Asia Pacific Journal of Research
A peer reviewed international Journal
IMPACT FACTOR : 6.58
Print -ISSN -2320 - 5504
Online-E-ISSN - 2347 - 4793

SUBSURFACE WATER MODELLING USING SWIM AND FEFLOW

***C. P. Kumar*[1], *B. K. Purandara*[2], *A. G. Chachadi*[3]**

[1]*Scientist 'G', National Institute of Hydrology, Roorkee – 247667 (Uttarakhand), India*

[2]*Scientist 'F', Hard Rock Regional Centre, NIH, Belagavi – 590001 (Karnataka), India*

[3]*Professor & Head, Department of Earth Science, Goa University, Goa – 403206, India*

ABSTRACT

Mathematical models provide a scientific and predictive tool for determining appropriate solutions to water allocation, surface water – groundwater interaction, landscape management or impact of new development scenarios. However, if the modelling studies are not well designed from the outset, or the model doesn't adequately represent the natural system being modelled, the modelling effort may be largely wasted, or decisions may be based on flawed model results, and long term adverse consequences may result. This article presents case studies on modelling of soil moisture movement (unsaturated flow) using SWIM and modelling of seawater intrusion (density-dependent groundwater flow) using FEFLOW.

***Keywords**: Unsaturated flow, Groundwater, Modelling, SWIM, FEFLOW*

1. Introduction

Groundwater development has shown phenomenal progress in our country during past few decades. There has been a vast improvement in the perception, outlook and significance of groundwater resource. Groundwater is a dynamic system. It is dynamic in the sense that the state of any hydrological system is changing with time, and in the sense that we are continually developing new scientific techniques to evaluate these systems.

The total annual replenishable groundwater resource of India is around 431 BCM. Inspite of the national scenario on the availability of groundwater being favourable, there are many areas in the country facing scarcity of water. This is because of the unplanned groundwater development resulting in fall of water levels, failure of wells, and salinity ingress in coastal areas. The development and over-exploitation of groundwater resources in certain parts of the country have raised the concern and need for judicious and scientific resource management and conservation.

A complexity of factors - hydrogeological, hydrological and climatological, control the groundwater occurrence and movement. The precise assessment of recharge and discharge is rather difficult, as no techniques are currently available for their direct measurements. Hence, the methods employed for groundwater resource estimation are all indirect. Groundwater being a dynamic and replenishable resource is generally estimated based on the component of annual recharge, which could be subjected to development by means of suitable groundwater structures.

Mathematical models are tools, which are frequently used in studying groundwater systems. In general, mathematical models are used to simulate (or to predict) the groundwater flow. Predictive simulations must be viewed as estimates, dependent upon the quality and uncertainty of the input data. Model conceptualization is the process in which data describing field conditions are assembled in a systematic way to describe groundwater flow processes at a site. The model conceptualization aids in determining the modelling approach and which model software to use.

This article presents two case studies – (a) modelling of soil moisture movement using SWIM (Soil Water Infiltration and Movement) and (b) modelling of seawater intrusion using FEFLOW (Finite Element FLOW).

2. SWIM Case Study - Modelling of Soil Moisture Movement

The objective of the study was to simulate the movement of soil moisture in Barchi watershed (sub-basin of Kali river in North Kanara district of Karnataka) using the SWIM model. The SWIM (Soil Water Infiltration and Movement) is a software package developed by Division of Soils, CSIRO, Australia (Verburg et al., 1996) for simulating infiltration, evapotranspiration, and redistribution. It has been selected for the present study in view of its simplicity, ease of use, graphical display of intermittent results, and use of input parameters (soil moisture characteristics) which can be directly measured in the field/laboratory.

2.1 Study Area

The Barchi watershed upstream of Barchi is located in the leeward side of western ghat and is a sub-basin of Kali river. It lies in Haliyala taluk of Karwar (North Kanara) district in Karnataka. The location and drainage system of Barchi watershed is shown in Figure 1.

The Barchinala stream originates from Thavargatti in Belgaum district at an altitude of about 734 m, 20 km north of Dandeli and flows through North Kanara district of Karnataka State. The catchment is relatively short in width and river flows in a southerly direction and joins the main Barchi river near the gauging site. The geographical area covered by Barchi watershed is 21.126 km^2. The watershed lies between 74^{o}36’ and 74^{o}39’ East longitudes, and 15^{o}18’ and 15^{o}24’ North latitudes.

