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IMPACTS OF THE CLIMATE CHANGE ON THE OPERATION OF A FRESHWATER COOLED ELECTRIC POWER PLANT

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Abstract

Climate change predicted for the northern hemisphere and its regional version will modify the environment and, as a consequence, the conditions of a wide range of human activities. Among others, the energy demand and production is also affected. This paper, by a case study analysis of an electric power plant supplied with freshwater cooling system deals with the latter. Changes of hydrological regime, i.e. flow rate and water temperature are predicted to change unfavourable: lower flow rate and higher temperature during the critical period. Mitigation of disadvantages are manifold, but without any endangering of the safety operation, additional investment and operation costs could be predicted.

Keywords: climate change, electric energy production, thermal pollution, water quality control.

1. Background and Objectives

Climate researchers generally agree that in the atmosphere the increased concentration of some anthropogenic greenhouse gases: carbon-dioxide, methane, dinitrogen-oxide, halogen hydrocarbon result the enhancement of the greenhouse effect and consequently the global warming up of the Earth (KACZMAREK et al., 1996; VILLACH-BELLAGIO, 1987). The production of the greenhouse gases began at the 19th century after the Industrial Revolution and has been increasing from the middle of our century; this phenomenon is considered to be the reason of the 0.5K warming up of the Earth experienced in the last 120–150 years. Though the identification of different climate models with the old data is nearly impossible, it is fact that the warming up simulated by the climate models and the current increase of the air temperature are not inconsistent with each other.

There is more uncertainty in connection with the regional climate consequences of the global warming up. Because of different uncertainties, different climate models – even the General Circulation Models (GCM) considered to be the best one – are modelling not simply a new equilibrium climate situation but several potential ones. These so-called climate scenarios are considered to be potential but not sure consequences of the global warming up (HULME et al., 1990).

The climate change could affect the operation of the power plants by two ways: (1) through the modification of the countrywide energy demand and (2) through the modification of physical environment as boundary condition of a plant operation.

This paper focuses on the latter. It aims at (1) the presentation of a simplified prediction method of the change of the boundary conditions, i.e. the change of flow rate and the water temperature of the Danube at the section of the power plant, and (2) the evaluation of the economic consequences of the new conditions considering the plant operation, i.e. the necessary reconstructions and their costs.

2. Sensitivity of the Hungarian Economy Concerning the Climatic Conditions

The Hungarian economy was characterized by an extensive development from 1960 till the middle of 1970's. The domestic energy consumption increased by 60%. The structure of energy sources essentially changed during this period. The relative contribution of solid fuels decreased from 75% to 50% between 1960 and 1970. At the same time, the share of hydrocarbon in energy supply increased and reached 42.5% in 1970.

These tendencies lasted until 1978, then the volume of the domestic energy consumption started to stagnate for short period. Energy demand was increasing again during the 1980's. As regards the gross energy use, the portion of the material branches was declined from 71.2% per year to 60.7% between 1970 and 1980 and, at the same time, the ratio of non-material branches significantly increased. From the mid eighties a significant and almost continuous decrease of energy consumption can be detected. Reasons are threefold : decrease of production of the Hungarian economy (late eighties and nineties), structural change of economy, and increasing efficiency as far as energy consumption is concerned (*Fig. 1*).

Analyses show that sensitivity of the Hungarian economy to the air temperature is about 12 PJ/C. The total yearly energy use was altering between 1300–1500 PJ in the '80s. Because of the stagnating economy and the uncertainties of the transition period of the Hungarian society and economy (modification of the structure of economy, rising energy prices etc.), it has been detected 1300 PJ as a maximum in the early '90s. Energy consumption used for heating and influenced directly by the climate conditions of winter represents about 350 PJ/year. Latter is estimated by 450-500 PJ yearly for the next decades (FARAGÓ et al., 1991).

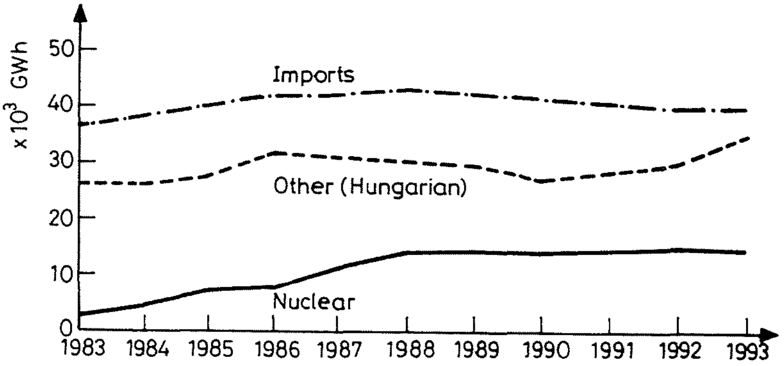


Fig. 1.

Taking into consideration the empirical data and model analyses, a significant dependence can be laid down as a fact : if the mean winter temperature changes by 1 °C, it would cause the change of 6% of opposite sign in the domestic energy use for heating purposes. It means the energy amount of 20 PJ yearly in absolute terms. Accepting the estimation before mentioned this specific rate can hit 27–30 PJ/C as well.

3. Technical and Environmental Controls of the Boundary Conditions on the Plant Operation

Predictable changes of boundary conditions were evaluated on the example of the river Danube. A power plant operation is controlled by the cooling system in different ways. A set of factors forms physical-technical boundary conditions while the others do environmental ones. Latter is formulated in the environmental standards and measures. Essential hydrological parameters involved are the flow rate $\mathbf{Q}(\mathrm{m}^3/\mathrm{s})$ or water level in the river bed $\mathbf{H}(\mathrm{m})$ and water temperature in river $\mathbf{T}(\mathrm{C})$, namely the extremely low discharge (water level) and the extremely high temperature. Further parameters, such as the probability and duration time of events characterized by these parameters can be deduced.

The physical-technical considerations represent a direct impact on the cooling system operation while the environmental parameters an indirect one. In this approach the cooling process is taken into consideration as a system while the river forms its environment.

