Working Paper

On the Sensitivity of Runoff to Climate Change

Zdzisław Kaczmarek

WP-90-58
October 1990

IIASA

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Foreword

Human activities associated with the utilization of natural resources benefit societies, but may also cause serious disturbances in the natural environment. In particular, changes in climatic processes may affect both the water resources availability and demand for water by agriculture, industry and population. There is need for an intensive research on possible consequences of climatic variations on hydrological processes, as well as on development of methods for incorporating hydrological uncertainties into planning and operation of water resource systems. The IIASA *Water Resources Project* concentrates its activity on the effects of anthropogenic changes on inland waters on a global and regional scale.

This paper by Professor Zdzisław Kaczmarek deals with the sensitivity of river runoff to changes in precipitation, air temperature and net radiation. The problem is controversial, mostly due to difficulties in relating the outputs of General Circulation Models to the main hydrological fluxes. At the same time a quantitative assessment of runoff changes due to variations in climate forcing is a prerequisite for rational decision making in water management. Professor Kaczmarek's discussion of this important issue may contribute to the better understanding of complex interdependence of climatic and hydrological phenomena.

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ON THE SENSITIVITY OF RUNOFF TO CLIMATE CHANGE

*Zdzisław Kaczmarek**

Sensitivity of runoff to climatic and other environmental changes is of particular interest to water resource planners and decision makers because alterations in surface water availability may highly influence regional management strategy. Wigley and Jones [11] claim that "...runoff is always more sensitive to precipitation changes than to evapotranspiration changes, particularly for higher values of (runoff coefficient)." Such a general conclusion has been supported by some other authors [2,6]. The question arise whether such a generalization is correct?

Let us first examine shortly the reasoning presented in the Wigley and Jones' paper. The authors define sensitivity of *runoff change* to *changes* in precipitation and evapotranspiration as partial derivatives

$$S_\alpha = \frac{\partial \rho}{\partial \alpha} \text{ and } S_\beta = \frac{\partial \rho}{\partial \beta} \tag{1}$$

where $\rho = R_1/R_0$, $\alpha = P_1/P_0$ and $\beta = E_1/E_0$ denote changes (ratios) of runoff, precipitation and evapotranspiration for future (index 1) and present (index 0) climatic conditions. It can be easily shown that

$$\rho = \frac{\alpha - \beta(1-\delta_0)}{\delta_0} \tag{2}$$

where $\delta_0 = R_0/P_0$ is the runoff coefficient. Wigley and Jones calculated the partial derivatives

$$\frac{\partial \rho}{\partial \alpha} = \frac{1}{\delta_0} \text{ and } \frac{\partial \rho}{\partial \beta} = -\frac{1-\delta_0}{\delta_0} \tag{3}$$

implicitly assuming that α and β are *mutually independent* . Finally they obtained

$$\frac{\frac{\partial \rho}{\partial \alpha}}{\frac{\partial \rho}{\partial \beta}} = -\frac{1}{1-\delta_0} \tag{4}$$

Because $\delta_0 < 1$ and the absolute value of (4) is always greater than 1, the authors conclude that the runoff ratio ρ is more sensitive to change (ratio) in precipitation than to change (ratio) in evapotranspiration.

The above argumentation would be correct in the case if changes in precipitation and evapotranspiration be independent. This may be true in the case of *potential* evapotranspiration, but is obviously incorrect for *actual* evapotranspiration, which highly depends on precipitation. Therefore α and β are mutually dependent and the formulae (3) and (4) cannot be applied for the sensitivity assessment. We will now analyse the sensitivity problem, as defined by Wigley and Jones, taking into account this interdependence.

