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GEOGRAPHIA POLONICA 45, 1983

THE CLASSIFICATION OF MORPHOLOGICAL FEATURES — A LOGISTIC REGRESSION APPROACH

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INTRODUCTION

Many features observed by the Geomorphologist raise an interesting question. namely: do all the observations belong to one or more morphological populations? Detailed field measurements of form may help solve this type problem, but in doubtful cases one may have to resort to some statistical device which allows a certain probability to be attached to an individual that will help decide to which of two possible populations it belongs.

In this paper we shall describe an example of a problem raised during the mapping of terracette forms near Salford where there was good documentary evidence that the forms belonged to two populations, natural and man made. Visually, the two populations of terracettes appeared similar and it seemed reasonable to suppose that only careful measurement of the actual morphology might distinguish them.

In dubious cases assignment to one population or the other can be made via logistic regression, which because of its properties is advantageous to other methods which might be used to discriminate between the two genetic types of terracette. Hitherto this type of statistic has been little used in Geography, but as we shall indicate it has considerable advantages over other commonly used methods such as ordinary least squares regression and discriminant analysis.

DATA COLLECTION AND SITE INFORMATION

The terracettes studied in this paper are developed on a complex slope above the right bank of the R. Irwell, Manchester (O. S. Grid Ref. SD 783032). The lowest part of the slope complex is a fluvio-glacial terrace which is mostly buried by coal slag which was heaped on the fluvio-glacial material until 1971 when reclamation work was begun by Lancashire County Council. The upper slopes, developed on the coal slag have been terraced by the County Council into three major units; an upper slope has a modal slope angle of 34–35° (as measured with a Pitty Pantometer),

a middle slope an angle of 36–37° and the lowest slope developed on the coal slag, 28–29°. Beneath the lowest slope of the terraced slag heap the fluvio-glacial material develops a slope having a modal angle of 36–37° (Fig. 1).

In May 1971 the County Council decided to sow grass (*Deschampsia flexuosa*)

Fig. 1. Reclamation site, Clifton, Manchester, SD 783032, showing terraced slag heap

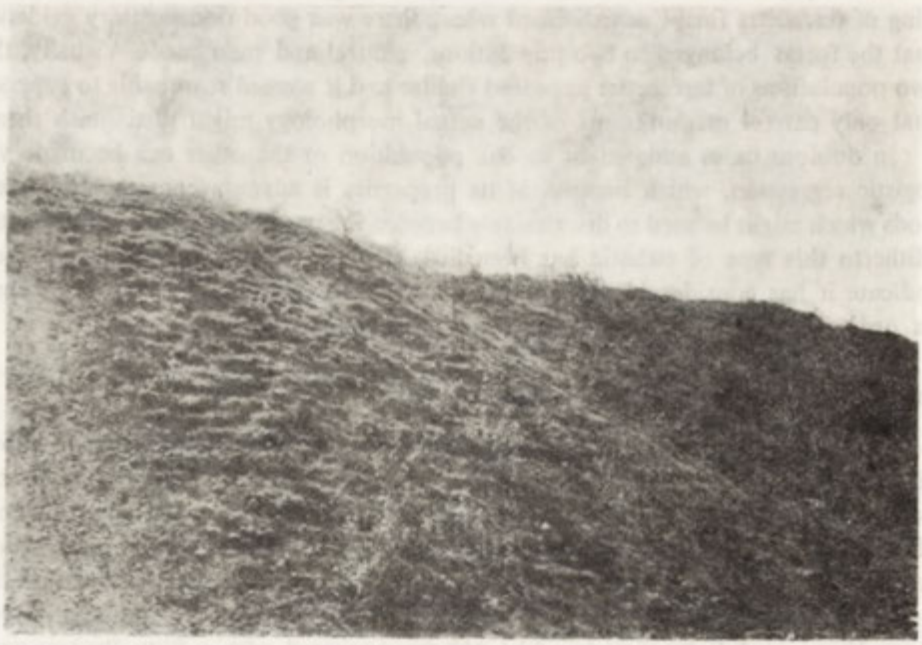

Fig. 2. Man-made terracettes on northeast facing slope at Clifton, Manchester, SD 783032

in rows, across the face of those slopes developed on the slag. The objective of this scheme was to help stabilize the slope; it would also improve the aesthetic appearance of the site which has considerable recreational potential. At the present time the rows of *Deschampsia flexuosa* closely resembles naturally occurring terracettes; indeed, prior to obtaining site information from Lancashire County Council there was some debate amongst the authors as to the origin of these features (Figs. 2 & 3). Natural

Fig. 3. Well-established man-made terracettes at Clifton, Manchester, SD 783032

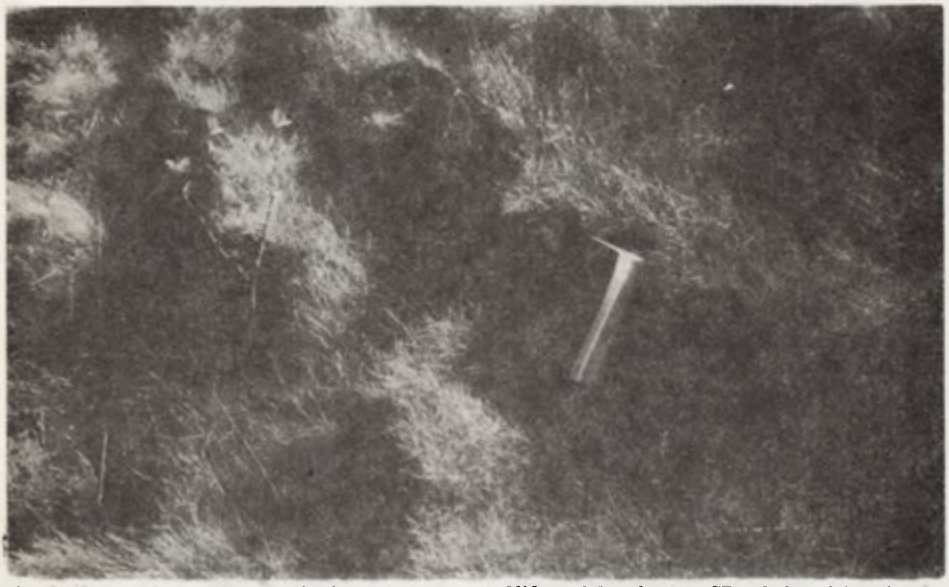

Fig. 4. Natural terracettes on the lowest terrace at Clifton, Manchester, SD 783032. Note book is 20 cm long

terracettes, probably formed by slumping, occur on the lower slopes developed on the fluvio-glacial material. They are covered with naturally sown *Deschampsia flexuosa* and were not disturbed by the reclamation programme (Fig. 4).

During the course of their research on the genesis of terracettes the authors usually measured the following morphological properties of a terracette to facilitate description; riser angle, riser length, tread length and tread angle. These four measurements for 31 natural and 31 man-made 'terracettes' are presented in Tables 1 and 2. The 62 sets of observations formed the data for the analysis we describe in this paper.

TABLE 1. Terracette morphology. Natural Terracettes ($Y = 1$) Site: Robin Hood Siding, Clifton, Manchester. Grid Ref. SD 783032 No. of Observations = 31 Bearing 320°

Riser angle degrees	Riser length metres	Tread angle degrees	Tread length metres
50.00	00.11	11.00	00.46
58.00	00.12	07.00	00.29
84.00	00.07	08.00	00.25
72.00	00.10	08.00	00.36
76.00	00.16	14.00	00.40
57.00	00.20	06.00	00.28
74.00	00.14	09.00	00.20
77.00	00.22	12.00	00.33
71.00	00.19	10.00	00.45
62.00	00.15	12.00	00.43
56.00	00.18	10.00	00.28
74.00	00.22	03.00	00.21
86.00	00.15	16.00	00.22
83.00	00.22	07.00	00.27
88.00	00.15	10.00	00.35
89.00	00.22	15.00	00.33
72.00	00.23	13.00	00.30
83.00	00.16	14.00	00.37
83.00	00.13	13.00	00.29
80.00	00.17	19.00	00.50
88.00	00.19	08.00	00.20
79.00	00.12	16.00	00.21
79.00	00.18	08.00	00.28
90.00	00.29	14.00	00.53
72.00	00.10	15.00	00.28
84.00	00.27	17.00	00.24
79.00	00.19	10.00	00.28
77.00	00.19	06.00	00.25
66.00	00.16	12.00	00.32
74.00	00.21	07.00	00.23
70.00	00.27	07.00	00.25

TABLE 2. Terracette morphology. Man-made terracettes ($Y = 0$) Site: Robin Hood Siding, Clifton, Manchester. Grid Ref. Sd 783032 No. of observations = 31 Bearing 320°

Riser angle degrees	Riser length metres	Tread angle degrees	Tread length metres
79.00	00.11	17.00	00.47
55.00	00.22	17.00	00.40
61.00	00.17	17.00	00.46
59.00	00.25	20.00	00.45
62.00	00.18	21.00	00.40
66.00	00.26	16.00	00.48
61.00	00.16	12.00	00.44
55.00	00.20	17.00	00.50
59.00	00.13	11.00	00.25
85.00	00.14	18.00	00.31
75.00	00.13	13.00	00.46
69.00	00.17	13.00	00.34
79.00	00.15	17.00	00.24
77.00	00.16	16.00	00.39
77.00	00.18	16.00	00.34
86.00	00.20	18.00	00.39
63.00	00.24	18.00	00.40
76.00	00.21	13.00	00.38
80.00	00.29	13.00	00.29
63.00	00.20	14.00	00.50
51.00	00.22	22.00	00.33
63.00	00.26	10.00	00.38
70.00	00.19	17.00	00.38
52.00	00.28	21.00	00.29
82.00	00.21	16.00	00.35
54.00	00.25	20.00	00.32
52.00	00.24	22.00	00.32
73.00	00.14	14.00	00.38
66.00	00.14	23.00	00.37
62.00	00.20	27.00	00.39
67.00	00.26	19.00	00.41

SOME MODELS OF BINARY RESPONSE

In order that the reader fully appreciates the analytical problem and the advantages of a logistic approach it is necessary to present a little background to the most commonly employed methods for dealing with the above type of problem.

Because we have data which we can assign to one of two groups, natural or man-made terracettes, we may refer to these as binary response data. We shall wish to use a statistical model which will help assign terracettes of more doubtful origin found at the site, to either of the two identified groups using the morphological properties we have measured. Obviously, in this expository example the initial distinc-

tion between the two populations of terracettes has been considerably aided by good documentary information; it is not difficult, however to imagine situations where such information is unobtainable. In these cases the geomorphologist might well consider adopting statistical devices to help him sort out the position of difficult cases.

DISCRIMINANT ANALYSIS

In discriminant analysis, man-made and natural terracettes are assumed to be drawn from two distinct populations. The aim is to calculate from the explanatory variables, X_i, a score or discriminant function which may be used to assign cases into one or other population.
The function takes the form

$$Z = X\lambda.$$

Fisher (1936) stated the problem as one of deriving a linear function of the observed variables X such that the separation of the difference between their means, is greatest in relation to the variance within each population. Necessary conditions for this analysis are that the X variables follow a multivariate normal distribution with equal variance-covariance matrices in the two populations. The square of the distance between the means of the population is

$$(\bar{Z}_1 - \bar{Z}_2)^2 = \Big(\sum_{i=1}^{k} \lambda_i d_i\Big)^2 = \lambda' d\, d' \lambda,$$

where

$$d = \begin{bmatrix} \bar{X}_{11} & \bar{X}_{12} \\ \bar{X}_{21} & \bar{X}_{22} \\ & \vdots \\ \bar{X}_{k1} & \bar{X}_{k2} \end{bmatrix},$$

and the variance within the population is

$$S^2(Z) = \sum_{i=1}^{k} \sum_{j=1}^{k} \lambda_i \lambda_j S_{ij} = \lambda' S_p \lambda.$$

Where S_p is the common variance-covariance matrix, Fisher's proposal was to determine λ so as to maximize

$$\frac{(\bar{Z}_1 - \bar{Z}_2)^2}{S^2(Z)} = \frac{\sum_i (\lambda_i d_i)^2}{\sum_i \sum_j \lambda_i \lambda_j S_{ij}}.$$

Differentiating with respect to λ_i and setting to zero, we obtain the equations of the form

$$\lambda_1 S_{i1} + \lambda_2 S_{i2} + \ldots + \lambda_k S_{ik} = c d_i, \quad i = 1, \ldots, k,$$

where c is a constant which may be chosen as unity since only the ratios of λ_i can be uniquely determined

$$\therefore \lambda = S_p^{-1} d.$$

In the binary response problem our aim is not so much to classify but more to predict the probability that a given observation will be a success or otherwise. To formulate our problem in this manner we can arbitrarily assign the names 'success' and 'failures' to the two populations of terracettes; in generating the prediction equations these two groups of data are distinguished by assigning the dummy values 1 and 0 to observations on the 'success' or 'failure' variable.

Discriminant analysis may be extended so that the discriminant score, Z, can be translated into a probability statement. Quarmby (1967) shows how this results in a logistic relationship where the probability of an observation coming from population 2 given X is

$$\text{prob}(y_i = 0 \mid X) = \frac{1}{1+e^{-Z}}.$$

However this is no more than a special case of the logistic analysis, to be described later, but the discriminant approach is valid only if the distribution of X is multivariate normal with equal variance covariance matrices in the two populations. On theoretical grounds, the maximum likelihood method of logistic analysis would seem preferable since it does not assume any particular distribution for X.

This is especially true when many of the independent variables are qualitative.

MULTIPLE REGRESSION

The general linear model of n observations on $k+1$ variables may be stated as

$$y = X\beta + u,$$

where:

X is an $n \times k$ matrix of explanatory variables,

β is an $k \times 1$ vector of coefficients of explanatory variables,

u is an $n \times 1$ vector of disturbances.

Ordinary Least Squares (O.L.S.) makes the following assumptions:

(I) $E(u) = 0$,

(II) $E(uu') = \sigma^2 I$, i.e. the homoscedastic assumption,

(III) X is a set of fixed numbers,

(IV) X has rank $k < n$.

Thus the conditional expectation of y given X is

$$E(y \mid X) = X\beta.$$

The O.L.S. estimates of the β are

$$\hat{\beta} = (X'X)^{-1} X'y.$$

When the dependent variable is dichotomous we may assign the values 0 and 1 according to

$$y_i = \begin{cases} 1 \text{ if the event occurs,} \\ 0 \text{ if the event does not occur.} \end{cases}$$

In this case the conditional expectation of y given X may be interpreted as the conditional probability that the event will occur given X

$$\text{i.e. } E(y|X) = \text{prob}(y = 1|X) = X\beta.$$

The predicted value of y ($\hat{y} = X\hat{\beta}$) is an estimator of this conditional probability. This is a computationally simple method which can be useful, but the method suffers from a number of defects.

Firstly, the O.L.S. assumption of homoscedasticity is violated. Consider the ith observation

$$y_i = X_i'\beta + u_i, \text{ where } X_i'\beta \text{ is the } i\text{th row of } X\beta,$$

$$u_i = y_i - X_i'\beta.$$

Since y_i is either 0 or 1, u_i must be either $-X_i'\beta$ or $1-X_i'\beta$.
If $E(u_i) = 0$ then its distribution must be

u_i	$f(u_i)$
$-X_i'\beta$	$1-X_i'\beta$
$1-X_i'\beta$	$X_i'\beta$

with variance

$$\begin{aligned} E(u_i^2) &= (-X'_i\beta)^2(1-X'_i\beta)+(1-X'_i\beta)^2(X'_i\beta) \\ &= X'_i\beta(1-X'_i\beta) \\ &= E(y_i)[1-E(y_i)]. \end{aligned}$$

Thus the variance-covariance matrix is

$$E(uu') = \begin{bmatrix} X_1'\beta\,(1-X_1'\beta) & 0 & \cdots & 0 \\ 0 & X_2'\beta\,(1-X_2'\beta) & & \vdots \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & 0 & X_n'\beta\,(1-X_n'\beta) \end{bmatrix}$$

The disturbance term is, therefore, heteroscedastic, varying with X_i.

Within the range $0.2 \leqslant E(y_i) \leqslant 0.8$ the variance of the disturbance term changes relatively little and so within this range there is unlikely to be a serious loss of efficiency in using O.L.S.. However, for values outside this range the loss of efficiency,

because of heteroscedasticity, may be serious. In this case generalised least squares (G.L.S.) is the appropriate model.

Because of $X_i'\beta$ are unknown, Goldberger (1964) has suggested a two-step procedure where $X'\beta$ is estimated from the O.L.S. regression in the 1st step, giving an estimated variance-covariance matrix

$$E(uu') = \hat{\Omega} = \begin{bmatrix} X_1'\hat{\beta}(1-X_1'\hat{\beta}) & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & X_2'\hat{\beta}(1-X_2'\hat{\beta}) & & & & \\ & & \cdot & & & \cdot \\ \cdot & \cdot & & \cdot & \cdot & \cdot \\ \cdot & & \cdot & & \cdot & \cdot \\ \cdot & & & \cdot & & \cdot \\ 0 & \cdot & \cdot & \cdot & 0 & X_n'\hat{\beta}(1-X_n'\hat{\beta}) \end{bmatrix}$$

The 2nd step is to obtain $\hat{b}_{\pm} = (X'\hat{\Omega}^{-1}X)^{-1}X'\hat{\Omega}^{-1}y$.
A second defect of the multiple regression model is that because the y_i are not normally distributed, the usual distributional tests (t and F) associated with O.L.S are totally unreliable, particularly in small samples.

Thirdly, the most serious restriction on the usefulness of linear regression arises from the condition

$$0 \leqslant \text{prob}(y_i = 1) \leqslant 1$$

and the model may well predict values outside this range.

LOGISTIC REGRESSION

In view of the problems which might arise when using the O.L.S. approach, there are two alternative techniques which create a transformation of the linear combinations $X\beta$, such that while X may take values from $-\infty$ to $+\infty$, $E(y)$ is limited to the range (0, 1). These two approaches are probit and logit analysis which both have a long history in biometrics. The logit transformation, which we shall describe here, is similar to the probit analysis (Finney, 1971) and of the two, logit is generally preferred on practical and theoretical grounds (Berkson, 1951, p. 338).

If we let p_i be the probability of success of the ith observation for a given set of k X's and postulate a dependence

$$\text{prob}(y_i = 1|X) = p_i = \frac{e^{X_i'\beta}}{1+e^{X_i'\beta}},$$

$$\text{prob}(y_i = 0|X) = 1-p_i = \frac{1}{1+e^{X_i'\beta}},$$

hen

$$\log\left(\frac{P_i}{1-p_i}\right) = X_i'\beta = \gamma_i.$$

The linear logistic model is $\gamma = X\beta$ and γ_i is the logistic transform of the probability of success p_i.

The parameters of the model may be estimated by maximum likelihood methods using an iterative process (Warner, 1962, p. 19; Cox, 1970, pp. 87–91). The likelihood of the sample is

$$L = p_1 p_2 \dots p_s (1-p_{s+1})(1-p_{s+2}) \dots (1-p_n),$$

$$\log L = \sum_{i=1}^{s} \log p_i + \sum_{i=s+1}^{n} \log(1-p_i) = \sum_{i=1}^{s} X_i'\beta - \sum_{i=1}^{n} \log(1+e^{X_i'\beta}).$$

Differentiating $\log L$ with respect to β and setting to zero gives the normal equations determining the maximum likelihood estimates of the β's.

$$\frac{\delta \log L}{\delta \beta} = \sum_{i=1}^{s} X_i' - \sum_{i=1}^{n} X_i' \frac{e^{X_i'\beta}}{1+e^{X_i'\beta}} = \sum_{i=1}^{s} X_i' - \sum_{i=1}^{n} X_i' p_i = 0.$$

For the purpose of this study we have used a slightly modified form of the logit model as proposed in Fisher and Yates (1963, p. 16),

$$\text{i.e. } E(y_i = 1 \mid X) = \text{prob}(y_i = 1 \mid X) = \frac{e^{2\gamma_i}}{1+e^{2\gamma_i}},$$

$$\text{so that } \frac{1}{2} \log e \frac{p_i}{1-p_i} = \gamma_i$$

which is estimated by $\hat{\gamma}_i = X_i'\hat{\beta}$.

The computer program used for the logit analysis in this study is the Quantal Regression Program by D. Clayton of the London School of Hygiene and Tropical Medicine.

RESULTS

An initial O.L.S. regression was fitted to the data prior to logistic analysis. This was appropriate for two reasons. Firstly, it seems likely that many researchers would approach this data problem via O.L.S. and we were interested to see if any predicted values of fell outside the range (0, 1) which is a problem we have previously mentioned. Secondly, because logit analysis is an iterative process estimated starting values of the parameters may be supplied; O.L.S. regression was used to provide these starting values. The following O.L.S. results were achieved

$$\hat{y} = \underset{(0.4717)}{1.0582} + \underset{(0.0045)}{0.0089X_2} - \underset{(0.9565)}{0.7960X_3} - \underset{(0.0109)}{0.0524X_4} - \underset{(0.6140)}{0.9030X_5},$$

$$R^2 = 0.476,\ F_{4,57} = 12.95,\ (P \ll 0.0001),\ (\bar{R}^2 = 0.439).$$

Eleven of the predicted values fell outside the range (0, 1). The above regression coe-

fficients were used as starting values for logit analysis which after 400 iterations gave the following results:

$$\hat{\gamma} = 1.1699 + 0.0607X_2 - 4.8637X_3 - 0.2967X_4 - 1.7358X_5.$$
$$(1.1685)\ (0.0276)\quad (4.0811)\quad (0.1007)\quad (2.2882)$$

Likelihood Ratio $\chi^2_4 = 42.047$, $(P \ll 0.0001)$.

The fit of the logistic model may be investigated by finding the values of $\hat{\gamma}$ for each case and comparing them with the observed responses (Table 3 and Fig. 5). It can be observed that the scatter of points conforms reasonably well to the logistic curve. It is also possible to show graphically how well the model separates the two populations of terracettes. Figure 6 shows two histograms for the 'success' and 'failure' population of terracettes and illustrates very clearly how the 'success' cases are associated with dominantly positive values of $\hat{\gamma}$ and the 'failure' cases with negative values. This is rather like viewing the projected scores on to the discriminant axis in discriminant analysis. Clearly the logistic model has been quite successful in predicting the two types of terracettes.

TABLE 3. Logistic regression. The distribution of $\hat{\gamma}$

$\hat{\gamma}$	No of terracettes	'Successes' (Natural terracettes)	Proportion of success
< −1.0	16	1	.062
−1.0 to 0.5	3	1	.33
0.5 to 0	9	2	.22
0 to 0.5	15	8	.53
0.5 to 1.0	4	4	1.0
> 1.0	15	15	1.0
	62	31	

If we compare the estimated parameters of the O.L.S. regression model with that of the logistic we observe that both have identified the same variables as being significant. In particular we may note that the two populations of terracettes differ most significantly with regard to riser angle (X_2) and tread angle (X_4). As the signs of

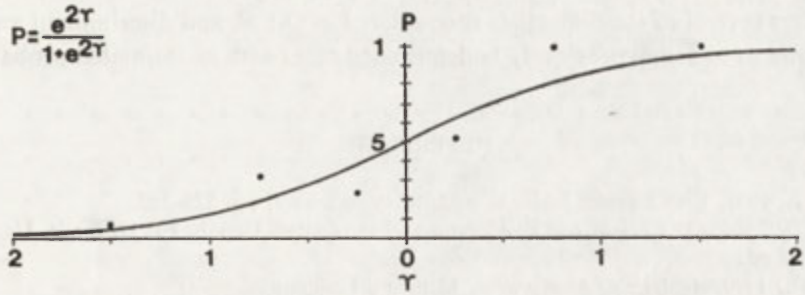

Fig. 5. Estimated values of $\hat{\gamma}$ compared with a logistic curve

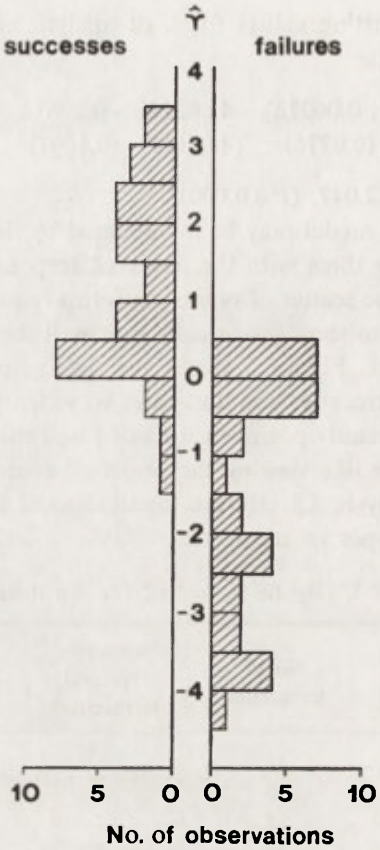

Fig. 6. Histogram illustrating the distribution of $\hat{\gamma}$ for the two terracette populations

the two parameter estimates indicate, larger values of $\hat{\gamma}$ are associated with larger rises and tread angles; that is, the natural terracettes population on the whole, higher riser and tread angles than the man-made terracettes.

CONCLUSIONS

Logistic regression has been shown to be a useful alternative approach in distinguishing numerically between two visually similar slope features. As a method it overcomes several of the difficulties encountered in O.L.S. and discriminant analysis and allows us to assign previously undetermined cases with an estimated probability.

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ORIGIN OF THE YOUNGEST FILL REVEALING HUMAN ACTIVITY: AN EXAMPLE OF THE CZYŻÓWKA VALLEY (SANDOMIERZ UPLAND)

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Interesting informations on the age and structures of the youngest sediment cover have been inferred from a 6 m deep drainage ditch (Photo 1) running a great distance along the bottom of the Czyżówka valley (Chrapanów village) in the Sandomierz Upland.

The Czyżówka valley is one of dry valleys of the north-western Mesozoic margin of the Holy Cross Mts. It stretches from Ożarów Sandomierski to Zawichost where it joins the Vistula valley. There is no permanent stream along the whole Czyżówka valley. The upper and the middle parts of the valley are dry, and not until its lower part, starting from Czyżów, does water appear, in a ditch dug along the axis of the valley. The studied locality is situated at a distance of about 10 km to the west of the Vistula valley.

The southern slope of the valley in the studied area is higher and steeper than the northern one. It is built of deposits of the Middle-Polish glaciation covered by Würm loessy series. The loess plateau reaches 210 m a.s.l. The northern slope has no loessy cover and rises to 185 m a.s.l. The bottom of the valley is flat and even, up to 0.5 km wide, and lies at altitude of 157–160 m. It consists of loesssic silts covering (Fig. 1 — layer 5e) thin sandy and rubble-clayey deposits (layers 5b, c, d) resting on the bedrock (layers 1, 5a).

Higher up there is at places an indistinct terrace. It occurs 3–5 m above the bottom of the valley and is built of a variety of deposits; at the surface there are outcrops of fine-grained and vari-grained sands and loessic silts. According to Jersak (1976) the 3 m terrace in the Czyżówka valley near Ożarów Sandomierski is of Eemian-Würm age. Above the terrace there is a plateau built of fluvioglacial sands and gravels, covered by partly denudated till of Middle-Polish glaciation (Fig. 1, layer 3) and sometimes overlaid by loess. This level is situated 12–15 m above the bottom of the valley (if the loessy cover is not taken into account). A schematic section across the valley near Chrapanów is shown on Fig. 1.

Phot. 1. Drainage ditch in the bottom part of the Czyzówka valley in Chrapanow. General view. A horizon of the palaeosol is seen
Photo D. Kosmowska-Suffczynska

CHARACTERISTIC FEATURES OF DEPOSITS AND THEIR AGE

At the bottom of a ditch in fluvial deposits (Fig. 2, Photo 2) at a depth of 5.60–6.00 m there are greenish fine-grained Cenomanien sands (Fig. 2, layer a), (Bielecka, 1968) or, occasionally, Turonian limestones and gaizes (Fig 1, layer 1). The top surface of these deposits is inclined and disappears in the northern part of the ditch. Above there is a sandy-clayey-rubble series (up to 0.5 m thick), rust-coloured, impregnated with iron compounds (Fig. 2, layer b), overlaid by fine-grained structureless yellow-grey sands up to 0.7 m thick (layer c). Within the sands there is a thick (0.5 m) humus horizon of a fossil soil (layer d). The top surface of soil is inclined northwards from 4.5 m to over 6.0 m showing a fragment of a fossil slope of the Czyżówka valley.

The fossil soil is overlaid by a series of decalcified loessic silts (layer e) with rhythmic horizontal bedding and, locally, with streaks of dusty sands. In the northern part of the ditch the silts are over 6 m thick.

Radiocarbon dating has been carried through in the Radiocarbon Laboratory of the Archeological and Ethnographical Museum (by A. Kanwiszer) for the lower and upper humus series[1] (Photo 3). The bottom part of the soil was dated for 11 000± 380 BP (Lod. 17) and its top part for 5140±120 BP (Lod. 18). A description of the method for determination of 14C activity in natural samples has been published by Bem et al. (1978).

[1] Radiocarbon analysis were paid for by the Committee of Quaternary Research of the Third Department, Polish Academy of Sciences. I am indebted to the Committee for the subsidies in 1976.