High land region consists of dissection of high hills and ridges forming part of the foot hills of western ghats. It consists of steep hills and valleys intercepted with thick forest. The slopes of the ghats are covered with dense deciduous forest. Forest cover occupies around 76% of the study area. The watershed is mainly covered with Bamboo, Teak and mixed plantations. The brownish and fine-grained soils are the principal types of soils found in the area. The following land uses were observed in the watershed:

1. Bamboo plantation = 04 %
2. Teak plantation = 40 %
3. Mixed forest = 32 %
4. Agricultural land = 24 %

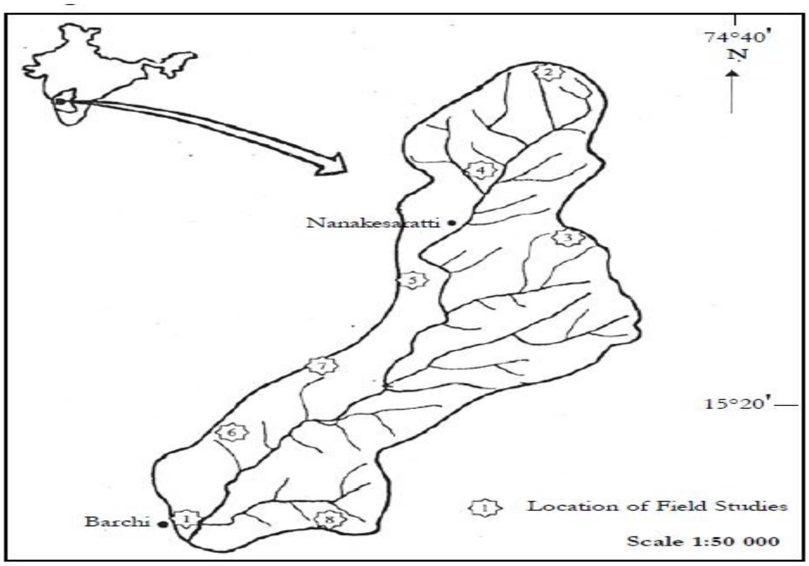


Figure 1: Drainage System of Barchi Watershed

The stream gauging site is located at an elevation of 480 m, where the nala crosses Dandeli-Thavargatti road, about 5 km from Dandeli. The stream is a 4th order stream and joins main Barchi river downstream of the gauging site. A full fledged meteorological station, maintained by Water Resources Development Organisation (WRDO), Karnataka, is located near the gauging site.

The Barchi raingauge station is located at 15°18’ N and 74°37’ E. Average annual rainfall for the watershed is 1500 mm, majority of which occurs during the south-west monsoon period. Depth to water table varies between 4 to 12 metres during pre- and post-monsoon periods. The yield of borewells in the study area is found to vary between 120 gallons per hour to 1170 gallons per hour.

2.2 Methodology

The study involves modelling of soil moisture movement in Barchi watershed using the SWIM model. The following steps were undertaken for the study.

- Field investigations: Measurement of saturated hydraulic conductivity at 8 locations using Guelph Permeameter and soil sampling.
- Laboratory investigations: Determination of saturated moisture content, and soil moisture retention characteristics using the Pressure Plate Apparatus.
- Modelling of soil moisture movement using the SWIM model: Daily rainfall and evaporation data of Barchi for the period 1996-97 to 1999-2000 were used for the study. Water balance components like runoff, evapotranspiration and drainage (recharge to groundwater from rainfall) were determined through SWIM.

SWIM is an acronym that stands for Soil Water Infiltration and Movement. It is a software package developed within the CSIRO Division of Soils for simulating infiltration, evapotranspiration, and redistribution. The first version (SWIMv1) was published in 1990 (Ross[2], 1990). Version 2 of the model (identified as SWIMv2.0), which combines water movement with transient solute transport and which accommodates a variety of soil property descriptions and more flexible boundary conditions, was completed in 1992.

