*Hydrology of Warm Humid Regions* (Proceedings of the Yokohama Symposium, July 1993).
IAHS Publ. no. 216, 1993.

# The hydrological effects of clearing tropical rainforest and of the implementation of alternative land uses

**J. M. FRITSCH**
*ORSTOM, BP 5045, F-34032 Montpellier Cedex, France*

**Abstract** The paired watershed approach was carried out on eight treated and two control watersheds in French Guyana to access on a small scale the effects of mechanized deforestation of the Amazonian forest. A 2-year calibration period has shown a wide range of runoff under forest: runoff ranged from 1 to 5, i.e. stormflow volumes varied from 7.3% to 34.4% of the rainfall, according to the soil characteristics. The initial treatment (logging followed by mechanized land clearing) has created bare soil conditions for seven of the watersheds. The first year increases of stormflow were very high (228 to 714 mm, or 166% to 299% in relative terms). Higher relative increases were observed for the watersheds having low runoff in natural conditions. The treatments applied include natural regrowth of the forest, tree plantation, grazing and fruit tree plantation after clearing and traditional slash-and-burn agriculture without clearing. The evolution of runoff was monitored and compared to the calculated forest runoff during the first years following the application of the treatments.

## CONTEXT AND EXPERIMENTAL DESIGN

The objective of the study was to access on a small experimental scale the effects of mechanized deforestation of the Amazonian primary forest and of several uses of the land implemented after clearing. The experiment took place in French Guyana (Fig. 1) where large-scale development projects were anticipated (paper pulp industry, cattle raising).

According to the geographical location (5°30′N, 53°W), the climate is of the humid tropical type. The average interannual rainfall on the experimental sites during the study was 3350 mm, with extreme observed values of 2394 mm and 3680 mm. The rainy season lasts from December to June and there is a relatively dry season from July to November. The wettest month is May with an average around 550 mm, but monthly totals of over 1000 mm are not uncommon and have been observed twice during the last 10 years. As tropical cyclones never hit the region, short-duration rainfall does not show exceptional values. Nevertheless, the one-hour precipitation reaches 50 mm for a 2-year return period and 70 mm for a 10-year return period. For maximum daily rainfall, the values are 145 mm and 200 mm, respectively, for the 2-year and the 10-year return periods.

Ten small watersheds, with areas between 1 and 2 ha were selected under natural forest conditions (Roche, 1982). The control sections were equipped with 30°V-notch sharp-crested weirs for seven of the watersheds and H-flumes for the other three. The

