Functioning of a Small Experimental Watershed in the Serra do Mar, Brazil The need of a Multidisciplinary Approach

L.Barbiero[1], P.Curmi[2], S.Furian[1,3] F.C.S.Arcova[4], V.Cicco[3,4]
1 – IRD-CEFIRSE, Indian Institute of Science, Dept. of Metallurgy, Bangalore 560 012, India.
2 – French Institute of Pondicherry, 11, St Louis Street, PB 33, Pondicherry 605 001, India.
3 – USP-FFLCH, Indian Institute of Science, Dept. of Metallurgy, Bangalore 560 012, India.
4 – Instituto Florestal de Sao Paulo, Rua do Horto, 931 – 02377-00 Sao SP - Brazil

Abstract

In the Serra do Mar region, in southeastern Brazil, few is known about the flows of water into the soil cover. A good understanding of these flows is however essential for better management of (i) the water that supplies the highly populated Paraiba valley and the city of Rio de Janeiro, and (ii) the widespread landslide processes that are likely related to the slope feature. The analysis of a database of seven years of rainfall-discharge makes it possible to highlight the temporary storage of water into the soil cover of an elementary watershed. A structural analysis of the slope morphology revealed that the soil mantle is mainly characterized by (i) a gibbsitic saprolite, (ii) various kalinitic horizons within the ibbsitic material, (iii) kaolinito-gibbsitic topsoil horizons. The morphology and dynamics of this soil cover are discussed according to the thermodynamic stability of gibbsite and kaolinite acompnying the solution percolation through soil profiles. The physical features of the soil indicate that water is retained briefly within a microaggreated horizon during intensive rainfall. Because of the inclination of kaolinite compact horizon, any excess water within it flows laterally downslope and accumulates in the lowest part of the slope. This leads to landslipping, the main process of landform development in the region. The organization of the soil cover along the slope allows to identiy two main water reservoir, one superficial, which chemical composition is likely in agreement with the kaolinitic and organic environment and the other one deeper, and likely at the equilibrium with the gibbsite. The next research should be focused on the identification of the geochemical signature of each reservoir and their contribution to the waterflow at the outlet of the watershed at the scale of the year and of the rainy event.

Introduction

In the eastern part of the São Paulo State in Brazil, the Serra do Mar region, covered with Atlantic forest, supplies in water both the Paraiba valley and the city of Rio de Janeiro. A good management of water at different scales is crucial in this area with high density of population. However, data about the hydrological functioning of watersheds in this region are surprisingly scarce compared to that of Amazonian watersheds. An hydrological balance has been carried out on two small experimental watersheds by Fujieda et al. (1997) using ten years of field measurements and hydrograph analysis. The results indicate that 15 % of the annual rainfall is intercepted by the forest and return directly to the atmosphere while 85 % of the rainfall reaches the forest floor where it infiltrates and remains in the soil cover. The total volume of the stormflow is about 11 % and the evapotranspiration has been estimated as 15 % of the annual rainfall. According to this study, about 59 % of the rainfall is stored in the soil cover and contributes to the stream baseflow.

Another distinctive feature of this region is the widespread landslides that are reported almost every year (Furian et al., 1999). Many studies have involved statistical estimates of the location of landslides and the conditions of climate, bedrock geology, slope steepness, vegetation cover and human occupation leading to their occurrence. This has shown that landslides occur principally in the Serra do Mar complex, at the end of the rainy season when rainfall is most intense. Guidicini and Iwasa (1976) showed that the probability of landsliding is increased when rainfall exceeds 250 mm in 24 h, regardless of antecedent rainfall. Cruz (1974) emphasized the role of slope steepness: slopes exceeding 40 % encourage landslides, regardless of vegetation cover and human occupation. Landslide processes occur mainly on the lowest third of the slope. Small landslides occur in the middle slope and readjust the slope topography after the main landslides have occurred downslope. These landslides contribute significantly to landscape evolution in this region.

Although De Ploey and Cruz (1979), Furian (1999), and Fujieda et al. (1997) concluded that the hydrology of the slopes should be studied in more detail, the flows of water into the soil cover remains unknown. The objectives of this work are to identify the organization of the soil cover in this region, to understand water flows into it to relate these to landslide processes and to propose a route for future investigations on the hydrology of this area at the watershed scale.

Site

The studied area is located in the Serra do Mar State Park at 23°S between the Serra do Mar and the Atlantic Plateau in the eastern part of São Paulo State, Brazil (Fig. 1). Uplifted since the Oligocene, these plateaux of 1000-2000 m altitude belong, with the Serra da Mantiqueira, to the uppermost surface of the block mountains of southeastern Brazil's Atlantic margin. They correspond to the headwaters of the Paraiba basin. From 800 to 1500 m altitude, the region is covered with a mountain rainforest of the "Atlantic forest" domain called Mata Atlântica. The tree layer of the forest reaches 20-30 m in height. The wet tropical climate belongs to type "Cwa" of Köppen (Furian, 1999) with altitude and orographic influences, and with rainfalls in all the seasons. Annual rainfall ranges from 2000 to 2500 mm, with a rainy season from September to March giving 71% of the annual rainfall. The number of rain days ranges from 127 to 179, with a mean of 153 days between 1983 and 1992 (Fujieda et al., 1997). The chemical weathering of the crystalline Precambrian basement has resulted in sandy loam regoliths with a maximum thickness of 15 m (Bigarella *et al.*, 1965). Recent evolution of slopes in the Serra do Mar has been mainly controlled by mass movements, including slumping and planar slides in the regolith, rockfalls and rockslides.

