EVALUATION OF THE REDUCTION OF THE VOLUME OF FLOW CARRIED BY CERTAIN RIVERS OF PUERTO RICO AND ITS POSSIBLE CORRELATION WITH CHANGES IN LAND USE, FROM 1508 TO PRESENT

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The author assumes full responsibility for the research methodology and conclusions.

ABSTRACT

Historical evidence and oral accounts seem to indicate that there has been a significant reduction in the flow of many rivers in Puerto Rico. Several possible causes for this phenomenom have been mentioned, including the well documented, slight, but significant decrease in the average rainfall since the 1930's, the diversion of flow for irrigation and human water consumption, and the changes in land use that have taken place in the island.

After an analysis of part of the existing historical evidence, which is found to be inconclusive, this paper undertakes a statistical study of available data for certain rivers in Puerto Rico. The hypotheses of the decrease in rainfall and in river volume of flow are tested, as well as the possible effect of land use changes in the basin upon the river's flow.

The statistical analyses suggest that, within the period and basins studied, a decreasing precipitation may have cancelled an increasing proportion of run-off resulting from land use changes to avoid significant variations in volumes of flow.

PART I:

QUALITATIVE ANALYSIS OF HISTORICAL IMFORMATION

PRE-HISTORIC PERIOD:

There is no archaeological evidence of significant changes in land use during the period when the island was inhabited by Indians.

1508 TO 1870:

The relevant data that exists from this period is:

* accounts left by several chroniclers who travelled through the island and described both the rivers and the land uses (1,7, 13, 14, 15)

* periodic economic reports of the agricultural production and the degree of urbanization in the different jurisdictions

* industrial archaeology remains evidencing land uses and navigation in certain river basins (22)

* descriptions of individual farms, including their equipment, main products and the acreage put into each crop found in title deeds and legal records

* descriptions, drawings and surveys of certain individual farms which adquired water rights from the Spanish Crown, found in the Puerto Rico Archives and the Spanish Archives

* descriptions and foundation dates of sugar haciendas and "central" mills (2, 8, 22)

OBJECTIVE:

Compare the chronicler-reported sizes of the rivers with their present state.

DATA USED:

Accounts of the chroniclers

Personal observation of the rivers

Synthesis of land use changes through the period

Personal knowledge of industrial archaeology and engineering history evidence of river navigation

PROCEDURE:

There is no quantitative information of water flow during this period (measurement methods had not been developed yet); therefore, the sizes of the rivers were taken qualitatively from the historical accounts of the chroniclers. Since this data was so imprecise, it was considered incongruent to go into details of land use, so this was also treated in the same broad, descriptive manner as had been the sizes of the rivers by the sources. Table I was prepared using the accounts of the period. It presents the general word patterns used by each chronicler to describe specific rivers which are mentioned by more than one of them but were not used for comparison with today

Table 1: Comparison of Chronicler Judgements

RIVER / CHRONICLER	RIO PLATA	RIO ARECIBO	RIO LOIZA	RIO GUAJATACA	RIO JACUAGUAS
Melgarejo	Large; carries much water	carries much water	carries much water	little importance	
Miyares	carries much water				
Abbad	carries much water; navigable up to town	carries much water	used for carrying logs	carries pretty much water	good depth; comfortable for ships
Ledrú		depth is limited to 3m. by sand bars	navigable		
Córdova		carries much water; navigable up to down	carries much water; navigable through the district		carries much water

because they now have large dams.

Each chronicler may have perceived the same river in a different manner, depending on his background, objective, outlook and season of observation. This cross-tabulation permits us to deal in a systematic way with the personal bias of each of them, as well as with the seasonal differences in their visits. (See Note 1.)

With this background, Table II presents for comparison the descriptions by the chroniclers of the selected rivers, along with a judgement by the author of how the appearance of the river compares to the concensus of the accounts. This has been done taking into account the perspective of the times: the chroniclers travelled in coastal vessels and they penetrated into the rivers through their mouths.

RIVER SELECTION CRITERIA:

The criteria used for selecting the rivers to be compared through time in this part were:

*Those mentioned in at least two accounts

*Location in different regions, all with milder dry seasons

*Basins which suffered significant land use changes during the period

*Absence of major dams today

LAND USE CHANGES ON THE BASINS

(For more detailed descriptions, see Appendix 1)

The land use patterns on the basins selected for comparison, all of which are humid, were similar up to the early 20th Century, except for the fact that there was no significant cultivation of tobacco on the Culebrinas basin, and that some changes took place earlier in certain basins than in others. The Bayamon basin was developed before any of the others, followed by Culebrinas and Manati, then Cibuco, Humacao and Guayanes. None of the basins belongs to a strong coffee region. (Coffee cultivation, after initial clearing of the land, offers permanent tree cover.). Tobacco (a crop requiring cleared land and much plowing), was found to some extent on all except for Culebrinas; the rest of the crops were similar across the basins, even if in varying proportions. (See Note 2.)

The development pattern up to the 19th Century was the following: gradual deforestation for hardwoods and firewood, small-scale agriculture and cattle pastures, usually starting from the river banks and progressing inland. In the 19th Century, first the lowlands were extensively converted into sugar plantations; then, in the second half of that period, coffee became prevalent in the steeper slopes, with some competition by tobacco, all following the above time-table for the different basins In the early 1900's, sugar cane virtually monopolized the lowlands (flat land and low hills) while tobacco was gradually displacing coffee on the mountains.

In recent times, since the decade of 1955-65, Bayamon has been invaded by urban sprawl, but the urban growth in the rest of the basins has been moderate, with Cibuco in the lead. From all the others, coffee and tobacco have virtually dissapeared from the steeper slopes, displaced by pastures, minor crops, and some spontaneous deforestation. Sugar cane is now cultivated only on the flatter lands of the Culebrinas and Guayanes basins, to a minor extent on Humacao, and very little on Manati and Cibuco, none remains on the Bayamon basin.

Culebrinas has seen the fewest land use changes in this century.

CONCLUSIONS:

The historical evidence given by the chroniclers in the form of descriptions of rivers included in Table II, compared to what can be observed today, seems to indicate, but not conclusively, that some rivers in Puerto Rico may have decreased in flow since the early 19th Century.

