WORKING PAPER

THE INFLUENCE OF THE UNDERLYING LAND SURFACE ON THE WATER EXCHANGE BETWEEN EARTH AND ATMOSPHERE.

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Foreword

In this Working Paper, the authors produce maps of IWR, an index of water exchange variability proposed by the National Environment and Climate Monitoring Laboratory, Moscow (see Lisseev and Minin, 1986). Values of the index are computed from measurements of monthly precipitation and estimates of monthly evapotranspiration obtained from a large number of heat budget stations in the Soviet Union. Values of IWR correspond remarkably with ecosystem types, the isopleths being closely packed along ecotones (separating forest and taiga, for example).

Given some future climate scenario, the method could be used to estimate changes in the locations of ecotones. Thus the paper is a contribution to the ICSU IGBP program (International Geosphere-Biosphere Program) and as such, is to be welcomed.

Bo R. Döös
Leader, Environment Program

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1. INTRODUCTION

The water exchange between land and atmosphere is a process of great importance to the biosphere. In fact, the hydrologic cycle is the main process through which living organisms are provided with water and nutrients. The role of ecosystems in the regulation of this water exchange is not as yet clear. The local hydrologic cycle is, in particular, as follows: precipitation falls on the land, is transformed by the ecosystem, and returns to the atmosphere by evapotranspiration. The type of ecosystem influences the input-value (precipitation) only to a small degree. Such influences have been explored by Konstanitov (1963), Fedorov (1977), Rakhmanov (1984), etc. But our knowledge of an ecosystem's ability to influence the output (evapotranspiration) is not sufficient. This paper is devoted to a new method of investigating this important problem.

2. METHODOLOGY

An ecosystem is a unit of the biosphere in which different parts - vegetation, soil, the atmospheric boundary layer, animals - are connected by fluxes of matter and energy. Problems arise when researchers attempt to estimate an ecosystem's

* Natural Environment and Climate Monitoring Laboratory GOSKOMGIDROMET and USSR Academy of Sciences, Moscow.

behavior, as there are no exact methods of observation and measurement. Therefore, a new method to reveal and estimate the influence of an ecosystem on exchange processes is proposed. This method used a comparison of ecosystem input and output fluxes, and is based on a statistical analysis of a long-term series of observations, yielding climatic values.

The method is based on a comparison of time variabilities of local moisture fluxes. Precipitation (P) is considered as the input value, and evapotranspiration (E) as the output value. The growing season and the individual months are analyzed. The purpose is to study the range of "output" changes (E) that correspond to the range of the "input" changes (P) for different ecosystems, using a new index IWR, proposed in Minin (1986; 1988a). The index IWR is the ratio of the precipitation and evapotranspiration variabilities as follows:

$$IWR_p = \frac{P_p - P_{100-p}}{E_p - E_{100-p}} \qquad (1)$$

Here, IWR - index of water exchange; p - probability (%) of any value exceeding some fixed level, i.e., $p = p(X > X_p)$; P_p, P_{100-p}, E_p, E_{100-p} - monthly amounts of precipitation (P) and evapotranspiration (E) during the growing season for probability p or $100-p$. The index of time-variability is $\delta X_p = X_p - X_{100-p}$, where X is any variable. The probability p may be connected with a time interval (for example, p=20% means a 5-year period). X_p is a mean maximal value for a statistical period determined by probability (p), and X_{100-p} is a mean minimal value for the same period.

Three situations are possible (Figure 1).

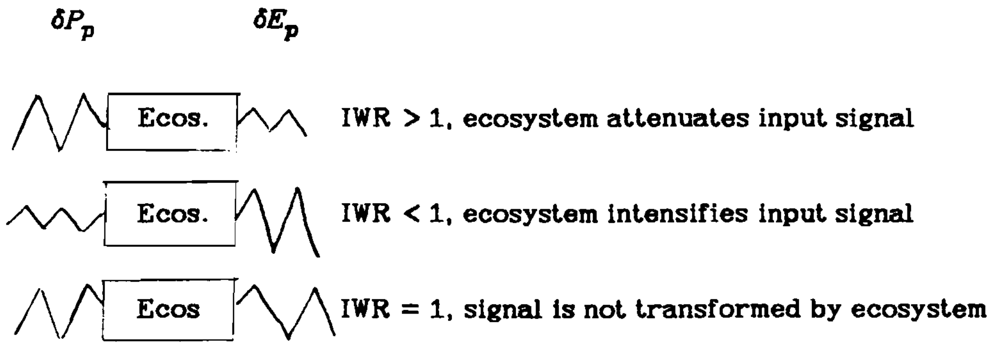


Figure 1: Scheme of ecosystem's influence on the water exchange.