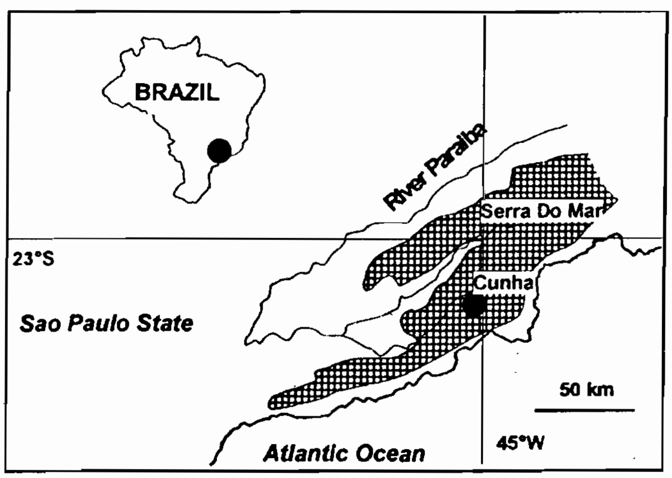

Fig. 1: Location of the studied site

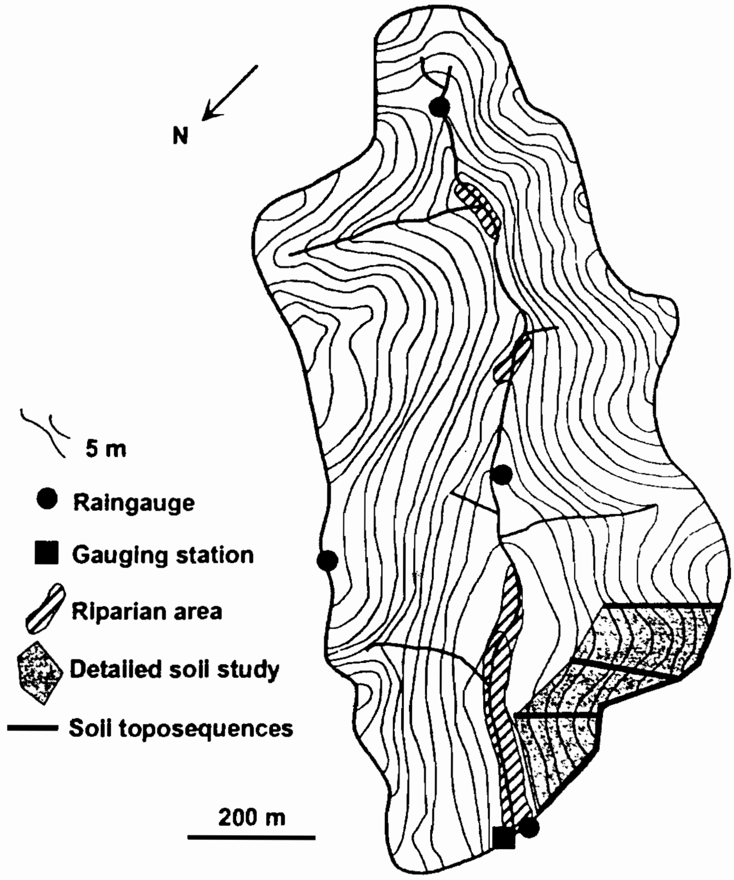

Fig. 2 : Morphology of the watershed and location of the soil study, raingauges and gauging station

The fieldwork was concentrated on a small (56 ha) watershed of the River Paraibuna in the district of Cunha, known as the "D" watershed in the Serra do Mar State Park, and managed by the Instituto Florestal de São Paulo (Fig. 2). Cunha is part of the granite-gneiss high plateaux of the Serra do Mar. The watershed is characterized by steep hillslopes (46% on average), a large riparian area and a Northwest aspect. The mean channel slope is 19.9 %. The watershed is covered with the rain forest.

Methods

Rainfall and discharge: This watershed is equipped to acquire hydrological data (rainfall and discharge) for more than 20 years. Rainfall within the watershed was measured with 4 tiping-bucket raingauges. The actual rainfall within the watershed was calculated by an arithmetic mean method (Shimomichi et al., 1987). Streamflow at the outlet of the watershed was measured with a trapezoidal flume with a stilling pond equipped with a continuous stage recorder. The rating curve for the flume was determined by current metering at different stages at the gauging station (Cicco et al., 1987). Seven years of daily rainfall-discharge measurements on the D watershed, ranging from November 1986 to October 1993, were selected for this study. Both rainfall and discharge events were shared out into 11 classes (<4 ; 4-6 ; 6-8 ; 8-10 ; 10-15; 15-20; 20-30; 30-40; 40-50; 50-100; >100 mm). For each class, the time of return was defined as:
Time of return for class C = (number of days of the collect)/number of days with event in the class C).

The times of return of both rainfall or discharge classes were compared.

In a second step, considering that about 20 mm of rainfall could be stored into the soil cover without significant contribution to the stormflow, daily rainfalls were corrected as follow:

$Rainfall_{corr.}$ = Rainfall – 20 mm.

The times of return of both $rainfall_{corr.}$ or discharge classes were compared.

Soil cover: The soil mantle organization was reconstructed along four sequences located on the crest line and on the slope. The mineralogy was studied by X-Ray diffraction analysis (XRD) on randomly oriented powder and orientated deposit of the <2µm fraction, which was studied in 5 conditions: K saturation, Mg saturation, Mg saturation and treatment with glycol ethylene, heating at 450°C and 550°C. Undisturbed blocks were collected and impregnated with an acetone-diluted polyester resin (Scott-Bader Crystic) after dehydration by acetone exchange, and vertical thin sections (70 x 110 mm) were made. Some samples were collected for SEM (XL 20 Philips at 15 kV) observations of the morphology of weathering features at the crystal level and punctual microanalyses (LINK Analytical eXL energy dispersive X-Ray system).

In order to quantify the macroporosity, a fluorescent dye was added to the resin (Ciba Geigy Uvitex OB). Images from thin sections were captured by reflected UV light (Hallaire and Curmi, 1994), which caused pore space to appear as bright area on the dark background. Images were digitalised using the Visilog system with a spectral resolution of 256 grey levels and a pixel size of 10 µm. The pores were identified by simple threshold partition. Overall macropore connectivity in each thin section was classified visually as low, medium or high.

The pore size distribution, between 0.0037 and 100µm equivalent radii, was studied with a CARLO ELBA 2000 mercury porosimeter using air-dried centimetric aggregates outgassed at room temperature. Water retention curves were determined on 5-10 cm^3 samples by sorption through membrane filters according to Tessier and Berrier (1979) for the low suction range (pF 1-3) and by pressure membrane equipment for greater suctions. The shrinkage of the soil samples was slight, so the shrinkage curves were estimated from the apparent volumes at pF 2 and 6, using the kerosene method developed by Monnier et al. (1973).

Total analyses have been performed after alkaline fusion using lithium tetraborate. Fe, Al and Ti were quantified by colorimetry, Ca, Mg and Mn by atomic adsorption, Na and K by emission. Si was quantified by gravimetry. Total chemical analyses of the secondary minerals produced by weathering have been performed using a three acid digestion method. Semi quantitative estimations of the abundance of secondary mineral phases of gibbsite and kaolinite were calculated from the Ki indice ($Ki = SiO_2/Al_2O_3$) according to Pedro (1966).