The weight of these judgements is limited by the fact that they mainly concern the river mouth, which is unstable in form and thus changeable in a few years. Its perception depends not only on subjectivity, but also on the tide and on the season in which the observation was made and the climate conditions which preceeded the visit.

Table II: Comparison of Descriptions of Selected Rivers

CHRONICLER \ RIVER	RIO BAYAMON	RIO CIBUCO	RIO MANATI	RIO GUAYANES	RIO HUMACAO	RIO CULEBRINAS
Melgarejo 1582	Navigable	large		large		
Miyares 1775	used for shipping produce		its swells flood its valley			
Abbad 1778					no depth for larger vessels	carries much water; lighters sail up to the Hermitage (1 mi.)
Ledrú 1797		not as large as Río Plata	rather navigable		entered by small craft	catalogued as small
Córdova 1820-1835		carries much water; navigable	carries much water; navigable up to the towns center	permanent; carries pretty much water		carries pretty much water
PRESENT	descriptions could apply (its mouth has been altered)	probably smaller today	descriptions could still apply	probably smaller today	seems challower today	descriptions could apply

PART II: QUANTITATIVE ANALYSIS

1870 TO 1910:

During this period, there was some measurement of both precipitation and flow, but the latter was limited to the Ponce region rivers, whose basins suffered significant aquifer extraction, which had many dams for irrigation use and which underwent few land use changes. Moreover, the measurements were generally unreliable because they were mostly executed by interested parties for water rights petitions and litigations. Therefore, this period was not used in the quantitative analysis.

1910 TO 1955:

The period between these dates has much more precipitation data, and the flow of those rivers that had dam projects is well documented. However, there was little change in land use; there was no measurement of evaporation rates, nor of city water extraction. This period was not studied either.

1955 TO THE 1970'S

Considerable land use changes occurred in this period of abundant climatological and flow data, during which there was a drastic increase in urbanization and a decline in sugar production. Therefore, this period was used for the statistical analysis.

OBJECTIVES.

1. Determine if during the part of the period for which there is complete data for each particular basin selected, there did occur a statistically significant reduction of the contributing precipitation and/or of the volume of flow.

2. Determine wether the recent changes in land use within the basins of the above rivers have had an effect upon their volume of flow and/or run-off proportion.

MODEL OF THE HYDROLOGICAL SYSTEM

The hydrological system modelled below by regression procedures has been simplified as shown in Figure 1. There are three "independent" variables: precipitation, evaporation rate, and land use changes.

Precipitation contributes to flow directly. Rainfall

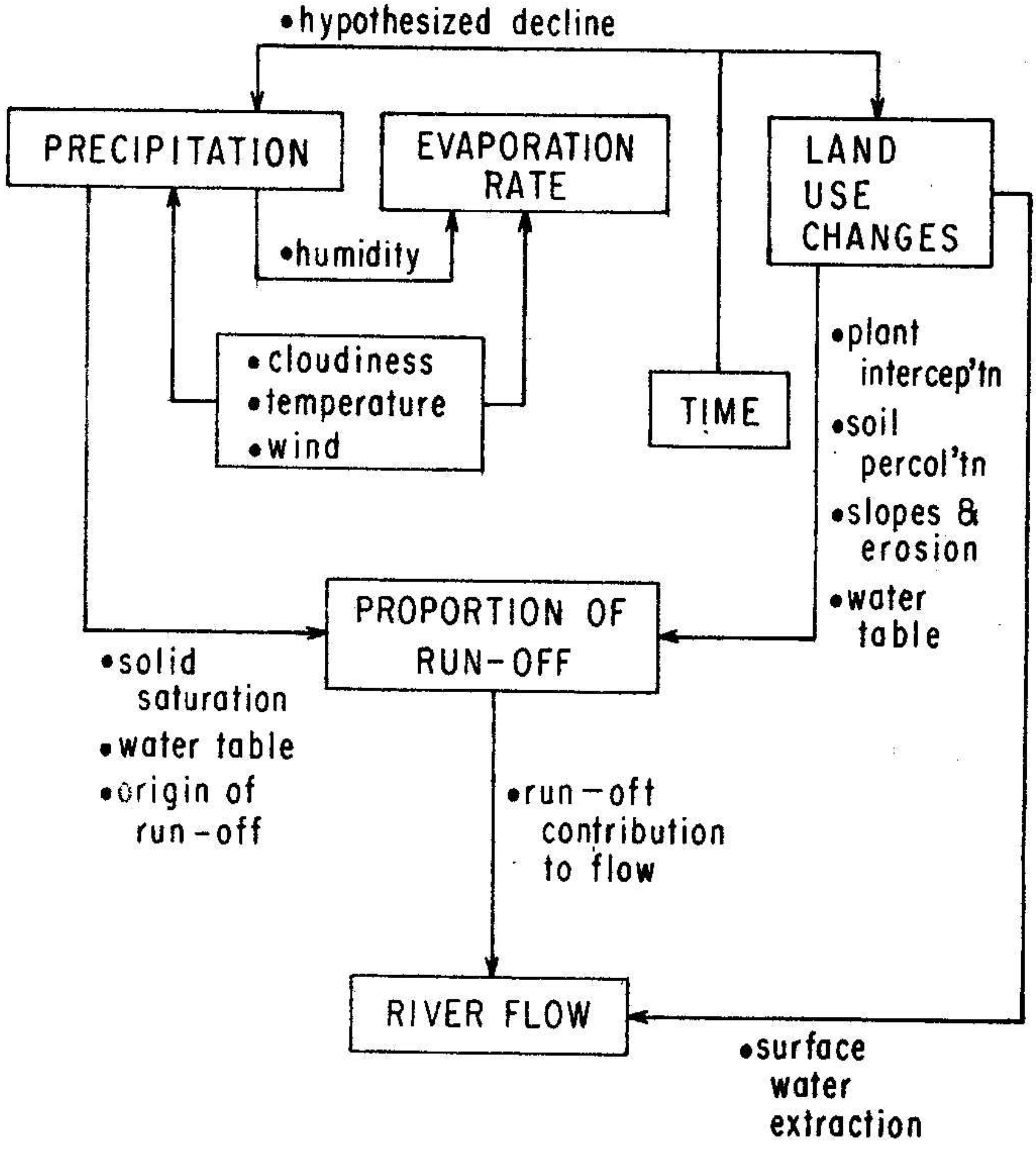

Figure I:

Simplified Hydrological Model

is correlated with evaporation rate because both are affected by cloudiness, temperatures and wind; in addition it affects evaporation directly by increasing humidity. It also affects the proportion of run-off (vs. proportions of plant interception, evaporation and soil percolation) by decreasing the latter because of soil saturation and by raising the water table, which may augment the output of springs.