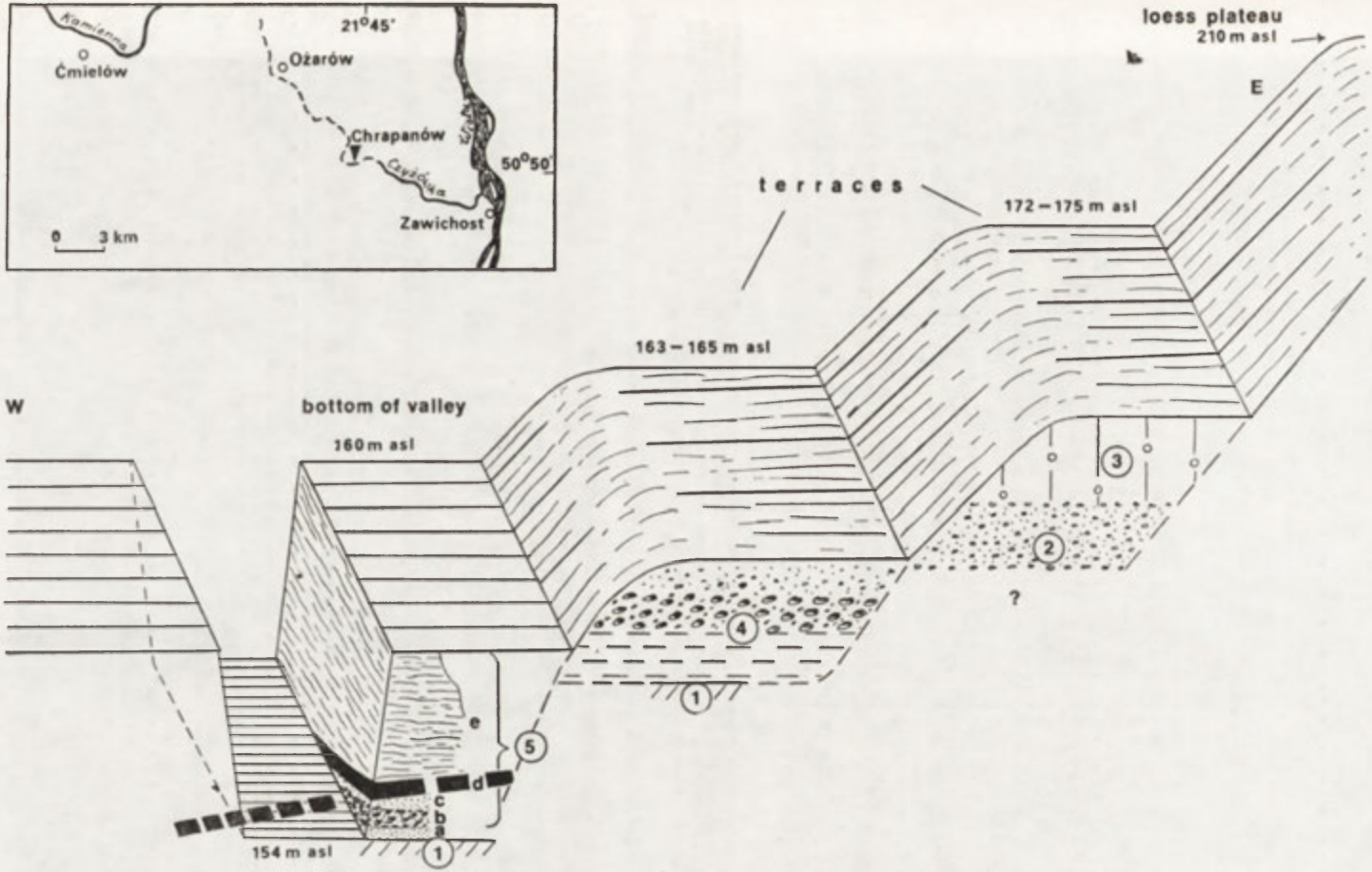


Fig. 1. Schematic section across the Czyżówka valley near Chrapanów

1 — Cretaceous bedrock with Cenomanien sands (a), 2 — fluvioglacial sands and gravels deposited during the advance of Middle-Polish Glaciation, 3 — till of Middle-Polish Glaciation, 4 — Eemian-Würm deposits 5 — Late Würm and Holocene deposits; b, c, d, e — see Fig. 2

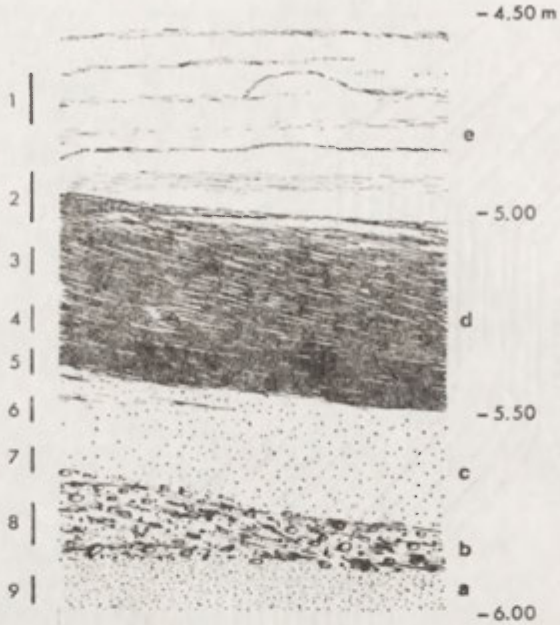
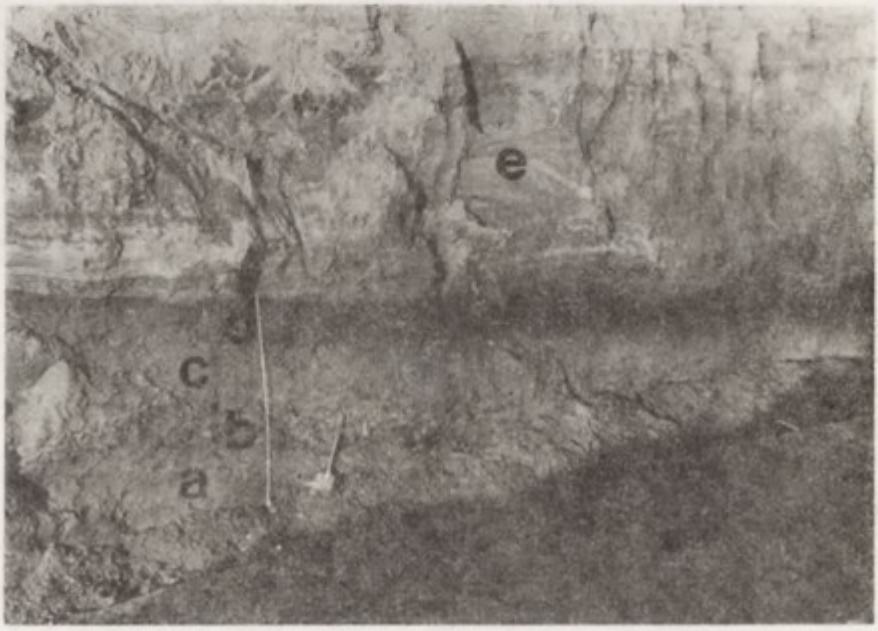


Fig. 2. Exposure in the ditch at Chrapanów

a — Cenomanien yellow-green fine-grained and dusty sands, b — rust-coloured (with iron compounds) vari-grained clayey sand with gravel of Scandinavian and local origin, c — yellow-grey structure-less fine-grained sand, HCl-, d — dark-grey -brown humus layer formed of fine-grained sand, with single charcoal, HCl-, slightly washed at the top, e — loessy silts with horizontal bedding, and streaks of dusty sands in places, HCl-. Numbers mean places of sampling. Granulometric composition and physico-chemical data — see Fig. 3



Phot. 2. Drainage ditch in Chrapanów. Detailed view. a, b, c, d, e, — see explanation to Fig. 2.
Photo D. Kosmowska-Suffczyńska

Phot. 3. Palaeosol. Dantgin years BP. Chrapanów: bottom of the valley
Photo D. Kosmowska-Suffczyńska

Fragments of pottery found in the upper part of the soil have been estimated by Professor Dr. W. Chmielewski as from the late Middle Ages (14th and 15th century)[2].

The lowest clayey-rubble series can be referred to the Older Dryas period, and the age of the youngest visible erosion in the Czyżówka valley to a period just before or at the very beginning of Older Dryas. Structureless sands overlying the clayey-rubble series may correspond with the Allerod period at the end of which the soil (dated for 11 000 BP at the bottom) developed.

These datings usually agree with data from other areas. The oldest filling of erosive channels at the margin of the Carpathians in the Wisłok and San valleys is correlated with the Allerod (Ralska-Jasiewiczowa, Starkel, 1975). In the meanders of the San valley the Allerod peats were also found by Mamakowa (1962). In the Sandomierz Upland Jersak (1973; 1977) speaks of erosive cuttings at the end of the Oldest Dryas or at the beginning of the Older one; sometimes they are covered by debris of washed solifluction deposits. Klatka (1968, p. 91) wrote "Exposures in Nietulisko, Kunów and Sieradowice suggest that the most intensive bottom erosion occurred in the Older Dryas". In more distant areas (in northern Poland) the processes of cutting and deepening the valleys are also referred to the Older Dryas (Churska, 1966).

The age and origin of the fossil soil in the exposure are difficult to interpret. The humus series (up to 0.5 m thick) dated for 11 000±380 BP at the bottom and 5140± 120 BP at the top should represent (from a climatic and floristic point of view)

[2] I wish to thank Professor Dr. W. Chmielewski for identification of pieces of pottery discovered.

a very heterogeneous period, starting at the end of the Allerod and lasting till the very end of the Atlantic — the beginning of the Subboreal periods (Photo 3). But there are no distinct changes in its profile. The age of the upper part of the fossil soil may be rejuvenated (Gerasimov, 1976), but it seems rather unlikely that the whole humus horizon is of Allerod age, the more so as it is developed in the Czyżówka valley (in Chrapanów) quite differently than are other known and described soils of that age (Konecka-Betley, 1977). Primary features of the soil already developing in the Allerod should have been subjected to changes in the more humid climate of the Boreal and Atlantic periods.

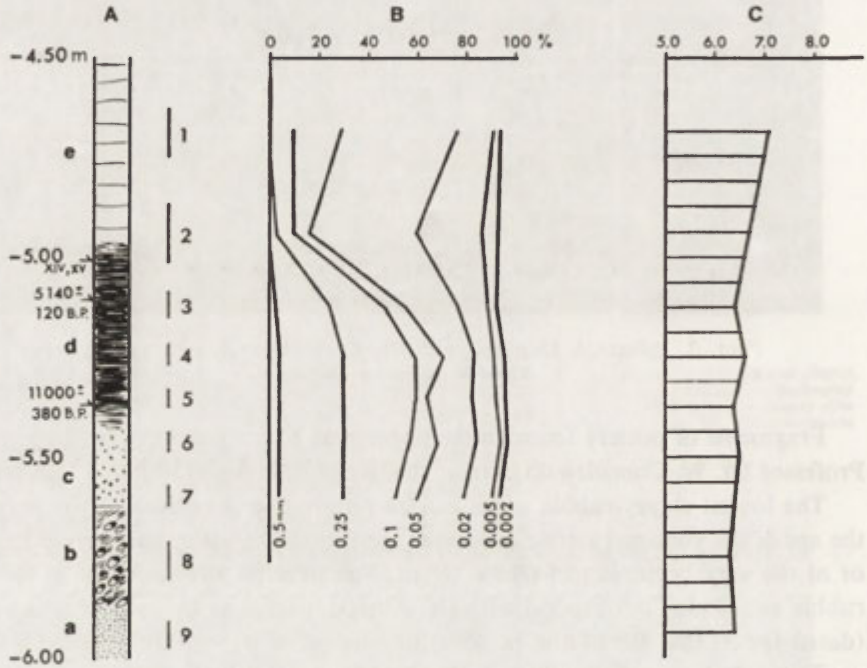


Fig. 3. Granulometric composition and some physico-chemical
A — sequence of deposits; a, b, c, d, e — as on Fig. 2, numbers mean places of sampling, B — granulometric composition,

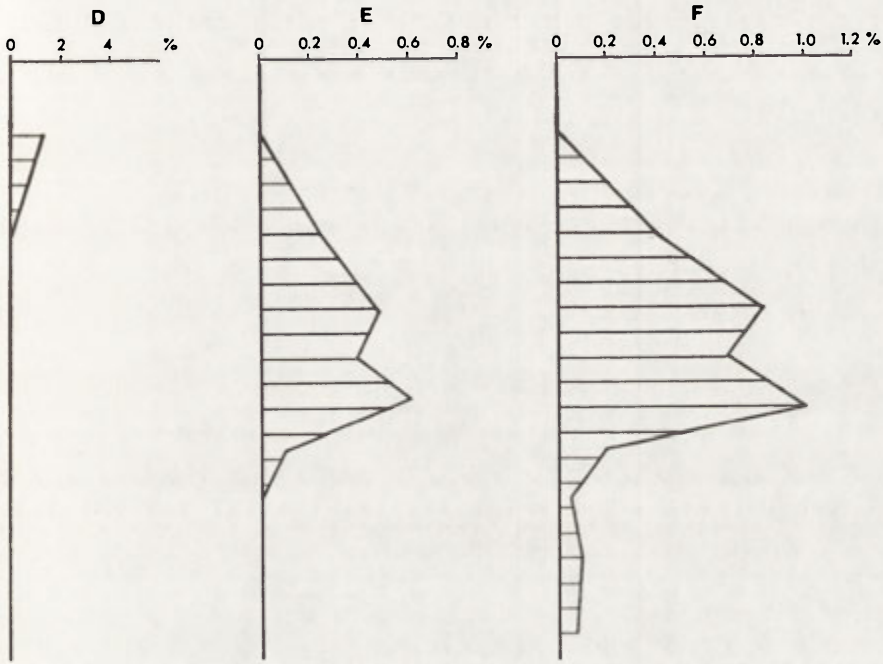
TABLE 1. Some physico-chemical properties of a palaeosol from Chrapanów (values after K. Konecka-Betley)

Sample number	pH H_2O	pH KCl	$CaCO_3$ %	Organic C %	Humus %
1	7.8	7.1	1.25	0.01	0.02
2	7.3	6.7	0.0	0.24	0.41
3	7.0	6.4	0.0	0.48	0.83
4	7.1	6.6	0.0	0.39	0.67
5	6.9	6.4	0.0	0.59	1.02
6	7.2	6.5	0.0	0.11	0.19
7	7.3	6.4	0.0	0.03	0.05
8	7.2	6.3	0.0	0.06	0.10
9	7.5	6.4	0.0	0.04	0.07

Some physico-chemical properties of a fossil soil and its granulometric composition are presented in Table 1 and 2 and on Fig. 3. The studied soil includes only a single horizon — a humus one, developed in fine-grained sand with 1% maximum content of humus (content of organic carbon is up to 0.6%), completely devoid of calcium carbonate and with pH (in KCL) of about 6.5.

The characteristic features of the soil were discussed with Konecka-Betley.[3] According to her suggestions it was found to be a chernozem soil with a contribution of meadow vegetation and a high level of ground water.

Allerod soils in dune sands (studied in detail by Manikowska: 1966, 1970) are



features (Chrapanów). Values after Doc. Dr. K. Konecka-Betley
C — pH in KCl, D — $CaCO_3$ contents, E — contents of organic C, F — humus contents

poorly developed podsols with a distinct characteristic maculation. They have developed in a quite humid climate below a forest floristic cover. A probable Allerod soil (without radiocarbon dating) is mentioned by Jersak (1965, 1973, 1975, 1977) as being in the Sandomierz loessy areas. According to him, it is a poorly developed soil with an accumulative thin horizon, thus representing a short period of climate amelioration.

The Allerod soil in Chrapanów (is it only the Allerod soil?) has the most similarities with the Allerod soil in the 2nd terrace of the Vistula valley in Całowanie near Karczew (Konecka-Betley, 1974). Probably these similarities are the result of similar humidity conditions on both localities.

[3] I am especially obliged to Docent Dr. K. Konecka-Betley for consultation in the field and advice during studies of the locality.

TABLE 2. Granulometric composition from Chrapanów (values after K. Konecka-Betley)

Sample number	> 1mm	< 1mm	Percentage content of fraction diameter in mm								In all		
			1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	1–0.1	0.1–0.002	< 0.002
1	0.0	100	0.0	0.8	9.2	17	50	14	1	8	10	67	23
2	0.1	99.9	0.2	2.7	7.1	6	44	25	6	9	10	50	40
3	1.0	99.9	3.7	22.0	21.3	8	22	10	4	9	47	30	23
4	1.6	98.4	5.0	24.7	30.3	10	13	8	2	7	60	23	17
5	1.2	98.8	4.2	26.0	29.8	4	18	10	1	7	60	22	18
6	0.9	99.1	4.7	25.5	27.8	10	15	11	1	5	58	25	17
7	0.4	99.6	4.0	24.0	24.0	8	19	12	1	8	52	27	21

An explanation of the full origin and type of the studied soil is still incomplete. It needs more detailed pedologic studies and more samples dated by radiocarbon method. Also, the conclusions about the age of accumulation of the bottom deposits forming the lowest bottom terrace of the Czyżówka valley have to be drawn with particular care as shown, among others, by studies in Brzeźnica on Wisłoka (Kowalkowski, Starkel, 1977).

Phot. 4. 6 m thick series of loessy silts covering a layer of pottery from late Middle Ages, Chrapanów bottom of the Czyżówka valley
Photo D. Kosmowska-Suflczynska

The studied locality provides interesting information on the age of deposits that overlie the palaeosol and form the present bottom of the Czyżówka valley (Photo 4). Pottery of the late Middle Ages found in the top of the humus series determines the age of the youngest, very thick (in places over 6 m), accumulative cover in the Czyżówka valley as only about 500 years.

THE PROBLEM OF THE YOUNGEST ACCUMULATIVE COVER

One may ask the reason for a slow filling of the Czyżówka valley till late Middle Ages and for the almost catastrophic intensity of that phenomenon since the 14th

century. Another problem needing explanation is the intensity of this process in the Czyżówka valley where the accretion rate of alluvium is much greater than in the nearby Vistula valley or even in the valleys of the Carpathian foreland.

It is possible that some processes of slope degradation have already been connected with Neolithic human farming, developed in the fertile loessic areas of Sandomierz Upland (Dobrowolska, 1961; Czarnecki, Grzybowska, 1976). Nearby in Ćmielów (Gawroniec) a Neolithic settlement has been found. Its inhabitants were occupied in farming — wheat and other useful plants were known, as well as animal husbandry. The Neolithic agriculture that developed at the expense of forest areas seems to have attained a high degree of development. The extent of farming and its importance for the inhabitants of Gawroniec can be estimated on the basis of a large volume of reserve containers and ground granaries found near earthen houses (Podkowińska, 1956, p. 36). Besides Gawroniec in the neighbourhood of the Czyżówka valley many other Neolithic settlements have been historically confirmed (Fig. 4; Jażdżewski, 1965; Podkowińska, 1953; Żurowski, 1929).

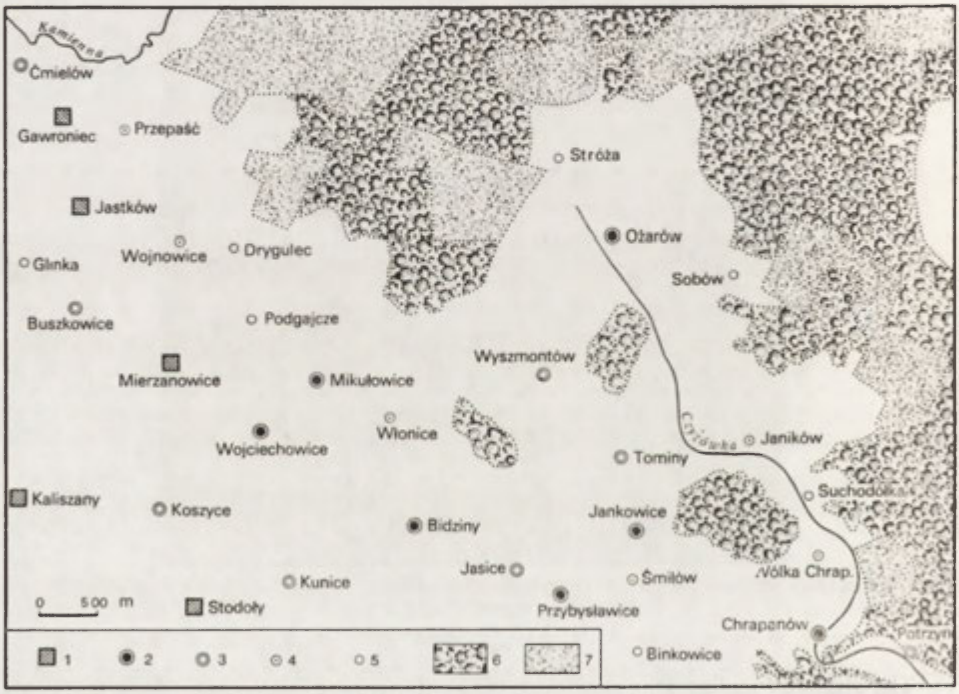


Fig. 4. Changes of colonization since Neolithic age and changes of forested area since the beginning of the 19th century in the drainage basin of upper Czyżówka and Krzczonowianka

1 — Neolithic settlements after historical sources, 2 — settlements of the second half of the 14th century, 3 — settlements of the end of the 15th and the beginning of the 16th centuries, 4 — settlements of the end of the 16th century, 5 — settlements of the end of the 18th and the beginning of the 19th centuries, 6 — forest after the map of Mayer v. Heldensfeld (1801-1804), 7 — present forest

Sources: Mayer v. Heldensfeld (1808), J. Gąssowski (1957) K. Jażdżewski (1965), M. Kamińska (1964), R. Mochnacki (1937), A. Pawiński (1886), Z. Podkowińska (1953), *Słownik Geograficzny* (1880), J. Żurowski (1929)

A reconstruction of the landscape of the Czyżówka valley in the Neolithic period seems difficult. Human activity in that period can not be excluded, but a general deforestation and a human interference in the environment is decisive in later periods.

In the 3rd – 1st centuries B. C. the Małopolska Upland was embraced by Celtic culture. At that time there was the very beginning of metallurgy, accompanied by vast deforestation (Radwan, 1963, 1966). In the 1st – 5th centuries A.D. the Holy Cross metallurgy was one of the most important in Europe. More advanced tools were used in farming. The colter and primitive plough were replaced by a colter with an iron blade what enabled a deeper ploughing but, at the same time, facilitated the surface wash. After a period of migration of tribes, the 7th – 8th centuries were the turning point in the development of farming when corn-growing started to be popular (Dembińska, 1972). The greatest intensification of farming occurred in the 13th century and lasted till the very end of the 15th century — in this period the use of a plough became more and more common. A rental system introduced in the country required an increase of cultivation area at the expense of the forest. The process of a too intensive occupation of the previously forested areas concerned the enlighted people of the time, and already at the beginning of the 15th century several regulations to prevent a deforestation had been enacted. New foundations of towns and villages were common. At the end of Middle Ages the Małopolska Upland was one of the most populated regions of Poland (up to 25 inhabitants per 1 km^2). Particularly intensive accumulation in the valleys at the end of the Middle Ages was mentioned by Ralska-Jasiewiczowa and Starkel (1975).

MODERN PERIOD

The humus horizon is overlying a thick (over 6 m) series of loessy silts (Photo 4, Fig. 1, layer 5e) dated for a period from the 15th up to the end of 19th century when regulatory actions were realized (Czarnecki, Grzybowska, 1976). The described locality proves the occurrence of an almost catastrophic intensity of slope wash. After the destruction of soil it reached the bedrock and deposited large quantities of sediments in the valley, by flood water mainly. The large supply of deposits from the slopes, the intensified irregularity of river discharge due to the devastation of the natural vegetation, the predominance of river-load material over a transport capacity of the stream and thus its overloading, all these resulted in a tendency of river-channel change from meandering type to braided river pattern, and in a quick vertical alluvium increment (Starkel, 1977). In the 16th century the metallurgy in the Old Polish Basin was at its height (Bielenin, 1956): in 1577 there were 64 iron-works in this area. In the 17th century metallurgy was gradually decaying there due mainly to excessive deforestation. At the end of the 16th century there were also symptoms of soil impoverishment as a result of too much intensive cultivation.

The second half of the 19th century was the important period of agriculture development. After peasant enfranchisement large areas given for servitudes were deforested. Besides, many fish ponds and mill races formed in the 15th century disappeared at that time (Falkowski, 1975). From the beginning of the 19th century the composition of plants culture has changed from the introduction of two new species of root crops — sugar beets and potatoes. This change contributed considerably to a more intensive surface run-off from cultivated slopes. The fact is emphasized by Klimek and Starkel (1974), and Ralska-Jasiewiczowa and Starkel (1975), who cite Gil and

Słupik (1972) that in the areas under cultivation nowadays the coefficient of surface run-off from a potato field after a hard rain is 23.6% whereas from a meadow or from a corn field is less than 0.1%.

In the 19th century better tools and better organization came into day. The mechanization of farming had an important role in accelerating a process of slope degradation.

The first precise map of the Czyżówka valley was not made until 1801–1804 (map of Mayer von Heldensfeld). It shows a view of settlements and roads very similar to the present one. But some differences can be seen in the extent of woods (Fig. 4). Chrapanów and other villages in its neighbourhood are already quite well developed. The Czyżówka valley near Chrapanów was, as it is now, a dry valley. Besides there were other streams: for example, in Wyszmontów was one with three dams and a mill (unpublished data of Historical Atlas Group) and there was a stream with a small reservoir starting at Tominy. The largest forest areas spread between Jankowice, Wólka Chrapanowska and Janików.

According to historical data Chrapanów was already built in the 12th century. The data for 1578 (Pawiński, 1886, p. 177) inform: "col. 6, lan. 3, hort. c.a. 1, desert lan 1/2" i.e. 6 peasants, 50 hectares, 1 farmer with a field, several acres deserted. Using proper re-count we may presume about 38 inhabitants. At the same time there was also a mill with one wheel (unpublished data of Historical Atlas Group), what may be evidence of the flow of Czyżówka near Chrapanów. In 1827 Chrapanów included 19 houses and 142 inhabitants (*Tabella Miast, Wsi*..., 1827). In 1880 there were already 48 houses (*Słownik Geograficzny*..., 1880). From data of 1921 Chrapanów had over 372 people (*Skorowidz miejscowości Rzeczypospolitej Polskiej*..., 1925). Similarly, the development of other villages may have taken place much earlier (Fig. 4) than shown on the map of Mayer von Heldensfeld and thus suggests an immediate increase of population in a period from the end of the 17th century up to the beginning of the 19th century and also at the beginning of the 20th century.

The Sandomierz region road system is also of older origin. According to Wąsowicz (1967) it was already fully developed in the 11th–12th centuries and used by a far-reaching international as well as domestic trade (e.g. salt trade). The author wrote about roads existing in the early Middle Ages which ran through places Czyżów and Zawichost (the latter being in early Middle Ages a fort).

CONCLUSIONS

Investigations in the Czyżówka valley indicate an extraordinarily rapid rate of alluvia accumulation in the modern period. Up to the Middle Ages alluvium accretion was comparatively slow. Catastrophic intensity of the slope degradation and accumulation of deposits in valleys from the 14th–15th centuries was the result of progressively more active human interference in the geographical environment.

Mechanization in agriculture, the beginning of root-crop cultivation and the destruction of so-called small-water retention played a most important role. Then followed the destruction of protective soil cover, and the rate of surface outflow

and slope downwashing increased. Large amounts of sediment supplied to the river channel, the irregular channel discharge due to lack of natural vegetation cover, and the overloading of flood waters caused extremely quick alluvia accretion. A more humid climate from the middle of the 16th century up to the middle of the 20th century might also be of consequence (Hess, 1968). Comparison with the nearby Vistula and other valleys shows that the rate of alluvia accretion was considerably slower there than in the Czyżówka valley.

Falkowski's studies suggest that in a period from 3400 BP to 300 BP the Vistula was a meander-type river with a vertical stabilization of the valley bottom. Not until the 15th century, due to the development of husbandry did the river channels start to change from a system of meandering type to a braided pattern. This process was delayed by a still existing system of so-called small retention. It was again accelerated in the 19th century when the fish ponds and water mills were destroyed (Mycielska-Dowgiallo, 1977). The effect of this process is visible in the rate of accumulation in the Vistula valley. According to Falkowski (1975), the same amount of deposits (1 m thick) was accumulated in the Vistula valley from World War First to the present as in the period from the 16th to the 19th century. Thus in the Vistula valley there is a 2 m thick series of alluvium, accumulated since the 16th century, i.e. almost 3 times less than in the Czyżówka valley.

In the Wielopolka valley of the sub-Carpathian trough only 7 metres of alluvial deposits dating from the end of Würm period have been accumulated (Starkel, 1957). Starkel (1968, 1972) suggested that in the valleys of the basins in the Carpathian Foreland a particularly thick series of river muds (about 5 m) have been deposited for the last 2000 years. Thus we can see that even in that area the rate of accretion of alluvium was considerably slower than in the studied region. Comparable data can only be obtained from the valley in which the natural processes of erosion and deposition have been changed by the construction of dams. Such a situation occurs in the Wisłoka valley (Dęborzyn) where during 15 years a 2.5–3.0 m thick series of river muds has been deposited (Klimek, Mamakowa, Starkel, 1972), and in the Świślina valley (right tributary of Kamienna river) where a quick deposit of river muds has been caused by a previously constructed dam in Nietulisko (Klatka, 1958, 1968). There is no reason to assume the existence of a water dam in the Czyżówka valley. There is no information about it; furthermore, the studied site is situated in the middle part of the valley without any permanent stream at least since 1800 (Mayer von Heldensfeld, 1808), but probably since an earlier time.

In the Czyżówka valley very active denudative processes caused by human interference in the environment (so-called anthropogenic aggradation: Kozarski, Rotnicki, 1977) were favoured additionally by the peculiar relief of the valley conditioned by its geological history. The formation of the valley was 'forced' during the advance of the ice sheet of Middle-Polish Glaciation when the valley was an outflow channel of fluvioglacial waters. The present down-grade of the Czyżówka valley equals 2‰ only, whereas the grade of neighbouring valleys, as well as the tributaries of the Vistula are, for example, 5.3‰ in the Opatówka valley and 5.6‰ in the Koprzywianka valley.

The small down-grade of the Czyżówka valley is a result of the inclination of its fossil bottom. The small inclination prevented an erosion of the accumulative cover (although the Vistula is in the vicinity) and caused a considerable predominance of river accumulation over erosion. The river was not able to erode or to carry away its alluvium which came mainly from slope wash left in the valley by flood waters.

Probably an insufficient (or a lack of) erosion depended also on geologic situation. In the bedrock there are Cretaceous and Jurassic rocks in which there is a deeper water circulation. A large part of the present bottom of the Czyżówka valley is under cultivation and the ground-water level in the axis of the valley occurs over 6 m below its bottom.

In conclusion we infer that explanation of certain processes which took place in historical times up to present days requires in some cases tracing back to the paleomorphology of the area.

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LES MÉTHODES D'ÉTABLISSEMENT DES CARTES TOPOCLIMATIQUES

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1. QU'EST-CE QUE LA TOPOCLIMATOLOGIE?

Il y a déjà un quart de siècle, en 1953, que le célèbre climatologue américain C.W. Thornthwaite a proposé à Washington, au cours de la première réunion de la Commission de Climatologie de l'OMM (Organisation Météorologique Mondiale), un terme nouveau: topoclimatologie. Ce terme, comme celui du topoclimat, s'est répandu assez rapidement dans la littérature scientifique. Etymologiquement, topoclimat ne peut signifier que climat d'un lieu. En effet, 'topos' en grec (correspondant à 'locus' en latin) signifie littéralement lieu. Pourtant, lieu peut être compris de deux façons: 'sensu stricto' en tant que point, 'sensu lato' en tant qu'endroit ou petite région, c'est-à-dire une portion de la surface terrestre. Topoclimat serait donc synonyme de climat local, et topoclimatologie signifirait science du climat local. Il est toujours utile de remplacer une expression composée de plusieurs mots par un seul terme, beaucoup plus fonctionnel. En particulier, il facilite la création d'expressions dérivées, par exemple d'adjectifs, comme topoclimatique ou topoclimatologique, ce qui serait difficile à partir du terme 'climat local'. De plus, 'topos' et 'climat' sont tous les deux d'origine grec, ce qui permet leur réunion en un seul mot.

C. W. Thornthwaite, lui même, envisageait le topoclimat comme le climat d'un lieu ou d'un espace très petit ("... the climate of a very small space might be called topoclimate ..."), et la topoclimatologie comme une branche de la climatologie étudiant le climat local. "Topoclimatology can only mean the study of the climate of a place" (Thornthwaite, 1958). Pourtant, ceci pose d'emblée la question suivante: où se situe la limite entre le topoclimat et les autres notions telles que le macroclimat, le mésoclimat et le microclimat? Il est évident que le climat de chaque point du globe est conditionné par des facteurs astronomiques, régionaux et locaux. Il semble donc que l'on puisse définir le topoclimat comme le climat se formant sous la seule influence des facteurs locaux, c'est-à-dire existant en un lieu donné ou dans ses environs les plus proches. L'acceptation de ce principe faciliterait la détermination de la place de la topoclimatologie dans les sciences du climat: nous avons affaire à une échelle topoclimatique lorsque le climat est fonction de facteurs tels que le relief, la végétation, les eaux, les sols etc. En étudiant les phénomènes climatiques à une échelle plus grande, la situation est inverse; par exemple, la couverture végétale

cesse d'être un facteur climatique mais devient fonction du climat. Evidemment, il n'est pas simple de définir où se situe la limite entre ces deux types de relations; en effet, il faut se rappeler que les liaisons et les influences entre les différentes composantes de l'environnement géographique sont le plus souvent réciproques. Ceci nécessite de trouver, sur l'échelle des phénomènes examinés, un point à partir duquel une des directions d'influence commence à dominer la seconde.

D'une façon générale, on peut dire que, dans la hiérarchie climatologique (macroclimat, mésoclimat, microclimat) le topoclimat occupe une place intermédiaire entre le méso- et le microclimat. Evidemment, les limites entre ces notions sont assez floues et ne peuvent pas être déterminées de façon rigoureuse. Il semble pourtant que l'on puisse s'entendre sur la constatation suivante: si le mésoclimat est une notion régionale, le topoclimat est plutôt une notion typologique. Ainsi donc, chaque mésoclimat pourrait se diviser en une série de topoclimats, par exemple les topoclimats de vallées, de prés, de forêts, de terrains urbanisés etc. Par contre, la notion de microclimat se rapporte aux variations non seulement horizontales mais aussi verticales. Ainsi, on parle des microclimats des différents étages forestiers ou du microclimat des espaces clos, par exemple d'une cale de navire. De ce point de vue, le microclimat est déjà dépourvu de caractère géographique, contrairement au mésoclimat et au topoclimat. Généralement, les données d'observation des principales stations météorologiques suffisent à décrire les conditions macro- ou mésoclimatiques. La localisation de ces stations doit répondre à certaines exigences, assez strictes: terrain plat, découvert, pelouse coupée courte. Dans des conditions différentes nous aurions affaire à des topoclimats différents. Chacun d'eux peut être caractérisé quantitativement par les écarts entre les valeurs des éléments météorologiques observées en un lieu donné et à la station fondamentale. Ces écarts, en principe, doivent toujours se rapporter au même niveau standardisé des mesures sous abri au dessus de la surface du sol (ou plutôt au dessus de la surface active). De cette façon, la notion de topoclimat, contrairement au microclimat, concernerait toujours la couche basse de l'atmosphère, ou plus précisément la couche limite de surface dans laquelle les flux verticaux d'énergie (chaleur) et de masse (H_2O, CO_2, etc...) sont conservatifs.