Results

Hydrology: The relationship between the times of return for rainfall or discharge for each class in presented in Fig. 3. The probability of rainfall in the class <4, 4-6, 6-8, 8-10, 10-15, and 15-20 mm is almost similar. Therefore, the time of return for rainfall events of these classes is constant. For classes higher than 15-20 mm, the time of return increases. On the other side, the time of return for discharge increases continually with the rate of the class. For the higher classes (10-15 mm to > 100 mm), the time of return for rainfall increases 10 times more rapidly than the time of return for discharge.

After correction of the data, and in order to take in consideration that about 20 mm of rainfall could be stored into the soil cover, the relationship between both $rainfall_{corr.}$ and discharge times of return changes and increases proportionally to the unit slope with the rate of the class.

Catena organization: Figure 4 shows the distribution of soil horizons in sequence 2, which can be divided into two zones, the upslope and downslope domains.The upslope domain consists of a 12m thick ferrallitic soil. It is mainly composed of a sandy gibbsitic weathered material derived from the parent rock (G Horizon). The original mineral structures and that of the rock itself are preserved in gibbsite pseudomorphs, which results in a gibbsitic horizon with a box-work micro-structure. The polysynthetic twinning of plagioclases and the cleavage of amphiboles are also preserved in the gibbsite, indicating that the formation of gibbsite was the first stage in weathering of the parent rock. Only quartz and muscovite were unaltered at this stage. The structure of the parent rock is also preserved in millimetric gibbsitic veins that probably infilled fissures in the parent rock. The total porosity of this horizon is about 40%, exhibiting a bimodal distribution (Fig. 5). On thin sections, the macroporosity of this horizon is about 25 % with medium connectivity. This gibbsitic weathering level is overlain by a pebbly and blocky horizon composed of ferruginised gibbsitic material. The structure of the parent rock is still preserved in the blocks. Although the soil fauna has burrowed into the superficial horizons, it is still possible to identify relics of the millimetric gibbsitic veins. The proportion of kaolinite increases towards the top of the profiles and reaches about 60 % of the secondary minerals in the superficial horizon.

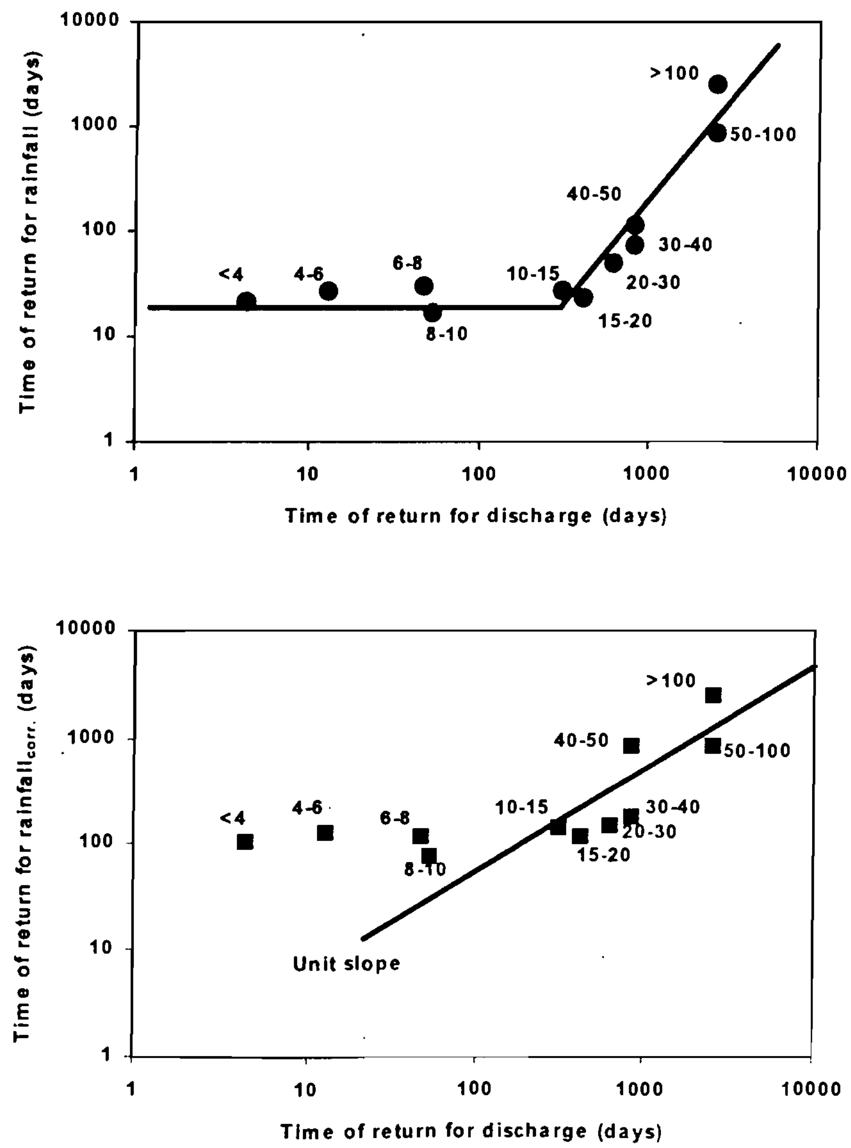

Fig. 3 : Relationship between the time of return for rainfall and discharge (a) and rainfall corrected and discharge (b) for each class.