Table 1
Impacts of the essential boundary parameters

	Physical-technical considerations		Environmental considerations	
	Q(H)	T	Q(H)	T
Input	(+)	(+)	0	0
Output	0	0	(+)	(++)

A simplified ranking of essential parameters considering their impacts on cooling system is summarized in *Table 1*, where (+) shows a low impact, while (++) a high one.

Physical-Technical Considerations

Parameters affecting technically the system input are the flow rate and the water temperature. Since the minimum flow rate of Danube ever registered is six times higher than the cooling water discharge actually necessary and three times higher than the cooling water discharge of the extended power plant capacity in the future, it can be taken in account as a soft control parameter. It means, that during an extremely low flow rate the water level of the river is not high enough for discharge the cold water channel by gravity. This situation could be eliminated by additional pumps placed at the mouth of cold water canal. From technical point of view the possibility of solution exists since the site is prepared. So this event would only cause a certain increase of operation costs and there would be necessary neither reduction of energy production nor break down. In like manner, the impact of low water temperature /with ice events by chance/ on the input can eliminate easily by the operation of warm water feedback, while the high temperature does not affect the water intake at all. At the output there is not any constraint affecting the power plant operation.

In sum, it can be concluded that the probable changes of the hydrological regime of Danube forced by climate change will not be able to damage the operation process or to produce nuclear endangering and will only occur certain additional cost at the very most.

Environmental Considerations

On the input side any change of the flow regime cannot be evaluated from environmental point of view. Real restriction arises at the output side. Since the thermal loading of power plants using freshwater cooling system can cause pernicious change of water quality in rivers, in order to protect the water quality and to avoid harmful thermal pollution, the load became limited by regulations.

The regulation of the thermal loading varies from country to country, according to the climate, the water quality, and the hydrological conditions, but usually the following parameters are limited :

- the highest temperature in the river, $T_{\max}$;
- the maximum temperature difference, i.e. warming up of the river, T_{diff};
- the rate of the heating, concerning the water reach below the mixing zone.

Some examples from the countries of the temperate zone are listed in *Table 2*. The Hungarian regulation is very similar to these examples as far as the permitted highest temperature in the mixing reach is concerned: 'The increase of average temperature of Danube water caused by the recharged warm cooling water should not exceed 2 °C, and the maximum temperature should be 30 °C, at the very most, 500 m far downstream from the discharge point.'

Table 2
Limits of the thermal pollution

State	Warming up permitted, T_{diff} at the discharge °C	along the mixed reach °C	Highest temperature permitted, $T_{\max}$ at the discharge °C	along the mixed reach °C
New York	–	2.8	32.5	30
Belgium	–	–	–	25
France	10	–	–	30
Germany	10	5	30	28
Switzerland	–	3	30	25
Netherlands	–	3	30	25
former USSR	–	summer 3 winter 5	–	–

Considering the limit of 30 C, which possibly will be valid in the future as well, the highest 21 – 25 °C temperature of the Danube and the 8 (9) °C nominal temperature difference at the condensers, it is evident that the most important boundary parameter is the Danube temperature. That is why its increase forced by climate change is in focus.

The amount of excess heat discharged into the rivers changes the original, 'natural' temperature conditions of the water body, as a consequence of which the chemical, physical and biological characteristics determining the quality of water may become unfavourable, the undesirable phenomenon of thermal pollution takes place. Worth mentioning that the power plant itself impacts the water quality – basically the aquatic life – not only by thermal pollution but also by mechanical and other physical ways. Effects can be listed as follows :

a) The thermal effects start with the sudden rise in the temperature of water in the condensers and they continue in the warm water channel and river reach affected.

b) Mechanical effects on water and the aquatic organisms are caused by the pumps lifting the fresh water onto the treatment process, by the treatment technology (filtration) and by the outlet construction of warm water channel where the water was passing through the energy dissipator and dropped by 2–10 m into the river.

c) The change of dissolved oxygen content of water as physical impact is also determined by the cooling process. While a) and b) are unambiguously disadvantageous, the dissolved oxygen concentration changes both negatively and positively inside the cooling system : in the warm water the concentration can be expected to decrease owing to reaction kinetic reason but it rises significantly in the energy dissipator (SZOLNOKY, 1980, 1985 ; ÖLLŐS et al., 1989).

The aquatic life affected can be taken into account separately by the plankton, benthon and the nekton.

A) The most important biocoenosis of the rivers is generally the plankton determining the self-purification ability. Since they drift in water and move together with it, on those existing in the cooling water, the thermal load has a direct influence. Therefore the following consequences are probable (KHALANSKI, 1973):

   1) Mechanical damage in the course of passing through the cooling system and its constructions.

   2) In the condensers the cooling water is heated up very rapidly (in about 6–12 s) to the mean maximum temperature. However, a part of water particles and organisms get in direct contact with the tube walls of about 40 °C for a longer or shorter period of time.

   This direct thermal effect may cause the death of living beings or changes in their life processes (growth, proliferation, etc.), or they might even lead to a rearrangement of the ecosystem. *Fig. 2* shows by taxonomy the heat suffering capability of organisms. As it can be seen, most of the planktonic species – except Bacteriophyta and Cynophyta – are endangered in the condensers. A lot of particles are heated up only by mixing, i.e. in an indirect way in the condensers. In the case of indirect thermal effects, the lack of oxygen, or as a consequence, the lack of food, as well as the unfavourable changes in the life processes (e.g. in succession) of the living being may occur. This condition also exists in the warmed part of the water body of the river. From this point of view, the oxygen content of the river is of primary importance. Special care has to be taken of the section being deeper and poorer in oxygen. The rise of growth rate of the bacteria by increasing temperature is well known. Further example is the change of the phytoplankton. The *Fig. 3* (ROCHLICH, 1972) shows which algae become dominant by rising water temperature. The thermal pollution increases the ratio of the disadvantageous blue algae.

B) The benthon sitting on the benthos is not moving together with the water, thus – in the case of the continuous operation of the power plant with practically constant thermal load – it is also subjected to a constant thermal load, hence it may be supposed that it is more heat-resistant than plankton.

C) The effect of the temperature changes for fish belonging to the nekton is known the best. For fish, a moderate uniform elevation in the temperature is of minor importance, while a longer residence in the warm water may be dangerous. However, this situation is practically negligible because fish can leave easily the uncomfortable water body.

