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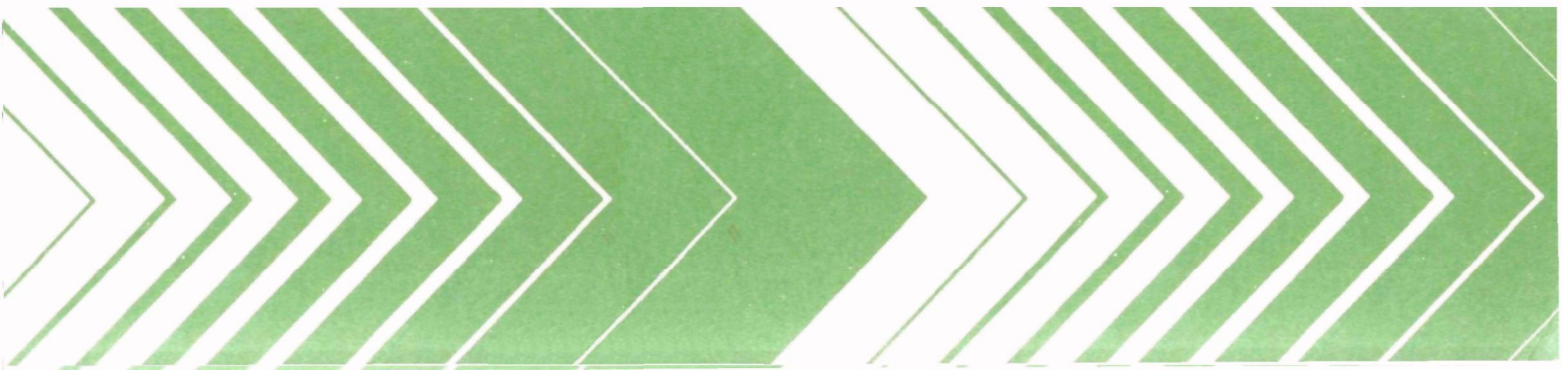
A Polish Research Project



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EPA-600/3-79-072
July 1979

EVALUATION OF EUROPEAN RIVERS FOR POWER PLANT COOLING

A POLISH RESEARCH PROJECT

by

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PL 480 Project No. PR-5-532-14

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report presents the results of a cooperative study by the Institute of Meteorology and Water Management of Poland under the Special Foreign Currency Program, PL-480.

The objective of this study was to determine the optimal mix of cooling system alternatives for stream electric generating stations to be located on Polish rivers.

James C. McCarty
Acting Director, CERL

ABSTRACT

The report describes analytical, laboratory, and field research conducted to optimize the use of rivers, specifically in Poland, for once-through cooling of steam electric power plants. Variations in river flow over several years are analyzed to determine statistically reliable low flows for various parts of the year. Variations in river temperatures are also analyzed to provide a statistically valid picture of annual temperatures in streams. Maximum discharge and receiving water temperatures, based on biological criteria, are coupled with natural flow and temperature variations to determine acceptable flow/temperature regimes for streams over an annual cycle. Controllable variables, such as repair schedules, reserve capacity, power plant site, hybrid cooling system size and operation, and low flow augmentation via reservoirs, are evaluated as mechanisms to modify electric power generation over an annual cycle. The acceptable temperature/flow regimes in streams are then compared to various power system configurations and schedules to optimize the annual generation of electric power. The following conclusions are reached, relative to Polish conditions:

- the installed capacity of open cycle cooling systems can be increased by about 25% without installing supplemental cooling.

- for increases greater than 25%, mechanical draft cooling towers and double pass condensers operated in a hybrid, open cycle is the most economical solution.

- low flow augmentation for power plant cooling via upstream reservoirs is economical only when used in a comprehensive water management plan.

This report was submitted in fulfillment of PL 480 Project No. PR-5-532-14 by the Institute of Meterology and Water Management, Warsaw, Poland under an agreement with the U.S. Environmental Portection Agency. This report covers a period from February, 1974 to December, 1977 and the report was completed as of May, 1978.