Let us assume that $E = E(P, S)$, where S is a set of climatic characteristics other than precipitation. Then

$$\beta = f(\alpha, S) \tag{5}$$

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and

$$\frac{\partial\rho}{\partial\alpha} = \frac{1}{\delta_0} - \frac{(1-\delta_0)}{\delta_0} \cdot \frac{\partial\beta}{\partial\alpha} \tag{6}$$

$$\frac{\partial\rho}{\partial\beta} = \frac{1}{\delta_0} \cdot \frac{\partial\alpha}{\partial\beta} - \frac{(1-\delta_0)}{\delta_0}. \tag{7}$$

The ratio of (6) and (7) has now the form of relative sensitivity

$$RS = \frac{\frac{\partial\rho}{\partial\alpha}}{\frac{\partial\rho}{\partial\beta}} = \frac{1-(1-\delta_0)\partial\beta/\partial\alpha}{\partial\alpha/\partial\beta-(1-\delta_0)} \quad . \tag{8}$$

It can be seen that only if α and β are independent and consistently $\partial\alpha/\partial\beta = 0$ and $\partial\beta/\partial\alpha = 0$, the (8) is equivalent to the relative sensitivity (4), derived by Wigley and Jones. As we observed before, this is however an unrealistic assumption.

Table 1: Characteristic of test river catchments.

Name of basin	Júcar	Vistula	Seine (to Paris)	Volga (Upper part)
Country	Spain	Poland	France	USSR
Area [km^2]	42,900	194,900	427,000	161,720
P_0 [mm]	519	604	715	520
T_0 [deg C]	13.7	7.5	10.0	2.8
Q_0 [W/m^2]	78	48	56	38
r_0 [mm]	985	611	702	476
R_0 [mm]	69	173	231	226
δ_0 -	0.133	0.286	0.323	0.435
E_0 [mm]	450	431	484	294
K -	0.88	0.55	0.76	1.16

According to general rules of differentiation $\partial\alpha/\partial\beta = 1 : \partial\beta/\partial\alpha$ and consequently after simple transformations we obtain

$$RS = \frac{\partial\beta}{\partial\alpha} \quad . \tag{9}$$

In order to apply (9) we should first define functional relationships $E = E(P, S)$ and $\beta = f(\alpha, S)$.

In the hydrological literature one can find a number of formulae relating actual evapotranspiration to climatic characteristics, from simple ones to sophisticated models. Taking into account the present limited reliability of regional climate predictions, it does not seem rational to base on complex models, for which it will be difficult to get necessary input data for future climatic conditions. We are particularly interested in functional relations which connect runoff with temperature, net radiation and precipitation, because these climate characteristics are commonly used for describing eventual changes of climate due to greenhouse effect.

From a number of such relationships the Langbein diagrams [7] and formulae derived by Budyko [1] and Turc [10] may be of interest for our analysis. All these methods relate the runoff

Table 2: Relative sensitivity RS for (Turc formula).

River basin	ΔT [deg C]	Change in precipitation [%]				
		-20%	-10%	0	+10%	+20%
Júcar	+1.0	0.843	0.773	0.706	0.643	0.583
	+2.0	0.881	0.815	0.751	0.689	0.631
	+3.0	0.917	0.855	0.794	0.735	0.678
	+4.0	0.950	0.893	0.836	0.779	0.724
Vistula	+1.0	0.495	0.398	0.322	0.262	0.216
	+2.0	0.556	0.452	0.369	0.304	0.251
	+3.0	0.621	0.511	0.422	0.350	0.292
	+4.0	0.690	0.574	0.479	0.401	0.337
Seine (Paris)	+1.0	0.579	0.478	0.396	0.330	0.276
	+2.0	0.640	0.535	0.448	0.376	0.317
	+3.0	0.703	0.595	0.503	0.427	0.363
	+4.0	0.768	0.657	0.562	0.481	0.413
Volga (upper)	+1.0	0.606	0.505	0.422	0.353	0.297
	+2.0	0.666	0.562	0.474	0.401	0.340
	+3.0	0.727	0.620	0.529	0.451	0.386
	+4.0	0.787	0.679	0.585	0.504	0.435

directly or indirectly to temperature and precipitation, which allows to find relationships (5) and (9). The Turc and Budyko formulae will be discussed here in some detail.