Land use changes affect the proportion of run-off because it can bring about changes in plant interception, subsurface water level, soil type and percolation, and slopes. They affect flow directly through changes in the extraction rates of surface water for human consumption and irrigation.

In turn, proportion of run-off affects flow directly by modifying the amount of precipitation which actually turns into flow.

It is hypothesized that time has been causing a decline in rainfall in the Caribbean area since the 1930's (5, 6). Of course, time is, by concept definition, an important component of land use changes.

In this work, we shall try to determine any effect tha [illegible] have had on precipitation (direct) and upon flow (indirect, through its effects upon precipitation and land use changes). We shall also try to determine any effects of land use changes on proportion of run-off (direct) and on flow (direct and indirect). Regression analysis permits us to control for certain effects and thus separate the effects which we want to measure, a feature that shall be needed in such a study. (See Appendix II, OVERVIEW OF REGRESSION ANALYSIS.)

DATA USED:

Precipitation: Daily precipitation averages for consecutive months, measured for the US Weather Bureau at one or more stations distributed within the basin and in its immediate vicinity. (19)

Evaporation: Daily evaporation averages for the corresponding months, measured for the US Weather Bureau at a station located within its same climatological region. (19)

Volume of Flow: Average daily flow of the basin's main river for the same months as above, measured either by the US Geological Survey or the Puerto Rico Water Resources Authority (now Puerto Rico Electric Power Authority) at a station located above any large reservoirs which may be in the river. (21, 23, 28)

Land Use: Acreage occupied by one key land use at three or four dates which include the period for which there is monthly data for all of the above, compiled in the Agricultural Census and subdivided according to municipalities. (Source: Puerto Rico Dept. of Agriculture and Agricultural Census information supplied to the author by personal communication.)

EXPERIMENTAL PROCEDURE

1. Five river basins were selected on the bases of:

a) different climatological regions:

South (dry season). Jacaguas and Coamo Rivers

North (year-round humid): Guajataca, Culebrinas and Loiza Rivers

b) occurrence of specific, significant land use changes during the period for which there is data.

c) since there is no data on the volumes of water extracted from the basin aquifers, those basins that have large numbers of wells were avoided.

2. In each selected basin, the flow station was chosen on the bases of availability of data and the inexistence of any large reservoirs upstream.

3. The precipitation stations located within the flow-contributing part of the basin which have data for the full period studied, plus any other similar adjacent ones which may be more representative of certain sections of the basin than the ones above, were identified. One of the closer evaporation stations, with a climate regime similar to the one of the basin, was selected.

4. The contribution of the precipitation stations to the prediction of the volume of flow was determined and a

weighted average precipitation was produced in order to have a single precipitation variable in the regressions and avoid multicollinearity.

5. Regression analysis was used to determine wether or not the measured monthly flow, or the weighted average precipitation, decreased with time during the period studied.

6. The acreage of the chosen land use which corresponds to each month of the period studied was scaled by assuming a linear behavior between the dates for which [illegible] available.

[illegible] For every month included since July, [illegible] the [illegible] flow was [illegible] by adding any quantity reported [illegible] by the [illegible] Rico Aqueduct and Sewer Authority [illegible] consumption. (18) There is no such data for [illegible] dates.

[illegible] the available evaporation data was incomplete and [illegible] very few years, it was used to compute an average evaporation rate for each month, which was then applied throughout the period studied, turning its corresponding varible into a seasonal adjustment.

9. For the Jacaguas River, the monthly flow was corrected by substracting the quantity of water discharged into the river by the Villalba penstalk, which originates at another basin.

10. Regression analysis was used to determine wether or not the contribution of the changes in land use to the

weighted average precipitati[illegible] was produced in order to have a single precipitation varial[illegible]le in the regressions and avoid multicollinearity.

5. Regression analysis was used to determine wether or not the measured monthly flov[illegible] or the weighted average precipitation, decreased wit[illegible] time during the period studied.

6. The acreage of the c[illegible]osen land use which corresponds to each month of [illegible]he period studied was scaled by assuming a linear behavior between the dates for which data is available.

7. For every month incl[illegible]ded since July, 1966, the volume of flow was corrected [illegible]y adding any quantity reported as extracted by the Puerto Ri[illegible]o Aqueduct and Sewer Authority for urban consumption. (18) [illegible]here is no such data for earlier dates.

8. Since the available [illegible]vaporation data was incomplete and only spanned very few yea[illegible]s, it was used to compute an average evaporation rate for [illegible]ach month, which was then applied throughout the period studied, turning its corresponding variable into a seasonal adjustment.

9. For the Jacaguas Riv[illegible]r, the monthly flow was corrected by substracting the quantity of water discharged into the river by the Villalb[illegible] penstalk, which originates at another basin.

10. Regression analysis was used to determine wether or not the contribution of th[illegible] changes in land use to the

variance of the corrected flow in each basin, after taking out the effects of the variations in precipitation and in evaporation, was significant.

ii. Regression was also used to determine if the contribution of land use changes to the proportion of run-off in each basin, represented by a dimensionless flow/precipitation ratio, was significant once the effects of precipitation and evaporation were controlled.

POSSIBLE SOURCES OF ERROR:

1. Measurement errors in the climatological, run-off or land use data. (Regression is not drastically affected by single outliers.)

2. Inaccuracy in the conversion of the agricultural data, which is organized by municipality, into a basin classification. This was done by means of judgements provided by the agricultural experts who provided the data. (Since this data was being used as a proxy for the general rate of change of land use, its exactness is not comparatively so important because it is, by nature, already an approximation.)

3. Sampling error from assuming that the climatological stations are representative for a basin, and from attributing representativeness to stations bordering on, but not within, the basin. (This is minimized by calculating a weighted average precipitation for use as a determinant of flow.)

4. The lag that takes place between an occurrence of a change in precipitation or a change in land use and their effect on the river flow, and for a change in land use to be completed and/or recorded. (This will not impede the detection of a general pattern by means of regression if there is significant change distributed in a long record.)

