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INFLUENCE OF LAND USE CHANGE ON DISCHARGE AND SEDIMENT TRANSPORT OF FLOODS

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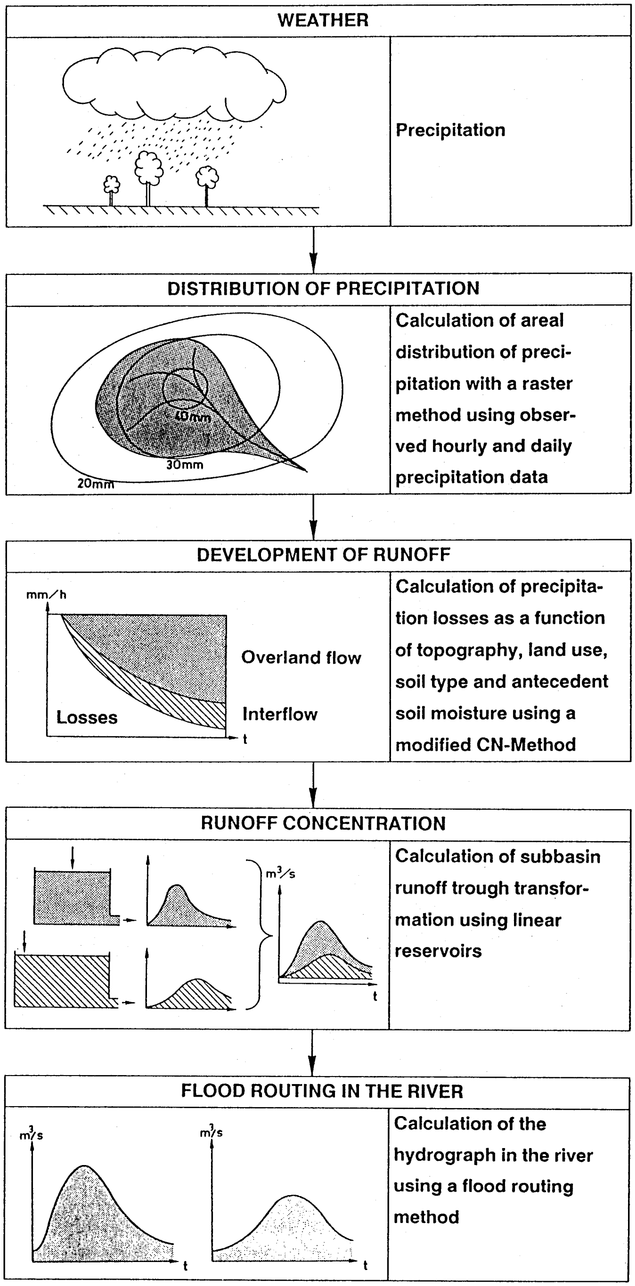
ABSTRACT Graphical relations between changes in land use and alterations of discharge and sediment yield during flood events are presented. They provide a means of obtaining quantitative estimates of the effects of changes in land use and are based on sensitivity analyses using a Rainfall-Runoff-Sediment model. Assuming these models are capable of simulating the processes that occur in nature with sufficient accuracy, the derived relations can be applied to catchment areas between 100 and 2500 km^2. They are verified using the data from the Rio Piray in Bolivia, a tributary of the River Amazon, where measurable changes in land use have occurred in recent years. The changes in runoff and sediment yield observed there correspond relatively well with those suggested by the graphical relations.

INTRODUCTION

Within the hydrological cycle natural vegetation has a regulating influence on runoff and it protects from erosion. Deforestation and urbanization not only increase the danger of flood inundation, but also promote erosion. In the literature (cf. Bosch & Hewlett, 1982; Hadley *et al.*, 1985) increases in discharge of up to 100% are reported as an effect of land use change. In the case of sediment yield values 310 times higher, compared to the original magnitude, were observed in small areas. Although these phenomena have long been known, no readily transferable quantitative relations do exist for predicting effects of land use change on discharge and sediment yield.

Discharge and sediment yield are influenced by many characteristics of the catchment as well as of the event. The interconnections are complex and are influenced by so many factors that they cannot be expressed directly in a system of equations. Thus, transferable relations can only be derived from data from numerous different catchments. For this, changes in land use must have occurred in the respective area, and, at the same time, observations of discharge and sediment yield must be available. These data are lacking. Nevertheless, for several years simulation models have been successfully used in hydrology. On the premise that such models can simulate the processes occurring in nature with sufficient accuracy, they can also be used for simulating the necessary data. The results of such simulations will be evaluated subsequently.

