

## **GEOCHEMICAL MASS BALANCE IN A SMALL WATERSHED IN THE SEASONAL TROPICAL REGION OF THE WESTERN GHATS : THE CASE OF A TRIBUTARY IN THE SOURCE REGION OF KOYNA, INDIA**

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**ABSTRACT :** The objective of the present study is to establish the rate of weathering profile development and the rate of denudation in a small watershed in Western Ghats. The Sonpar watershed is drained by the major right bank tributary of the Koyna river in the latter's source region. The basin covers an area about 45.59 sq.km (17.6 sq miles) and lies in the Raigad district of Maharashtra. Besides calculating the geochemical balance the paper provides an insight in the methodology applied, which involved number of steps like the assessment of the average weathering profile thickness, establishment of hydrological balance, calculation of hydrochemical analysis, assessment of silica losses during the course of weathering, calculation of denudation rate by estimating the total solutional and suspended loss. The rate of silica losses provides the rate of weathering profile development. All these calculations were carried out for the year 1989, by monitoring the river discharge and analysing chemically the samples of weathered material from the profile. The whole basin is characterized by steep slopes, some residual relatively flat, narrow stream terraces, a relatively high relative relief and is being dissected by streams and gullies. The estimated age of regolith formation and denudation seems to lie between 20,000 to 30,000 years.

### **INTRODUCTION**

The geomorphic processes that are responsible for shaping landforms have been studied since long. These studies focussed on the physical and chemical nature of the weathered mantle, its depth, movement of weathered material on slopes over longer distances and the relationship of the weathered mantle with environmental factors which determine rate of its development. In these studies the assessment of both the relative rate of formation of weathered material as well as the rate of its removal is of special important as it determines the development of the type of slope and landform.

Landforms associated with weathering processes are dominant in the tropical region as the bioclimatic environment is conducive to an intense rate of chemical weathering. In the tropics, temperatures are high throughout the year accompanied by high rainfall. This results in fast and dense growth of vegetation. High temperatures, high rainfall and luxuriant vegetation favour chemical weathering and leaching. Torrential rains cause removal of weathered material both in solid and the solute form. However, within the tropical region, it is the tropical ridge and valley landscape in which both chemical weathering and chemical

denudation are more intense than in any other bio-climatic region.

Different parts of India are characterized by differed moisture regimes. The amount and the intensity of rainfall and duration of rainy days vary greatly from region to region. Therefore, weathering and denudation rates are different in different bio-climatic regions of India. Not only the bio-climatic factors but the relief of the land plays an important role in the denudation of weathered material. It is expected that both production and removal rates of weathered material would be high in the tropical high relief area.

To understand the particular processes of landform development in the tropics and subtropics it is necessary to study both the rate of weathering profile development and the rate of denudation: chemical as well as mechanical. The result of both these rates weighed against each other will give the geochemical mass balance. The establishment of geochemical mass balance is of prime importance to geomorphology in the tropics and especially to applied fields in geomorphology, like landuse evaluation, soil erosion assessment, wasteland reclamation, sedimentation estimates, ecological planning etc.

However, to establish the geochemical mass balance is requires considerable field experments, because measurements and analyses of many factors have to be taken into account. The best suited method appeared to be to monitor the input and output of a small catchment which has a uniform rock type and bio-climatic environment.

According to E. T. Cleaves and others (1970) the geochemical budget or mass balance of a watershed may be formulated as :

$$\text{Input} = \text{Output}$$

(dissolved material (dissolved material in water leaving in precipitation the watershed

+ dissolved material in water

+ dissolved material temporarily stored in the watershed by weathering) and taken up by biomass)

Langbein and Schumm (1958) related erosion rates to mean annual precipitation and Corbel (1959) compiled the erosion rates of numerous rivers according to climate and terrain underlain by limestone. However, later the stress in the studies shifted to understanding the very complex nature of processes of geochemical transport by the rivers, e.g. the studies related to factors that control the sediment supply were carried out by Garner (1959) and Gibbs R. J. (1967). these studies showed that because of various micro-environments within the watershed the tributaries contribute different amounts and types of material to the main river.

The recent trend is to study the geochemical budget or mass balance between input and output in a well-defined watershed to assess rates of chemical weathering. Mass balance studies are widely considered as the most reliable means for making quantitative determination of rates of elemental transfers in the earth's surface environments (Clayton 1979). Therefore, the mass balance approach has been widely applied to assess the rate of chemical weathering, e.g. Bricker O. P and others (1968) and Cleaves E. T. and others (1970).

By corroborating mathematical models with empirical mass balance, the comparison between individual studies became possible. According to Velbel (1984) information regarding distribution of weathering rates in small watersheds may have two implications : one terrestrial eco-system management and the other to develop models of landscape evolution. Studies of watershed geochemical mass balances were largely developed and interpreted

by Garrels (1967), Garrles and Makenzie (1967), Cleaves and Bricker (1968), Cleaves, Godfrey and Bricker (1970), Cleaves, Fisher and Bricker (1974) as reported by Velbel (1985).