5. The assumption of linearity in the change of land use between the years for which data is available, combined with the size of the time spans (5 to 20 years) between those dates and the assumption that the land use selected has a rate which represents the effective rate of land use changes in the basin. (A second pattern was tried as a proxy for land use change, a linear time variable.)

6. The possibility that at least some of the several simultaneous changes in land use that actually took place have opposite effects upon run-off, and thus, that their effects on river flow cancelled each other. (Five basins were used, with different and with similar land use changes among them.)

7. The purely cyclical, average and sample charachter of the evaporation figures used. (The variation of this variable across the years is probably not as wide as its cyclical variation.)

8. The effect of the extraction of subsurface water, on which there exists no quantitative data, upon the water table and its possible interaction with river flow. (The basins were selected having this in mind, as mentioned

above.)

9. The correction of flow quantities by adding or substracting upstream additions or extractions of water can not be expected to be an accurate prediction of the amount of the amount of flow that would have occurred otherwise. (The same correction system was applied to all monthly figures, in order to minimise any possible effect on the results.)

11. Several years have been used for which no such corrections as the above had been made at all. (These years were run on separate regressions, and their results were given less weight than the ones above.)

Of these sources of error, numbers 5, 6 and 7 seem to be the most serious. All three of them result from the insufficiency of data on historical land uses. (See Note 3.)

DETAILED REGRESSION PROCEDURES: (12, 16)

Variable List:

FLOW = daily average flow in millions of gallons per day for each month, corrected for the upstream extraction or addition of water.

PREA, PREB, PREC,.. = daily average precipitation in inches per day for each month in station A, B, C,..

USOT = expected value of the area in acres occupied by the selected land use during the month

EVAP = average daily evaporation in inches for the month at the evaporation station chosen

ISEQ = sequence number assigned to the month, starting from "1000"

PREWA = (PREA*W1 + PREB*W2 + ...) / (W1 +W2 + ...), where the "W's" are the weights assigned to each station's data

RATIO = FLOW / PREWA

PREWA and RATIO have been added in order to have minimum correlation among the independent variables of the regression equa[illegible] used to determine the significance of the land use change. RATIO is a statistical reflection of the [illegible]drology concept of proportion of run-off, which is supposed to be determined, among other things, by the land use and the prevailing evaporation rates. RATIO includes the simultaneous seasonal variation of FLOW and of PREWA, and also the effect of soil saturation during the rainy season, which is reflected by a higher RATIO.

Calculation of the Average Precipitation.

The following hierarchical regressions were run for each basin

FLOW with EVAP(1), precipitation at stations within the contributing basin (2), precipitation at stations outside of the contributing basin (3).

(Note: The numbers in brackets indicate the order of the hierarchical inclusion in the regression operation. See Note 4.)

The standardized regression coefficients obtained above were used as the weights "W1, W2,..." in the equation defining PREWA.

Effect of Time upon the Contributing Precipitation Patterns and upon the River Flow:

The following simple regressions were run for each basin:

PREWA with ISEQ

FLOW with ISEQ

If they showed significant coefficients, this would indicate that the right hand variable, a proxy for time, was a good predictor of the left hand variable. That is, that rainfall and/or river flow have been changing with time significantly during the period analyzed. The sign should be negative (if time were significant) if it is to agree with the general pattern of rainfall established by the Weather Bureau.

Effect of Land Use Change upon the River Flow:

Land Use Variables:

USOT refers to a single land use change that has been linearly interpolated between a scant two or three data points, but about which there are some reasons to believe that it is either diagnostic of the general rate of land use change, or that it constitutes the most important change in itself.

ISEQ was used as a proxy for any constant, linear rates of land use changes which may have occurred during the period in the contributing basin. The indirect effect of time upon FLOW and RATIO should have been taken care of by the variations in precipitation; however, ISEQ can also represent changes in extractions of water which are not being considered, construction activity, spontaneous reforestation, or any other run-off-affecting changes that have an approximately linear variation with time.

Regression Equations:

The following hierarchical regressions were run for each basin:

(1) FLOW with PREWA(1), EVAP(2), USOT(3)

(2) FLOW with PREWA(1), EVAP(2), ISEQ(3

and:

(3) RATIO with EVAP(1), USOT(2)

(4) RATIO with EVAP(1), ISEQ(2)

Regression (1) permits us to test wether the inclusion of USOT adds significance to the explained variation in flow, after the effects of PREWA and EVAP have been removed. Regression (2) does the same with ISEQ, the other land use change variable.

The other regressions do the same for the computed, dependent variable RATIO. These regressions do away with the significant correlation existing between PREWA and EVAP, "independent" variables in (1) and (2), a condition which reduces the reliability of this methodology by violating an important assumption.

PART III: BASIN ANALYSES AND REGRESSION RESULTS

(See Appendix II, OVERVIEW OF REGRESSION ANALYSIS, for the meaning of the terminology used in the presentation of results.)

RIO COAMO

BASIN ANALYSIS

Variables

FLOW: Volume of run-off entering Coamo Dam, 1955-1969; corrected from July 1966 onward by adding the amount extracted upstream for Coamo's city water

EVAP: average evaporation cycle at the Aguirre station, which belongs to the same climatological region, although it is not within the watershed.

USOT: acres of corn (3,171 in 1949; 747 in 1959; 440 in 1964; 149 in 1970)

Comments

Hydrology: this watershed comprises a dry region which comes down south of the island's main divide, drained by the Coamo River and its tributary, the Cuyon. There is relatively little extraction of subsurface water, compared to other dry regions, because the lowlands have not been planted with sugar cane.

Land Use Changes: The principal land uses in this basin, which roughly corresponds to the jurisdiction of the city of Coamo, have been pasture, coffee, corn, and minor crops. The changes that have occurred during the period studied have been: growth of the urbanized area; drastic reduction of the cultivation of coffee at the highlands, mostly at the expense of pastures and minor crops; virtual elimination of lowland commercial cornfields, with most of their acreage going to pastures, pigeon peas ("gandures") and urbanization.

Sample Size

89 months (cases) altogether; 42 with corrected flow

REGRESSION RESULTS

Station Contribution to Flow

A test with the stations of Coamo and Aibonito showed the first to be a good predictor of FLOW, while the latter seems to behave independently. This coincides with the fact that Aibonito, although close to the basin's headwaters, belongs to a different climatological region.