SWIMv2 is based on a numerical solution of the Richards’ equation (1) and the advection-dispersion equation (2), as given below. The model deals with a one-dimensional soil profile.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\mathrm{K}\left[\frac{d\psi}{dp}\frac{\partial p}{\partial x} + \frac{dz}{dx}\right] + S \qquad \ldots(1)$$

with

$$-\frac{\psi-\psi_o}{\psi_1} = \sinh p \qquad \psi < \psi_o$$

$$-\frac{\psi-\psi_o}{\psi_1} = p \qquad \psi \geq \psi_o$$

where,

θ = volumetric water content (cm^3/cm^3);
t = time (h);
x = distance into the soil (cm soil);
K = hydraulic conductivity (cm^2 water/cm soil/h);
Ψ = matric potential (cm);
z = gravitational potential (cm);
S = source (or sink, if negative) strength (cm^3 water/cm^3 soil/h); and
ψ_o and ψ_1 = shifting and scaling parameters, respectively.

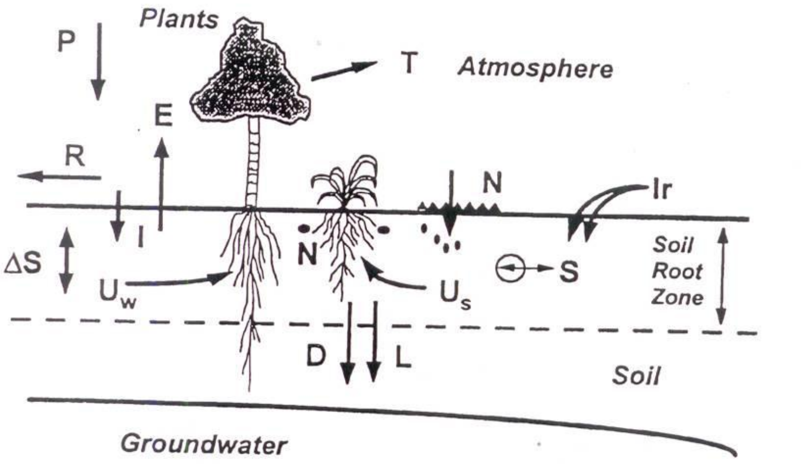
Solute movement is based on the following solute transport equation

$$\frac{\partial(\theta c)}{\partial t}+\frac{\partial(\rho s)}{\partial t}=\frac{\partial}{\partial x}\left[\theta D\frac{\partial c}{\partial x}\right]-\frac{\partial(qc)}{\partial x}+\phi \qquad \ldots(2)$$

where,

c = solute concentration in solution (μmol or μg solutes/cm^3 water);
s = adsorbed concentration (μmol/g soil or μg/g soil);
ρ = soil bulk density (g/cm^3);
t = time (h);
x = depth (cm);
θ = water content (cm^3/cm^3);
q = water flux density (cm/h);
D = combined dispersion and diffusion coefficient (cm^2/h); and
ϕ = source/sink term (μmol/cm^3/h or μg/cm^3/h).

The SWIM can be used to simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching. The physical system and the associated flows addressed by the model are shown schematically in Figure 2. Soil water and solute transport properties, initial conditions, and time dependent boundary conditions (e.g., precipitation, evaporative demand, solute input) need to be supplied by the user in order to run the model. The overall purpose of the model is to address issues relating to the soil water and solute balance. As such, it is a research tool that can be integrated in laboratory and field studies concerned with soil water and solute transport.



Components of the soil water and solute balances addressed by SWIMv2.1; P = precipitation, R = runoff, I = infiltration, U_w = water uptake, U_s = solute uptake, T = transpiration, E = evaporation, D = drainage, L = solute leaching, Ir = irrigation/fertigation, N = nutrients/fertiliser, ΔS = storage, S = solute source/sink.

Figure 2: Components of the Soil Water and Solute Balances Addressed by SWIMv 2.1

To model the retention and movement of water and chemicals in the unsaturated zone, it is necessary to know the relationships between soil water pressure (h), water content (θ) and hydraulic conductivity (K). It is often convenient to represent these functions by means of relatively simple parametric expressions. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model.