The relations between changes in land use and alterations in discharge and sediment yield are established according to the following procedure. Only flood events are examined since, on the one hand flood discharges with their risk of inundation are a menace to human activities and, on the other hand they transport the major part of the annual sediment load of a river. Of the sediment, only the suspended load is considered, as this, rather than the



Calculation of areal distribution of precipitation with a raster method using observed hourly and daily precipitation data

Calculation of precipitation losses as a function of topography, land use, soil type and antecedent soil moisture using a modified CN-Method

Calculation of subbasin runoff trough transformation using linear reservoirs

Calculation of the hydrograph in the river using a flood routing method

FIG. 1 Calculation procedure for the rainfall-runoff process.

bed load, is affected primarily by a change in land use. In addition, the suspended load often represents from 80 to 90%, sometimes even more, of the total load.

THE SIMULATION MODEL

Figure 1 shows a schematic of the simulation of a rainfall-runoff process. Except for the calculation of effective precipitation, well known hydrological methods are used. The computation of the effective precipitation is carried out according to an extended Curve-Number Method (Kleeberg & Øverland, 1990). The land use of a region is converted into CN-values (Curve Numbers; U.S. Soil Conservation Service, 1975) which specify the permeability of the soil surface, i.e. the infiltration of precipitation.

Figure 2 is a schematic representation of the procedure for the simulation of erosion and sedimentation processes. The main cause of denudation is precipitation. It causes erosion of sediment. The flow, induced by the precipitation, transports the detached particles. The amount of detached sediment is calculated by parametric functions (Øverland & Kleeberg, 1985). The applied algorithms represent the physical processes involved through several functions, whose parameters are partially calibrated with measured data, and partially determined directly from the existing land use. The land use is taken into account by C-factors (according to the Universal-Soil-Loss-Equation by Wischmeier & Smith, 1978) (Øverland, 1990). C-factors reflect the resistance of the ground surface to erosion.

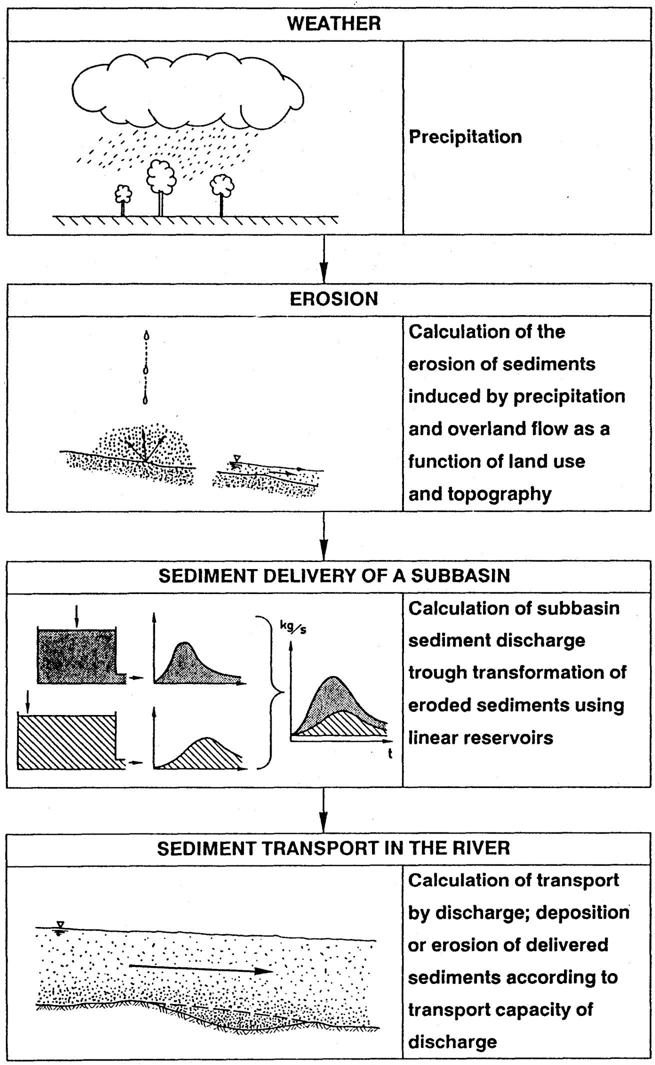
Using CN-values and C-factors to take the land use into account is only one possibility among others. It, however, is a suitable one because it is used frequently and thus relatively reliable information on the values for different land use is already available in the form of tables.

