Modelling of Seawater Intrusion in Coastal Area of North Goa

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Introduction

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 coastal areas assume a special significance since any developmental activity will largely depend upon availability of fresh water to meet domestic, industrial and agricultural requirements. However, fresh water resources in these coastal aquifers are likely to experience disastrous and irreversible impacts in the coming times due to overexploitation of groundwater resources and sea level rise. 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.

National Water Policy – 2002 also stresses that "*Over exploitation of ground water should be avoided especially near the coast to prevent ingress of seawater into sweet water aquifers*". The management of groundwater resources in coastal aquifers requires special attention to minimize the extension of seawater intrusion into aquifers and upconing of seawater near pumping stations. 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.

Coastal tracts of Goa are rapidly being transformed into settlement areas. The poor water supply facilities have encouraged people to have their own source of water by digging or boring a well. During the last decade, there have been large-scale withdrawals of groundwater by builders, hotels and other tourist establishments. Though the seawater intrusion has not yet assumed serious magnitude, but in the coming years it may turn to be a major problem if corrective measures are not initiated at this stage. It is necessary to understand how fresh and salt water move under various realistic pumping and recharge scenarios. Objectives of the present study include simulation of seawater intrusion in a part of the coastal area in Bardez taluk of North Goa, evaluation of the impact on seawater intrusion due to various groundwater pumping scenarios and sensitivity analysis to find the most sensitive parameters affecting the simulation.

Study Area

The study area lies in Bardez taluka of North Goa within the watersheds of Baga river and Nerul creek (around 74 km^2) and covered by Survey of India toposheets number 48E/10, 48E/14 and 48E/15 on 1:50,000 scale. It is bound by rivers Chapora and Mandovi in north and south directions respectively, besides Arabian sea in the west and encompasses coastal tract from Fort Aguada in the south to Fort Chapora in the north (15 km). The soils are predominantly of lateritic nature. However, the coastal areas are made up of alluvial soils composed of loamy mixed sand and loamy sands. Around 30 km^2 area close to the coast (15 km along the coast and 2 km wide) is more prone to seawater intrusion. Layout maps of North Goa and the study area are given in figures 1 and 2 respectively.