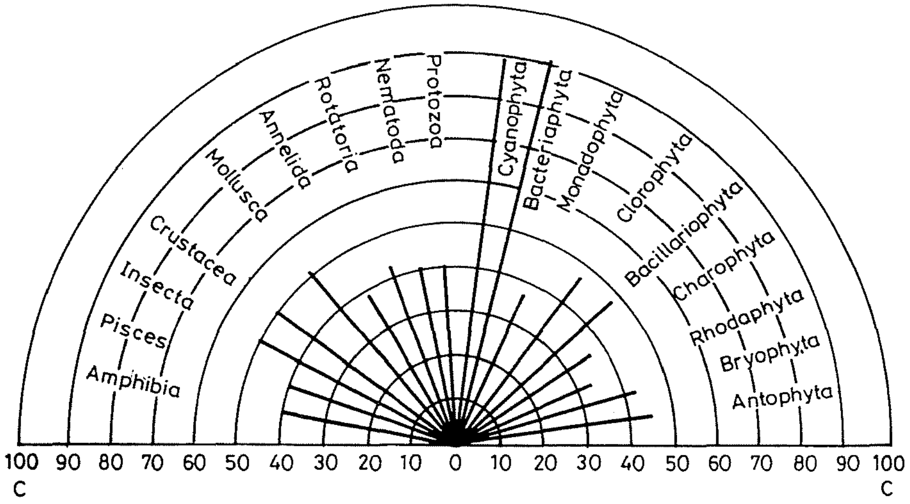


Fig. 2.

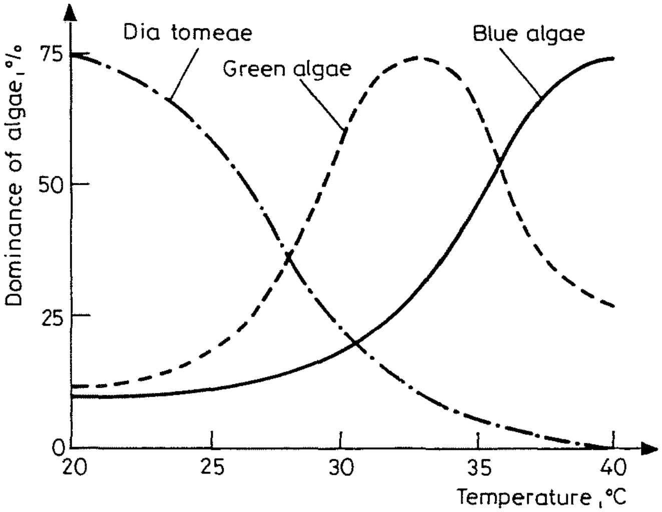


Fig. 3.

Summarizing the characteristics of the power plant impacts on the water quality one can state that those can be divided into two – an internal and an external – processes (OSZTHEIMER-SZABOLCS, 1978).

In the internal (cooling) system the change of temperature affects those planktonic organisms which move together with the cooling water. This pollution is affected rather by the power plant operation (the actual electric capacity and the rate of warming up in the condensers) than by any climate changes. The external process runs in the river and is affected heavily by the hydrological regime and so by the climate change.

Worth mentioning that the future change of the flow regime is also able to affect the rate of the thermal pollution in an indirect way. During the periods of the extremely low flow rates the mixing conditions could get worse. However, this parameter plays less important role than the temperature.

4. Climate Change Scenarios and Impacts on the Change of Parameters

The stream flow and the water temperature are depending on the climate, dominantly on the air temperature and the volume of the precipitation. The potential climate change – namely the change of the air temperature and the precipitation – can result such a big change in the flow rate and the water temperature which can affect the impact of the ecological consequences of the cooling water taken back into the river. In this section an assessment of the potential impacts of the potential climate change on the flow rates and the water temperature is explained. An analysis was performed on August data. The high temperature going together with a relatively small stream flow can result a critical period in August when the aquatic life of the river can be very sensitive on the impacts of the cooling water coming back from the plant. The assessment of the expected impacts of the climate change is based on empirical-statistical relations (NOVÁKY, 1994).

4.1 The Potential Climate Change

According to the climate models, if the atmospheric carbon-dioxide content will be doubled to the volume of the Industrial Revolution time, in the new climate equilibrium situation the possibility of the following data cannot be precluded in the catchment area of the Danube *Table 3*:

Table 3

Predicted climate change in the Danube catchment area

Period	Increase of the average air temperature	Increase of the average precipitation
Half year /winter/	5 K	0.4–0.6 mm/d
Half year /summer/	3 K	0.0–0.1 mm/d

In the case of a moderate climate change (hemispheric change) which is expected in the near future in our country, the winter average of the temperature will be by 1–2.5 K/K, and the summer average temperature by 0.8 K/K higher, while the yearly average of the precipitation will be by 60 mm/K lower than the present values (MIKA, 1990).

4.2 Impacts of the Potential Climate Changes

Basic Data of the Analysis

Data of the monthly average precipitation and air temperature (1946–1971) were available by the characterization of the future climate conditions on the Danube catchment area referring to the Nagymaros section. These data were prepared for the National Master Plan for Water Management (OVH, 1984) but the whole process had not been finished (KALMÁR, 1981). Data of the Hungarian and Austrian meteorological stations were applied for making the time series of the monthly precipitation and the average air temperature for the period 1946-1981. For the determination of territorial averages we counted the average of data of meteorological stations,

A strong correlation was found between the time series of the precipitation and temperature. The relation between them can be characterized by the 0.953 correlation factor (NOVÁKY, 1994).