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INTRODUCTION

This report describes research conducted to establish rules for estimating the optimum installed capacity of power plants with once-through cooling systems and with hybrid cooling systems. Hybrid systems can use cooling towers, cooling ponds and spray devices, intermittently or continuously to reduce the waste heat discharge to acceptable levels.

The factors used in determining the optimum installed capacity of a power plant are:

- representative low flows,
- acceptable temperature increases in the river below the discharge,
- power plant load.

1. Hydrological Basis

1.1. Introduction

This report deals with the possibilities of supplying steam electric power plants with cooling water from free flowing rivers (i.e., without artificial flow control). In the case of rivers used as a cooling water source, the probability of occurrence of low flows has a practical use because it enables proper estimation of the cooling capabilities of the river.

This report gives flow characteristics for a number of European rivers used for power plant cooling. The analyses are based on monthly low flows over many years. The report also presents views on minimum reliable flows in various countries for industrial needs, as well as for power plant cooling.

The investigations covered river basins which differed with respect to their size and character; thus, small, medium, and large basins, as well as mountain and lowland basins were investigated. Polish rivers have been studied in greater detail, since the basic data for their investigation were more available.

To meet the objective of this study, analyses were conducted to determine the following:

- magnitude of low flows and their annual distribution,
- magnitude and duration of the continuous low flows,
- characteristics of monthly low flows.

A total of 42 cross-sections on 25 rivers from various river basins were investigated. Data on the rivers and cross-sections investigated are given in Table 1.1. and on the map (Figure 1.1) at a scale 1:12,000,000. Note that Figure 1.1 uses the Polish spelling of some rivers.

Analyses were conducted using data from Polish laboratories and technical references as well as data from other European countries.

1.2. Reliable Flows

Until recently, the required conditions commonly assumed for open cooling system operation on rivers related the constant demand for cooling water to the minimum flow with a definite probability of occurrence; generally between 95 and 98%.

In analyzing the problem of low flow rates, it should be pointed out that such severe conditions for open cooling systems are not justified. The re-

TABLE 1.1. RIVERS UNDER INVESIGATION

No.	River	Cross-Section	Area of Basin (km^2)	Longterm Mean Annual Flow (m^3/s)	Years of Record	Country
1	2	3	4	5	6	7
1.	Vistula	Tyniec	7525	90.7	1921-73	Poland
2.	"	Jagodniki	12049	134	"	"
3.	"	Szczucin	23885	246	"	"
4	"	Sandomierz	31819	287	"	"
5.	"	Zawichost	50685	419	"	"
6.	"	Pulawy	57224	450	"	"
7.	"	Warsaw	84823	560	"	"
8	"	Plock	169386	909	"	"
9.	"	Torun	180780	972	"	"
10.	"	Tczew	194259	1020	"	"
11.	San	Radomysl	16823	135	"	"
12.	Narew	Ostroleka	21870	107	"	"
13.	Oder	Scinawa	29615	167	"	"
14.	"	Nowa Sol	37304	212	"	"
15.	"	Cigacice	39913	224	"	"
16.	"	Polecko	47293	266	"	"
17.	"	Slubice	53580	308	"	"
18.	"	Gozdowice	109364	528	"	"
19.	Varta	Gorzow Wlk	51893	206	"	"
20.	"	Poznan	25093	94.3	"	"
21.	Maric	Pazardzhik	4136	21.6	"	Bul-garia
22.	Arda	Studen-Kladenets	3407	58.6	"	"
23.	Dnieper	Kiev	328000	1360	"	USSR
24.	"	Kremenchug	383000	1430	"	"
25.	Dniester	Zaleszczyki	24600	214	"	"
26.	Neman	Kaunas	45700	270	"	"
27.	"	Smalininkai	81200	517	"	"
28.	Daugave	Dvinsk	64400	456	"	"
29.	"	Plavinskaja GES	81500	589	"	"

continued ...

Table 1.1 (cont.)

