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EVALUATION OF REMOTE SENSING TECHNIQUES TO THE DETECTION OF CHANGES IN A FLUVIAL SYSTEM DUE TO HUMAN INFLUENCE: THE EXAMPLE OF CANAS RIVER BASIN(SÃO PAULO STATE, BRAZIL)

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14. Abstract/Notes

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ABSTRACT

The main objective of this study is to exemplify the use of remote sensing data to evaluate human interference on fluvial systems. River Canas Basin was selected as test site since it belongs to Paraíba River basin where human action has disrupted natural equilibrium. Multitemporal aerial photographies were analysed so as to detect changes in fluvial morphology. The rate of environmental change was checked against remote sensing data available by using field work information. Results allowed the identification of temporal tendency of river channel changes as well as local factors which explains the variability of change rates.

KEY WORDS: remote sensing, fluvial system, human impact, environment.

I - INTRODUCTION

Fluvial systems can be considered in the global cycle of materials in Earth as responsible for the production and removal of sediments and solutes from land areas. During the process of removing and transporting materials produced in the drainage basin, rivers can suffer the influence of human action which can be both direct and indirect.

The construction of dams and channelization of rivers are examples of direct human action over fluvial systems. In the first case, man-made structures change the amount of water and sediment downstreams as well as the base level upstreams. In the second case, man-made structures change channel shape and channel parameters such as width, slope, bottom roughness, etc.

Indirect human action over fluvial systems can be exemplified by urbanization which changes the runnoff coefficient in a drainage basin.

The human action has made significant changes in the equilibrium of the fluvial systems as pointed out by Schumm (1956), Daniels(1960), Dolan et al. (1974), Ruhe et al. (1975), Hollis and Lucketti (1976), Knox (1977), Graff (1978), Williams and Wolman(1984).

Based on these contributions one can assume that human activities have a high potential of disrupting fluvial systems. Among the consequences of channelization, for instance, we can report: a) downcutting and widening the river channel (Daniels, 1960); b) flooding (Belt Jr., 1975); c) creation of agricultural land (Ruhe et al., 1975).

These examples indicate that the effects of human actions over fluvial systems are effective. Regardless this fact, we can observe many controversial points. First of all, these effects depend on the type of human interference as well as on the environmental variability. Secondly there is a time lapse between the human action and the response of the fluvial system to it. This time lapse can vary from one environment to another. Besides that, the detection of the disruption of equilibrium is highly dependent on the temporal and spatial scale used to evaluate changes of fluvial system (Thornes and Brunsden, 1977; Gregory, 1977).

A great problem in studying the human impact over fluvial systems is the lack of temporal data covering large areas and time.

Several authors (Gregory, 1977; Richards and Greenhalgh, 1984) have pointed out the limitations of interpreting channel adjustments based on samples obtained in few river cross-sections. The study of the effects of human actions on fluvial systems is limited by the techniques used for temporal observation. Historical data such as maps, reports, etc. are occasional and not precise(Thornes and Brunsden, 1977). Interpolation methods present also great limitations (Richards and Greenhalgh, 1984).

In this context, the main objective of this study is to exemplify the use of remote sensing data to evaluate human interference on fluvial systems.

Among the advantages of remote sensing we can mention the synoptic view of the terrain, which allows the evaluation of environmental variability of extensive areas. Using a remote sensing imagery we can detect the local conditions where human action took place and weigh man's role in the induced change of a fluvial system.

Since 1972 orbital remote sensing systems increased the frequency of data acquisition over large areas. According to Calabrese and Thome (1981) space acquired data offer the following advantages over conventional airborne-obtained data: a) repetitive monitoring of large areas to complement conventional data which is both temporally and spatially limited; b) synoptic data which, in conjunction with point observation, can expand information over larger areas.

The availability of new sensor systems operating in the infrared and microwave regions of the electromagnetic spectrum can also increase the amount of data on fluvial systems.

Several authors have showed the importance of both conventional and orbital remote sensing data to detect changes in fluvial systems. These contributions will be discussed in the next section.

II - REMOTE SENSING DATA APPLIED TO THE DETECTION OF FLUVIAL SYSTEM CHANGES

Remote sensing techniques are largely used by geomorphologists to map landforms. Verstappen (1977) has summarized both the main approaches and results of applying remote sensing data to geomorphology. In spite of that, some authors (Leopold et al., 1964; Thornes and Brunsden, 1977) have pointed out some constraints in applying them to fluvial change detection. Among the limiting aspects one can mention: a) variation in the frequency of data acquisition; b) variation of the environmental conditions during successive acquisitions; c) variation in the performance of the remote sensing system from one data take to another.