Table 4
Standard deviation and relative standard deviation of the annual average of the precipitation and temperature

	Precipitation	Air temperature
Standard deviation	117 mm	0.10 K
Relative standard deviation	0.122	0.10

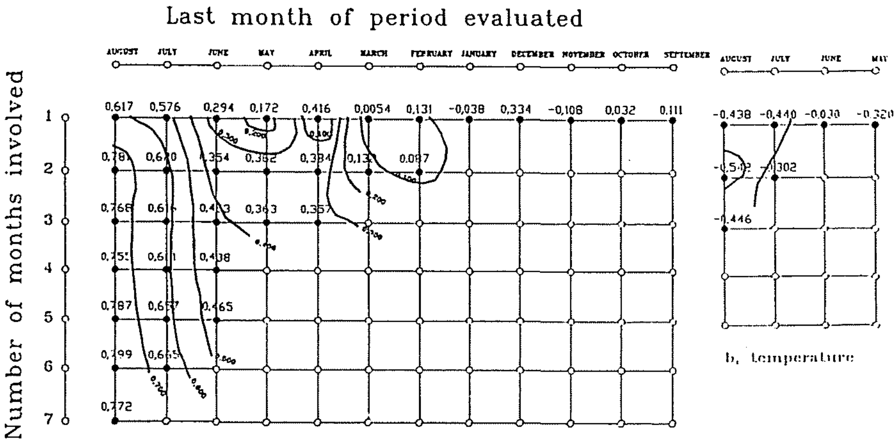
Considering the strong relation and the fact that in the climate impact assessments the changeable character of climate is dominant we found that the Austrian and Hungarian climate data were also sufficient for our analysis. So we could perform 36 year long climate time series for the section of the Danube in question. As regards the monthly mean stream flow at the Nagymaros cross-section, data are available for the period 1883–1993. However, the length of the climate time series is limited because of the 36 years long time series of the monthly mean temperature.

4.2.1.Connection between the August Runoff and the Temperature

Climate Impact on the August Runoff

Widely known that the runoff is dominantly determined by the precipitation and the temperature. A growing precipitation results growing runoff, while the increasing temperature results decreasing runoff because of the rising humidity and the surface evaporation forced by the higher temperature.

The starting point of our analysis was the fact that there is a connection between the precipitation, temperature and runoff. The phenomenon is improved physically. In the course of the climate modelling, different series of months were created with different starting points and lengths and determined their average precipitation and temperature. Then we ana-



a, precipitation

/values of nodes represent the correlation factors/

Fig. 4. Net optimization to find the best correlation. (Danube, Hungary)

lyzed their relation to the runoff in August supposing a linear connection between them (*Fig. 4*), (NOVÁKY, 1994).

The correlation factors of the different versions are shown as points in a grid system. Vertically the number of the months and horizontally the last day of the period taken into account is represented. *Fig. 4* shows the versions with the strongest connection. As regards the precipitation, it is the version taking into account a 5 month period – from April to August – with correlation factor: 0.787. By the analyses of temperature data, the highest correlation factor can be counted with a 2 month period (July–August). Having found the decisive periods from two different points of view, the analyses of the shape of relation between the runoff and the climate elements was carried out, respectively.

For the shape of the relation between the runoff and precipitation $R = f(P)$ the following a priori statements can be made: (1) This relation is a non-linear one. (2) The value of the runoff is not negative. (3) A zero precipitation does not mean necessarily a zero runoff. Because of the storing and delaying processes happening in the catchment area, the value of the precipitation in August could be over zero even if there was no precipitation in the decisive period (April–August).

For the analysis a transformation of the precipitation $P \rightarrow P^n$ and the average temperature $T \rightarrow T^n$ was made, where $n = 1, 1.5, 2$. Then the relation between the runoff and the transformed precipitation and temperature respectively was analyzed in the following forms: $R = f(P^n)$ and $R = f(T^n)$. If $n = 1$ then the relation is linear as it was supposed in the selection of the decisive period.