The present study is an effort to understand and estimate to a certain extent the geochemical aspect of a small watershed in a seasonal tropical environment. Such studies so far in India are very few. The most detailed study appears to be the highly sophisticated monitoring of a micro-watershed in the Gangetic plains by Savindra Singh and Alok Dubey (1996). The present study assesses the geochemical mass balance of a catchment larger than the Belan basin catchment monitored by Savindra Singh and Alok Dubey in a very

different physical setup, namely ridge and valley system, with the main emphasis on weathering and denudation.

**THE STUDY AREA**

Location : Sonpar catchment falls in the Western Ghats and is drained by a major right bank tributary of the Koyna river in the latter's source region. The basin covers an area of 45.59 sq km.s (17.6 sq. miles) and lies in the Raigad district of Maharashtra (Fig. No. 1).

The basin forms part of the broad Western Ghat zone. It lies in the vicinity of the crestline of the Sahyadri between the high plateau of Mahabaleshwar and Pratapgad which are above The basin forms part of the broad Western Ghat zone. It lies in the vicinity of the crestline

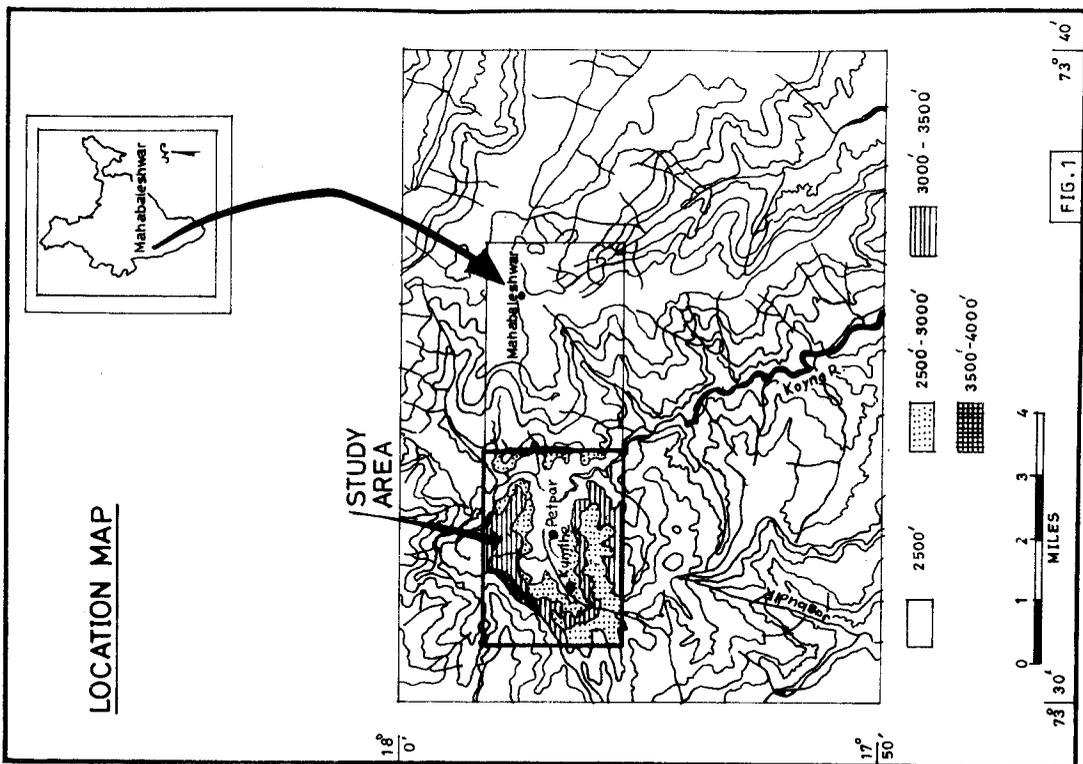


Fig. 1

of the Sahyadris between the high plateau of Mahabaleshwar and Pratapgad which are above 1200 m. ASL. The whole region characterized by steep slopes, some residual relatively flat, high altitude surfaces, narrow stream terraces, a relatively high relative relief and is being dissected by streams and gullies. Dikshit had observed, 'There are no gradual slopes on the Mahabaleshwar Plateau and in the adjoining areas' (Dikshit 1991). Therefore, the stream orders are not well established in this part of the main Koyna valley.

**Geology :** The study basin forms a part of the Deccan volcanic province. The area is characterized by basalts of Cretaceous-Eocene age, with remarkable horizontality of lava flows. The Deccan basalts are uniform in petrological composition. The most common rock is a normal augite basalt, of mean specific gravity 2.9 with high basicity. The uniformity in the chemical composition of Deccan basalt is demonstrated by Karkare (1965) and NAJFI et.al. (1981) and Joglekar (1989). Deccan basalt weathers relatively fast because of its chemical and mineralogical characteristics.