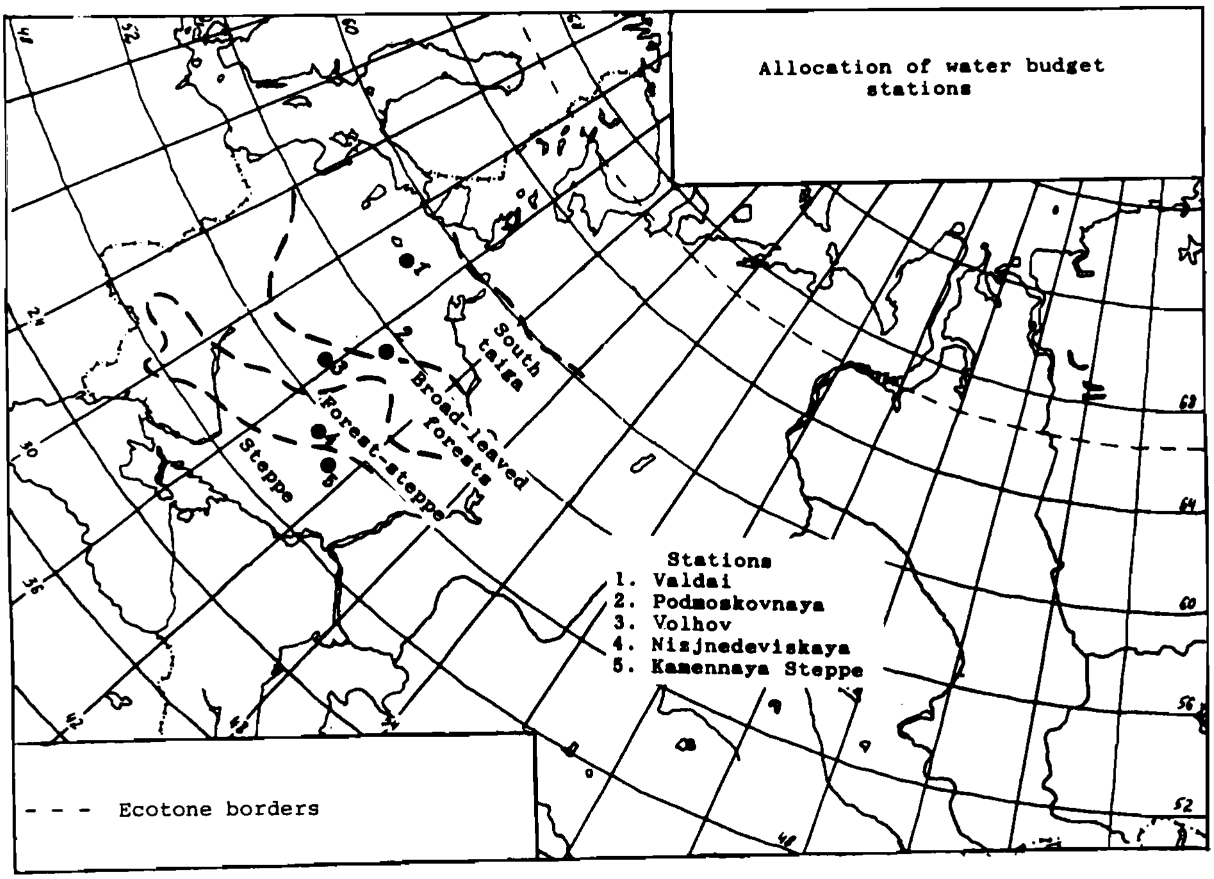


Figure 2: Location of water budget stations.

We investigated the behavior of this index during the growing season at six water-balance stations in the USSR (Figure 2). (The Primorskaya station, situated in a broad-leaved forest zone near the town of Ussuriysk in the far east of the USSR, is not shown in the figure.) We also investigated the time-space distribution of the index for boreal forests and steppe zones in the USSR. The investigations were based on a large climatological dataset. The monthly precipitation (measured) and evapotranspiration (estimated using the Budyko method) (Budyko, 1984) during the investigation are included in the analysis. The probability curve approximating the long-term series of meteorological data was determined by a method of Kolosov (1972), Kolosov and Lisseyev (1987) and Minin (1988a), based on Pearson three-type curves. The values of $P_{p,100-p}$ and $E_{p,100-p}$ were taken from these theoretical curves (Minin, 1988b).

At the regional level the data of monthly observed precipitation and estimated evapotranspiration were taken from Shver (1976) and Zubenok (1976) respectively. Space resolution was 2 × 2 degrees.

3. RESULTS AND DISCUSSION

3.1. *Local level*

A series of 124 monthly precipitation and evapotranspiration ranges has been analyzed. The series are successfully approximated by Pearson three-type theoretical curves, leading to the results shown in Table 1.

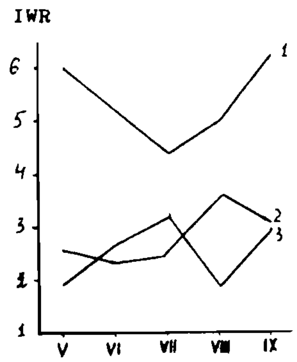
We notice that the relation Ca ≈ 2Cv (see Table 1, p.5) is approximately fulfilled both for precipitation and evapotranspiration. Shver (1976) obtained a similar result for precipitation in her analysis of numerous long-term series but the results for evapotranspiration have not previously been obtained. Knowledge of Ca/Cv helps to calculate E- and P-value probabilities on a regional level, when there is information of mean-values, Cv only.

Table 1: Values of Ca* and Cv**

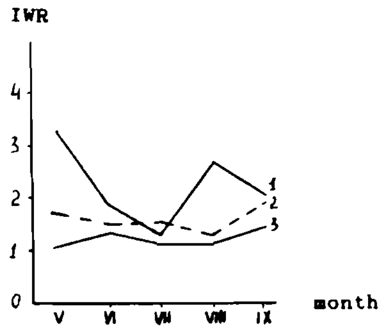
Ecosystems	Precipitation				Evapotranspiration			
	number of observation periods	Ca	Cv	Ca/ Cv	number of observation periods	Ca	Cv	Ca/ Cv
Forest and grass:								
Sum	40	38.3	24.08	1.7	54	29.1	16.16	1.7
Mean	40	1.0	0.60		54	0.5	0.30	
Under forest crown:								
Sum	15	18.4	9.56	1.9	15	12.2	5.92	2.1
Mean	15	1.2	0.64		15	0.8	0.39	
Total:								
Sum	55	56.7	33.64	1.7	69	41.3	22.08	1.9
Mean	55	1.0	0.61		69	0.6	0.32	

* Ca - coefficient of asymmetry; ** Cv - coefficient of variation.