Among those authors who have been applying remote sensing data to fluvial system studies, Conway and Holz (1973) reported the use of color and infrared aerial photographies to establish a chronology of fluvial changes. They used vegetation patterns as indicators of moisture changes in the floodplain.

When using vegetation patterns to infer changes in fluvial systems one must be aware on the date of acquisition of sequential remote sensing data. Vegetation can be used as indicator of fluvial changes only by comparing data taken during the same season (Svenson, 1972).

The time of acquisition is another important aspect to be considered. According to Seher and Tueller (1973) the best time to discriminate different vegetation cover is between 9 and 11 o'clock, because at this time plants reach the maximum vigour.

Conway and Holz (1973) recommended the dry season of the year as the best period to acquire remote sensing data for fluvial changes detection. According to these authors, during the low water level, the variation of hydrological parameters is not very significant, allowing the detection of long-term changes in river shape.

Espejo et al. (1973) reported the application of MSS/LANDSAT data to map river bed changes in the river EBRO (Spain). They compared different river features in aerial photographies taken in 1946 and 1956 to those features mapped on MSS imagery obtained in 1972.

The satellite data are valuable mainly because of their repetitive coverage which gives the opportunity of measuring gradual transformation of fluvial morphology.

Although MSS/LANDSAT data have increased the amount of information to study human impact over fluvial systems, they present some limitations. Taking in account the World Meteorological Organization specifications, MSS/LANDSAT data could be used to study channel morphology in drainage basins with areal extent greater than 1000 km². Considering the improved spectral resolution of TM data (after launch of LANDSAT 4 and 5) from now on rivers basin with less than 100 km² can be evaluated.

In spite of the potential of remote sensing, there are some misuses of this technology in change detection studies. The great falacy in using remote sensing to change detection is to assume constant environmental and data acquisition conditions among successive data takes.

The rate of environmental change must also be considered when using remote sensing for change detection. The spatial resolution of the sensor system will interfere in the change evaluation since for small rates of environmental changes, a high resolution system will be necessary (Howarth et al., 1982). Because of that, one must specify the temporal and spatial resolution of the sensor system taking in account the environmental change rate of the fluvial system under study.

One must also be aware that it is not enough to detect changes but it is also necessary to measure these changes. This ability however varies with the image contrast and the contrast with the weather conditions during data acquisition as well as with target conditions. The effects of contrast, exposure, gamma and target size on errors of measurements were studied by Welch (1969). Although the observations of this author are related to photographic systems, they can be extended to other remote sensing systems.

According to Rosenberg (1971) the resolution is not a sufficient parameter to determine the useful information content of an imagery for earth resources observations because, for the same sensor system, the resolution will vary for objects of different shape, size, arrangement and contrast. This means that the resolution for any real object on a remote sensor product is likely to be different from the specified resolution (nominal resolution).

Based on the conclusions from Rosenberg (1971) and Welch (1969) one cannot use the theoretical resolving power of the sensor system to estimate the minimum mapping unit on the ground. According to Welch (1972) the measurability threshold ranges from 1.5 to 2.0 times the size of the minimum detectable target.

Parry and Turner (1971) suggested the use of the minimum contrast resolution to determine the minimum mapping unit.

From previous considerations one can deduce that the evaluation of fluvial changes from remote sensor data is not a simple task, advantages and disadvantages must be considered. To exemplify and discuss these problems the results of a case study at the Canas river basin (Sao Paulo State, Brazil) will be presented.

III - THE CANAS RIVER BASIN: THE RESPONSE TO MAN'S MANIPULATION

1. The study area.

Canas is a tributary of the Paraība do Sul river (Figure 1). Canas river basin covers an area of approximately 100 km^2. This river basin can be divided into three sections:

a) a flat area where its floodplain coalesces to the Paraība river floodplain, at an average altitude of 550 m;

b) a hilly section composed by sediments from the Taubatē sedimentary basin (Tertiary) at an average altitude of 600 m;

c) a montaneous section upstream carved on migmatites and granites and disposed as parallel chains at altitudes ranging from 700 m to 1000 m.

The Canas river basin is subjected to an average rainfall ranging from 1300 mm to 1500 mm distributed over two well defined seasons: the rainy season (October to March) and the dry season (April to September).