**Bio-climatic Environment :** The temperature and precipitation conditions are important as they determine the rate and intensity of chemical weathering as well as removal of elements released during the course of weathering. The temperatures are generally high in the study area throughout the year. The mean temperatures of the cold season (December) and the summer are 21.4 C and 29.6 C respectively. (Satara station). Much of the rainfall is concentrated between June and September. The rainfall distribution is mono-modal with maximum rainfall during July. The

rainfall record for the study area, from Pratapgad station, which is monitored by the Irrigation Department of Government of Maharashtra, taken during the years 1989 to 1992 shows an average of 6689 mm of rainfall which is greater than the average for the Western Ghat climatic region. Such a high amount of rainfall is responsible for high rates of weathering, leaching and erosion. The combination of heavy rainfall and high temperatures has given rise to forests of moist deciduous to semi-evergreen types. Approximately one-third of the study area is under thick cover of this type of luxuriant vegetation. However, the practice of shifting cultivation has given rise to a secondary forest.

Characteristics of the weathered mantle within the basin topography.

Weathering profile in the study area represented pronounced chemical weathering. The thickness of the weathered mantle is generally shallow on the upper slopes and goes on increasing towards the lower section of the relief. The general observations in the study area suggest that the thickness of the weathering profile is related more to the position within the basin topography. By detailed survey and interpolation it was estimated that average thickness of the weathering profile is 2.2 metres.

The advance stage of weathering was established by analysing the physical and chemical character of the weathered mantle. The fine grading of particle sizes show a high proportion of silt and clay. The  $K_i^*$  and the  $S_f^*$  indices suggest desilification. The total elemental losses indicate a high degree of weathering. The predominance of gibbsite,

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\* To describe the degree of weathering  $k_i$  and  $s_f$  indices are used. The weathering process of silicate minerals normally leads to loss of silica and relative gains of iron and aluminium. Therefore ratio of silica to aluminium ( $k_i$ ) index and silica to iron ( $s_f$  index) gives relative gains or losses of silica.

haematite, goethite and montmorillo-nite and kaolinite show different stages of weathering. The concentration of the smectites in the lower portion of the weathering profile and the kaolinite group in the upper part suggest maturity of the weathering profile.

## METHODOLOGY

The methodology followed in this paper to arrive at the geochemical mass balance involved the number of steps of analysis and calculations. The aim of the calculations is to find : 1) the rate of weathering or saprolite formation in the study catchment and 2) rate of denudation i. e. solute loss and suspended sediment loss. This however, involves to calculate the following aspects first :

- hydrology of the basin by computing rainfall volumes and run-off volumes
- calculation of chemical and mechanical denudation of the basin by analysing runoff water chemistry and computing suspended sediment load.

— geochemical mass balance, involving calculations of rate of weathering and rate of denudation

## Hydrology of the Basin

Surface run-off, groundwater flow and evapotranspiration are parts of a continuous hydrologic cycle primarily dependent upon precipitation and temperature. The hydrologic mass balance for a single drainage basin is expressed by the formulae :

$$P = R + S + E$$

where

P = precipitation,

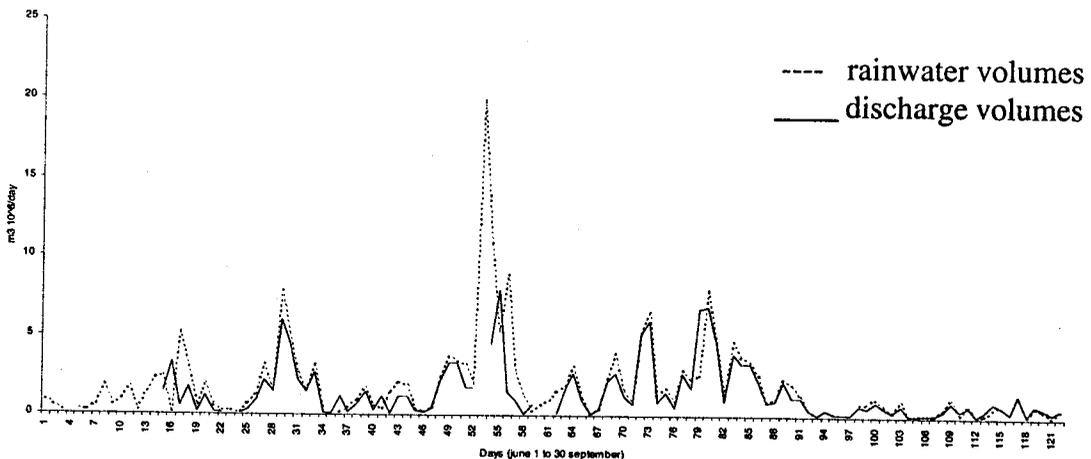
R = run-off (direct + base flow),

S = ground water storage and

E = evapotranspiration.

The rainfall in the study area is concentrated in the four monsoon months viz: June, July August and September. Therefore, the bulk of the river discharge also occurs during the monsoon season. In this study the rainfall data were collected during the monsoon season of 1989.

