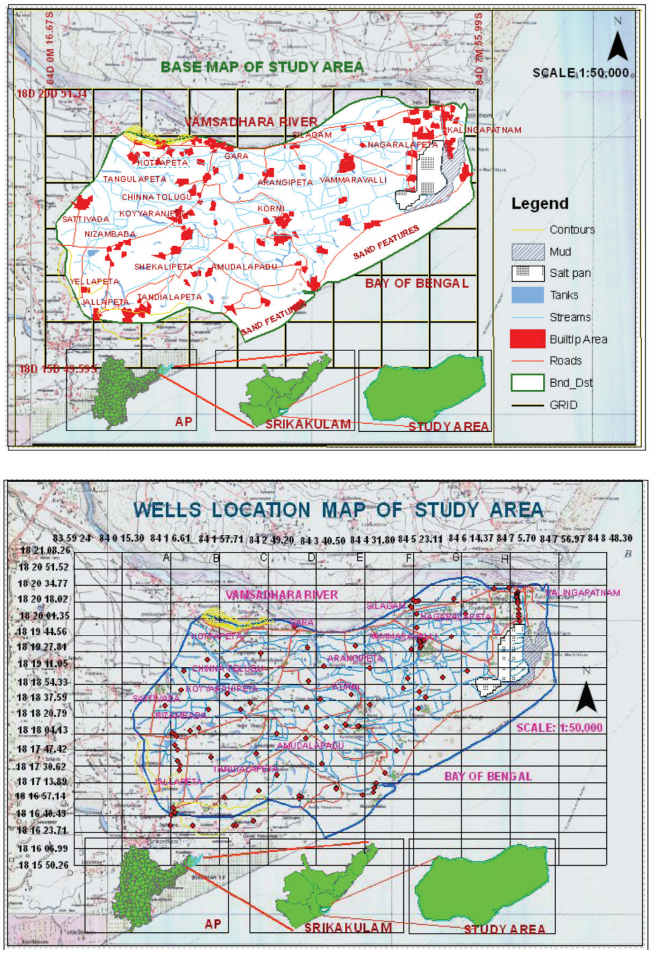


Figure 1: Wells location map.

coordinate range of 18° 19′ 59.88″ N, 84° 3′ 0″ E and 18.3333 N, 84.05 E. There are 24 village panchayats in GaraMandal, and the study area covers an area of 70 square kilometers. The south-eastern boundary of the Mandal is a coastal shoreline bounded by the Bay of Bengal. The length of the shoreline is approximately 20 kilometers. The eastern region touches river Vamsadhara, which acts as a natural boundary to the study area as shown in Figure 3 (wikipedia.org/Gara, 2018). The study area is approximately 70 km^2 and 97 observation wells are located in the study area. The well location map of the study area along with latitude and longitude is shown in Figure 1.

Methodology

Basically, a groundwater model is a simplified representation of the natural groundwater flow system. Without them, it would be impossible to evaluate all of the natural processes that impact a hydrogeologic design. The validity and performance of the model are demonstrated by its application to real field situations and a comparison of results with the prototype data is carried out.

Numerical groundwater modeling is a tool that can aid in studying groundwater problems and can help increase our understanding of groundwater systems (Harbaugh, 2005). Visual MODFLOW is the most complete and easy-to-use graphical modeling environment for professional 3-D groundwater flow and contaminant transport simulations. Conceptualising the model of the study area is the most important step in the groundwater model process. This is a process of visualisation of different hydro geological and ground water flow conditions in the study area.

Input for Visual Modflow (Hydrological, 2005)

- Prepare the base map from toposheet of the study area by using surfer
- Elevations of wells in the study area
- Hydraulic parameters of ground water (conductivity, evapotranspiration)
- Boundary conditions (constant heads)
- Pumping wells, observation wells, recharge, drains and rivers.