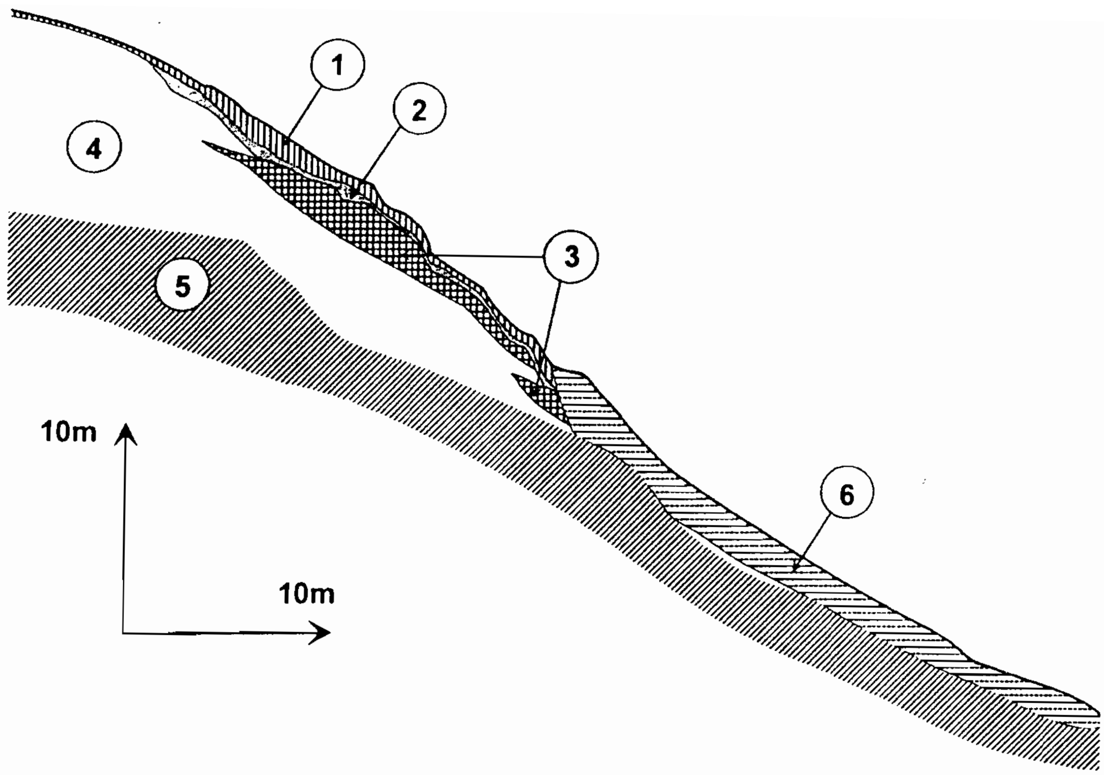

Fig. 4. Distribution of the main horizons along toposequence 2. 1 – Kaolinitic superficial horizons; 2 – Microaggregated Horizons (mh1 and mh2); 3 - Kaolinitic horizons within gibbsitic horizon Parent rock; 4 - Gibbsitic Horizons; 5 - Parent rock; 6 - Downslope domain.

In the lower part of the upslope domain, a compact clay loam kaolinitic horizon (here called K horizon) occurs within the G horizon. The proportion of kaolinite is about 85 % of the secondary minerals. This K horizon has a unimodal distribution of pore sizes (Fig. 5), which is almost entirely microporosity (90% of the pores intruded by mercury). Although the total porosity reaches 51 %, the image processing revealed that the macroporosity of the K horizon is only about 9.3 % with low connectivity. The water retention and shrinkage curves indicate that this K horizon is almost saturated at pF3 (87 %, Fig. 6). It is tongue-shaped and is truncated by the superficial porous microaggregated horizons (mh1 and mh2). These are conformable with the slope topography. A second clay loam kaolinitic horizon (K horizon) appears downslope at 2-2.5 m depth, also within the sandy G horizon but beneath the first K horizon. Detailed study of the contact between the K and G horizons showed that the structure of the K horizon truncates that of the G material, indicating that the latter developed first from the bedrock and subsequently changed into a kaolinitic material. At this contact, evidence of dissolution of quartz and gibbsite is observed by SEM. Therefore, resilication of gibbsite into Kaolinite has been postulated in this environment (Furian et al., 2002). In thin sections, the mh1 horizon seems to have arisen from the destruction of the gibbsitic box-work structure, whereas the mh2 horizon is composed of biofabrics and is burrowed by the soil fauna. The proportions of kaolinite reach respectively 40 and 55 % of the secondary minerals. These microaggregated horizons exhibit a bimodal pore size distribution (Fig. 5), corresponding to intra- and inter-aggregate pores as in other ferrallitic soils (Curmi et al., 1994). The macroporosity is about 36 % with high connectivity. At low suction (pF3), water occupies only 50 % of the pore space of the microaggregated horizons (Fig. 6).

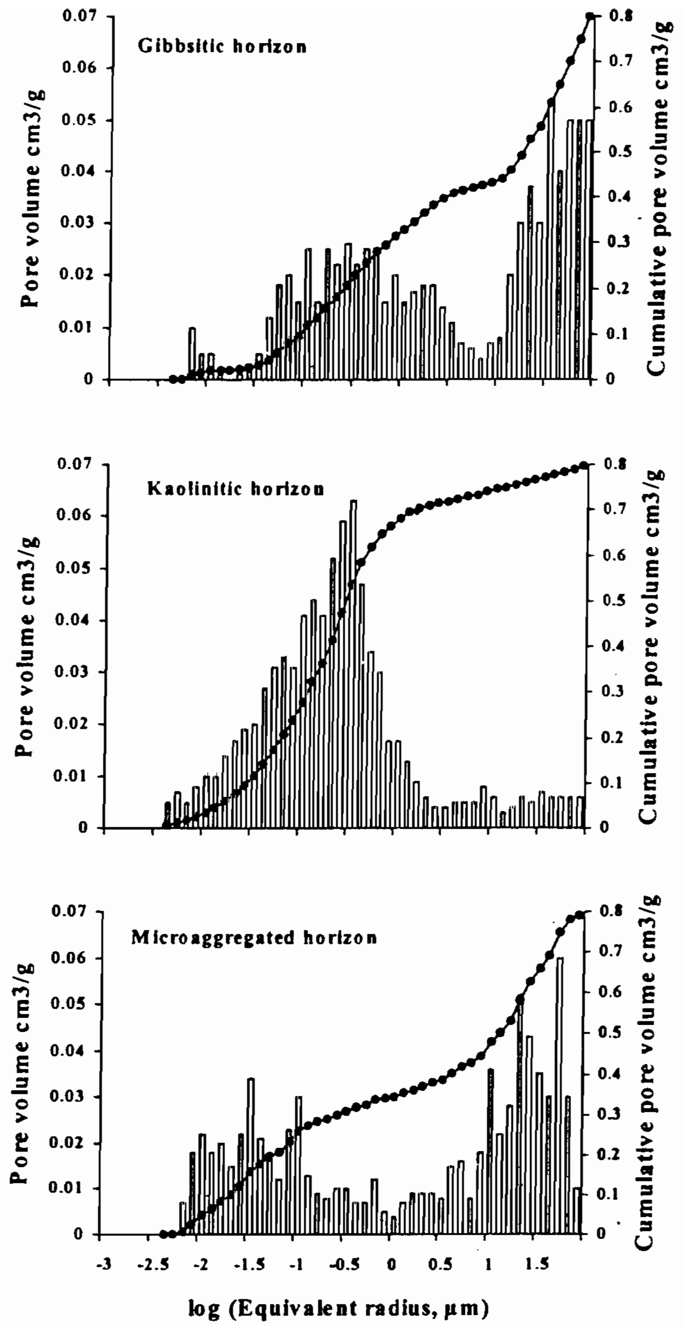

Fig. 5. Mercury porosimetry curves of gibbsitic (G), kaolinitic (K), and microaggregated (M) horizons: differential and cumulative pore volumes shown as a function of calculated pore radius

On the middle part of the slope, the upslope soil cover is abruptly truncated over its whole thickness by the material of the downslope cover, which clearly differs from that of the upslope one. The downslope domain (not detailed in Fig. 4) is composed of superficial horizons overlying a clay horizon with many randomly oriented blocks. The clay horizon rests directly and abruptly on the hard bedrock. Remnants of box-work gibbsite occur, but are frequently associated with unweathered minerals such as hornblende, other amphiboles, microcline and biotite.