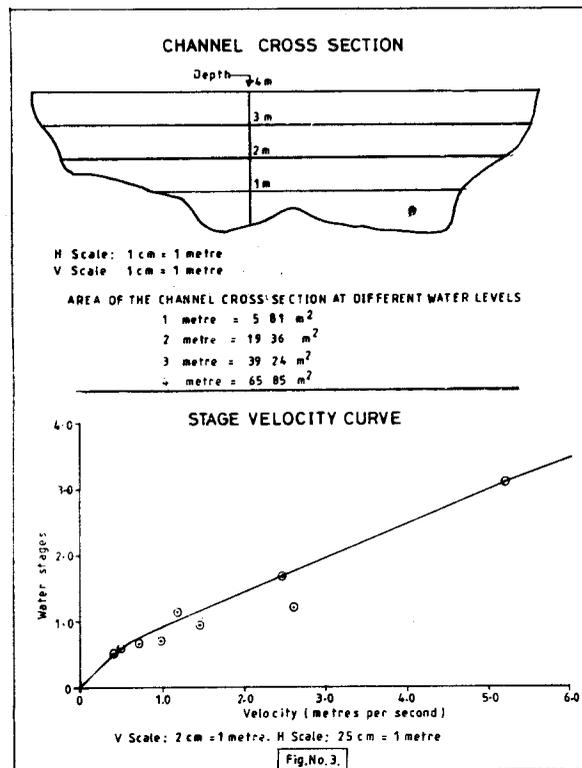
### HYDROGRAPH



**Fig. 2 : Hydrograph**

Total rainwater volumes of the year 1989 =  $221.16 \times 10^6 \text{ m}^3$

Total discharge volumes of the year 1989 =  $173.68 \times 10^6 \text{ m}^3$



**Fig.3 :**

The daily rainfall data were collected from Pratapgad, station of Irrigation Department, Govt. of Maharashtra. The daily rainfall values were then converted to rainwater volumes by using the following method. The multiplication of the total area of the basin in metres and the daily rainfall in metres gave the daily rainwater volumes in cubic metres received on that particular day. The summation of the rainwater volumes of all the rainy days gave the estimate of total rainwater volumes received during 1989 (fig. No. 2).

Similarly discharge volumes were computed using the following method:

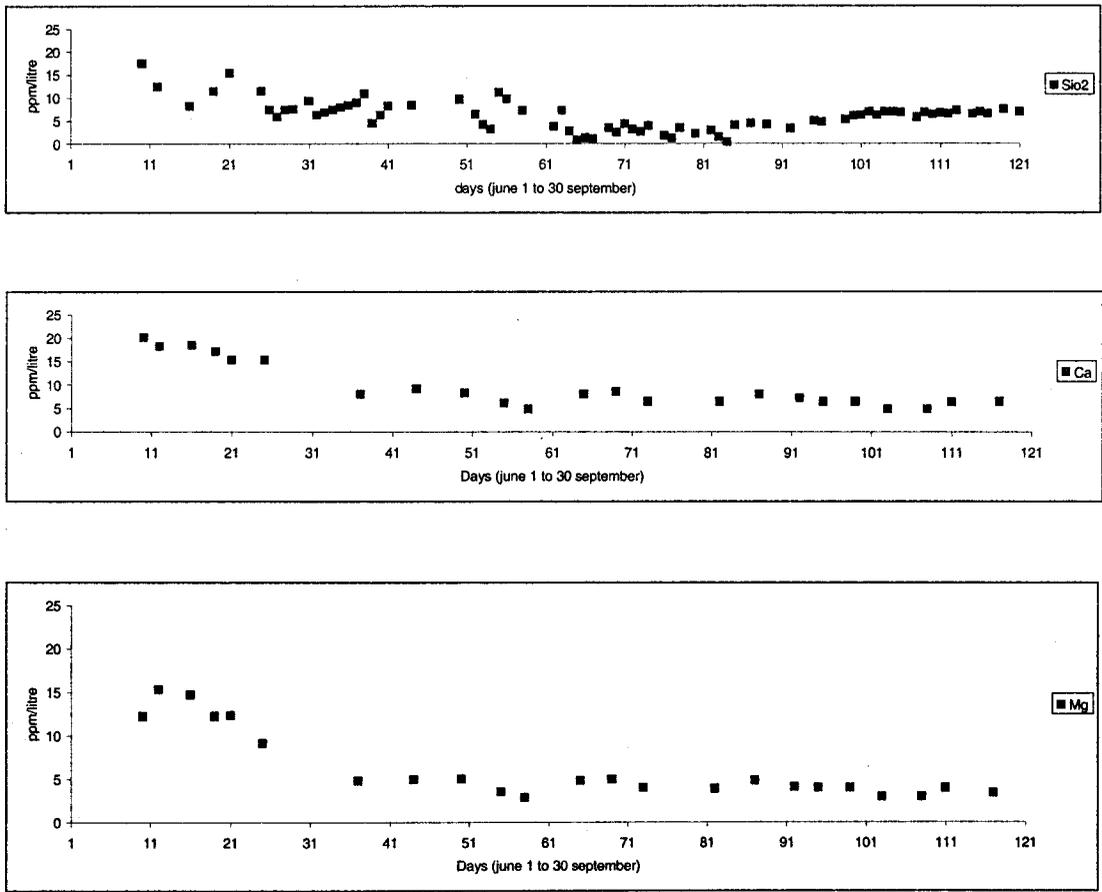
The cross section of the stream channel was drawn by making an actual dumpy-level survey at the outlet of the basin. (near Sonpar village)