Since the beginning of the nineteen century the Canas river basin was subjected to intense human influence. By 1800 the Paraība valley was covered by a dense tropical forest which was destroyed and occupied by coffee plantations. By 1880 the natural soil fertility was already extremely reduced and former coffee planted areas became pasture lands. As a result of this indirect human action on a fluvial system, the original soils on the steep hillslope were eroded. Without the forest cover, annual flood damages steadily increased within the Rio Paraíba basin.

To prevent flooding as well as to increase agricultural areas at the floodplains by 1950 the São Paulo State government started engineering works, including the construction of dams on the upper section of the Paraíba and the straightening of its channel at the section between Cachoeira Paulista and Jacareí by cutting the meandering channel.

As a part of these engineering works, some tributaries of Paraíba river were subjected to channelization and flow regulations.

The channelization of Rio Canas started by 1958 and induced the following channel transformations: a) straightening; b) deepening; c) clearing; d) diking. Those channel changes were restricted to the lower reaches, where Rio Canas cuts the Rio Paraíba floodplain.

Figure 2 shows the longitudinal profile before and after the channelization works. As one can observe in Figure 2, the base level was lowered around 50 cm and channel length was reduced around 140 m.

Besides those manipulations of channel variables the Canas was also submitted to flow control. While by 1960 the average maximum discharge was around 140 cm^3/s, since 1973 the average maximum discharge is around 60 cm^3/s. The differences between the two periods were not meaningful for minimum discharges, whose average remained around 45 cm^3/s.

As one can deduce from previous observations, while channelization would potentially increase the bank erosion and deepen the channel upstream affecting even the tributaries, the flow control can have an opposite effect if the sediment contribution from side slopes and tributaries remains constant. In this case one will observe the stabilization of banks and sedimentation process.

In complex cases like that, conventional methods for monitoring channel changes can be useless. In these cases remote sensing data can be useful.

IV - METHOD OF ANALYSIS

To evaluate man action over the Canas fluvial system the following assumptions were made: a) sequential aerial photographies acquired over a large time span could highlight changes in a fluvial system; b) the channel variables such as width, depth, and pattern can be used as change measurements.

Channel changes were measured on aerial photographies (Table 1) taken on 7 different periods. Due to the differences within remote sensing products a series of procedures were implemented to minimize them.

First of all, to reduce the effect of detectability variation from one data set to another, a generalization level compatible to the set presenting the worst detection level was selected. Considering that detectability depends on the ground resolution presented by photographic set, the minimum mapping unit was initially determined based on the ground resolution available at that set (Parry and Tuner, 1971; Welch, 1969).

Table 2 presents the values of resolution and minimum measurable unit for each product assuming the limiting target contrast of 1:1.6.

Besides the ground resolution, photographic scale also interferes on the ability of taking the measurements. Although one can determine a minimum measurable unit of 1m, we must consider that at the scale of 1:25.000 this unit will actually measure less than 0,1mm, whereas at the of 1:5.000 its size on photographies will be 0,2 mm. So when comparing measurements taken at one scale with those taken at another scale, one will compare measures subjected to different precision levels.

By considering these variations of scales it was decided to define the minimum mapping unit based on the 1:25.000 scale. The minimum measurable unit was equal to 2.5 m on the ground which corresponds to 0,1 mm at the scale 1:25.000.

To reduce the effect of radial displacement on the measurements, samples were selected as much as possible in the central portion of the photography. Topographic charts were used to perform scale corretions for each photographic portion where the measurement should be taken (Curry, 1967).

The measurements of channel width and length were taken directely over the photos under a K.E. (8x) magnifier attached to a scale with precision of 0,1 mm.

Although these procedures could minimize the errors derived from measurements using different data sets, one can also consider the bias derived from the comparison between products with different contrast, sensitivity, taken for different purposes and under different environmental conditions.

To minimize those problems some change indicators were selected whose characterization was not dependent on tonality which is an image parameter highly affected by the variation of the data acquisition conditions.

As quantitative indicators the following variables were selected: channel width and length of the channel submitted to entrenchment. Both can be identified stereoscopically and are less dependent on the differences of ground conditions between different data sets.

Qualitative indicators were also selected such as: channel pattern changes and channel agradation. Table 3 presents some photographic features used to characterize both qualitative and quantitative indicators.

Photographic interpretation started with 1973 data which correspond to the halftime of the period under analysis. Samples indicating channel changes on 1973 photos were checked on the ground. After field check those samples were located on the remaining photographic sets.

Rates of fluvial system changes were estimated according to the following procedures: a) the channel width for river channels larger than 2,5 m was measured and compared with the data set referred at Table 1; b) the extension of the channel submitted to scour (incision on floodplain) was measured and compared; c) changes recorded by qualitative indicators were analysed and samples were classified in two classes:stable sites (where no change was observed); and unstable sites (where changes were observed); d) tables and graphics were organized to interpret the results.

