Estimation of surface runoff and groundwater recharge in Goa mining area using daily sequential water balance model - BALSEQ

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Abstract Aquifer recharge is an important component of the hydrological cycle not only for the quantification of groundwater resources but also for the determination of the vulnerability of an aquifer to pollution. Daily sequential water balance method BALSEQ (developed at the National Laboratory of Civil Engineering, Lisbon, Portugal) has been used to estimate aquifer recharges and surface runoff. The method is fast, and can be used for regions with scarce hydrologic data. The model requires daily rainfall, monthly potential evapotranspiration, runoff curve number (*CN*) and maximum soil moisture available for evaporation as input data. The output data include daily and monthly values of surface runoff, actual evapotranspiration, aquifer recharge and soil moisture. This method was applied satisfactorily to a coastal watershed in Goa, India.

Key words BALSEQ; aquifer recharge; curve number; water balance; runoff

INTRODUCTION

Aquifer recharge is an important component of the hydrological cycle. Recharge quantification not only helps in groundwater potential estimation, but also helps in the determination of aquifer vulnerability to pollution. Recharged water transports a contaminant vertically to the water table and horizontally within the aquifer. Also, the quantity of water available for dispersion and dilution of the contaminant in the vadose zone and in the saturated zone is controlled by the recharge rate and the quantity. In general, the more the recharge the more is the potential for groundwater pollution as the contaminants are moved at a faster rate in a larger quantity, if the contaminant source is unlimited. On the other hand, better quality of groundwater recharge can cause more dilution and dispersion and thus, decrease, the pollution potential, if the contaminant source through which recharge is taking place is limited in quantity (Aller *et al.*, 1987). Therefore, it is pertinent to estimate the reliable quantity and rate of aquifer recharge. There are several methods that can be used for the assessment of aquifer recharge such as

1. Soil water balance
2. Monthly sequential water balance
3. Empirical methods
4. Groundwater balance/water table fluctuation method
5. One-dimensional soil water flow model
6. Inverse modeling technique, and
7. Isotope and solute profile techniques etc.

Some of these are more commonly used than others. Their main disadvantage is the fact that some of the regional variables, which have influence on the recharge process, for instance, updated characterization of land cover and/or land use of the catchment are difficult to account for in the computation of recharge. The simplest method amongst them consists of assigning an infiltration coefficient to each lithological type, and thus the recharge is obtained by multiplying this coefficient by precipitation. Other empirical methods are based on the relations among different variables of the hydrological cycle.

The monthly sequential water balance method takes into account all variables that influence recharge, allowing the consideration of recharge by lateral flow as well. Hence, this method is more advantageous as compared to the other methods especially when longer periods of recharge estimation are considered. In the monthly sequential balance equation, it is necessary to know the values of precipitation and potential evaportranspiration for each of the selected time intervals, as well as the field capacity. The recharge is the sum of groundwater discharge and storage variation in the aquifer. The application of monthly sequential balance is valid only when the precipitation regime is uniform throughout the month as may be depicted by rainfall data. If the monthly precipitation is less than the monthly potential evapotranspiration, then there will be no recharge. In fact during a month, the precipitation value may be very high in some days and low/nil in others. This means that if a shorter period is considered, the precipitation may be higher than the potential evapotranspiration and there may be some recharge. Therefore, in monthly sequential balancing, the estimated aquifer recharge gets fairly attenuated.

The modeling of daily sequential water balance is therefore desirable in order to counter the recharge attenuation encountered in monthly sequential balancing. The realization of this problem led to the development of the mathematical model BALSEQ (acronym of SEQuential BALance) for the assessment of daily sequential water balance, at the National Laboratory of Civil Engineering, Lisbon, Portugal. This model was initially intended for evaluation of the aquifer recharge of the Portuguese Island of Port Santo with a semi-arid climate (cf. Lobo-Ferreira, 1981b and Lobo-Ferreira *et al.*, 1981). Later, it was used to estimate aquifer recharge in different zones of Portugal.

THEORY OF BALSEQ MODEL

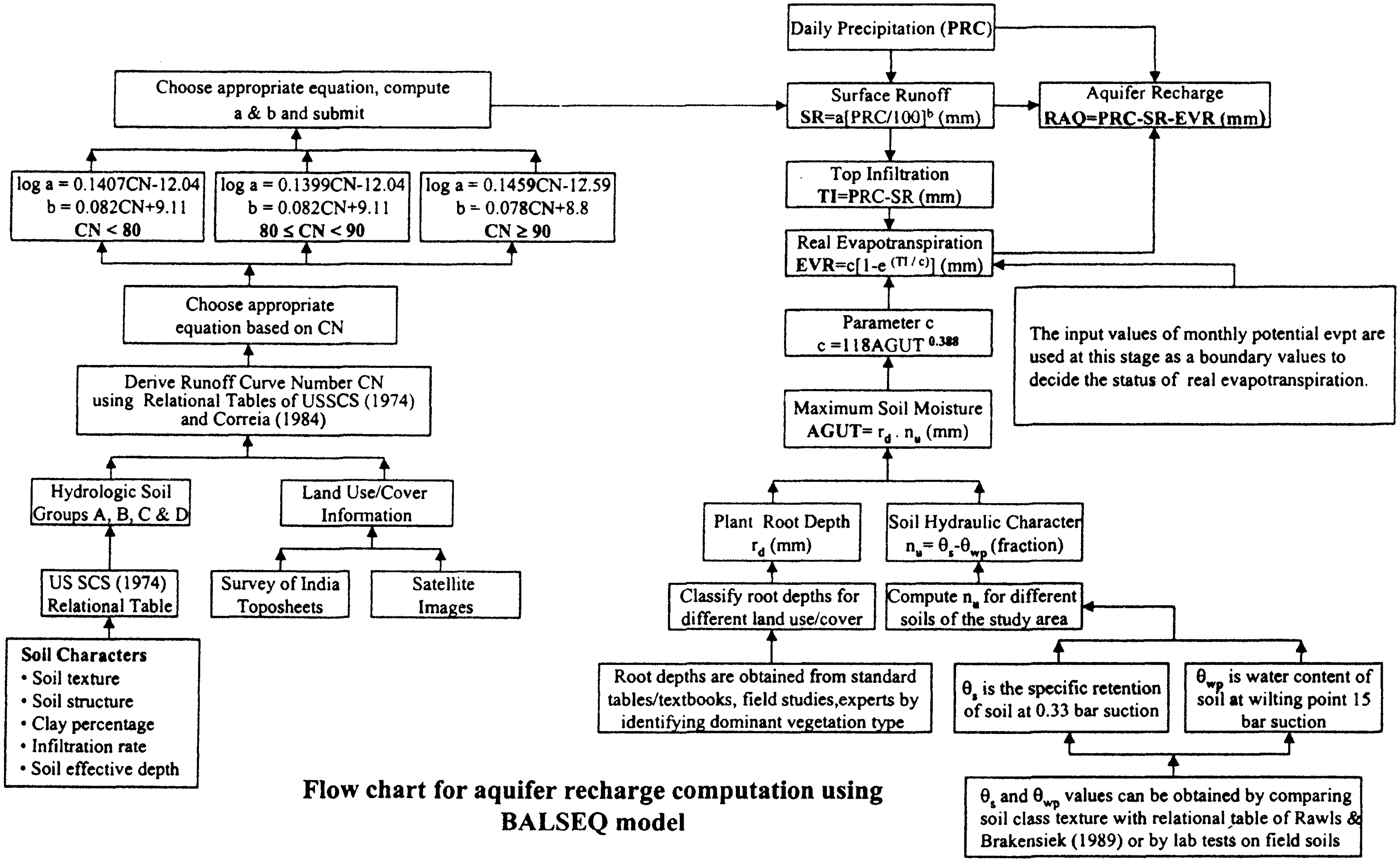
The model uses a daily time increment and the data necessary for the execution of the model are:

1. Daily values of precipitation (mm)
2. Monthly values of potential evapotranspiration (mm),
3. Runoff curve number (*CN*) according to the U.S. Soil Conservation Service; the value of *CN* is a value between 0 and 100. Zero corresponds to a soil with infinite hydraulic conductivity and 100 to a soil that is totally impermeable.
4. Maximum amount of water available for evapotranspiration, [This is reflected by variable called AGUT; which is the amount of water necessary to increase the soil moisture of the evapotranspiration zone from its lower most value (wilting point, θ_{wp}) to the level of specific retention of the soil. The depth of evapotranspiraton zone is considered approximately equal to the root depth of vegetation. With root depth of the plants in the area under study and the difference between field capacity (at 0.33 bar suction) and wilting point (at 15 bar suction) of the soil in this zone, the value of AGUT is estimated.]
5. Soil moisture at the first day of the balance. [The model is designed in such a way that it begins recharge computation just before the beginning of rainy season (May in India) and hence, soil moisture during this dry period is assumed to be of minor importance and is assigned zero in the model.]

The model considers the runoff curve number *CN* as invariable in time and makes it possible to obtain a recharge value, which must be considered as the potential recharge, because it assumes that the water table is sufficiently deeper so that there is no rejected recharge and also, it does not consider the possible existence of less permeable layers in the vadose zone. The aquifer recharge is quantified considering a minimum residence time of infiltrated water below the soil of at least 1-day. After the minimum time of presence in the geologic formation, the ground water may emerge to the surface again either as springs or feeding watercourses. The different model outputs, important for aquifer recharge estimation are surface runoff, actual evapotranspiration and deep percolation. It is stressed here that the model does calculate deep percolation (infiltration below the evapotranspiration zone) and assumes that this deep infiltration equals the aquifer recharge. The actual evapotranspiration is the quantity of the water that actually goes to the atmosphere in the region under the influence of existing meteorological conditions. The model BALSEQ uses a daily time increment and calculates the surface runoff (SR) using the following Eq. (1) (cf. USDA, 1972 Lobo-Ferreira, 1981b):

$$SR\ (mm) = 25.4(PRC/25.4 - 200/CN + 2)^2 / (PRC/25.4 + 800/CN - 8) \qquad (1)$$

where, PRC is the daily precipitation (mm), *CN* is the runoff curve number, and SR is the daily surface runoff (mm). Complete details of the input data and computational procedures are listed in the following flow chart.



Flow chart for aquifer recharge computation using BALSEQ model

If the daily precipitation is less than the value computed from Eq. (2), the precipitation is totally added to the soil moisture content, which is subsequently evapotranspired until the maximum value of daily evapotranspiration is reached.

$$PRC\ (mm) > 5080 / CN - 50.8 \quad (2)$$

Once the value of daily precipitation is higher, the surface runoff is calculated as per Eq. (1). The deep (groundwater) recharge takes place whenever the soil moisture content exceeds the value of the variable AGUT. The surplus water will be the value of aquifer recharge. The study of the relation between surface runoff with precipitation and runoff curve number for five watersheds in Portugal (Vermeulen *et al.*, 1994) has indicated that the surface runoff increases with higher values of precipitation and runoff curve number, as depicted in Fig. 1.