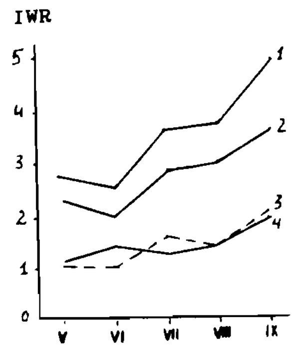
The dynamics of $IWR_{20\%}$ in different ecosystems during the growing season is shown in Figure 3. In most cases, the index increases during the growing season. However, the curves for forest and meadow (Figure 3a) are different; maximum values for forest occur in August and September and for meadow in June and July. This may be related to different vegetative dynamics of these ecosystems. The grass develops more quickly during the growing season than the forest in Valdai. Figure 3d shows that $IWR_{20\%}$ has a minimum value in July in the crop-fields (Figure 3d). This is due to the fact that harvesting of the plant communities leads to a reduction of the water exchange regulatory properties, indicating the important role of human activity in water exchange. A similar effect is also be revealed on a regional level.



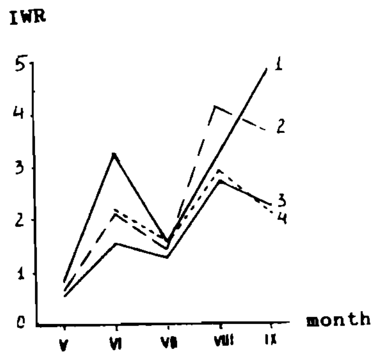
a) Valdai: 1. under the crown of spruce forest; 2. spruce forest; 3. meadow



b) Volhov: 1) virgin soil; 2) glade in forest; 3) under the crown of mixed forest



c) Podmoskovnaya st.: 1) under the crown of birch forest; 2) meadow 3) Kamennaya Steppe, virgin soil; 4) Nizjnedeviskaya, virgin soil



d) Primorskaya st.: 1) virgin soil; 2) spring wheat; 3) clover; 4) soya

Figure 3: The dynamics of $IWR_{20\%}$ in different ecosystems during the growing season.

The mean probability values of IWR for all studied ecosystems (excluding "under the crown") are as follows: $IWR_{20\%} = 2.15$; $IWR_{5\%} = 2.22$; $IWR_{1\%} = 2.23$.

3.2. *Regional level*

The results of the statistical analysis at the local level have been used for regional level studies. Mean amounts of precipitation and evapotranspiration and its Cv were taken from Shver (1976) and Zubenok (1976). Then probabilistic amounts of precipitation and evapotranspiration for probability p and $100-p$ in each cell $2° \times 2°$ grid were calculated from the statistical tables for Pearson's third type curves (Klibashev and Goroshov, 1970). The calculation carried out allowed us to construct charts of IWR and also of variabilities of precipitation and evapotranspiration for monthly and seasonal time-scales. We chose the probability 20% because errors due to a lack of exact amounts of Ca and Cv in each cell are a minimum in the calculations, due to the nature of Pearson's three-type curves (Kolosov and Lisseyev, 1987).

The map of precipitation variability (Figure 4) shows more variability in the boreal forest zone during the growing season than the steppe or desert zones (in absolute sums, here and later, the values are in centimeters). The regions with larger variability coincide with the forest-steppe and steppe of the USSR. There are almost homogeneous fields of variability in the boreal forest.

The map of seasonal variability in evapotranspiration (Figure 5) is developed from a paper by Antonovsky and Kolosov (1987) on energetically active regions over land. One important sign of such regions is the high time-variability of output water-fluxes. Over the plains of the USSR, two energetically active regions, situated in forest-steppe and steppe zones on the European territory and in West Siberia, were revealed. These regions are very sensitive to climatic changes.