Preparation of Base Map by Surfer 8.0

First, collect the toposheet of the study area and import the toposheet in surfer 8.0. Fix the toposheet by entering co-ordinates in meters. Right click and click digitise so we can view the co-ordinates on the right side of the plot. When we digitise the boundary we have to copy the first value in the .bln format and paste it at the end of

Table 1: Locations and elevations of wells in line A

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1974819	9073563	4.01	5.8	1.83
2	1975007	9073725	6.02	5.7	-0.36
3	1975049	9074448	5.15	6.7	1.54
4	1975142	9074124	6.27	7.7	1.42
5	1976516	9073865	6.19	9.7	3.46
6	1976489	9074362	7.88	10	2.09
7	1976455	9074718	9.44	12	2.6
8	1976289	9074436	7.13	12	5.04
9	1976197	9074891	6.57	10	3.64
10	1975989	9074945	6.36	4.6	-1.75
11	1975911	9075366	4.47	5.2	0.72
12	1975821	9075194	3.35	4.1	0.78

the sheet so that we can close the boundary (Bresnahan et al., 2002). And finally, we can save the file. And for drainage, we can digitize the entire drainage in the same file by double entering and finally we can save the file. Import well points in the base map. After importing the wells go to the edit button and click select all and go to map icon and click on the overlays the figure will adjust. If it does not adjust the coordinates will be wrong and we have to check. Finally, save the file in *.shp file or .dxf as shown in Figures 2 to 5.

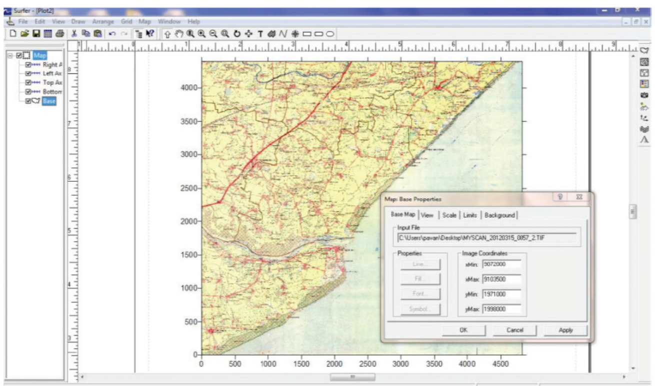


Figure 2: Fix the toposheet by entering co-ordinates.

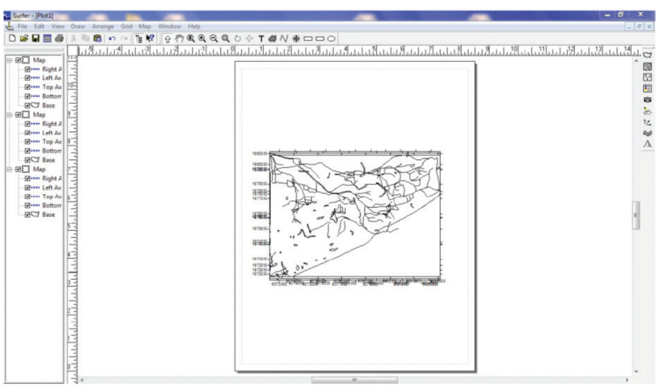


Figure 3: Digitize the boundary, streams and tanks.

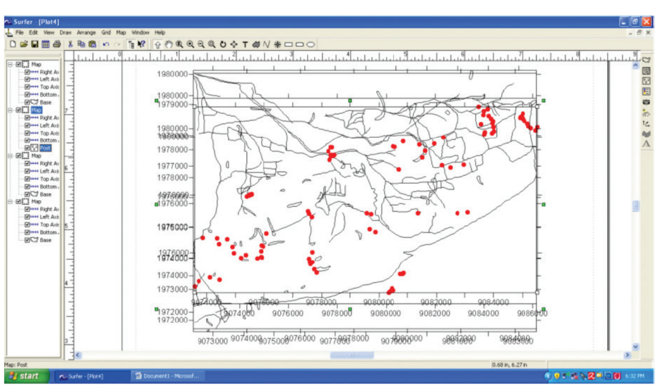


Figure 4: Import the well points in the base map.