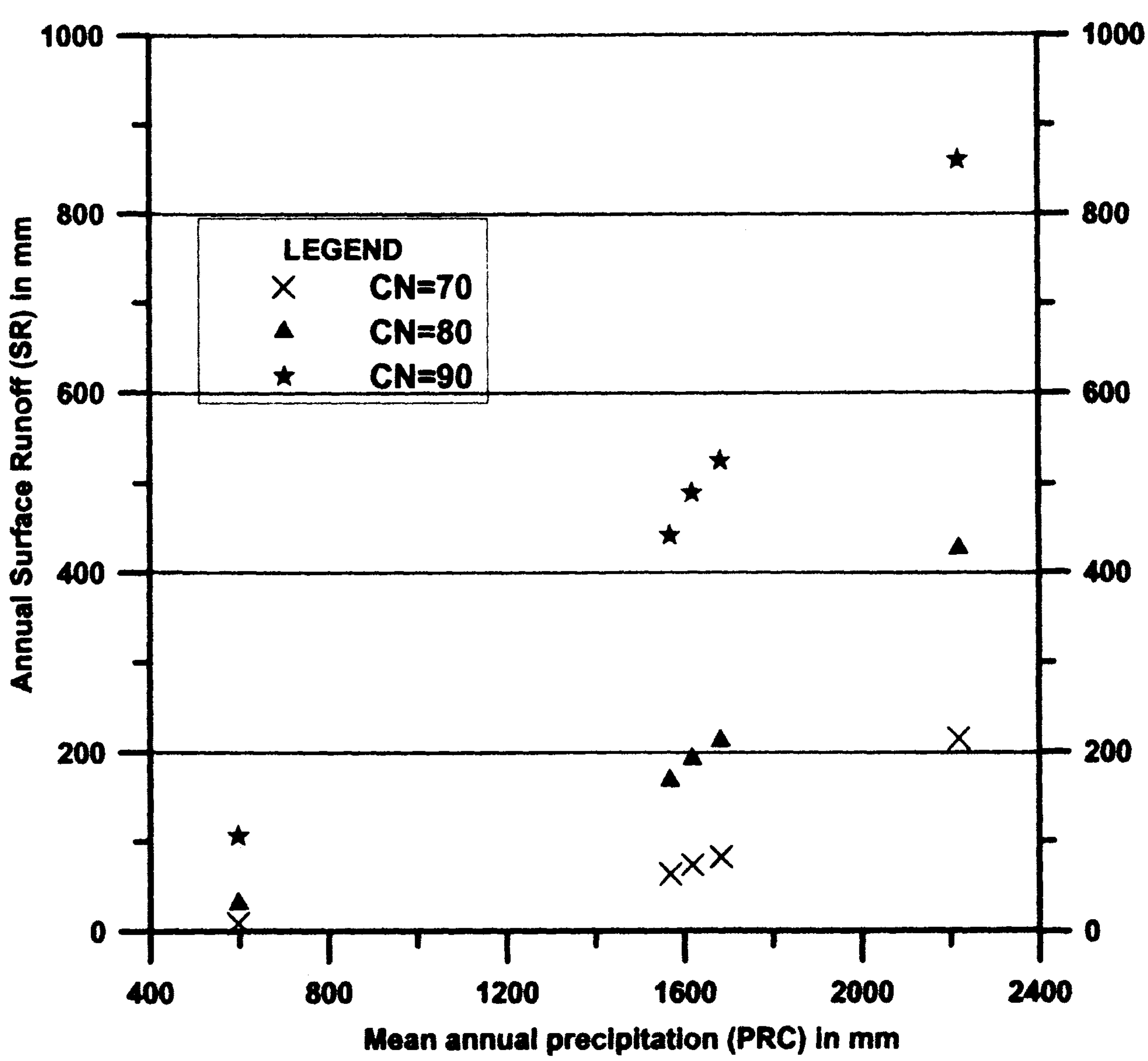


Fig.1 Relation between rainfall, surface runoff and runoff curve number for a watershed in Portugal

The following expression was proposed as a best-fit expression for surface runoff:

$$SR\ (mm) = a\ (PRC/100)^{b} \quad (3)$$

where SR is daily surface runoff (mm); PRC is daily precipitation in mm and *a, b* are parameters

The regression analysis provided the following values of parameters a and b:

$CN = 70$; $a = 0.005$ and $b = 3.4$
$CN = 80$; $a = 0.16$ and $b = 2.5$
$CN = 90$; $a = 3.5$ and $b = 1.78$

The variation of parameters a and b in Eq. (3) were plotted for CN values of 70, 80, 90, and 100 as shown in Fig 2.

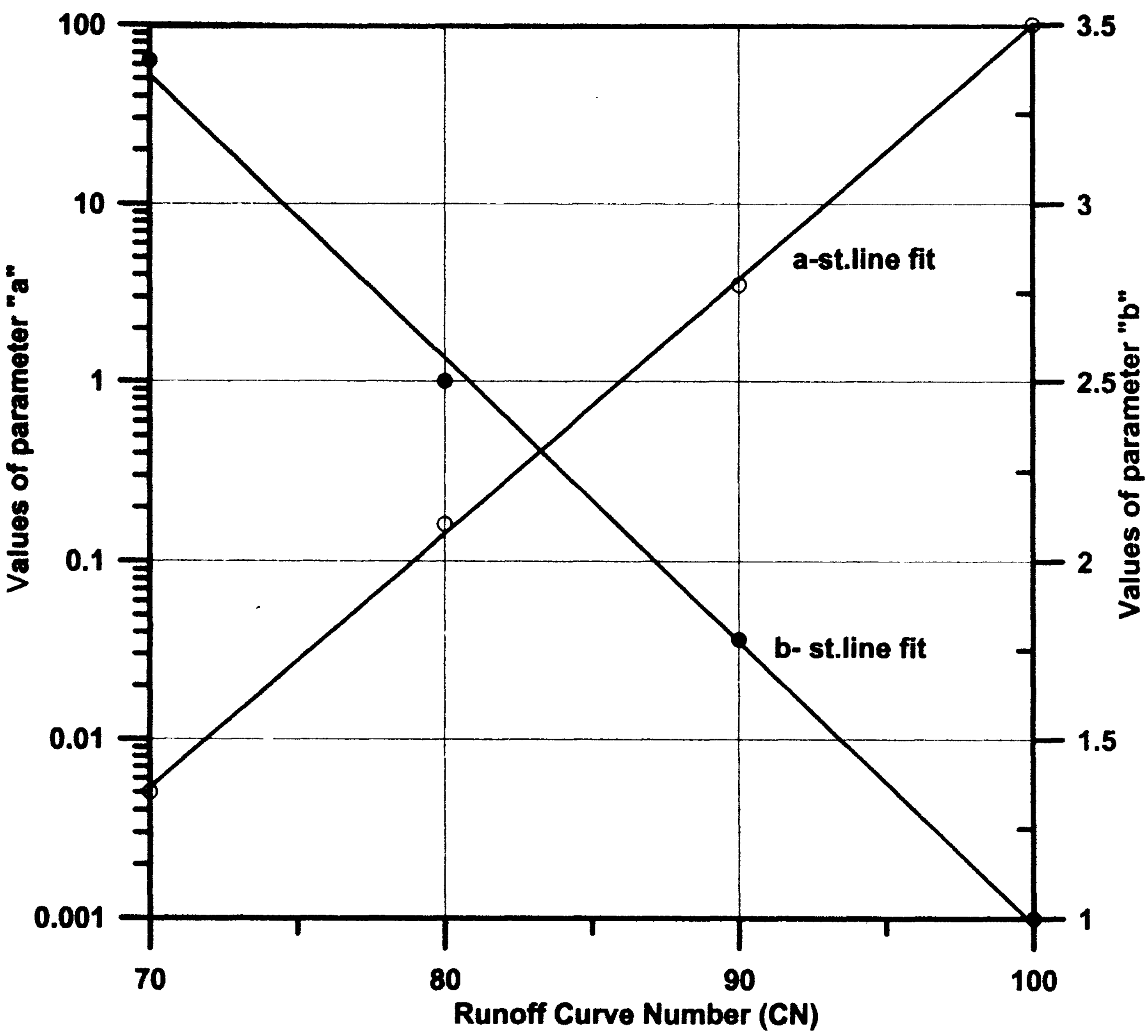


Fig. 2 Variation of parameters a and b with CN.