V - RESULTS AND DISCUSSION

On 1973 photos 46 samples were identified as subjected to channel changes(Figure 3). This number did not remain constant for all dates due to technical requirements for precise measurements.Table 4 presents the average variation of channel change measurements from 1962 to 1978.The analysis of the data from Table 4 indicates two types of changes which are probably inconsistent: 1)the decrease of the segment subjected to channel entrenchment; 2) the decrease of the channel width. According to the theory, one should expect from 1962 to 1973 an increase of the channel length subjected to entrenchment into the flood plain as well as a channel widening (Daniels, 1960, Schumm,1956).

These inconsistencies can be explained by the methodology used to acquire the data on aerial photography. The channel entrenchment was identified on the image by searching river segments where the channel appeared to incise the flood plain. This criterion, although being useful, is subject to misinterpretation because it is affected by variations of the land use patterns in the flood plain. The channel samples located in the flood plain sections subjected to vegetation regrow from 1962 to 1973 did not present evidence of entrenchment on aerial photographies. This explains the decrease of the channel length undergoing channel scour. On the other hand by means of field checking these samples could be related to river segments where the process of channel incision into the rio Canas flood plain was not active any more in 1982. This probably is due to the fact that for the decennium 1962 to 1972 one could detect two types of channel response to river channelization namely: a) channel segments where incision was still active in 1972 expressed by the increase of the entrenchment length in this time span; b) channel which had undergone entrenchment by 1962, but had already been stabilized by 1973.

As far as the reduction of the channel width from 1962 to 1973 is concerned, field observations lead to the conclusion that it resulted from the inconsistency in determining the bankfull level. For samples located in sections with steep and well defined banks, bankfull level could be easily determined, whereas in sections without these conditions, it did not occur, specially because of the interference of the ground condition variations from date to date. The occurrence of shrubs alone can impose errors in the delimitation of the bankfull channel.

Another important aspect observed on Table 4 is the great variability of the data. The average increase of the river segment subjected to channel entrenchment is around 23 meters, but the variability is enormous, indicating that the fluvial system response to channelization varied within the drainage basin according to local factors such as lithology, channel hierarchy, land use, etc. These aspects will be further analysed.

During the evaluation of environmental variability within river Canas basin at least two factors which could explain the great variation in channel change rates from 1962 to 1973 have been identified: a) the structural set of the basin which is crossed by fault systems perpendicular to the basin axis; b) the geomorphological context where the sample was taken.

Table 5 presents the results of the channel change rates down and upper Fartura fault. These results showed that: a) the Fartura fault can be considered as a local base level which inhibits the effect of channelization upstream; b) entrenchment upper Fartura fault is not related to river Canas channelization. As a matter of fact it could be related to an episody of excessive rain during the summer (march) of 1967 with 581 mm of precipitation in one month. It was the highest registered monthly precipitation from 1961 to 1981.

This high precipitation could have reactivated former entrenched channels from the period just after the removal of tropical forest.

Table 5 also shows that variability of change rates was not reduced by using two subsets of samples. This is probably due to the variation of local conditions as stated by Andrews (1979) and Williams and Wolman (1984). Among those factors these authors reported the differences in bank material, vegetation, bedrock outcrop, stratigraphy etc.

To evaluate local factors, data were classified into two subsets: stable samples and unstable samples. The following criterions were used to classify these data: a) each sample which did not present change from time t_1 to time t_2 was classified as stable; b) each sample which presented any change from time t_1 to time t_2 was classified as unstable.

The following two sections in the Canas basin have been distinguished after an analysis of the spatial distribution of these samples: a) the first section is formed by the lower basin and is characterized by the small percentage of unstable samples and high rates of channel changes; b) the second section is formed by the upper basin and is characterized by the high percentage of unstable samples and low rates of channel changes and variability in channel change rates.

The small percentage of unstable samples in the lower basin can be explained by its geomorphological set. The lower basin is characterized by a low hilly terrain underlain mainly by Tertiary sediments. The maximum heights are just over 600 m and the average ground slope is around 5.6^0. The hills are covered by grass and shrub. This area is mainly used for cattle raising. The actual geomorphological processes acting on the slopes are mainly sheetwash and surficial soil creep. No "accelerated" erosion as understood by Sthraler (1956) can be observed on this basin section as a whole. This area is covered by soils with resistance to erosion. The high rates of channel changes can be considered as an effect of channelization. By lowering the local base level of the Canas river channel as well as its tributary channels, the human action breaks the balance between variables which can be considered as independent (sediment load and discharge) and dependent (channel slope, channel morphology). The channel widening and entrenchment start as a response to channelization and the rates of operation, although being affected by local factors, tend to be higher near the zone submitted to the engineering work.