Therefore, for this basin:

PREWA = PRECOAMO

Effect of Time

*Regr Co-1: PREWA with ISEQ (180 cases)

B(ISEQ) = -0.052; F = 0.477 < 3.89

*Regr Co-2a: FLOW with ISEQ (138 cases)

B(ISEQ) = -0.024; F = 0.076 << 3.91

*Regr Co-2b. FLOW with ISEQ (42 cases)

B(ISEQ) = -0.072 F = 0.209 < 4.08

Although the negative sign in Co-1 supports the hypothesis that rainfall has been declining in recent times, the significance achieved is very inconclusive. In the case of FLOW, both raw, measured flow (Co-2a) and corrected flow (Co-2b) have F-statistics which discard any significant effect of time upon stream flow.

Land Use as Predictor of FLOW (42 corrected flow cases)

*Regr Co-3. FLOW with PREWA, EVAP, USOT

R sq = 24.5%; D-W = 2.03

for USOT: r sq = 2.3%

B = 0.155;

F = 1.17 < 4.08 at 0.05

*Regr Co-4: FLOW with PREWA, EVAP, ISEQ

R sq = 50%; D-W = 2.03

for ISEQ: r sq = 2.3

B = -0.155

F = 1.17 < 4.08 at 0.05

Due to the structure of the approximation used for the acres of corn in this basin, the effects of USOT and ISEQ as proxies for land use changes are identical, except for the signs, during the short period having corrected flow data. The longer period with raw flows (not shown) was even less conclusive. Although the signs are consistent with the expectations, no effect of land use change on flow can be inferred from this data

Land Use as Predictor of RATIO (42 corrected flow cases)

*Regr Co-5. RATIO with EVAP, USOT

R sq = 10.6%; D-W = 1.26

for USOT: r sq = 6.9%

B = -0.262

F = 3.00 < 4.08 at 5% sign

*Regr Co-6: RATIO with EVAP, ISEQ

R sq = 10.6%, D-W = 1.26

for ISEQ: r sq = 6.9%

B = 0.262

F = 3.00 < 4.08 at 5% sign

As above, both land use change proxies show the same regression effects. They explain almost 7% of the ratio's variance in the sample data, after controlling the effects of evaporation, but there is only about an 75% probability that they do represent a true tendency of run-off proportion to diminish with the land use changes which prevailed during the period studied.

RIO JACAGUAS

BASIN ANALYSIS.

Variables

FLOW: Volume of run-off entering Guayabal Dam, 1955-1969, corrected from July 1966 onward by adding the quantity extracted for city water, and the substracting the trans-basin quantity diverted to the Rio Jacaguas by the Canal de Aceitunas penstalk.

EVAP: average evaporation cycle at the Aguirre Station, which belongs to the same climatological region, but is outside of the basin.

USOT: acres of corn (538 in 1949; 181 in 1959; 69 in 1964, 59 in 1970)

Comments

Hydrology: This basin is drained by the rivers Jacaguas and Toa Vaca, both of which enter Guayabal Reservoir. It is a semi-dry region, but there is comparatively little extraction of water from below the surface.

Land Use Changes: The area drained corresponds roughly to the jurisdiction of the town of Villalba. There has been very little sugar cane in this region in recent times. The prevailing land uses at the beginning of the period studied were coffee and minor crops in the highlands; corn and pasture in the lowlands. Today, there is much less coffee, and more pasture; corn has given way to pigeon pea ("gandures") bushes, and pastureland has grown. There has also been some urban growth.

Sample Size

180 months, 42 with corrected flow

REGRESSION RESULTS:

Station Contribution to FLOW

The four stations used are all within the basin and not far from each other. Their precipitations are thus very highly correlated, and a regression of FLOW with their statistics yielded invalid results due to multicollinearity. Because of the above, and since they are all within the basin and contribute direcltly to FLOW, PREWA was defined as their arithmetic mean:

PREWA = (PREACEITUNAS + PRECAONILLAS + PREGUAYABAL + PREVILLALBA) / 4

Effect of Time

*Regr J-1: PREWA with ISEQ (180 cases)

B(ISEQ) = -0.095; F = 1.62 < 3.89

*Regr J-2: FLOW with ISEQ (42 cases)

B(ISEQ) = -0.059, F = 0.141 << 4.08

With the data used, it can not be established that rainfall is being affected by time, although the sign of the inconclusive relation is as expected.

In the case of FLOW, there is nothing to point at any variation other than randomness, again in spite of the apparently correct sign.

Land Use as Predictor of FLOW

*Regr J-3: FLOW with PREWA, EVAP, USOT

R sq = 74.3%; D-W = 1.95

for USOT: r sq = 0.012%

B = -.0116

F = .018 <<< 4.08

*Regr J-4: FLOW with PREWA, EVAP, ISEQ

R sq = 74.1%; D-W = 1.95

for ISEQ: r sq = 0.02%

B = 0.014

F = 0.30 <<< 4.08

Neither land use change variable has any value for the determination of FLOW in this basin for the period studied.

Land Use as Predictor of RATIO

*Regr J-5: RATIO with EVAP, USOT

R sq = 36.4%; D-W = 1.95

for USOT: r sq = 6.23%

B = -0.25

F = 3.82 < 4.08 at 5% sign

*Regr J-6: RATIO with EVAP, ISEQ

R sq = 30.3%; D-W = 1.73

for ISEQ: r sq = 0.2%

B = 0.044

F = 0.109 < 4.08 at 5% sign

In the case of RATIO, the land use proxy, ISEQ, has no apparent influence, but the acres-of-corn proxy, USOT, has a significant effect upon it. The results indicate a probability of about 90% that the proportion of run-off has increased with a variation which corresponds to the approximate decrease of corn acreage.

RIO GUAJATACA BASIN

BASIN ANALYSIS

Variables

FLOW: volume of run-off entering the Guajataca Dam, 1955 to 1969; there has been no significant extraction of water upstream during the period above.

EVAP: average evaporation cycle at the Corozal station, which is in a similar climatological region, but outside of the basin.

USOT: acres of sugar cane (4,400 in 1949; 5,000 in 1969; 2,511 in 1975)

Comments

Hydrology: This river drains the valley of Lares through a canyon running north through a karst region, where the boundaries of the rest of its watershed are unknown. This is a wet region, with no known significant extraction of sub-surface water.