Pour la notion du topoclimat ainsi définie, différents chercheurs ont utilisé et utilisent toujours des termes divers. Dans la littérature allemande, outre topoclimat (Tanner, 1971) et climat local "Lokalklima", on rencontre souvent "Geländeklima" et "Geländeklimatologie" (Knoch, 1949) ainsi que "Kleinklima" (Geiger, 1961). Quelques chercheurs identifient topoclimat et mésoclimat en les considérant comme synonymes (Wallén, 1968). Par contre, dans les travaux des climatologues soviétiques le terme microclimat est le plus souvent employé pour aborder les phénomènes météorologiques à la même échelle que celle que nous avons décrite ci-dessus (Gol'tsberg, 1967, Kausyla, 1972a, Chtcherban, 1968). L'étude de M. M. Yoshino, qui passe en revue de façon exhaustive et très détaillée les différentes définitions utilisées (Yoshino, 1968), montre que dans ce domaine il règne une grande hétérogénéité, qui provoque des confusions, et rend très souvent difficile la compréhension des déductions de certains auteurs. Tout ceci implique la nécessité de mettre de l'ordre dans la terminologie.

L'utilisation des termes topoclimat et topoclimatologie possède encore un autre avantage: la liaison, établie au moins par les géographes, entre les cartes topoclimatiques et topographiques. Ainsi, on se rend compte immédiatement quelle est l'échelle de l'étude. Cependant, ce rapprochement peut présenter un inconvénient: la confusion entre le terme "topographie" (topography) et celui du "relief du terrain". En effet, on dit parfois qu'un terrain est dépourvu de topographie quand il est plat, sans relief (Bitan, 1975). C'est pourquoi certains chercheurs (Geiger, 1969) considèrent la topoclimatologie comme une partie de la climatologie s'occupant uniquement de l'influence des formes du terrain sur le climat local. Cependant, il faut rappeler que topographie signifie littéralement description d'un lieu ou d'une petite zone. C'est ainsi que Thornthwaite comprenait la topographie et justifiait ainsi sa proposition du terme topoclimatologie.

2. ESSAI DE CLASSIFICATION DES CARTES TOPOCLIMATIQUES

Le but principal de la topoclimatologie est l'explication et la quantification des mécanismes d'influence des facteurs locaux sur les différents processus et phénomènes météorologiques. Une des tâches les plus importantes de la topoclimatologie est aussi, et sans doute, la cartographie détaillée du climat. Dans beaucoup de pays des nombreuses expériences ont été réalisées dans cette direction au cours des dernières décennies. Ainsi, des cartes climatiques détaillées ont été établies pour différentes régions, à différentes échelles et à l'aide des méthodes différentes. Leurs contenus sont très variés, ce qui empêche leur comparaison.

Il n'est pas possible dans cet article de citer tous les essais actuels de cartographie détaillée du climat. Constatons seulement que les cartes appellées "topoclimatiques" ne répondent pas toutes à la définition proposée du topoclimat. Ainsi, par exemple, la carte topoclimatique de Roumanie, dressée à l'échelle de 1:1 500 000 (Neamu et al., 1970a) montre, en couleur, 8 étages climatiques, et, à l'aide de symboles, 11 "topoclimats élémentaires" tels que les topoclimats de vallées, de dunes de lacs etc. De plus, la carte indique la répartition de 63 "topoclimats complexes" qui constituent plutôt les régions climatiques de Roumanie, caractérisées par les valeurs moyennes des éléments météorologiques principaux. De même, une autre, carte appelée "topoclimatique", de 1:500 000, présente, à l'aide de couleurs, les zones d'altitude, et, à l'aide de symboles, quelques formes du relief. Elle indique aussi les aires de différentes formations végétales et les zones d'action des vents locaux (foehn, mistral).

On peut distinguer trois groupes de cartes climatiques détaillées selon leur contenu:

a — les cartes présentant la distribution géographique des principaux éléments climatiques ou des indices du climat (cartes analytiques);

b — les cartes présentant la division du terrain étudié en unités climatiques ayant un caractère plus typologique que régional; il s'agit donc des types de topoclimats et non pas des microrégions (cartes synthétiques);

c — les cartes présentant l'évaluation des conditions climatiques sous diverses

optiques, par exemple du point de vue de l'agriculture, de la sylviculture, du tourisme, des transports, etc. (cartes d'évaluation).

Cette classification ne constitue évidemment qu'une convention. Il arrive que sur une même carte l'on trouve des éléments caractéristiques de deux ou même de trois groupes distingués, ce qui rend son classement parfois difficile. Comme chaque groupe exige des méthodes différentes, cette classification possède aussi un caractère méthodologique.

2.1. LES CARTES ANALYTIQUES

Il est évident que les cartes du premier groupe, montrant la distribution géographique des éléments ou des indices du climat, doivent être fondées sur des données d'observations ou de mesures. Cependant, il est rare que l'on dispose de résultats d'observations et de mesures portant sur une longue période et issus d'un réseau dense de stations météorologiques, établi spécialement pour le terrain étudié; un réseau qui, confronté aux stations climatologiques, apporterait des compléments d'information indispensables. Ce procédé de recherche est trop onéreux pour qu'on puisse l'appliquer à des régions, même de surface restreinte. C'est pourquoi, dans la plupart des cas, on utilise les résultats de mesures sporadiques, exécutées durant des périodes relativement courtes, à des époques choisies de l'année ou même au cours de journées caractéristiques. Ces mesures peuvent être effectuées soit en postes fixes soit en patrouilles. Ici, le choix des points de mesure, représentant toutes les particularités du terrain étudié, est d'une importance fondamentale. Le climatologue doit donc avoir une bonne connaissance du terrain et des lois régissant l'influence des différents facteurs locaux sur le topoclimat. Une formation de caractère géographique se révèle ainsi indispensable.

Le choix de la période des mesures et de leur durée est pour le moins aussi important. En général, il n'est pas possible d'effectuer des mesures au cours de toutes les situations météorologiques typiques pour la région. D'ailleurs, ce n'est pas toujours nécessaire. Le plus souvent, la période qui nous intéresse est celle où les variations spatiales du phénomène étudié sont les plus accentuées. On sait que les différences de température et d'humidité sont les plus grandes lors d'un ciel serein ou à nébulosité faible, et par calme ou par vent faible. Par ce type de temps, appellé souvent "radiatif", on s'efforce d'exécuter des mesures devant servir à l'établissement de la carte topoclimatique. Pourtant, il est certain que quelques phénomènes météorologiques se caractérisent par une grande différenciation aussi au cours d'autres types de temps: par exemple, la vitesse du vent, et, liée à celle-ci, la pollution atmosphérique. De nouveau, ceci montre la nécessité d'une bonne connaissance des problèmes micrométéorologiques compris en tant que physique de la couche limite de surface. Ces difficultés pourraient être en partie résolues en effectuant des mesures par un système stationnaire, simultanément en plusieurs endroits, pendant une période suffisamment longue pour englober au moins les situations les plus caractéristiques, sinon toutes les situations météorologiques. Pourtant, cette solution n'est pas toujours réalisable car elle se révèle aussi trop coûteuse.

Le domaine et la nature des mesures peuvent être très divers. D'une part, elles ne peuvent pas être "standardisées" comme celles effectuées dans les stations du réseau météorologique fondamental. Néanmoins, il est toujours intéressant de faire des mesures ponctuelles en liaison avec la station météorologique la plus proche, ce qui facilite l'interprétation ultérieure des résultats obtenus. Enfin, dans les recherches topoclimatologiques, il convient plutôt de déterminer les écarts des valeurs des éléments étudiés entre les postes de mesure et la station de référence, que de mesurer leurs valeurs absolues. Ce fait n'est pas sans influence sur le choix des instruments et des techniques de mesure les plus adéquates.

Les instruments doivent être relativement simple à manier, facile à transporter et à installer. Mais ils doivent aussi assurer une précision indispensable. Rappellons que les mesures à distance (télémesures) comportent les erreurs relativement faibles. Il s'agit par exemple des mesures à l'aide de thermomètres électriques, qui permettent d'éviter les perturbations dues à la présence de l'observateur ou du moyen de transport.

En ce qui concerne la forme cartographique, la méthode des isarythmes est rarement utilisée. En effet, elle ne rend pas de façon réelle la différenciation dans l'espace des traits du topoclimat. C'est pourquoi la plupart des cartes topoclimatiques présente les conditions thermiques du terrain par zones plus ou moins chaudes, délimitées d'ailleurs de façon assez peu rigoureuse. C'est le cas de la carte des "climatopes", exécutée à l'échelle de 1:25 000 pour une petite région de la R.D.A. (Haase, 1964). Elle présente, entre autres, trois zones froides de vallée (intensités: très forte, forte et faible) et trois zones chaudes de versant (intensités: faible, forte et très forte) qui se forment pendant les nuits claires; il y a aussi quatre zones thermiques se manifestant pendant la journée et dépendant du bilan local du rayonnement solaire. En ce qui concerne la présentation des conditions thermiques, la carte topoclimatique des environs de Bâle, également à l'échelle de 1:25 000 (Marr, 1970) ressemble à la carte précédante. Elle indique 5 zones froides (intensités: normale, faible, moyenne, forte et très forte) au cours de la nuit, mais une seule zone chaude au cours de la journée.

On peut mentionner aussi une série de cartes détaillées des environs de la station balnéaire de Ciechocinek en Pologne, à l'échelle de 1:50 000 (Kozlowska-Szczęsna, 1964, 1965) présentant, par zones, la répartition nocturne et diurne des écarts (positifs, négatifs ou nuls) de la température de l'air, de l'humidité relative, et de la vitesse du vent, par rapport aux valeurs relevées à la station météorologique locale.

2.2. LES CARTES SYNTHÉTIQUES

Il découle des considérations précédentes que les résultats des mesures des éléments du climat constituent la base des cartes analytiques. Par contre, c'est à partir de la connaissance de la distribution spatiale des facteurs du climat qu'on construit les cartes synthétiques présentant les aires des différents topoclimats. Dans ce cas, les mesures instrumentales sont évidemment nécessaires. Mais elles ne servent qu'à caractériser quantitativement les différences entre les topoclimats. De plus, elles permettent de contrôler les conclusions de l'analyse de la distribution spatiale des fac-

teurs du climat. Rappelons que la base principale de la délimitation des unités topoclimatiques n'est pas la connaissance de la répartition des éléments (comme par exemple de la température), mais celle des facteurs qui la régissent.

Un grand nombre d'informations nécessaires peuvent être obtenues à partir de l'analyse de la seule carte topographique. Il s'agit ici avant tout du relief, ou plus précisément, de la pente et de l'exposition des versants, qui ont une importance particulière pour l'insolation de la surface active. C'est pourquoi, l'estimation cartométrique du degré d'insolation du terrain, constitue très souvent une des bases de l'établissement des cartes topoclimatiques (Quitt, 1965, 1970). Pourtant, on ne peut pas oublier que le bilan radiatif de la surface active et, en conséquence, les conditions thermiques des couches basses de l'atmosphère dépendent non seulement de la quantité de rayonnement solaire direct, mais du rayonnement global, donc de la somme du rayonnement direct et du rayonnement diffusé. Ceci nécessite également la prise en compte de l'occultation de l'horizon et, surtout, de l'influence de la nébulosité, et en particulier, de son évolution journalière, caractéristique pour la région étudiée. Malheureusement, la légende ou la description des cartes n'indiquent pas toujours ce qu'il faut comprendre par insolation (ou par insolation relative): est-ce le flux du rayonnement direct ou du rayonnement global par unité de surface?

La distribution spatiale des autres facteurs influençant le climat à l'échelle locale, et dont la connaissance est indispensable pour la délimitation des divers topoclimats, peut être définie à partir de l'analyse de différentes cartes thématiques comme, par exemple, la carte pédologique, hydrographique, phytosociologique, d'occupation du sol etc. Cependant, toutes ces cartes n'existent pas toujours pour le territoire étudié. C'est pourquoi le climatologue est souvent obligé de les préparer lui-même. Bien entendu, il n'est pas nécessaire de prendre en considération toutes les caractéristiques d'un facteur représentées sur les cartes thématiques habituelles. Il suffit de tenir compte des traits qui sont importants pour les conditions topoclimatiques. On rencontre des exemples intéressants de ce type de catographie préparatoire, qui facilite énormément l'établissement de la carte topoclimatique proprement dite (Kausyla, 1971, 1972b). L'analyse de la photographie aérienne, effectuée sous cette optique, peut être aussi très utile.

Si les différences dans la structure du bilan thermique de la surface active constituent le critère de la classification des topoclimats, la préparation de telles cartes de base devient indispensable. On peut citer, à titre d'exemple, les cartes des diverses propriétés physiques de la surface active, comme: le coefficient de réflexion (albedo) qui est décisif pour la quantité du rayonnement solaire absorbé, le degré de l'occultation de l'horizon, important pour le bilan radiatif de grandes longueurs d'onde, la capacité calorifique du sol dont dépend le flux conductif (Paszyński, 1964). On peut ajouter d'autres propriétés, comme le paramètre de rugosité qui joue un rôle décisif dans le transfert turbulent, ou la résistance de surface, qui agit sur l'évapotranspiration actuelle. Leur connaissance permet la détermination des valeurs relatives des composantes du bilan thermique, c'est-à-dire de leurs écarts par rapport aux valeurs considérées comme "normales", observées sur un terrain plat, dégagé, correspondant aux conditions des stations météorologiques fixes.

Il existe un grand nombre de cartes présentant les aires des topoclimats distingués. La carte topoclimatique du bassin de la Nida moyenne en Pologne méridionale (Paszyński, 1963, 1966, 1968) en fournit un exemple. On y trouve 9 types de topoclimat. Le critère de classification a été les valeurs des écarts (positifs, négatifs, ou pratiquement nuls) des trois termes principaux du bilan thermique de la surface active: flux radiatif, flux conductif, flux turbulent de chaleur latente. Les écarts du quatrième terme, flux turbulent de chaleur sensible, ont permis le regroupement des neuf types en trois groupes de topoclimats.

La typologie topoclimatique proposée par M. Hess de l'Université de Cracovie, a été élaborée sur des principes totalement différents. Elle prend en considération les conditions thermiques et hygrométriques, caractéristiques de différentes formes du relief, calculées à partir de la moyenne annuelle et de la variation journalière de la température de l'air (Hess et al., 1975). Cette méthode a été appliquée à la cartographie de quelques régions de la Pologne méridionale. On y a distingué des unités typologiques appelées d'ailleurs mésoclimatiques ou microclimatiques (Klein, 1974, Niedźwiedź, 1967, Niedźwiedź, Obrębska-Starklowa, 1972, Obrębska-Starklowa, 1972).

Des essais semblables de cartographie des types de climat ont été réalisés dans différents pays. On peut citer entre autres les cartes topoclimatiques du delta du Danube en Roumanie (Neamu et al., 1970b), de la péninsule Tihany et des environs de la station balnéaire de Heviz en Hongrie (Endrödi, 1972) ou des quelques zones en URSS (Karing, Iygi, 1974). Cependant, ces essais n'ont jamais été appliqués à l'ensemble du territoire national ou même à une région étendue.

Souligons que dans de nombreux cas les unités topoclimatiques distinguées portent des noms de caractère géomorphologique, comme par exemple "mésoclimat des fonds de vallées" ou "région du mésoclimat de plateau". L'utilisation d'une telle terminologie peut être justifiée car, à cette échelle, les différences topoclimatiques d'une région de montagne dépendent avant tout du relief. Néanmoins, le caractère climatologique de chacune de ces dénominations doit être nécessairement indiqué. Sinon la carte topoclimatique n'est qu'une carte géomorphologique. La meilleure solution serait d'utiliser des noms issus directement de la climatologie. Pourtant, ceci n'est pas toujours simple, étant donné la complexité du problème.

2.3. LES CARTES D' ÉVALUATION

En ce qui concerne le troisième groupe de cartes topoclimatiques, il convient de noter que toute évaluation ne peut être effectuée que par rapport à des besoins pratiques bien définis. Il n'est même pas toujours correct de parler d'évaluation des conditions climatiques pour l'agriculture car chaque type de culture possède des exigences spécifiques. Ainsi, par exemple, les conditions propices au maraîchage peuvent être défavorables à la culture du blé et inversement. Donc, le but de chaque carte topoclimatique comprenant des éléments d'évaluation doit être clairement précisé.

La plupart de cartes topoclimatiques de ce type, que l'on pourrait appeler "d'évaluation", sont établies pour les besoins des différentes branches de l'agriculture.

Ceci n'est pas étonnant, car l'agriculture est certainement une des activités économiques les plus dépendantes du climat. L'étude du topoclimat pour les besoins agricoles s'appelle agrotopoclimatologie, et les cartes correspondantes sont des cartes agrotopoclimatiques (Hogg, 1968, Schnelle, 1968, Van Eimern, 1968a, 1968b, Wallén, 1968). De nombreuses cartes climatiques détaillées sont aussi effectuées pour d'autres besoins pratiques, comme par exemple pour l'urbanisme (cartes établies en Pologne par le bureau d'études physiographiques "Geoprojekt"), ou pour la récréation et loisir (cartes topoclimatiques des stations de cure en Pologne, établies par l'Institut de Géographie de l'Académie Polonaise des Sciences).

L'étude du climat du canton de Vaud en Suisse (Primault, 1972) est un excellent exemple d'étude topoclimatique effectué pour les besoins de l'aménagement régional. Elle comporte une série de cartes à l'échelle de 1 : 200 000 ou même à 1 : 500 000. Les cartes présentent d'une part la distribution des différents éléments et indices du climat (par exemple: nombre de jours de gel, durée d'insolation possible, vents locaux, brouillards) et, d'autre part, l'évaluation du climat pour divers besoins (par exemple: horticulture, viticulture, habitation, climatothérapie, industrie, tourisme). Quelques unes de ces cartes contiennent aussi des indications concernant l'amélioration des conditions climatiques existantes. Dans ce but l'auteur préconise la plantation de rideaux-abris ou l'irrigation de complément dans certains endroits présentés sur des cartes séparées. L'étude comprend 28 cartes dont la plupart, selon notre définition, pourrait être appeler topoclimatiques. Cependant, il manque une carte synthétique des types de topoclimats.

Rappelons ici les méthodes d'évaluation par points, utilisées pour l'établissement des cartes topoclimatiques de ce type. Ces méthodes se fondent sur l'attribution conventionnelle à chaque lieu d'un certain nombre de points selon un schéma préparé d'avance. Les principes de ce mode d'évaluation ont été établis pour les besoins de l'agriculture (Uhlig, 1954). On a essayé de déterminer ainsi le niveau de risque des situations gélives d'origine locale. Une méthode semblable a été proposée pour les besoins de l'urbanisme (Böer, 1952, Gregor, 1958). Cependant, ces méthodes, par nature, ne sont jamais absolument objectives. C'est pourquoi les résultats obtenus ne sont pas toujours satisfaisants.

L'élaboration correcte de cartes d'évaluation nécessite une coopération étroite entre climatologue et d'autres spécialistes. En effet, le climatologue ne peut pas connaitre parfaitement les exigences de toutes les activités économiques et sociales.

Il semble que le meilleur moyen serait d'établir les différentes cartes d'évaluation à partir d'une carte détaillée des topoclimats, présentant les aires des unités typologiques fondamentales. Ces unités peuvent donc être évaluées de diverses façons, en fonction des besoins pratiques.

3. PROJET DE LA CARTE TOPOCLIMATIQUE DE POLOGNE

Tenant compte des considérations précédentes il apparait nécessaire d'établir une carte topoclimatique pour l'ensemble du territoire national. Cette carte correspondrait à d'autres cartes détaillées du pays, comme les cartes géomorphologiques, hydro-

graphiques, pédologiques, etc. Elle serait la carte fondamentale permettant l'établissement d'une série de cartes dérivées (cartes d'évaluation, du 3ème groupe), réalisées pour les besoins des différents domaines de l'économie nationale. La méthode élaborée par le Département de Climatologie de l'Institut de Géographie de l'Académie Polonaise des Sciences, pourrait servir de base à l'établissement d'une telle carte initiale.

Cette méthode repose sur le principe suivant: On attribue aux plus petites unités géographiques déterminées d'avance, un contenu climatologique qui est, dans ce cas, la structure du bilan thermique de la surface active. De cette façon, la connaissance du caractère des échanges d'énergie à la surface limite Terre-atmosphère, est le point de départ de la méthode, ces échanges étant le processus fondamental de la formation des conditions climatiques en un lieu donné. L'avantage essentiel d'une telle carte est son approche génétique à la topoclimatologie. Si, par exemple, nous nous intéressons au problème de gelées locales, on peut, à partir d'une telle carte, définir non seulement les aires de leur apparition particulièrement fréquente, mais aussi les causes de ce phénomène. La connaissance de ces causes est indispensable aux choix des moyens d'intervention les plus appropriés pour lutter contre les gelées et même pour améliorer les conditions climatiques existantes. En effet, il est important de savoir si les gelées, fréquentes en un lieu donné, sont dues à une advection locale d'air froid qui s'écoule des terrains voisins plus élevés, ou à une mauvaise conductivité thermique du sol, ou à des pertes de chaleur particulièrement grandes résultant d'une évapotranspiration intense, ou, enfin, à toute autre cause.

La méthode proposée a été déjà mentionnée dans le chapitre précédent, concernant les cartes synthétiques. Elle est décrite de façon détaillée dans (Paszyński, 1966).

Évidemment, la méthode nécessite encore des perfectionnements et des études complémentaires. Cependant, les résultats de son application à la cartographie topoclimatique à 1:100 000 de quelques petites régions en Pologne indiquent qu'elle pourrait être utilisée pour l'établissement de la carte topoclimatique de l'ensemble du territoire national.

Ce type de cartographie constitue une des missions les plus importantes de la climatologie contemporaine.

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TOPOCLIMATIC INVESTIGATIONS OF HEALTH RESORTS

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The interest taken in the local climate of health resorts results from the significant role it plays in medical treatment. Therefore, methods of evaluating topoclimatic conditions of health resorts should make use of the fact that the atmospheric environment affects the human body. What seems to meet this need are among other things, those methods which consist in investigating the process of heat exchange between the human body and the atmosphere.

In Poland there are about fifty health resorts. The climate of the majority of them has already been described in studies of a monographic nature. These studies are based above all on the analysis of multiannual data obtained from local meteorological stations, the analysis being made from the point of view of needs and requirements of bioclimatology, as well from the results of field investigations (mainly expeditions). The objective of these investigations is to understand the spatial differentiation of topoclimatic conditions, and their final result — a classification map showing areas of different degrees of usefulness for climatotherapy. Works and studies of this kind are being carried out first of all at the Department of Climatology of the Institute of Geography and Spatial Organization of the Polish Academy of Sciences in Warsaw, in the Balneoclimatic Institute in Poznań, at the Department of Bioclimatology of the Institute of Meteorology and Water Management in Warsaw, and in geographical institutes at the universities in Łódź and Lublin.

As a result of cooperation between the Balneoclimatic Institute in Poznań and the Institute of Meteorology and Water Management a bioclimatic monograph of twenty-two Polish health resorts was prepared (Jankowiak, Parczewski, 1978). The monograph includes the characteristics of some significant features of bioclimate and an evaluation of their use for climatotherapy.

What should be mentioned first of all among studies on the climate of health resorts are those which take the energy exchange between the human body and the environment as a basis for distinguishing topoclimatic units. In the bioclimatological studies of Polish health resorts some complex bioclimatic indices such as sensible temperatures and the cooling power of air are most frequently used to this end.

In a bioclimatic monograph of Ciechocinek T. Kozłowska-Szczęsna (1964) for the first time presented maps of equivalent-effective temperatures (NTE) for the area

of this health resort and explained the causes of their deviations. On the basis of areal distribution of sensible temperatures (NTE and RTE) and the values of the cooling power of air a bioclimatic classification of a number of health resorts was made mainly for mountain regions, in the Carpathians of: Iwonicz (Krawczyk, 1975), Rymanów (Krawczyk, 1977), Szczawnica (Zych, Kłysik, 1974), Krynica (Baliński, 1974), Żegiestów (Nurek, 1979); in the Sudetes of: Kudowa (Kozłowska-Szczęsna, 1975), Świeradów (Kozłowska-Szczęsna, 1976), Polanica (Zawadzka, 1976), Cieplice Śląskie (Kozłowska-Szczęsna, 1977), Kowary (Kozłowska-Szczęsna, 1978), Bolków (Kozłowska-Szczęsna, 1978); as well as of upland ones: Busko (Dykczyńska, 1966), Nałęczów (Michna, Paczos, Zinkiewicz, 1976), and lowland and seaside health resorts: Połczyn (Kozłowska-Szczęsna, 1979), Krynica Morska (Marciniak, 1975), Kołobrzeg (Tyczka, 1964). Due to general urbanization and the rapid growth of many health resorts an increase in air pollution began to be an important problem, considered from the point of view of bioclimatology. Therefore, air quality started to be regarded as a criterion of evaluation of topoclimatic conditions in some bioclimatic studies (Zych, Kłysik, 1974; Baliński, 1974; Kozłowska-Szczęsna, 1975; Zawadzka, 1976). Other criteria of evaluation are based on physico-chemical factors which influence the human body. The question here is that of air ionization and the aerosol content in the air of maritime origin (Tyczka, 1964, 1968).

The present study presents an attempt to evaluate topoclimatic conditions of a small health resort in the Carpathians (Iwonicz) by the method of the heat balance of the human body.

What was taken as a basis for consideration was M. I. Budyko's equation of the heat balance (Budyko, 1971; Liopo, Tsitsenko, 1971) which includes all the significant meteorological factors influencing the heat budget of the human body, as well as the kind of clothes and the level of physical activity. The equation after some modifications) takes the following form

$$R_K + M = LE + P + R_L.$$

The income side of the equation includes:

R_K — solar radiation absorbed by the surface of human body,

M — metabolic heat production.

The expediture side contains:

LE — evaporational loss of heat,

P — turbulent loss of sensible heat,

R_L — heat loss by long-wave radiation.

Such forms of heat exchange as heat losses by respiration and by conduction through contact with the ground were not taken into account due to their insignificant numerical values. The components of the equation may be expressed in $\mathrm{cal \cdot cm^{-2} \cdot min^{-1}}$ or in $\mathrm{W \cdot m^{-2}}$. Our considerations refer to a human body with a constant heat production ($M = 70\ \mathrm{W \cdot m^{-2}} = 0.1\ \mathrm{cal \cdot cm^{-2} \cdot min^{-1}}$), dressed in ordinary summer clothes with constant thermal insulation properties (1 CLO).

The unit of the lateral surface of a vertical cylinder was assumed to be the model surface when calculating radiation fluxes. Then

$$R_K = \left[S \frac{\operatorname{ctg} h}{\pi} + \frac{1}{2} Q + \frac{1}{2} (S+Q) a_0 \right] (1-a_c),$$

where:

S — intensity of direct solar radiation on a horizontal surface,
h — Sun's altitude,
Q — intensity of diffuse solar radiation on a horizontal surface,
a_0 — albedo of the ground surface (assumed to be 0.20),
a_c — albedo of the skin-clothing surface (assumed to be 0.30).

Heat exchange by long-wave radiation (R_L) occurs between the human body surface and the atmosphere and ground. According to the assumption of isotropic distribution of radiation fluxes, the long-wave radiation of the unit of the accepted model of a body equals half the long-wave radiation flux of the ground surface including corrections due to the temperature differences between the human body surface and the atmosphere as well as the ground. The long-wave radiation of the ground surface was calculated from Jefimova's empirical formula. Thus

$$R_L = \frac{1}{2} [s\sigma T^4 (a - b \cdot e)(1 - c \cdot n)] - 2s\sigma T^3 (T_g - T) + 4s\sigma T^3 (T_S - T),$$

where:

s — emissivity of the radiating surface = 0.95,
σ — Stefan-Boltzmann constant,
T_s — skin temperature,
T — air temperature,
T_g — temperature of the earth's surface,
e — vapour pressure,
c — coefficient characterizing the type of clouds,
n — cloudiness,
a and b — regression coefficients.

The turbulent flux of sensible heat was calculated from the formula

$$P = \varrho c_p D (T_s - T),$$

where:

ϱ — air density,
c_p — heat capacity of air,
D — coefficient of turbulent diffusion proportional to the square root of wind velocity,

and analogically, the flux of heat exchange due to transpiration of the human body surface

$$LE = L\varrho D (q_s - q) a,$$

where:

L — latent heat,

q_s — specific humidity of saturated air in skin temperature,
q — specific humidity of air,
a — coefficient characterizing the ratio of transpiration from the human body surface and evaporation from the water surface, when $a = f(T_s)$.

The final form of the equation of the heat balance of the human body (Krawczyk, 1979) includes also the kind of clothes, as a constant coefficient of heat conductivity of clothes is introduced. This coefficient determines heat diffusion in clothes and depends primarily on their thermal insulation which can be expressed in conventional units (CLO).

The basic material for the solution of the equation of the heat balance of the human body was provided by our own field measurements carried out in Iwonicz in 1971–1973. All meteorological elements enumerated were measured simultaneously in three points of the health resort, every hour between 7 a.m. and 8 p.m. The points represented: the centre of the health resort and the bottom of the valley of the Iwonicz brook (measuring point 'C'), an interforest glade on the slope exposed to the North-East (measuring point 'E'), and the upper parts of woodless slopes (measuring point 'G.W'). The difference in height between the lowest and the highest measuring points was about 100 m. The location of measuring points is shown in Fig. 5.

In order to investigate the process of heat exchange between the human body and the atmosphere and ground in Iwonicz the notion of the structure of the heat balance of the human body was used, i.e. the ratio of absolute values of heat lost by the human body and the heat contained in the body at a given moment. It was assumed that:

$\frac{LE}{R_K+M}$ means relative heat lost for transpiration in the heat balance of the human body,

$\frac{P}{R_K+M}$ means relative heat lost by the turbulent exchange of sensible heat,

$\frac{R_L}{R_K+M}$ means relative heat lost by long-wave radiation.

The sum of these quotient is always

$$\frac{LE+P+R_L}{R_K+M} = 1.0.$$

Then, quantitative relations between heat losses by transpiration, turbulence and long-wave radiation were divided into four groups of structural patterns, and their frequency (in percentages) serves as a basis for distinguishing bioclimatic units in the investigated area of the health resort.

Thus, the turbulent type of structure of the heat balance of the human body was distinguished. Then

$$\frac{P}{R_K+M} > \frac{LE}{R_K+M} > \frac{R_L}{R_K+M} \text{ type 1A,}$$

or

$$\frac{P}{R_K+M} > \frac{R_r}{R_K+M} > \frac{LE}{R_K+M} \text{ type 1B.}$$

The transpirative type of structure of the heat balance of the human body occurs when

$$\frac{LE}{R_K+M} > \frac{P}{R_K+M} > \frac{R_r}{R_K+M} \text{ type 2A,}$$

or

$$\frac{LE}{R_K+M} > \frac{R_r}{R_K+M} > \frac{P}{R_K+M} \text{ type 2B.}$$

The radiative type of structure of the heat balance of the human body occurs when

$$\frac{R_r}{R_K+M} > \frac{P}{R_K+M} > \frac{LE}{R_K+M} \text{ type 3A,}$$

or

$$\frac{R_r}{R_K+M} > \frac{LE}{R_K+M} > \frac{P}{R_K+M} \text{ type 3B.}$$

When the numerical values of all three forms of heat exchange were equal — the fourth, mixed type of structure of the heat balance of the human body occurred (type 4).

The analysis of the daily frequency of occurrence of different types of structure of the heat balance of the human body (Figs. 1–4) shows that the investigated area of Iwonicz-Zdrój is considerably differentiated in this respect. In the lower parts of the area (i.e. at the bottom of the valley of the Iwonicz brook and in lower parts of the surrounding elevations covered by forest and represented by the 'C' and 'E' measuring points) the transpirative type of structure of the heat balance of the human body holds from 9 a.m. till 4 p.m. and prevails in summer (Fig. 2). The maximum number of structural patterns occurs at 5 and 6 p.m. It can be supposed that it is exactly at that time of the day when different physical processes more or less equally take part in the formation of the thermal equilibrium of our body. At 7 and 8 p.m. in the centre of the health resort the predominance of heat exchange by long-wave radiation (3A and 3B type) is due to temperature differences between the human body and surrounding objects (atmosphere, ground).

The process of heat exchange was slightly different on the slopes of Góra Winiarska (Winiary Hill). During the whole day the turbulent type of structure of the heat balance of the human body (1A and 1B type) prevailed there, which is related to the higher wind velocity in this part of the health resort. What is peculiar is the fact that during the day the 2B type hardly ever occurs on the slopes of Góra Winiarska. It means that although transpirational heat exchange occurs there, turbu-

lent exchange, and not long-wave radiation, is the second most important kind of heat loss.