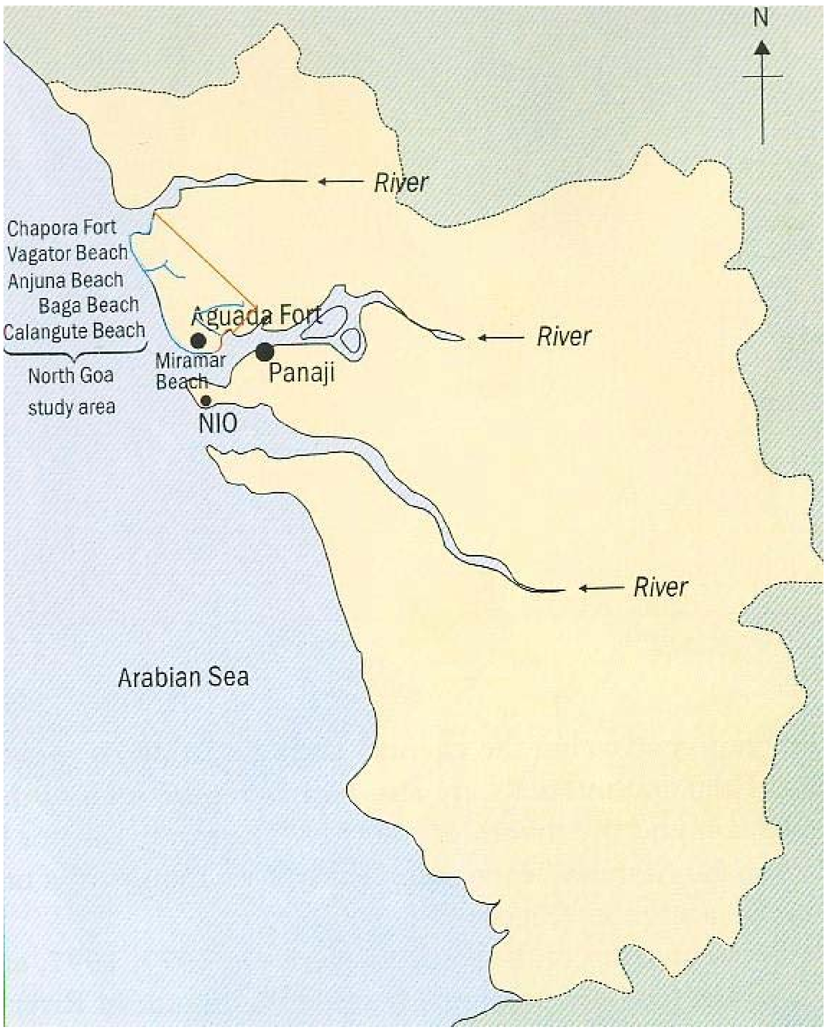

Figure 1: Location Map of Study Area in Goa

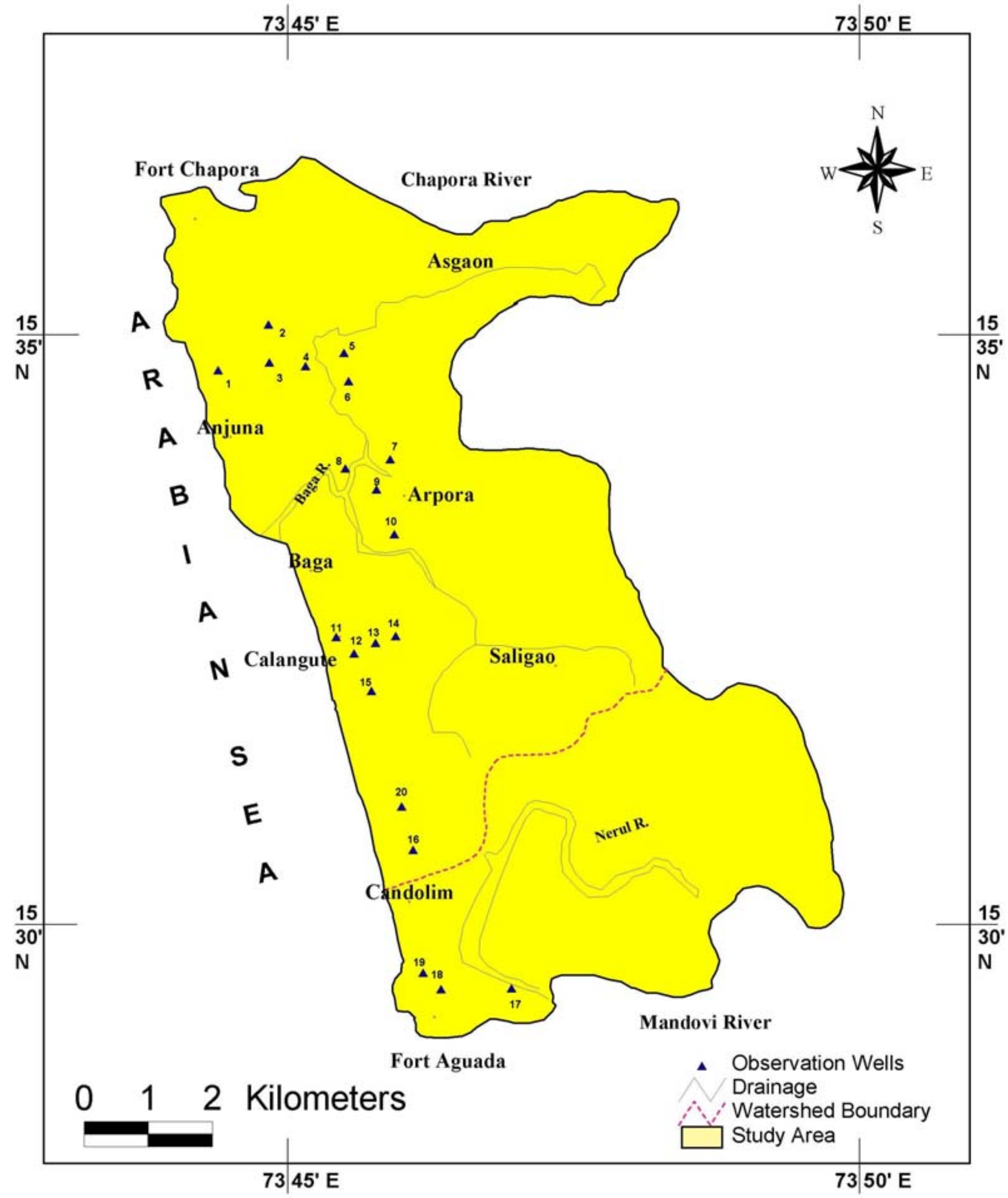

Figure 2: Layout Map of the Study Area

Laboratory and Field Investigations

Twenty observation wells were identified in the study area (as indicated in figure 2). Monthly groundwater level data was measured in observation wells (September 2004 to August 2005) and groundwater samples were collected in September, November 2004, January, March, April, May 2005. Salinity for collected groundwater samples was measured in the laboratory. Based upon the bi-monthly measurements of salinity, groundwater quality in all the observation wells was found to be reasonably fresh, both in pre- and post-monsoon periods. It can be attributed to the fact that the transition zone of fresh water-saline water lies below the shallow open wells, as evidenced by vertical electrical soundings.

Figure 3: Measurement of Groundwater Level in Observation Well Number 10

Apparent electrical resistivity (ohm-m) was measured in four profiles along the Bardez coast (Anjuna, Baga, Calangute, Candolim) at 18 locations upto 525 metres from the coast (Table 1). The inter-electrode separation was kept at 10 meter, that is, the resistivity values measured are at 10 m depth plane. The seawater mixed zone is witnessed along Anjuna (12 to 45 ohm-m) and Baga beach (4 to 46 ohm-m) sections along the low lying sandy alluvial areas. Very close to the sea, relatively higher apparent resistivity values are due to dry sand dunes. However, along Calangute (75 to 900 ohm-m) and Candolim (142 to 700 ohm-m) beaches, there is no indication of seawater mixing at 10 m depth, as all values are higher.

Seven vertical electrical soundings were carried out at monitoring well sites 1, 3, 6, 7, 8, 15 and 17 (Table 2). These were restricted to a depth of 20 m to know any change in the quality of water vis-à-vis seawater intrusion (3 m to 20 m with 1 m interval). As seen from the apparent resistivity values, well numbers 6, 7 and 8 show low values of resistivity (2 to 33 ohm-m) below about 12 m depth, indicating the presence of seawater or mixed zone below this depth. However, at other sites, there is no indication of the seawater mixing upto 20 m depth. It is noted here that wells located in low lying sandy alluvial areas show seawater mixing than the wells located in laterites at higher altitudes. In both laterite and alluvial soils, the wells are built well above the salt water – fresh water interface and hence no change in water quality was found in summer also.