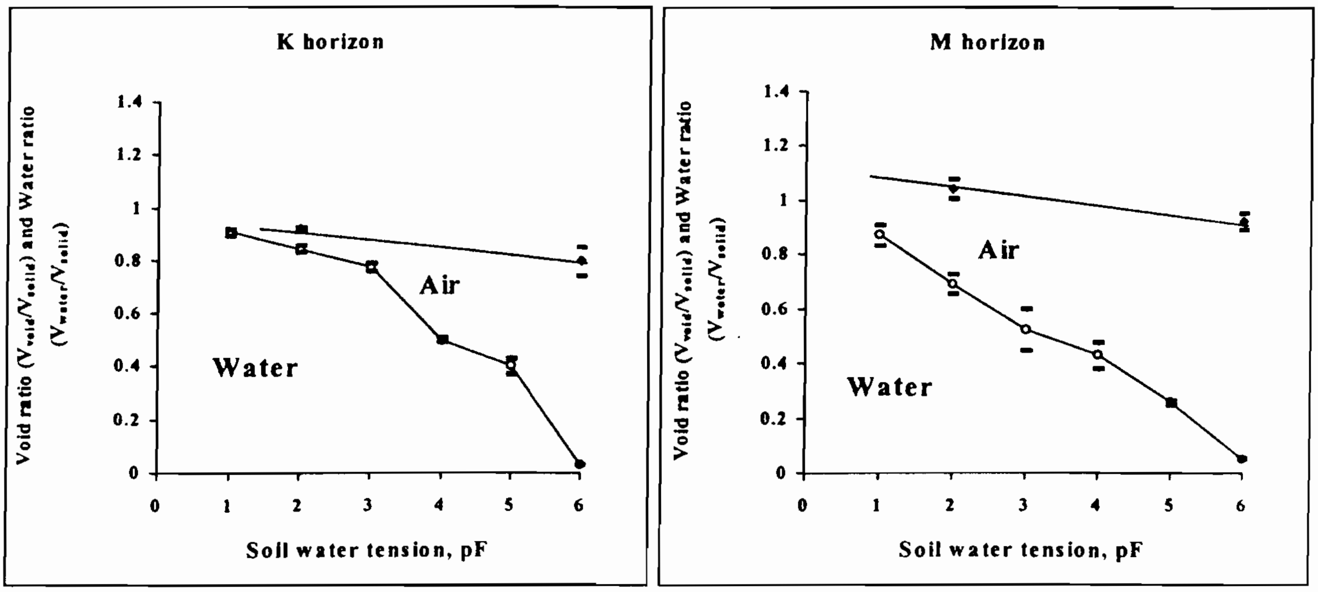

Fig. 6. Water retention and shrinkage curves of kaolinitic K and microaggregated M horizons.

One of the main features of the whole soil system is the presence of kaolinitic horizons (K horizon) into the gibbsitic weathering material (G horizon). According to the morphological study of the 3 other toposequences, the limits of the K horizons and of the colluvium on the slope are drawn of Fig. 7. The distribution of the K horizons is complex; they occupy a large part of the soil mantle, but are truncated downslope by the colluvium.

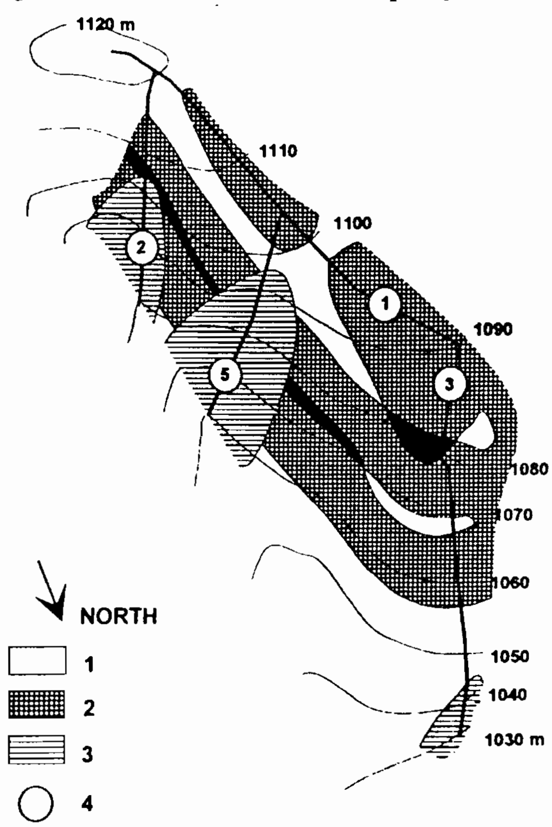

Fig. 7 :. Distribution of the K and G horizons in the upslope domain, and areas of the downslope domain. Map based on sequences 1, 2, 3 and 5.
1 - G horizons; 2 - K horizons within G horizon; 3 - Downslope domain; 4 – Toposequence.

Discussion

Soil cover organisation and mineralogy: The upslope soil cover is derived from the in situ gibbsitic weathering of the bedrock, the structure of which is preserved in the soil, even up to the surface horizons where gibbsitic veins occur. Therefore, three characteristics of this soil cover do not match with the normal distribution of gibbsite and kaolinite in lateritic profiles. They are:

1. A bauxitic weathering of the parent rock, without kaolinite intermediate formation;
2. the presence of kaolinite in the topsoil horizons;
3. the presence of kaolinitic compact clay loam horizons into the gibbsitic saprolite.

Various observations in the region around Cunha indicate that this type of soil cover is widespread in the Serra do Mar. Therefore, the relative stability of gibbsite and kaolinite is discussed below.

The gibbsitic saprolite : Although the parent rock is rich in quartz, a gibbsitic weathering is observed where we could expect kaolinite. The gibbsite-quartz association is however possible if the kaolinite stability shifts from K1 to K2 as indicated on Fig. 8. K1 value corresponds to a relatively well-crystallised kaolinite and without impurities. In the kaolinitic clay loam horizon, the low discremination of the secondary picks of kaolinite by XRD analysis indicates a low cristallinity. Therefore, the gibbsite-quartz association (D on Fig. 8) is possible.