On cloudy days (i.e. with cloudiness $\geqslant 3/10$) the turbulent type of structure of the heat balance of the human body prevails resulting in a lower frequency of the transpirative type (Fig. 3).

On the other hand, on clear days (i.e. with cloudiness amounting up to 2/10 of the sky cover) the structure of the heat balance of the human body is more stable in Iwonicz. It is reflected both in a smaller number of structural patterns and in firm prevalence of the transpirative type (2A and 2B) which apart from evening hours prevailed in the whole investigated area (Fig. 4). This is so because on clear days the human body absorbs the maximum quantity of short-wave solar energy, and what follows the skin temperature rises and sweat glands become active. Weak air flow in turn, which accompanies radiational weather, makes it difficult for the excess of heat to be evaporated by turbulence in such air conditions. Therefore, the maintainance of thermal equilibrium of the body will depend on great efficiency of the thermoregulation system.

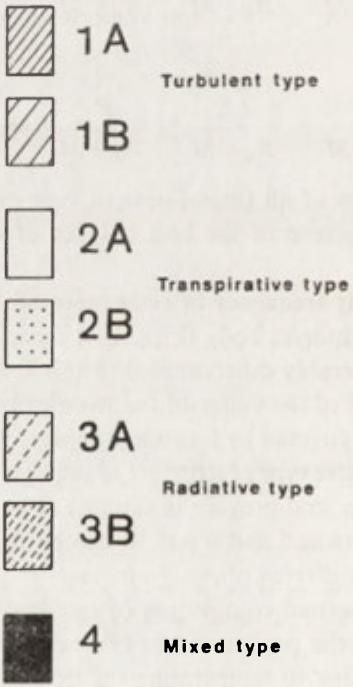

Fig. 1. Structural types of the heat balance of the human body. Explanations of figures 2,3 and 4

The presented distribution of frequency of types of the structure of the heat balance of the human body is characteristic of the local climate in Iwonicz-Zdrój and depends on areal differentiation of those meteorological elements which influence the kind of heat exchange between the human body and the atmosphere and ground. What is most impoıtant is the air flow. Natural orographic conditions make wind

velocities in the centre of the health resort, which is surrounded by afforested elevations much weaker than woodless slopes of Góra Winiarska. Therefore, the turbulent exchange of sensible heat is the main in the expediture side of the heat balance equation.

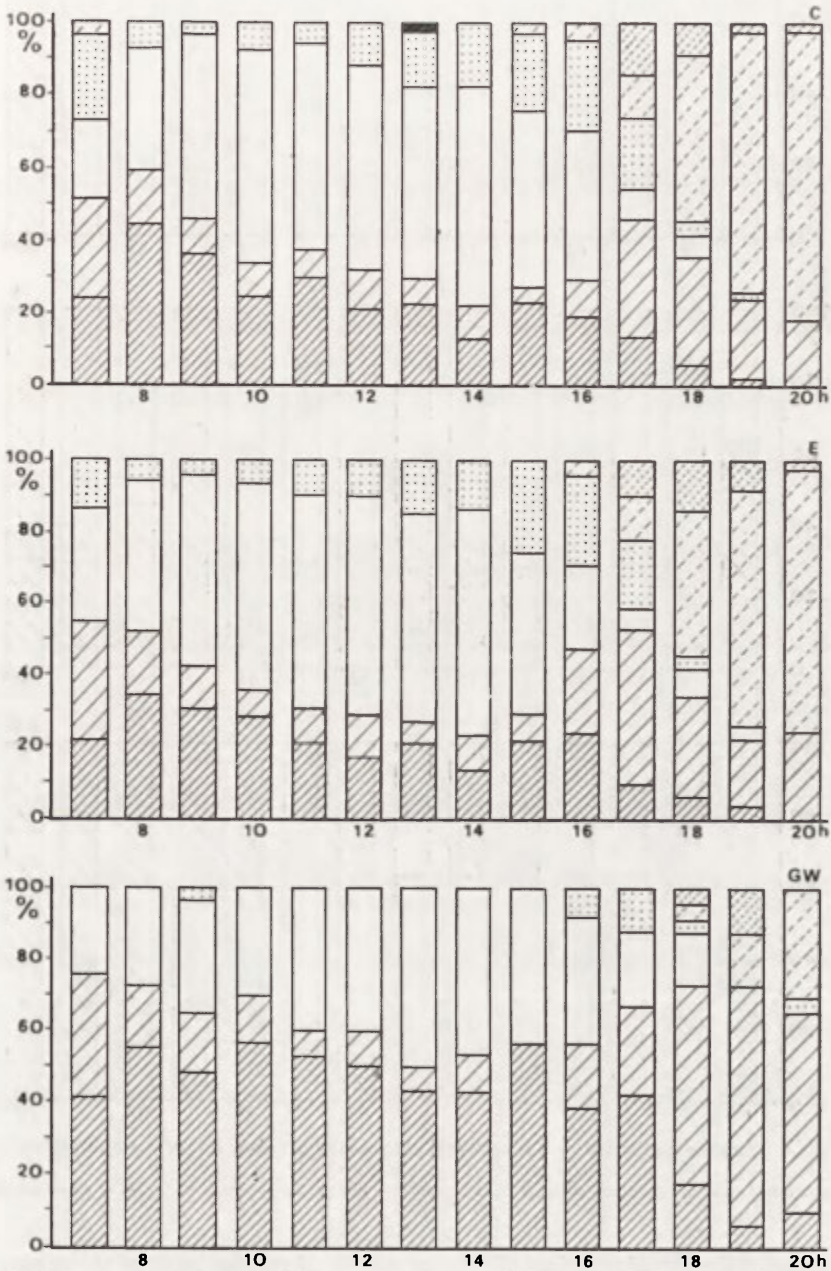

Fig. 2. Daily course of frequency of the structural types of the heat balance of the human body (mean values from all days)

C — measurement point in bottom of valley, E — measurement point in interforest glade, G. W. — measurement point on woodless slope

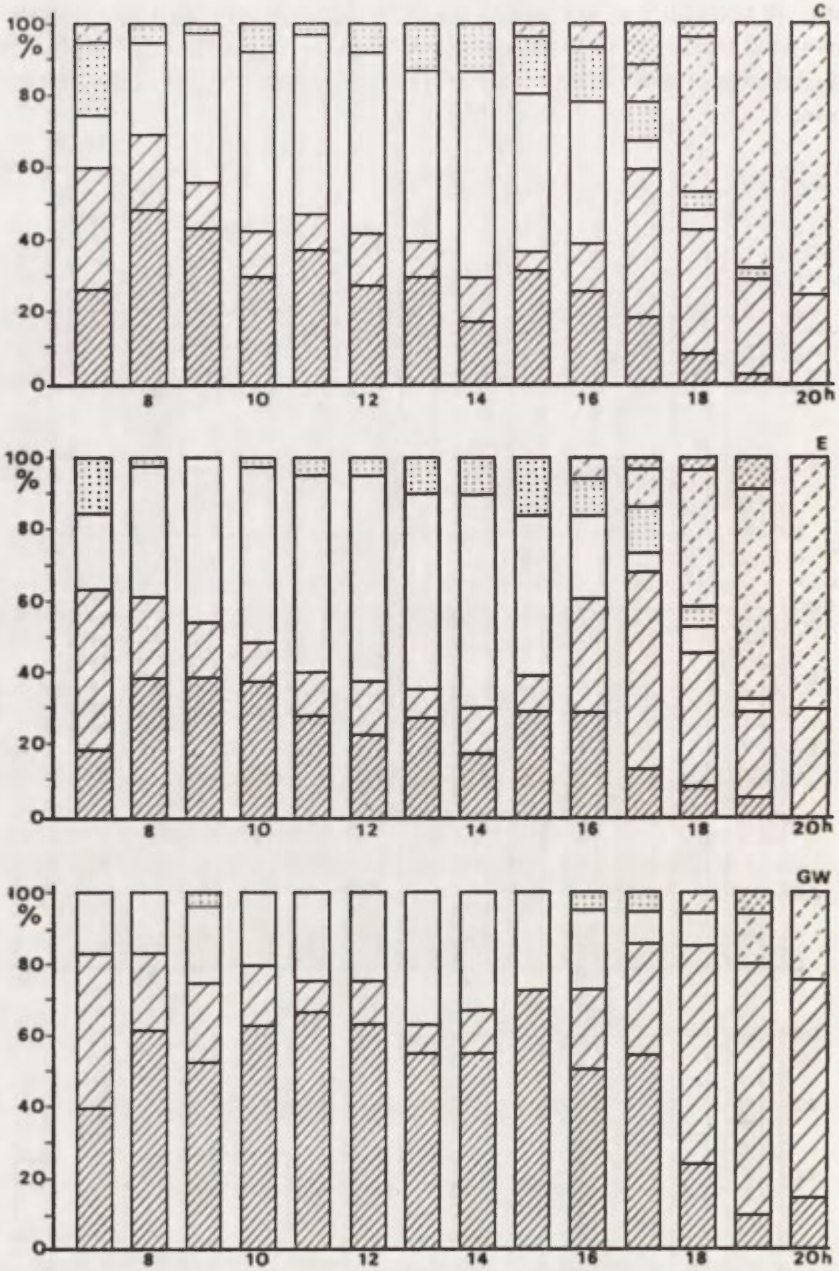

Fig. 3. Daily course of frequency of the structural types of the heat balance of the human body (mean values from cloudy days)
C — measurement point in bottom of valley, E — measurement point in interforest glade, G. W. — measurement point on woodless slope

The local climate of Iwonicz-Zdrój was evaluated on the basis of the assumption that data referring to the heat exchange between the human body and the atmosphere and ground were of great significance for bioclimatology of the human being.

TABLE 1. Mean frequency (in percentages) of the occurrence of different types of structure of the heat balance of the human body in Iwonicz

Type of weather	Measurement point	Types of structure of the heat balance 1A	1B	2A	2B	3A	3B	4
summer period	bottom of valley ('C')	20.2	15.2	35.8	11.8	15.1	1.8	0.1
	interforest glade ('E')	18.1	17.7	37.6	10.8	13.4	2.4	0.0
	woodless slope ('G.W')	41.0	23.4	29.4	2.0	3.2	1.0	0.0
summer period cloudy days	bottom of valley ('C')	25.2	19.4	31.5	8.7	14.3	0.9	0.0
	interforest glade ('E')	22.6	23.4	33.9	6.8	12.4	0.9	0.0
	woodless slope ('G.W')	49.1	27.4	19.5	0.9	2.8	0.3	0.0
summer period clear days	bottom of valley	5.5	2.8	48.3	20.9	17.6	4.4	0.5
	interforest glade ('E')	5.0	1.1	48.3	22.5	16.5	6.6	0.0
	woodless slope	10.7	8.3	66.7	6.0	4.8	3.5	0.0

The frequency of occurrence of different types of the structure of the heat balance of the human body (Table 1), and especially of the transpirative and turbulent types, was accepted as a basis for distinguishing bioclimatic units in the investigated area. It was assumed that the measuring points reflected the orographic conditions of Iwonicz-Zdrój well, and on this assumption it was stated that the investigated area could be divided into two units differing in the degree of influence of climatic factors on the human body (Fig. 5).

The first unit included the valley of the Iwonicz brook as well as the lower and middle parts of the surrounding elevations covered by mixed forest and characterized by considerable shading of the horizon. In summer, heat is taken off the human body mainly by means of evaporation. The loss of heat in the afternoon and evening is caused in this part of the health resort usually by long-wave radiation.

The second unit covers the remaining part of the investigated area, i.e. the woodless top and middle parts of Góra Winiarska. The turbulent type of structure of the heat balance of the human body which is very stable during the day prevails in this area. Bioclimatic conditions are more advantageous there, and only during cloudy weather and during the advection of air masses from the North-West, the human body may be exposed to substantial heat losses.

The two units distinguished according to bioclimatic criteria are separated by a forest boundary running in a W-E direction along the slopes of Góra Winiarska.

Taking into consideration the reactions of the human body to different impulses of the atmospheric environment one can state that the local climate of Iwonicz-Zdrój, evaluated from the point of view of the structure of the heat balance of the human body, is differentiated in summer both spatially and in respect of time. This is not

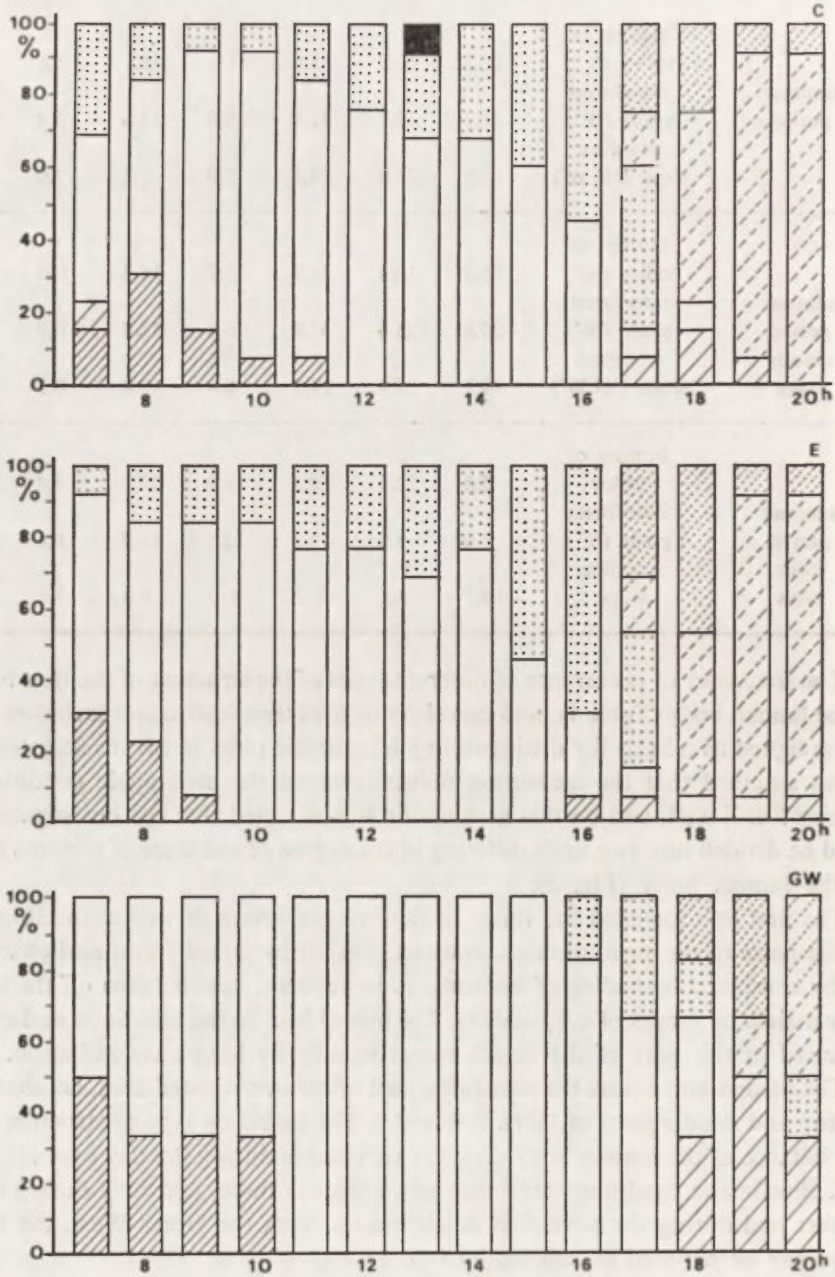

Fig. 4. Daily course of frequency of the structural types of the heat balance of the human body (mean values from clear days)

C — measurement point in bottom of valley, E — measurement point in interforest slope, G. W. — measurement point, on woodless slope

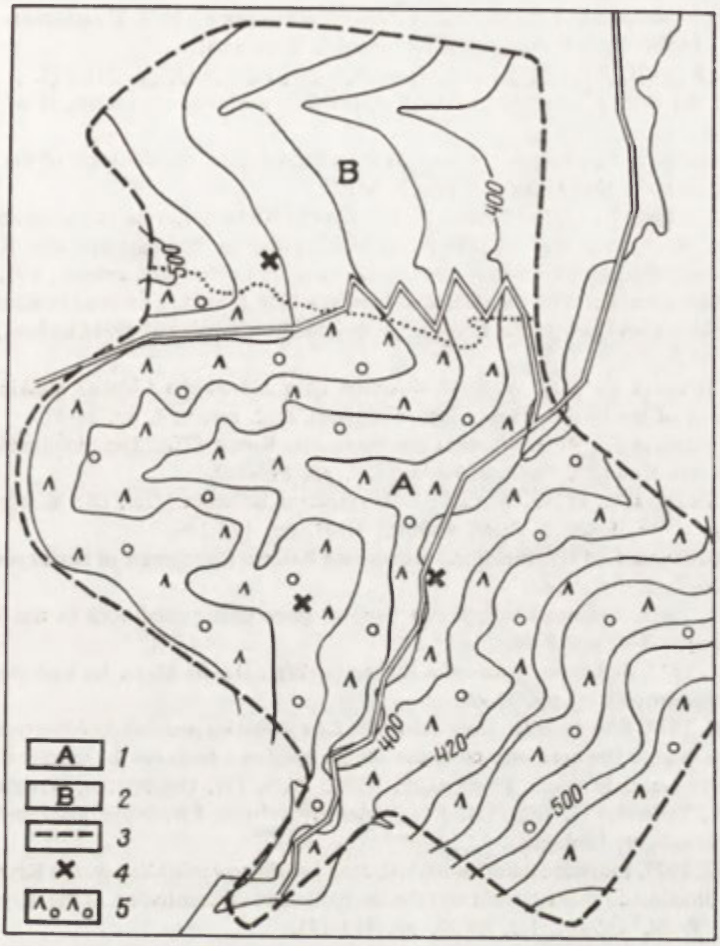

Fig. 5. Bioclimatic units in the Iwonicz health resort
1 — areas with a dominant transpirative type of structure of the heat balance of the human body during the summer, 2 — areas with a dominant turbulent type of structure of the heat balance of the human body during the summer, 3 — border of investigated area, 4 — measurement points, 5 — mixed forest

indifferent to the human being because the greater differentiation of local bioclimatic conditions in a small area the greater the burden on the thermoregulation system, and it is through this system that our body is able to maintain a thermal equilibrium in spite of changing physical conditions of the atmospheric environment.

To end with, it should be stated that this research method applied to the evaluation of bioclimatic conditions of health resorts provides information which may be useful in climatotherapy, and therefore, it should be more frequently applied in bioclimatology.

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CLIMATIC FLUCTUATIONS IN CRACOW CITY, 1826–1975

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INTRODUCTION

The problems of both large-scale and local climatic fluctuations and oscillations are treated, in the current world publications, from many sides and in detail. Recent research of the short-term climatic variations and their trends proves that for a better understanding of the mechanism and reasons for those variations it is necessary to apply radiosonde stations around the world. Those assumptions have been accepted by the Global Atmospheric Research Program (GARP) which in 1979 began intensive research into atmospheric processes by radiosondes and satellite measurements. The network of about 3000 surface stations will not play an insignificant role in this program (Borisenkov, 1976; Declaration of WMO ... 1977; GARP ... 1977, Boryczka, 1978). Traditional climatic observations, made close to the surface of the Earth are also significant in explaining the changes of such elements of climate as air pressure, air temperature and precipitation.

These elements were measured in the same place, from 1826, at the station of the Jagiellonian University. It can be included with those long, uninterrupted meteorological series of observations particularly useful to study long-term fluctuations of the already mentioned elements of climate.

The meteorological station of the Jagiellonian University is located in the Botanical Garden. The height of the thermometers is 221 m a.s.l. and the height of the mercury barometer — 220 m a.s.l. Observations of air pressure and air temperature were made three times per day at various local or official hours solar mean time. The weather was observed at the seven various term-hours during the period 1826–1975. Mean temperatures were corrected, changing these means into true means (Trepińska, 1971). Mean values of air pressure are remained the same with regard for the inconspicuous corrections. Amount of precipitation was taken since 1876 at the morning observation, once per day and is assigned to the previous day. A Hellman-rain-gauge with openings measuring 200 cm^2, placed 1 m above the ground, was used.

Available average data of air pressure and air temperature from 1826 to 1975 and data for precipitation since 1876 allow us to present climatic trends for a period of 150 or 100 years. It may be assumed that Cracow is a representative station for the area of Central Europe (Trepińska, 1971, 1973) thus the variability of average

pressure, temperature and precipitation (that last on a smaller scale) refers also to the mentioned area, particularly to the stations situated in cities, which have gone through similar stages of industrialization and increasing air pollution. Those above mentioned processes influence, as is well known, the origin and intensification of 'heat islands', increased cloudiness, decreased sunshine etc. (Hess, 1974; Paszyński 1976).

OUTLINE OF THE PRESENT DAY RESEARCH INTO CLIMATIC FLUCTUATIONS

Climatic fluctuations may be classified (Lamb, 1966, 1972) according to their nature, amplitude and duration. They may be rhythmic or arhythmic, pulsating, intermittent or sporadic, recurring or non-recurring, regular, sudden, micromeso- or macro-sized, transitory (several years), those lasting for many years or even many centuries. The word 'fluctuation' means some non-periodic variation of the climate and the word 'oscillation' means a more regular variation of climate in short or long periods. A more exact expression seems to be 'the variability' with reference to short-term climatic fluctuations.

More detailed study of climatic oscillations and fluctuations was conducted toward the end of the 19th century. That research has been considerably increased thanks to the introduction of satellite and radiosonde techniques. However this period is too short (satellite research since 1958) to detect changes of climate in even short-term oscillations, but the possibility of the introduction of a simultaneous and identical research system around the whole Earth is the great advantage of that type of work.

American and Soviet scientists who represent two satellite powers, and climatologists from the German Federal Republic and Japan (Kukla and the others, 1977; Angell, Korshover, 1978; Yamamoto and the others, 1977; Dronia, 1974) have got interesting results. Those results concern large-scale oscillations of climate. In the Earth's atmosphere, a tropic belt, two extratropic belts and polar zones on the Northern and the Southern hemispheres have been distinguished. The most recent papers of American scientists (Bryson, Mitchell, Willet) have noted the existence of thermic fluctuations during the last 20 years (1958–1977). Those fluctuations show a decreasing trend, in the other words, a cooling trend. This tendency is shown by a drop in temperature measured on 100 hPa (mb) layer, even of 1 °C in some parts of the globe, by the drop of surface temperature, the increase of the lapse rate in the Northern hemisphere with a simultaneous decrease in the Southern one, the movement of the vertical range of the large circumpolar Arctic vortex and a rise of temperature in the Northern hemisphere in the extratropic east longitudes. While in nearly the whole troposphere a cooling trend has been noticed, the atmosphere over Europe has shown a contrary, warming trend. In the last few years a large change from year to year has been observed.

As to the result of the most recent studies of the trends of the global climate, the publication 'New Data on climatic trends' (Kukla and the others, 1977) seems particularly valuable. The authors make it clear that the satellite technique does not allow us to examine local trends of different weather parameters. Local trend may appear

to be very different from those described by the authors average variations for particular zones of the globe. It refers, for instance, to Cracow where in the range of surface temperatures the warming trend remains while the authors of 'New Data ...' have stated the existence of a cooling trend in the Northern hemisphere from 0.1 to 0.2°C per decade in the period 1950–1975 in free atmosphere, a relatively small cooling trend on the surface layer, but at the same time a considerable variability in the direction of the trend during this period. It seems reasonable to supplement these global data with local data, the more so as there is the possibility of using such long series of observations as the one from Cracow.

As to reasons for the climate changes — the following elements are taken into consideration: the increase of carbon dioxide content in the atmosphere and the increase of the greenhouse effect (Bryson, 1973), the increase of ozone (Dziewulska-Łosiowa, 1976), the delivery of great amounts of mineral dust and gas to the atmosphere because of volcanic eruptions (Mitchell, 1961; Yamamoto, 1975, 1977) and the changes of the solar constant caused by the cyclic variability of the radiation of the Sun's photosphere (Budyko, 1969; Loginov, 1971; Mustel, 1974; Willet, 1966; Lamb, 1972). The comparison between the changes in solar activity and the range of air temperature shows certain correlations with reference to longer periods, whereas in the study of temperature variability from year to year unequivocal results have not been achieved yet. The Russian climatologist Dzerdzeyevskii (1962) and physicist Wangenheim (Girs, 1974) see the reason for the climatic oscillation in the origin and evolution of thermobaric waves reaching down to the low stratosphere. Changes in the arrangement of those waves cause the domination of the zonal (western) circulation during certain years or the domination of meridional circulation during other ones.

The paper written by Hess (1967) presents some interdependences between the course of air temperature at Cracow and the other phenomena. The author considers the results of the computation made with longer series of air temperature (1780–1963). The period 1780–1825 was completed by the reduction to a given period of the measurements from the meteorological station at the city of Wilno.

Concerning the annual averages of air temperature Hess (1967) found that the cumulated frequency of annual mean temperature 8.1°C equals 50%, in other words, there is a 50% probability that the annual temperature will be lower than 8.1°C, and a 50% probability that the annual temperature will be higher than 8.1°C. He found also some regularities in the course of winter temperature. They show a well-marked rhythm and periodicity which are a reflection of the periodicity in the course of Wolf numbers. The most severe winters may occur about the half year after the maximum of sunspots, less severe winters the half year before the minimum of sunspots and the mildest winters the half year before the maximum, with a series of more mild winters previous to that. The author indicates the possibility of the dependence of the occurrence of severe and mild winters on the 90-year cycle of solar activity. The most important result in this paper is the calculation of the cumulated frequency of the differences between the mean temperature of the successive months. They reflect a large variability of air temperature from season to season.

This, out of necessity, incomplete and cursory review of several papers shows, that long and short-term climatic variations and climatic trends are being carefully observed all over the world.

THE METHOD OF THIS STUDY AND THE CHARACTERISTICS OF DATA

In this paper I want to present fluctuations of the average annual values of air pressure and air temperature in Cracow during a period of 150 years (1826–1975) and annual amounts of precipitation during a period of 100 years (1876–1975). The series was presented in the other papers (Hess, 1967; Trepińska, 1971, 1973, 1977). Valuable observational data from the university's station authorizes us to make a statement that even the small changes of mean values of pressure or temperature have their physical reasons, and do not result from the accidental change of the instruments or from the change of the observer.

In the scientific description of data the statistical methods, which are applied in climatology, have been used. The method of running means (with different starting periods) and the method of cumulated amounts of deviations from the average are used in the general presentation of climatic trends. Running means for periods of 5- and 11-years have been used. To show trends in periods shorter than 150 and 100 years I have presented average air pressure, air temperature and precipitation in every period of 25 years in Table 1. Means, averages and standard (square) deviations are calculated for the each period of 25 years separately and their comparison shows changes in those periods. At the end of Table 1 the values of pressure and temperature are shown for the period of 150 years and those of precipitation for the period of 100 years.

The discussed range of the average values of atmospheric pressure is adjusted to the sea-level. Monthly mean air temperatures are computed from the true means, i.e. from the 24-hour means.

TABLE 1. Air pressure, air temperature (1826–1975) and precipitation (1876–1975) in Cracow

Years	Air pressure in hPa			Air temperature in °C			Precipitation in mm		
	mean	deviation		mean	deviation		amount	deviation	
		average v	square σ		average v	square σ		average v	square σ
1826–1850	1016.0	1.12	1.45	7.6	0.75	0.97			
1851–1875	1016.4	0.91	1.13	7.7	0.77	0.99			
1876–1900	1015.7	0.54	0.71	8.0	0.48	0.66	687	64.3	80.4
1901–1925	1016.1	1.04	1.29	8.2	0.53	0.63	713	99.4	124.8
1926–1950	1016.6	0.98	1.19	8.5	0.69	0.91	648	71.6	89.5
1951–1975	1015.8	1.03	1.28	8.7	0.57	0.69	705	100.6	119.8
1826–1975	1016.1	0.97	1.22	8.1	0.72	0.91			
1876–1975							688	85.1	106.9

VARIABILITY OF AIR PRESSURE IN CRACOW

Average annual values of pressure during the period of 150 years fluctuated in a range from 1013.4 hPa (1836) to 1019.7 hPa (1832). The variability of means within the range of 6.3 hPa and also the spread of data taken directly from the barometer (about 82 hPa) seem to be considerable for the temperate zone. Average variability of annual values of pressure is 1.25 hPa. The mean value of the drops of pressure equals —1.28 and the mean value of the rises of pressure equals 1.22 hPa. The coefficient of variation is 0.12%.

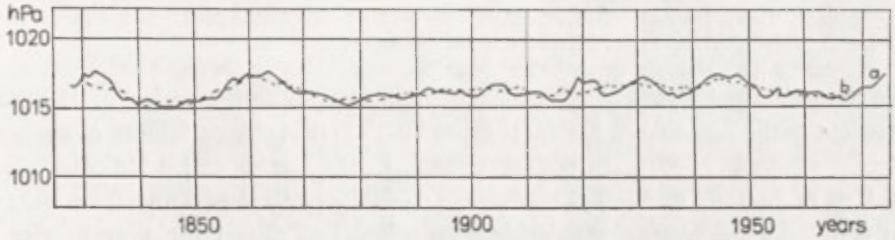

Fig. 1. Variation of the annual mean of air pressure (1826–1975)
a) 5-year running means, b) 11-year running means

Figure 1 shows, smoothed by running means for periods of 5- and 11-years, the course of annual values of air pressure during the period of 150 years. It can be seen that the years 1829–36, 1853–62, 1904–75 were characterized by an increased variability of air pressure from year to year. In the years 1856–63 a rise of averages can be seen and the following years are characterized by a decreasing trend and then a repeated increase in the 1940s. There is a certain analogy with the course of the 100-year cycle of solar activity presented elsewhere (Trepińska, 1971, 1976). The highest mean values of Wolf numbers occured in the 1850s and in the 1960s. It is possible that the increase in solar activity or the beginning of the phase of increasing activity is shown in the presented course of average values of pressure. Relatively large variations in the averages from year to year is not in opposition to the general direction of the trend.

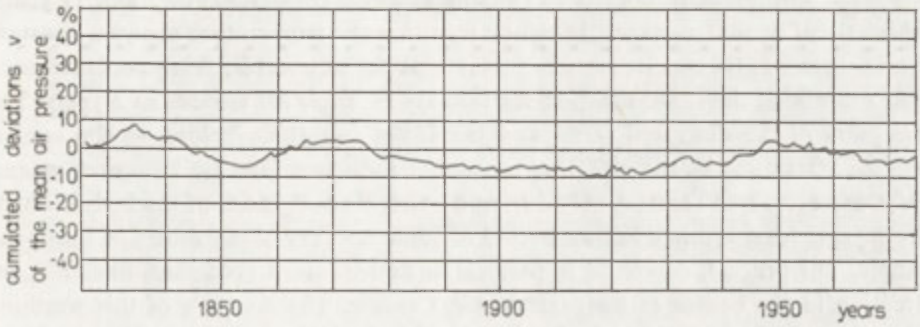

Fig. 2. Variation of deviations of annual mean of air pressure from the climatological normal
x axis — years; *y* axis — cumulated deviations *v* from mean air pressure, in percentage

The variability is presented in Fig. 2. The slope of the curve in relation to the x axis shows the size of the trend of the pressure variations. The most considerable annual change took place in the years 1842–65, 1941–66, that is when solar activity increased during the roughly 90 year cycle.

The presented range of air pressure is, of course, a reflection of changes in circulation occuring in the atmosphere above Central Europe. Now, the variations in the range and trends which are examined by means of precise methods could be extrapolated backwards, if only well-founded analogies with the changes during the last years could have been discovered.

VARIABILITY OF AIR TEMPERATURE IN CRACOW

Average annual values of air temperature in Cracow in the period of 150 years fluctuated in the range from 5.3°C (1829) to 10.0°C (1934). A variability of averages within the bounds of 5.7°C in the same place is considerable and it indicates a certain lack of climatic stability. The average variability of temperature from year to year is 0.92°C, the average temperature drop is −1.02°C and the average rise of temperature is 0.83°C. The coefficient of variation is 11.2% during this period.

The low temperatures of winter months during some years were the main cause of considerable negative deviations. Standard deviations of mean monthly temperatures during winters are about three times bigger than the deviations during summer months, therefore winter temperature greatly influence the value of annual averages.