Table 1: Apparent Electrical Resistivity Values (ohm-m) in Four Profiles along the Bardez Coast

S. No.	Distance from Coast (m)	P1	P2	P3	P4
		Anjuna	Baga	Calangute	Candolim
1	15	**30**	70	150	700
2	45	**40**	**46**	820	555
3	75	**45**	**35**	612	142
4	105	**32**	**25**	360	421
5	135	**26**	**28**	110	281
6	165	**24**	**22**	75	153
7	195	**20**	**30**	125	184
8	225	**15**	**32**	242	255
9	255	**14**	**24**	410	431
10	285	**12**	**20**	623	236
11	315	**13**	**31**	531	165
12	345	**13**	**32**	415	242
13	375	**14**	**20**	324	281
14	405	**16**	**30**	470	641
15	435	**20**	**20**	684	531
16	465	**21**	**10**	650	426
17	495	**24**	**5**	835	186
18	525	**18**	**4**	900	200

Table 2: Apparent Electrical Resistivity Values (ohm-m) at Observation Well Points in the Study Area

AB/2 (m)	Apparent Electrical Resistivity Values (ohm-m) at Monitoring Well Numbers						
	1	3	6	7	8	15	17
3	410	448	80	102	231	1988	333
4	436	446	65	84	277	665	356
5	467	521	63	72	202	900	373
6	505	595	68	62	180	256	393
7	536	613	82	58	138	850	383
8	541	521	74	51	120	156	381
9	533	482	47	45	102	780	381
10	544	389	62	42	62	194	327
11	528	339	56	40	61	125	339
12	539	314	23	25	45	128	314
13	581	264	**24**	**22**	**41**	158	290
14	582	245	**19**	**18**	**31**	165	276
15	563	246	**20**	**16**	**32**	164	246
16	561	240	**21**	**17**	**33**	215	240
17	543	226	**13**	**15**	**25**	265	226
18	609	233	**16**	**12**	**10**	315	203
19	566	215	**12**	**18**	**3**	452	226
20	520	214	**9**	**17**	**2**	351	202

Finite Element Simulation Model

For the present study, a finite-element model (FEFLOW) was selected for model simulations. The FEFLOW is an interactive finite element simulation system (Version 5.1) for three-dimensional (3D) or two-dimensional (2D), i.e. horizontal (aquifer-averaged), vertical or axi-symmetric, transient or steady-state, fluid density- coupled or linear, flow and mass, flow and heat or completely coupled thermohaline transport processes in subsurface water resources (groundwater systems). The package is fully graphics-based and interactive. Pre-, main- and post-processing are integrated. There is a data interface to GIS (Geographic Information System) and a programming interface. The implemented numerical features allow the solution of large problems.