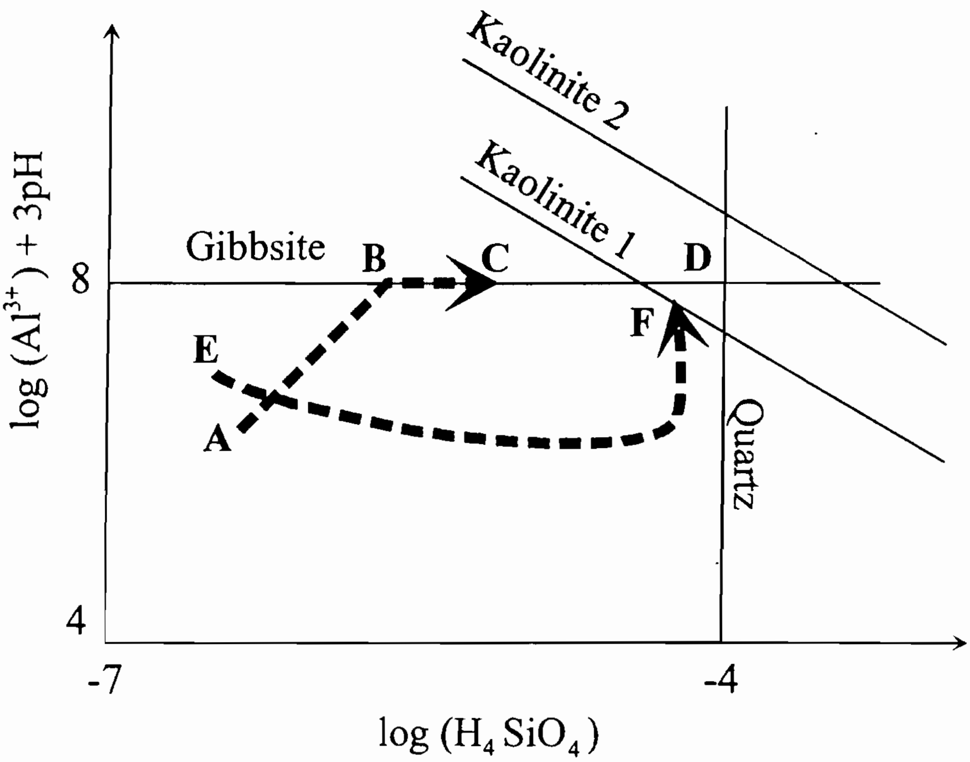

Fig. 8. : Advance of the soil solution in a gibbsite-quartz-kaolinite equilibrium diagram. A, B, C: The soil solution leaves the system before the equilibrium with respect to kaolinite being reached; E, F: Advance considering the role of the complexing organic matter (modified from Lucas et al., 1996)

The gibbsite-quartz association can also be obtained by considering a fast renewal of the soil solution, under conditions of humid climate and good drainage. This is particularly possible, as the kinetics of dissolution of the quartz is very slow. The solutions reach the equilibrium with respect to the gibbsite (B on Fig. 8) but leave the system before the reaction of dissolution being finished, and before the double point of the equilibrium with respect to gibbsite/kaolinite being reached. In this case, the profiles are, to some extent, truncated by the bottom, the depth horizons classically expected in a water percolating model, are not formed (Fritz, 1975), and gibbsite-quartz association is observed in the soil.

The kaolinitic topsoil horizons : The proportion of kaolinite is higher in the topsoil horizon than at depth, in the sandy gibbsitic material. This phenomenon, which today could appear classical, has been particularly studied in Amazonian forest environment of Brazil (Lucas et al., 1993). These authors have shown that the forest recycles significant quantities of chemical elements, particularly Si and Al, maintaining a dynamic equilibrium and causing the stability of kaolinite in the topsoil horizons. A similar recycling is probable under the coastal Atlantic rain forest, which still cover a large area of the Serra do Mar.

The compact kaolinitic clay loam horizons : The presence of the compact kaolinitic horizons within a gibbsitic weathering material sets more problems. It cannot indeed be attributed to a recycling of solution enriched in Si and Al by the top of the profile because of the geometry of this horizon, being intercalated between two gibbsitic horizons. The examination of the contact inform us that the development of kaolinitic material at the expense of the gibbsitic one is today in process.

The transition from the gibbsitic saprolite to the kaolinitic clay loam horizon corresponds to a high increase of the volume of fine pores, with an equivalent diameter around 0.3 µm (Fig. 5). The gibbsitic horizon exhibits a strong connected macroporosity, permitting a quick percolation of fresh solutions, undersaturated with respect to quartz and gibbsite and able to dissolve these minerals. In the compact kaolinitic horizon, the solutions are slowed down and/or concentrated under the effect of evaporation by the forest, and kaolinite can precipitate. This assumption can explain the self-upslope development of kaolinitic clay loam horizon. The phenomenon can be initiated by the numerous micaceous layers, which were observed in the gneiss saprolite, the micas being transformed into kaolinite, contrary to the feldspars, which are transformed directly into gibbsite. On the other hand, this assumption does not make it possible to explain why the dissolution patterns of quartz and gibbsite is observed just upslope of the kaolinitic clay loam horizon.

The role of organic matter is also determinant in the solution-kaolinite equilibrium conditions. The complexing organic matter formed by the biological activity in the topsoil horizons substracts a large proportion of Al from the solution as it has been observed in Amazonian Oxisols (Cornu, 1995, Eyrolle et al., 1996). These complexes are retained onto material of high surface exchange and cannot migrate out of the system. Between the rainy events and at depth, due to the mineralisation of the organic matter and the increase in Al contents and pH value, the solution reached the equilibrium with respect to kaolinite (E, F on Fig. 8) (Lucas et al., 1996). This process could also explain the intermediate kaolinitic clay loam horizon within the gibbsitic saprolite.