The high percentage of unstable samples in the upper basin can also be explained by geomorphological aspects: the upper basin is characterized by steep slopes carved in migmatites and granites. The main erosion process occuring on the valley-side slopes are: rill erosion, slumping and basal stream undercutting. These processes of accelerated erosion and deposition in the upper river basin are still a response of this river system to the deforestation process which occurred in the beginning of the nineteenth century.After over a century the upper basin system tends to a nonsteady - state with small rates of channel changes.

This new "equilibrium" could be easily disrupted by infrequent high precipitations or local human activities. These disturbances however seem to be rapidly absorbed by the fluvial system within few years.

Based on these observations, the analysis at the other photographic data available from the region under study was restricted to the low Canas river basin.

Figure 4 presents the temporal variations of two samples in the lower Canas river basin. The analysis of Figure 4 indicates the following aspects: a) sample 3G tends to have the segment subjected to channel incision decreased from 1962 to 1973, but from 1957 to 1962 it presented an increase in the river segment, subjected to channel incision, with an average rate of 66m/year; b) both samples (3G and 4G) presented a high rate of channel incision from 1957 to 1962 and a low rate from 1962 to 1973. This tendency is in accordance to the models proposed by Knox (1977) and Scheidegger (1983) which state that the channel change increases with time at decreasing rates.

The change rate differences between samples 3G and 4G were related to variations in channel slope. Keeping constant other factors, those channels with a small declivity tend to return to a stable condition more rapidly when compared to channels with a high declivity.

After a temporal analysis of remote sensing data we could identify the following factors as responsible for local variations in the channel change rates: a) channel direction as related to weakness zones of the crust; b) local channel gradient; c) land use; d) fluvial hierarchy; e) landscape structure.

For the qualitative analysis from the time-lapse 1957 to 1981 it was assumed that the reduction of the channel incision process, the lateral deposit colonization, the bank vegetation growth, all these factors represent a change in channel state from erosion to aggradation.

This tendency can be observed on Figure 5 where the percentage of unstable samples was plotted against time. The analysis of Figure 5 allows to verify that the curve can be divided into the following tendencies: a) from 1957 to 1973 there is a slow decrease in the percentage of incision of channels; b) from 1973 to 1981 the curve presents a high gradient indicating that the percentage of samples with incision evidences decreased rapidly.

As we can also observe at this graphic during 1975 Canas river basin was submitted to a flow regulation. This could explain the decrease of the channel incision process.

If the channelization works during 1958 induced the occurrence of incised channels whose envidence was slowly deleted, flow regulation in 1975 induced a more drastic change in channel equilibrium, resulting in a strong aggradation process.

VI - CONCLUSIONS

In spite of the technical limitations of remote sensing data available to the study, we can conclude that the temporal analysis of those data was of extreme value to the study of the relationship between the human action and river system equilibrium.

The analysis of remote sensing data allowed us to identify the temporal tendency of river channel changes as well as to determine the local factors which explain the variability in change rates. After a multitemporal analysis of the remote sensing data used, it was possible: a) to determine channel incision rates; b) to identify channel incision and channel widening as the main river system reaction to channelization; c) to establish the sequence of channel changes in the last 24 years; d) to estimate the average rate of channel changes.

The results also showed that the Canas river fluvial system reacted more rapidly to the flow regulations than to the base level change. So the time lapses of fluvial systems to human action are largely dependent on the type of impact produced.

Further studies must be done so as to evaluate the potential of orbital data to determine change rates in fluvial system for larger areas.Those types of studies would be of great value to evaluate the environmental impact of the construction of dams in Brazil.