From the above figure, it is seen that for CN=100, the values of a and b are 100 and 1 respectively. The Eq. (3), therefore, reduces to SR=PRC, by substituting the values of a=100 and b=1. It, therefore, indicates that for CN=100, all the precipitation contributes to surface runoff (in case of impermeable surface). The straight line that fits in Fig. 2 corresponds to the following equations involving a and b.

$$\log a = -12.24 + 0.1424\, CN \tag{4}$$

$$b = 8.9 - 0.079\, CN \tag{5}$$

Using the parameters *a* and *b* from the above Eqs. (4) and (5), the surface runoff values computed for different *CN* (70,80,90) have been compared with the observed, as shown in Fig.3. It is seen from the comparison plot that errors increase particularly for large values of *CN*.

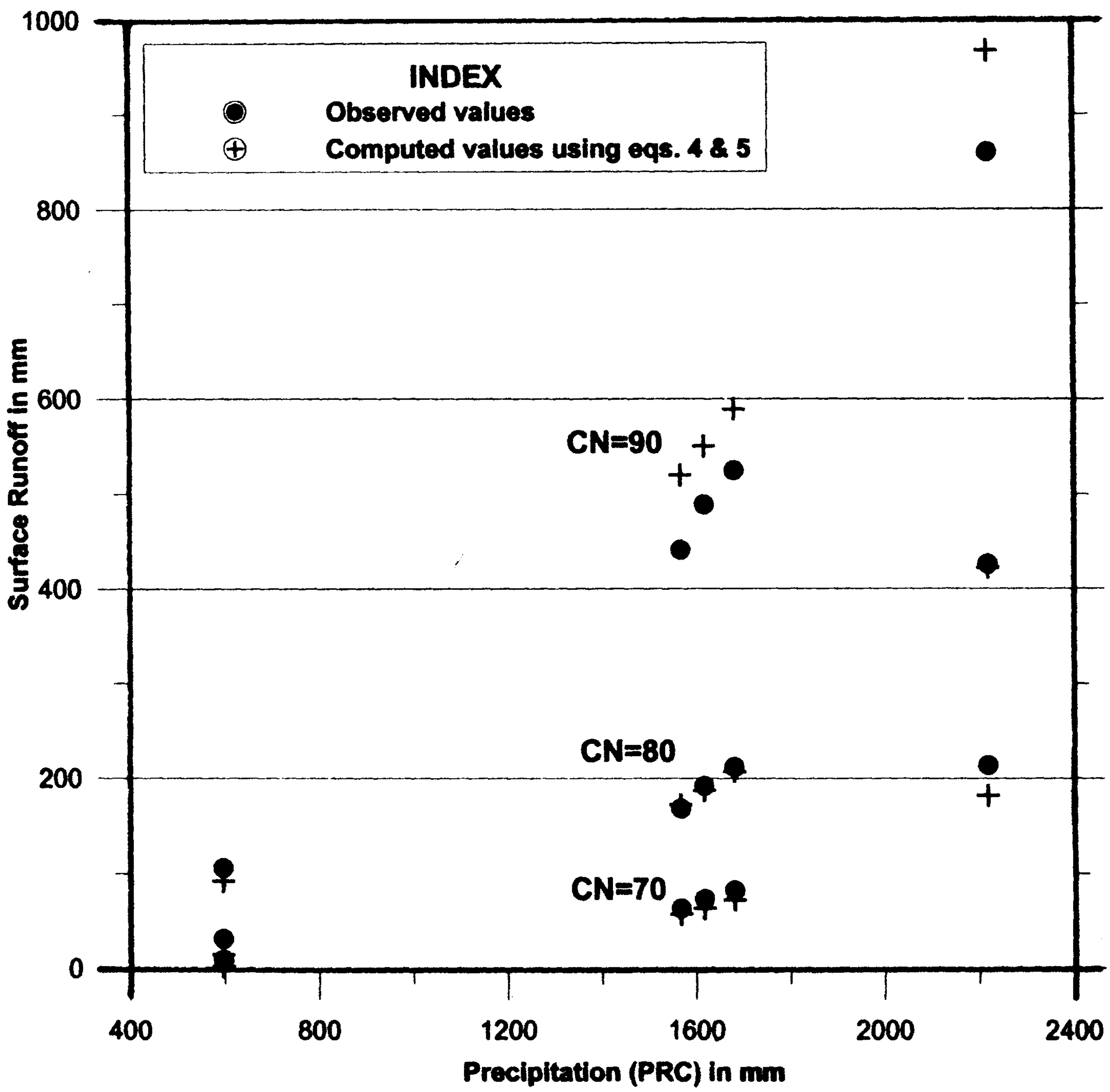


Fig.3 Comparison of the observed and the computed runoff values

It is seen from Fig. 2 that the plots of parameters *a* and *b* with respect to *CN* show three segments between the *CN* values 70-80, 80-90 and >90, and hence, the generalized expressions derived for parameters *a* and *b*, as given in equations (4) and (5), give some errors in the computed values of surface runoff. Therefore, in order to refine the estimates, each of the segments of *a* and *b* plots in fig. 2 were used to derive the expressions for the parameters *a* and *b*, as shown below.

$$\log a = 0.1407\,CN - 12.0, \quad CN<80 \quad (6)$$
$$b = -0.082\,CN + 9.11, \quad CN<80 \quad (7)$$
$$\log a = 0.1399\,CN - 12.04, \quad 80 \leq CN<90 \quad (8)$$
$$b = -0.082\,CN + 9.11, \quad 80 \leq CN<90 \quad (9)$$
$$\log a = 0.1459\,CN - 12.59, \quad CN \geq 90 \quad (10)$$
$$b = -0.078CN + 8.8, \quad CN \geq 90 \quad (11)$$

The estimates of surface runoff using the parameter a and b from above Eqs. (6) to (11) indicate that reliable surface runoff estimates can be made, as depicted in Fig.4.