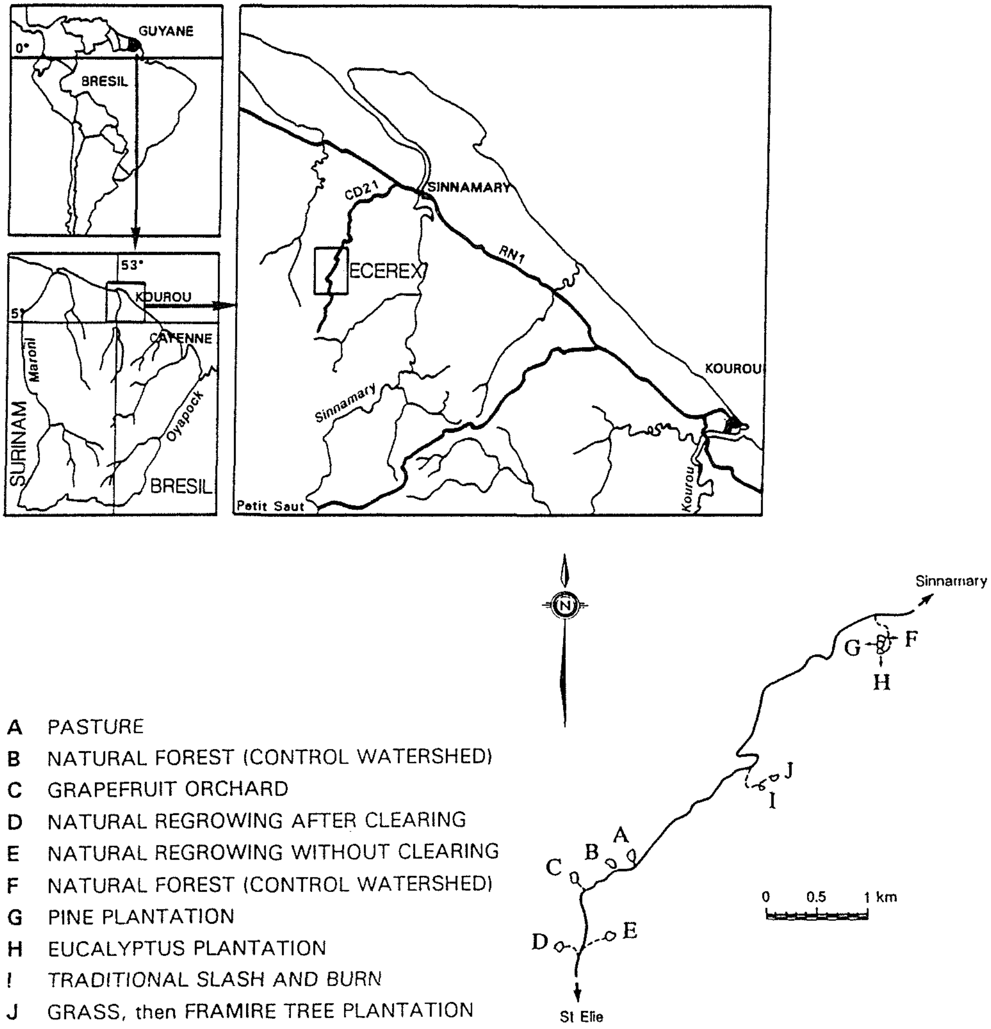

**Fig. 1** Site situation.

waters levels were monitored by high-speed chart recorders. A daily raingauge recorder was installed in a clearing near each hydrometrical station.

The watersheds are identified by the letters A to J, following the order of the beginning of the observations (measurements began in January 1977 on A and B and in December 1979 on I an J). The distance between the two more distant watersheds (D and H) is 5 km (Fig. 1).

The paired watershed approach (Hewlett & Helvey, 1970) was used. For all watersheds hydrological monitoring under natural forest conditions was carried for a minimum two-year calibration period. Then two basins were assigned as control watersheds and kept in their natural condition, while the treatments were implemented on the eight remaining experimental watersheds.

## GEOLOGY AND SOILS

The geological basement is composed of mica-schists, which come to the surface in the form of deep alteration cover. The landscape is composed of small hills less than 100 m high, with steep slopes (15% to 40%). As soon as the watersheds reach a few hectares in size (2 to 5), the streams come out onto flat bottoms.

The soils belong to the red ferralitic soil family (French classification system) and the mineral and textural compositions are quite homogeneous all over the area. But as far as infiltration is concerned the soils show a very broad range of behaviour (Boulet, 1979).

(a) In some areas the drainage of the profile is good and infiltration is fast and deep, even during heavy storms. It is only after continuously wet periods that watersheds developed on these **V**ertical **D**rainage soils (VD) may show significant floods, in terms of volume and peak discharge. Some hills are entirely composed of soils of this type, but VD soils are more frequent on the summits.

(b) In other areas, infiltration is blocked some 20-50 cm below the surface by a layer whose structure is relatively more compact than the upper one. Short-lived perched water tables and pockets of stagnant water are formed in the upper horizon. The soils are characterized by an internal **L**ateral **D**rainage (LD) while vertical infiltration becomes very poor. Even after moderate rainfall, strong superficial runoff is generated by processes known as saturation excess overland flow and return flow (Dunne, 1978). These soils are widespread and they make up the most common type in the region.

(c) The occurrence of water tables in the flats is another major hydro-pedological feature in this area. For some of the watersheds, the water table, generally fed by lateral subsurface drainage along the slopes, comes up to the surface during the core of the rainy season.

The combination of these three features (VD soils, LD soils and water table dynamics) results in very different hydrological regimes on watersheds which nevertheless have similar features in geology, area, shape, slope, and vegetation.

The main characteristics of the experimental watersheds are given in Table 1. The VD soil type ranges from 0 to 99% and three basins frequently have water tables coming to the surface, with typical extensions between 4% and 14%, which means that

**Table 1** Characteristics of the experimental and control basins.

| Basin characteristics | C | I | E | D | B | A | J | G | F | H |
|---|---|---|---|---|---|---|---|---|---|---|
| Drainage area (ha) | 1.6 | 1.1 | 1.6 | 1.4 | 1.6 | 1.3 | 1.4 | 1.5 | 1.4 | 1.0 |
| Slopes % (maximum on each bank) | 20-17 | 23-23 | 30-20 | 28-18 | 17-17 | 20-20 | 32-29 | 34-26 | 35-31 | 24-19 |
| Vertical drainage soils area (%) | 99 | 60 | 57 | 60 | 10 | 0 | 2 | 0 | 0 | 0 |
| Water table extension (%) (coming to the surface during the rainy season) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 4 | 14 |

The *Water Table extension* was determined during the soil survey (it is the more frequent extension of the water table during the rainy season).

the runoff generated by direct precipitation over the open water tables can be a very significant process.