In addition to the land use parameters (CN-value and C-factor), the model also contains other parameters, some of which are physically-based, whereas others are not. Physically-based parameters include the basin area, slope, river length and others. In contrast, the speed of the reaction (fast/slow reaction) of a region to the imposed load is not provided. Rather, it must be derived from calibration during the application of the model using measured precipitation, discharge and sediment concentration.

RELATIONS BETWEEN CHANGES IN LAND USE AND ALTERATIONS OF DISCHARGE AND SEDIMENT YIELD

Sensitivity analyses are performed with this model. First, 5000 data sets with different data for catchment areas and events were created, and for each data set discharge and sediment yield were calculated for 13 different land use conditions, characterized by CN-values and C-factors. The size of the catchments included in the data sets are ranged from 100 to 2500 km^2, and the shape, i.e. narrow or wide, and the altitude of the terrains also varied. The variation was interpreted using a random generator. In order to include not only shape and size of the basin, but also different climatic conditions, precipitation and soil moisture also were varied, with respect to altitude as well as space and time. The mean areal precipitation varied from 40 to 110 mm and precipitation durations less than or equal to 2 days were used.

The evaluation of the simulation results was restricted to three significant parameters, specific discharge of peak flow, depth of runoff and sediment yield. The relative changes (i.e. in percent) of these parameters in relation to an initial value were examined. Thus it can be shown that neither the size of the basin, nor the reaction of the basin, nor the duration of the precipitation had a significant effect on changes in discharge and sediment transport. Nevertheless, relations between the original land use condition and the magnitude of the flood event can be established. These relations are presented as graphs in Figs. 3 to 5.



Precipitation

Calculation of the erosion of sediments induced by precipitation and overland flow as a function of land use and topography

Calculation of subbasin sediment discharge trough transformation of eroded sediments using linear reservoirs

Calculation of transport by discharge; deposition or erosion of delivered sediments according to transport capacity of discharge

FIG. 2 Calculation procedure for erosion and sediment transport processes.

VERIFICATION OF THE ESTABLISHED RELATIONSHIPS

The relations were verified using data from catchments of the Rio Piray, a tributary to the River Amazon in Bolivia (Fig. 6). Between 1980 and 1983 measurable change in land use occurred there through settlement and the resulting deforestation and urbanization of originally undisturbed terrain. The original land use at two times in the past can be established from maps and areal photographs. Simultaneously, since the mid 70's, hydrological and meteorological data have been collected systematically.

Based on the historical land use data and on socio-economical data and trends two new scenarios of land use were created. One of them represents the land use in the year 2000 as it will be, projected from the present rate of development. The second scenario represents

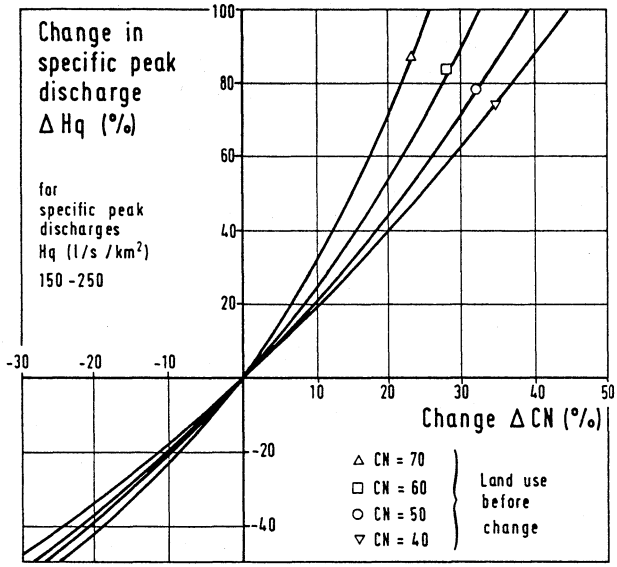


FIG. 3 Relationships between change in land use (represented as ΔCN of CN-value) and change of the specific discharge of peak flow ΔHq.

the land use as it should be, incorporting effective environmental manangement. It assumes development in the catchment of the Rio Piray and the neighbouring regions, whereby afforestation and other protection measures will be introduced in such a way that the risk of floods is reduced and the increasing erosion stopped. In Table 1 the mean CN-values and C-factors for four states of land use, for selected sub-basins of the Piray River, are listed.