Estimation of actual evapotranspiration

If the soil moisture content expressed in mm at the end of the rainy day is lower than the potential evapotranspiration, the available moisture is used for real evapotranspiration. On the other hand, if the soil moisture content is higher than the potential evapotranspiration, the actual evapotranspiration equals the potential evapotranspiration and the reminder is the soil moisture storage (Lobo-Ferreira & Rodrigues, 1988). In other words, the actual evapotranspiration is regarded as the function of the precipitation minus surface runoff, i.e. PRC - SR = Top Infiltration (TI). The study of the relation between the actual evapotranspiration with top infiltration (TI) and the parameter AGUT have shown that the actual evapotransipiration is higher with higher values of AGUT and TI. The following relation is derived for actual evapotranspiration (EVR):

$$EVR\ (mm) = c \times (1 - e^{TI/d}) \quad (12)$$

where, c and d are parameters and TI is expressed in mm.

The regression analysis of the actual evapotranspiration and the top infiltration shows that in all the cases c is more or less equal to d and hence, Eq. (12) is rewritten as:

$$EVR\ (mm) = c \times (1 - e^{TI/c}) \quad (13)$$

The relation between parameter c and AGUT (the maximum soil moisture) is shown in Fig 5. The values of AGUT range from zero to 363 for the present study area. As seen from the figure, it has been suggested to apply a non linear law for extrapolation reasons. The actual evapotranspiration has to be zero if AGUT equals zero. The expression for parameter c is obtained as:

$$c = 118 \times (AGUT)^{0.388} \quad (14)$$

Given the root depth (r_d) of the plants and the difference between field capacity and wilting point of the soil ($\theta_s - \theta_{wp}$) in the area, the value of AGUT can be calculated as:

$$AGUT = r_d\,(\theta_s - \theta_{wp}) \quad (15)$$

where, r_d is depth of root zone in mm; θ_s is field capacity at root zone (at 0.33 bar suction); θ_{wp} is water content of soil in root zone at wilting point (at 15 bar suction).