Elevations of Wells in the Study Area

The surface elevations of the selected wells in the study area are shown in Figures 1-4 and their corresponding reduced levels (R.L) are as tabulated in Tables 1-8 for wells A-H respectively.

Direction of Flow and Velocity of Ground Water

Computation of ground water velocities is an important component of modeling contaminant transport in the subsurface. The groundwater velocity for different bore wells in the recharge and discharge areas was estimated. Groundwater levels are essentially controlled by the type of rock, fracture patterns, physiographic features, and rainfall distribution in space and time. The movement of the water table caused by uniform recharge (spreading) is considered. The more exact potential theory was used to determine the motion of

Table 2: Locations and elevations of wells in line B

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1978031	9075559	3.95	4.5	0.5
2	1978020	9075554	5	4.4	-0.65
3	1978009	9075493	4.23	3.4	-0.81
4	1977988	9075473	5.25	4.3	-0.95
5	1977955	9075383	3.6	3.8	0.24
6	1976659	9076080	7.1	6.5	-0.65
7	1976216	9075968	7.24	5.5	-1.71
8	1976238	9075899	2.2	4.8	2.61
9	1976054	9075889	3.23	2.4	-0.83
10	1975849	9075882	3	0.3	-2.66
11	1975828	9075923	5.82	3	-2.78
12	1975795	9075756	1.23	3.7	2.43

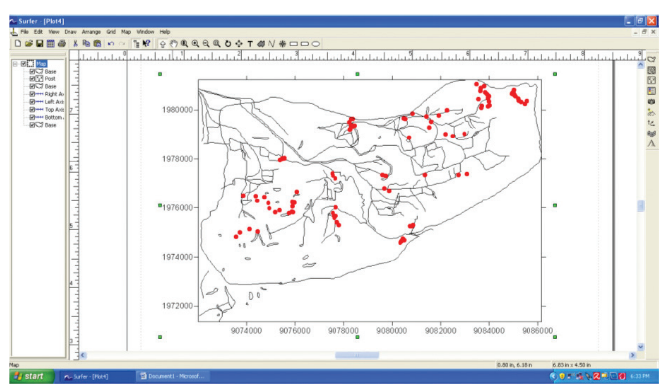


Figure 5: After overlays the boundary, streams, tanks and well points.

Table 3: Locations and elevations of wells in line C

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1977415	9077530	2.26	9.1	6.84
2	1977333	9077550	2.52	8.2	5.63
3	1977223	9077651	2.25	8.9	6.6
4	1976014	9077666	3.28	8.6	5.36
5	1975781	9077562	2.5	8.5	5.99
6	1975667	9077589	2.53	8	5.43
7	1975674	9077668	2.03	8.1	6.03
8	1975593	9077611	2.5	8.5	5.97
9	1975416	9077732	3.14	9.1	5.98
10	1975305	9077817	2	6.6	4.58

Table 4: Locations and elevations of wells in line D

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1979635	9078324	4.29	7.2	2.91
2	1979630	9078373	3.22	7.2	4.02
3	1979500	9078237	2.67	7.5	4.86
4	1979373	9078314	3.2	7.2	3.98
5	1979372	9078348	4.31	7.7	3.42
6	1979368	9078449	4.82	7.4	2.55
7	1979354	9078421	4.38	5.2	0.81
8	1979340	9078392	5.1	5.6	0.52
9	1979227	9078288	3.28	4.3	0.99
10	1979211	9078267	3.18	4.3	1.09

Table 5: Locations and elevations of wells in line E

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1974755	9080445	2.71	7.2	4.52
2	1974690	9080500	4.45	5.5	1.01
3	1974659	9080386	5.24	4.5	-0.73
4	1974600	9080340	5	3.2	-1.77
5	1975255	9080753	4.01	3.9	-0.1
6	1975250	9080827	5.84	3.8	-2.01
7	1975288	9080864	4.22	4.4	0.18
8	1976702	9079873	4.52	4.7	0.17
9	1976800	9079668	4.1	4.5	0.4
10	1977350	9079582	3	6.7	3.65
11	1977318	9079722	3.1	6.4	3.25