The measurements of θ(h) from soil cores (obtained through pressure plate apparatus) can be fitted to the desired soil water retention model. Once the retention function is estimated, the hydraulic conductivity relation, K(h), can be evaluated if the saturated hydraulic conductivity, K_s, is known. In the present study, parameters of van Genuchten model were derived for soil moisture retention and hydraulic conductivity functions. For the van Genuchten[3] model (1980), the water retention function is given by

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) = [\,1 + (\alpha_v\,|h|\,)^n\,]^{-m} \quad \text{for } h < 0$$
$$= 1 \quad \text{for } h \geq 0 \qquad \ldots(3)$$

and the hydraulic conductivity function is described by

$$K = K_s\, S_e^{1/2}\,[\,1 - (1 - S_e^{1/m}\,)^m\,]^2 \qquad \ldots(4)$$

where, S_e is effective saturation; θ_r is residual water content; θ_s is saturated water content; α_v and n are van Genuchten model parameters; $m = 1 - 1/n$.

Modelling of soil moisture movement in Barchi watershed was done using SWIM. The model was simulated for 1461 days (1 May 1996 to 30 April 2000). One vegetation type (teak, covered in most parts of the watershed) was considered for the study. Exponential root growth with depth and linear interpolation with time was assumed. The following vegetation parameters were adopted for the simulations:

Root radius (rad) = 0.5 cm
Root conductance (groot) = $4.0 * 10^{-7}$
Minimum xylem potential (psimin) = -15,000 cm
Root depth constant (xc) = 150 cm
Maximum root length density (rldmax) = 4 cm/cm^3

2.3 Results and Discussion

Soil moisture retention characteristics were determined in the laboratory using the Pressure Plate Apparatus. The experimental soil moisture retention data were fitted to the van Genuchten[3] model (1980). Residual moisture content (θ_r) was assumed to be equivalent to moisture retained corresponding to 15 bar pressure. The parameters of soil moisture retention function and hydraulic conductivity function were obtained through non-linear regression analysis. Tables 1 and 2 present the van Genuchten parameters α and n (equations 3 and 4) for upper and lower soil layers in Barchi watershed. Average values of these parameters were also determined through non-linear regression analysis and used in modelling of soil moisture movement through SWIM.

Table 1: van Genuchten Parameters for Upper Soil Layer

Station	K_s (cm/hour)	θ_r	θ_s	van Genuchten Parameters		Proportion of Variance Explained (%)
				α	n	
1	0.58	0.08	0.37	0.0073	1.434	80.78
2	0.57	0.14	0.37	0.0023	1.509	74.08
3	0.60	0.09	0.38	0.0021	1.465	79.07
4	0.18	0.30	0.53	0.0067	1.523	92.00
5	0.20	0.28	0.53	0.0129	1.373	80.66
6	0.18	0.28	0.53	0.0235	1.300	64.09
7	0.24	0.25	0.52	0.0020	1.580	84.07
8	0.16	0.30	0.54	0.0019	1.552	91.51
Average	0.339	0.215	0.471	0.0047	1.4385	24.43

Table 2: van Genuchten Parameters for Lower Soil Layer

Station	K_s (cm/hour)	θ_r	θ_s	van Genuchten Parameters		Proportion of Variance Explained (%)
				α	n	
1	1.66	0.11	0.38	0.0148	1.563	97.04
2	0.60	0.09	0.32	0.0045	1.760	99.52
3	0.007	0.06	0.43	0.0154	1.358	87.12
4	0.58	0.14	0.41	0.0134	1.310	81.71
5	0.58	0.16	0.43	0.0070	1.444	91.68
6	0.18	0.28	0.53	0.0235	1.300	64.09
7	0.59	0.13	0.31	0.0120	1.596	95.35
8	0.60	0.20	0.45	0.0123	1.688	91.97
Average	0.648	0.121	0.394	0.0095	1.4212	58.31

Based upon the available information, two distinct soil layers were identified (0-45 cm and 45-150 cm). Saturated hydraulic conductivity was measured at 8 locations in the study area by using Guelph Permeameter (locations are shown in Figure 1). The average saturated hydraulic conductivity values for the upper layer (0-45 cm) and lower layer (45-150 cm) were found to be 0.339 cm/hour and 0.648 cm/hour respectively.

2.3.1 Model Conceptualization

The profile is 150 cm deep with surface at 0 cm and bottom boundary condition applying at 150 cm. Vapour conductivity is not taken into account, nor is the effect of osmotic potential. There are two hydraulic property sets (for upper and lower soil layers) that are applied to 31 depth nodes of the 150 cm deep profile. Hysteresis is not taken into account.