## HYDROLOGICAL REGIMES UNDER NATURAL FOREST CONDITIONS

On such small watersheds, the major part of the runoff occurs in the form of stormflow, as baseflows usually cease after several hours without any rainfall. This is the prevalent situation for seven basins, only three of them (F, G and H) having a very weak baseflow during dry periods. Quickflow was separated from total stormflow by the graphical recession curve technique (Dubreuil, 1974). Taking into account the small size of the drainage basins, the analysis will concentrate on the variations of **total stormflow** volumes in natural and manmade conditions.

### Variability of runoff in space

The variability of runoff among the set of basins was determined during a 2-year calibration period (1978-1979) with all the basins in natural forest conditions (Table 2 and Fig. 2). With similar rainfall conditions, *Storm runoff ranged from 1 to 5*, i.e. stormflow volumes varied from 7.3% to 34.4% of the rainfall.

As previously discussed, differences in soil conditions and water table dynamics are mostly responsible for these variations, as shown by the regression between the percentages of soils with Vertical Drainage and stormflow volumes (Fig. 3).

**Table 2** Rainfall and runoff in primary forest conditions.

| Watershed | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | 3423 | 3267 | 3265 | 3257 | 3350 | 3102 | 3173 | 3165 | 3285 | 3219 |
| Stormflow | 650 | 595 | 239 | 480 | 426 | 1058 | 947 | 1088 | 364 | 748 |
| % of rain | 19.0 | 18.2 | 7.3 | 14.8 | 12.7 | 34.1 | 29.9 | 34.4 | 11.1 | 23.3 |
| Total flow | 665 | 615 | 332 | 511 | 434 | 1493 | 1370 | 1577 | 460 | 831 |
| % of rain | 19.4 | 18.8 | 10.2 | 15.7 | 13.0 | 48.1 | 43.2 | 49.8 | 14.0 | 25.8 |

Interannual averages. All values in mm.

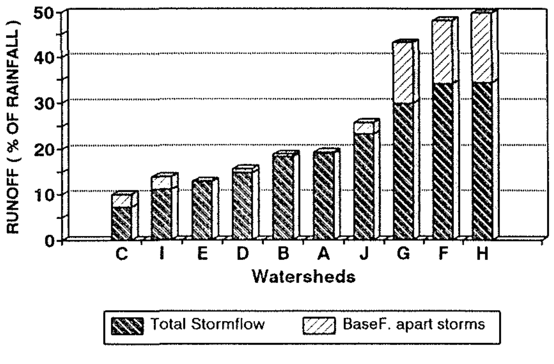

**Fig. 2** Variability of runoff in space (rainforest conditions).

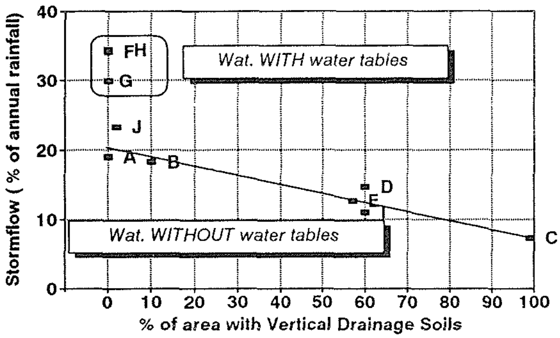

**Fig. 3** Variability of stormflow with soil types and water table dynamics (rainforest conditions).

## Variability in time

Runoff variability in time in the natural ecosystem can be assessed through the control watersheds which remained untouched during the experiment. Data collected on control watershed B during seven years show storm runoff variations between 300 mm and 723 mm, i.e. *a variability in the range of 2.4.*

# THE TREATMENTS

Two watersheds were selected as control basins. Watershed F with strong runoff was assigned as control for the basins with rising water tables and LD soil types (i.e. G, H and J), while control B was used for the other basins where the water table dynamic plays a minor role and having mixed soils types (VD and LD types). This is the typical situation for basins A, D, E and I. One experimental basin (C) with a very low runoff coefficient due to a high percentage of VD soils (99%) has to be monitored using the B control catchment as well, even if the hydrological processes and behaviour of the two catchments are significantly different.

The treatments applied were those planned in the development projects and usually implemented in the region: *logging* of large trees is the first step. All trees with diameter of more than 40-cm are cut down with chain saws. Stems are cut into logs. A light caterpillar tractor (D4) equipped with a straight blade opens skidder access tracks (typical extension 240 m $ha^{-1}$). The logs are yarded uphill by a rubber-tyred skidder. The smaller trees are still uncut, all the roots are in place, and crowns and slash are left on the site. *Land clearing* for agricultural purposes generally follows the logging. Clearing is achieved with heavy caterpillar tractors (D8 or D9) equipped at the front with a cutting blade to fell the remaining trees, and with an hydraulic claw system at the rear to pull out the roots. Finally, the slash is gathered along the contour lines by a caterpillar tractor with a rake blade. The slash is burnt whenever a relatively dry period occurs.