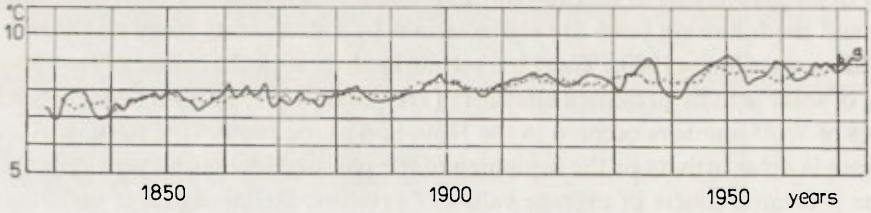

Fig. 3. Variation of the annual mean of air temperature (1826–1975)
a) 5-year running means, b) 11-year running means

Figure 3 presents, smoothed by running averages for periods of 5 and 11 years, the course of annual averages. It can be seen that the temperature shows a constant increasing trend. Of course, certain fluctuations are noticeable. They are better seen while examining the curve showing the running averages for periods of 5 years. The first years of the discussed series and the 1850s and 1870s belong to the coolest periods. Starting from the 1890s we can notice a distinct increase in annual means, which is maintained continuously during the first three decades of the 20th century. Those years form the well known period of contemporary oceanization of European climate. The process, described in publications on frequent occasions, finds its confirmation in the course of temperatures in Cracow. The set-back of this warming trend happened in 1939 and continued till 1948. But during this period only three years had an average annual temperature lower than the climatological normal of

8.1°C. The warming trend still remains, particularly since 1974, mainly because of mild winters. Summer seasons have been rather cool.

Parallel to the course of pressure (Fig. 1) in the course of the annual temperature, periods of greater variability of temperature from year to year can be distinguished. Those were the years 1828–40, 1853–71, 1896–1909, and 1939–75. The 20th century is characterized by violent fluctuations of temperature and a less stable range of fluctuations.

A detailed analysis of thermic trends in Cracow makes it possible to distinguish three periods in the course of temperatures since 1826: 1) 1826–80 with large oscillations of annual means, with the predominant number (40 out of 55 years) of the averages showing negative deviations from the mean of the period of 150 years, with several frosty winters; 2) 1881–1938, with smaller fluctuations of temperatures, with a continuous warming trend, without severe winters (one exception — winter 1928/29); 3) 1939–1975 with a rapid increase of means, with diminishing differences of temperatures between each season and with a large variability from year to year. Similarly a larger variability in the course of air pressure can be noticed in the third period. It testifies to the fact that the reason may be found in general atmospheric circulation.

Described elsewhere (Trepińska, 1971) harmonic analysis of mean annual temperatures showed that the period of the 131 years taken into consideration has the largest amplitude, which means that the course of the curve of temperatures is characterized by a systematic increase. It was proved by the smoothing of the temperature course as running averages for a period of 35 years. Harmonic analysis also made it possible to distinguish two groups of periods with a small amplitude 0.1–0.2°C. They are 10.9, 11.9 and 13.1 years, and 14.6 and 16.4 years. It suggests the existence of races of a certain periodicity in the range of temperatures nearing the solar activity

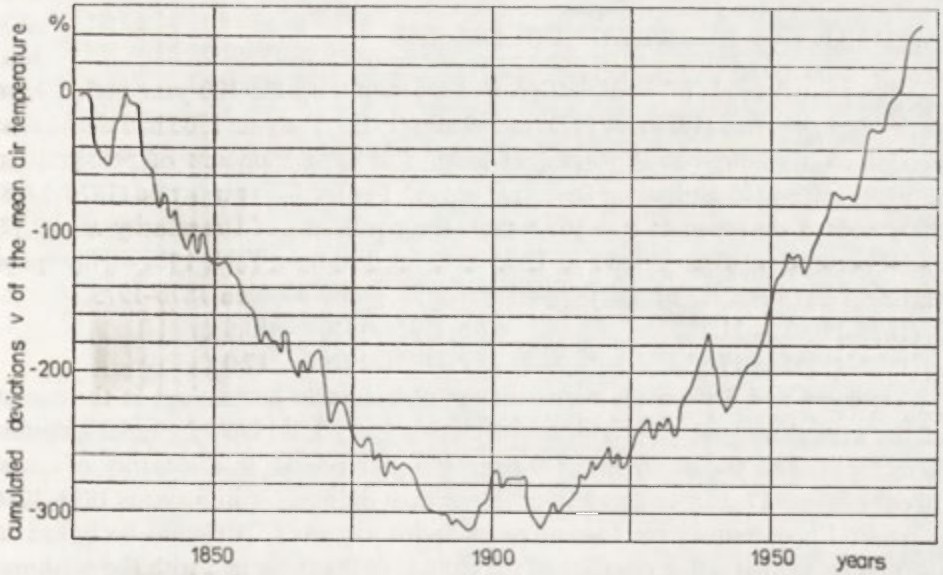

Fig. 4. Variation of deviations of mean air temperature from the climatological normal
x axis — years; *y* axis — cumulated deviations *v* from mean air temperature, in percentage

cycle of about 11 year. The influence of this cycle seems, however, to be strongly involved by the overlapping of other phenomena, among which apart from the already mentioned human activity, are important but irregular volcanic eruptions and hence a drop in incoming solar radiation. The fact that severe winters have appeared in Cracow with a certain delay compared to the maximum Wolf numbers in the above mentioned cycle, seems to be important. Shifts in the phase of the occurrence of mild and severe winters seem to be of several years in comparison with the minimum and maximum of solar activity. The delaying of mild winters occurs in relation to the lowest Wolf numbers and of severe winters in relation to the highest Wolf numbers.

The trends in the course of average annual temperatures in Cracow are shown in Fig. 4, by means of a diagram of cumulated deviations from the average of the period of 150 years, as percentages. It can be seen that till the 1890s the annual averages were, in general, of lower value than the average for 150 years. Certain fluctuations with the warming trend occured then but the fundamental change in the direction of the curve has been noticable since 1909. Lower annual means from the 1940s caused a change of the direction of the curve but since 1944 a steep, rising curve has shown a rapid increase in annual means. Only a few of the more severe winters (1955/56, 1962/63, 1969/70) are shown on the diagram as lines which are curved downwards.

The analysis of variability tendency of temperature by means of different methods shows a continuous increase, which does not, however, mean that all the seasons are warmer. It concerns, first of all, late autumn and winter. Individual occurrences of more frosty winters as in 1978/79 do not influence the direction and the related continentality of our climate. In such a case a series of severe winters should have occured. So far we have noticed milder winters starting from 1971/72.

VARIABILITY OF PRECIPITATION IN CRACOW

The annual totals of precipitation in Cracow during the 100 year period have varied from 469 mm (1921 and 1932) to 998 mm (1912). The year 1966 had the highest precipitation among recent years (994 mm). The annual amount of precipitation shows considerable oscillations from year to year. For the 103 year period (1876–1978) the standard deviation is $\sigma = 105.5$ mm, the coefficient of irregularity $x = 2.12$, and the coefficient of variation $z = 15.35\%$. Using data from Table 1 the coefficient of variation has been calculated for periods of 25 years, between 1876–1975.

z_1(1876–1900) = 11.7% z_3(1926–1950) = 13.8%
z_2(1901–1925) = 17.5% z_4(1951–1975) = 17.0%

Figures 5 and 6 show the occurrence of considerable fluctuations in the course of the annual amount of precipitation. During the years 1876–92 annual amounts were lower than the mean values for the 100 year period, in a majority of cases. 10 out of those 17 years had an amount lower than the mean. During years 1893–1916 a relatively continuous increase of precipitation occurred. It should be linked to the process of increasing oceanity of the climate at that time and with the predominance of western circulation. In the following years till 1957, precipitation decreased,

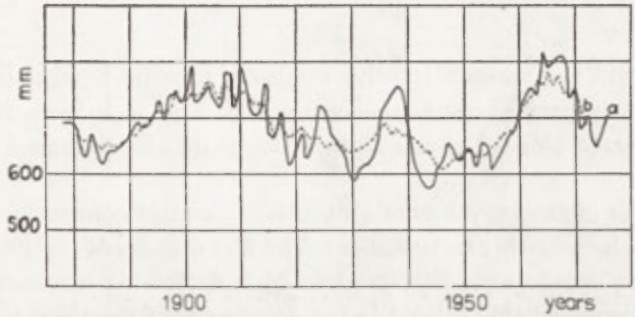

Fig. 5. Variation of the annual amounts of precipitation (1876–1975)
a) 5-year running means, b) 11-year running means

but a certain increase occurred between 1933–40. But the mean amount for the period of 25 years (1926–50) is the lowest (648 mm). During the 11 years (1941–51) only one year (1949) had an amount of precipitation somewhat exceeding the climatological normal. It testifies to a climatic shift towards continentality. Till 1966 a certain tendency to increasing precipitation can be noticed, but already in the following years a decrease occurred again. In the most recent periods the smallest annual totals of precipitation occurred in 1973 (517 mm) and in 1976 (568 mm). In 1977 and 1978 precipitation totals slightly exceeded the average for the period of 100 years (694 and 703 mm) although they were lower than the average amount for 25 years (1951–75; Table 1).

Providing that the direction of the thermic trend can be clearly considered as a warming one with certain short-term fluctuations, the analysis of the course of precipitation shows striking oscillations. If one wants to qualify the direction of the trend of oscillations of the precipitation, the division of 100 years into shorter periods has to be taken into consideration. During the whole 100 year period there is not one identical direction and rate of variability of precipitation trend, but the periods with lower and higher totals of precipitation are easy to distinguish.

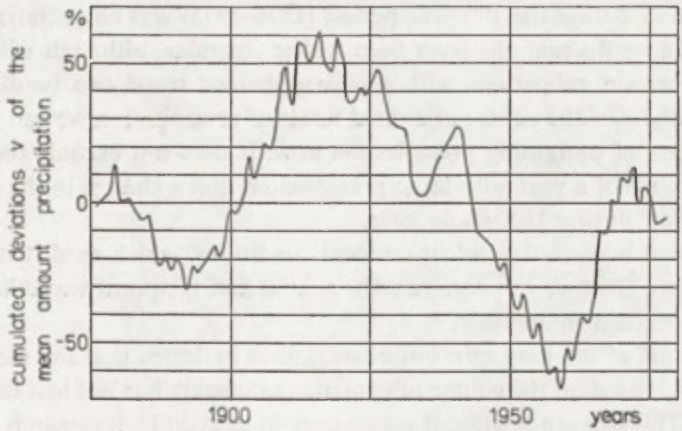

Fig. 6. Variation of deviations of annual amounts of precipitation from the climatological normal
x axis — years, *y* axis — cumulated deviations *v* from mean amount of precipitation, in percentage

CONCLUSIONS

In the light of the present intensive studies of climatic changes it seems necessary to present the general results achieved so far from the analysis of the interrupted series of meteorological observations made at the climatological station of the University.

In the course of annual values of air pressure a certain concurrence with the 100 year cycle of solar activity can be noticed. The first decades of the 20th century and the most recent decade were characterized by a decreasing tendency of values of pressure. It is unmistakably related to the dominance of the zonal type circulation over Central Europe.

In the course of air temperature a continuous increase of annual means can be noticed, i.e. a warming trend. Periods of variations of circulation from the meridional type to the zonal type, or periods with a predominance of mixed type circulation appear in numerous non-periodical fluctuations. The analysis of the 100 year course of solar activity and 11 year cycles, as well as of other reasons for the climatic changes (first of all human activity) points to the persistence of the direction of the trend, although the possibility of more severe winters occuring should also be taken into consideration. It is possible that the considerable variability in the general atmospheric circulation during recent years may disturb the climatic trend.

The temporal variability in temperature in Cracow has tended to increase over the recorded period (19th and 20th centuries) in accordance with the increase in Western and Central Europe. Comparing the temperature of Cracow with that of other localities in Europe we can see that Cracow is more closely correlated with localities situated to the West. For instance, the correlation coefficient for Cracow and Vienna was $r = +0.92$ (winter months temperature 1881–1950), and for Cracow and Kiev $r = +0.79$ (also winter months 1881–1950). Vienna, although situated nearer to Cracow than Kiev is more to the South and more separated because of the mountain ranges. The stronger correlation of Cracow and Vienna temperatures allows us to see a greater influence of the air-masses from the West or South-West.

Precipitation during the 100 year period (1876–1975) was characterized by great variability. Those fluctuations have been rather irregular, although within the 100 year period certain subperiods with a clearly defined trend can be distinguished. From the analysis of the course of annual totals of precipitation we can suggest that there is a phase of decreasing precipitation now. It does not exclude the possibility of the occurrence of a year with large precipitation and a change in the distribution of precipitation during the whole year.

Precipitation is more dependent on local conditions, which modify its frequency and dimension. Thus we can compare the spatial and temporal variability in precipitation by detailed maps only.

The example of the long series of observations indicates that the method of climate research, based on the course of climatic parameters has not lost its immediate importance. This fact is not without significance in such difficult research as the study of climatic variation.

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INFLUENCE OF HUMAN ACTIVITY ON WATER CIRCULATION

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Man's influence on inland waters is so varied that any attempts to grasp the whole of the question and to set the problems connected with it in order present great difficulties. However, it seems to be useful to make such attempts as they can make it easier to draw up research issues.

What is the result of this influence is change in the hydrosphere. They may refer to: water quality, the structure of circulation and water relationships, i.e. to a set of hydrographic features of an area arising out of water circulation in the existing conditions of the geographical environment.

The present article discusses only one section of the problems connected with this issue, i.e. changes in the structure of water circulation under the influence of man's activity. Nothing is said of the equally important issues of changes in water quality and water relationships, the latter being closely connected with the structure of circulation and examinable only with definite examples.

The starting point of our considerations is the scheme of water circulation which links the different elements of the geographical environment: atmosphere, pedosphere, lithosphere, hydrosphere and biosphere. In this structure the concept of hydrosphere has to be defined accurately. Here it will refer only to reservoirs of both running and stagnant waters (though in hydrological investigations of definite areas it is more reasonable to take not only surface water but also groundwater as a water component of the environment).

The state of management of geographical space also calls for the anthroposphere to be separated as a distinct element. This concept is not defined precisely. What we shall understand by the anthroposphere is people, areas with an artificial surface, and artificial objects in the landscape. Thus, we shall include in the anthroposphere neither quarries nor planted forests and potato fields, nor artificial water reservoirs in spite of the fact that they are the results of man's activity. In each of these cases we deal only with modifications of different components of the natural environment. On the other hand, what we shall consider to be the elements of the anthroposphere are: built-up areas, hardened roads or areas, slag heaps, dumping grounds, etc.

Among the above mentioned six components of the geographical environment in a freely chosen land sector there occurs multidirectional water exchange (Fig. 1).

The atmosphere sends water in different forms of precipitation to all the remaining components. The amount of water received by the components is affected by climate and the character and size of the reception surface.

Water falling on the pedosphere soaks into it or flows over its surface to the hydrosphere. Infiltrating water is retained in the soil from where it is returned to the

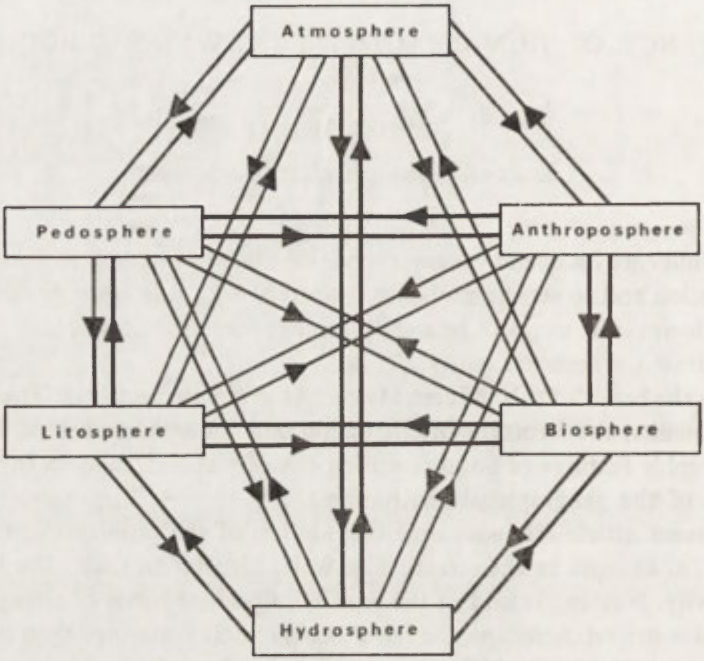

Fig. 1. Scheme of water circulation between components of the natural environment

atmosphere by direct evaporation or through plants; it seeps through the soil to the hydrosphere or infiltrates the lithosphere. A certain amount of water gets into the anthroposphere through overland flow on built-up areas, and is drained off to collectors from drained areas or drawn from shallow wells.

Water falling straight onto bare rocks or supplied to the lithosphere from soil may be returned to the atmosphere through evaporation or to the pedosphere through capillary rise. It also flows away to the hydrosphere by means of surface and underground runoff. It is absorbed by plants through the root system and drawn off by people for consumption.

From the hydrosphere water is carried to the atmosphere through evaporation from free water surfaces. It soaks to the pedosphere, especially in periods of high water level, and to the lithosphere through bottoms of reservoirs pervious to water. It is absorbed by water plants, drunk by animals and drawn off by people.

The biosphere gives water back mainly to the atmosphere through the process of transpiration and evaporation from the surface of plants (interception). A certain amount of water retained on the surface of plants flows and drips onto the soil sur-

face, and in some cases onto water, rock or built-up surfaces. Small amounts are taken by people in vegetable and animal food.

From the anthroposphere water evaporates or flows to the neighbouring areas. Above all, however, it is directed to soil irrigation, plant watering, and the watering of animals, and after consumption it is returned to the hydrosphere, less frequently to the lithosphere. A certain amount of water gets to the lithosphere as leaks from the water-supply and sewage systems.

The described diagram includes all the directions of water exchange in the conditions of man's economy[1], but it does not describe all the ways of water shifts between the components of the environment. Neither does it determine the role played by individual connections as this role is affected by climate, conditions in an area and human interference and is strongly differentiated in space.

The introduction of the element of anthroposphere into the system of water circulation changes the original set-up of elements and their connections which correspond to natural conditions, and, thus presents the influence of man on the structure of water circulation in a general way. To evaluate this influence, however, it is first of all necessary to examine which ways of exchange are completely artificial links — requiring not only special devices but also additional force, which ones are modified and how; and which ones resist man's influence. The considerations are presented in the diagram in which links are marked in three categories: those created intentionally by man and not occurring in nature, those consciously changed by man and those undergoing unintended changes (Fig. 2). Nothing is said of those ways of circulation the changes of which are difficult to discover or of little importance. To avoid too numerous repetitions the order of descriptions will correspond to that of the elements and only ways of water shifts to the remaining elements of the system are discussed.

Man's influence on precipitation is relatively little. The artificial seeding of rain still remain at the stage of tests and the results obtained so far do not allow us to draw explicit conclusions. Furthermore, changes within other components of the environment do not cause any possible changes of precipitation amounts to be certainly stated. Perhaps changes in wooded area may influence the amount of precipitation. Many researchers have arrived at such a conclusion. What is still standing, however, is Penmann's opinion[2], that there are no sufficient grounds to confirm this dependence. Controversial views on this subject, which can be found in a great number of publications, are perhaps accounted for by the fact that forest acts jointly with other components of the environment and, therefore, its role examined in isolation is not easy to grasp and, undoubtedly, not the same everywhere. Forest can also increase the amount of water obtained from the atmosphere through condensation in the form of dew, hoar-frost etc. which are very difficult to measure.

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[1] The question of introducing desalted sea waters to inland circulation has been omitted because at the time being it is of little importance.

[2] H. L. Penman, Vegetation and hydrology, *Technical Communication* 53, 1963, Commonwealth Bureau of Soil, Harpenden.

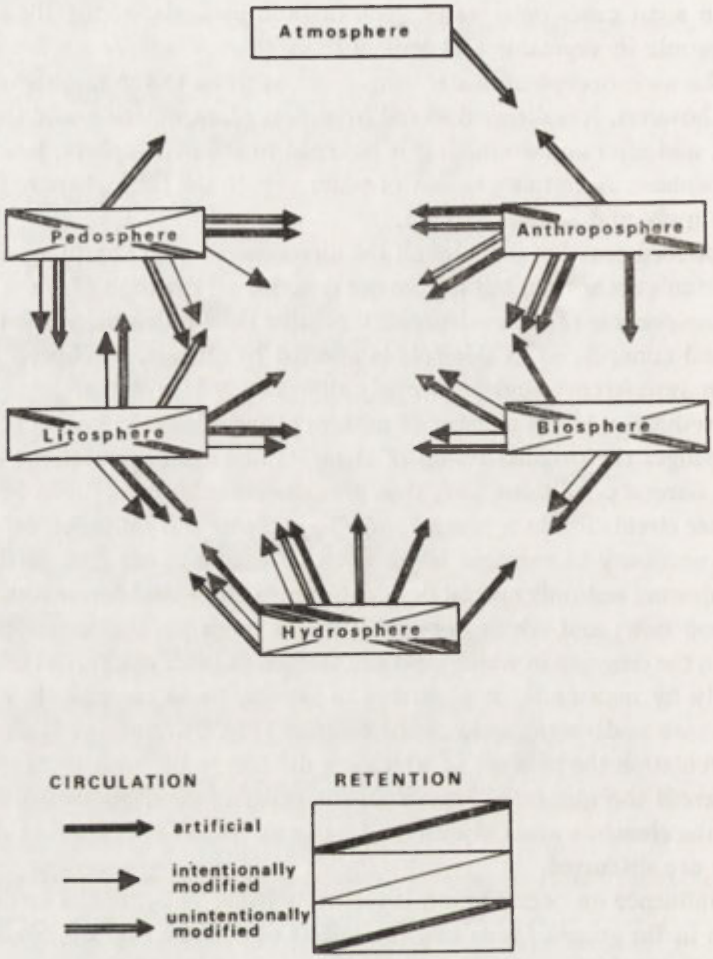

Fig. 2. Character of water shifts

The increase in precipitation may be due to the construction of large water reservoirs. The influence of water surface, however, is surely limited to the areas not far away from the shores, similarly as in case of natural lakes. Rain regime can be also subject to variation owing to changes of the intensity of evaporation and conditions of vapour condensation.

An unquestionable influence, although spatially limited, is the development of cities and industry on the amount and presumably the distribution of precipitation. What is being recorded in urbanized areas is an increase in the number of condensation nuclei, an increase in turbulence and convection, and cloudiness as well. Thus, conditions conducive to increases in precipitation amounts are created. Although it is not estimated that studies carried out so far have solved the problem, still some results, e.g. in Bremen and Hamburg (Massing) or in Amsterdam (Zuidema) seem to confirm such an influence of cities. According to Landsberg in urbanized areas

the amount of precipitation is, on the average, greater by 5–10 per cent than in rural areas[3].

Man's influence on water circulation is much stronger through his activities in the pedosphere. The soil is a very complex subsystem and man's interference may result in substantial changes in it. Conscious influence aiming at the growth of soil productivity is exercised through cultivation which improves soil properties by supplying it with substances which aim to increase the content of nutrients or to improve the structure, and through land melioration which is aimed at changing water—air relationships. Destructive influence, most frequently unintended, leads to unfavourable changes in the physical properties of the soil, its matter and biological activity, and consists in the reduction of its profile or its complete erosion. These actions change the moisture capacity of soils, which in turn leads to changes in evaporation and direct runoff. The amounts of water absorbed by plants and sent to the lithosphere are also changed.

Some of these changes are intended, e.g. excess water diversion from farm lands to the hydrosphere through drainage ditches, either directly or indirectly through the anthroposphere with the help of sewerage systems. What is also intentional are actions leading to an increase of soil moisture capacity and resulting from this the increased consumption of water for transpiration. In some cases it is also intended to increase the seepage of water into the lithosphere. What is unintended is an increase in evaporation from the soil and overland flow occurring with unsuitable cultivation due to decreased soil moisture capacity or incorrect melioration. Drainage works concern not only soils but also the upper part of the lithosphere, and through the hydrotechnic works necessary for their accomplishment also to the hydrosphere. They change not only the water—air relationships of the soil but also its structure and the progress of chemical and biochemical processes in both soil and subsoil. Thus, they influence all the basic processes in water circulation such as: overland flow, infiltration, evaporation, and soil, surface and underground retention. In a number of publications it is pointed out that the results of both irrigation and draining after some time often prove to be unfavourable for soils and for other components of the environment.

The role of soil — which, as Lvovich[4] expressed it vividly, converts meteorological phenomena into hydrological ones — is tremendous in water circulation. Therefore, the influence on soils should not be exercised and studied only from the point of view of the needs of farming. Soil should be also treated as a means for influencing water circulation. In spite of the fact, however, that so much has been written on the subject of the influence of soils on water circulation, the view that — apart from other methods of action — agronomics and agromelioration should be

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[3] Cf. H. Massing, Hydrological effects of urbanization in the Federal Republic of Germany, in: *Hydrological effects of urbanization*, Studies and Reports in Hydrology 18, 1974, UNESCO, Paris; F. C. Zuidema, Hydrological effects of urbanization in the Netherlands, *op.cit.*; H. E. Landsberg, Climates and urban planning. Urban climates, *Proc. WMO Symp.*, *Technical Note* 108 WMO—No. 254, Brussels 1970.

[4] M. I. Lvovich, *Miroviye vodniye resursy i ikh budushcheye* (Water resources in the world and their future), Moskva 1974.

applied in the water economy as important means of conscious influence on water circulation has not been generally approved of.

From the lithosphere water is drawn artificially in different ways — from simple to very complex ones — to meet the necessities of life and economic needs, and also pumped from mines. The consumption of water may lead to the lowering of the underground water table, to changes of hydrogeological relationships and ground water storage. The lowering of the water table affects the process of capillary rise, the amount of water absorbed by plants and surface water phenomena. The excessive pumping of underground waters caused the shrinking of springs and marshes, decrease of underground runoff, a decrease of underground retention and changes in the water balance. Mining works are frequently the reasons for changes in the direction of groundwater circulation and the convergence of water of different aquifers.

Both opencast and underground mining also frequently lead to changes in relief which account for changes in the direction and speed of water flow. Depressions in the topographic surface are subject to underflood and, therefore, water reservoirs or swamps may occur in them. Thus, soil and surface retention and evaporation are changed.

Changes in relief occur also in connection with other branches of the economy such as: farming (terracing of slopes), building industry (levelling of topographic irregularities, scarps), communication (earthworks), hydrotechnics (channels, ditches, embankments). They are also accounted for by an intensification of the natural processes of erosion, accumulation, deflation, mass movements, suffusion — due to economic activity. All these activities influence the process of runoff and surface retention, and, through this, evaporation and infiltration. Their great importance is due to the commonness of transformations of the lithosphere and especially of relief.

Retention of water in the lithosphere can be changed both intentionally and casually not only as a result of the above-mentioned different activities but also can be increased consciously by artificial alimentation of underground reservoirs.

Our knowledge of the role of vegetation in water circulation is fairly good. The most important thing is that natural vegetation, and especially forest, strongly limits or completely eliminates the overland flow. What is increased, on the other hand, is infiltration and retention, especially of snow, in forested areas. And it is due to this that forest regulates runoff. What are controversial, however, are findings concerning the influence of forest not only on the amount of precipitation but also on the water balance. The majority of studies point out that forest increases evapotranspiration and, thus, decreases runoff. However, quite contrary results of investigations can be quoted, especially from areas having hard winters. Most probably losses through evapotranspiration are balanced by excessive infiltration from the snow cover which is protected by forest. The investigations carried out, especially in the USSR lead to such a conclusion[5].

It is generally known that the role of vegetation depends on its kind. Some plants and forms of their cultivation exert an influence contrary to that of natural vege-

[5] *Bilan et tendences de la recherche en hydrologie*, Etudes et Raports d'Hydrologie 10, 1972, UNESCO, Paris.

tation — they intensity runoff and weaken infiltration. Besides, the influence of different cultivation is widely varied. One of its characteristics is the fact that the majority of areas cultivated with plants are covered only seasonally. Therefore, vegetation may perform its protective function only in the periods of its growth unlike natural communities which affect the process of runoff and infiltration through the root system even in the periods of biological stagnation.

Changes of vegetation result in an increase or decrease in transpiration, changes of interception, intensification or weakening of the process of infiltration, surface runoff to the hydrographic network and short-period retention, especially of snow.

The influence of vegetation on water circulation is closely connected with the influence of soils and it is often difficult to separate them. Therefore, it was considered admissible to mark in the diagram in Fig. 2 changes in the sending of water by the biosphere, though these changes refer to water which is given back rather by an area covered with vegetation than by the vegetation itself.

The hydrological role of vegetation has been used since long ago, especially to limit surface runoff in order to protect soils against denudation and to curb erosion in river channels. Large areas of forest are being kept to protect water and soil. Intensively transpirating plants are being grown to dry too wet areas. However, it cannot be said that vegetation is being used sufficiently to control water circulation. The experience gathered in experimental basins shows to what extent the structure of circulation can be changed only as a result of change in land use. These experiments should encourage a wider use of phyto-meliorations in the water economy.

The major changes introduced intentionally by man in the hydrosphere consist in creating artificial, and changing natural water reservoirs, regulating conditions of runoff in river valeys, constructing artificial watercourses — from ship channels to drainage and irrigation ditches, and constructing devices for water shifts and consumption. Drawn water is directed to the anthroposphere to meet municipal and industrial needs or to pedosphere to agricultural lands and forests. It can be also used for sprinkler irrigation, and then a part of it is kept on the surface of plants.

Changes introduced intentionally bring about either anticipated or unexpected results. Changes of water surface — which may occur not only due to the creation of reservoirs but also as a result of melioration (e.g. diminishing the extent of perennial swamps) or as a side-effect of other activities (e.g. mining) — result in changes of the amount of evaporation. In the vicinity of reservoirs the conditions of runoff of waters, direction of percolation and conditions of infiltration may be changed. Thus, water is sent to the atmosphere, pedosphere or lithosphere in different amounts. Also river regulation and channel building affect water circulation indirectly intensifying, in one direction or the other, the exchange of water between the pedosphere and lithosphere on one hand and the hydrosphere on the other.

From the anthroposphere water is directed artificially to the hydrosphere in the form of sewage, and in the periods of excess water which result from rains and thaws through storm drains, or even by means of transport (removal of snow from cities). Water from water-supply systems is also used for the watering of plants, and for different methods of irrigation. Municipal wastes are also directed to the pedosphere

or even to the lithosphere. Furthermore, changed conditions in built-up areas cause changes of evaporation, infiltration and runoff. In large urbanized areas a specyfic structure of water circulation is created which is completely different from that in the areas with natural conditions or the areas transformed by man's activity but not urbanized. Nowadays, much attention is being paid to the questions of the influence of urbanization on water circulation and water relationships. Even a new branch of science has emerged, i.e. municipal hydrology which investigates hydrological results of man's activity in urbanized areas where man's influence in relation to area unit is strongest, and where changes are greatly differentiated, their dynamics being often exceptionally high[6].

Changes of water circulation must be reflected in the water balance. In the same climatic conditions — i.e. at the same amounts and distribution of precipitation and temperature oscillations — the remaining elements of the balance, evapotranspiration, runoff and retention are subject to changes. Not only the annual runoff is changed but also its composition. Due to the different intensity of the process of overland flow and infiltration the proportion of water from underground resources and water flowing directly over the surface of an area are modified. This affects the changeability of river discharge which has a bearing on the amount of disposable water. The quality of river water is also affected, as it is the intensity of discharge which influences the processes of soil erosion and consequently the amount of bed load of rivers and the supply of components causing the eutrophication of natural waters. Channel processes and conditions of sewage neutralization also depend on the changeability of flow. Thus, changes of the structure of circulation may bring about different results in the field of the water management.

The structure of water circulation can be changed due to man's very varied activities. The first factor in these changes is hydrotechnic works which are aimed at a better use of water resources or the improvement of water relationships. Apart from direct transformations of the hydrosphere they result in such effects as changes of circulation which reveal themselves either immediately or with a delay, sometimes a very lengthy one. These effects are often anticipated, though it frequently happens that anticipation refers only to their character and not their dynamics, spatial extent or influence on the remaining elements of the geographical environment. Completely unexpected results which are often unfavourable for the environment and the economy may also occur.