1	2	3	4	5	6	7
30.	Vltava	Modrany	26703	146	1941-70	Czecho-slova-kia
31.	Vah	Sala	10619	150	"	"
32.	Danube	Budapest		2350	1954-69	Hungary
33.	"	Orsova	576000	5490	1941-70	Rumania
34.	Olt	Rimnieu Vilcea	15292	124	"	"
35.	Siret	Racaciuni	19539	100	"	"
36.	Bistrita	Bicaz		40.5	"	"
37.	Seine	Paris	43800	253	1927-65	France
38.	Garonne	Mas D'Agenais	52000	590	1921-65	"
39.	Dordogne	Dome (Cenac)	8700	180	"	"
40.	Loire	Mont-Jean	110000	847	"	"
41.	Rhone	Beacaire	95000	1705	"	"
42.	Rhine	Bale	35925	1035	'	'

5 Fig.1.1. AREA UNDER INVESTIGATION

sults of these investigations show that there is a period within the annual power plant operation cycle in which the water demand drops by about 25%. Apart from that, minimum flows with a probability of occurrence p=95% and p=98% are infrequent and of short duration. Thus, they do not represent the normal flow conditions at the power plant intake. This aspect of minimum flows is also pointed out by some hydrologists (Laszloffy 1960, Zielinska 1964, Remenieras 1972). Data from several steam power plants confirm this thesis, since the total demand for water exceeds the minimum flows in rivers quite frequently (Table 1.2.).

Power plant operating experiences were used to work out the new methods for low flows estimation and their classification concerning steam power plants cooling cycles water demand. In 1966, the Polish Union of Power Engineering assumed that flows with the probability of occurrence p=95% in December would ensure guaranteed capacity of the plant; while in November, January and February it is possible to reduce the power of the plant by 10%. Reduced load requirements during the summer months provide reduced flow requirements in the summer.

One of the first methods of calculating minimum flows for open cycle cooling systems was presented in 1968 (Gadkowski). In this method, the year is divided into two periods: winter, November through April; and summer, May through October. Analyses showed that low flows in both periods are at the same level. However in winter, under low water temperatures, it is necessary to use recirculation (intake heating) which reduces intake demands. This means that flow shortages for open cooling cycle operation usually occur only in the summer.

To determine the minimum reliable flow, a 95% guaranteed water supply for steam power plants is the practice in Poland. This means that hydrological conditions should safeguard the power plant operation through 95% of the year; for the remaining 5% of the year (i.e., 18 days in the summer) flows may be lower than the reliable value. This condition was related to a dry year with a probability of occurrence, p=95%.

The rules of the minimum reliable flows in other European countries are presented below:

In Romania (Zanavello 1964), low flow rates of 10 consecutive days with a frequency of occurrence p=95% are recommended.

An interesting method for low flow evaluation was worked out in Hungary where reliable flows lasting for 80% of August and 97.5% to 99.0% of September were taken as reliable low flow rates. During other months, the reliable flows are assumed to last for 100% of the time.

In West Germany, low flow rates of 20 consecutive days with a frequency of occurrence once in 30 years are recommended. In the temperature calculations for the Neckar River in West Germany (Flinspach 1973), low flows occurring at least 10% of the time in June, July and August in the years 1951-1965 have been accepted as reliable flows.

TABLE 1.2. COMPARISON OF OPEN COOLING SYSTEM FLOW REQUIREMENTS AND LOW RIVER FLOWS FOR SOME STEAM POWER PLANTS.

Power Plant / Country	Power Plant Capacity (MW)	Cooling Water Flow (m^3/s)	River	Low Flows (m^3/s)	Hydrological Characteristic of Low Flows
Vitry sur Seine / France	1,000	34	Seine	29	Lowest monthly flow
Montereau / France	750	27	Seine	25	Average yearly low flow
Lacq-Artix / France	375	20	Gave du Pou	13 15 27	Absolute minimum Average yearly low flow Flow of 329 days duration (Q_{329})
Beautor / France	375	14.1	Oise	7	Average yearly low flow
Blenod / France	1,000	40	La Moselle	19 4.3	Low monthly flows in Sept. and Oct. p=10% Daily minimum in 1972
Godin / Czechoslovakia	200	9	Morava	5.52 8.54	Flow of 364 days duration Flow of 355 days duration
Skawina / Poland	550	24	Vistula	13.8	Lowest monthly flow
Neckar / West Germany	900	40	Neckar	20	Average yearly low flow
Chesterfield / USA	1,212	44	James	14	Average yearly low flow

In France, the Interdepartmental Mission (AFdB 1975), established to evaluate low flows, has analyzed the following methods of classification of minimum flows:

- low consecutive flows of a duration of 10 and 30 days,
- low monthly flows with a probability of occurrence, p=90%.