Model Setup and Simulation Results

The aquifer domain of the study area (74 km^2) was discretized using 6 nodal triangular prism elements with 52,656 mesh elements and 32,053 mesh nodes. The vertical discretization corresponds to 7 slices and 6 layers. The top slice was defined as free and movable (water table). Geological profile in low lying area (ground elevation 0 – 20 m above mean sea level) was assigned as 15 – 30 m deep sandy soil (upto 10 – 15 m below mean sea level) underlain by 1 – 2 m clay layer and then basement rocks (phyllite, graywacke, schist etc). Geological profile in plateau area (ground elevation 20 – 80 m above mean sea level) was assigned as 0 - 75 m deep laterite (upto 0 – 10 m below mean sea level) underlain by 2 – 5 m clay layer and then basement rocks. The boundary conditions for the flow simulation are as follows:

- A coastal head boundary along the coastal zone (western boundary) at the top and bottom slices of the aquifer; FEFLOW uses head (h) instead of pressure with $h = (e_w / e_s) Z$, where e_w and e_s represent ambient and seawater densities respectively and Z is the depth below sea level. The head was calculated in each constant-head boundary node.

- No flow boundaries are specified in the eastern boundary and right part of the northern boundary, where it forms the watershed boundary of Baga and Nerul rivers.

- Southern boundary (Mandovi river) and left part of the northern boundary (Chapora river) are described by third-kind (Cauchy) boundary condition, Transfer. Internal flow boundaries (Baga river and Nerul river) are also described by Transfer boundary condition.

The boundary conditions and initial concentration for the transient state solute transport are dependent on the flow simulation results. For this model, solute transport concentrations are expressed in terms of total dissolved solids (TDS). A concentration of 35,425 mg/l (seawater TDS) is used along the coastal zone where simulated inflow from ocean occurs (mass boundary of 1^{st} kind). The initial concentration of the groundwater was set to 0 mg/l.

The aquifer geometry was adopted, as defined in previous studies. Reference zero elevation was assumed at 50 m below mean sea level. Only few measured hydrodynamic data are available and incorporated in the model. Four values of hydraulic conductivity ranging from 0.381×10^{-4} to 3.657×10^{-4} m/s were measured through pumping tests. Data regionalization for hydraulic conductivity over the study area has been carried out using Akima inter/extrapolation. No measurement of dispersivity has been made, this parameter was therefore estimated by trial and error using prior information from similar cases. Molecular diffusion was assumed as 1.00×10^{-9} m^2/s. Initial head data have been measured in 20 observation wells. Data regionalization for hydraulic heads over the study area has been carried out using Akima inter/extrapolation.

The transient state simulation of the solute transport was carried out using automatic time step control via predictor-corrector schemes, with initial time step length as 0.001 day and final time as 3650 days (10 years) to reach steady state conditions. Calibration objective for the mass transport was focused mainly at observation wells near Anjuna and Baga beaches and Baga river where resistivity survey has indicated the presence of brackish water.

Mean annual rainfall is estimated to be 2714 mm, based upon daily rainfall data of Panaji for 20 years (1984 to 2003). Rainfall recharge values for laterite and west coast were adopted as 7% and 10% respectively, as recommended by "Groundwater Resource Estimation Methodology - 1997". Annual groundwater draft for the study area was worked out by using the reported density of wells as 25 wells per km^2 and average annual groundwater draft per structure as 0.65 ha-m. Porosity for sandy alluvium, laterite and clay were assumed to be 0.32, 0.21 and 0.42 respectively. Specific yield for sandy alluvium, laterite and clay were assumed to be 0.16, 0.025 and 0.03 respectively.