Subsequently, different scenarios have been tested :

(a) **Natural regrowing.** The exploitation of the ecosystem is limited to the logging phase and no following action is undertaken. Two different trials of regrowing were tested:

  - watershed E: natural regrowing after logging only.
  - watershed D: natural regrowing after logging **and** land clearing.

(b) **Plantation of fast growing trees** after logging and land clearing :
  - watershed G: plantation of **pine trees** (*Pinus Caraïbea*, var. *Hondurensis*).
  - watershed H: plantation of **eucalyptus** (*E. grandifolia, Flores*).

(c) **Plantation of fruit trees**. The catchment having the best soil conditions, was dedicated to an orchard trial, i.e. plantation of grapefruit tree (pink pomelo) on watershed C.

(d) **Grazing** on fodder grass. Plantation of *Digitaria swazilandensis* grazed by cattle on watershed A.

(e) **Traditional slash-and-burn shifting cultivation**. Although this manual agricultural technique was not in the scope of the development projects, it was tested as a reference to mechanized treatments on watershed I.

Six of the eight treated watersheds had completely **bare soil** at the beginning of the treatment (the exceptions were basin I converted into slash-and-burn cultivation and basin E in which all big trees were logged, but subsequent land clearing had not been done). This was an opportunity to carry out an assessment of the hydrological effects for an identical situation of soil cover on watersheds whose respective behaviour has been very different.

## CALCULATION OF RUNOFF IN FOREST CONDITIONS FOR THE TREATED WATERSHEDS

For the prediction of runoff from treated watershed (as if they were under forest), several multiple regression models were adjusted using the data collected during the calibration period. The most significant model had generally been a multilinear correlation using the runoff of the control and the difference of rainfall between the control and the experimental watershed. For seven watersheds out of the eight, regressions at the single storm level led to the most accurate estimations. For one of the watersheds only (C), a nonlinear model working at a ten-day scale had to be used. The data collected during the two-year calibration period was divided into two samples (periods I and II). The data of period I were first used to calibrate the correlation models; the accuracy was then tested on data from period II. Period II was then used for cross-calibration and period I for validation. On cumulative annual basis, the accuracy of the forest runoff prediction with a 90% interval of confidence is around or better than 5% (Table 3), i.e. the method is able to detect in a significant way, any modification in runoff greater than these thresholds. The double-mass curve technique was used as well to detect and access the modifications which had occurred on the treated watersheds (Fig. 4).

**Table 3** Accuracy of the reconstruction of annual runoff under forest (validation at 90% confidence level interval).

| Treated watershed (control watershed): | | | | | | | |
|---|---|---|---|---|---|---|---|
| A(B) | C(B) | D(B) | E(B) | G(F) | H(F) | I(B) | J(B) |
| 7.4% | 12.0% | 5.3% | 5.6% | 2.6% | 3.2% | 6.4% | 4.3% |

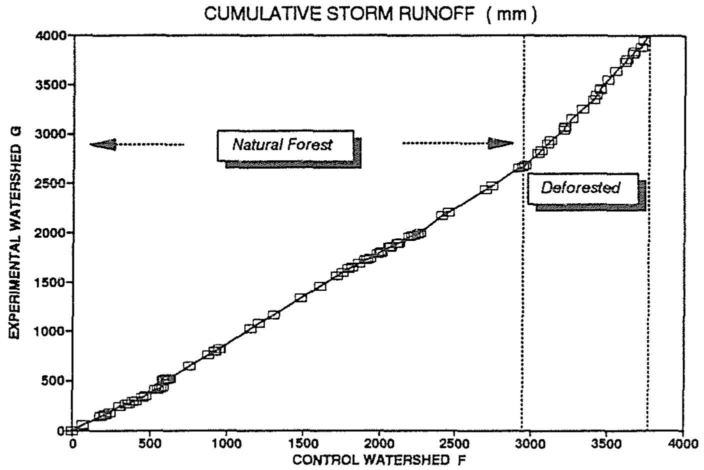

**Fig. 4** Double-mass curve. Experimental watershed G and control F.

## MODIFICATION OF RUNOFF AFTER LAND CLEARING (ON BARE SOIL)

Depending on the watershed the bare soil period refers to different years, but always includes the main part of the rainy season, from January to July. Storm runoff increases (i.e. the part in the observed runoff due to treatment, expressed in mm) during this first rainy season after logging and clearing are given in Table 4.