The Turc relationship may be presented in the form

$$E = \frac{PL_T}{\sqrt{KL_T^2 + P^2}} \tag{10}$$

or

$$R = P[1 - \frac{L_T}{\sqrt{KL_T^2 + P^2}}] \tag{11}$$

where L_T is a function of temperature

$$L_T = 300 + 25T + 0.05T^3 \quad . \tag{12}$$

The parameter K may be estimated for a given river catchment on the basis of known values of runoff, precipitation and temperature. A generalized value $K = 0.9$ has been suggested by Turc if there is no possibility of calibration. The formulae (10) and (11) are valid for $P > (1-K)^{0.5}L_T$.

Let us now denote $\lambda = T_1/T_0$, where T_1 and T_0 are mean annual temperature values for the future and present climates. It can be easily shown that

$$\beta = \frac{E_1}{E_0} = \frac{\alpha L_{\lambda T_0}}{(1-\delta_0)\sqrt{KL_{\lambda T_0}^2 + \alpha^2 P_0^2}} \tag{13}$$

and

$$\alpha = \frac{P_1}{P_0} = \beta\sqrt{K}(1-\delta_0)\frac{L_{\lambda T_0}}{\sqrt{L_{\lambda T_0}^2 - \beta^2(1-\delta_0)^2 P_0^2}} \tag{14}$$

Differentiating equation (13) we get

$$RS = \frac{\partial\beta}{\partial\alpha} = \frac{L_{\lambda T_0}}{(1-\delta_0)\sqrt{KL^2_{\lambda T_0}+\alpha^2P_0^2}}[1 - \frac{\alpha^2P_0^2}{(KL^2_{\lambda T_0}+\alpha^2P_0^2)}] \quad (15)$$

or

$$RS = \frac{K(1-\delta_1)^3}{(1-\delta_0)} \quad (16)$$

where $\delta_1 = R_1/P_1$ is the runoff coefficient suitable for future climatic conditions.

Table 3: Relative sensitivity RS for (Budyko formula).

River basin	ΔT [deg C]	Change in precipitation [%]				
		-20%	-10%	0	+10%	+20%
Júcar	+1.0	0.869	0.812	0.758	0.706	0.656
	+2.0	0.875	0.819	0.764	0.713	0.663
	+3.0	0.880	0.825	0.771	0.719	0.671
	+4.0	0.886	0.831	0.777	0.726	0.678
Vistula	+1.0	0.670	0.582	0.505	0.437	0.379
	+2.0	0.685	0.597	0.519	0.451	0.392
	+3.0	0.699	0.611	0.533	0.465	0.405
	+4.0	0.714	0.626	0.548	0.479	0.418
Seine (Paris)	+1.0	0.655	0.566	0.489	0.422	0.364
	+2.0	0.669	0.580	0.502	0.434	0.375
	+3.0	0.682	0.593	0.514	0.446	0.386
	+4.0	0.695	0.605	0.527	0.458	0.398
Volga (upper)	+1.0	0.632	0.541	0.462	0.395	0.337
	+2.0	0.652	0.560	0.481	0.412	0.354
	+3.0	0.672	0.580	0.499	0.430	0.370
	+4.0	0.691	0.598	0.517	0.447	0.386

Because $\delta_0 < 1$ and $\delta_1 < 1$ one may expect that also the sensitivity parameter $RS < 1$. To confirm this, four river basins in Europe have been selected with differentiated climatic conditions (Table 1), and the RS values were calculated by means of (15) for several climate scenarios. The results given in Table 2 clearly show that for all regions under investigation, from semi-arid to cold-humid, and for all climatic scenarios the sensitivity of runoff change to precipitation change is less than to evapotranspiration change. Let us now consider the Budyko formula which may be presented in a form

$$E = \sqrt{rP[1-\exp(-r/P)]\tanh(P/r)} \quad (17)$$

where

$$r = 12.61\,Q \quad (18)$$

is the water equivalent [in mm] of the mean annual net radiation $Q[W/m^2]$. Denoting as before $\rho = R_1/R_0$, $\alpha = P_1/P_0$, $\beta = E_1/E_0$ and $\lambda = r_1/r_0 = Q_1/Q_0$ we obtain from (17)

$$\beta = \frac{\sqrt{\lambda r_0 P_0}}{E_0}\sqrt{\alpha[1-\exp(-\frac{\lambda r_0}{\alpha P_0})]\tanh(\frac{\alpha P_0}{\lambda r_0})} \quad (19)$$