Initially, there is no water ponded on the surface. Runoff is governed by a simple power law function and a surface conductance function. No bypass flow was included. A matric potential gradient of 0, i.e. “unit gradient”, has been applied as bottom boundary condition throughout the simulation. Cumulative rainfall and evaporation records (daily) for the period 1996-97 to 1999-2000 were given in the input file for determination of water balance components (runoff, evapotranspiration and drainage).

2.3.2 Simulation of Water Balance Components

The model parameters (soil moisture characteristics) were actually measured in the field and laboratory. Therefore, the model does not require any calibration as such. The model was validated by comparing the observed and simulated runoff. However, the observed runoff values were suspected to be erroneous in view of inaccurate positioning of zero of gauge.

Self-recording raingauge data (hourly rainfall values) were not available for the watershed. Therefore, daily rainfall values were used. However, with the available input data and parameters, the model was found to underestimate the runoff values. It happened because daily rainfall data generated low rainfall intensities (distributed over 24 hours) with most of the rainfall infiltrating into the ground and contributing less runoff. Therefore, daily rainfall values were equally distributed to 4 hours for the periods exceeding 20 mm rainfall in a day. This made a better agreement between the observed and simulated runoff and therefore validated the model. The distribution of daily rainfall into 4 hours was decided on the basis of trial simulations by testing varying divisions with part of actual data. The resulting water balance components for the simulation period have been presented in Table 3.

Table 3: Water Balance Components for the Barchi Watershed

Year	Rainfall (mm)	Infiltration (mm)	Drainage (mm)	ET (mm)	Runoff (mm)	Runoff Coefficient (%)	Recharge Coefficient (%)
1996-1997	1345.85	1083.37	514.46	519.52	262.48	19.50	38.22
1997-1998	1765.25	1195.05	698.63	500.43	570.20	32.30	39.58
1998-1999	1241.30	1087.46	579.55	507.92	153.84	12.39	46.69
1999-2000	1886.80	1278.18	784.90	493.28	608.62	32.26	41.60
Total	6239.20	4644.06	2577.54	2021.15	1595.14	24.11	41.52

The yearly rainfall varied between 1241 mm to 1887 mm during the period under study. It can be observed from Table 3 that the drainage (recharge from rainfall) varies from 38% to 47% with the average value being 42%. The runoff coefficient was found to vary between 12% (low rainfall year) to 32% (high rainfall year) with the average value being 24%. Runoff coefficient was found to be lower in low rainfall years (1996-97 and 1998-99). It can be attributed to low rainfall intensities enabling more infiltration and lesser runoff. Antecedent moisture conditions also play an important role in the runoff generation process. Simulation of variable infiltration suggests that it has relatively little effect on evapotranspiration, but considerable effect on point drainage.

2.4 Conclusion for SWIM Case Study

Application of SWIM model is one of the simplest techniques, which is well suited for unsaturated zone. SWIM is a software package for simulating water infiltration and movement in soils. Water is added as precipitation and removed by runoff, drainage, evaporation from the soil surface and transpiration by vegetation. The simulator assumes that conditions can be treated as horizontally uniform, flow is described by the Richards equation and soil hydraulic properties can be described by simple functions. While this is adequate for many purposes, there are situations where it is not and the simulation results should never be applied uncritically.

Water balance components like runoff, evapotranspiration and drainage were determined through SWIM for the period 1996-97 to 1999-2000. The ground water recharge was found to vary between 38% to 47% of rainfall while the runoff coefficient varied between 12% (low rainfall year) to 32% (high rainfall year) for the study period. Variable infiltration was observed to have relatively little effect on evapotranspiration, but considerable effect on drainage.

The SWIM model demonstrated the possibility of predicting water balance components of the unsaturated zone, but only with careful selection of input parameters. It would appear that when actual observed data is not available, it would be difficult to rely upon numerical models alone.

3. FEFLOW Case Study - Modelling of Seawater Intrusion

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 this 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.

3.1 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 3 and 4 respectively.