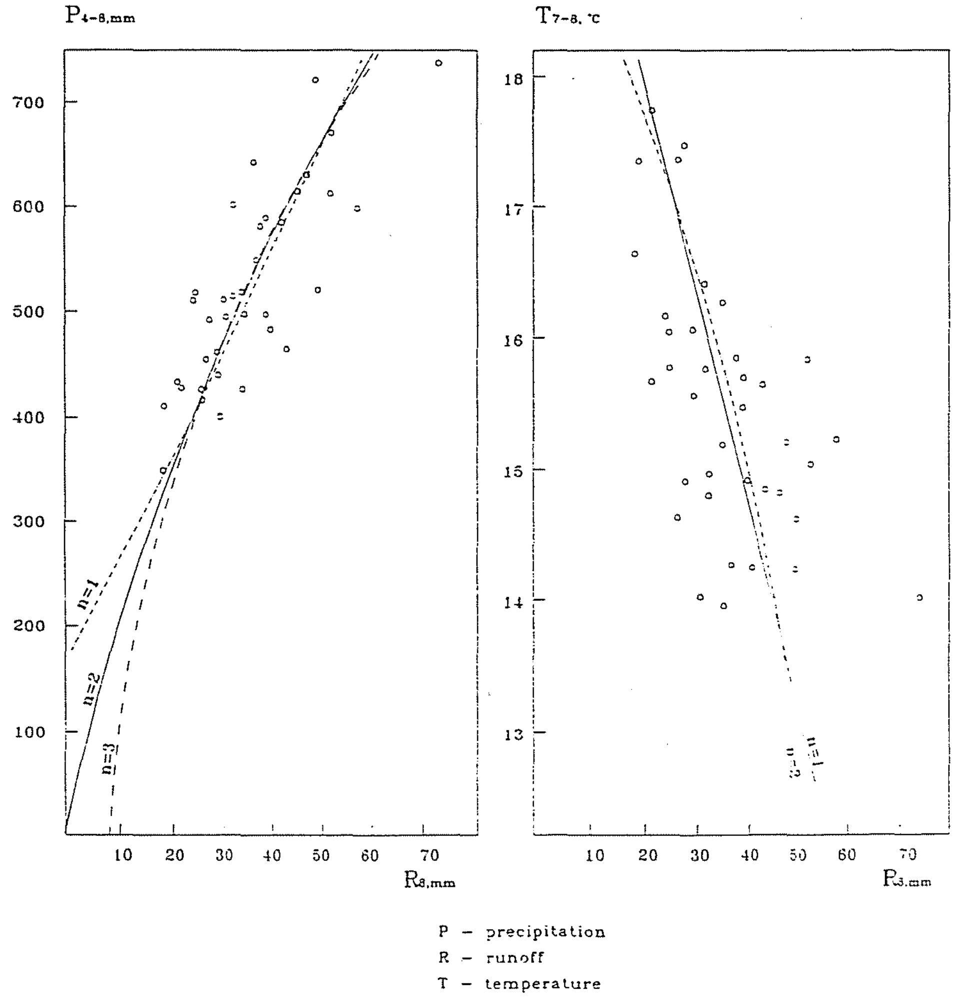


Fig. 5. Empirical relation between runoff and climatic factors

Fig. 5 shows the relation of the runoff – precipitation and the runoff – temperature in function of n. It can be seen that if $n = 1$, i.e. the relation is linear, the precipitation under about 170 mm results runoff with negative value, in the case when $n = 1.5$ zero precipitation results zero runoff and when $n = 2$ then $R_{\text{min}} = 10$ mm. Since the runoff with negative value cannot be explained, the linear relation can be excluded. However, any selection between the cases $n = 1.5$ and $n = 2$ (or any other ones) is nearly impossible because there is no information about $R_{,8,\mathrm{min}}$ at zero precipitation. This shape of the relation is of high importance because – as *Fig. 5* also shows – the curves which are in good correspondence inside of the decisive period are considerably different from each other outside of it. We have found similar problem analyzing the runoff – temperature relation (NOVÁKY, 1994).

When $n = 1$ the form of the relation is as follows:

$$R_8 = 0.101^* P_{4-8} - 16.60 \ . \qquad (1a)$$

When $n = 1.5$ the relation between the runoff in August and precipitation in the period from April to August is as follows:

$$R_8 = 0.00291^* P_{4-8}^{1.5} + 0.91 \ , \qquad (1b)$$

where the subscript shows the number of months taken into account. The strength is characterized by a correlation factor 0.791. Following (1b), the probable confidence domain of the August runoff on the 95 % probability level is 34.5–36.8 mm. The probable value estimated from the samples is 35.7 mm. It means that the difference between the two probable values is 1.2 mm (3%) on the 95% probability level, which can be a consequence of the stochastic relation itself.

When $n = 2$, the form of the relation is the following:

$$R_8 = 0.000094^* P_{4-8}^{2} + 9.729 \ . \qquad (1c)$$

The strength of the relation can slightly be increased taking an additional explaining factor, i.e. average temperature in July-August into account. For instance beside (1b) we got the following relation

$$R_8 = 0.00253^* P_{4-8}^{1.5} - 0.0843^* T_{7-8}^{2} + 25.65 \ , \qquad (2)$$

which is represented in *Fig. 6*. The correlation factor is 0.814. According to the analysis of the variance in the model (2), the variance of the August runoff is explained by the precipitation (62.3%), temperature (3.9%) and random event (33.7). The relation of the precipitation-runoff cannot be improved strongly by considering the temperature. The time series of the runoff can be isolated into three ones. The first two are determined by the precipitation and the temperature, while the third one shows the impact of the random events. The last time series is not autocorrelated and does not

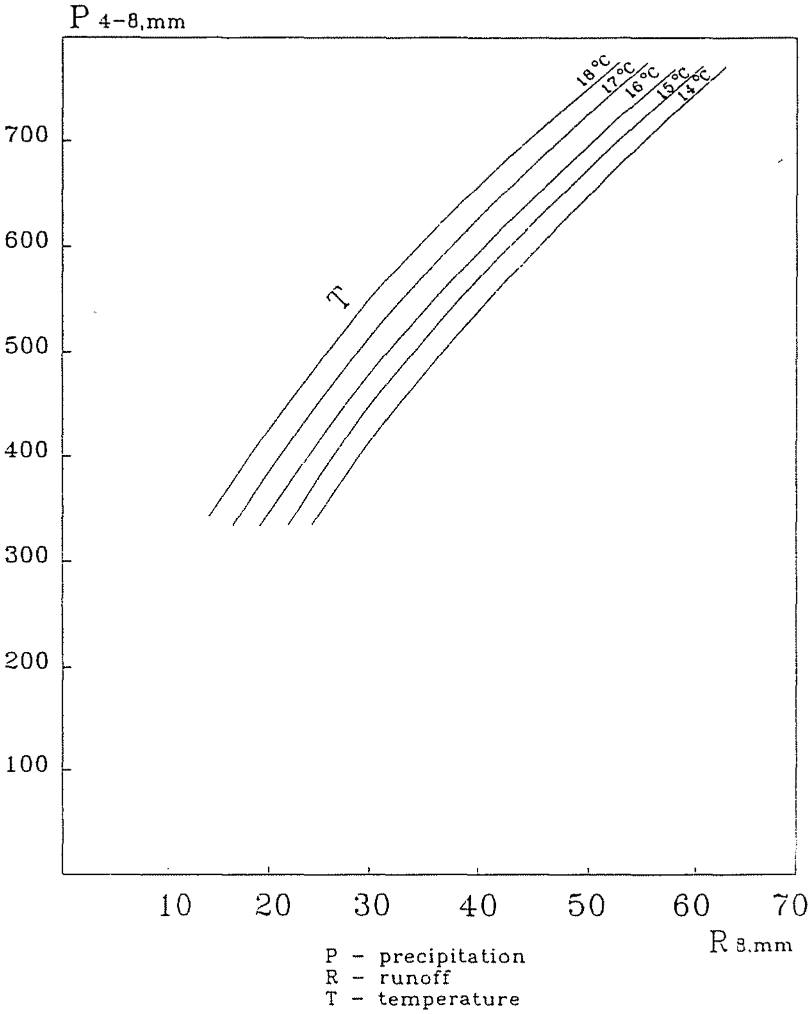


Fig. 6. Climatic dependence of runoff in August

show any trend. According to the peak probe it can be considered to be a so-called whitenoise-like process, so we can say that the model is nearly optimal.

Climate Impact on the August Water Temperature

Similarly to the process described above we found the decisive period where the strength of the relation between the average temperature and the average water temperature in August is the highest. Applying once more the net optimization method it can be stated that the decisive period is August (*Fig. 7*).