Land Use Changes: This watershed includes part of the jurisdiction of Lares, and part of San Sebastian's.

Altogether, sugar cane was the prevailing land use during the period studied, peaking around 1969. There has also been a growth of the urbanized area.

Sample Size

180 months, with no correction required. All the regressions used all of the available cases.

REGRESSION RESULTS

Station Contribution to FLOW

The two stations used, Guajataca Dam and Lares, are within the basin, but some distance apart and in different geological and ecological regions. The regression used to determine the weights was valid, and the coefficients were used to weight the stations in:

PREWA = (PREGUAJATACA(0.43) + PRELARES(0.26)) / (0.43 + 0.26)

Effec of Time

*Regr G-1: PREWA with ISEQ

B(ISEQ) = -0.68, F = .819 < 3.86 at 0.05 sign

*Regr G-2: FLOW with ISEQ

B(ISEQ) = .033, F = 0.197 << 3.86

Time may have had a negative effect upon rainfall during the period studied, but the evidence is very questionable. There has been no apparent effect on FLOW.

Land Use as Predictor of FLOW

*Regr G-3: FLOW with PREWA, EVAP, USOT

R sq = 34%; D-W = 1.84

for USOT: r sq = 0.09%

B = 0.030

F = 0.232 < 3.86 at 0.05 sign

*Regr G-4: FLOW with PREWA, EVAP, ISEQ

R sq = 34.5%; D-W = 1.85

for ISEQ. r sq = o.49%

B = 0.070

F = 1.31 < 3.86 at 0.05 sign

While the approximate rate of change of sugar cane acreage in the basin shows no effect on FLOW, the time proxy for land use changes, ISEQ, does a better, although inconclusive, job.

Land Use as Predictor of RATIO.

*Regr G-5: RATIO with EVAP, USOT

R sq = 0.7%; D-W = 1.77

for USOT: r sq = 0.52%

B = 0.073

F = 0.933 < 3.86 at 0.05 sign

*Regr G-6: RATIO with EVAP, ISEQ

R sq = 1.33%; D-W = 1.77

for ISEQ: r sq = 1.16%

B = 0.108

F = 2.08 < 3.86 at 0.05 sign

As above, USOT is of no value, but, through ISEQ, the current land use changes can be considered, with a probability of around 75%, to have had a positive influence on RATIO.

RIO CULEBRINAS

BASIN ANALISYS

Variables

FLOW: the volume of water passing at a point between San Sebastian and Moca, near the Quebrada Morones, 1967-1974; corrected by adding the amount reported as extracted for the city of San Sebastian.

EVAP: average evaporation cycle at the Adjuntas Substation, which is beyond the basin, but in a similar climatological region

USOT: acres of sugar cane (8,262 in 1949; 12,490 in 1969; 7,500 in 1975)

Comments

Hydrology: This watershed comprises a wet region which includes parts of Lares and of San Sebastian. There are no major dams in this river and no known significant extraction of subsurface water.

Land Use Changes: The prevailing land use here has remained sugar cane, with some loss since 1969 to pasture and urbanization.

Sample Size

There are 89 months of data, all with corrected flows.

REGRESSION RESULTS

Station Contribution to FLOW

There was available one station on the basin (San Sebastian) and two just beyond (Lares near the headwaters, and Coloso near the mouth, beyond the flow station used). A regression produced valid coefficients, which were used as weights in

PREWA = (PRESSEBASTIAN(0.65) + PRECOLOSO(0.04) + PRELARES(0.09)) / (0.65 + 0.04 + 0.09)

Effect of Time

*Regr Cu-1: PREWA with ISEQ

B(ISEQ) = -0.139; F = 1.71 < 3.96 at 5% sign

*Regr Cu-2: FLOW with ISEQ

B(ISEQ) = 0.003; F = 0.001 << 3.96

Time seems to have a questionable effect upon rainfall, and no effect upon the volume of water carried. The sign of the rainfall indicates an expectation-consistent probable decline

Land Use as Predictor of FLOW

*Regr Cu-3: FLOW with PREWA, EVAP, USOT

R sq = 49.8%, D-W = 1.17

for USOT: r sq = 0.5%

B = -0.073

F = .867 < 3.96 at 0.05 sig

*Regr Cu-4: FLOW with PREWA, EVAP, ISEQ

R sq = 50.5%; D-W = 1.20

for ISEQ: r sq = 1.2%

B = 0.112

F = 2.044 < 3.96

In this case, based on 89 months of corrected flow, USOT, the acreage dedicated to sugar cane, has had a very questionable, negative effect, if at all. ISEQ has a stronger positive effect, but which is still inconclusive.

The inadequate Durbin-Watson statistic points out at the fact that the variance of the residual increases significantly with time; this violates one of the mathematical assumptions on which regression is based and affects the reliability of these Culebrinas results. An examination of a scattergram of the residuals points out at the possibility of a non-linear relationship in this case.

Land Use as Predictor of RATIO

*Regr Cu-5: RATIO with EVAP, USOT

R sq = 17.3%, D-W = 0.727

for USOT: r sq = 9.5%

B = -0.31

F = 9.86 > 3.96 at 0.05 sign

*Regr Cu-6 RATIO with EVAP, ISEQ

R sq = 17.0%, D-W = 0.716

for ISEQ r sq = 8.17%

B = 0.236

F = 8.36 > 3.96 at 0.05 sign

It may be concluded, although under doubts cast by the autocorrelation indicated by the Durbin-Watson statistic, that, as time has passed, the ratio of flow/precipitation has increased significantly. Since the effect of the changes in sugar cane acreage, which peaked during the period studied, is slightly stronger than that of the linear time proxy, the weight of land use change upon RATIO is reinforced.

RIO GRANDE DE LOIZA

BASIN ANALYSIS

Variables

FLOW: the amount of water passing near the mouth of the Caguitas River, just beyond the city of Caguas, 1966-1972, corrected by adding the amounts reported as extracted for the city of Caguas.

EVAP: the average evaporation cycle measured at the Gurabo Substation, just beyond the watershed and within the same climatological region.