Changes of the structure of water circulation may also result from actions which do not refer directly to the hydrosphere but to other components of the environment, and this, by means of a chain reaction, leads to changes in water circulation. This is the mechanism of feedbacks. Hydrotechnic works change water circulation and are followed by a change in the intensity of natural physical, chemical and biochemical processes involving the participation of water. This leads to transformations of the elements of the geographical environment. The changing environment with its elements exposed to different economic activities creates new conditions for natural

[6] Cf. footnote 3.

processes, which is followed by modifications of water circulation. This can be presented in a simple diagram:

hydrotechnic works		economic activity concerning other elements of the environment (changes of land use, intensification of farming, mining works, urban growth and industrial development, communication)
↓		↓
natural processes to which water is submitted and in which it participates	⇄	elements of the geographical environment
↓		↓
water relationships		geographical environment

In spite of the simplicity of the diagram the mechanism of transformations is very complicated. This is accounted for by the multitude of processes involved and their interdependences. This is presented in another diagram (Fig. 3) which shows the directions of influence of hydrotechnic works on elements of the natural environment.

The complexity of these issues makes the studies of transformations of the structure of water circulation a very difficult task. The dynamics and direction of changes depend not only on the character of their influence but also on the susceptibility of the hydrosphere and the whole environment to change. Therefore, the same kind of economic activity brings about varying results in different geographical conditions. This seems obvious when we examine contrasting areas — situated in different climatic zones — or with a totally different relief or geological structure. Much more thorough observation is necessary when the geographical environment is not so strongly differentiated. We know, however, that the differentiation of the environment exists even in regionally homogeneous areas. Therefore, it is necessary to follow local set-ups of components determining the specific character of the processes which make up water circulation.

In spite of the difficulties involved we should conduct more and more comprehensive studies of changes in the structure of water circulation as one of the basic kinds of changes in the hydrosphere. This condition is necessary for a full evaluation of the rationality of the economy. Such studies call for specialists from different branches of science; however, a significant role might also fall to geographers specializing in water issues due to their professional approach to complex studies of the environment.

Three kinds of research tasks can be distinguished. One of them is to study the influence on water circulation exerted by definite economic objects, e.g. storage reservoirs, the intake of groundwaters melioration system in a river valley, etc. This is a partial task of a wider problem, that of the influence of investments on geographical environment.

The second task is a widening and generalization of the first one and consists in studying the influence on water circulation exerted by a definite kind of economic activity such as: river regulation, land use, mining, urbanization. These are impor-

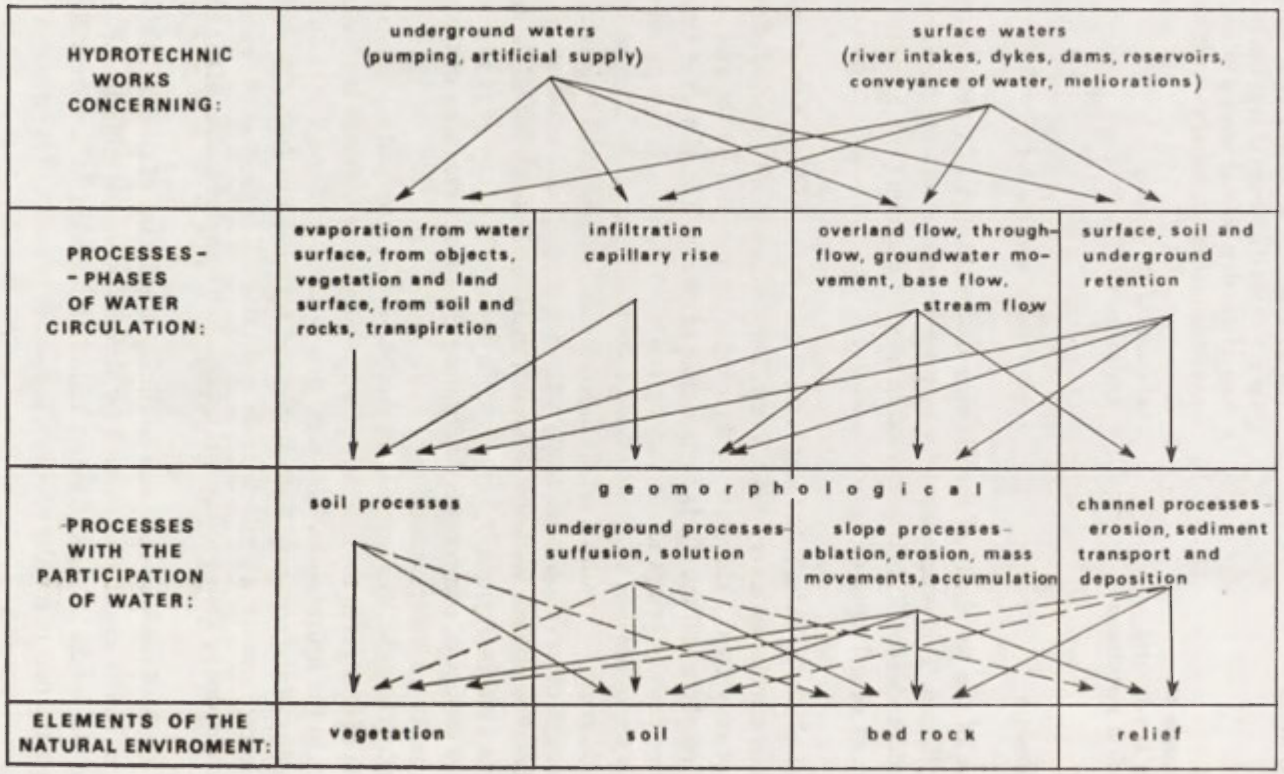

Fig. 3. Ways of influence of hydrotechnic works on elements of the geographical environment

tant research problems making it possibleto evaluate the effects of different forms of human activity on the natural environment.

The third task is to study changes of water circulation in a chosen area. This task agrees with the former one if the area is of a homogeneous economic, agricultural or forest character, or if it is an urban area. Large areas, however, with a complex economy require studies covering all the forms of influence on water circulation.

The structure of water circulation is subject to changes owing to direct or indirect interference into it; at the same time it undergoes self-regulation and evolution. Only comprehensive studies of these changes make it possible to fully evaluate, and, thus, to express well-founded conclusions in the field of rational management and protection of water resources and of the geographical environment as a whole.

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STRUCTURAL CHANGE AND SELECTED DIMENSIONS OF TECHNOLOGICAL CHANGE

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INTRODUCTION

If we propose to provide meaningful answers to the question 'how and why does economic development take place in open, mixed regional economies in economically advanced countries?' we must, among other things, seek a greater understanding of the processes of structural change. As François Perroux has indicated, the study of economic growth in essence is the study of industrial change (Perroux, 1973).

Another eminent economist, Simon Kuznets, has also underscored the importance of industrial structure in the following statement:

"The industrial structure of national output and productive resources is a key aspect of an economy in the process of growth because it permits us to observe the impact of the advance in technological knowledge, the differential response of demand to increased productive capacity and rise in per capita income, and the shifts in the size and location of groups in society associated with the different industries" (Kuznets, 1966; p. 161).

A few years later in his acceptance speech for the Nobel Prize in economic science Kuznets defined a country's economic growth

"... as a longterm rise in capacity to supply increasing diverse economic goods to its population, [a] growing capacity based on advancing technology and the institutional and ideological adjustments that it demands" (Kuznets, 1973).

A few months earlier in Edinburgh at a conference on *Economic Development in the Long Run*, Professor Barry Supple discussed his concept of economic development. He stated that:

"What we actually think of as economic development is not solely its outcome in terms of increasing quantities of income and wealth, but also (and perhaps primarily) a set of large-scale changes in economic and social processes and attitudes. These are changes — in population and its distribution, technology, industrial structure and business organization, patterns of consumption and investment and so forth" (Supple, 1972).

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The importance of structural change in bringing about improved economic conditions in an underdeveloped region, at the French Provincial scale, was strongly brought out by Professor M. Penouil at the 1967 conference of the International Economic Association at which the topic of backward areas in advanced countries was discussed. Professor Penouil said that his study, *The Appraisal of Development Policy in the Aquitaine Region*, led him to conclude that:

"No development policy for a backward area is possible or efficient unless a radical overall structural transformation can be carried through" (Penouil, 1969). Clearly the relationship between structural change and the process of economic growth and development remains significant despite changing geographic scales. However, effecting a change to a more desirable economic structure is a major problem facing not only underdeveloped regions but all regions whose people wish to benefit from a continuing process of economic development. Successive patterns of economic development associated with regional structural transformations may be measured against measuring rods provided by each society's dynamic value system.

OBJECTIVES

In this paper some aspects of structural change will be discussed conceptually so as to obtain a better understanding of the process of economic development. More specifically, attention is focused on a number of relationships between economic efficiency considerations and structural change and also on the role of technological change in enhancing the economic efficiency of economic activities and in changing the composition of an economy's outputs.

Initially, structural change is examined from a sectoral perspective at a highly aggregated three-sector level, then at the microlevel of the industry. The development stages and growth pole theoretic frameworks are used for this purpose. Attention is focused on the explanatory power of such concepts as productivity, income elasticity of demand, technological change, and on competition as a behavioral rather than a taxonomic concept. In conclusion, the economic development implications of a number of different kinds of technological changes are discussed briefly. Selected dimensions of the diffusion of new technology are examined at a conceptual level in order to identify concepts and relationships which seem to have meaningful explanatory value toward achieving a greater understanding of the nature and economic significances of the connections between economic development, structural change, and technological change.

STRUCTURAL CHANGE – SECTORAL PERSPECTIVES

MACRO VIEW

We are familiar with structural changes which are associated with the technological advancement of economies. Economists and economic historians have drawn

our attention to the decline in the agricultural sector's share of the total work force and national product in the present economically advanced countries over the last century. The decline of agriculture was accompanied by a growth in economic significance of the manufacturing and service sectors.

"Explanations for these secular structural changes tend to focus on two variables. One of these is ... the increased economic efficiency of the agricultural sector. Productivity increases have been sufficiently great and sustained to provide larger outputs per worker. The second explanatory variable is ... the effect of a rise in real income which is associated with the rise in productivity in the agricultural sector. Of course, such a rise in real income is only partly accounted for by changes in economic conditions within the agricultural sector. This so-called autonomous rise in real income, operating through income elasticity of demand, brings about structural change" (Thomas, 1974).

This rather simple explanatory mechanism for structural change is premised on the belief that where per capita income is rising then income elasticity of demand is a strategic variable. It is assumed that at some level of per capita income the Engel curve for any simple product will flatten and even turn down. Thus, as the income effect on the rate of growth of demand for the product becomes negligible, subsequent growth would tend to be that brought about by an increase in the size of the population. This time horizon applicable for each Engel curve will be influenced by income and population changes and by changes in the consumption functions of various income groups (Bruton, 1960).

The empirical bases for the roles of income elasticity of demand as significant explanatory mechanism for structural change are not well established. However, Bruton has noted that the hypothesis concerning the form of the Engel curves 'is not inconsistent with the data' (Bruton, 1960; Leser, 1963). The hypothesis appears to have been primarily used

" ... to explain the decline in the size of agricultural output, relative to total output, as an economy emerges from a very low and constant per capita income status into a situation where per capita income is increasing" (Bruton, 1969, p. 264). Subsequently, changes in the structure of demand which accompany increases in real per capita incomes provide one level of explanation for the growing proportions of the expanding per capita incomes allocated to the purchase of manufactured products and the various kinds of services.

The re appears to be a paucity of discussion as to how and why changes occur in the structure of demand. Yet such a discussion seems desirable if we are to gain a clearer and fuller understanding of the processes of structural change. In addition, how did the initial real increase in per capita incomes come about so as to trigger the income elasticity of demand mechanism which in turn brings about changes in the structure of the economy? Presumably an increase in productivity provides a plausible explanation – but then how and why did such an initial rise in productivity take place and what role was played by technological change? Macro explanations of structural change inevitably, it seems, assume a mechanistic character.

INTERMEDIATE VIEW

Unbalanced growth theorists such as Perroux, Chenery, Watanabe, and Hirschman have provided us with additional insights concerning the process of structural change. These insights, however, have been primarily developed in connection with growth processes connected with industries in the manufacturing sector (Perroux, 1970, 1963; Chenery and Watanabe, 1958; Hirschman, 1958).

In his growth pole theory, Perroux provides an explanation of how and why certain changes occur in an economy's economic structure. He describes how an initial expansion in a motor or propulsive industry *directly* induces changes in activity levels in backward and forward technologically linked industries referred to as 'affected' industries (Thomas, 1972).

Propulsive industries are defined as modern large-scale oligopolistic industries

" ... which during certain periods ... have growth rates for their own products higher than the average growth rate for industrial productions and for the product of the national economy" (Perroux, 1963, p. 95).

Indirectly induced changes in activity levels in other industries in the economy will tend to result from the initial expansion of output by the propulsive industry as a result of the operation of income and investment linkage multipliers.

PROPULSIVE INDUSTRY ECONOMIC SYSTEM

Induced expansion within an economic system connected in this manner by technological, income, and investment linkages to a propulsive industry provides a description of how changes may occur in the industrial composition of an economy. Conceptually one may think of a *round of economic growth* directly and indirectly induced by the expansion of output by the propulsive industry as a short-period phenomenon. Unfortunately, we do not have precise and accurate information on the length of time it takes for the growth effects within the propulsive industry economic system to work themselves out. Differences in input-output linkages of various propulsive industries, variations in price elasticities of outputs and inputs from industry to industry over time, availability of adequate supplies of inputs, availability of excess capacities, and speed of capacity expansion within industries in the various economic system are but a few of the variables which would tend to determine the duration of this kind of 'round of economic growth'. Usually the duration of a round of growth may be thought of as lasting some months to a few years rather than five to ten years or more. Of course, the scalar effects induced within such a round of economic growth may also be affected by variables in addition to those just mentioned. For example, over time variations may occur in the magnitude of expansion of output which initiates rounds of growth by propulsive industry.

In assessing the impact of a round of economic growth induced by a propulsive industry on the industrial composition of an economy, we need to know the nature of influences generated by other rounds of growth in similar or different stages of development which may be underway simultaneously in the economy. It is possible to conceive of these rounds of economic growth induced by different propulsive

industries as having reinforcing as well as inhibiting effects on economic growth within each other's economic systems. We also need to know if there is a part of a specific national or subnational economy that remains unaffected by expansions or contractions in the size of propulsive industries within and/or outside specific regions. How long can one part of a regional economy remain insulated from other parts of the regional and national economy? Answers to such questions provide information on the economic connectivity characteristics of regional, national, and international economies and also provide information on a facet of their economic structures. Connectivity patterns represent vehicles of possible economic growth or contractions. It would appear that temporal information concerning the industrial and spatial characteristics of these technological, income, and investment multiplier linkages within propulsive industry economic growth systems would represent valuable inputs for the development of viable regional economic development policies. Unfortunately, there is not much information on this subject (Beyers, 1973, 1974; Erickson, 1973, 1974, and 1975; LeHeron, 1973, 1974).

OTHER STRUCTURAL ELEMENTS

Growth pole theory as articulated by Perroux does call attention to structural elements in addition to industrial composition. Perroux in his explanation of economic growth and structural changes states that:

"There is *no real situation* to which the stationary equilibrium corresponds and ... ... a stable stationary equilibrium is only a device for marking and classifying changes and instabilities ... the analysis at hand integrates the numerous forms of monopolistic competition in the largest sense of the word (monopolies, oligopolies, and combinations of the two)" (Perroux, 1970, p. 99).

Of interest to our analysis of the process of structural change, especially short-period changes in industrial composition, is Perroux's linking of market structure characteristics with patterns of change in outputs within a cluster of industries focused on a propulsive industry. For example, Perroux observes that:

"Often, the system of the cluster of industries is by itself 'destabilizing', because it is a combination of oligopolistic forms ... The 'destabilizing' effect of each of these systems taken by itself is a practice in growth when, over a long period, the dominant firms increase the productivity of the industry and realize an accumulation of efficient capital greater than that which would have resulted from an industry subjected to a more competitive system" (Perroux, 1970, p. 100).

Perroux's classic 1955 article on the notion of the growth pole is replete with perceptive suggestive connections between market structure and structural change. However, the connections need to be more rigorously articulated. Received oligopoly theory has tended to focus considerable attention on the question of price competition associated with an oligopolistic market structure. Analysts largely viewing the subject within the static marginalist equilibrium theoretical framework have been much concerned with the allocative inefficiencies which stem from imperfections in the market as manifested in an oligopolistic or monopoly structure.

OLIGOPOLY AND COMPETITION

It appears that Perroux believes oligopolistic industry clusters introduce disequilibrium into the economy which he associates causally with growth processes and structural change. He infers that industries operating within a 'more competitive system' would have much less impact on economic growth and structural change.

When Perroux refers to the concept of competition in discussing certain kinds of industries operating in a 'more competitive system,' he is alluding to one facet of a more comprehensive concept of competition as generally used in post-neo-Keynesian growth theory or as used by Adam Smith (McNulty, 1968). If we were to use the concept of competition as used by Perroux in the quotation above, we may infer that the most competitive system is that which operates under conditions of perfect competition. Here, then, the concept of competition is defined in terms of the concept of a competitive market as dealt with exhaustively in the received theory of price (pp. 641–42).

McNulty, in his recent thought-provoking article observed that:

"One fundamental deficiency of competition, as the concept has been employed in economic theory, is that it has never been related in a systematic way to costs of production" (p. 650).

COMPETITION–A BEHAVIORAL CONCEPT

From the standpoint of understanding economic growth processes and structural change, it is essential that in addition to recognizing the significance of price competition we also appreciate the dimensions of competition related to costs of production. There are many insights of merit concerning the concept of competition as viewed from the perspective of economic growth, for example, those of Schumpeter. A somewhat overstated point of view on this matter was expressed by Schumpeter and quoted by McNulty:

"It is *not* ... (price) competition which counts but the compensation from the new commodity, the new technology, the new source of supply, the new type of organization ... competition which commands a decisive cost or quality advantage and which strikes not at the margin of the profits and the outputs of the existing firms but at their foundations and their very lives" (p. 654).

It seems that the crucial concept of competition needs to be behavioral in nature when used in growth theory rather than a taxonomic concept as used in traditional market structure analysis in price theory. The analytical relationships between oligopolistic industries and their competitive behavioral roles within economies of various kinds need to be more rigorously articulated in growth theories such as Perroux's growth pole theory. For example, we need to know more about the nature of oligopolistic structures within propulsive industry economic systems and how these are related to various changes in the output of industries in these systems. It would be of interest to know if oligopolistic disequilibria associated with a short-period propulsive industry round of growth may be primarily associated with price competition forces and whether or not long-period economic growth is associated with competition

forces largely associated with cost-reducing and new product-creating technological changes (Thomas, 1975a).

There is reason to believe that the oligopolistic structure of some large-scale industries contributes to their growth and changing product mix. Some large-scale oligopolistic industries are, however, not fast growing nor do they manifest significant product change. What is the role of oligopolistic structure in the different patterns of growth and product change exhibited by industries with high degrees of economic concentration? Recent investigations into the role of market structure in the growth of a rather limited number of industries and firms reveal complex dynamic relationships (Channon, 1973; Knickerbocker, 1973; Stopford and Wells, 1972; Wrigley, 1970). For these and other reasons we are unable at present to make definitive statements concerning the relationships between the oligopolistic structure of industries and processes of economic growth and structural change.

STRUCTURAL CHANGE – TECHNOLOGICAL CHANGE

THE LONG PERIOD

In reviewing Perroux's perceptive and stimulating explanation of economic growth and industrial structural change as revealed especially in two major articles which appeared in 1955 and 1963 (Perroux, 1970, 1963) one may conclude that he has focused his attention primarily on mechanisms which explain a *short-period* round of growth connected to a propulsive industry economic system (Thomas, 1964, p. 42). We also need to focus attention on forces and mechanisms which contribute to a more meaningful explanation of industrial structural change which takes place in the *long-period.* Of course, short-period and long-period changes are underway simultaneously in any economy. It is suggested, however, that there are analytical merits associated with the creation of such a dichotomy.

When discussing long-period structural changes in the economy, we note that Perroux, as well as Kuznets, Schumpeter, and other eminent growth theorists, stresses the importance of technological change as an explanatory variable. In a short paper it is not possible to discuss this important variable in a satisfactory manner. Nevertheless, it is important to comment briefly on what one considers to be an increasingly important set of relationships between technological change and structural change. The connections among technological change and economic growth and structural change are indicated very briefly prior to a discussion of a few selected aspects of this set of relationships between technological change and changes in the structure of manufacturing.

It would be appropriate at this time to mention Schmookler's definition of this exceedingly elusive and complex concept of technological change. He said:

"When an enterprise produces a good or service or uses a method or input that is new to it, it makes a technological change. The first enterprise to make a given technical change is an innovator. Its action is innovation" (Schmookler, 1966, p. 2). This definition of technological change focuses attention on two components—the one related to cost reduction and the other related to new product or new industry

creation. An enterprise may use new technology in an embodied form in machinery, new kinds of buildings, for example, and/or in disembodied form as new business organizations or management structures.

In 'private enterprise' and 'mixed economies' it is assumed that embodied and disembodied innovations will have favorable effect on the economic efficiency of innovating and subsequent imitator firms. Associated cost reduction and increased efficiency in the use of inputs tend to be manifested in productivity increases. Firms and industries experiencing rapid technological changes tend to have high rates of productivity increase and tend to have rapid growth in their outputs and usually they are also high-wage industries (Fabricant, 1959; Salter, 1966; LeHeron, 1972). When an innovation is in the form of a new product or service it may be viewed conceptually as the beginning of a new industry. The majority of such innovations die in infancy but some grow and stay in production for considerable periods of time. Contemporary studies of product cycles are providing much information on the various phases in expansion paths of product and service innovations (Thomas, 1974, pp. 63–65; 1975a). Such studies of a wide range of products and services should provide valuable insights into the process of structural change.

DIFFUSION PROCESS – DIFFUSION OF TECHNOLOGY

The search for a better understanding of the process of economic development and structural change leads to an examination of technological change because of its direct and indirect connections with scalar and qualitative changes in output, income expansion, and new industry-creating roles. The nature and rate of technological change within firms also tend to play a major role in determining their intra- and interindustry, and intra- and interregional competitive positions (in a behavioral sense, as used hereafter) (Thomas, 1974, pp. 51–65). Thus we now focus attention on the process of new technology diffusion. Subsequent discussion is focused on new technology diffusion as viewed from an aspatial perspective and examined within the technological gap and product-cycle analytical frameworks. Comments on the spatial perspective used to discuss the diffusion of new technology in a regional context are to be found in recent papers by the author and other writers such as Vernon (1974) and Nabseth and Ray (1974).

DIFFUSION – ASPATIAL PERSPECTIVE

American economists have mainly studied the diffusion of new technology from a sectoral perspective with a neoclassical economic framework. In the case of manufacturing they have been concerned with articulating the role of technological change in the development of various patterns of economic growth and structural changes within the sector as a whole or with respect to its component industries (Thomas and LeHeron, 1975). A growing number of such studies, primarily focused on embodied technological change, have also

" ... been carried out at the firm level, but it is not always clear whether the plants examined belong to single or multiplant firms, or whether the plants are single or multi-industry firms" (p. 12).

Technological progress and changing factor prices bring about changes in the methods and techniques of producing raw materials, goods, and services. Technological change, however, seems to introduce continuous disturbances into the economy and adjustments to these disturbances by the industries and firms making up the economy tend to be slow. Net additions to new technology vary in their nature due to variations in the growth rates of the different branches of knowledge relative to the industrial arts.

It is customary to think of new technology as being manifested in embodied or disembodied form (Brown, 1966; Salter, 1966). This dichotomous classifications scheme appears to be largely based on the need for investment of physical and/or human capital if embodied technological change is to take place. It is assumed, however, that disembodied technological change 'does not require gross investment to carry it into place' (Brown, 1966, p. 77). An ambiguity concerning the definitions of embodied and disembodied technological change needs to be examined and hopefully eradicated. However, such a dichotomous classification scheme retains considerable utility since embodied technological changes appear to be nonbehavioral in nature, whereas disembodied technological changes highlight behavioral characteristics.

The majority of studies of technological change from sectoral or organizational (firm) perspectives tend to be aspatial in character. In other words, attention is focused in these studies on the inter- and intraindustry, and inter- and intrafirm diffusion of new technology without an accompanying significant interest in *where* new technology originates and *what* are the spatial and locational characteristics of the subsequent diffusion of this new technology in geographic space. These studies reflect major interest because technological change increases the productivity of industries and firms. Such productivity increases exert a major influence on the capability of these industries and firms to expand their levels of output because the consequent realization of production cost efficiencies tends to enhance their competitive positions. Resultant differential scalar changes in affected industries and firms thus accompany these technological changes. Income expansion effects associated with productivity increases also have their impact as they induce changes in the industrial structure through the influence of income elasticities of demand.

TECHNOLOGICAL GAP

If we are concerned with the general question of how new technology enhances the competitive positions of industries and firms, the concept of the technological gap provides a useful framework for examining some facets. The framework of analysis provided by the technological gap concept is premised on the belief that at any point in time there is a particular body of technological knowledge that can be used viably within the existing economic system. At a particular point in time there is a particular body of technological knowledge used by the existing economic system. When the actual use of a particular body of technological knowledge is less than the potential use at that time, a technological gap exists and the economic system is not as efficient as it could be. Clearly, adverse economic impacts resulting from the existence of these gaps may be viewed from the perspectives of firms in the private sector,

the government, and that of individuals in a society. However, we have at this time little more than intuitive quantitative measures of technological gaps thought to exist in all economies. Nevertheless, belief in the existence and significance of these technological gaps is widespread among researchers on this topic (Thomas and LeHeron, 1975).

Attempts to provide an economic measure of the technological gap in various manufacturing industries have generally used the performance of the 'best-practice' firm or plant in the industry as a measuring rod against which to measure the performance of other plants such as average-practice or worst-practice plants. In effect, the best-practice firm or plant serves as a surrogate for what is technologically possible and economically viable in various industries (Thomas and LeHeron, 1975, pp. 250–51, notes 48, 74, 85). Questions have been raised recently concerning the validity of some of the best-known measures of the technological gaps in selected manufacturing industries (Gregory and James, 1973). Consequently, one may safely say that better data and better designed research projects are needed before we can make meaningful observations concerning the economic dimensions of the technological gap in components of the manufacturing sector.

Be that as it may, the existence of the gap is assumed by governments in many parts of the world who attempt, through the provision of various kinds of financial assistance, to effect the intra- and interfirm and intra- and interregional transfer of new technology. However, the roles of governments of various kinds in influencing the process of technological change are exceedingly diverse and complex, and little understood, even though they are believed to be most significant.

The last decade and a half has witnessed a tremendous increase in interest in carrying out studies on technological change. A great many of these have provided information and insights concerning how technological gaps come into being and how some forces tend to inhibit and others facilitate the development of technological gaps within and among firms, industries, and economies at different geographic scales. One may conveniently classify these studies as those focused on (1) the nature and significances of connections between inventions and innovations and the roles of research and development; and (2) the transfer of technology.

In this short paper it is not possible to discuss adequately these two types of studies. However, further information on the topic is provided in recently published papers (Thomas, 1975). At this time, attention is called to a large body of literature on information concerning new technology—its creation or generation; diffusion and utilization. Especially noteworthy in this respect are the growing number of studies on the roles of multiregional corporations in the creation of new technology and its sectoral and geographic transfer (Vernon, 1974). With respect to the utilization of information on innovations which offer opportunities for firms to reduce their production costs (and/or enable them to produce new products), one is forcefully struck by the long time it seems to take for a major innovation to diffuse through an industry and through geographic space. This process tends to take many decades rather than a few years and it appears to be the case both when the new technology is embodied in new machines and when it is embraced in major changes in the organiza-

tion and management of firms. Problems connected with the vertical, or within firm, and horizontal, or among firms, transfer of information on new technology tend to be the composite product of the influences of human behavior, technical, organizational, financial, and other factors. Many recent studies have been focused on the influence of these factors on the transfer of new technology (Thomas, 1975b).

PRODUCT-CYCLE FRAMEWORK

A significant next subject is new technology which when adopted tends to reduce production costs. Concomitantly considered is the role of new technology as it relates to the creation of new products and new industries, for this is a topic that bears directly on the process of structural change. In this connection, one of the most useful analytical frameworks has been that of the product cycle. Utilizing this framework, Vernon, Hirsch, and others have, in the last decade, advanced intriguing hypotheses, largely untested, concerning product and industry expansion paths (Thomas, 1975a). The life cycles or the expansion paths of viable new products may be characterized by a number of phases which manifest different growth rates. Initially, growth is relatively slow and this phase is followed by a period of rapid growth. Later, the growth rate falls, stabilizes, and then tends to decline.

In industries studied, such as synthetic materials and electronics, the initial or slow growth phase is characterized by high unit costs and relatively high product prices, and labor-intensive production functions with a high proportion of scientific and engineering inputs. There also appears to be a considerable degree of price inelasticity of demand for the product. New technology which tends to bring about production-cost efficiencies is apparently not as important in this phase as new technology which brings about qualitative changes which enhance the marketability of the product.

However, the rapid growth phase which follows experimentation with alternative production functions virtually ceases and the importance of cost-reducing technological changes gains emphasis as competition between producers and producers of good substitutes increases. In the subsequent phase, when the growth rate of output eventually declines, it is evident that cost-reducing technological changes prove to be inadequate to prevent the decline of the total output of the product or the total output of the product in a specific region. Increasingly, successful competition by substitutes and/or changes in consumption functions contribute to growth rate characteristics of the product cycle in this final phase.

In this discussion of the product cycle, attention is primarily focused on the characteristics of the new-product innovation and its expansion curve and the role of technological change. Another perspective would be provided by the study of the role of new-product innovations in increasing the economic efficiency of industries which use these new products in various forms as inputs. In this connection it would be useful, but extremely difficult, to examine the impact associated with the diffusion of new-product innovations used as inputs on the quality of intermediate or final inputs in the economy.

CONCLUDING STATEMENT

In this paper an attempt is made to underscore the dynamism of the process of structural change. Attention is focused on long-period changes in the industrial composition of an economy which are associated with the process of economic development. Industrial structures which exhibit new positive scalar and qualitative changes also appear to be positively associated with societies which manifest improvements in their levels of economic well-being.

In order to achieve a greater understanding of the processes of economic development and structural change, attention was drawn to the explanatory power of income elasticity and technological changes associated with new product or new industry creations. Technological changes which increased the productivity of industries and firms appeared to have a major influence on the capability of these firms and industries to expand their levels of output because the realization of production cost efficiencies tended to enhance their competitive positions. The concept of the technological gap appears to be a useful organizing framework for the study of technological changes which enhance economic efficiency in production. Some technological changes can be viewed as new products and services and thus as new industries. The expansion paths of new products may be usefully analyzed within the temporal framework provided by the product-cycle concept.

Clearly both structural change and technological change are exceedingly complex phenomena. Their importance as stressed here signifies a need for much greater study of the nature and meaning of their interconnections in the process of economic development.

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INFORMATION ACCESSIBILITY FIELDS, MIGRATION FIELDS AND THE GRAVITY MODEL

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INTRODUCTION

Geographers have increasingly been trying to measure and work with variables that deal with cognitive information (Downs and Stea, 1973 and Gould and White, 1974). The usual purpose for gathering cognitive information is to use it as an independant variable to explain the distribution of some pattern produced by the decisions of individuals who supposedly used the information as the basis of their decisions. It is clearly an attempt to relax the economic man assumption frequently used in deterministic models which assume that man as a decision-maker has perfect information and also has perfect ability to use the information (Wolpert, 1966). Although a number of studies have used techniques borrowed from psychology to measure the specific beliefs and attitudes subjects have concerning individual geographic units (Downs, 1970; Burnett, 1973; Demko, 1974; Lowenthal and Riel, 1972; and Lloyd, 1975), few attempts have been made to measure the total amount of information individuals or groups of individuals have acquired for specific geographic units. The total amount of information, although it is perhaps more difficult to accurately measure than specific beliefs and affects, would seem a logical starting point as we try to build knowledge of the cognitive environment.

EXAMPLES IN THE LITERATURE

Two recent articles (Gould, 1975 and Webber, Symansky, and Root, 1975) have tried to deal with the very difficult problem of measuring the amount of information people have about a set of places. Gould says, "We may be able to speak of an *informational environment*, one of those 'invisible landscapes' to coin the phrase of the psychologist Stea (1967), which are becoming increasingly important". He goes on to say that people acquire information in a number of ways, formal education, travel, through the media, by interacting with friends, and so on. Since the information concerning individual places will be retained in varying degrees by different people, a direct and exact measurement of the amount of information an individual or group of individuals might have about a set of places is virtually impossible. Therefore we must turn to surrogate measures.