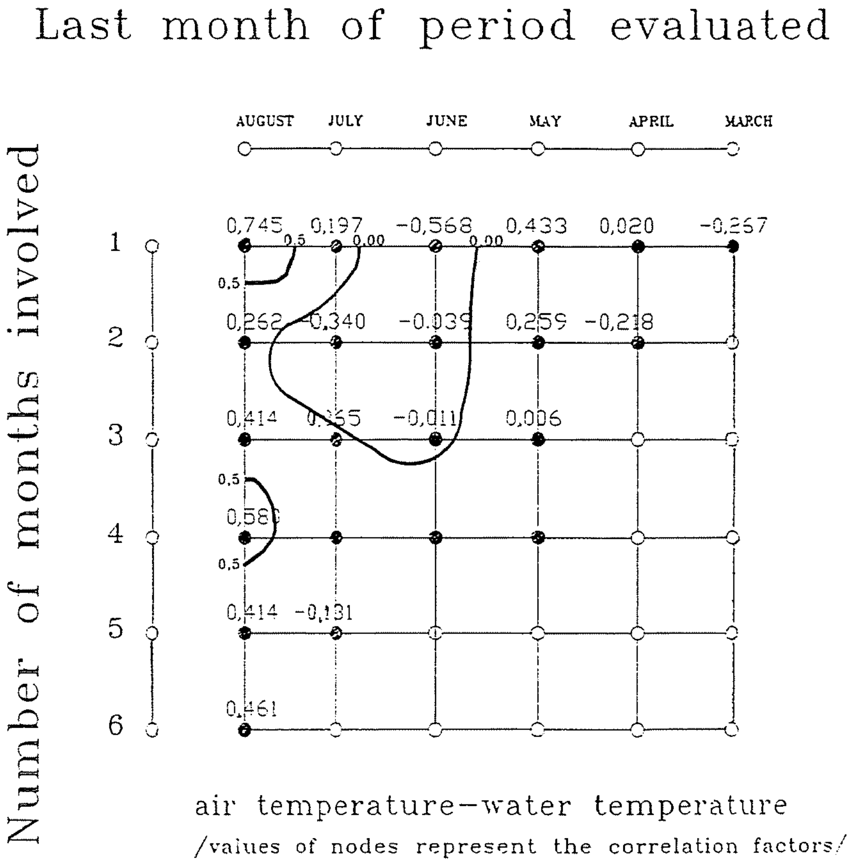


Fig. 7. Net optimization to find the best correlation.(Danube, Hungary)

The regressive connection for the water and air temperature in August is the following:

$$T_{w,8} = 0.683^{*}T_{a,8} + 8.965\ , \qquad (3)$$

where $T_{w,8}$ – water temperature in August, and
$T_{a,8}$ – air temperature in August

The correlation factor of this relation is 0.745. The relation (3) should not be overestimated because of the small number of the samples. The relation cannot be improved by taking the water temperature data of the previous months or the runoff into account.

According to the variance analysis, 56% of the variance of the average August water temperature can be explained by the monthly average air temperature. The time series of the water temperature can be isolated into two parts. The first is determined by the air temperature while the second one shows the impact of the random events. The latter time series is not autocorrelated, and does not show any trend. It can be considered a so-called whitenoise-like process. The random factor plays a very important role in the relation. The probable confidence domain of the August water temperature on the 95% probability level is 18.8–19.7 K. It means that the 1 K fluctuation of the water temperature values can be a consequence of the stochastic relation itself.

4.2.2. Impact Assessment of the Climate

Climate Scenarios

In the climate impact assessment two climate scenarios were accepted (MIKA, 1991):

I. scenario

The first estimate is a moderated (1 K) hemispheric warming up. In this case the expected increase in summer mean temperature is 0.8 K, and the decrease in yearly precipitation is 20–100 mm. The most probable value is 60 mm in Hungary. The mentioned decrease means 0.055–0.274 mm/d in precipitation intensity.

II. scenario

According to the second scenario the carbon-dioxide concentration of the air has doubled to the one at the beginning of the Industrial Revolution. In this case the expected increase in summer mean temperature is 3 K, and it goes together with the increase in precipitation intensity (0.0–0.1 mm/d).

The climate scenarios give only the long-term averages and so we do in our climate impact assessment, as well. Another fact worth to mention is that the estimations for precipitation and air temperature refer mainly to the summer half-year (in some cases to the whole year) in the climate scenarios while the models of the climate-runoff and the climate-water temperature based on the old observations require climate data with shorter time-scale. For the connection the climate models to scenarios, adoption of further assumptions are necessary:

- the change of the mean temperature in August and July–August is equal to the one of the summer half year;
- the change of the precipitation intensity, both in August and April--August period are equal to the one estimated for a long period, i.e.

its most probable decrease 0.164 mm/d in the first scenario and the increase 0.0–0.1 mm/d in the second one,
- the rate of the climate changes in the Danube catchment area and in the country are similar.

Impact of the Climate Changes on the August Runoff

The impact assessment of the climate change is performed by the climate scenarios I and II.

The perfect verification of the climate models is almost impossible because the independent samples being different from the ones used in our analysis are not available. There is only one possible way to perform a partial verification of the model: cutting the time series of the climate and the runoff data used for calibration into shorter periods. (The word 'partial' means that these data are not independent.)

For partial verification of the model (1) we selected two 10 year long periods with the largest and smallest volume of the precipitation from the time series 1945–1981, and compared the values of the August runoff of observation and estimation (*Table 5*).

Table 5
Verification of the climate–runoff model

Partial verification of the climate – runoff model (1)					
10 years long period of the	precipitation mm	runoff mm	runoff estimated mm		
			$n = 1$	$n = 1.5$	$n = 2$
largest volume of precipitation	636	48.4	47.6	47.7	47.7
smallest volume of precipitation	414	25.0	25.2	25.5	25.8

The estimated and observed values of the runoff obviously agree. The volume of the precipitation in the most rainy 10 years is higher by 23%, in the driest 10 years is lower by 25 % than the mean precipitation counted with the data of the whole period. So the climate model seems to be verified. *Table 5* also shows that the runoff data counted with the models using different n factors do not differ considerably, i.e. it is not important to select the shape of the precipitation – runoff relation – at least in connection with the mean runoff. The model (2) contains two independent variables: the precipitation and the temperature. We could not perform the verification of the model (2) similarly to the one of the model (1) as the time series was too short. The impact on different changes of precipitation of the August runoff according to the model (1) can be seen in *Table 6*. The results estimated using the model (2) which takes both the precipitation and the temperature into account are represented in *Table 7*. The results especially the latter ones must have been appreciated with care because of the lack of verification (NOVÁKY, 1994).