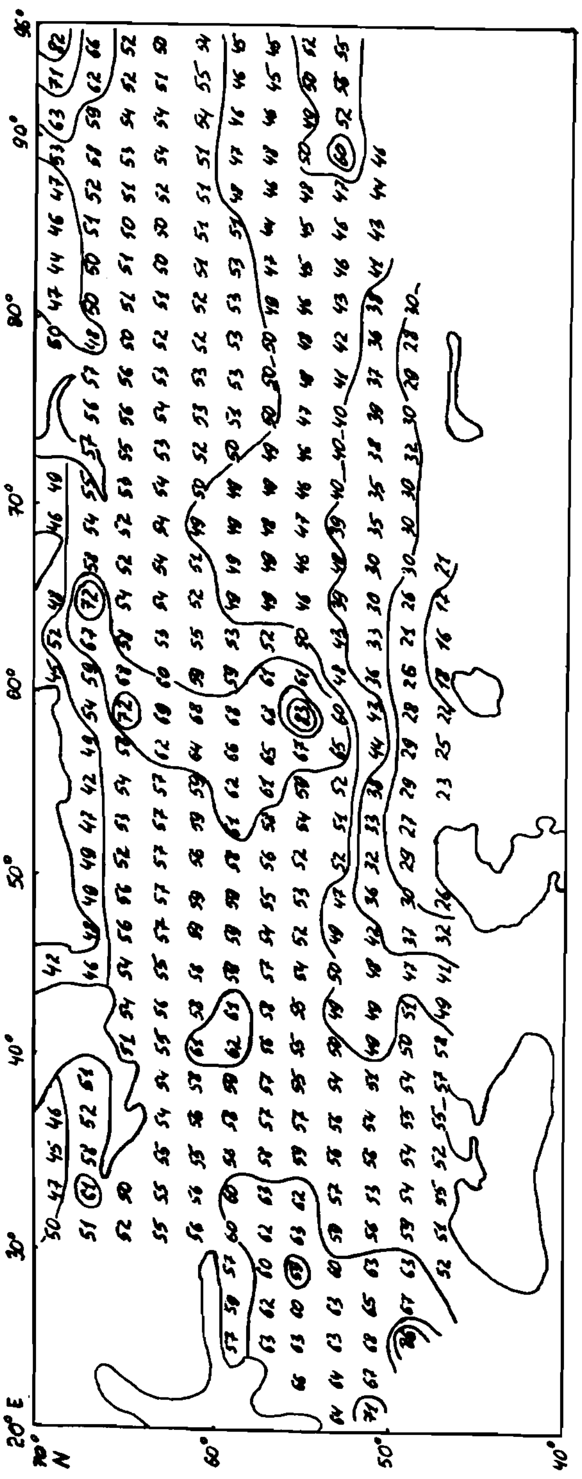


Figure 4: Mean variability of precipitation for the growing season ($\delta P_{20\%}$)

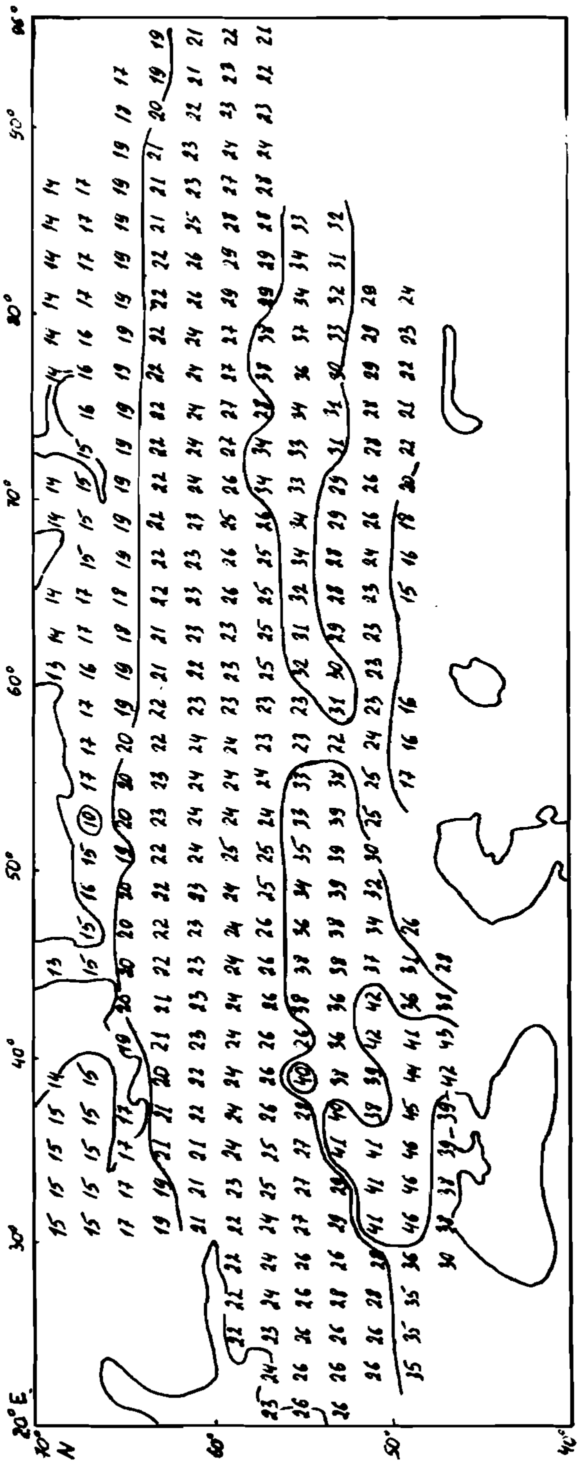


Figure 5: Mean variability of evapotranspiration for the growing season ($\delta E_{20\%}$)