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TABLE 1

PHOTOGRAPHIC PRODUCTS AVAILABLE TO THE RESEARCH

YEAR OF ACQUISITION	MONTH OF ACQUISITION	SCALE ++	FILM TYPE	RESOLVING POWER * (lines/mm)	OBSERVATIONS
1957	Jun	1:25000	Panchromatic +	50	* for target object contrast of 1:1.6
1962	Jul	1:25000	Panchromatic +	50	+ when it was not possible to determine the film number, the worst quality film was considered to estimate the resolving power. ++ average scale
1973	Jul	1:25000	Panchromatic +	50	
1974	Jun	1:5000	Double-X Aerographic	50	
1976	Apr	1:15000	Aerocolor Negative	40	
		1:22500	Infrared Aerographic	40	
1977	Sep	1:11000	Plus-X Aerographic	50	
1981	Feb	1:7000	Aerocolor Negative	40	

TABLE 2

VARIATION OF MINIMUM MAPPING UNIT WITHIN THE AVAILABLE PHOTOGRAPHIC DATA SET

	RESOLVING POWER (lines/mm)	GROUND DETECTION RESOLUTION	MINIMUM MENSURABLE UNIT
1:25000	50	0.50m	1.00m
1:5000	50	0.10m	0.20m
1:15000	40	0.37m	0.74m
1:22500	40	0.56m	1.12m
1:11000	50	0.22m	0.44m
1:7000	40	0.18m	0.36m

TABLE 3

PHOTOGRAPHIC FEATURES RELATED TO THE CHANNEL CHANGE INDICATORS

TYPE OF CHANNEL CHANGE INDICATOR	PHOTOGRAPHIC FEATURES APPLIED TO THE IDENTIFICATION
River channel entrenchment on flood plain	River channel deeply incise in the alluvium; Abrupt and vertical river banks without vegetal cover; Incipient terrace formed by incision.
Change in channel pattern	Presence of central bars Meander cutoff Lateral formation of bars Bank collapse
Channel aggradation	Vegetation spread into the old channel Presence of the aquatic vegetation

TABLE 4

CHANNEL CHANGES AVERAGES FROM 1962 TO 1972

TYPE OF CHANGE	AVERAGE (METERS)	VARIATION COEFFICIENT(%)
Increase of the river segment subjected to entrenchment from 1962 to 1973	22.8	79
Decrease of the river segment subjected to channel entrenchment from 1962 to 1973	14.9	78
Bankfull channel widening from 1962 to 1973	9.0	124
Decrease of the bankfull channel width from 1962 to 1973	4.5	74

TABLE 5

THE EFFECT OF STRUCTURE ON THE CHANNEL CHANGE MEANS AND VARIABILITY

CANAS BASIN SECTION	LOWER FARTURA FAULT		UPPER FARTURA FAULT	
TYPE OF CHANGE	AVERAGE (METERS)	VARIATION COEFFICIENT(%)	AVERAGE (METERS)	VARIATION COEFFICIENT(%)
Increase of the river segment subjected to channel entrenchment from 1962 to 1973	40.60	50	18.9	66
Decrease of the river segment subjected to channel entrenchment from 1962 to 1973	-	-	10.9	95
Bankfull channel widening from 1962 to 1973	9.0	124	-	-
Decrease of the bankfull channel width from 1962 to 1973	3.3	82	-	-