USCT acres of sugar cane (11 728 in 1949, 1,605 in 1969, 640 in 1979)

Comments

Hydrology This wet area is drained by the Loiza and two of its tributaries, the Cayaguas and the Turabo Rivers. It comprises a large valley and its encircling mountains, north of the island's main divide.

Land Use Changes This watershed includes most of Caguas and of San Lorenzo. Its prevailing land use was traditionally suger cane in the lowlands, with tobacco and minor crops in the mountains. The main changes during the period studied was the dissappearance of tobacco, the substitution of the sugar cane by pastures, and of both by urban sprawl.

Sample Size

There are 62 non-consecutive months of data, all with corrected flows.

REGRESSION RESULTS

Station Contribution to FLOW

There was one station with sufficient data for the corrected flow period within the basin, San Lorenzo, and one outside, but relatively well placed, Cidra. Other stations which have existed in that basin have had very poor records for the period. Separate simple regressions showed the degree of correlation of the station regimes to corrected flow to be very similar, so the coefficients used for computing PREWA were

PREWA = (PRECIDRA+ PRESLORENZO) / 2

Effect of Time

*Regr L-1. PREWA with ISEQ

B(ISEQ) = 0.042, F = .105 << 4.00 at 5% sign.

*Regr L-2. FLOW with ISEQ

B(ISEQ) = 0.07, F = 0.297 << 4.00 at 5% sign

The above regressions show no evidence of either corrected flow or precipitation diminishing with time.

Land Use as Predictor of FLOW

*Regr L-3 FLOW with PREWA, EVAP, USOT

R sq = 75.9%, D-W = 2.17

for USOT r sq = 0.38%

B = -0.06

F = 0.903 << 4.00 at 5% sign

*Regr L-4 FLOW with PREWA, EVAP, ISEQ

R sq = 75.[illegible]%, D-W = 2.15

for ISEQ r sq = 0.16%

B = 0.04

F = 0.392 << 4.00 at 5% sign

The effect of both land use proxies upon river flow for Loiza is negligible and has no statistical significance.

Land Use as Predictor of RATIO

*Regr L-5. RATIO with EVAP, USOT

R sq = 11.1%, D-W = 2.35

for USOT, r sq = 8.4%

B = -0.29

F = 5.59 > 5.39 at 1% sign

*Regr L-6. RATIO with EVAP, ISEG

R sq = 9.52%; D-W = 2.32

for ISEG, r sq = 6.9%

B = 0.262

F = 4.48 > 4.00 at 5% sign

Both land use change variables indicate a significant and relatively strong relationship with the run-off proportion proxy, RATIO. The approximate rate of change of sugar cane acreage has a slightly more significant effect than the time proxy.

SUMMARY OF REGRESSION RESULTS

Tests of the hypothesis that rainfall and river flow have been decreasing with time.

Precipitation

All the basins give results which show a tendency towards a decline of rainfall with time, but the statistical significance is not conclusive.

Flow

observation is by itself inconclusive, even if it were corroborated by fact, because flooding can be the result of causes other than increased flow.)

Tests with RATIO

In all five basins, at least one of the variables which represent the rate of land use change has a probability of over 70% of having a significant (non-zero) effect upon the proportion of run-off, represented by the flow/precipitation ratio. In two of the basins, the significance probability is over 95%.

In the two well-defined, uniform-climate basins, Culebrinas and Loiza, USOT (sugar cane acreage) had a negative effect upon RATIO, slightly higher than the opposite sign effect of ISEQ, with both proxies being over 95% significant. Culebrinas, however, shows a sizeable autocorrelation problem with possibility of non-linear relationships among the regression variables.

In the Guajataca River basin, which includes a dryer, karst area of undefined boundaries, sugar cane acreage change had no significant effect; the linear proxy, ISEQ, had only 70%, and its effect was, as above, positive.

At the dryer basins, the significances of the land use variables were 90% at Jacaguas for the negative effect of corn acreage change with ISEu not significant, and about 75% at Coamo for a single, linear variable having a positive effect upon RATIO.

CONCLUSIONS

Since it is supported by further tests based upon more complete data, and it is weakly confirmed here, we can accept the hypothesis which proposes that rainfall has been decreasingg with time during recent decades.

However, there is no evidence in the basins included during the period studied which can point at any general reduction of flow with time, especially if we take into account the extraction of water for human consumption.

There is evidence, on the other hand, of a definite increase of the flow/precipitation ratio with time and/or the rate of land use change. It may be hypothesized that this phenomenom has cancelled, at least in these basins, the effect of the reduced rainfall, thus managing to avoid significant changes in the average volume of flow. However, this possibility is not supported by the inconclusive results of the tests on the effect of land use changes upon flow, with the variance due to precipitation and evaporation controlled.

Another related hypothesis which this study supports is that the change in land use away from sugar cane, coffee and corn, towards pasture and urbanization tend to increase the proportion of run-off. It seems that the effects may differ according to the basin's climate, as well as with all the other variables not included here, such as slopes and soil type

Still another hypothesis, which draws upon the subjective and inconclusive first part of the study, is that the volumes of flow of at least some of the rivers were reduced by the land use changes which took place during the 19th Century and the early 20th, but have held at least since the period studied.

NOTES

Note 1

The latter is something which is not well specified by most of the chroniclers, and, especially in the southern part of the island, volume of flow varies markedly with the season. A deeper study can try to determine the season in which a chronicler saw and described a river by using other information in the accounts, such as the folk celebrations and the agricultural cycles. Some of the chroniclers, however, appear to have obtained local information to supplement their observations, which makes their accounts stronger.

Note 2

The agricultural history data is from (9), with individualities inferred from the foundation dates of the towns located in each of the basins.

Note 3:

Once the Scientific Inventory Section of the Department of Natural Resources extends its detailed land use data bank to include more years (it only has one completed at present), a more reliable regression analysis may be run.

Note 4

The hierarchical inclusion procedure performs a series of regressions into which the independent variables are included in the order specified by the numbers in the brackets. First, a simple regression is carried out with just the (1) variable; second, a multiple regression is performed into which the (2) variable is added, and so on. It is prefered whenever the structure of the system is, as in this case, either known or hypothesized

APPENDIX I

DESCRIPTIONS OF THE SELECTED RIVERS AND THEIR BASIN LAND USE CHANGES

(See Note 2)

Rio Cibuco

This river comes down from the Montanas de Corozal and crosses a karst area before discharging through the coastal plain into the Atlantic Ocean.