Table 6: Locations and elevations of wells in line F

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1979854	9080848	2.65	6.1	3.48
2	1979770	9081918	3.56	6.5	2.92
3	1979742	9081410	2.98	6.6	3.66
4	1979662	9080481	2.21	6.2	3.95
5	1979648	9080546	3.1	6.3	3.15
6	1979528	9081604	2.86	6.4	3.55
7	1979283	9081518	2.46	7.1	4.66
8	1979020	9082188	2.36	7.1	4.74
9	1979037	9082965	2.14	7.3	5.17
10	1979992	9082242	3.36	7	3.61
11	1978940	9082490	2.61	6.3	3.73

Table 7: Locations and elevations of wells in line G

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1981043	9083475	3.19	3.9	0.67
2	1980769	9083642	3.76	4.3	0.58
3	1980888	9083663	2.58	4.7	2.14
4	1980962	9083797	4.02	4.4	0.42
5	1980721	9083830	3.62	5.1	1.52
6	1980635	9083911	2.78	2.9	0.1
7	1980552	9083983	4.52	0.8	-3.71
8	1980481	9083955	3.46	1.6	-1.87
9	1980342	9083999	2.67	0.7	-1.98
10	1980195	9084014	4.43	2	-2.41
11	1980138	9083951	4.33	3	-1.29
12	1980163	9083688	4.78	2.7	-2.09
13	1980097	9083680	4.77	3.6	-1.21

the water table resulting from recharge. For each theory, both a linear and a nonlinear version were considered. Finite difference schemes were employed to solve the nonlinear models. Analytical solutions exist for the linear models.

The hydraulic parameters of ground water are as follows: recharge value is 15 mm/year, evapotranspiration is 10 mm/year and constant head is 5-10 m. After entering the complete information, now run the simulation, go to the main menu save the before existing data and run the model and be prompted to select the run type. Now run type, a dialogue box will appear, select MODFLOW and translate and run and Modflow calculations are completed as shown in Figure 5. Next, go to the main menu select output, go to graphs, and check the co-relation factor near 0.9, then the direction of flow and velocity of ground water is perfect. The direction of ground water shown in the plot and the velocity of groundwater will appear when selecting velocities in options, side menu bar. Modflow gives the direction of flow and velocity of ground water in entire study areas as shown in Figures 6 to 9.

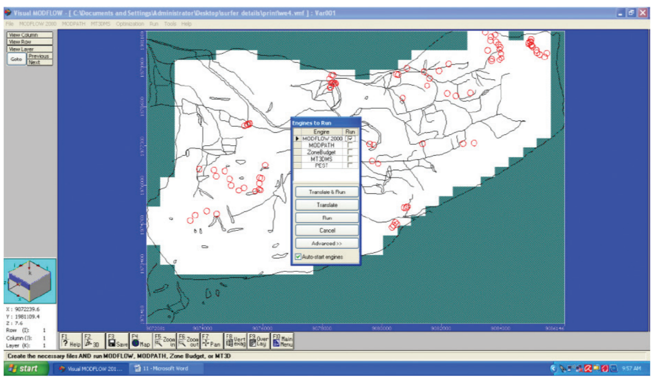


Figure 6: Run the Modflow.