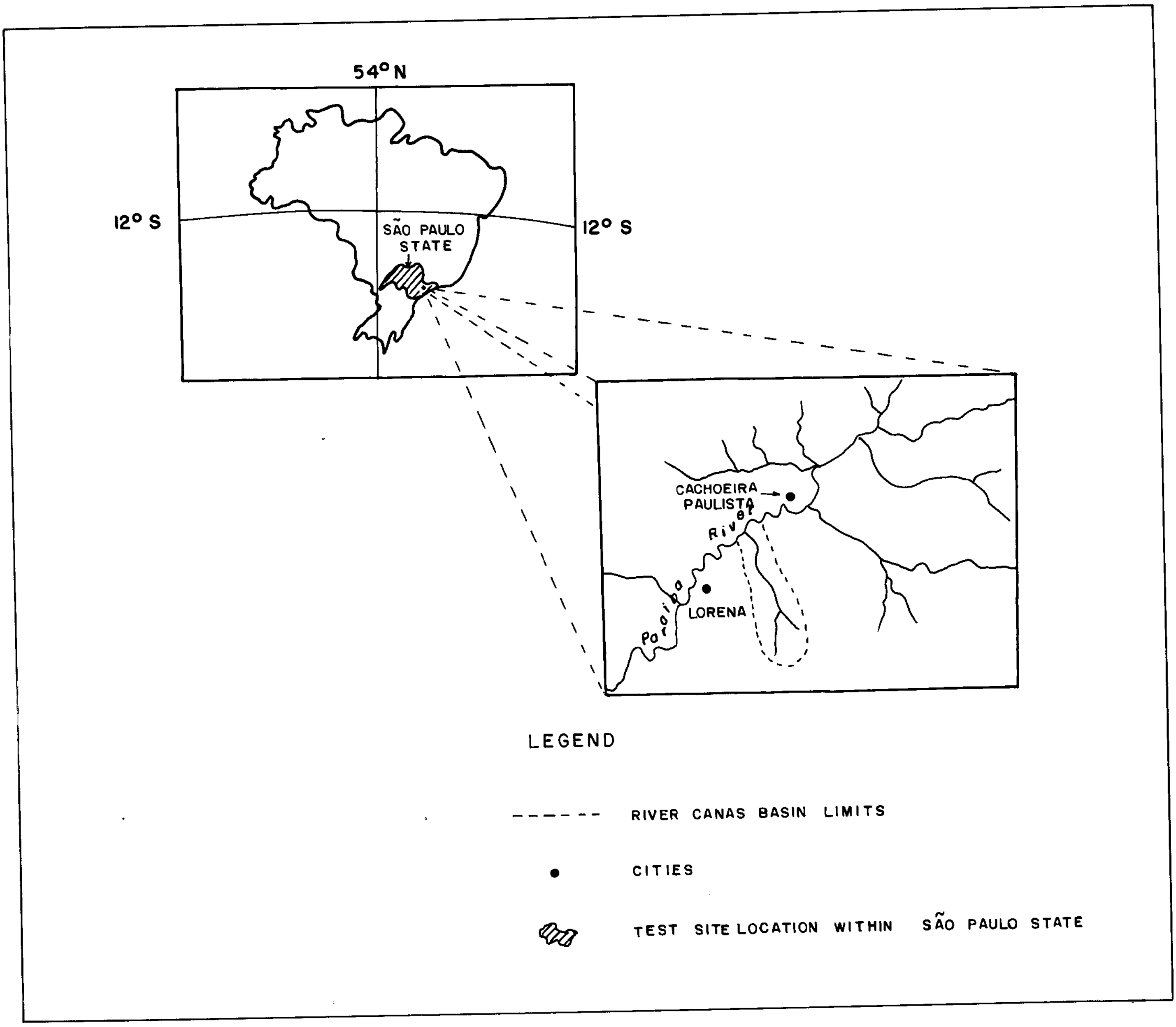

Fig. 1 - Location of study area.

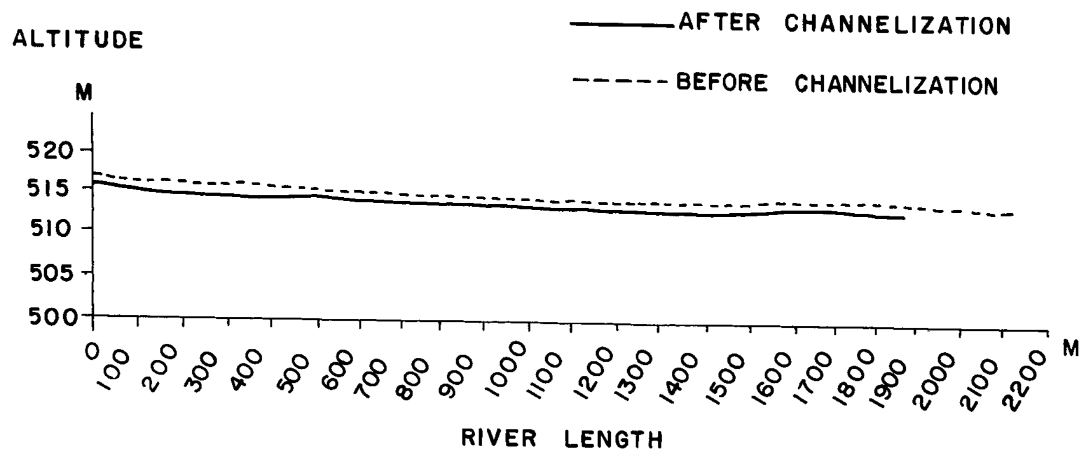

Fig. 2 - Longitudinal Profile of Canas River at the confluence to the Paraíba River.