TABLE 1 Mean CN-values and C-factors for the sub-basins in the catchment of the Rio Piray.

Sub-basin	Area (km^2)	CN-values to be achieved	before 1980	after 1983	year 2000	C-factors to be acheived	before 1980	after 1983	year 2000
Colorado	104	57.3	56.3	64.1	68.4	0.014	0.005	0.031	0.061
Bermejo	477	54.5	56.4	62.5	66.2	0.028	0.020	0.040	0.062
Piojeras	860	54.2	57.9	65.4	71.0	0.020	0.027	0.053	0.097
Angostura	1417	54.5	57.5	64.3	69.5	0.020	0.024	0.048	0.092
Elvira	99	65.1	64.6	67.9	74.7	0.021	0.011	0.019	0.113
Espejos	212	66.6	66.3	68.2	75.3	0.027	0.008	0.021	0.091
La Belgica	2870	60.5	63.5	67.8	74.3	0.040	0.030	0.049	0.133

In order to calculate the discharge and sediment transport the simulation model must

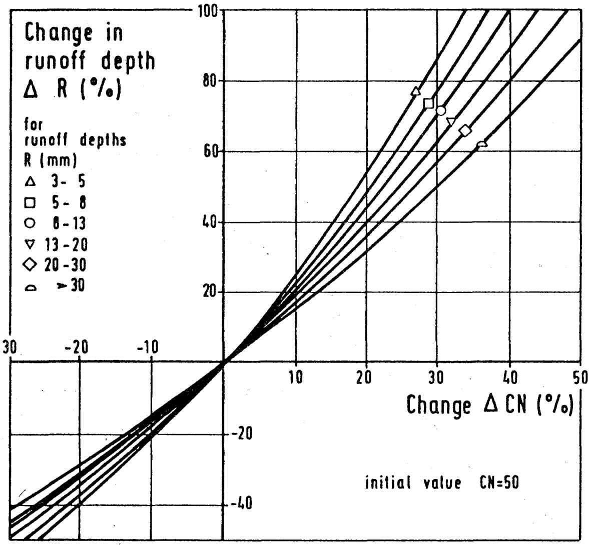


FIG. 4 Relationships between change in land use (represented as ΔCN of CN-value) and change of runoff depth ΔR.

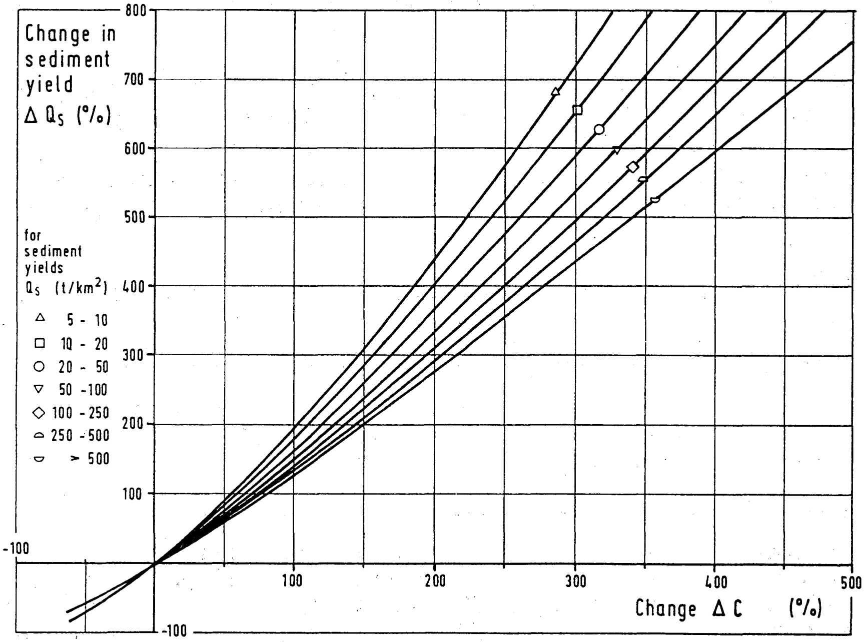


FIG. 5 Relationships between change in land use (represented as ΔC of C-factor) and change of sediment yield ΔQs.