This could give the area contained in the cross section of the stream channel. The velocities of the stream water were measured at different water levels. Taking into account these actual observations of velocities a stage-velocity curve was established to know the velocities at various water levels. (fig. no. 3) In the monsoon season of the year 1989 the change in the daily water levels were observed. By multiplying velocity associated with a particular day's water level by its corresponding channel cross sectional area one gets the actual average volume passing through the outlet of the basin per second. The daily discharge values were obtained by multiplying the actual discharge per second by  $60 \times 60 \times 24$  (86400 seconds) (fig. no. 2). While calculating the discharge volumes the

following assumptions were made :

1. The surface divide here is presumed to be the hydrologic divide, that is, all rain within that boundary constitutes the total input to the basin.
2. It is also presumed that the groundwater divide correlates with the surface topographic divide and therefore, only the groundwater within the divide contributes to the base flow in the study basin.

Based on monitored water levels and velocities discharge volumes were computed on the daily, monthly and yearly basis. The intensity and duration of rainfall are significant in determining the magnitude and duration of the water level changes in the stream channel. The fluctuations in the stage are more sudden and correspond to the rainfall event. The total rainwater volumes received during the year 1989 are  $218.77 \times 10^6$  cubic metres; while the total discharge volumes of the year 1989 are  $173.68 \times 10^6$  cubic metres. Almost



**Fig. 4 : Daily Solutional Losses**

(fig. in ppm)

Months	June	July	August	September
<b>Total</b>	$1021.48 \times 10^6$	$1551.31 \times 10^6$	$946.74 \times 10^6$	$210.55 \times 10^6$

Total solutional loss for the year 1989 =  $3730405.0$  ppm or  $3730.40 \times 10^6$  gms.  
 Thus per km.<sup>2</sup> solutional loss =  $81.81 \times 10^6$  gms.

79.38% of the rainwater goes out of the basin as river discharge. The rest  $45.09 \times 10^6$  cubic metres or 20.6% of the rainwater is partly stored in the regolith as ground water and partly taken up by plants and lost by evaporation.

### Hydrochemistry of the Basin

Fig. no. 4 presents analyses of water chemistry from samples taken at various discharges for the period June to September 1989. The output from the study basin is in the form of solution loss and mechanical transport. The solution loss is mainly due to through flow and very little base flow contribution, in that region. This has also been suggested by Joglekar while examining different morphogenic regions of Deccan volcanic province. Therefore, considering the above observation only the solution losses during the monsoon were computed.

### Solutional Loss

The one litre samples were analysed to find out the proportion of silica, calcium, magnesium and total dissolved solids. The proportions of silica, calcium, and magnesium of the respective days are multiplied by the discharge volumes of the same day so that the daily solutional loss can be estimated. Fig. no. 4 gives the daily concentrations of silica, calcium and magnesium as well mean concentrations for the months of June, July, August and September of these three elements

The total solutional loss,  $L_s$ , (ppm / year) for the basin can be calculated as :

$$L_s = q_1 (X_{ca_1} + X_{mg_1} + X_{si_1}) + q_2 (X_{ca_2} + X_{mg_2} + X_{si_2}) + \dots + q_{12} (X_{ca_{12}} + X_{mg_{12}} + X_{si_{12}})$$

where

$L_s$  = total solutional loss for the year 1989 (ppm)

$q_1, q_2, \dots, q_{12}$  = total monthly discharge ( $m^3$ )

$X_{ca_1}, X_{mg_1}, X_{si_1}, \dots$  etc. = mean monthly concentrations (ppm) of calcium, magnesium and silica calculated for four months June to September.

Total solution losses are  $81.81 \times 10^6$  gms per sq km of basin area for the year 1989. If the monthly totals of solutional loss are compared, the maximum loss is in the month of July which corresponds to the maximum discharge.

While using these values for the calculation of the rate of lowering of the geomorphic surface, it is necessary to assume several conditions. The solution load originates partly from the soil and partly from the saprolite. The leaching of saprolite contributes to higher solution load for the following reasons. 1) the proportion of saprolite is about 75% of the total regolith while the soil constitutes only 25%; 2) the soil constitutes a majority (70 to 80%) of secondary clay minerals such as oxides of aluminium, i.e. gibbsite, kaolinite, montmorillonite, etc. which are in the final stages of alteration and clay does not enter into solution. Therefore, leaching from the soil horizon may be limited.