According to (9) we finally get

$$RS = \frac{\partial \beta}{\partial \alpha} = 0.5\,\frac{\beta}{\alpha}\left[1 - \frac{\lambda r_0}{\alpha P_0[\exp(\frac{\lambda r_0}{\alpha P_0}) - 1]} + \frac{4\alpha P_0 \exp(\frac{2\alpha P_0}{\lambda r_0})}{\lambda r_0[\exp(\frac{4\alpha P_0}{\lambda r_0}) - 1]}\right] \tag{20}$$

which allows to calculate the sensitivity parameter RS for various climate scenarios. In conformity with the IPCC outcomes [4], the global net radiation may change due to increased concentration of greenhouse gases between 2.0 and 4.0 W/m^2 over the period 1990–2050, depending on emission scenario. Taking this into account and assuming various assumptions about precipitation change it is possible to calculate RS for the same river basins (Table 1), which were used to analyse the Turc formula. The results in Table 3 demonstrate that also for the Budyko method the RS values are in all cases less than one.

Table 4: Runoff increment ΔR [mm] as a result of climate change (Turc formula).

River basin	ΔT [deg C]	Change in precipitation [%]				
		-20%	-10%	0	+10%	+20%
Júcar	+1.0	-44.4	-28.9	-10.2	11.4	35.8
	+2.0	-50.2	-36.5	-19.8	-0.2	22.0
	+3.0	-55.5	-43.4	-28.6	-11.1	9.1
	+4.0	-60.3	-49.8	-36.8	-21.2	-3.0
Vistula	+1.0	-106.6	-65.4	-20.5	27.3	77.4
	+2.0	-122.8	-84.0	-41.3	4.7	53.2
	+3.0	-138.7	-102.6	-62.1	-18.2	28.4
	+4.0	-154.3	-120.9	-83.0	-41.4	3.2
Seine (Paris)	+1.0	-117.5	-71.5	-21.1	32.9	89.8
	+2.0	-133.0	-89.9	-42.1	9.5	64.2
	+3.0	-148.2	-108.0	-63.0	-14.0	38.4
	+4.0	-162.8	-125.7	-83.7	-37.4	12.5
Volga (upper)	+1.0	-86.9	-51.2	-12.8	27.9	70.3
	+2.0	-95.8	-61.8	-25.0	14.1	55.3
	+3.0	-104.2	-71.9	-36.8	0.8	40.5
	+4.0	-112.1	-81.6	-48.2	-12.2	26.0

For both Turc and Budyko formulae the results evidently contradict the conclusions of Wigley and Jones paper [11]. The reason for this is that for an unit increment of evapotranspiration ratio β the increase of runoff ratio ρ is always greater than for the unit increment of precipitation ratio α. We may notice that RS values obtained for both methods show similar tendencies. They decrease with the increase of precipitation and increase with the temperature or net radiation rise. The influence of ΔP is more significant for cold region (the Volga river basin) than for the semi-arid Júcar catchment. The impact of changes in temperature and net radiation is similar in all surveyed regions.

It should be however noticed that the matter under our analysis, as defined in (11), seems to be somehow academic. First, hydrologists and water resource planners will be rather interested in the consequences of climate change on runoff R, than in the sensitivity of $\rho = R_1/R_0$. Second, because of high interdependence between P and E there is no particular reason to investigate the sensitivity of runoff to evapotranspiration. The question how runoff is influenced by the main forcing climatic factors, such as radiation, temperature and precipitation, is of much greater importance. This latter problem has been i.a. discussed by Glantz and Wigley [2] and by Schaake [9]. Let us investigate it shortly.

Table 5: Runoff increment ΔR [mm] as a result of climate change (Budyko formula).