**Table 4** Runoff increases during the first rainy season following logging and land clearing.

| Watershed | Year | Observed runoff (mm) | Increase after clearing (mm) |
|---|---|---|---|
| C | 1979 | 682 | 304 |
| D | 1981 | 479 | 244 |
| A | 1979 | 1616 | 762 |
| J | 1983 | 1037 | 384 |
| G | 1981 | 1388 | 621 |
| H | 1981 | 1453 | 560 |

Some values are very high; as a comparison two of the highest, quoted in the literature, are 662 mm for Coweeta watershed no. 17 (Swank & Douglas, 1974) and 650 mm on a small watershed in New Zealand (Pearce *et al.*, 1980). The values of increase (prediction of the mean) as well as the respective values for the 90% interval of confidence are shown in Fig. 5. The increases calculated by the slope analysis of the double-mass curves are in the same range and are also shown on Fig. 5.

However, these absolute values of runoff do not give a clear understanding of the effects of land clearing, as :

(a) The data do not apply to the same year, so effects of interannual hydrological variability are included in the impacts of logging and clearing.

(b) It appeared that during this first rainy season after clearing, the analytical relationships between treated and control watersheds were unsteady during some

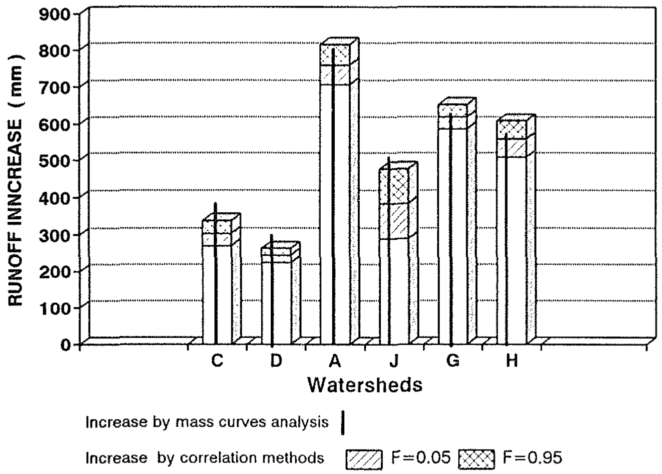

**Fig. 5** Increases in runoff on bare soil (in mm) during the rainy season after logging and land clearing:
– calculated by correlation (for the mean and the 90% interval of confidence);
– calculated by slope analysis of the double-mass curves.

weeks at the beginning of the period. This was due to slight differences and heterogeneity in treatments among the watersheds, and some time was necessary in order to come to a stabilized response. The selection of the period of stabilized response was done by the statistical method of Bois (1987). The implementation of the method is described in Fritsch (1990).

The results of the analysis carried out on the data of this steady behaviour period are given in Table 5 and are plotted in Fig. 6.

(a) The ratios of increase after clearing, expressed as a percentage of the runoff of the respective watershed under forest, range from 166% to 299%.

(b) When the watersheds are classified in ascending order of their observed runoff during the calibration period under forest (i.e. C, D, A, J, G, H), the percentage of increase has the descending order (Fig. 6) : in relative terms (%), increases are higher for the watersheds having low runoff in natural conditions than for those

**Table 5** Increase of stormflow runoff after clearing (stabilized response period).

| Watershed | C | D | A | J | G | H |
|---|---|---|---|---|---|---|
| Rainfall (mm) | 1448 | 2207 | 2349 | 2071 | 1445 | 1620 |
| Observed storm runoff "*bare soil*" (mm) | 342 | 450 | 1341 | 954 | 772 | 787 |
| (% of rainfall) | **23.6** | **20.4** | **57.1** | **46.1** | **53.4** | **48.6** |
| Calculated storm runoff "*forest*" (mm) | 114 | 181 | 627 | 483 | 414 | 475 |
| (% of rainfall) | 7.9 | 8.2 | 26.7 | 23.3 | 28.7 | 29.3 |
| Increase of runoff with *bare soil* (mm) | 228 | 269 | 714 | 471 | 358 | 312 |
| (% of rainfall) | **15.7** | **12.2** | **30.4** | **22.7** | **24.8** | **19.3** |
| Increase of runoff after clearing (%) | **299** | **249** | **214** | **197** | **187** | **166** |

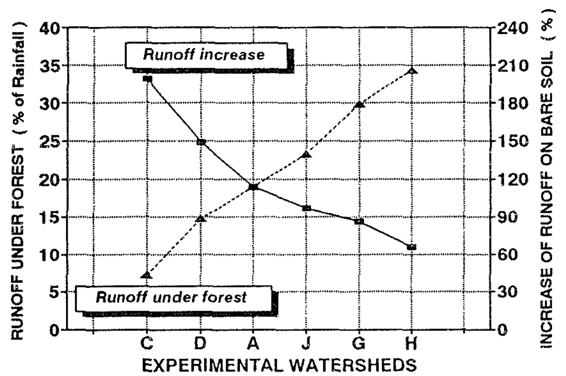

**Fig. 6** Increases of runoff after clearing, compared with runoff under forest.

which had previously shown strong runoff, i.e. the impacts of clearing are relatively stronger on the "good" soils.