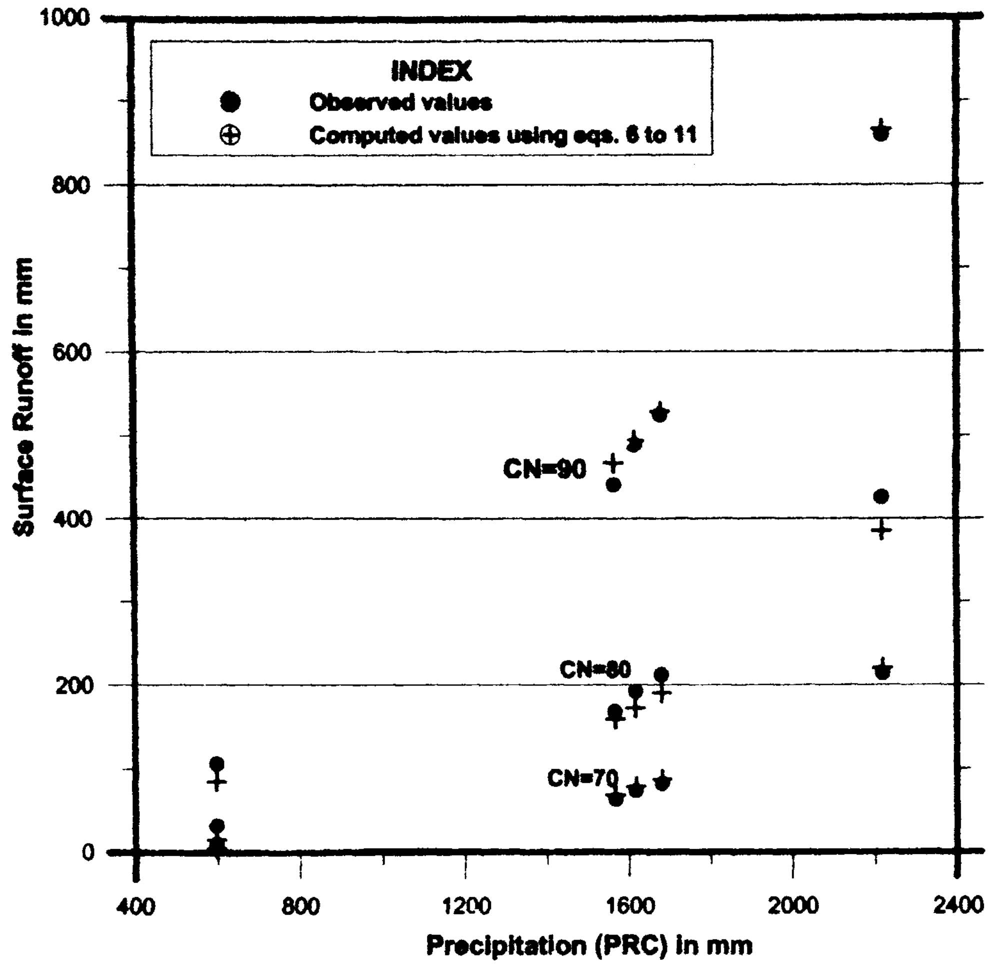


Fig. 4 Comparison of the observed and the computed runoff values

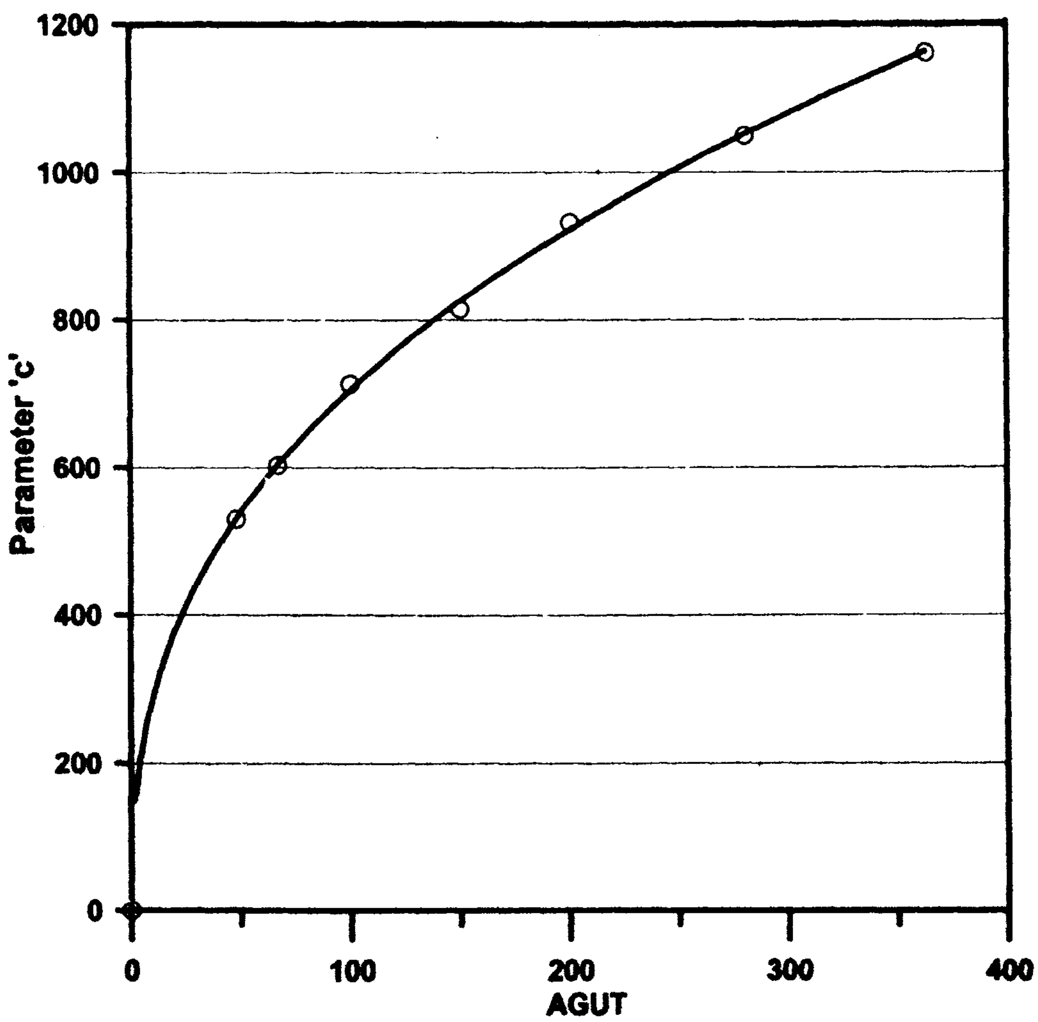


Fig. 5 Variation of parameter 'c' with AGUT for the study area

If (PRC – SR) of a day is higher than the actual evapotranspiration (EVR), deep infiltration (aquifer recharge) occurs. The aquifer recharge (RAQ) is given by the following mass balance equation:

$$RAQ = PRC - SR - EVR\ (mm) \qquad (16)$$

MODEL APPLICATION

The BALSEQ model was applied to a coastal watershed in North Goa and its reliability was verified by comparing the measured surface runoff values with the computed values. In this study, the BALSEQ model was applied to derive aquifer recharge in the iron ore-mining belt of North Goa (Fig.6). The entire study area of about 190 km^2 was classified into different land use/cover classes and the corresponding soil parameters were identified. Various steps, followed in computing the input parameters for the BALSEQ model, are summarised below:

1. The soil maps prepared by NBSS & LUP (1999) and other organizations were used to identify the soil types and their distribution in the present study area.
2. The soil texture classification was done using the soil classification triangle and the grain size data of different soils in the study area carried out by BRGM-IBM (1999), and TERI (1997).
3. Using the soil textures and other soil parameters of the study area, soils were classified into different soil classes (A, B, C & D) using the relational Table 1.
4. The land use/cover data were obtained form the latest Survey of India topographical maps and IRS satellite images. The soil class data derived at (3) above was assigned to each of the identified land use /cover areas.
5. Using land use/cover and corresponding soil class data, the runoff curve numbers, *CN* for each of the land use/cover class were determined from the relational tables.
6. With the help of identified soil textures, the hydraulic properties, θ_s and θ_{wp} of the soils were determined from the relational table of Rawls & Brakensiek (1989) (Table 2). The available soil moisture, (θ_s - θ_{wp}) values were then computed.

Table 1 Hydrologic soil classification based on U.S. SCS (1972)

Soil Character	Hydrologic Soil Groups			
	A	B	C	D
Soil Texture	Sand, Loamy sand	Sandy Loam, Silty Loam, Loam	Silt, Sandy Clay, Loam Clay, Loam, Silty Clay Loam	Silty Clay, Clay, Sandy Clay
Soil effective depth (cm)	>100	50-100	25-50	< 25
Clay percentage	0-8	8-25	25-40	>40
Infiltration rate cm/hr	>8.0	5-8	1.6-5.0	<1.6
Soil Structure	Simple grained, granular crumb	Granular crumb, sub angular blocky	Sub angular blocky, columnar prismatic	Platy massive

Note: Soil classes can also be determined by plotting sand, silt & clay percentages on US-SCS Triangular diagram.