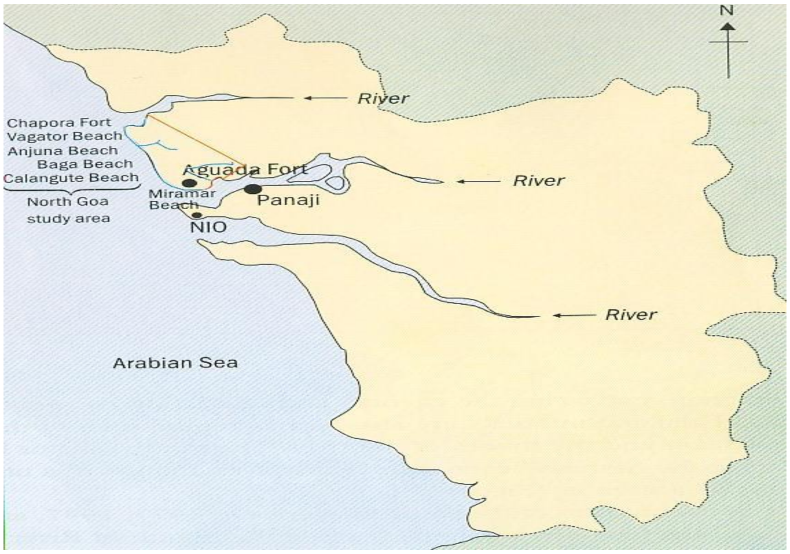


Figure 3: Location Map of Study Area in Goa

3.2 Laboratory and Field Investigations

Twenty observation wells were identified in the study area (as indicated in figure 4). 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.

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 4). 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.

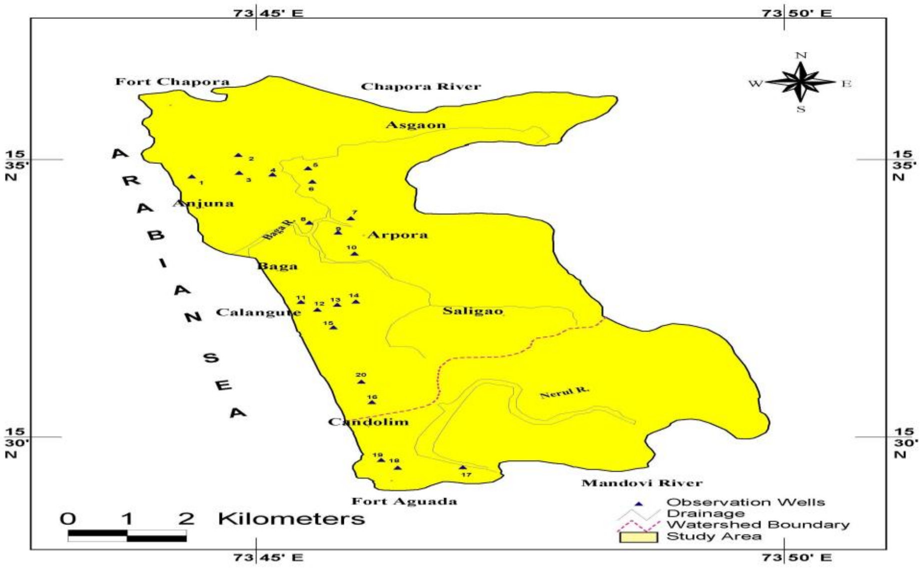


Figure 4: Layout Map of the Study Area

Seven vertical electrical soundings were carried out at monitoring well sites 1, 3, 6, 7, 8, 15 and 17 (Table 5). 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 4: 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 5: 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

3.3 Finite Element Simulation Model

For this 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.

3.3.1 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 1st 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.