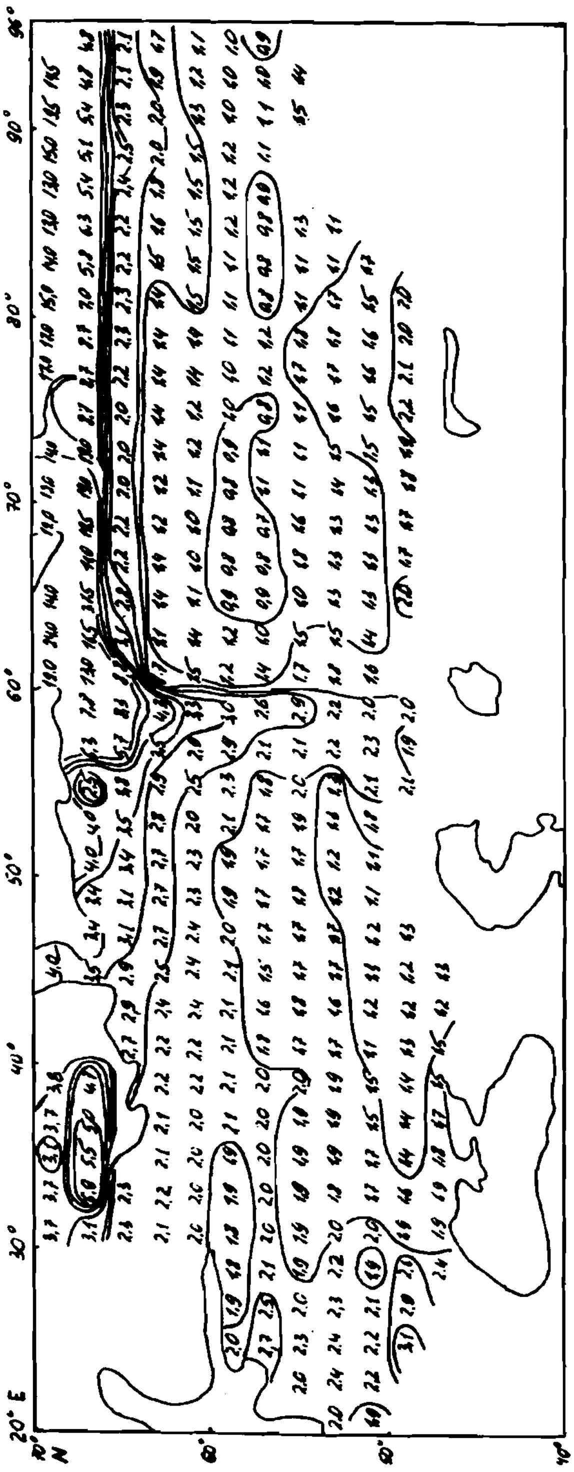


Figure 6: IWR$_{20\%}$ May

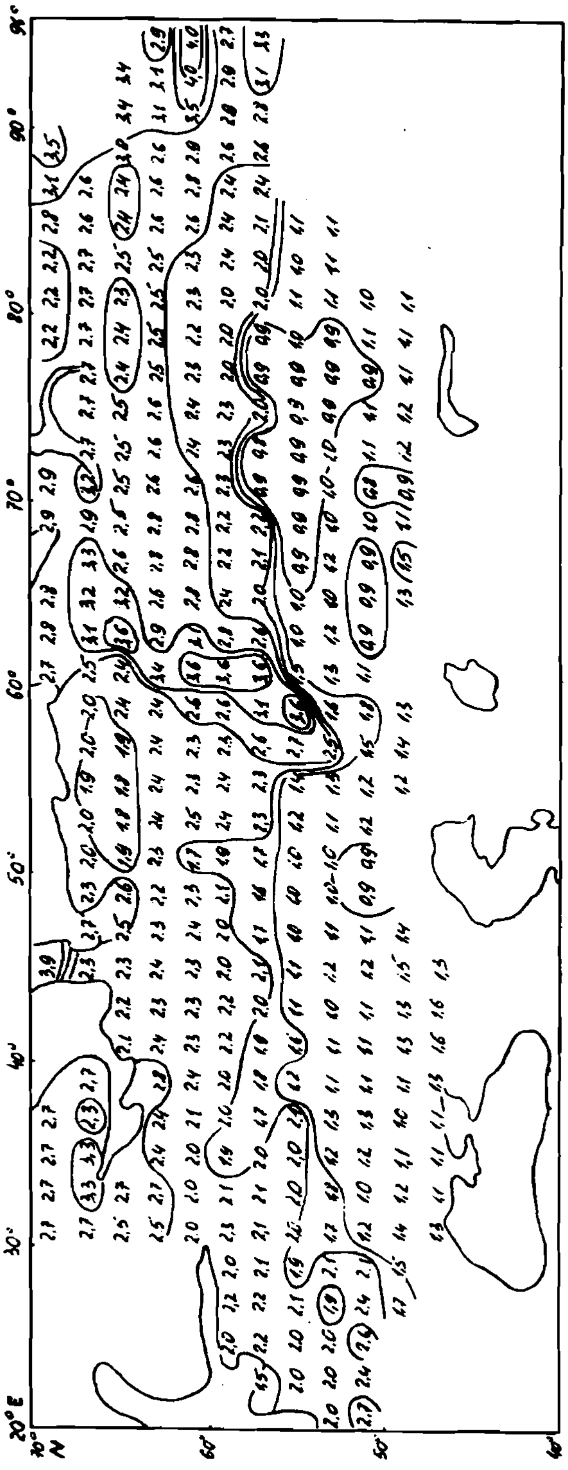


Figure 7: IWR$_{20\%}$ June

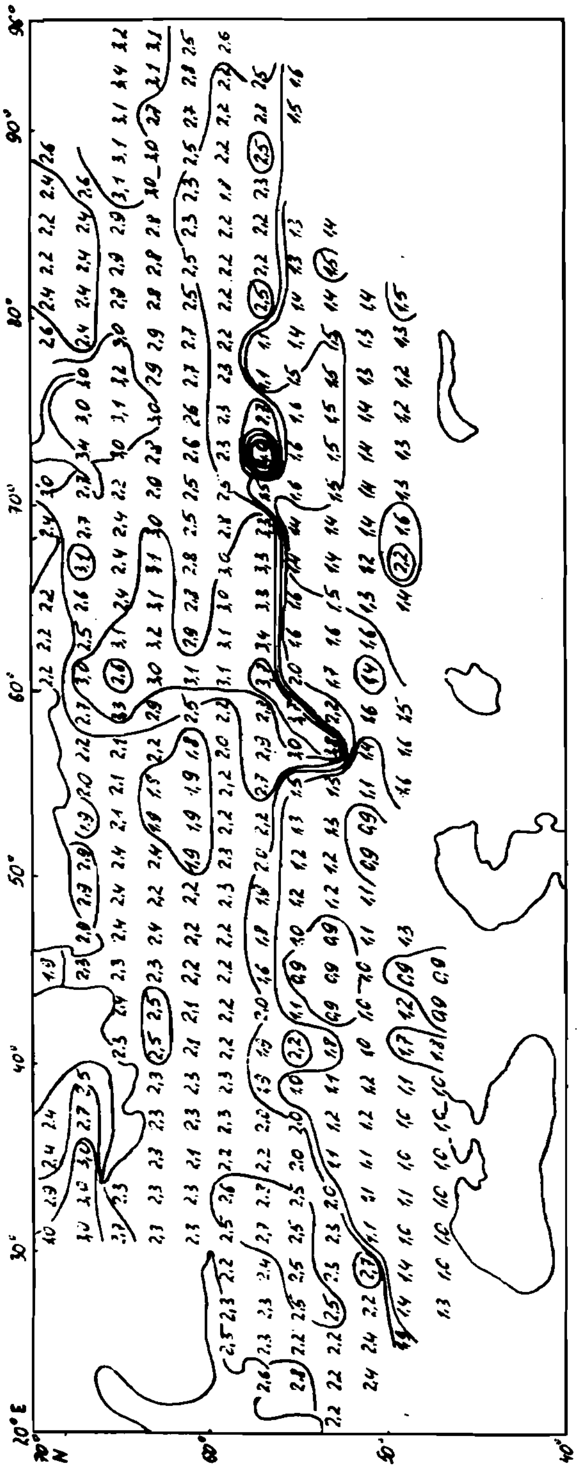


Figure 8: $IWR_{20\%}$ July

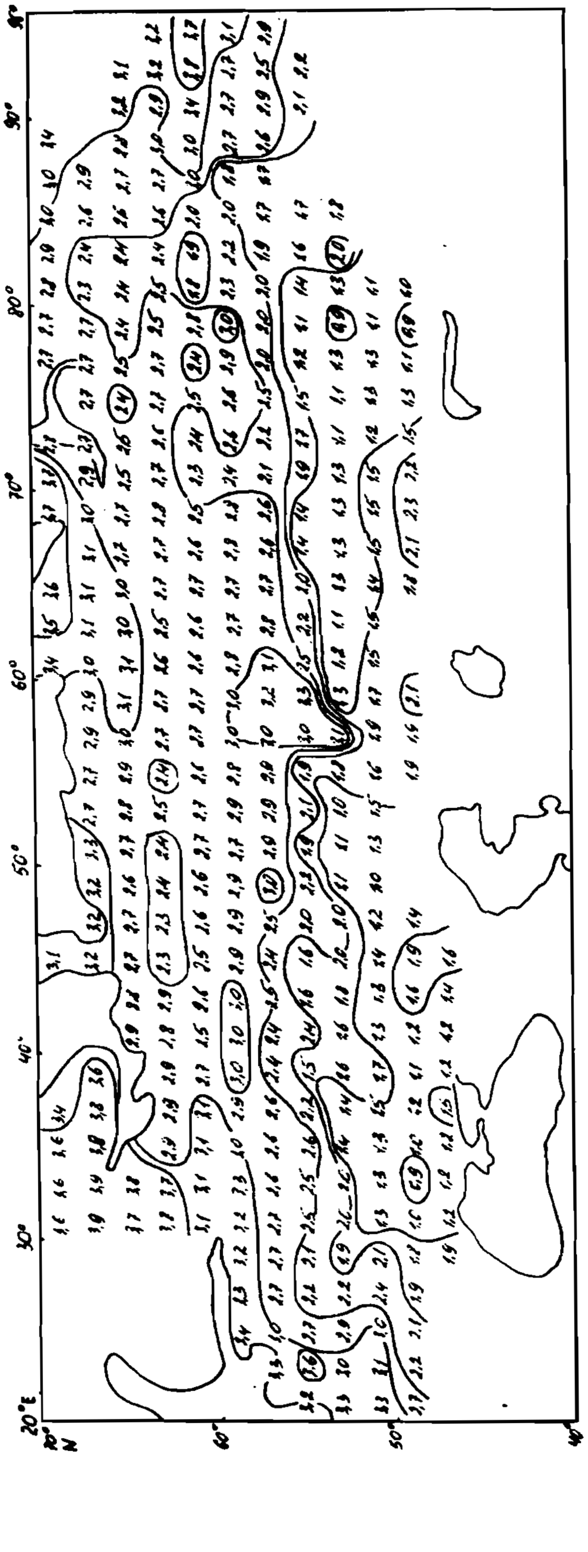


Figure 9: $IWR_{20\%}$ August

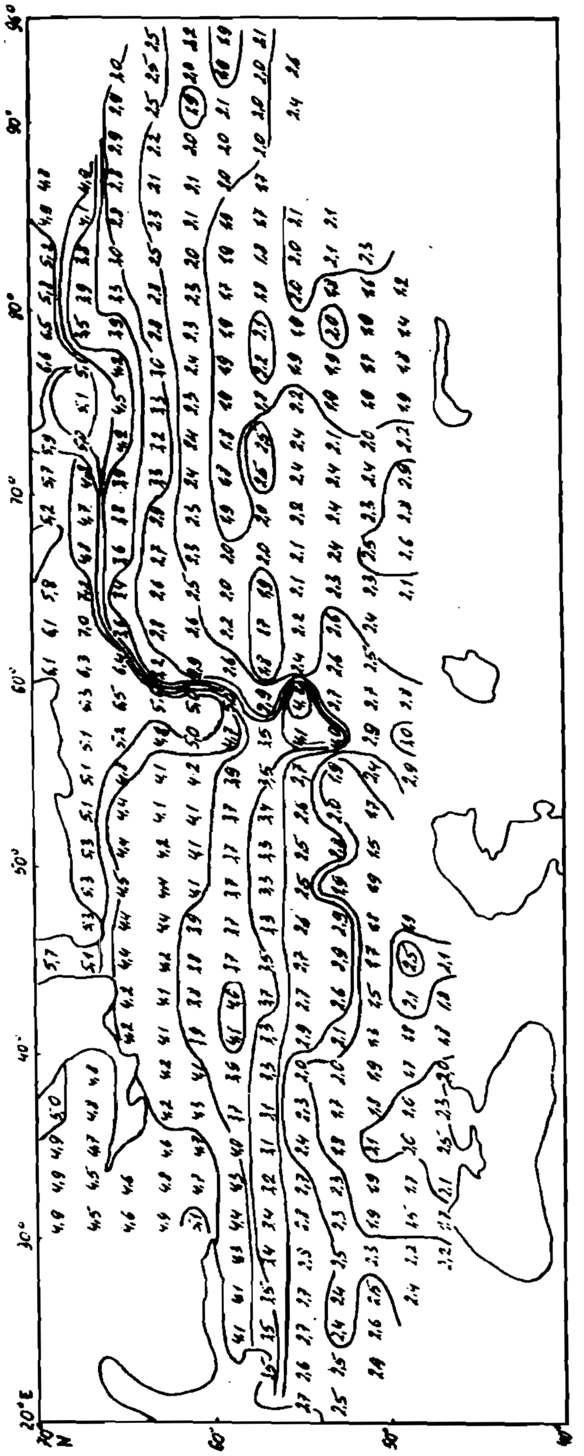


Figure 10: IWR$_{20\%}$ September

In Figures 6 to 10, the dynamics of $IWR_{20\%}$ during the growing season is shown. Some differences in the $IWR_{20\%}$ distribution over the European Territory (ET) of the USSR and in West Siberia (WSb) are observed in May. $IWR_{20\%}$ increases gradually from south to north over the ET while areas of $IWR < 1$ appear in the middle of WSb. There are no differences in water regulation between forest and steppe at the beginning of the growing season when the "green machine" does not work intensively.

In June, the forests over the ET and WSb show approximately equal values of IWR. The border between forest and steppe begins to be revealed by the strong gradients in IWR. In July, this border is much clearer. This is the month when differences in water regulation between forest and steppe are maximal. At this time of year in the middle latitudes, maximal biomass production and leaf area index occur. However, in the steppe zone of the ET, there area areas with $IWR \leq 1$. These are likely due to harvesting of grain crops, which takes place over a wide area practically simultaneously, disturbing the