River basin	ΔT [deg C]	Change in precipitation [%]				
		-20%	-10%	0	+10%	+20%
Júcar	+1.0	-30.8	-17.4	-1.4	16.9	37.7
	+2.0	-31.6	-18.5	-2.8	15.2	35.6
	+3.0	-32.4	-19.6	-4.2	13.6	33.6
	+4.0	-33.2	-20.6	-5.5	11.9	31.7
Vistula	+1.0	-76.0	-41.9	-4.3	36.2	79.4
	+2.0	-79.0	-45.5	-8.6	31.4	74.0
	+3.0	-81.6	-49.1	-12.7	26.6	68.7
	+4.0	-84.7	-52.5	-16.8	22.0	63.6
Seine (Paris)	+1.0	-91.7	-50.2	-4.6	44.6	96.8
	+2.0	-94.9	-54.0	-9.0	39.5	91.2
	+3.0	-98.0	-57.7	-13.4	34.6	85.7
	+4.0	-101.0	-61.4	-17.6	29.7	80.3
Volga (upper)	+1.0	-71.6	-39.8	-5.0	32.3	71.7
	+2.0	-75.1	-43.9	-9.8	26.8	65.7
	+3.0	-78.4	-47.9	-14.5	21.6	59.8
	+4.0	-81.7	-51.8	-19.0	16.5	54.1

Using the mean annual water balance equation $R = P - E$ and equations (10) and (17) of Turc and Budyko, we may easily calculate the runoff increments

$$\Delta R = P_1 \left[1 - \frac{L_{T_1}}{\sqrt{K L_{T_1}^2 + P_1^2}} \right] - P_0 \left[1 - \frac{L_{T_0}}{\sqrt{K L_{T_0}^2 + P_0^2}} \right] \tag{21}$$

and

$$\Delta R \doteq \sqrt{r_1 P_1 [1 - \exp(-r_1/P_1)] \tanh(P_1/r_1)} - \sqrt{r_0 P_0 [1 - \exp(-r_0/P_0)] \tanh(P_0/r_0)} \quad . \tag{22}$$

Values of ΔR, calculated for various climate scenarios, as applied to river catchments described above, are given in Tables 4 and 5. As it could be expected, ΔR depends both on the availability of precipitated water and on energy factors (air temperature and net radiation), but for feasible scenarios of climatic change the influence of P seems to be much stronger. This is in agreement with the conclusions of the IPCC Working Group on Climate Impacts [5] that "Based on empirical data and hydrological models, annual runoff appears to be more sensitive to changes in precipitation than to changes in temperature."

It is possible to find a simple regional parameter describing the relative importance of changes in P and T (or Q). The differentials

$$dR = \left(\frac{\partial R}{\partial P}\right)_0 dP + \left(\frac{\partial R}{\partial T}\right)_0 dT = P_0 \left(\frac{\partial R}{\partial P}\right)_0 \frac{dP}{P_0} + T_0 \left(\frac{\partial R}{\partial T}\right)_0 \frac{dT}{T_0}$$

Table 6: Sensitivity coefficient ψ_0 for selected river basins in Europe.

River basin	Turc formula $\psi_0(P,T)$	Budyko formula $\psi_0(P,Q)$
Júcar	-1.54	-1.53
Vistula	-3.16	-1.85
Seine	-2.60	-1.87
Volga	-11.24	-1.92

and

$$dR = \left(\frac{\partial R}{\partial P}\right)_0 dP + \left(\frac{\partial R}{\partial Q}\right)_0 dQ = P_0 \left(\frac{\partial R}{\partial P}\right)_0 \frac{dP}{P_0} + Q_0 \left(\frac{\partial R}{\partial Q}\right)_0 \frac{dQ}{Q_0}$$

where partial derivatives are calculated for the point (P_0, T_0, Q_0), describe the change of runoff as a consequence of unit increments of climatic elements.