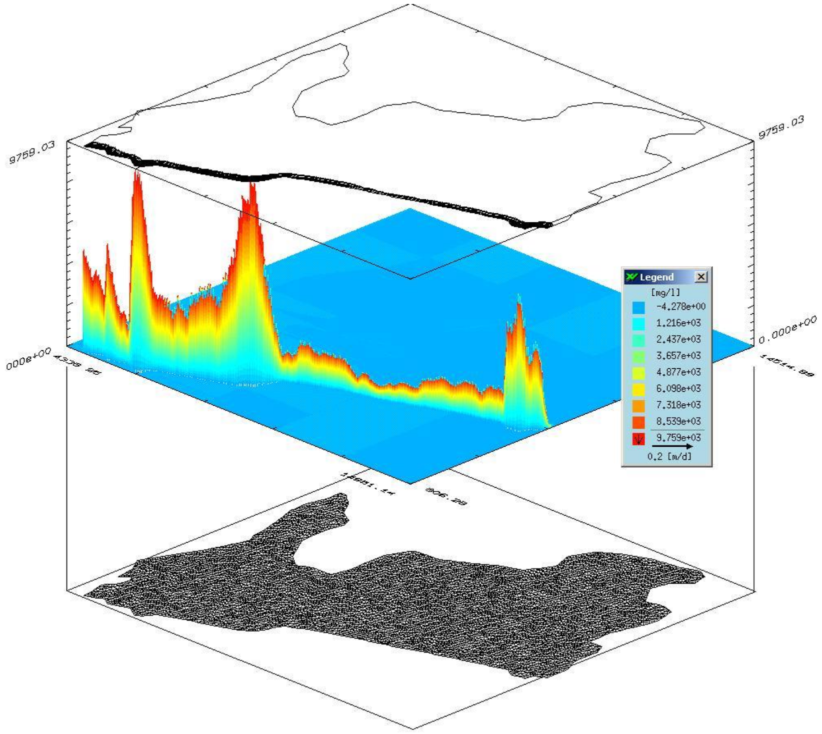


Figure 5: Three-dimensional Plot for Mass Distribution

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 5. 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 6. 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.

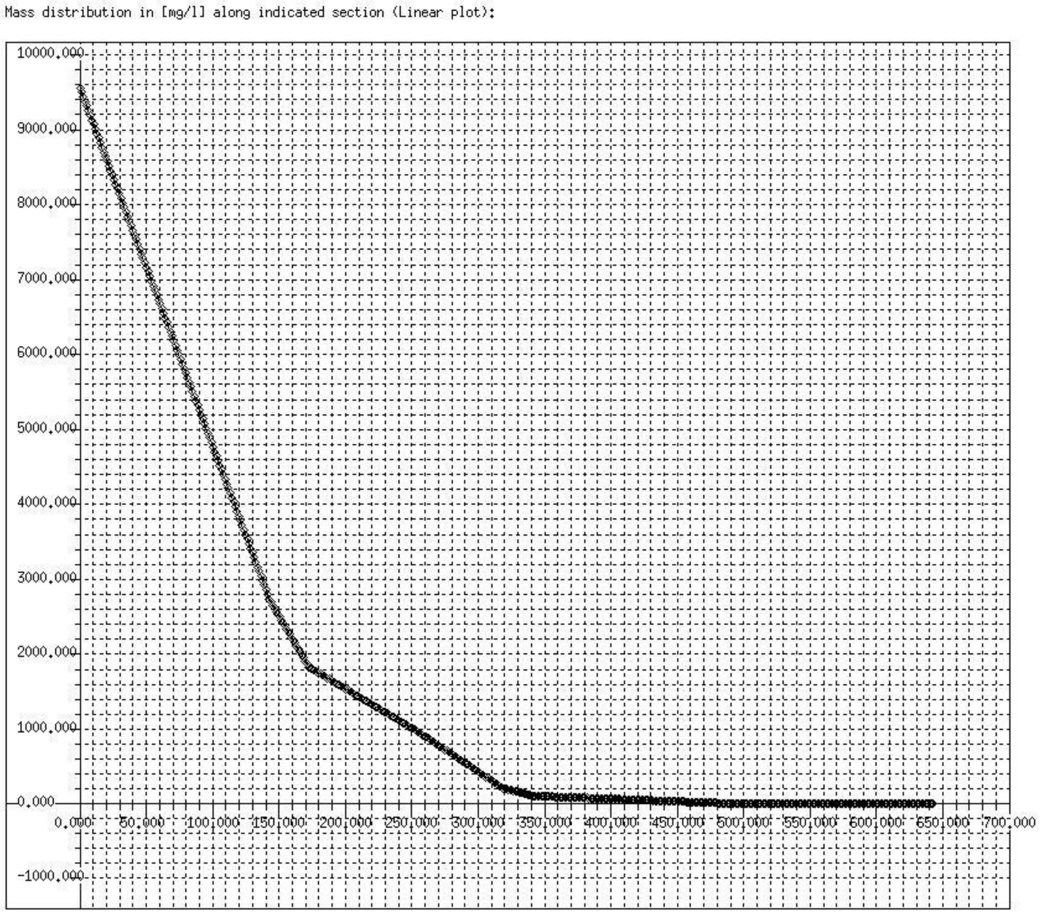


Figure 6: Mass Distribution along a Section

3.4 Conclusion for FEFLOW Case Study

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.