### Suspended Sediment Losses

The suspended sediment concentrations, per litre were computed daily from 15th June to 30th September 1989. By multiplying concentrations with the respective daily discharges, the daily mechanical transport of sediment in grams was derived. From these figures monthly and yearly totals were computed. Fig. No. 5 presents monthly and yearly total sediment transport out of the catchment. The total sediment loss,  $L_d$ , (gm / year) for the basin can be calculated as :

$$Ld = q_1 * d_1 + q_2 * d_2 + \dots + q_{12} * d_{12}$$

Where Ld = total suspended sediment loss,

$q_1 \dots q_{12}$  = total monthly discharge,

$d_1 \dots d_2 \dots d_{12}$  = average suspended sediments / month

The total transported suspended sediment for the year 1989 was  $5.1 \times 10^6$  kg. The sediment transported per sq. kilometre was  **$112.43 \times 10^6$  grams.**

### Total Sedimentary Loss

The total loss, Lt, can be calculated as a sum of the total solutional loss (Ls) and total suspended sediment loss. (Ld)

$$\begin{aligned} Lt &= Ls + Ld \\ &= 81.81 \times 10^6 + 112.43 \times 10^6 / \text{gm} / \text{sq. km.} \\ &= 194.24 \times 10^6 / \text{gm} / \text{sq. km.} \end{aligned}$$

The textural character of the suspended sediment is also shown in Fig. No. 5. Almost 75% of the suspended sediment is made of fine particles, i.e.  $<2\mu$ , 13% silt or  $2\mu$  to  $20\mu$  and 12% of coarser material or  $<20\mu$ . The solutional load carried by the river water in the study area is almost 42% of the total load transported by the river.

These results were compared with those of Gibbs R. J. (1967) who worked in the Amazon basin. He arrived at the total loss  $115.8 \times 10^6 / \text{km}^2$  for the Amazon basin. He has distinguished between mountain rivers and low land rivers. The mountain rivers show a range of solutional load of  $92.8 \times 10^6$  and  $152.0 \times 10^6 / \text{km}^2$ . However, the mechanical transport of the young tertiary mountain (Andes) rivers is very high (ranging between  $251.5 \times 10^6$  and  $307.1 \times 10^6 / \text{km}^2$ ) as the source region do not have the tropical

environment. In the present study the figure of the rate of chemical denudation is comparable with those of Gibbs but not the rate of mechanical denudation. The solutional load is comparatively high in the present study area. It is  $81.81 \times 10^6$  gms /  $\text{km}^2$  which amounts to 42% of the total denudational loss. Taking these points into consideration the higher solutional load is justified as chemical weathering is dominant here. The study area receives heavy rainfall leading to higher run-off. The yearly estimates of solutional losses given by Dethier (1984) for 23 catchments from Washington state, USA, range between  $18.6$  and  $97.6 \times 10^6$  gms /  $\text{km}^2$  / year with average of about  $34 \times 10^6$  gms /  $\text{km}^2$  / year. While Thomas Paces (1984) gives estimates for two basins from central Europe. The annual outputs because of weathering in these two basins are  $61 \times 10^6$  gms /  $\text{km}^2$  / year and  $57 \times 10^6$  gms /  $\text{km}^2$  / year.

All these examples of geochemical balance studies show that there is a great variation in the output both solutional and mechanical sediment losses. The studies quoted by Dethier especially show that inspite of similar environmental conditions the range of output estimates is quite large.

## GEOCHEMICAL MASS BALANCE

### 1. Rate of weathering or saprolite formation

The annual solution losses from the basin are mostly due to chemical weathering and roughly coincide with the annual rate of chemical weathering. Even though solutional losses from the basin were estimated for the year 1989, the annual variation in the solution loss are likely to be considerable because of rainfall variability. It would be necessary to establish

\* silica losses from the weathering profile for the region is calculated by analysing weathered horizon / regolith chemically from the study area.

solution losses over longer periods to arrive at more precise estimation.

The depth of weathering profiles vary greatly in the basin, because of high relief conditions. Therefore, it is extremely difficult to estimate rates of profile development. However, from the computed estimates of solution loss in the year 1989 a rough rate of profile development can be determined based on some assumptions. These assumptions are given below :

a) Iso-volumetric development of weathering profile;

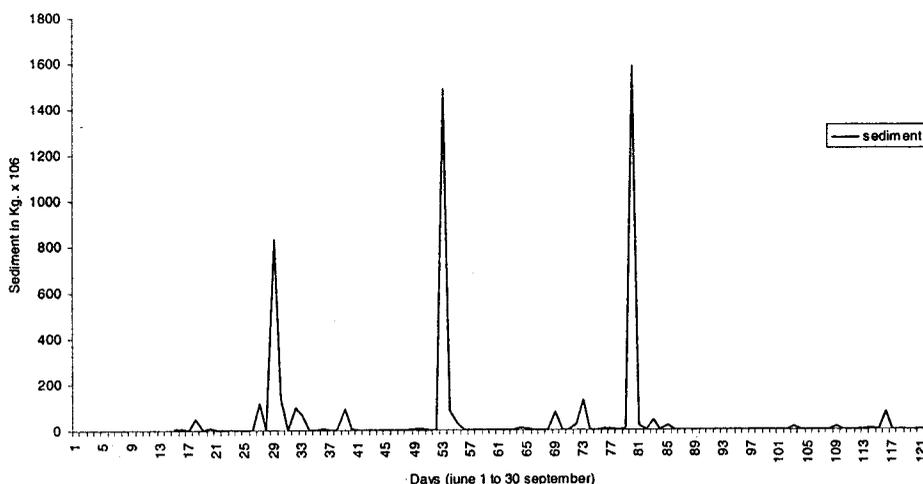
b) Density of basalt is 2.9;