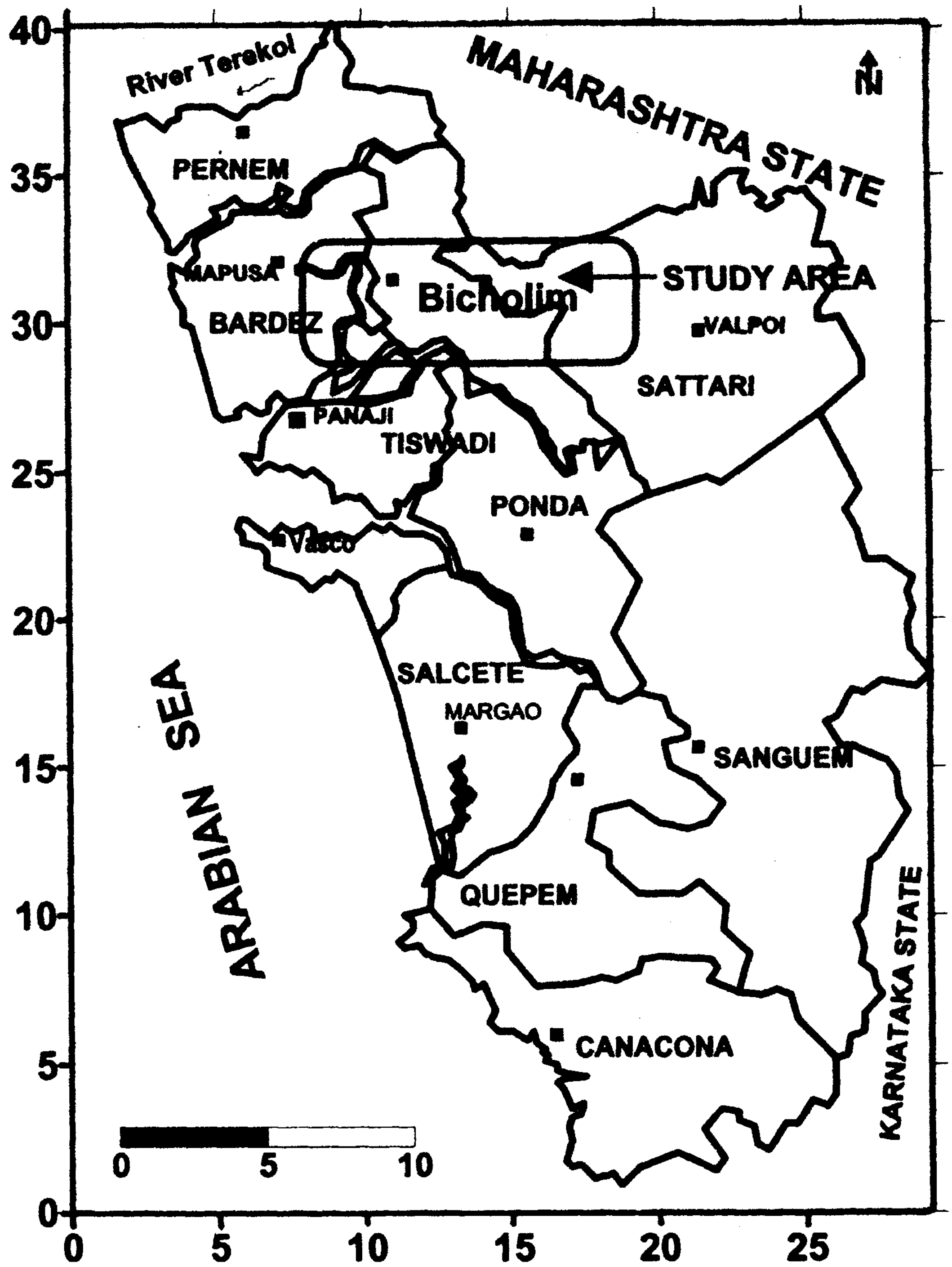


Fig.6 Location map of the study area in Goa, India

Table 2 Hydrologic soil texture and the corresponding moisture contents (after Rawls & Brakensiek, 1989)

S.No	Soil texture class	Water retained at 0.33 bar suction (cm^3/cm^3) [field capacity (θ_s)]	Water retained at 15 bar suction (cm^3/cm^3) [wilting point (θ_{wp})]	Available soil moisture (θ_s-θ_{wp})
1	Sand	0.091	0.033	0.058
2	Loamy Sand	0.125	0.055	0.070
3	Sandy Loam	0.207	0.095	0.112
4	Loam	0.270	0.117	0.153
5	Silt Loam	0.330	0.113	0.217
6	Sandy Clay Loam	0.255	0.148	0.107
7	Clay Loam	0.318	0.197	0.121
8	Silty Clay Loam	0.366	0.208	0.158
9	Sandy Clay	0.339	0.239	0.100
10	Silty Clay	0.387	0.250	0.137
11	Clay	0.396	0.272	0.124

7. The depths of evapotranspiration zone, which is considered as equal to the plant root depth, were collected from agriculture departments, personal communications with the forest officials and the published literature for each of the land use/cover class in the study area. The prominent vegetation types in each of the land use/cover class were identified from field survey.
8. Having determined the soil hydraulic properties as at (6) and the corresponding plant root depth at (7), the maximum amount of soil water available (AGUT) in the evapotranspiration zone was computed for each of the land use/cover classes.
9. The monthly potential evapotranspiration for the study area was calculated using Thornthwaite equation [$PET = 1.6b\ (10t/I)^a$; where a and b are parameters , I is annual heat index, and t is mean monthly temperature] for 8 years duration from 1995 to 2003. These data, in digital form were stored in the EVPTMN.DAD file, as required by BALSEQ model. The monthly potential evapotranspiration values were used as boundary values in equation (13) to decide the status of actual evapotranspiration, EVR. If the soil moisture content at the end of a rainy day is lower than the potential evapotranspiration, the available moisture is used for actual evapotranspiration. If the soil moisture is higher than potential evapotranspiration, then actual evapotranspiration equals the potential evapotranspiration and the reminder is stored as soil moisture subject to a maximum AGUT value, and the excess moisture goes into as aquifer recharge or deep infiltration.
10. Daily rainfall data for the years 1995 to 2003 (8 years) were collected from the raingauges located in the study area and stored in the PRECMN.DAD file, as per the format required by BALSEQ model. The rainfall data was checked for its consistency using CORBALG, a FORTRAN program specially designed for the purpose.
11. The BALSEQ model was run separately for each of the land use/cover classes with the derived input parameters, as shown in Table 3 and the corresponding outputs were obtained. The summarized output data (annual average values) are presented in Table 4.

DISCUSSION OF RESULTS

The summarized results of the BALSEQ output data for all land use/cover classes for the mining study area are given in Table 4. Having derived the unit depths (mm) of aquifer recharge (RAQ) and surface runoff (SR) for each land use /cover class, the corresponding volumes of RAQ and SR can be quantified by multiplying the area under each land use/cover with an appropriate unit conversion factor. In the present study, 10 watersheds covering about 190 km^2 of the total area were assessed for aquifer recharge.

Figure 7 provides a plot of the averaged values the various water balance components used and derived in the model for agricultural land.

Table 3 BALSEQ model input data for aquifer recharge estimation in mining area

Land Use	Soil Type	Soil Class	Curve Number CN	Vegetation type and root depth	θ_s (fraction)	θ_{wp} (fraction)	$(\theta_s - \theta_{wp})$ (fraction)	AGUT (mm)
Agriculture land	Sandy loam	B	95	Paddy, 60cm	0.207	0.095	0.112	67
Forest land	Clay loam	C	70	Mixed, 300cm	0.318	0.197	0.121	363
Builtup/Industrial area/Hard surfaces	Clay loam	C	91	Scarce, 300cm	0.318	0.197	0.121	363
Pastures/Grass land/Open scrubs	Clay loam	C	75	Small, seasonal grass, 40cm	0.318	0.197	0.121	48
Barren/Fallow/Degraded/ Waste land	Clay loam	C	91	No vegetation	0.318	0.197	0.121	0
Mine pits	Clay loam	C	91	No vegetation	0.318	0.197	0.121	0
Barren dumps	Sandy loam	B	95	No vegetation	0.207	0.095	0.112	0
Vegetated dumps	Sandy loam	B	82	Cashew, 250cm	0.207	0.095	0.112	280