This humid climate region is supposed to have been almost completely forested in pre-historic times. During the latter 18th Century, deforestation for cattle ranges, small scale agricultural plots and use of wood became common. In the 19th century, the practice became extensive in order to make way for sugar cane in the lowlands and for coffee and tobacco in the slopes. Except for isolated areas of karst brush, deforestation became almost complete during the first part of this century, with sugar cane and firewood as the main motives. In the more recent years, cane has given way to considerable urban growth and to pastures; coffee and tobacco have yielded acreage to minor crops, pastures and spontaneous reforestation.

Rio Bayamon

This river runs straight north from the Cordillera Central, draining a penneplain and crossing a hilly area with some limestone, before discharging onto the edge of San Juan Bay.

This humid climate region is supposed to have been almost completely forested in pre-historic times. During the 17th and 18th Centuries, deforestation for cattle ranges, small scale agricultural plots and use of wood became common. Since the 16th Century there had been sugar haciendas at the banks, but they were small units. In the 19th Century, deforestation became extensive in order to make way for sugar cane in the lowlands and coffee and tobacco in the headwater slopes. The haciendas near the mouth used the river for transportation. Except for a few isolated areas of limestone, deforestation became almost complete during the first part of this century, with sugar cane and firewood as the main motives. In the more recent years, sugar cane has completely given way to suburban surbwi and pastures; coffee and tobacco to small crops, to pastures and to spontaneous reforestation.

There is a minor reservoir, the Lago de Cidra, at the Rio Bayamon headwaters.

Rio Culebrinas

This river drains a valley that runs east-west between the Cordillera Central and large karst formations, it drains into the Canal de la Mona.

Its basin was almost completely forested since pre-historic times. Significant deforestation was taking place near its mouth in the 17th Century, and it creeped up-river the 18th. In the 1800's, the basin came to be farmed more extensively for sugar cane and coffee. In the 20th Century, sugar cane became its major land use by far, with pasture and minor crops partly displacing coffee on the hills. More recently, urban growth and some spontaneous reforestation have occurred.

Rio Humacao

This river drains the humid southeastern slopes of the Cordillera Central and its coastal plain into the Caribbean Sea. It has a relatively small basin.

Its formerly prevailing forests began to be depleted around the end of the 18th Century for firewood, hardwoods, grazing and agriculture. In the first part of this century, most of them were gone, substituted in the slopes by pastures and minor crops, plus some coffee and tobacco; sugar cane occupied practically all of the plains and lower hills. Recently, sugar cane has been giving way to pastures in the hills, while coffee and tobacco are gone from the slopes, substituted by pastures and bananas. Lowland urban growth has been significant.

Rio Guayanes

This river drains a small, humid basin, just southwest of the Rio Humacao's, into the Caribbean Sea.

After deforestation inroads since the late 1700's, its forests were displaced by sugar cane in the lowlands around the middle of the 19th Century, while in the highlands they held for two or three more decades. Tobacco, coffee, pastures and minor crops were the prevailing land use on the slopes while sugar cane completely dominated the lowlands during the early 1900's. Recently, sugar cane has been limited to part of the plains, displaced from the low hills by pastures and from part of the flat land by industry and urban growth. On the mountains, pastures and minor crops now prevail.

Rio Manati

This river drains a large, humid basin. Its headwaters neighbor those of Rio Cibuco on the Cordillera Central. It traverses a hilly countryside and a karst area before discharging on the Atlantic Ocean through a flat valley.

Its basin remained heavily forested until there took place small-scale inroads of the same nature as in other basins during the first part of the 18th Century. Its flood plain was converted into sugar plantations and its mountains slowly cleared for agriculture and firewood during the early 1800s. At the turn of the century, most forests were gone except for a few forest pockets, with pastures, tobacco, coffee and minor crops growing on the steeper slopes and sugar cane in the lowlands. In recent times, most of the sugar cane has given way to pasture, rice and significant urban growth; coffee and tobacco to pasture and to some extent to reforestation.

APPENDIX II

OVERVIEW OF REGRESSION ANALYSIS

THE LINEAR REGRESSION MODEL

Multiple linear regression is a numerical technique for modelling relationships among variables. One of these is designated as dependent, and a least-squares approximation is calculated, based on assuming the rest of the variables as being orthogonal and equally distributed. (Note: For a thorough discussion of regression theory and techniques see

The resulting model has the following form

$$Y' = A + B1*X1 + B2*X2 + \ldots + Bn*Xn$$

The coefficient "B1" of the independent variable "X1" is defined as the expected change in "Y" with a unit change in "X1", with all the other "X's" held constant. In this application, the coefficients used have been standardized for making them dimensionless.

STATISTICS

The statistics used here for interpreting the regression results are:

Multiple Correlation Squared (R sq.)

(variation in "Y" explained by the combined linear influence of the independent variables / total variation in "Y")

This indicates the percentage of the total variation of the dependent variable which is explained by the set of independent variables in the regression equation

Squared Part Correlation (r sq)

This corresponds to the change in "R sq" when a variable is added to the regression, indicating its power to explain the previously unexplained variation

Significance (sign)

This concept pertains to extending to the real world the findings based on a sample. For example, if we have that the regression coefficient of a specific variable is

B = 0.105, (sign) 0.05,

this means that the probability that the real world coefficient "B" is actually equal to zero, that the one calculated by the regression from the sample equals 0.105, is less than .05, or than .10

The statistic "F" indicates the significance of specific "B's" in a multiple regression equation

F = ("R sq" for the variable whose B is being evaluated) / ((1 - "R sq") / degrees of freedom),

Thus,

$F = 1.72 < 2.85$ at .05

means that the statistic F for the specific B is less than the F which belongs to a significance level of .05, which is equal to 2.85 for the corresponding degrees of freedom.

RESIDUAL ANALYSIS

In order to verify if the basic regression assumptions of linearity, equal distribution of residuals and independence of residual variance are met, we have used:

* direct examination of residuals by means of scattergrams

* the Durbin-Watson statistic, which indicates autocorrelation: the value assumed by the dependent variable in one sequenced case is a significant predictor of the next case's value:

If D-W = 2, then autocorrelation = 0

If:

$1.6 < D\text{-}W < 2.4$,

the degree of autocorrelation is being taken here as acceptable.

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