Longitudinal and transverse dispersivity were modified uniformly by trial and error in order to match the measured salinity values from the observation wells. Several runs were carried out to approach the solution. Final calibrated longitudinal and transverse dispersivity are 50 m and 5 m respectively. The calibration process shows that the mass transport model is sensitive to the dispersivity values.

Three-dimensional plot for mass distribution has been presented in figure 4. It indicates 3 peaks where salinity near the coast exceeds 6000 mg/l. Along these three sections, the salinity of groundwater was found to be greater than 500 mg/l upto 300 m inland, the maximum (near the coast) being 9400 mg/l, 9600 mg/l and 6800 mg/l respectively. The computed salinity in the aquifer show a sharp decrease of salinity from the coast towards inland. As an example, for the middle section, the salinity varies from 9,600 mg/l to 500 mg/l from the coastal front to a distance 300 m, as shown in figure 5. The model was not fully calibrated because of uncertainties in the hydrodynamic flow and mass transport data used. However, the results show that the density dependent 3D model is reasonable.

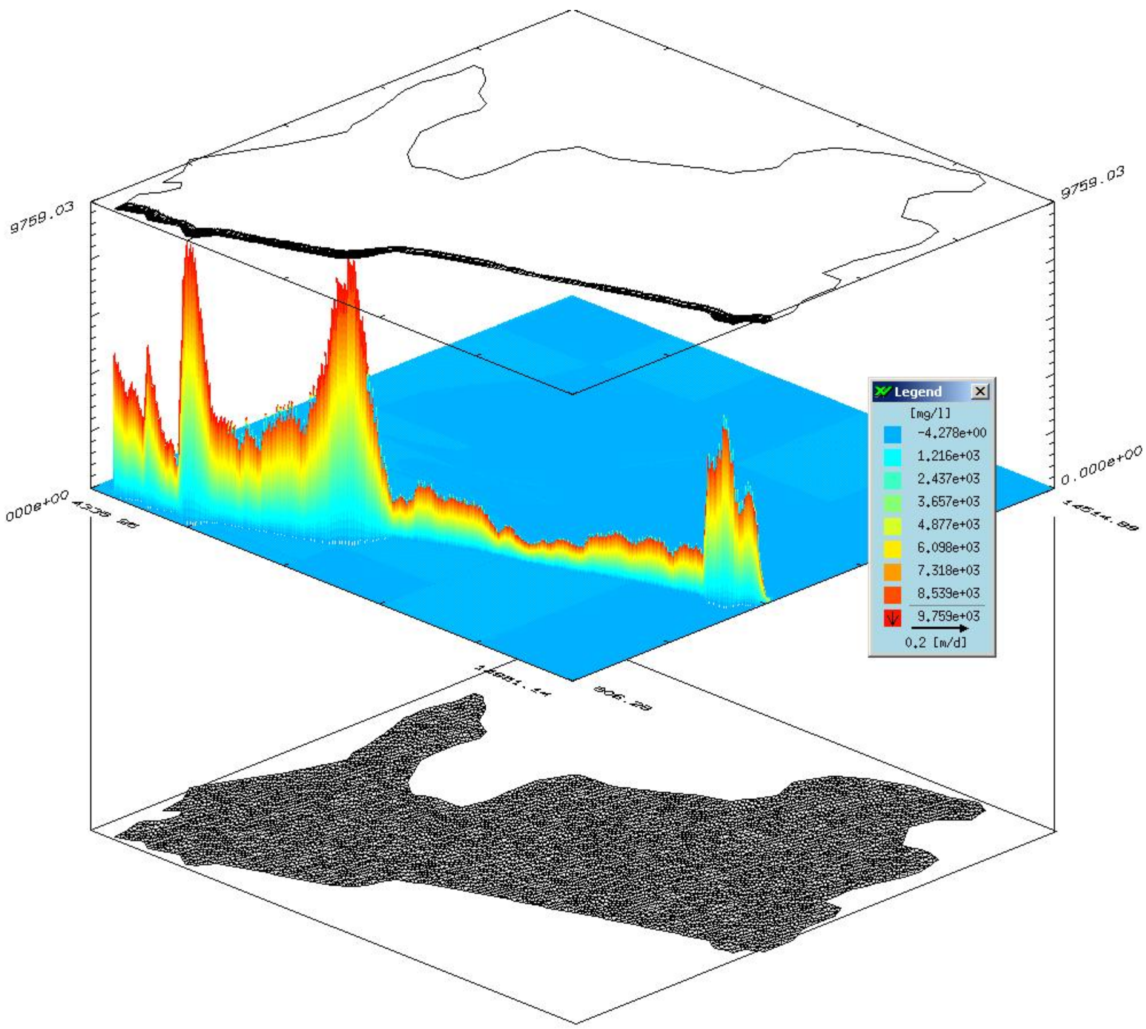

Figure 4: Three-dimensional Plot for Mass Distribution

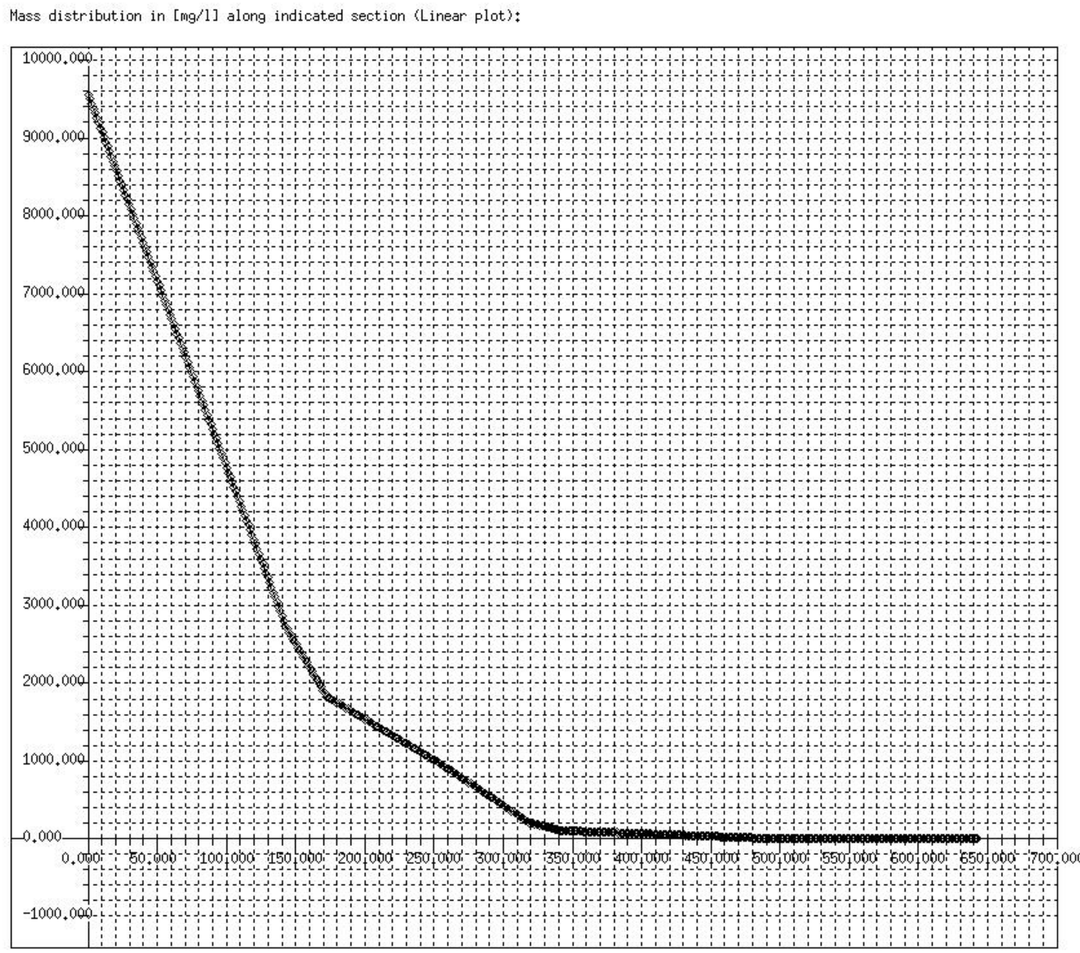

Figure 5: Mass Distribution along a Section

Conclusion

The above results indicate that presently, seawater intrusion is confined only upto 300 m from the coast under normal rainfall conditions and present draft pattern. It may be slightly more for low rainfall years. However, seawater intrusion may further advance inland if withdrawals of groundwater by builders, hotels and other tourist establishments continue to increase in the coming years. Therefore, corrective measures with proper planning and management of groundwater resources in the area need to be initiated at this stage so that it may not turn to be a major water quality problem in the coming times. This study will guide in making management decisions to monitor and control seawater intrusion and planning of groundwater development in the area.

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