Identification of the landslide risk: The observations and measurements emphasize the contribution of weathering and pedogenesis to landscape evolution. Fast circulation of water is possible into the G saprolite according to the connectivity of the macroporosity. The dissolution of gibbsite and quartz and the formation of kaolinite generate tongues arranged along the slope like tiles on a roof. During the fieldwork, waterlogging after rainfall was observed in the M horizons overlying the K horizons, what is consistent with the severe decrease in the vertical infiltration rate at this contact, and influencing the flow of water on the slope. A three-stage model of increasing development of K horizons (Fig. 9) is proposed. In the first stage (a), the K horizons are thin and separated and vertical

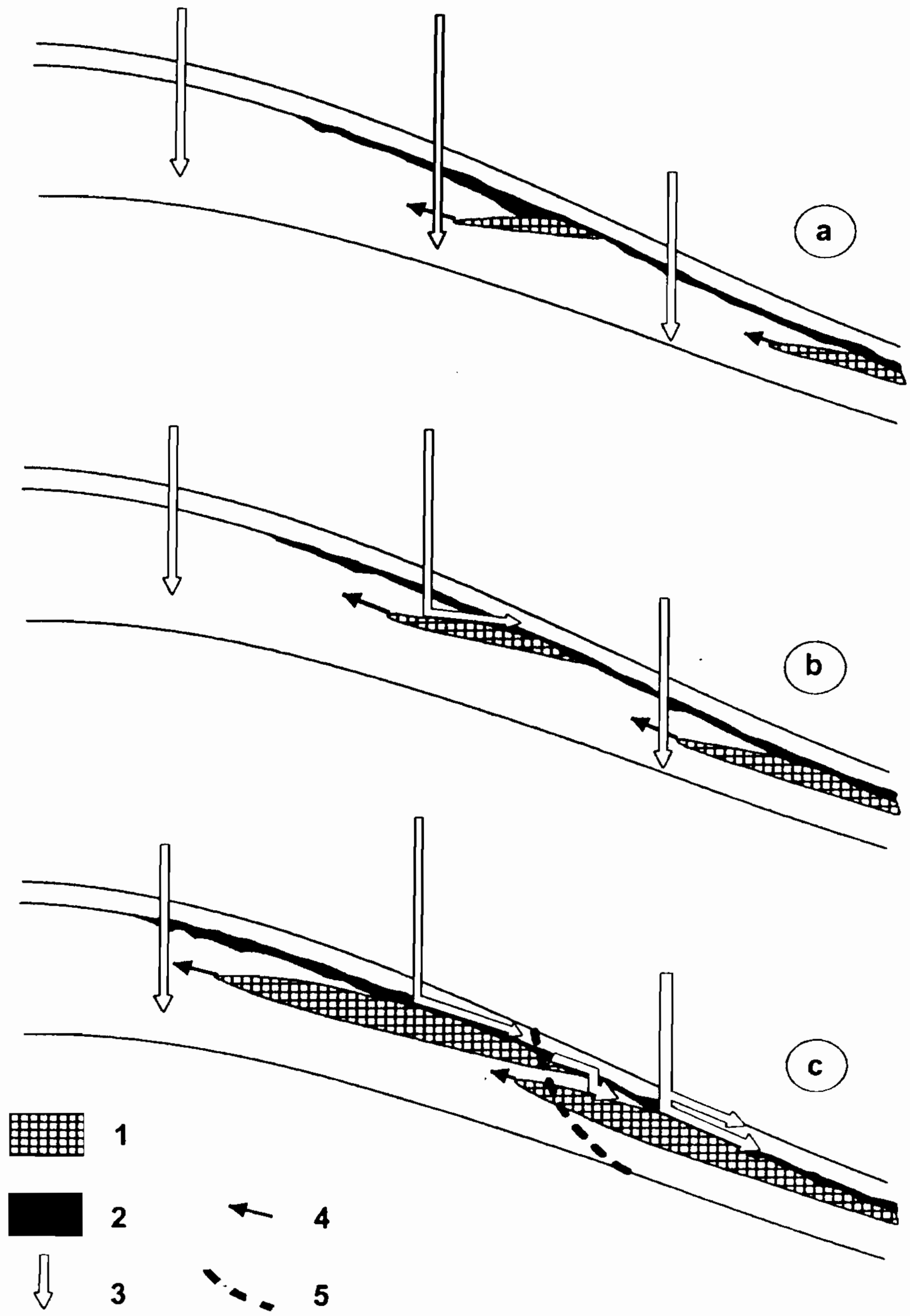

Fig. 9. : Model proposed for the contribution of weathering and pedogenesis to landslide processes. a) Vertical drainage predominates - low risk of landslide on the slope; b) lateral drainage increases - medium risk of landslide on the slope; c) lateral drainage predominates - high risk of landslide on the slope. 1 – K horizons; 2 – M horizons; 3 – Water flows; 4 – Lateral evolution of the K horizons; 5 – Landslide.

drainage in the sandy gibbsitic weathering material predominates. Little lateral flow is observed and the water infiltrates homogeneously along the slope. The risk of landslide is low. In the second stage (b), the K horizons are more strongly developed and the proportion of lateral subsurface drainage increases. The risk of landslide then also increases. In the third stage (c), the K horizons are strongly developed and the subsurface lateral drainage predominates, canalising the water downslope during intense rainfall. The water in the macroporosity of the M horizon can create a consequent overload in the lower third of the slope. The mass of retained water, within a 0.3m thick microaggregated horizon, increases from 100 kg/m² at pF3 to 200 kg/m² at pF1, increasing the slope instability. The risk of landslide is then very high. As the K horizons evolve laterally and upslope at the expense of the G horizon, the mass of water and the risk of landslide increase with the development of this singular pedological system.

Hydrogeochemical model and proposal for the next research: The non linearity of the relationship between the times of return for both rainfall and discharge indicates a structure of the watershed and a probable storage of rainwater into the soil cover. For rainfall events below 20 mm the stormflow remains low or moderate. The increase of the time of return for $rainfall_{corr.}$ and discharge proportional to the unit slope. confirm the growth estimate of the water stored in the soil before the contribution to the stormflow. The identification of the soil organisation makes it possible to propose a model for hydro geochemical functioning of the watershed. The soil cover is a substantial water reservoir according to the thickness of the weathering saprolite. Two arguments supports that the time of persistence of the water is low. The first one is that the solutions leaves the system before reaching the thermodynamic equilibrium with respect to kaolinite. The second argument is of physical nature, the bimodal pore size distribution and the connectivity between macropores of the gibbsitic saprolite allows a fast circulation of the water. This deep water, which likely exhibit a chemical signature of the gibbsitic environment, provide the baseflow all along the year. A second reservoir occurs temporarily into the superficial microaggregated horizons where the compact kaolinitic horizon prevent the vertical flows. Indeed, the water retention and shrinkage curves indicate that almost 50 % of the porosity of the M horizons could be briefly occupied during intense rainfall. The hypodermic flows contribute to the stormflow as a supplement to the runoff over the saturated areas and likely exhibit geochemical features of the kaolinitic and/or organic environment.