Gould's method for obtaining a surrogate measure of the amount of information Swedish school children had about towns in Sweden was simply to ask the children, 'to write down in five minutes all the names of towns in Sweden they could recall'. The frequency with which the towns appeared on the aggregated lists was used to construct information surfaces. The Webber, Symansky, and Root study attempted to measure the amount of information a sample of Colombian peasants had acquired for a set of villages which formed a periodic market system. Their surrogate measure of the information the peasants had acquired for the villages was measured by asking subjects, 'to specify the major market day in each of the twenty-four places'. They equated the aggregate accuracy of knowledge concerning the market day with the aggregate amount of information the sample population had acquired for the villages.

TABLE 1. A summary of results for ten samples of swedish school children*

Regional name	Age level	Population parameter	Distance parameter	Coefficient of multiple regression
Norrtalje	16 1/2	0.80	−0.64	0.72
Eskilstuna	11 1/2	0.83	−0.53	0.69
Nassjo	18 1/2	0.88	−0.68	0.76
Kalmar	16 1/2	0.81	−0.59	0.76
Skovde	16 1/2	0.78	−0.38	0.69
Orebro	18 1/2	0.86	−0.19	0.69
Gavle	16 1/2	0.86	−0.51	0.69
Harnosand	11 1/2	0.95	−0.83	0.74
Ornskoldsvik	18 1/2	0.86	−1.03	0.83
Skelleftea	18 1/2	0.89	−0.95	0.88

Source: Gould, 1975.
* A logarithmic transformation of the original variables was used for all variables.

TABLE 2. A summary of Webber's results for a sample of colombian peasants*

Regional	Age level	Population parameter	Distance parameter	Coefficient multiple regression
La Union	Adults	−0.69	−1.422	0.87

Source: Webber, Symansky, Root, 1975.
* A logarithmic transformation of the original variables was used for all variables.

Both studies went on to suggest that the variation of 'total amount of information' could be explained by a simple gravity model (See Tables 1 and 2 for a summary of their results). Gould makes the argument as to why the gravity model should explain the variation of 'the total amount of information' as follows:

"It is people, after all, who generate information, and we might expect regions with many people to generate more information than those with few. Conversely,

we might expect regions close to a group of children to transmit stronger information 'signals' than those further away. In brief, information may be a function of the traditional gravity model variables, population and distance".
Whenever one ventures into an unknown territory, the first few explorations are likely to be very simple excursions, and it may be helpful if an old friend is brought along for support. Our old friend, the gravity model, seems to be very useful in predicting these relatively simple measures of information.

INFORMATION AND BEHAVIOR

The gravity model has often been used to predict the flow of information between places. For example, the number of telephone calls between places (which one would assume results in a flow of information) has been successfully predicted by the gravity model (Mackay, 1958). Migration flows between places have also been shown to be highly predictable by the gravity concept. However successful the gravity model has been empirically, it has been criticized as an 'empirical regularity to which it has not been possible to furnish any theoretical explanation', (Olsson, 1965). Since it is often necessary to recalibrate the model for different subgroups of migrants and different time periods, the gravity model has proven useful to those who wish to predict migration flows, but has not proven very satisfying to those who wish to explain the process.

Curry (1972) has suggested that it may not be appropriate to compare the gravity model parameters which are meant to measure the frictional effect of distance. He suggests that the parameters are affected by the autocovariance of the distribution of population. As Gould (1975) explains, "The problem is that in calibrating a gravity model statement to a particular set of information, we may be convoluting both the effects of human behavior and the effects of map pattern or arrangement". Gould suggests that the distance parameters he calibrated for the Swedish school children data (see Table 2) do not measure the friction of distance so much but 'appear to index the *relative accessibility* of a location within the information space of Sweden'

This paper will examine the notion that the flow of migrants between any two states of the United States is related to how accessible information concerning the destination state is to the population of the origin state. Both the flow of migrants between places *i* and *j*, and the amount of information people living in place *i* have about place *j*, can be predicted by the gravity model. It therefore seems reasonable to hypothesize that the basic *Migration Fields* in the United States should be related to *Information Accessibility Fields.*

DATA

Obviously the best way to obtain an estimate of the amount of information the aggregate population of each state in the United States has about each of the other states would be to gather a sample similar to Gould's or Webber's for each of the states. Since this is economically not possible at present, another means of estimating

information has been used. Given the distribution of population in the United States, how much information the population of a particular state (state i) would have about the other states should be a function of: (1) the population size of the other state (P_j), (2) the distance between state i and state j (D_{ij}), and (3) the population of state i (P_i).

If we consider a 48 by 48 information matrix for the contiguous states of the United States, given the findings of Gould and Webber, we might estimate a value for each of the elements of the matrix (in a relative sense) by use P_iP_j/D_{ij} as a surrogate measure[1]. If the columns of the information matrix were compared, we might find a number of states that were very similar in terms of their overall relative accessibility to the information environment. This could be statistically measured by computing the correlation coefficient between all of the columns of the information matrix. If a sufficient number of states have similar accessibility to information, factor analysis could be used to extract a number of accessibility dimensions from the correlation matrix. Such an analysis was performed for the 48×48 information matrix described above using a principal component solution and a varimax rotation of all factors accounting for more than 5% of the total variation.

INFORMATION ACCESSIBILITY FIELDS

The results (Figure 1) reveals three major dimensions. The factor loadings (the left column) relate to states receiving information and the factor scores (the right column) relate to states that are sending the information. If we consider maps (Figure 2, 3, and 4) showing the flows of information from state to state, we might talk about *Information Accessibility Fields* (IAF). The three IAF's isolated by the analysis are labeled: (1) Eastern, (2) Midwest/South, and (3) Central/Western.

The Eastern field indicates that the New England, Mid-Atlantic, North and South Carolina in the South-Atlantic, and Ohio and Indiana in the Midwest all have high accessibility to the IAF represented by this factor. The states sending the greatest amount of information within this field (indicated by high factor scores) are the larger (more populous) eastern states, e.g. New York, Massachusetts, Pennsylvania, New Jersey, Maryland, and Ohio. The Midwest/South IAF, with states in these regions having high loadings, have access to an information field with sources (high factor scores) such as Illinois, Michigan, Missouri, Georgia, Florida, and several other southern states. The third IAF, relating to the Central/Western United States as receivers of information have greatest access to information from an eastern state (New York), two midwestern states (Illinois and Michigan), and a number of western states (Texas, Colorado, Washington, Oregon, and California).

It is interesting to note that some states are located in such a position, relative to the distribution of population, that they have high access to information provided by more than one field. For example, North Carolina, South Carolina, and Indiana load greater than 0.6 on both the Eastern and Midwest/South IAF's. Min-

[1] The data matrix was transformed using a log transformation and the D_{ij} for the diagonall elements (where $i = j$) was set equal to half of the smallest row element.

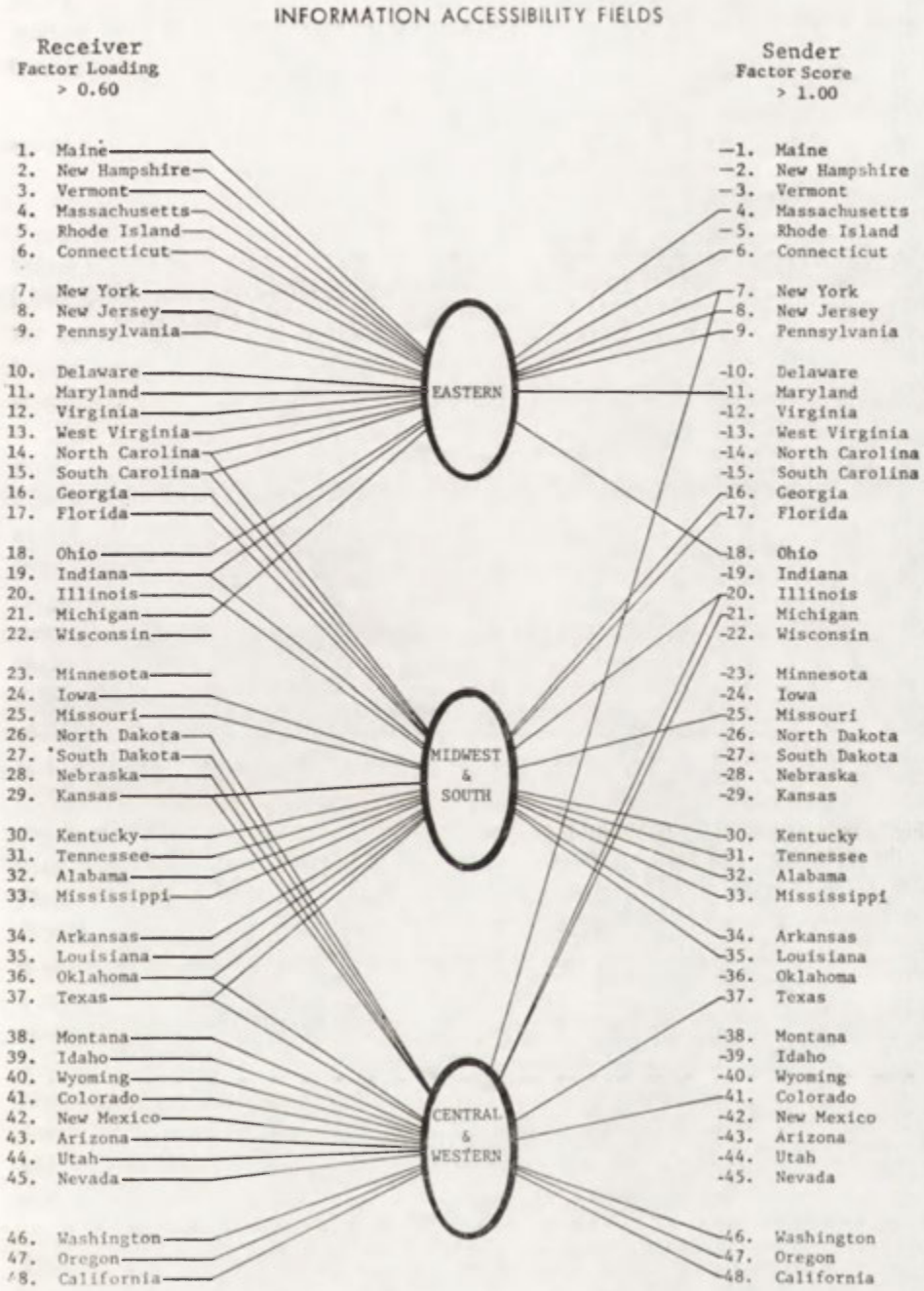

Fig. 1. Three information accessibility fields accounting for 93.1% of the total variation

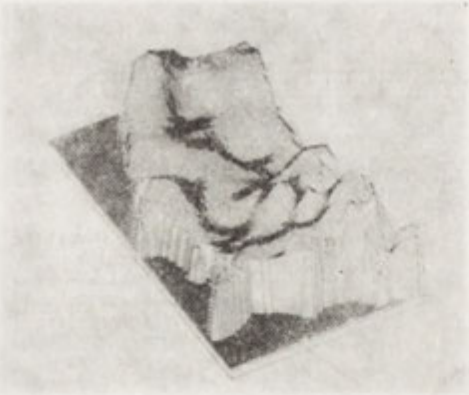

Fig. 2. Information accessibility field for the eastern states

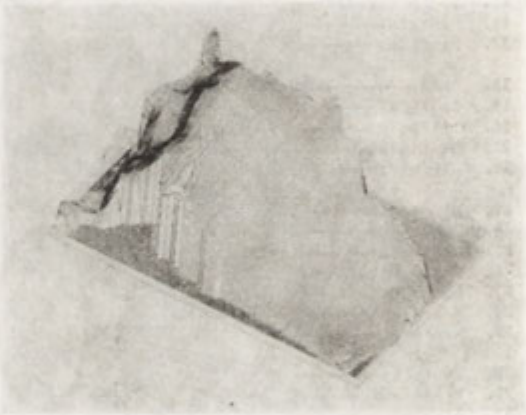

Fig.3. Information accessibility field for the midwestern and southern states

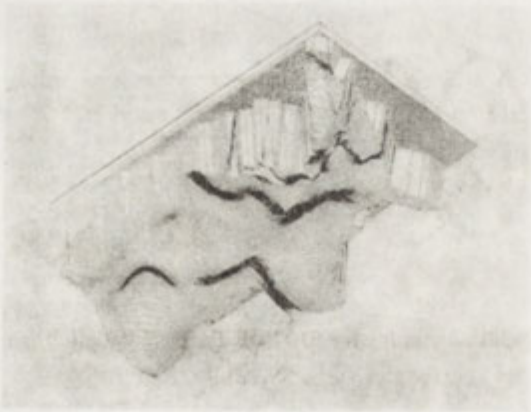

Fig. 4. Information accessibility field for the central and western states

nesota and Wisconsin are the only states that do not load above 0.6 on any of the IAF's. On the sender's side, New York and Illinois are both major sources of information for two IAF's. This is obviously due to their large populations and relative locations in space.

MIGRATION FIELDS

Are the Information Accessibility Fields which were isolated by the factor analysis a reasonable measure of the basic structure of information flows in the United States at the macro level, or are they mere artifacts of the factor analytic technique? Any surrogate measure will obviously lack credibility until it can be verified with the actual data. Actual information flow data is not available, but the migration behavior supposedly resulting from decision-makers having access to this information is easily obtained from the 1970 United States Census.

The basic structure of the migration flows can be obtained using procedures similar to those used for the surrogate information flow matrix. A 48 by 48 migration flow matrix[2] with columns relating to the states where the migration flows originate and the rows relating to the destinations of the flows was factor analyzed and revealed four basic dimensions, each accounting for at least 5% of the variance. The factors (Figure 5) identified by origin states with high loadings, i.e. (1) Eastern, (2) Midwest/South, (3) North Central, and (4) Western, can be thought of as Migration Fields (MF). Recent work by Schwind (1975) and earlier work by Berry (1966) under the title of General Field Theory used similar procedures to determine the basicstructure of migration flow matrices. Figures 6, 7, 8, and 9 are maps showing the distribution of the factor scores for each of the migration fields.

The Eastern MF (Figure 5) has the major flow of migrant originating in New England, New York, New Jersey, Pennsylvania, and Maryland. The same states, with the exception of Rhode Island, which is not a major destination, plus Virginia, Florida, and California are the major destinations for the Eastern MF. The Midwest/ /South MF basically links states in these two regions in a circulation cell. The cell is slightly assymmetrical, however, in that Michigan is a major destination, but not a major origin, and West Virginia is a major origin for the MF, but not a major destination. The North Central MF connects the origin states of Wisconsin, Minnesota, Iowa, North Dakota, South Dakota, and Nebraska to these same states plus the midwestern states of Indiana, Illinois, and Michigan. These three states are destinations for both the Midwest/South and the North Central MF. The Western MF has western states as origins and destinations. It is asymmetrical in that Montana and Wyoming are major origins, but not major destinations.

It is worthy of note that several states (Virginia, Florida, Indiana, Michigan, Texas, Colorado, and California) have more than a regional appeal for migrants in that they are destinations for more than one MF. On the origin side, only Maryland, a major origin for both the Eastern and Midwest-South MF's, has a high loading on

[2] The data matrix was transformed using a log transformation.

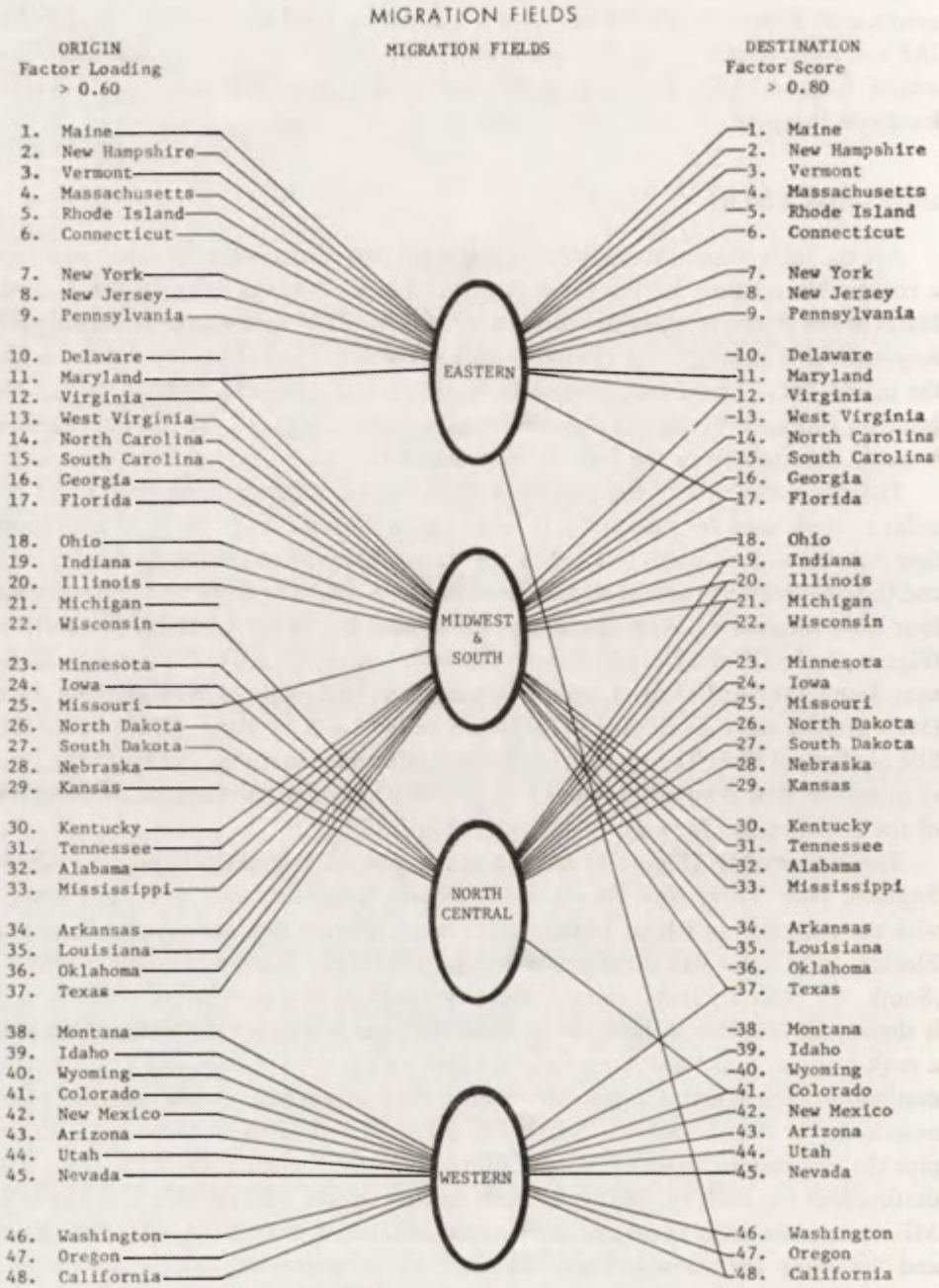

Fig. 5. Four migration fields accounting for 83.2% of the total variation

more than one field. Other interesting anomalies were Delaware and Kansas, which are not major origins or destinations for any of the four MF's, and Michigan, which is not a major origin state for any of the MF's, but is a destination state for two fields.

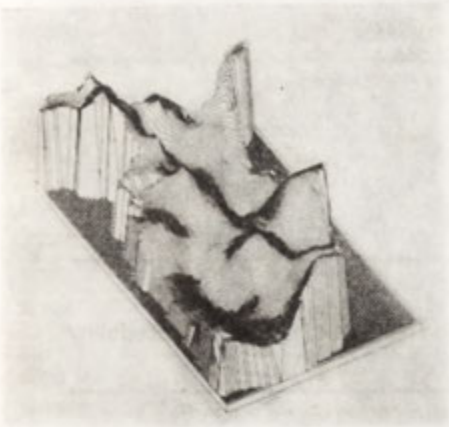

Fig. 6. Migration field for the eastern states

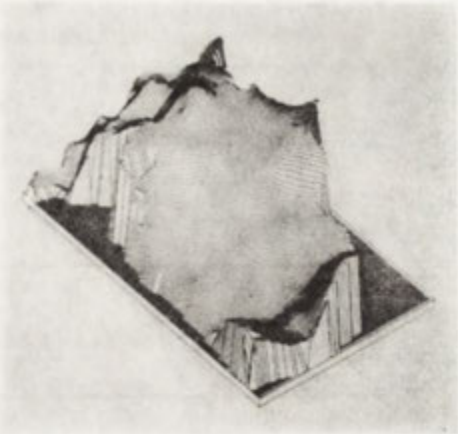

Fig. 7. Migration field for the midwestern and southern states

Fig. 8. Migration field for the north central states

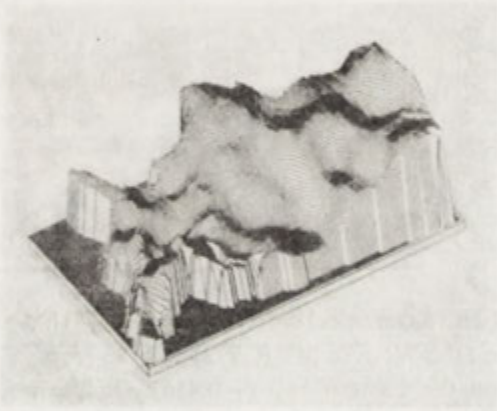

Fig. 9. Migration field for the western states

COMPARING THE INFORMATION ACCESSIBILITY FIELDS AND THE MIGRATION FIELDS

If the P_iP_j/D_{ij} hypothesis is a reasonable surrogate for information flows and if the probability of a migrant going to a state is dependent on his accessibility to information concerning that state, the MF's should match with the IAF's. To test the notion that the basic structure of the flow of 'information' is similar to the basic structure of the flow of migrants a canonical correlation analysis was computed between the factor scores from both factor analyses (Tables 3 and 4). This matches the states as senders of information with states as destinations in the migration process.

The canonical correlation analysis indicates that all three of the possible canonical correlations are highly significant (Table 3). The first pair of canonical variables

TABLE 3. Canonical correlation analysis between the migration fields and the information accessibility fields

Canonical variable	Canonical correlation	Chi-square	Degrees of freedom	Significance
1	0.978	325.3	12	0.0001
2	0.965	186.5	6	0.0001
3	0.889	68.6	2	0.0001

TABLE 4. Canonical loadings for the migration fields and information accessibility fields

Canonical variable	Migration fields			
	Midwest-south	Western	Eastern	North central
1	0.190	0.772	−0.456	0.401
2	0.913	−0.276	0.146	0.263
3	−0.075	0.422	0.876	0.219
	Information accessibility fields			
	Eastern	Central-western		Midwest-south
1	−0.598	0.791		0.139
2	0.425	0.163		0.890
3	0.680	0.590		−0.434

(with a canonical correlations of 0.978) have relatively high positive loadings (Table 4) on the Western MF (0.772) and the North Central MF (0.401) and a negative loading on the Eastern MF (−0.456). On the information accessibility side, the Central-Western IAF has a corresponding positive loading of 0.971 and the Eastern IAF has a corresponding negative loading of −0.598. The second pair of canonical variables (with a canonical correlation of 0.965) matches the Midwest-South MF with a loading of 0.913 and the Midwest-South IAF with a loading of 0.890. The third pair of canonical variables (with a canonical correlation of 0.889) has its highest loadings on the Eastern MF (0.876) and the Eastern IAF (0.680). These very high canonical correlations and the corresponding loadings suggest a very strong structural similarity between the fields representing the accessibility of information and the fields relating to the flow of migrants.

SUMMARY

Because surrogate measures of information were used in this analysis no conclusive generalizations can be made, but the following conclusions are in order. The basic structure of the P_iP_j/D_{ij} surrogate information flow matrix has a relatively simple structure with three dimensions accounting for 93.1% of the total variation.

The basic structure of the migration flow matrix is also relatively simple with four dimensions accounting for 83.2% of the total variation. Even more important is the fact that the MF's and the IAF's appear to be very similar, indicating that the flow of information could be very similar to the flow of migrants within each field individually and within the United States as a whole.

Some states are destinations in a number of MF's, e.g., California, Florida, Texas, and Colorado, but are not active senders of information in more than one IAF. This suggests that the P_iP_j/D_{ij} estimate of information flow is not an adequate measure for these states, or that the quality of the information is more important than the total amount for these states.

The work of Gould (1975) and Webber (1975), along with this analysis suggests that information, spatial behavior, and the gravity model are all interrelated. However, as Webber put it, 'the relationship between behavior and knowledge is mutual or circular and extremely complex'. Until we can develop methods that can disaggregate the quantity and quality of information used by decision-makers, we can only predict behavior, and not truly explain it.

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STATISTICAL GEOMETRY OF GEOGRAPHICAL POINT PATTERNS

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Few geographers would disagree that geography now has as one of its central objectives the study of variation in the spatial domain[1]. In this context one important class of problem is the study of pattern in discrete homogeneous events. It is argued that pattern is brought about by some process or other and should such a process have strong spatial implications it will be expressed in the pattern of events[2]. Knowledge of the phenomenon in question may suggest the type of process generating the pattern. A theoretical pattern, based on such information, may then be compared statistically with the actual pattern[3].

In practice the main difficulty has been the lack of an appropriate method for measuring pattern in discrete events as defined by Hudson and Fowler[4]. Pattern is a zero-dimensional characteristic of a spatial arrangement which describes the spacing of a set of objects with respect to one another[5].

Commonly employed techniques to measure pattern are nearest neighbour analysis and quadrat analysis[6]. Neither of these techniques measures pattern *per se* nor are they without considerable operational problems. These matters have been dealt with at length in the literature and will not be discussed further in the present study[7].

[1] For a dissenting view see, for example, S. R. Eyre, The spatial encumbrance, *Area* 5 (1973), 320–324.

[2] See Chap. 6 in: D. Amedeo and R. G. Golledge, *An introduction to scientific reasoning in geography* (1975).

[3] A clear account of this type of reasoning using the quadrat method and chi-square goodness of fit test is: D. W. Harvey, Geographical processes and the analysis of point patterns, *Trans. Inst. Brit. Geogr.* 40 (1966), 81–95.

[4] J. C. Hudson and P. M. Fowler, *The concept of pattern in geography*, Dept. Geography, University of Iowa, Discussion Paper Series 1 (1966); A. Rogers, *Statistical analysis of spatial dispersion* (1974).

[5] J. C. Hudson and P. M. Fowler, op. cit.

[6] P. J. Clark and F. C. Evans, Distance to nearest neighbour as a measure of spatial relationships in population, *Ecology* 44 (1954), 349–360; S. de Vos, The use of nearest neighbour methods, *Tijds. voor Econ. Soc. Geogr.* 64 (1973), 307–319; A. Rogers, op. cit.

[7] For a detailed discussion of the problems involved in using these two methods see: A. Rogers, op. cit.; B. J. L. Berry, Problems of data organization and analytical methods in geography, *J. Amer. Stat. Assoc.* 66 (1971), 510–523; S. de Vos, op. cit.

Recently, Boots has suggested an alternative method of pattern analysis based on the properties of Delaunay triangles[8]. Concurrent research by the present authors has also been along such lines. Here we shall present a more complete account than that presented by Boots; in particular we shall describe in detail the nature of the three main statistical parameters employed in the proposed method.

DEFINITIONS AND BASIC IDEAS

The concepts described here has been known at least since 1908 and have appeared under different names in a variety of applications[9]. To keep this expository account more or less self-contained a number of standard results are summarized and reproduced here[10].

It has been said that the core of geographic questions is the geometric properties of geographic distributions[11]. With this point of view in mind our aim here is to give a systematic method of describing the geometric statistics of an irregular distribution of objects over a plane. An essential first step is a definition of 'neighbour' which does not depend on some arbitrary metrical criterion, and which also takes into account the relative directions as well as the distances of adjacent objects.

Consider plane region R containing a number of specified objects, arranged in a more or less irregular fashion. These might be drumlins, plants or towns defined by points on a map. To keep the discussion general we call them 'sites'. For any given site A, we assign a 'neighbourhood' N_A. Here N_A consists of all points on the plane nearer to A than to any other site. The shape of each neighbourhood is a polygon, often called a 'Voronoi polygon'. With the exception of points lying on a boundary between neighbourhoods, clearly all points in the plane lie inside some neighbourhood and so the process breaks down R into a set of close-packed polygons. This set will be called a 'Voronoi honeycomb'.

In Figure 1 the neighbourhood N_A of A is shaded. The 'geometric neighbours' (or simply neighbours) of site A are those with neighbourhoods having a common boundary with N_A. It is seen in Figure 1 that A has six neighbours, $B_1, \ldots, B_6$. Each portion of the boundary N_A consists of the line perpendicularly bisecting the line joining A to the corresponding neighbour.

It should be noted that the definition of 'neighbour' given here is not determined solely by distance. It is perfectly possible for another centre C to be nearer than one of the A — neighbours although C itself is not a neighbour of A[12]. Occasionally

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[8] B. N. Boots, Delaunay triangles: an alternative approach to point pattern analysis, *Proc. Assoc. Amer. Geogr.* 6 (1974), 26–29; See: A. Getis and B. Boots, *Models of spatial processes*, C.U.P. 1978 for a recent treatment.

[9] See, C. A. Rogers, *Packing and covering* (1964), for early references.

[10] These results are available in a large number of scattered papers in different disciplines. A short review of this literature is found in: R. Collins, Melting and statistical geometry of simple liquids, Ch. 7 in: C. Domb and M. S. Green (eds), *Phase transitions and critical phenomena*, vol. 2 (1972).

[11] R. D. Sack, Geography, geometry and explanation, *Ann. Assoc. Amer. Geogr.* 62 (1972), 61–78.

[12] See, for example: R. Collins, A sum rule for two-dimensional fluids, *J. Phys.* C. 1 (1968), 1461–1472.

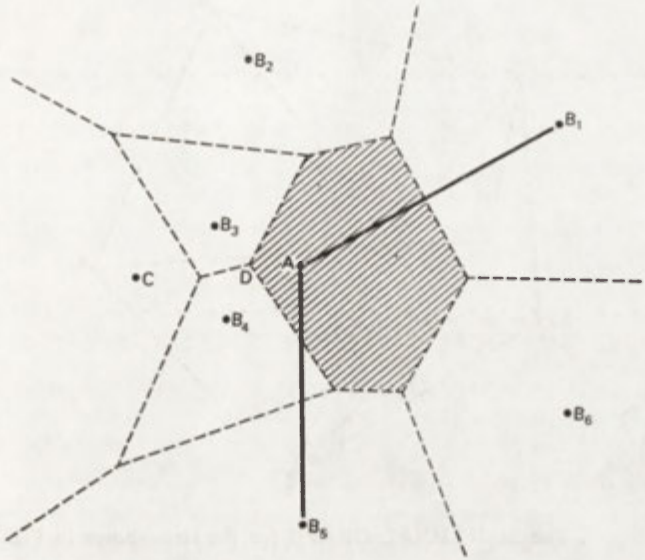

Fig. 1. A Voronoi Polygon (Shaded). B_1 is a direct neighbour of Site A an B_5 an indirect neighbour

it is useful to distinguish further between 'direct' neighbours such as B_1, where the line AB_1 actually intersects the common boundary of their neighbourhoods, and B_5, where it does not (Figure 1).

Except for some regular lattices of points arranged in a strictly periodic pattern (such as rectangular pattern of sites) it may be assumed that exactly three neighbourhoods meet at one point; for example D in Figure 1. Any exceptions will be coincidences and statistically may be considered as having zero total probability. With the exception of the degenerate case of the square lattice such cases will not be considered further in this paper. It follows that if all neighbour pairs are joined by straight-line links the result is the subdivision of the plane region R into a network of links which is called the SIMPLICIAL GRAPH (or Delaunay graph) and is the dual or inverse of the Voronoi honeycomb in a topological sense.

The simplicial graph for the sites shown in Figure 1 may be seen in Figure 2. Clearly the corresponding Voronoi honeycomb can be immediately constructed from the simplicial graph of any arrangement of sites, and *vice versa*; each contains a complete alternative description of the arrangement of sites. Which is the more relevant for particular applications will depend on circumstances. From a theoretical point of view the simplicial graph is slightly easier to study.

The main statistical parameters of interest are:

(i) the 'coordination number' q of a typical neighbour which is the number of its geometric neighbours.

(ii) the link length l between a typical pair of geometric neighbours.

(iii) the angle θ at a typical vertex of a neighbour triangle.