first be calibrated. This was done by using the data for 48 flood events, observed between 1976 and 1986. Discharge and sediment concentrations were recorded at Bermejo, Angostura, Espejos, and La Belgica, and precipitation was measured at about 30 stations, of

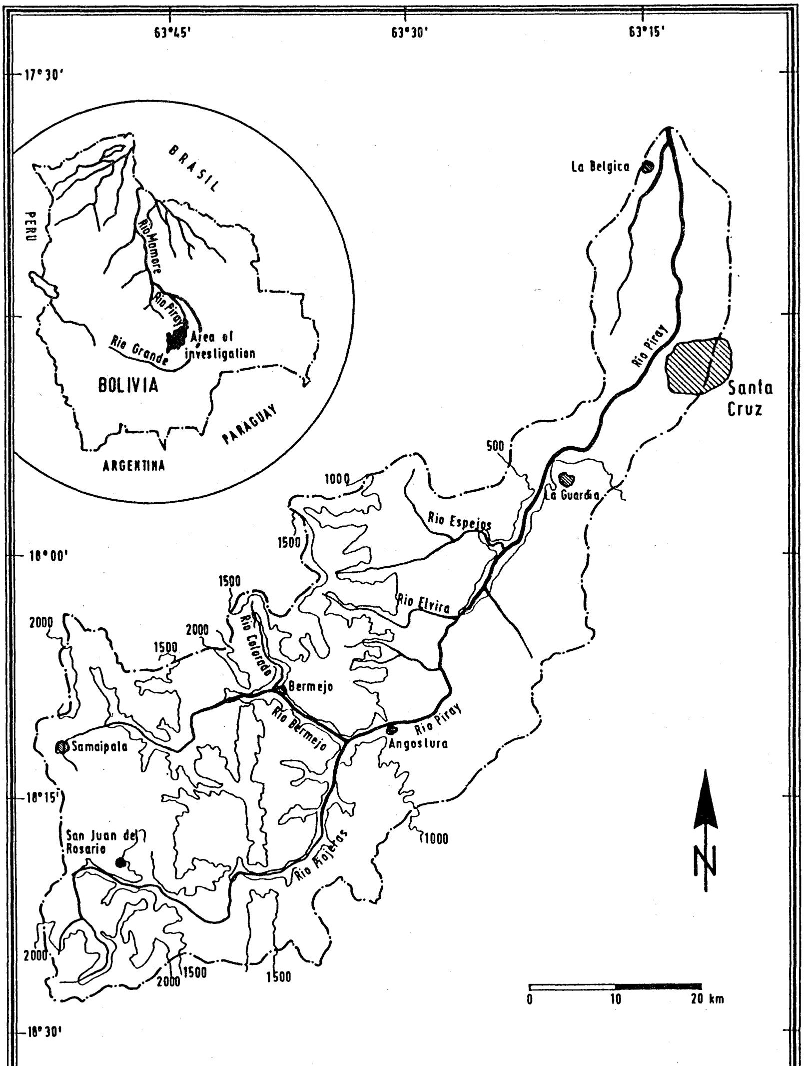


FIG. 6 Catchment of the Rio Piray/Bolivia.

which 10 were equipped with recorders. Using the calibrated models, discharge and sediment transport were calculated for four different states of land use and precipitation from 1976-1986. Figures 7 and 8 give examples of the discharge hydrographs and sediment transport, calculated for these different land use states.

The hydrographs deviated significantly according to the land use state. These differences, however, were not identical for all events. On the contrary, differences in the increase of discharge and sediment transport were observed from one event to another. The