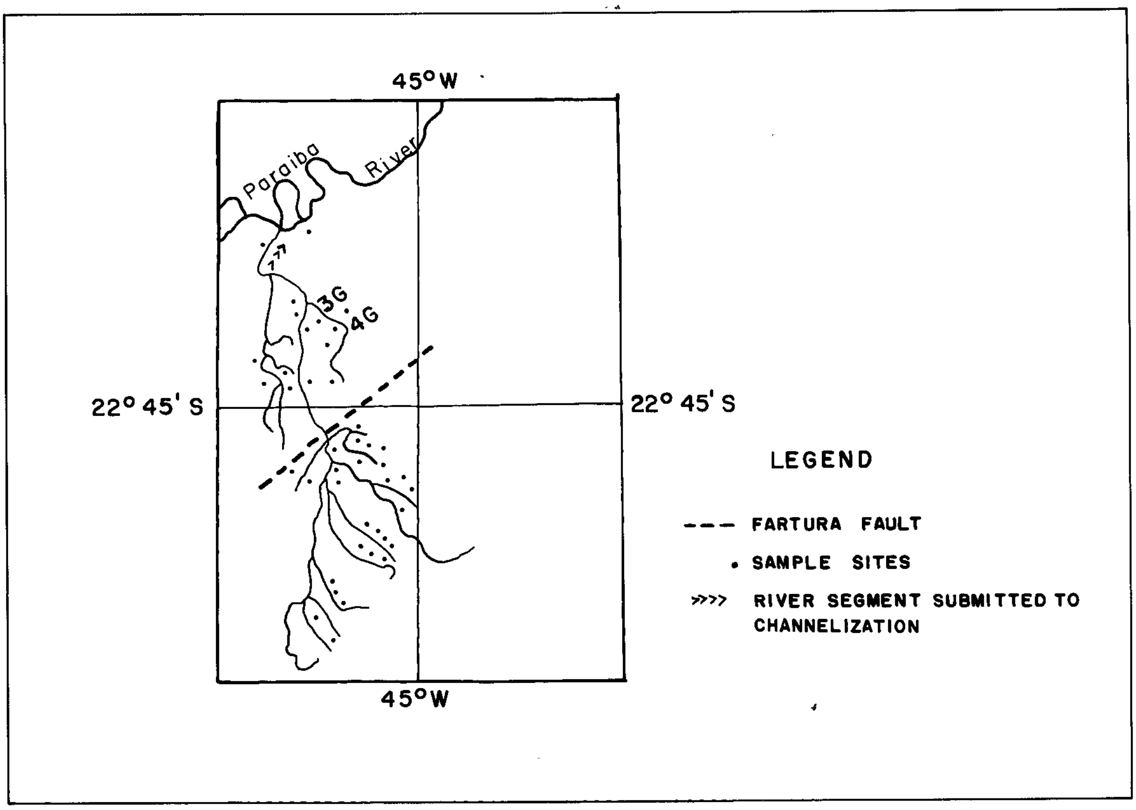

Fig. 3 - Samples subjected to channel changes.

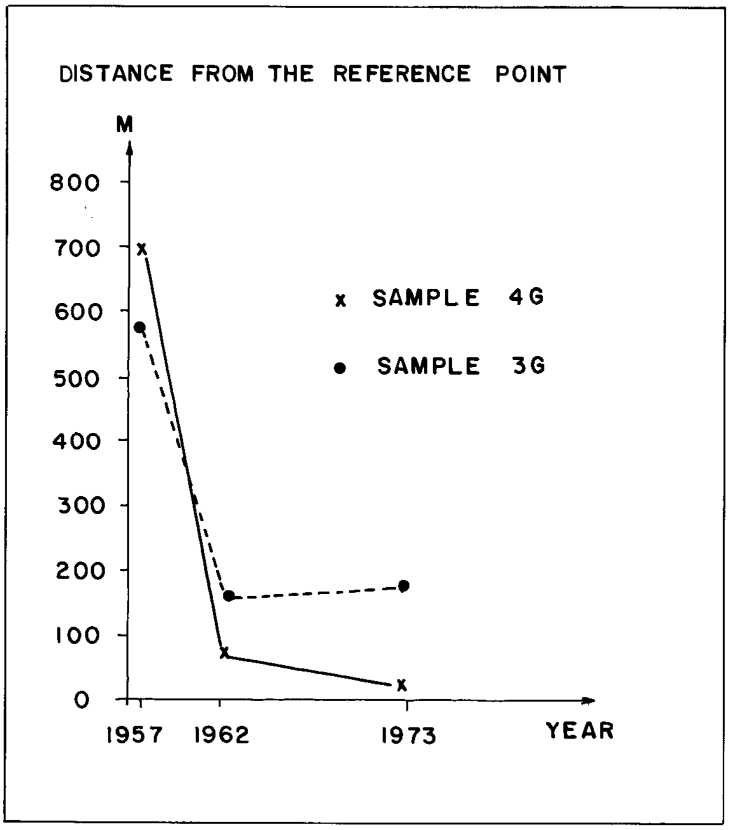

Fig. 4 - Local variability of channel changes rates.