References

1. Chachadi, A.G. (2000). Strategies for Water Resources Management in the Coastal Zones of Goa. Coastal Zone Management, S.D.M.C.E.T, Dharwad & IGCP-367, Special Publication, Volume No. 2, pp. 165-168.

2. Chachadi, A.G. and C. Joaquim S. John (2000). Geoelectrical Studies in Ascertaining Fresh-Water Zones in Coastal Goa. Coastal Zone Management, S.D.M.C.E.T, Dharwad & IGCP-367, Special Publication, Volume No. 2, pp. 169-172.

3. Chachadi, A. G., J. P. Lobo-Ferreira, Ligia Noronha and B. S. Choudri (2002). Assessing the Impact of Sea-Level Rise on Salt Water Intrusion in Coastal Aquifers using GALDIT Model, Coastin – November 2002, TERI, pp. 27-32.

4. Cheng, Alexander H.-D. (2003). Groundwater, Saltwater Intrusion in. Encyclopedia of Water Science, Marcel Dekker, Inc., pp. 404-406.

5. COASTIN (2001). GIS and Mathematical Modelling for the Assessment of Groundwater Vulnerability to Pollution: Application to an India Case – Study Area in Goa. 2nd Year Report, April 2001, 69 p.

6. Diersch, H.-J. G. (2002). FEFLOW Reference Manual, Finite Element Subsurface Flow & Transport Simulation System. WASY Institute for Water Resource Planning and Systems Research Ltd., Berlin, 278 p.

7. FEFLOW (Finite Element Subsurface Flow & Transport Simulation System) Demonstration Exercise, WASY Institute for Water Resource Planning and Systems Research Ltd., Berlin, 2004, 48 p.

8. FEFLOW 5.1 (Finite Element Subsurface Flow & Transport Simulation System) User's Manual, WASY Institute for Water Resource Planning and Systems Research Ltd., Berlin, 2004, 168 p.

9. Goa University (2000). Aquifer Testing, Observation Well Networking, Electrical Profiling and Groundwater Draft Estimation, Baga Watershed, Bardez, Goa. Department of Geology, Goa University, Goa, 46 p.

10. Groundwater Resource Estimation Methodology - 1997. Report of the Groundwater Resource Estimation Committee, Ministry of Water Resources, Government of India, New Delhi, June 1997.

11. Kumar, C. P. and B. K. Purandara (2003). Modelling of Soil Moisture Movement in a Watershed using SWIM. Journal of The Institution of Engineers (India), Agricultural Engineering Division, Volume 84, December 2003, pp. 47-51.

12. Kumar, C. P., A. G. Chachadi, B. K. Purandara, Sudhir Kumar and Raju Juyal (2007). Modelling of Seawater Intrusion in Coastal Area of North Goa. Water Digest, Vol. II, Issue 3, September-October 2007, pp. 80-83.

13. Lobo-Ferreira, J. P., Maria C. Cunha, A. G. Chachadi, Kai Nagel, Catarina Diamantino and Manuel M. Oliveira (2003). Application of Optimization Models for Satisfaction of Water Resource Demand of Tourist Infrastructure. In. Coastal Tourism, Environment, and Sustainable Local Development (Ed. Noronha et al.), Chapter 14, pp. 305-320.

14. Purandara, B. K. and C. P. Kumar (2000). Simulation of Soil Moisture Movement in a Forested Watershed. ICIWRM-2000, Proceedings of International Conference on Integrated Water Resources Management for Sustainable Development, 19-21 December, 2000, New Delhi, India, pp. 833-839.

15. Ross, Peter J. (1990). SWIM - A Simulation Model for Soil Water Infiltration and Movement. Reference Manual to SWIMv1, CSIRO Division of Soils, Australia, 1990.

16. Verburg Kirsten, Peter J. Ross and Keith L. Bristow (1996). SWIMv2.1 User Manual. CSIRO Division of Soils, Australia, Divisional Report No. 130, 1996.

17. van Genuchten, M. Th. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Sci. Soc. Am. J., Volume 44, 1980, pp. 892-898.