Since the interior angles of a triangle total 180°, the average value $\bar{\theta}$ of θ must be 60° in all cases. Similarly it follows that provided the plane region R is large enough to

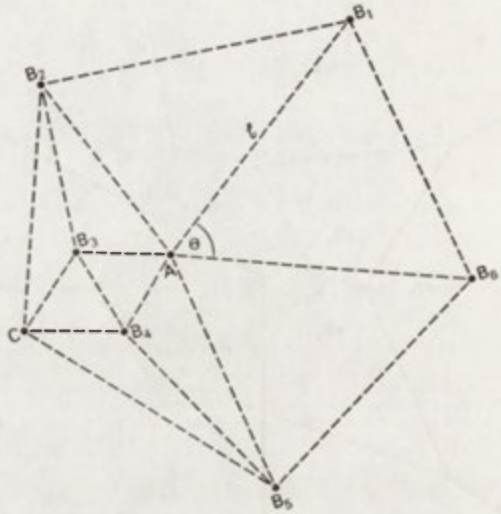

Fig. 2. The SIMPLICIAL GRAPH for the sites shown in Fig. 1

neglect edge effects (involving incomplete neighbourhoods) and there is no systematic pattern distortion near the boundaries, then the average coordination number $\bar{q}$ must be 6, whatever the pattern[13]. As far as the authors know, there is no corresponding general result for $\bar{l}$.

The statistical distributions of q, l and θ vary considerably from case to case. Let w_q be the probability that a site selected at random has coordination q, $\psi(l)\,dl$ be the probability that a typical link length lies between l and $l+dl$, and let $W(\theta)\,d\theta$ be the probability that a typical vertex angle lies between θ and $\theta+d\theta$. The set of numbers w_q and the functions $\psi(l)$ and $W(\theta)$ can then be used as indicators of statistical correlations in particular cases. Except for the degenerate or coincidental cases of zero total probability we must have

$$\sum_q q\,w_q = 6, \tag{1}$$

and

$$\int_0^\pi d\theta\,\theta W(\theta) = \frac{\pi}{3}. \tag{2}$$

Much of the purely mathematical work has been concerned with much more general arrays of sites in spaces of n dimensions[14]. Most of the applications in physics have been concerned with three-dimensional arrays of atoms in solids and liquids[15].

[13] For a short formal proof see: Collins, 1972, op. cit.

[14] C. A. Rogers, op. cit.; E. N. Gilbert, Random subdivisions of space in crystals, *Ann. Math. Stat.* 83 (1962), 958–971.

[15] J. Ziman, Principles of the theory of solids (1972); J. D. Bernal, A geometrical approach to the structure of liquids, *Nature* 183 (1959), 141–147; J. D. Bernal and J. L. Finney, Geometry of

In three dimensions the neighbourhoods become Voronoi polyhedra. They are sometimes called Dirichlet regions and (in solid state physics) Wigner-Seitz cells or Brillouin zones. Applications in two-dimensions have been limited mainly to astronomy crystal sections and, to limited extent, forestry and geography[16].

HEXAGONAL HONEYCOMBS (Figure 3)

This is the case produced by close packing hard identical discs on a plane. If ϱ is the density of centres in the plane then all the neighbour links are of length

$$b = \sqrt{\left(\frac{2}{\varrho\sqrt{3}}\right)}. \tag{3}$$

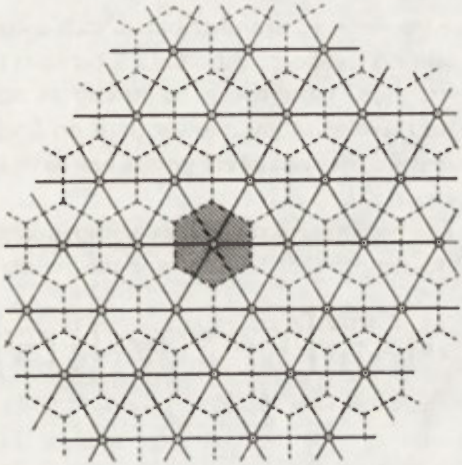

Fig. 3. A hexagonal Honeycomb

Each neighbourbood is a regular hexagon of side $\sqrt{(2/3\varrho\sqrt{3})}$. All coordination numbers are 6, so that

$$W_q = \begin{cases} 1 & (q = 6) \\ 0 & (q \neq 6) \end{cases}, \tag{4}$$

random packing of hard spheres, *Disc. Farad. Soc.* 43 (1967), 62–69; J. L. Finney, Random packings and the structure of simple liquids. I — the geometry of random close packing, *Proc. Roy. Soc.* A 319 (1970), 479–493; op. cit. II — the molecular geometry of simple liquids, 495–507; R. Collins, 1968 and 1972, op. cit.

[16] T. Kiang, Random fragmentation in two and three dimensions, *Z. Astrophysik* 64 (1966), 433–439; J. L. Meijering, Interface area, edge length and number of vertices in crystal aggregate with random nucleation, *Philips Res. Rept.* 8 (1953), 270–290; A. R. Fraser and P. Van den Driessche, Triangles, density and pattern in point populations, *Proc. 3rd Conf. Advisary Group of Forest Statisticians* (1970), 277–285; B. N. Boots, Some models of the random subdivision of space, *Geogr. Ann.* 55B (1973), 34–48.

and since in all such cases we have $\theta = \pi/3$ and $l = b = \sqrt{(2/\varrho\sqrt{3})}$ then we can write formally

$$\psi(l) = \delta\left(l - \sqrt{\frac{2}{\varrho\sqrt{3}}}\right), \tag{5}$$

and

$$W(\theta) = \delta\left(\theta - \frac{\pi}{3}\right), \tag{6}$$

where $\delta(x)$ is the Dirac delta-function[17].

COMPLETELY RANDOM (POISSON) PATTERNS

This is the case where the sites are distributed with a constant average density ϱ over the plane but with no local correlation at all between the occupation of adjacent regions. No geographical pattern can be strictly as random as this, since in the random distribution there is no finite lower limit on l, whereas in any practical geographical application the sites are never points but have some effective diameter σ so that we must have $\sigma \leqslant l$.

The Poisson case has been analysed and the corresponding $\psi(l)$ and $W(\theta)$ calculated[18]. Using suffix P to denote the Poisson case the results are

$$\psi_P(l) = \frac{\pi\varrho l}{3}\left[l\sqrt{\varrho}\, e^{-\pi\varrho l^2/4} + erfc\left(\frac{l}{2}\sqrt{\pi\varrho}\right)\right], \tag{7}$$

and

$$W_P(\theta) = \frac{4}{3\pi}\sin\theta\,[\sin\theta + (\pi-\theta)\cos\theta]. \tag{8}$$

In (1), *erfc* denoted the complementary error function[19].
No theoretical formula for the numbers w_q has yet been found, even in this limiting case. Graphs of $W_P(\theta)$ and $\psi_P(l)$ are presented in Figures 4 and 5. The mean value $\bar{l}_P$ of l_P can be shown from (7) to be given by

$$\bar{l}_P = \int_0^\infty dl\, l\psi_P(l) = \frac{32}{9\pi\sqrt{\varrho}}. \tag{9}$$

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[17] The properties of $\delta(x)$ are given in many standard works. See, for example, B. Van der Pol and H. Bremmer, *Operational calculus* (1964).

[18] See, R. Collins (1968), op. cit., 1466; The probability density function for θ has also been derived by R. E. Miles, On the homogeneous Planar Poisson point process, *Math. Biosciences* 6 (1970), 85–127.

[19] M. Abramowitz and I. A. Stegund, *Handbook of mathematical functions*, Dover, New York 1965.

It can be verified that (8) satisfies the relation

$$\frac{\pi}{3} = \theta = \int_0^{\pi} d\theta\, \theta W_P(\theta) \tag{10}$$

as is required by equation (2).

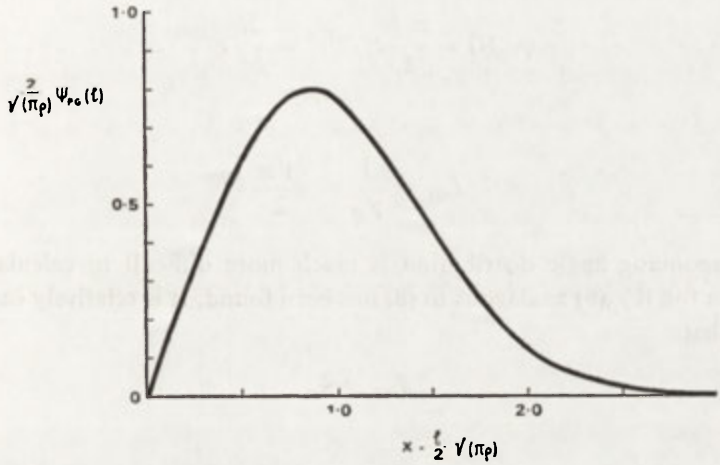

Fig. 4. Probability distribution link lengths — see equation 7

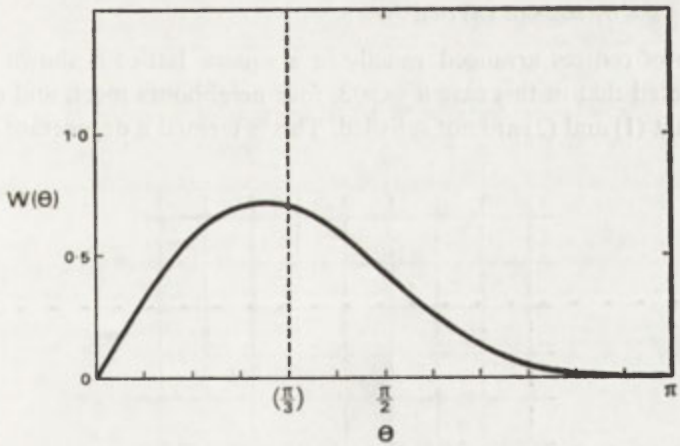

Fig. 5. Probability distribution Angles — see equation 8

Relation (7) takes a simpler form on introducing a characteristic length b by the relation

$$\pi\varrho b^2/4 = 1, \tag{11}$$

so that b is the diameter of a circle which on average will contain just one site. The (7) becomes

$$\psi_P(l) = \frac{4l}{3b^2}\left[\frac{2l}{b\sqrt{\pi}}e^{-l^2/b^2} + erfc\left(\frac{l}{b}\right)\right]. \tag{12}$$

The link length between direct neighbours only has a corresponding distribution given by

$$\psi_{PD}(l) = \frac{\pi\varrho l}{2}e^{-\pi\varrho l^2/4} = \frac{2l}{b^2}e^{-l^2/b^2} \tag{13}$$

giving

$$\bar{l}_{PD} = \frac{1}{\sqrt{\varrho}} = \frac{b\sqrt{\pi}}{2}. \tag{14}$$

The corresponding angle distribution is much more difficult to calculate and no closed form for $W_{PD}(\theta)$ analagous to (8) has been found. It is relatively easy to show however that

$$\bar{q}_{PD} = 4, \tag{15}$$

and hence

$$\theta_{PD} = \pi/2, \tag{16}$$

where suffix D refers to direct neighbours.

DEGENERATE CASE OF SQUARE LATTICE

The case of centres arranged exactly in a square lattice is shown in Figure 6. It may be noted that in this case $\theta = \pi/2$, four neighbours meet, and $q = 4$ for all centres so that (1) and (2) are not satisfied. This is termed a degenerate case because

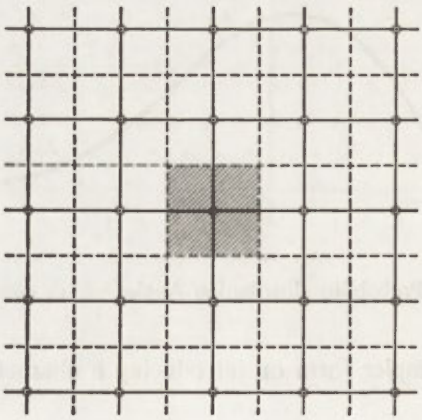

Fig. 6. A degenerate square lattice

a small random perturbation of all the centres from their original positions introduces extra neighbour links in such a way that the original conditions of the non-degenerate case are restored. This is illustrated in Figure 7. Neighbour pairs in the original lattice remain neighbours, but extra links are introduced across one or other of the diagonals of each of the original squares, so that the simplicial graph again consists of triangles.

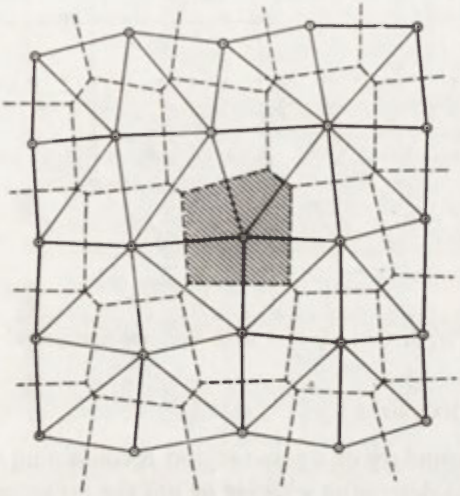

Fig. 7. Simplicial graph formed by small random perturbations of the pattern illustrated in Fig. 6

Although the average coordination number $\bar{q}$ of the perturbed (and non-degenerate) lattice is 6, the new coordination number of an individual centre may vary between 4 and 8, depending on the perturbations involved.

CONSTRUCTION OF VORONOI HONEYCOMBS – GENERAL PRINCIPLES

Given N sites A_i with coordinates (x_i, y_i) $(i = 1, 2, 3, \ldots, N)$ in a plane region R, the general problem is to find which of them are geometric neighbours, and then to construct the corresponding simplicial graph (and hence the equivalent voronoi honeycombs). Many of the methods of construction are based on the following simple geometric property.

Suppose A_1, A_2, A_3 are any three sites, and let γ be the circle passing through them. Then A_1, A_2, A_3 forms a triangle of geometric neighbours if and only if there are no other centres inside γ (cases where another centre falls exactly on γ are of zero total probability except for exactly regular lattices. If A_1, A_2, A_3 is a straight line then γ cannot be drawn, but A_1 and A_3 cannot then be neighbours anyway because of A_2). The proof of this property is given in Appendix 1.

It follows from the above that if A_1 and A_2 are already identified as neighbours, then the site A_3, to complete the neighbour triangle is that site which A_1, A_2 subtends the largest angle β (Figure 8).

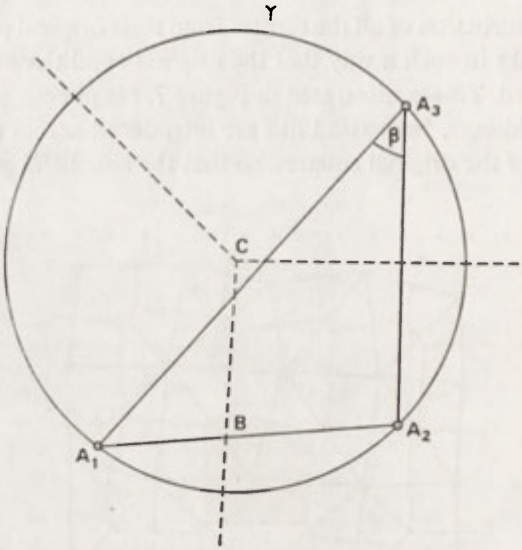

Fig. 8. Construction of a Voronoi honeycomb

THE PROBLEM OF MARGINAL SITES

Suppose Γ is the boundary of a plane region R containing sites. A common geographical problem is to determine whether or not the arrangement of sites is consistent with some specified statistical model. The commonest of these is the Poisson random distribution described previously. One method of approach would be to construct the simplicial graph of the sites, compile histograms of l and θ and a line charge for q (q being a discrete variable) and compare these with the corresponding distributions in the suggested model. In constructing the distribution of the coordination number of q, difficulties arise in dealing with a site such as A in Figure 9. The neighbourhood of A in Figure 9 is not a complete polygon, being bounded partly by

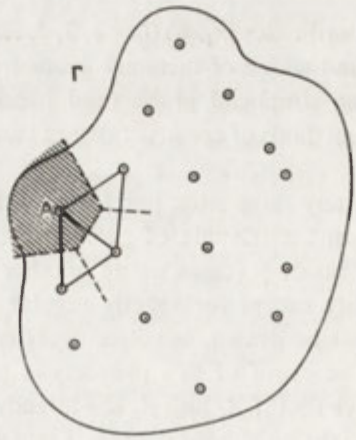

Fig. 9. Site A — a marginal site with an incomplete Voronoi polygon

a portion of Γ, and consequently no coordination number of q can be assigned to A. For simplicity we shall call a site of this type a 'marginal site'.

If Γ is an irregular or curved boundary there is no easy way of overcoming this difficulty; all such marginal sites must be discarded in constructing the q distribution. This represents a considerable loss of information, particularly when a number of sites is small. For example, in Figure 9, seventy-five per cent of the sites are marginal sites A lower bound for the proportion, f_{marg}, of marginal sites in a general case can be estimated by the following rough calculation for a circular boundary of radius R containing N sites.

Marginal sites will be those lying within al of the boundary, where a is some number of the order of unity, its precise value depending on the statistical distribution of sites. In any case, we may clearly expect that $0.5 < a < 1.5$. Taking the relative numbers of sites in two regions as proportional to their areas, the fraction f_{marg} of marginal sites is given by

$$f_{\text{marg}} = \frac{N_{\text{marg}}}{N} \simeq \frac{\pi R^2 - \pi(R-al)^2}{\pi R^2} = \frac{al}{R}\left(2-\frac{al}{R}\right). \tag{17}$$

We also have

$$l = \frac{\beta}{\sqrt{\varrho}} = \beta R\sqrt{\frac{\pi}{N}}. \tag{18}$$

Where $\beta \sim 1$ and is another number depending on the statistics. Hence we have

$$f_{\text{marg}} \simeq \frac{\gamma}{\sqrt{N}}\left(2-\frac{\gamma}{\sqrt{N}}\right), \tag{19}$$

where

$$\gamma = a\beta\sqrt{\pi}. \tag{20}$$

From equations (3) and (9), the values of β for the hexagonal lattice and Poisson random distributions are given by

$$\begin{aligned} \beta &= \sqrt{(2/\sqrt{3})} = 1{\cdot}07 \text{ (hexagonal)}, \\ \beta &= 32/9\pi = 1{\cdot}13 \text{ (Poisson)}. \end{aligned} \tag{21}$$

To obtain a rough estimate we may set $a = \beta = 1$ and $\gamma = \sqrt{\pi}$, when (19) becomes

$$f_{\text{marg}} \simeq \sqrt{\frac{\pi}{N}}\left(2-\sqrt{\frac{\pi}{N}}\right). \tag{22}$$

The variation of f_{marg} with N is shown in Figure 10. It clearly only has significance for $5 \leqslant N$ since for $N < 5$ all sites are marginal. Although derived on the basis of very rough approximation, trial reveals that (22) gives quite a reasonable guide for relatively small samples with $N \sim 10$.

It may be noted from Figure 10 that for $N = 100$, marginal sites form roughly 30 per cent of the total, and that even for $N = 1{,}000$ the proportion is still about

10 per cent. For boundaries of non-circular shape the fractions will be correspondingly higher.

Such a loss of information is only serious for the q statistic. The histograms for l and θ are much less affected since for these we only need complete links and triangles respectively, not complete polygons.

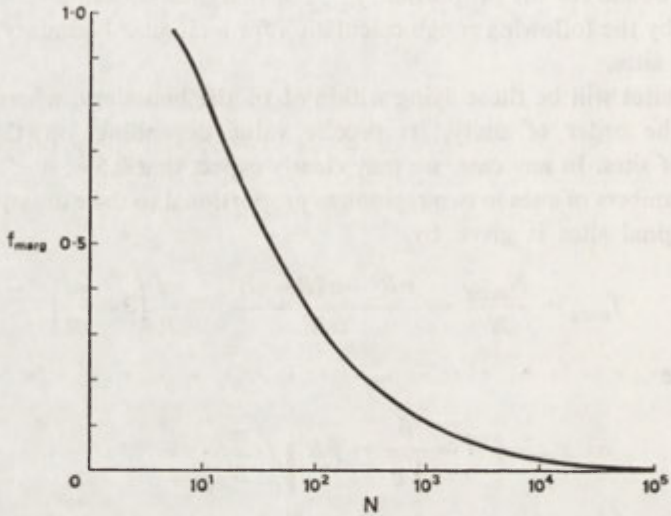

Fig. 10. The variation of f_{marg} with N, the number of 'sites'

PERIODIC BOUNDARY CONDITIONS

If the boundary Γ is rectangular the problem of marginal sites can be partially avoided by the device (well known to physicists and applied mathematicians) of applying 'periodic boundary conditions'. This involves repeating R and its site pattern across each of its straight line boundaries rather like a wallpaper pattern. This process is illustrated in Figure 11.

The rectangular region R is surrounded by eight similar regions. For each site, within R, eight 'image' sites are assigned as shown. For marginal sites their neighbourhood polygons are now completed by using these image sites. It is observed in Figure 11 that even in the case illustrated, where there are only two sites, it is possible to construct complete polygons. Obviously, in such an extremely small sample the statistics are dominated by the periodicity of the augmented pattern, but for larger values of N the effect is much less. For $N = 100$, for example, one may expect the slight distortion of the coordination number statistics to be much more acceptable than simply deleting the thirty or so marginal sites.

Clearly the method is not restricted to rectangular boundaries but will work for regions of any shape which, in repeating periodically in all directions, can be close-packed in a plane. Obvious shapes which satisfy this criterion are those of the parallelogram, regular hexagon and equilateral triangle.

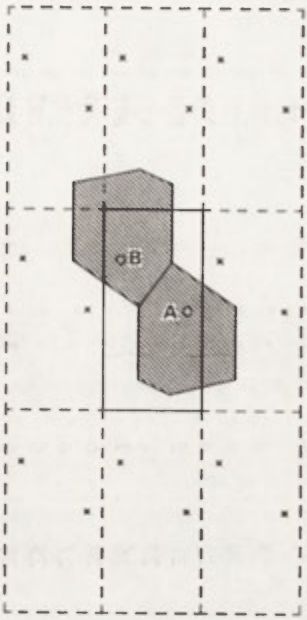

Fig. 11. 8 'Image' sites surrounding sites A and B

MONTE CARLO SIMULATION OF w_q

It has previously been indicated that no theoretical formula for the number w_q has yet been found. We have suggested, however, that the 'coordination number' q is an important statistical parameter and it is necessary to have some idea of its frequency distribution in the Poisson case.

In this study we have simulated ten random point patterns, each of 1000 points (Figure 12). The values of q have been collected from the corresponding simplicial graphs. The results are summarized in Table 1 and Figure 13.

It will be observed that there is relatively little variability between each simulation run due in the main to the satisfactorily large number of points. Any variability between simulations is, of course, due to random fluctuations. It is suggested that except for highly marginal cases these simulated data will be suitable for goodness of fit tests.

DISCUSSION

It is obvious that pattern is such a complex phenomenon that no single parameter could possibly provide a satisfactory description. The three parameters, q, l and θ, whilst not providing a complete description of the simplicial graph, in a mathematical sense, enable the researcher to tackle problems of pattern description in a more rigorous manner than hitherto. Furthermore, these parameters have the added advantage of being relatively easy to compute from the simplicial graph.

TABLE 1. Results of ten simulated patterns each of 1000 sites. Marginal sites are not included in the calculation

SIMULATION EXPERIMENT NUMBER	NUMBER OF NEIGHBOURS										
	3	4	5	6	7	8	9	10	11	12	Σ
1	7	119	220	257	171	76	32	4	2		888
2	16	103	234	256	167	76	30	6	3		891
3	7	103	246	263	171	79	23	4	2		898
4	12	103	213	294	165	77	21	5		1	891
5	7	105	251	253	167	77	23	11	1		895
6	9	109	235	239	191	89	16	7			895
7	15	96	236	275	169	75	26	6		1	899
8	8	93	249	257	185	70	27	4			893
9	7	101	230	280	176	68	25	6			893
10	7	99	253	272	157	72	28	6	3	1	898
Σ	95	1031	2367	2646	1719	759	251	59	11	3	Σ 8941
% frequency	1.06	11.53	26.47	29.59	19.22	8.48	2.80	0.66	0.12	0.03	

Let us suppose that we wish to examine a point pattern which we thought had been generated by a two-dimensional poisson process. The statistical distributions of q, l and θ can be collected from the simplicial graph and compared with the theoretical distributions of l and θ and the simulated distribution of q. If all three observed

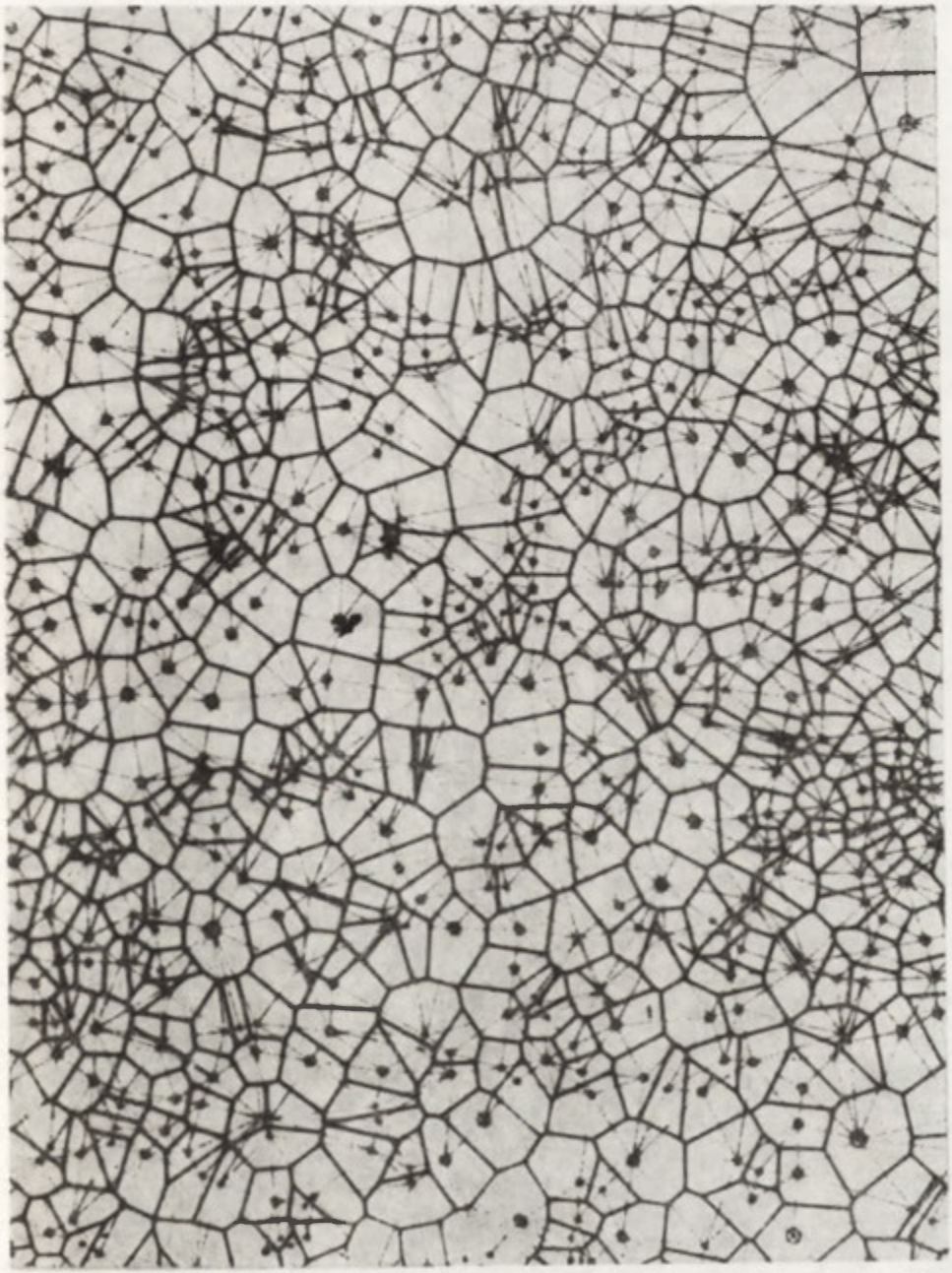

Fig. 12. One example from the ten simulated random point patterns. Voronoi polygons and the corresponding simplicial graph are shown $N = 1000$

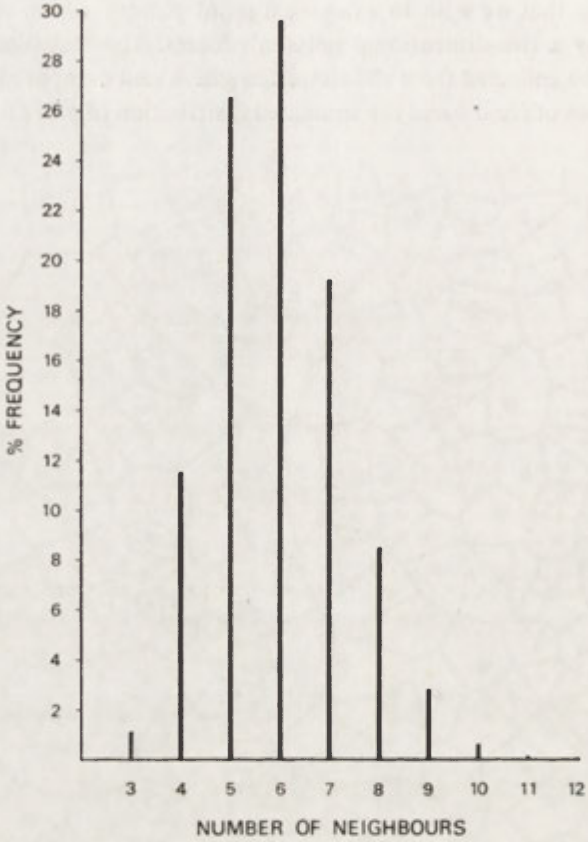

Fig. 13. Frequency distribution of 'number of neighbours', q

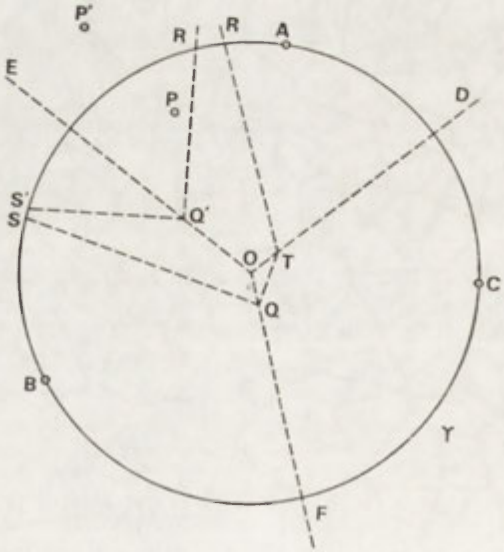

Fig. 14. Proof of the circle property for neighbour triangles — see Appendix I

frequency distributions are not statistically distinguishable from the expected distributions we could be reasonably sure that the point pattern was random. We can, of course, never be completely certain because, as we have said above, the three chosen parameters by themselves do not completely describe the simplicial graph. Should, however, one, two or three of the observed frequency distributions be distinguishable from the theoretical distributions we would have to reject the hypothesis that the point pattern was poisson, since some measure of order has been detected.

The derivation of the theoretical frequency distributions for the parameters l and θ required considerable mathematical skill and it is probable that geographers will have to wait for mathematicians to provide further theoretical distributions. This, of course, is not to say that theoretical point patterns other than the poisson case cannot be studied. Frequency distributions for q, l and θ for other point patterns, such as a binomial or negative binomial can be simulated in a manner similar to that described in this paper[20]. This latter topic and the effect of varying boundary conditions on the statistics are promising areas of future research.

Acknowledgements

We should like to thank Miss C. Minister and Mr R. Oliver, Cartographers in the Department of Geography, Salford University, for drafting final versions of the diagrams.

APPENDIX 1. Proof of the circle property for neighbour triangles

In Figure 14, A, B and C are sites and γ is the circle passing through them. If there are no other sites, then A, B and C will form a geometric neighbour triangle and the boundaries OE, OD and OF separating the neighbourhoods N_A, N_B and N_C will be straight lines intersecting at the centre O of the circle γ.

Now consider the effect of introducing another site P' outside γ. Without loss of generality it may be supposed to be in the original N_A. This introduces new lines $R'Q'$, $S'Q'$ into the Voronoi honeycomb but since they must intersect at Q' on OE which is short of O, the point O remains in the honeycombs and A, B, C remain mutual geometric neighbours, which remains true as long as any added sites are outside of γ. If the new site is at P *inside* γ, however, then the new lines in the honeycomb are RT, TQ and SQ. The whole of the line OE is now reversed from the honeycomb and so A and B are no longer geometric neighbours. Hence any other sites *inside* γ prevent A, B and C forming a neighbour triangle. This completes the proof.

[20] Details of the method may be found in the A. Rogers, op. cit.

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