Table 6
Impact on the August runoff
(model (1))

Impact of the change of the precipitation on the August runoff, model (1)								
Change of the precipitation, mm/d	−0.20	−0.15	−0.10	−0.05	0.00	0.05	0.10	0.15
Runoff, mm	32.3	33.0	33.7	34.5	35.6	36.0	36.8	37.6

Table 7
Impact on the August runoff
(model (2))

Impact of the change of the precipitation and the temperature on the August runoff, model (2)						
Change of the precipitation	Increase of the temperature, K					
mm/d	0.5	1.0	1.5	2.0	3.0	4.0
0.1	35.04	34.04	32.64	31.19	28.16	24.98
0.0	43.07	32.71	31.30	29.86	26.83	23.64
−0.1	32.76	31.40	30.00	28.56	25.52	22.30
−0.3	30.20	28.84	27.43	25.98	22.96	19.77
−0.5	27.71	26.35	24.94	23.49	20.46	17.28

According to the impact assessment one can say that 1 mm change in the precipitation during the April–August period, i.e. in summer, results about 0.1 mm change in runoff in August. Similarly, 1 K rise of the mean temperature in July–August period goes together with about 2.9–3.0 mm decrease of the runoff in August.

Taking into consideration the first climate scenario, which supposes a small increase in summer temperature and decrease of the annual precipitation our results were the following: 8% and 13% decrease in the runoff in August using the model (1) and (2), respectively.

The second climate scenario supposes a larger increase in the temperature and some increase in the precipitation. In this case the estimated decrease of the runoff was 12% and 23% using the model (1) and (2), respectively.

Impact of the Climate Changes on the Water Temperature

As far as the water temperature is concerned an especially short one, 14 years time series was available. So there was no opportunity for the verification even of a partial one. At the same time it is well-known from other analyses, that the relation between the air and the water temperature exists and shows linear characteristics (*Fig. 8*).

Table 8
Impact on the water temperature
(model (3))

Impact of the change of the air temperature on the water temperature in August						
Increase of the air temperature, K	0.5	1.0	1.5	2.0	3.0	4.0
Water temperature, K	19.8	20.2	20.5	20.9	21.6	22.2

The climate modelling process shows that 1 K change in air temperature is followed by 0.68 K change in the water temperature. The estimated increase in the water temperature in August is 0.5 K, according to the first scenario and it is 2 K according to the second one.

4.3 Impact of the Climate Change on the Hydrological Regime of the Danube at Paks Nuclear Electric Power Plant (NEPP)

Data sampled at the meteorological stations and the stream flow data of the Danube concern the section of Nagymaros. To get information about impact of the climate change at the Danube section of Paks NEPP, further transformations are needed, such as the transformation of runoff modification into the change of the flow rate and the transformation of the water temperature data at Nagymaros to Paks. Regarding the runoff – flow rate transformation we suppose a linear connection, i.e. the rate of change of the stream flow and of the runoff are equal. As far as the transformation of the water temperature data from the upper Nagymaros section to the lower Paks section is concerned, data of sampling stations situated along this reach were analyzed. Essential statements are as follows :

- The temperature of Danube at the upper section is far from the equilibrium determined by the special Hungarian climate. The monthly mean water temperature rises continuously in the Hungarian reach. The rate of the increase is not constant along the whole length but it is linear everywhere. The specific increase in Hungary is 0.53 – 0.67 °C/100 km during the summer months. (Values were derived from a long (1947–1987) and a short time series (1967–1987), respectively.)

- A trend analysis was also carried out for every sampling stations. The evaluation showed 1 °C increase of the water temperature during the last 40 years. However, it is characterized by ±0.5 °C random error at 95% probability level (NOVÁKY, 1994).

From these statements one could come to the following conclusions:

- Because of the linear interaction, the estimated rate of the increase of water temperature occurred by the climate change at Nagymaros can be seen valid at Paks as well.
- The increase of water temperature arisen from the I. climate change scenario should be treated carefully, because its range is similar to the random error of the water temperatures registered.

Prediction of the changes of the hydrological regime at Paks NEPP are summarized in *Table 9* where the (1) model for runoff and (3) model for water temperature are accepted.

Table 8 shows the impacts of different degree of the air temperature on the water temperature in August using the model (3).

Table 9
Predicted change of the boundary conditions

	Change of the flow rate, % Estimation by (1) model	Change of the temperature, °C Estimation by (3) model
I. climate change scenario	−8	+ 0.68
II. climate change scenario	−12	+ 2.0

5. Evaluation of the NEPP Impact on the Danube in Predicted Conditions

An exact calculation of the mixing–cooling process is available on the base of the equation of the 3D unsteady turbulent dispersion supplemented with the surface heat transport (CUNGE et al., 1980). Considering our analyses which aim at a temperature prediction very close to the discharge point, the surface heat transport is obviously negligible. Taking into account the extremely shallow river bed, neglect of any change along the depth can be admissible. Further simplifications were made by the next stipulations: heat discharge and the depth of water are constant in time and space,