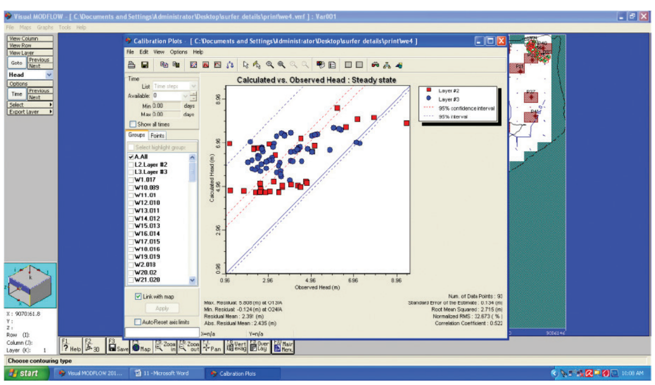


Figure 7: Verifying the Modflow result.

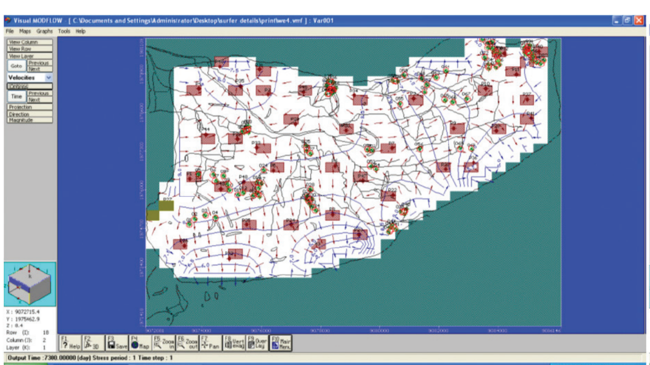


Figure 8: Direction of flow of groundwater.

Table 8: Locations and elevations of wells in line H

S. No.	*Latitude in m*	*Longitude in m*	*Water from G.L*	*R.L*	*From MSL in m*
1	1980806	9085017	3.37	4.4	0.99
2	1980738	9084996	3.45	3.7	0.28
3	1980712	9084996	3.42	3.9	0.45
4	1980694	9084942	2.83	3.7	0.82
5	1980665	9084920	2.2	3.5	1.25
6	1980625	9085028	2.43	3.4	0.97
7	1980602	9085028	2.13	3.4	1.26
8	1980560	9085071	2.55	2.7	0.1
9	1980458	9085190	3.45	3.9	0.46
10	1980375	9085212	2.39	3.1	0.66
11	1980356	9085532	2.47	3.3	0.78
12	1980314	9085298	2.65	2.8	0.15
13	1980236	9085460	1.19	2.8	1.65

Conclusion

Saltwater intrusions into the adjacent natural groundwater aquifers happen at many coastal belts causing the freshwater in the aquifer to degrade in terms of quality. In the present study area, the saltwater intrusions are determined in terms of direction and velocity of flow into the aquifer and are found to be 1.1 m/day. This range is categorised under the Sub-meter scale extent which is found to be of nominal effect on the hydraulic conductivity of freshwater aquifers. However, the long-term impact of these seawater interactions into the residing groundwater will be considerably affected by the formation of limestone caves and by reducing the hydraulic conductivity of the study area.

The visual Modflow model yielded precise results and is found to be 98% efficient when compared to the

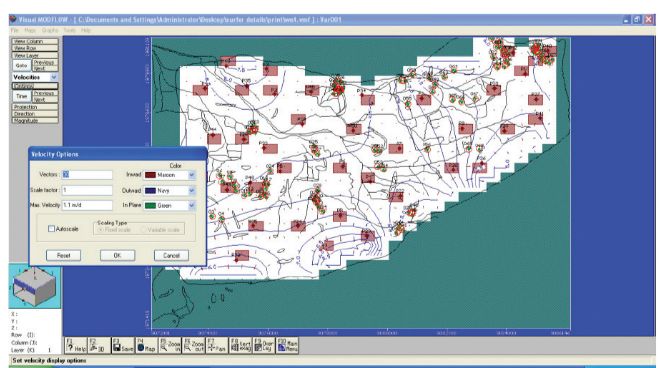


Figure 9: Velocity of groundwater.

simulated and actual values of velocity. The observation well's hydraulic conductivity will reduce with time due to long term wedge formations between the fresh water and seawater.

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