Table 4 Output results of the BALSEQ model for the mining area in North Goa

Land Use/Cover Classes Identified in the Study Area of North Goa Iron Ore Mining Belt [area in ha.]	Annual Mean ppt (mm)	Annual Mean Surface Runoff		Annual Mean Real Evapotranspiration		Annual Mean Aquifer Recharge	
		mm	% of rainfall	mm	% of rainfall	mm	% of rainfall
Agricultural land [9165]	3529.8	2607.8	73.87	382.2	10.82	539.8	15.29
Forest land [867]	3529.8	838.8	23.76	721.4	20.43	1969.7	55.9
Built up/Industrial /hard surfaces [392]	3529.8	2148.2	60.86	694.9	19.69	686.8	19.46
Pastures/Grass land/Open scrubs [1824]	3529.8	1055.3	29.89	396.0	11.21	2078.5	58.88
Barren/Fallow/Degraded/waste land [4341]	3529.8	2148.2	60.85	191.2	5.41	1190.5	33.74
Mine pits [944]	3529.8	2148.2	60.85	191.2	5.41	1190.5	33.74
Barren dumps [534]	3529.8	2607.8	73.87	191.0	5.41	731.0	20.72
Vegetated dumps [142]	3529.8	1438.7	40.75	628.5	17.8	1462.7	41.45

From the figure it is seen that during rainy season (June-Sept), the actual evapotranspiration is limited by the potential evpotranspiration while during the summer the actual evapotranspiration is limited by available water in the top soil zone. When the top infiltration exceeds the actual evpotranspiration, the aquifer recharge (deep infiltration) and surface runoff take place.

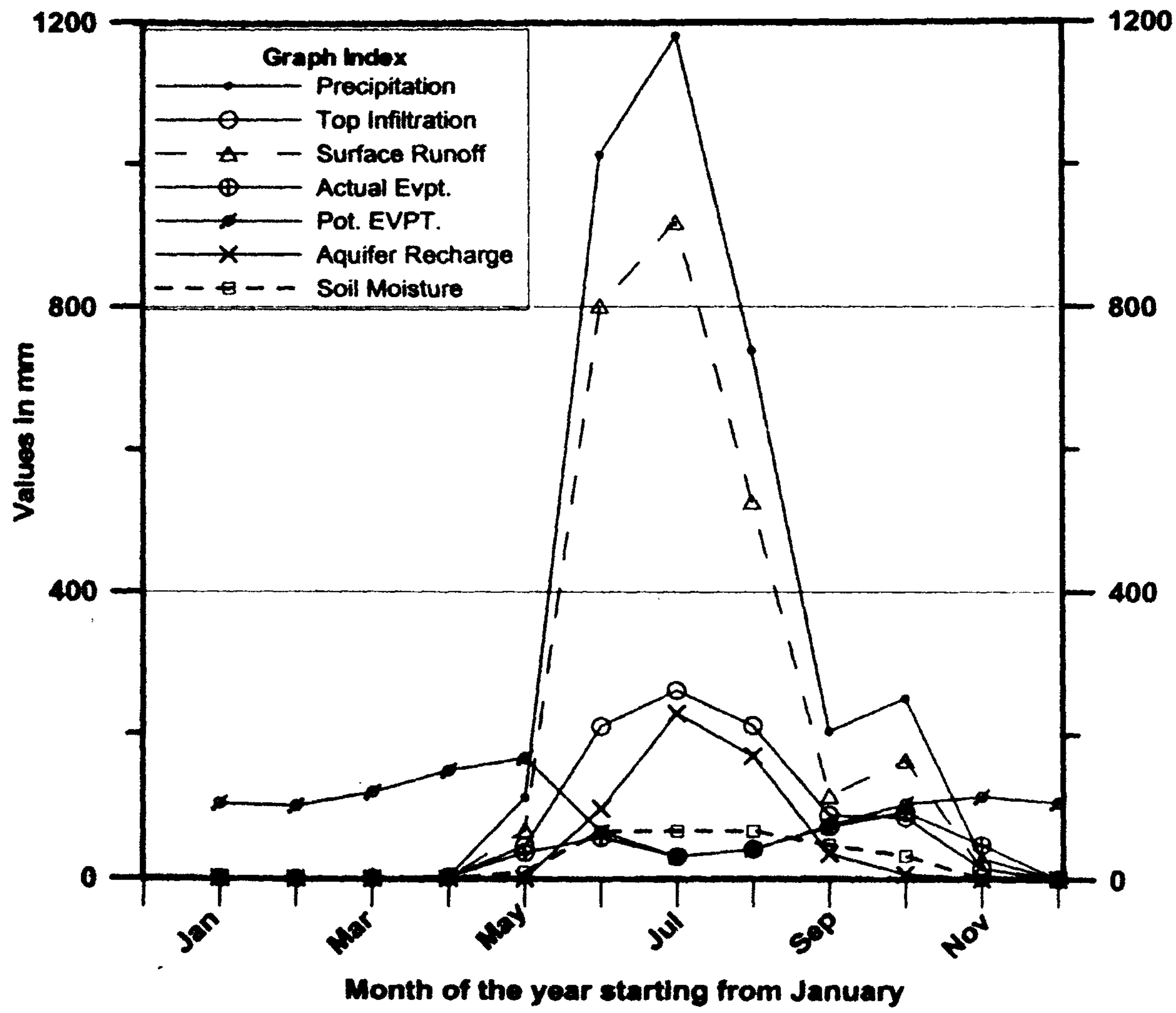


Fig.7 Aquifer recharge variation with input-output data of BALSEQ model for paddy fields in the study area.

The water levels in the active mine pits are invariably kept below the local groundwater levels by continuous pumping throughout the year and hence, there is no scope of groundwater recharge from the pits to the aquifers. Therefore, active mine pits should be considered as lost areas of groundwater recharge. However, the abandoned mine pits storing water in them can recharge the surrounding aquifers under favorable hydrogeological conditions.

CONCLUSIONS

A method based on daily rainfall data has been developed for assessing the aquifer recharge and surface runoff in a watershed. The results of the model can be used for quantification of the change in volume of aquifer recharge and surface runoff arising out of change in land use patterns in the watershed. The aquifer recharge in the investigated watershed varies from 15 to 59% and surface runoff from 24 to 74% of the annual mean precipitation. Forest lands and pastures show the highest aquifer recharge.

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