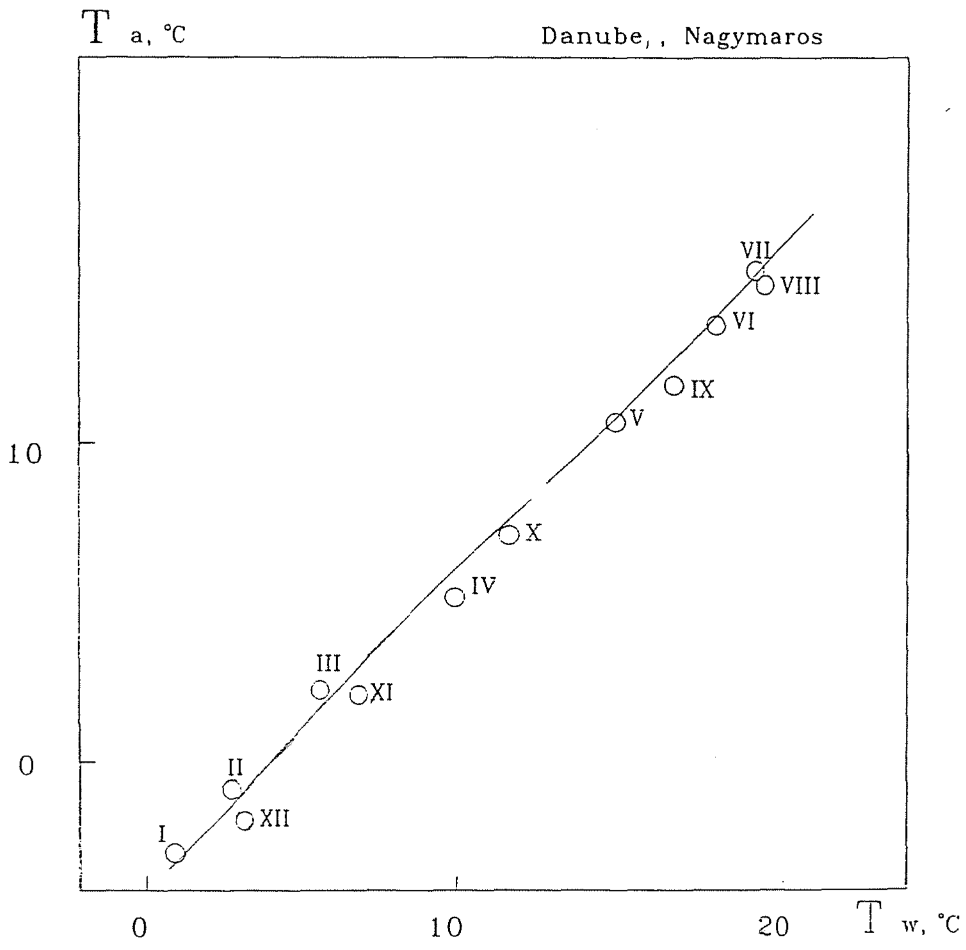


Fig. 8. Link between monthly mean air temperature (Ta) and monthly mean water temperature (Tw)

respectively, and the transversal convection is negligible considering the low flow rate, and the permanent flow velocity (SOMLYÓDY, 1985)

$$v_x \frac{\partial T}{\partial x} - D_y \frac{\partial^2 T}{\partial y^2} = 0 \ , \tag{4}$$

where T [C^0] average temperature at a certain point,

v_x [m/s] flow velocities by x coordinate,
D_y, [m^2/s] turbulent dispersion coefficient.

The vertically average water temperature – supposing a stream flow discharge – is as follows:

$$t = \frac{M}{2d\sqrt{\pi D_y v_x x}} \exp\left(\frac{-v_x}{4D_y x} y^2\right) , \tag{5}$$

where $M = Q^* dT$ and the transversal parameter $y = 0$ at the place of discharge.

In this case the width of the affected water body, i.e. the width of the warm water sheaf (B) is :

$$B = 4.3\sqrt{\frac{2D_y x}{v_x}} . \tag{6}$$

In case of bank discharge the width of warm water sheaf is as follows:

$$B = 2.15\sqrt{\frac{2D_y x}{v_x}} . \tag{7}$$

The water body affected by the thermal pollution was calculated, taking into account the climatically modified hydrological regime and the available operation of power plant. The question to be answerred was the violation of the permitted water temperature in the Danube.

It should be underlined that because of simplifications, the results should be treated carefully. For example, calculating some historical events and making comparison between the measured and calculated temperatures, a certain over-estimation came about.

6. Conclusions

1) For the analysis of the climate impact on the operation, the joint events of the extreme flow rate and the water temperature values are needed which happen in August.

2.) The regional average temperature increases parallel to the mean hemispheric temperature. By the I. scenario the expected increase of the summer mean temperature is 0.8 K linked with 60 mm decrease of the yearly precipitation. Using the models (1) and (2), the decreases of the August runoff are 8% and 13%. In the II. scenario, the values aforementioned are 3 K and about 0.0 mm, respectively. In this case the estimated decreases of the August runoff are 12% (model (1)) and 23% (model (2)). As far as the climatic dependency is concerned the modelling process shows that 1 K change in air temperature is followed by 0.68 K change of the water temperature. The estimated increase of the water temperature in August is 0.5 K according to the first scenario and it is 2 K according to the second one.

3) In case of the existing river bank discharge the peak temperature of Danube at the checking point exceeds the limit (30 °C) even in the case of the moderated I. climate scenario, and obviously there is no way for further extension of the power plant capacity.

4) Mitigation possibilities of the thermal load are threefold: (a) modification of the operation, (b) changing the river bank discharge for a river bed outlet(s), and (c) modification of the cooling system by inserting cooling towers or ponds. The first intervention occurs only at additional operation cost while the others need investment cost as well.

5) In case of the I. climate scenario, the solution (a) is suitable if the extension of the power plant capacity is out of question. However, the increased capacity needs the solution (b) with one concentrated outflow at the stream line. The higher regional warming (II. climate scenario) indicates the solution (b) with concentrated and with distributed discharge as options. The first one is suitable at the actual power plant capacity while latter is needed in case of extension.

6) If the I. climate scenario will happen the most moderate economic consequence is more than 150,000 USD additional operation cost with surplus of temporarily worsening power plant efficiency. In this case there is no capacity extension. The extended capacity costs are about 27,000 thousand USD as investment cost without additional operation cost. Taking the II. scenario into account, the keeping of the actual capacity needs about 14,000 thousand USD investment cost, while the approximate price of the extension could reach 30,000 thousand USD. By experts' opinion the construction of cooling towers needs significantly higher investment and operation costs, while for the partial utilization of waste heat a realistic market is necessary.

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