c) Silica content of basalt is 48%;

d) Mean yearly silica losses 6.6 ppm;

e) Compute surface run-off is  $173.68 \times 10^6$  cubic metres.

The silica lost in the form of solution through discharge is computed as a weathering rate, because thorough desilification is the characteristic weathering process in the tropics. And silica losses are equated with corresponding rate of weathering profile or clay formation. (Joglekar, 1989). The



**Fig. 5 : Suspended Sediment Transport**

(figures in Kg. x 10<sup>3</sup>)

Months	June	July	August	September
<b>Total</b>	1167.2	1890.4	1954.2	114.1

Total of the year 1989 =  $5126.13 \times 10^3$  Kg. / total area or  $112.43 \times 10^3$  Kg. / Km.<sup>2</sup>

**Textural Character of the Suspended Sediment**

	>20f	2-20f	<2f
<b>%</b>	12.84	12.95	74.20
<b>Kg.</b>	$6.58 \times 10^5$	$6.63 \times 10^6$	$38.04 \times 10^6$

>20f = Coarse sediment      2-20f = Medium sediment      <2f = Fine sediment

weathering rate is given as silica losses / m<sup>2</sup> of ground surface / year which is computed as :

$$Lsi = 0.75 \times Ra \times si_{\text{mean}}$$

where

Lsi = total silica losses in mg. / m<sup>2</sup> / year.

Ra = annual rainfall (mm),

si<sub>mean</sub> = per litre mean silica concentration for monsoon season 1989.

$$\begin{aligned} Lsi &= 4894.7 \times 0.75 \times 0.0066 \\ &= 24.26 \text{ mg/m}^2 \text{ / year} \end{aligned}$$

The silica released because of weathering in the weathering profile is computed as follows :

#### Silica released / m<sup>3</sup>

$$\begin{aligned} &= 10000 \times \text{Density of Basalt} \times \text{Silica losses (\%)} \\ &= 10000 \times 2.9 \times \% \text{ Silica losses from weathering profile for the region*} \\ &= 2.9 \times 10,000 \times 25.91 \\ &= \mathbf{751390 \text{ mg.}} \end{aligned}$$

Once both the release of silica per cubic metre in the weathering profile and the loss of silica because of solutional denudation is known the rate of development of weathering profile can be computed as follows :

Duration in years for weathering development of one metre deep profile

$$\begin{aligned} &= (\text{the silica release due to weathering / m}^3) / (\text{silica loss / m}^2 \text{ / year}) \\ &= 751390 / 24.26 \\ &= \mathbf{30972 \text{ years}} \end{aligned}$$

This result shows the rate of profile development to be of about 30,000 yrs. Leneuf and Aubert had suggested a span of 22000 to 77000 years for the development of one metre

thick profile in the tropics. The present results are comparable with their findings and appear to be reasonably valid. (M. F. Thomas, 1974)

However, the rate computed by Dr. Joglekar (1989) in the same bio-climatic, morphogenic region was about 20,000 yrs. for the development of 1m. of weathering profile. The differences in these rates by a factor of 0.5 (50%) may be due to the difference in the computed mean silica loss for the same morphogenic region. The mean silica loss computed by Dr. Joglekar was 15 ppm while in the present study it is 6.6 ppm. The reason for the difference may lie in the different time span of observations. Dr Joglekar's observations of stream water silica relate to June and July only. The mean silica loss in the present study is based on the observations taken between June and September. In August and September silica concentration drops considerably which lowers the figure of mean silica loss. The mean silica loss value computed in the present study is less than that computed by Dr. Joglekar by a factor of 0.5 (50%) and therefore, the rate of profile development is also lower than that indicated by him.