(c) However, in absolute figures (mm), the highest increases were observed on the watershed which already had large stormflow runoff under natural conditions.

## EVOLUTION OF RUNOFF AFTER APPLICATION OF THE TREATMENTS

### General

The effects of the treatments on the runoff of the experimental watersheds during the years following logging are summarized in Table 6. The results are presented in Fig. 7 (left column) for the experiments linked with forestry speculation (tree plantation or natural regrowing) and in Fig. 7 (right column) for those which focus more on agricultural practices (pasture, orchard, slash-and-burn).

**Table 6** Increases of stormflow runoff during treatments (as % of forest runoff).

| | Year 1<br>Bare soil(a) | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 |
|---|---|---|---|---|---|---|
| C Grapefruit | 199 | 73 | 17 | 63 | 46 | |
| I Traditional slash and burn (no clearing) | | 23 | 30 | | | |
| E Logging and regrowing (no clearing) | | 4 | 26 | 2 | 6 | |
| D Logging and regrowing | 149 | 40 | 32 | 16 | | |
| A Grazing of fodder grass | 114 | 59 | 63 | 47 | 27 | |
| J Grass plantation | 97 | | | | | |
| G Pine trees | 87 | 62 | 33 | | | 12 |
| H Eucalyptus | 66 | 47 | 12 | | | 8 |

[a] stabilized response period.

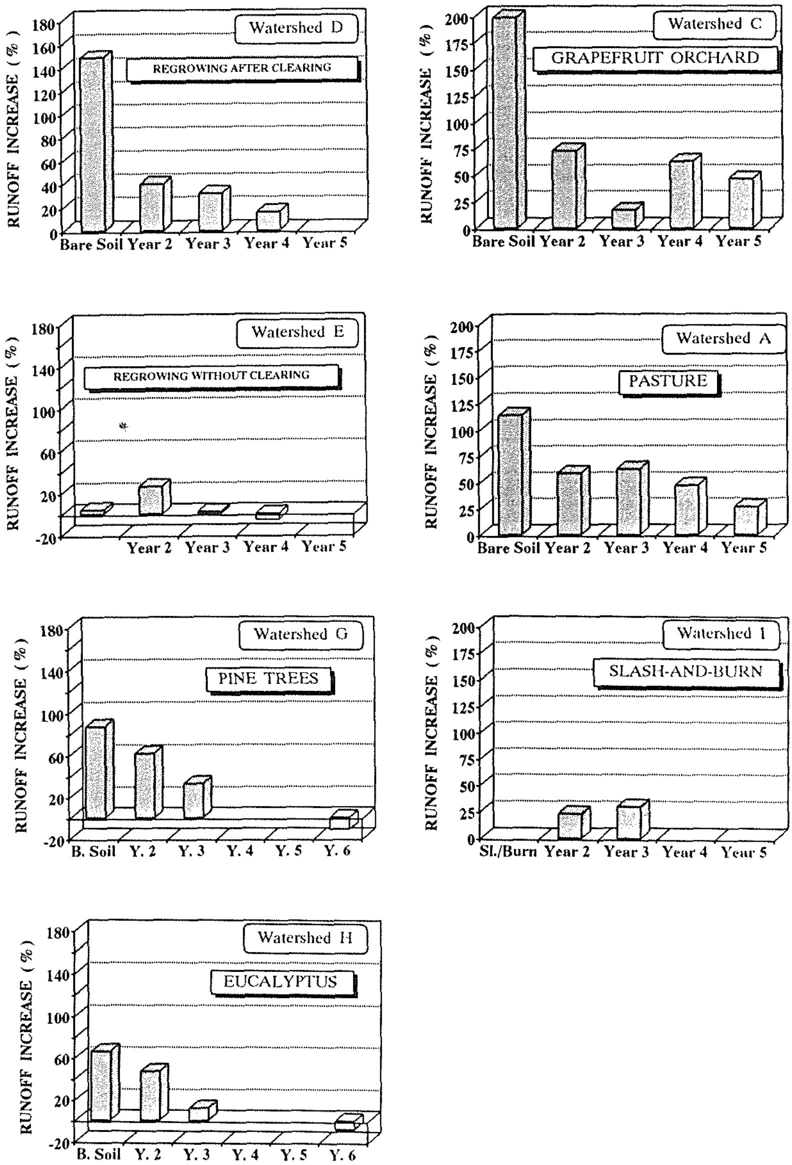

**Fig. 7** Increases of runoff with time:

- for the experiments linked with forestry speculations (tree plantation or natural regrowing);
- for the experiments focusing on agricultural practices (pasture, orchard, slash and burn);

(vertical scales are different between columns).