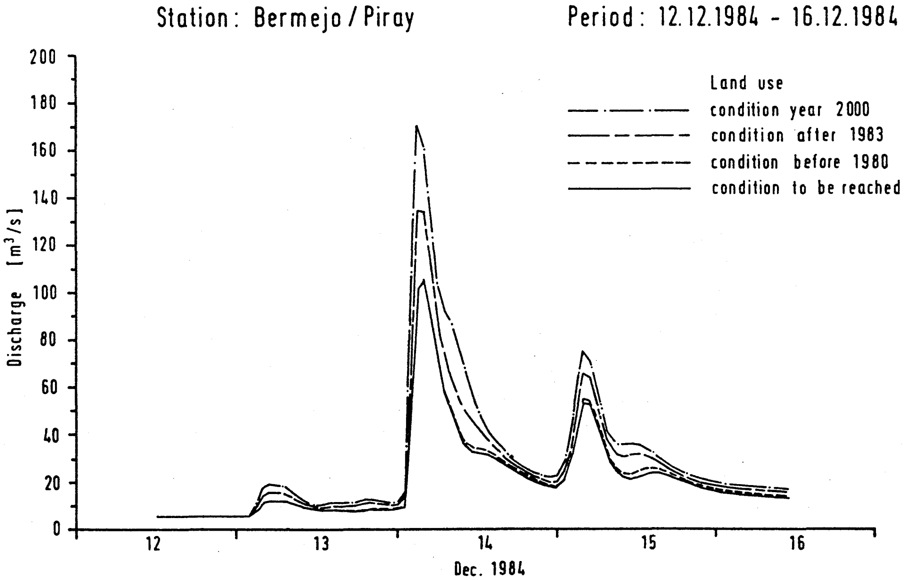


FIG. 7 Estimated discharges for the four land use states at Bermejo for the flood event of 14 December 1984.

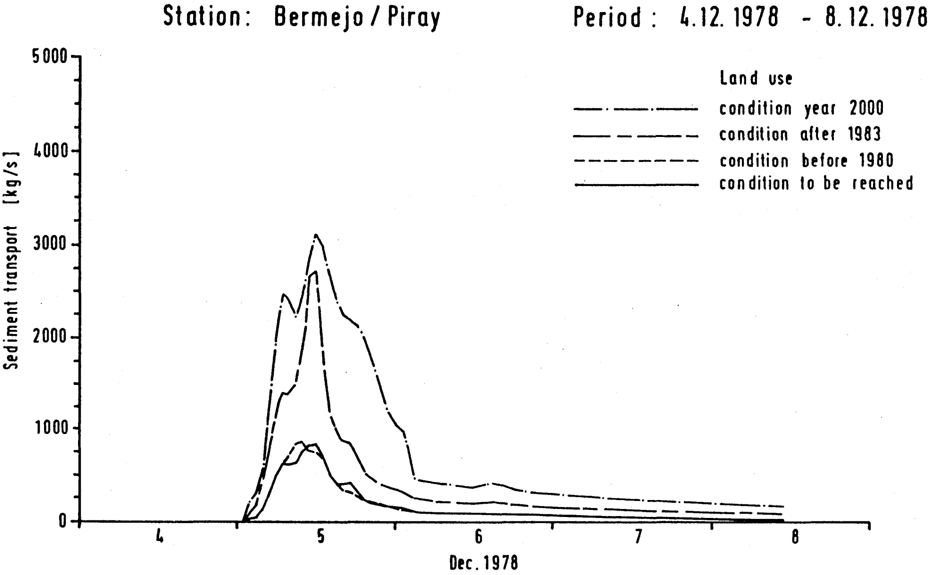


FIG. 8 Estimated sediment discharge for the four land use states at Bermejo for the flood event of 5 December 1978.

mean increase in peak flows and runoff depths in the Rio Piray catchment resulting from changes in land use, was between 5 and 30%, depending on the location. The mean sediment yield of flood events increased of 90 to 700%.

In order to compare the changes of discharge within the catchment of the Rio Piray with the relations established previously, the mean CN-values (Table 1) are required. The CN-values (with the exception of the Colorado) were smallest for the state of land use which should be achieved. For this reason the CN-values will be related to this land use state. As shown above, changes in discharge were influenced by the original state and the magnitude of the event. Figure 9 provides a comparison between the relationships, as derived earlier, and the changes shown by basins with CN ≈ 55 (Colorado, Bermejo, Piojeras and Angostura) for the planned land use. The graph represents the mean of all floods with specific discharges at peak flow (Hq) of 250-400 l s^{-1} km^{-2}. As can be seen from the figure, the changes in discharge within the Piray catchments coincide well with the aforementioned relationships.