This hydro-geochemical model has to be validated by a coupled hydrological and geochemical monitoring of the slope (Curmi et al., 1998 ; Durand and Juan Torres, 1996). Our present knowledge of the soil cover organization will guide for the location of the piezometry and tensiometry measurement stations along the slope. One station will be located upslope for the monitoring of the vertical transfert and the quality of the deep water reservoir. Another one will be located in the middle of the slope, where kaolinitic compact horizon occurs, in order to check the superficial water flow and its chemical composition.

Conclusion

The management of the Cunha watershed in the Serra do Mar region is based on a multidisciplinary approach. The hydrological study indicates that the soil clearly contribute to the water storage during rainfall and along the year. The pedological approach based on the structural analysis of the soil cover makes it possible to identify the organisation of the soil mantle, and based on the mineralogical features, to understand the genetic relationships between the different horizons according to the quality of the percolating waters. The study of the physical features of the soil horizons allows to identify the potential reservoirs and the probable ways of water flow. The next research effort should focus on the identification of the chemical signature of both deep and superficial reservoirs and on their contribution to the discharge using hydrograph deconvolution.

This work was supported by a CAPES-COFECUB Cooperation No 35/87.

References

Bigarella, J.J., M.R. Mousinho, and J.X. Silva.1965. Considerações a respeito da evolução das vertentes. Bol. Parana. Geogr.16/17, 85-116.

Cicco V., Emmerich W. and Fujieda M., 1987. Determinação da curva chave do vertedouro da bacia hidrográfica experimental D, no Parque Estadual da Serra do Mar-Núcleo Cunha, SP. Bol. Tècn. I.F. 41, 79-96.

Cornu, S., 1995. Cycles biogéochimiques du silicium, du fer et de l'aluminium en forêt amazonienne. Ph.D. Thesis, University Aix-Marseille III, 411 p.

Cruz, O., 1974. A Serra do Mar e o litoral na area de Caraguatatuba. Tes. Monogr. 11, IG-USP.

Curmi P., Durand P., Gascuel-Odoux C., Mérot P., Walter C. and Taha A., 1998. Hydromorphic soils, hydrology and water quality: spatial distribution and functional modelling at different scales. Nutrient Cycling in Agro-ecosystems 50, 127-142.

Curmi, P., Kertzmann, F.F. and Queiroz Neto, J.P., 1994. Degradation of structure and hydraulic properties in an oxisol under cultivation (Brazil). In: Ringrose-Voase A.J. and Humphreys G.S. (Eds), Soil Micromorphology: Studies in management and genesis. Proc. IX Int. Working Meeting on Soil Micromorphology, Townsville, Australia. Dev. in Soil Sci. 22, Elsevier, Amsterdam , pp. 569-579.

De Ploey, J. and Cruz, O., 1979. Landslides in the Serra do Mar, Brazil. Catena 6, 111-122.

Durand, P. and Juan Torres, J.L., 1996 – Solute transfer in agricultural catchments: the interest and limits of mixing models. Journal of Hydrology 181, 1-22

Eyrolle, F., Benedetti, M., Fevrier, D. and Benaim, J., 1996. The distribution of colloidal and dissolved organic carbon, major elements and trace elements in small tropical catchments. Geochimica et Cosmochimica Acta 60 19 , 3643–3656.

Fritz, B., 1975. Etude thermodynamique et simulation des réactions entre minéraux et solutions. Application à la géochimie des altérations et des eaux continentales. Mém. Sci. Géol. 41, 152 pp

Fujieda M, Kudoh T., Cicco V. and Carvalho J.L., 1997. Hydrological processes at two subtropical forest catchments: The Serra do Mar, São Paulo, Brazil. Journal of Hydrology 196, 26-46.

Furian S., Barbiéro L., Boulet R., Curmi P. Grimaldi M. and Grimaldi C. 2002 – Distribution and dynamic of gibbsite and kaolinite in an oxisol of Serra do Mar, southeastern Brazil. Geoderma, 106 (1/2), 83-100.

Furian, S., Barbiéro, L. and Boulet, R., 1999. Organisation of a soil mantle in tropical south-eastern Brazil (Serra do Mar) in relation to landslide processes. Catena 38 (1), 65-83.

Guidicini, G. and Iwasa, O.Y., 1976. Ensaio de correlação entre pluviosidade e escorregamentos em meio tropical úmido. Publicação IPT 1080, São Paulo, 48 pp.

Hallaire, V. and Curmi, P., 1994. Image analysis of pore space morphology in soil sections in relation to water movement. In: Ringrose-Voase A.J., Humphreys G.S. (Eds), Soil Micromorphology: Studies in management and genesis. Proc. IX Int. Working Meeting on Soil Micromorphology, Townsville, Australia, Developments in Soil Science 22, Elsevier, Amsterdam, pp. 559-567.

Lucas, Y., Luizão, F.J., Chauvel, A., Rouiller, J. and Nahon, D., 1993. The relation between biological activity of the rain forest and mineral composition of soils. Science 260, 521-523.

Lucas, Y., Nahon, D., Cornu, S. and Eyrolle F., 1996. Genèse et fonctionnement des sols en milieu équatorial. C.R. Acad. Sci. Paris 322, Iia, 1-16.

Monnier, G., Stengel, P. and Fies, J.C., 1973. Une méthode de mesure de petits agglomérats terreux. Application à l'analyse des systèmes de porosité du sol. Ann. Agron. 24, 533-545.

Pédro, G., 1966. Interêt géochimique et signification minéralogique du paramètre moléculaire Ki = SiO_2/Al_2O_3 dans l'étude des latérites et des bauxites. Bull. Gr. Fr. Argiles 18, N.S. 13, 19-31.

Shimomichi, P.Y., Cicco, V., Arcova, F.C.S. and Faria, A.J., 1987. Correlação entre métodos de cálculo de precipitação média mensal em bacia hidrográfica experimental. Bol. Tècn. I.F. 41 (1), 1-26.

Tessier, D. and Berrier, J., 1979. Utilisation de la microscopie électronique à balayage dans l'étude des sols. Observations de sols humides, soumis à différents pF. Sci. du Sol 1, 67-82.

ICHWAM 2002

INTERNATIONAL CONFERENCE ON HYDROLOGY AND WATERSHED MANAGEMENT - 2002 + HYDERABAD +

Proceedings of
International Conference on

HYDROLOGY AND WATERSHED MANAGEMENT

With a Focal Theme on Water Quality and Conservation for Sustainable Development

(18 th - 20 th December, 2002)

(Volume - [illegible])

EDITOR IN CHIEF [illegible]ARA RAO

EDITORS [illegible] REDDY

K. [illegible]

CENTRE FOR WATER RESOURCES

Institute of Postgraduate Studies & Research

Jawaharlal Nehru Technological University

Hyderabad, A.P., India.