One general conclusion is that runoff whose increase has been very high during the year immediately following logging and clearing, was reduced in very significant terms on all the watersheds. The analysis can be carried out in more detail as follows:

## Differences between logging-only and logging followed by land clearing

An easy comparison can be drawn between the experiments carried out on watershed D (natural regrowing after logging followed by extensive land clearing) and watershed E (natural regrowing after logging only). As these two watersheds have shown very similar hydrological regimes under natural conditions, and were deforested during the same year, it can be assumed that the differences between treatments account directly for the differences in runoff.

The severe logging which took all large trees in watershed E led to a maximum annual increase in runoff which was at the very most 26% higher than it would have been under natural forest, while with the additional effects of land clearing the increase was as high as 149% during the period of steady response. The hydrological effects of land clearing are extremely strong, even if compared with severe mechanized logging.

During the fourth year after logging the runoff was only 16% greater than it would have been under forest for the cleared watershed. For the logged-only basin, the calculated increase is −6%, which according to the accuracy of forest runoff calculation is not significantly different from zero. This does not mean that the ecosystem in its fullest sense has recovered its natural characteristics. As proved by the studies carried out in the other disciplines, major changes will affect, among others, the botanical features and the soil conditions for decades or even longer periods.

## The tree plantations

Watersheds G and H, which had the poorest soil conditions, were assigned to fast growing tree plantations, i.e. pine trees on G and eucalyptus on H. Although the increases in the first year were the lowest proportionally when compared to the other watersheds, the negative effects remained at a constant high level during the second year after clearing. The figures were +62% (year 2) and +87% (year 1) for G and +47% (year 2) and +66% (year 1). It was only during year 3 after clearing, that a significant reduction of runoff was observed on the eucalyptus plantation, while the value still remained at a rather high level of +33% for the pine plantation. The explanation of these figures is in the forestry management techniques: it is necessary to protect the young pines and eucalyptus from natural regrowing which development is faster than that of the plantations and therefore the surrounding area has to be cleared regularly. During years 2 and 3 these forestry techniques artificially maintained soil conditions which were quite similar to those observed during year 1 immediately after land clearing and accordingly, the hydrological response was still high.

On these two watersheds, additional measurements were taken during year 6 after deforestation (i.e. on five-year old trees).The annual storm runoff would have been less for the plantations than under primary forest, more precisely −12% for the pines and −8% for the eucalyptus (figures significant at 0.05). But this was during a particularly dry year for the region (the annual rainfall was "only" 2394 mm). As such conditions were not observed during the calibration period, the regression models is probably not be able to predict the runoff under forest with the required accuracy this particular year.

## The grazing experiment

This trial was on a Digitaria swazilandensis plantation grazed by 5 to 10 young bulls per hectare (which is a load equivalent to 1200 to 3300 kg $ha^{-1}$). Such a semi-intensive design strongly differs from the common ranching system in use in the Amazonian region, with loads ranging from 0.28 to 1.3 animal per hectare (respectively Fearnside, 1979 and Myers, 1982). Propagation by cuttings was the technique used for plantation of the swazilandensis grass, thus creating conditions for fast expansion of the forage and close vegetal cover a few weeks after the beginning of the rainy season. Nevertheless the runoff maintained high levels of increase for three years, with values around 60% for the two first years and 50% for the third year. It was only four years after plantation that a decreasing trend was observed with increases slightly under 30%: grazing is an agro-economic speculation which induces stormflow volumes definitely higher than under forest. This conclusion is of some importance as grazing is widespread in South American tropical countries and stretches over large areas as the only form of land use.

## The traditional slash-and-burn cultivation

No machinery was used on this watershed at all. Planting and harvesting was done by hand, the only mechanical input being the use of portable chain saws to fell the trees. This traditional cultivation is for family supply and comprises a broad variety of plants such as water melon, corn, cassava, banana, pineapple, sweet potato, etc. Compared to most of the mechanized trials, the hydrological impacts were rather low: a 23% increase in runoff was observed during the first year and a 30% increase during the second. An extension of the area planted with corn during the second year may account for this difference. If these increases were actually slight, especially for a watershed where VD soils are dominant, it is nevertheless clear that manual slash-and-burn cultivation has significant effects on the water cycle.

## The grapefruit orchard

Watershed C, with the best soils in terms of internal drainage and agricultural potentiality was used for the plantation of grapefruit trees (480 small trees planted in a 7 × 5 m design). In addition, a grass cover of Brachiaria USDA was planted between the trees to protect the soil. As it was previously stated, watersheds with large areas of VD soils (as for watershed C where this percentage is 100%), were very sensitive to any treatment and that relative increase in runoff would easily reach high values.

After an increase of practically 200% calculated for the core of the first rainy season for a bare soil situation, the increases dropped to lower figures such as 73% (year 2), 17% (year 3), 63% (year 4) and 46% (year 5). As the forest storm runoff of this watershed was very weak (i.e. 7.3% of the rainfall), the volumes of water corresponding to these data are nevertheless small, i.e. 196 mm (year 2), 25 mm (year 3), 141 mm (year 4), 128 mm (year 5).