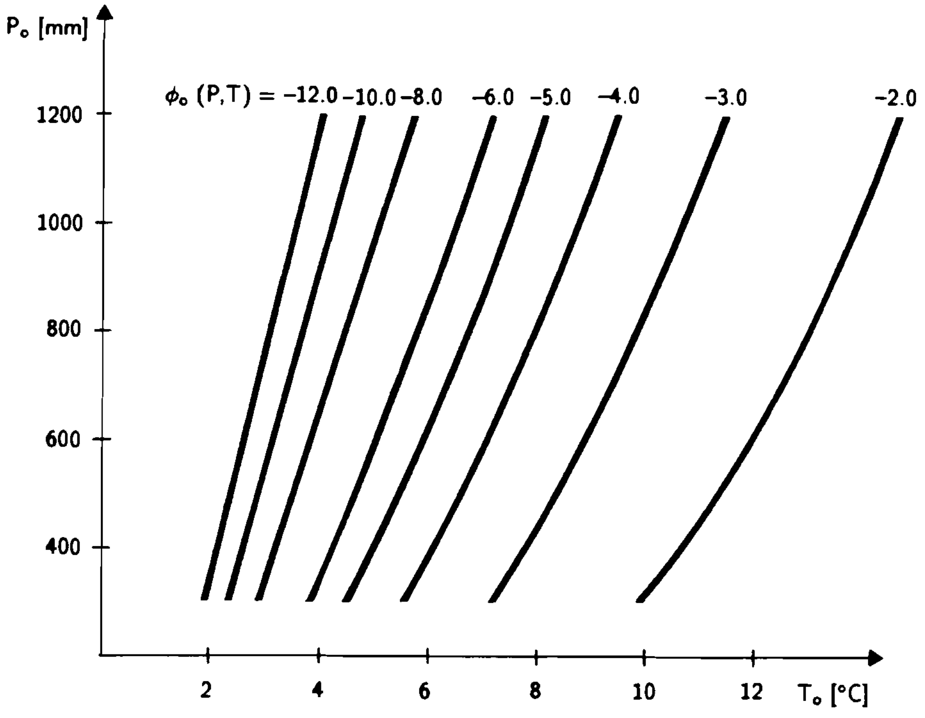

Figure 1: Relative impat of ΔP and ΔT on catchment runoff (Turc formula).

The parameters

$$\psi_0(P,T) = \frac{P_0(\frac{\partial R}{\partial P})_0}{T_0(\frac{\partial R}{\partial T})_0} \tag{23}$$

$$\psi_0(P,Q) = \frac{P_0(\frac{\partial R}{\partial P})_0}{Q_0(\frac{\partial R}{\partial Q})_0} \tag{24}$$

depend only on the present-day mean annual values of climatic elements and may be used to characterise the relative impact of these elements on the catchment runoff. After differentiation of (11) we obtain for the Turc formula

$$\psi_0(P,T) = -\frac{P_0 L_0[1 - E_0/P_0(1 - E_0^2/L_0^2)]}{E_0 T_0[(1 - K \cdot E_0^2/P_0^2)(25 + 0.15T_0^2)]} \tag{25}$$

where $L_0 = L_T$ and $E_0 = E(P_0, T_0)$. Similarly we may get for the Budyko relation

$$\psi_0(P,Q) = \frac{2E_0 ch^2\frac{P_0}{r_0} - r_0[1 - e^{-r_0/P_0}(1 + \frac{r_0}{P_0})]sh\frac{P_0}{r_0}ch\frac{P_0}{r_0} - P_0(1 - e^{-r_0/P_0})}{P_0(1 - e^{-r_0/P_0}) - r_0[1 - e^{-r_0/P_0}(1 - \frac{r_0}{P_0})]sh\frac{P_0}{r_0}ch\frac{P_0}{r_0}} \tag{26}$$

where as before $r = 12.61Q$. Numerical values of $\psi_0(P,T)$ and $\psi_0(P,Q)$ for various climates are shown on Fig. 1 for the Turc formula, and on Fig. 2 for Budyko formula. Particular values of these parameters for the Júcar, Vistula, Seine and Upper Volga river catchments are given in Table 6. It can be seen that absolute values of $\psi_0(P,T)$ are much higher for colder than for warmer regions. Both parameters are increasing with the increase of mean annual precipitation.