## 2. Rates Of Denudation

The total solution and mechanical loss measured during the year 1989 has been taken for for determining the denudation rate, i.e., removal of 1 m thick layer of weathering profile from the basin. The method adopted is as follows :

The specific gravity of unweathered basalt is assumed to be 2.9. Hence the volume of 1 gm. can be calculated as follows :

$$\begin{aligned} V &= M / SG \text{ (specific gravity)} \\ &= 1 / 2.9 \\ V &= 0.3448 \text{ cm}^3 \end{aligned}$$

However, as the basalt weathers its specific gravity decreases and volume increases. From the analysis of the present study, it is estimated that the average specific gravity of the weathered basalt is 2.3. Therefore, the volume of one gram of weathered material can be computed as :

$$V = 1 / 2.3$$

$$= 0.4347 \text{ cm}^3$$

Therefore, by subtracting the volume of 1 gram of unweathered basalt, the additional volume created by weathering is derived. The additional volume is calculated as :

$$\text{Increase in volume} =$$

$$\text{volume of weathered rock}$$

$$- \text{volume of fresh rock}$$

$$\text{Increase in volume} = 0.4347 - 0.3448$$

$$= 0.0899$$

From this the additional volume created in 1 m thick layer of the basin area is computed as follows :

If the increase in  $0.3448 \text{ cm}^3$  is by  $0.0899 \text{ cm}^3$ , then the increase in  $1 \text{ cm}^3$  will be  $0.26 \text{ cm}^3$

Therefore, in  $1 \text{ m}^3$  the increase in volume would be  $0.26 \text{ m}^3$ . The 1 m thick layer of the basin area will have an additional volume of

$$= 45590000 \text{ m}^3 \times 0.26$$

$$= 11853400 \text{ m}^3.$$

As stated earlier the computed denudation in the year 1989 is  $194.24 \times 10^6 \text{ g} / \text{km}^2$ . To convert this into volume it follows that :

$$= 194.24 \times 10^6 \times 0.3448$$

$$= 66.97 \times 10^6 \text{ cm}^3 / \text{km}^2$$

Therefore, for the total basin area, the volume lost in the year 1989 is :

$$= 66.97 \times 10^6 \times 45.59$$

$$= 3050.162 \times 10^6 \text{ cm}^3 \text{ or}$$

$$= 3050.162 \text{ m}^3$$

Therefore, to denude 1 m thick rock layer of the basin or  $45590000 \text{ m}^3$  volume will require a time period of :

$$= 45590000 / 3050.162$$

$$= 14932.05 \text{ years.}$$

However, to denude the additional volume of  $1185400 \text{ m}^3$  will require a time period of

$$= 11853400 / 3050.1623$$

$$= 3886.1539 \text{ years}$$

Therefore, to denude 1 m thick layer of the basin rock or the rate of denudation will be :

$$= 14932.05 + 3886.1539$$

$$= 18818.2 \text{ years.}$$

This may be rounded off to **19000 years**

According to the above computation, the rate of denudation is considerably higher than that of sprolite formation rate, which is based on the average silica losses. Considering the difference between input and output of the mass balance, however, the following considerations may be taken into account.

- 1) The study was undertaken in the year of excessive rainfall (20% above mean) and hence a increased rate of denudation.
- 2) It is unlikely that the denudation rate is as fast as 19000 years / 1 metre layer over longer periods, for many weathering profiles are mature as shown by chemical and minerological analysis of the weathering profiles. (S. P. Gole)
- 3) Occasionally slightly higher denudation rates may also be attributed to high land utilization and shifting cultivation.
- 4) This higher rate can be attributed to the peculiar character of the basin, and a smaller basin size Schumm, (1963).

## CONCLUSIONS

1. The hydrological balance in this heavy rainfall basin shows that about 80% of the rainwater goes out of the basin in the form of surface runoff, while 20% is partly stored by the regolith and partly by the vegetation or lost by evapotranspiration. Fluctuations in the discharge level and volume are directly related to rainfall intensity. The proportion of base flow to total surface flow appears to be very small.
2. The hydrochemistry of the stream water shows that the concentration of calcium and magnesium is comparatively high in the months of June and July and goes on decreasing in August and September. In case of silica, the concentration is high in the months of June and July, decreases in August but again increases in September. The proportion of total solution loss to total loss is about 42% which appears a little higher compared with the estimation of other workers, but considering the dominance of chemical weathering this proportion is justified.
3. The rate of saprolite formation has been based on the assumption that silicate weathering and clay formation are the dominant weathering processes; therefore the rate of saprolite formation has been based on silica losses and the estimate was 30,000 years to form 1 metre deep layer of weathering profile. The mean silica losses and total silica loss estimates are almost half that calculated by Dr. Joglekar. However, when compared with the other studies they appear reasonably valid. The estimates of silica losses are smaller than those determined by Dr. Joglekar, as they are based on average silica concentrations for all the four monsoon months. Therefore, the saprolite formation or weathering profile development rate based on silica loss is also slower than his, i.e., 30000 years to develop one metre deep layer of weathered profile.
4. The denudation rate was calculated on the basis of both suspended and solutional losses, and the estimated solutional denudation rate was approximately 19,000 years to denude 1 metre layer of the basin rock.
5. These results are significant in the absence of any mass balance studies in the Western Ghats. Dr. Joglekar arrived at slightly different rate of saprolite formation, namely, 20,000 years. However, as to our knowledge, estimates of denudation rates of Western Ghats have not been undertaken so far. More accurate estimates of rate of denudation and profile development may be derived, if observations are taken over longer period of time.
6. The present analysis of mass balance showed a difference between the rate of denudation and the rate of weathering profile formation. However, for reasons given above, both the rates may be in near balance over longer period of time.

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