There was no control watershed within the experimental design having the same regime as watershed C and as such, the accuracy of forest runoff calculation is the lowest of the overall experimental set (Table 3). As such, data of years 2, 4 and 5 are not statistically different (significant at 0.05). It can be assumed that the stormflow of the orchard was nearly 50% higher than under forest, but the evolution in time cannot be estimated.

## CONCLUSIONS

As far as hydrological regimes of small watersheds are concerned, the natural ecosystem is very heterogeneous: the hydrological response to the same amount of rainfall ranged from 1 to 5 in the natural ecosystem, while the effects of treatments never exceeded a range of 1 to 3. In consequence, a precise knowledge of the initial situation is required before any treatment is applied in order to get any chance of assessing accurately the effects of land-use changes. In this case the combined bi-disciplinary approach made by the hydrologist and the soil scientist has provided the basics for such understanding.

For six of the watersheds on which mechanized logging and clearing was conducted, a comparative bare soil situation was realized and a steady response to rainfall was observed after some weeks. Very strong increases of storm runoff were highlighted with averages over the core of the rainy season ranging from +66% to +200% when compared with runoff under forest. The strongest impacts were observed on the watersheds initially having weak storm runoff and a general rule confirmed on all watersheds was that the lower the forest runoff, the higher the increase

It can be assumed that for all forestry options (regrowing, plantation) the runoff will decrease with time and nearly return to the previous values after some years. In the case of grazing, stormflow increases remained at a steady level of +30% to +60% during the first four years.

Other results have been achieved such as on-site erosion measurements, sediment flow monitoring (Fritsch & Sarrailh, 1984) and assessment of hydrological effects on stormflow for individual storms and for ten-day periods and on peak flows (Fritsch, 1990).

**Acknowledgements** This research programme was conducted by ORSTOM (l'Institut Français de Recherche Scientifique pour le Développement en Coopération) and CTFT/CIRAD (Centre Technique Forestier Tropical/Centre International pour la Recherche en Agronomie Tropicale).

## REFERENCES

Bois, Ph. (1987) Contrôle des séries chronologiques corrélées par étude du cumul des résidus. In: *Deuxièmes Journées Hydrologiques de l'ORSTOM*, 89-99. Col. Colloques et Séminaires, ORSTOM, Paris.

Boulet, R. (1979) Méthodes d'analyse et représentation des couvertures pédologiques des bassins-versants ECEREX. In: *L'Ecosystème Forestier Guyanais*, 11-17. Bulletin de Liaison du Groupe de Travail, ORSTOM, Cayenne, no.1, février 1979.

Dubreuil, P. D. (1974) *Initiation à l'Analyse Hydrologique*. Masson, Paris.

Dunne, T. (1978) Field studies of hillslope flow processes. In: *Hillslope Hydrology* (ed. by M. J. Kirkby), 227-293. John Wiley, New York.

Fearnside, P. M. (1979) O desenvolvimento da Floresta Amazonica: problemas prioritàrios para a formulaçào de directizes. *Acta Amazonica*, **9**(4) suplemento, 123-129.

Fritsch, J. M. (1990) Les effets du défrichement de la forêt amazonienne et de la mise en culture sur l'hydrologie de petits bassins versants. Doctorate Thesis, Université des Sciences et Techniques de Montpellier (France), novembre 1990.

Fritsch, J. M., Sarrailh, J. M. (1986) Les transports solides dans l'écosystème forestier tropical humide guyanais. Effets du défrichement et de l'aménagement de pâturages. *Cah. ORSTOM, série Pédol.*, **XXII**, 93-106.

Hewlett, J. D. & Helvey, J. D. (1970) Effects of forest clear-felling on storm hydrograph. *Wat. Resour. Res.* **6**, 768-782.

Myers, N. (1982) Depletion of tropical moist forests: a comparative review of rates and causes in the three main regions. *Acta Amazonica*, **12**(4), 745-758.

Pearce, A. J., Rowe, L. K. & O'Loughlin, C. L. (1980) Effects of clearfelling and slash-burning on water yield and storm hydrograph in evergreen mixed forests, Western New Zealand. In: *The Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins* (Proc. Helsinki Symp., June 1980), 119-127. IAHS Publ. no. 130.

Roche, M. A. (1982) Comportements hydrologiques comparés et érosion de l'écosystème forestier amazonien à Ecerex en Guyane. *Cah. ORSTOM, série Hydrol.* **XIX**(2), 81-114.

Swank, W. T. & Douglas, J. E. (1974) Streamflow greatly reduced by converting deciduous hardwood stands to pine. *Science* **185**, 857-859.