dynamics of natural processes. It is interesting that the July amounts of $IWR_{20\%}$ over the steppe (stations: Bolchov, Nizjnedeviskaya and Kamennaya Steppe) (Figure 3), are 1.2 -1.6, while $IWR_{20\%}$ for agricultural areas in the steppe zone is 0.9%. Such an example shows a way to compare the water regulatory properties of natural and agricultural ecosystems.

The existence of similar areas in WSb in May and June may be explained by the continentality of the climate. The large-scale variation of evaporation is typical for WSb, but water is always available for evaporation in spring after the snow melt, in bogs, forest-steppes, lakes, etc.

In August, the contrast in IWR-values between forest and steppe is less than in July. New growth slows down, while leaves begin to fall from the trees. The difference in IWR values disappears in September.

Thus the water regulatory behavior of ecosystems during the growing season is different; it is more variable in the steppe and more stable in the forest. By means of the IWR-method, we are able to identify regions which would be the first to respond to climate changes and other regions which would be the last in their response. It is quite clear that the former are characterized by IWR < 1, and the latter by IWR > 1. We suppose that the ecosystem processes in such homogeneous areas develop in a similar way. This knowledge is useful in designing an optimal network of monitoring stations.

A map of mean values of $IWR_{20\%}$ for the growing season is shown in Figure 11. Of interest is that the line for $IWR_{20\%} = 2.0$ coincides exactly with the border between forest and forest-steppe zones (forest: IWR = 2.0-3.0; steppe: approximately 1.5). Maximum values of IWR on the ET occur between 56 and 64 degrees N. They practically coincide with the area of coniferous and coniferous broad-leaved forests. The line 2.5 separates the broad-leaved spruce undertaiga forests and broad-leaved lime-oak and oak forests. So the coniferous ecosystems of the ET may attenuate the variability of moisture conditions to a far greater degree than other ecosystems. In the WSb, the largest values of IWR also coincide with areas of coniferous forests (spruce, Siberian pine, fir) and moss moors. Both in the ET and the WSb, the values of IWR are a maximum in the middle and south taiga, declining to the north and south of this zone.

Mean values of $IWR_{20\%}$ for the forest ecosystems are 2.5, for the steppe 1.5, and for agricultural land at the regional level (taking into account the results of the study at the local level) 1.2. This means that forest reduces the variability of the climatic signal 2.5 times, steppe 1.5 times and farmland only 1.2 times.

Nowadays, the land surface is transformed by human activities of different kinds. So our estimates of the water regulatory properties of different ecosystems give a possibility to estimate the changes in these properties at the global level (Table 2).