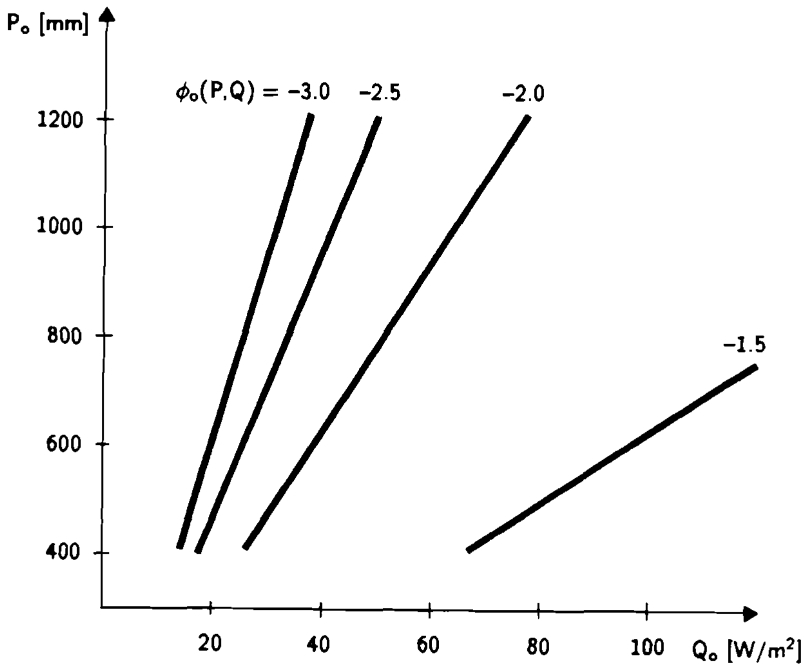

Figure 2: Relative impat of ΔP and ΔQ on catchment runoff (Budyko formula).

An approximate value of $\Delta R = R_1 - R_0$ may be obtained from a relation valid for the Turc formula

$$\Delta R \approx \left(\frac{\partial R}{\partial P}\right)_0 P_0(\alpha - 1) + \left(\frac{\partial R}{\partial T}\right)_0 T_0(\lambda - 1) \tag{27}$$

which after transformation gives

$$\Delta R \approx \left(\frac{\partial R}{\partial T}\right)_0 \Delta T \left[1 + \psi_0(P,T)\frac{\alpha - 1}{\lambda - 1}\right] \quad . \tag{28}$$

Similarly for the Budyko formula

$$\Delta R \approx \left(\frac{\partial R}{\partial Q}\right)_0 \Delta Q \left[1 + \psi_0(P,Q)\frac{\alpha - 1}{\lambda - 1}\right] \tag{29}$$

The first factor at the right-side of equations (28) and (29) presents the change of runoff due to change in temperature or in net radiation. The elements in brackets are amplification factors explaining the impact of changes in precipitation on the runoff changes. It may be shown that $\Delta R > 0$ in the case when the absolute value of the parameter (23) or (24) is greater than $(\lambda - 1)/(\alpha - 1)$. For example, the Vistula river basin can be characterized by $P_0 = 604$ mm and $T_0 = 7.5$ deg C. On the basis of (11) and (28) we receive

$$R = -20.4 \Delta T \left[1 - 3.16 \frac{\alpha - 1}{\lambda - 1}\right]$$

For the 10% increase of precipitation and 2.0 degrees increase of temperature, i.e. for $\alpha = 1.1$ and $\lambda = 1.27$, the amplification factor is equal to

$$1 - 3.16 \frac{0.10}{0.27} = -0.17$$

Consequently, the Vistula basin runoff may increase approximately for 3.5 mm. The exact ΔR value, given in Table 4, is 4.7 mm.

The above considerations are based on simplified transfer functions linking runoff with climate characteristics. It can be assumed, however, that the accuracy of Turc or Budyko formula in estimating annual runoff is adequate to the reliability of present generation of Global Circulation Models in assessing *regional* climatic changes. Nevertheless, results discussed in this paper should be understood rather as a qualitative description of the climate/runoff sensitivity problem than a precise quantitative estimation of sensitivity parameters.

When more reliable climatic information will be available, more sophisticated hydrological models should be used, taking into account the intraannual distribution of hydrological and climatological elements, the effect of snow melting processes and other important factors.

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