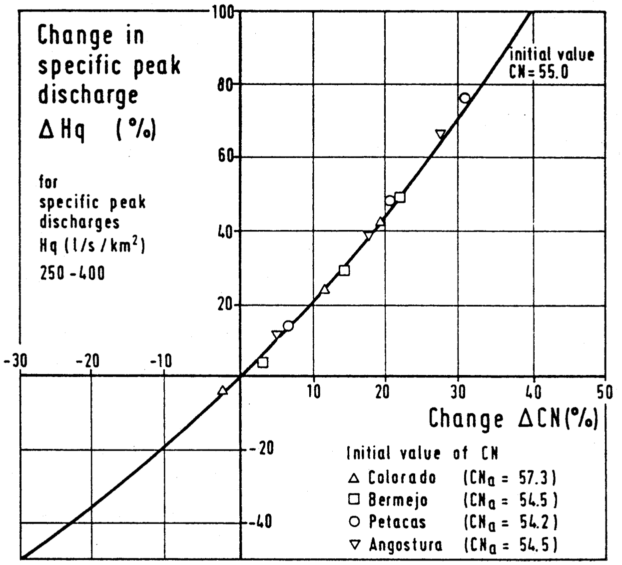


FIG. 9 Changes in specific peak discharge Hq in the watersheds of Rio Piray (symbols) compared to the established relationships (line).

The changes in sediment yield were related to the land use state before 1980, because the C-factors were smallest for this condition (cf. Table 1). For comparison floods were used that had a sediment yield (Q_S) of 50-100 t km^{-2} for the pre-1980 state. Most of the floods used were located within this range. The graph in Fig. 10 compares the curve deduced from the simulations for the fictitious catchment areas with the means for all floods within the aforementioned range. Figure 10 shows that several values deviated further from the curve than was the case for discharge (Fig. 9).

The largest deviations were associated with the gages at Espejos and La Belgica. This was expected, because sediment transport at these sites is limited predominantly by the transport capacity of the river. The transport capacity is not sufficient to transport all the delivered sediments. This causes sediment deposition and river silting, which is observed within this part of the Rio Piray. The sediment transport, as estimated from the sediment yield, therefore, differed from the actual value for these two gages. For all other catchments, however, good coincidence exists.

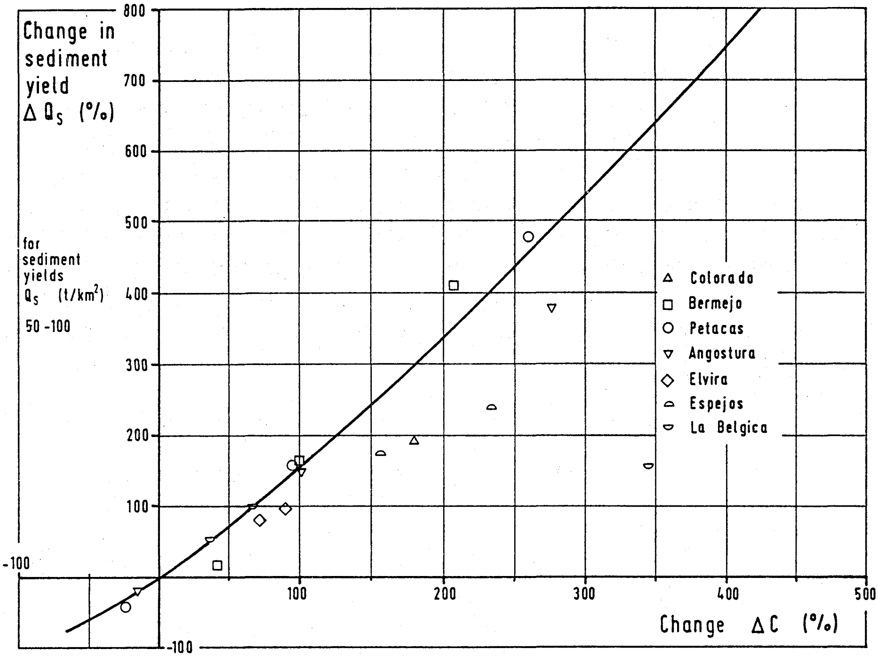


FIG. 10 Changes in sediment yield Qs in the watersheds of the Rio Piray (symbols) compared to the established relationships (line).

CONCLUSIONS

The investigations show that relatively small changes in land use can produce significant change in the peak flow and the runoff depth. Especially serious effects of the changes are observed for erosion and the resulting sediment discharge. The consequences are silting and river displacement and thus an increase in the risk of flooding.

The relations presented are valid if it can be assumed that the model used can simulate the natural processes of rainfall-runoff and erosion-sedimentation, and that the changes in land use can be expressed as CN-values and C-factors. Based on the results obtained for the catchment of the Rio Piray this would seem to be true.

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