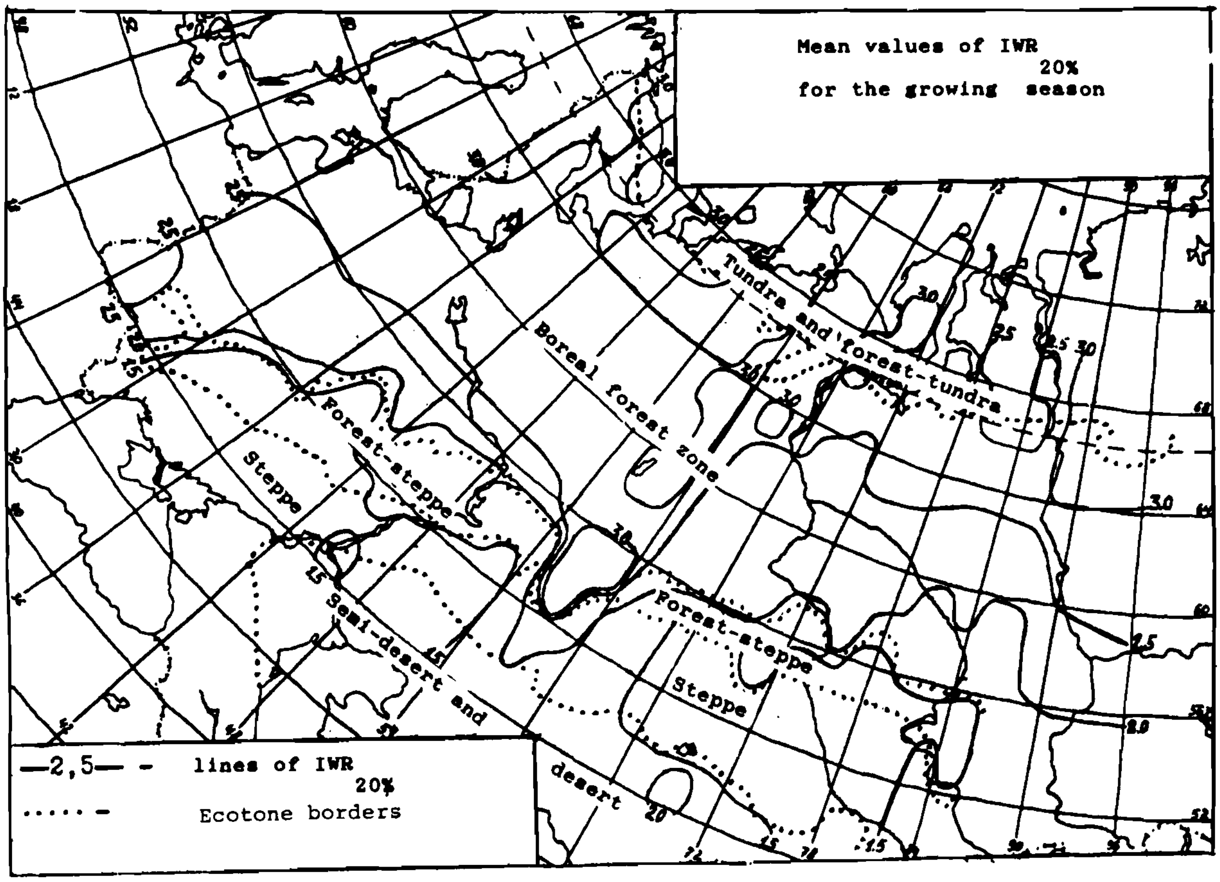


Figure 11: Mean values of $IWR_{20\%}$ for the growing season.

Table 2: Estimates of some consequences of land ecosystem changes by man. (Lisseev and Minin (1986), with additions by authors).

Character of ecosystems transformation	Area of influence mln.sq.km. area	% of land area A%	Estimates of some parameter changes LE(Wt/m^2)	H(Wr/m^2)		Changes of IWR
Natural ecosystems (forest, steppe, etc.)						
into buildings, roads, engineering constructions	4.5	3	+5	-20	+5	2.0 → 1.0
into wasteland	4.5	3	+5	-15	+10	2.0 → 1.0
into reservoirs	0.4	0.3	-10	+20	0	
Forests into meadows, pastures, shrubs, swamp	40	27	+8	-25	+5	2.5 → 1.5
Steppe, prairie into fields	14.3	9.6	0	-5	+5	1.5 → 1.2
Irrigation	2.7	1.8	-7	+15	-6	
Land under the influence of reservoirs on the groundwaters in the USSR	1	0.7	-4	+10	0	
Draining land	2	1.3	+5	-5	+5	
Total	69.4	46.7	+5	-17	+5	2.2 → 1.4

A - albedo; LE - fluxes of latent heat; H - fluxes of explicit heat; total values are calculated as weighted average.

The level of water exchange regulation by ecosystems is reduced by 1.6, changes taking place in the structure of the heat balance and in albedo. Our results (especially for albedo) correspond to the estimates obtained by Ephimova (1983) and Budyko (1984).

General changes in surface properties are the result of active transformation of land surfaces by human activities increasing during the past 200 years. This may have had some harmful consequences. For example, 40 droughts occurred in Russia from the Xth to the XIIth centuries (an average of one drought per 20 years). In the XIXth century, there were ten severe droughts (approximately 1 in 10 years). In the XXth century, the frequency of droughts increased to 1 in 3 years (Shipunov, 1985) The most severe droughts occur in the steppe and forest-steppe zones of the USSR. As a result, dust storms become more frequent, causing soil erosion. We must remark that areas where dust storms occur frequently are areas where IWR < 1 in June and July.

4. CONCLUSION

A method of estimating the water regulatory properties of land ecosystems is suggested, based on the comparison of variabilities of the input (precipitation) and output (evapotranspiration) water signals. We have shown quantitatively that forest ecosystems have stronger regulative properties than grasses or crops. At the regional level, mean values of $IWR_{20\%}$ are: forest 2.5, steppe 1.5, and farmland 1.2. Human activities have a strong influence on the dynamics of IWR in ecosystems on different time-space scales. Impacts occur at regional and global levels.

Charts are presented that show the spatial distribution of an ecosystem's potential response to climatic variations and fluctuations of different time-scales. Identification of regions responding similarly to climatic changes is very important for optimal allocation of environmental monitoring stations, in modelling of climate or the biosphere, and in the exploration of biosphere sustainability.

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