As a result of this classification, low monthly flows occurring once in 10 years were recommended as reliable to water management authorities.

In the United States, 7 day consecutive low flows with the probability of occurrence p=90% are most often assumed as reliable flows. In some cases, however, this rule is modified (e.g., in temperature computations regarding steam power plants situated on the Ohio River, low flow rates of 30 consecutive days with a frequency of occurrence once in 10 years were assumed as reliable flows, Butz 1974).

On the basis of the above review of various opinions regarding reliable flows for evaluating cooling system operation in the steam power plants, low monthly flows with a probability of occurrence of p=90% are assumed as reliable flows in this report.

1.3 Magnitude and Distribution of Minimum Reliable Flows

1.3.1. Minimum Reliable Flows in Polish Rivers

As discussed in section 1.2. low monthly flows with a probability of occurrence of p=90% are proposed as the base for hydrological analyses of open and combined cooling cycles. Such flows are treated as minimum flows for the evaluation of the effective power output for power plants with open cooling systems. In addition, lower monthly flows with a probability of occurrence, p=95%, are suggested as worst case conditions.

To standardize the results of the investigations carried out for different types of rivers, coefficients previously suggested by Gadkowski, K_{ip} (i.e., coefficients of flow distribution according to equations 1.1 and 1.2) have been used. This form of expression has recently become more and more widely used (Bratranek 1966, Laszewski).

$$K_{i\ 10\%} = \frac{Q_{min\ 90}}{Q} \qquad (1.1)$$

$$K_{i\ 5\%} = \frac{Q_{min\ 95}}{Q} \qquad (1.2)$$

where:

Q = mean annual flow of many years,
$Q_{min\ 90}$ = low monthly flow of the probability of occurrence, p=90%,
$Q_{min\ 95}$ = low monthly flow of the probability of occurrence, p=95%.

Coefficients of distribution, $K_{i\ 10\%}$ for Polish and other European rivers are given in Table 1.3 and Figures 1.2 and 1.3.

If the values of the coefficient, $K_{i\ 10\%}$, are analyzed for the Vistula and Oder Rivers, each year may be divided into three periods:

- from February to June - a favorable period for open cooling systems of steam power plants due to high spring flows,
- from November to February - a safe period for open cooling systems of steam power plants with slightly increased flows,
- from July to October - a critical period for open cooling systems of steam power plants, i.e. a period of summer and autumn low flow rates.

In the critical periods, special attention should be paid to months characterized by minimum coefficients of distribution. All along the Vistula they occur in September, but on the Oder they occur at different times in various stretches of the river. In the upper stretches of the Oder, they occur in October, in the middle stretches in September, and in the lower reaches in August. However these differences are slight and if the Vistula and Oder distribution coefficients are compared (see Figures 1.2 and 1.3), it is seen that their values and distribution throughout the year are similar. Slightly higher coefficients occur all along the Oder in November, December, January and February, while in the summer and autumn months the coefficients of distribution are similar for both rivers.

A comparison of individual stretches of the Vistula and Oder indicates a displacement of the maximum spring flow in the lower stretch from March to April in relation to the middle and upper stretch. All through the remaining part of the year (in summer, autumn, and winter) the K_{ip} coefficient values of the lower Vistula stretch are about 5% higher than those of the upper and middle stretches. In the Oder, this increase is even higher.

Considering the possibility of using these stretches for cooling, this phenomenon should be pointed out as very favorable. The most suitable distribution coefficients, from the point of view of cooling, appear in the lower stretch of the Oder.

Among other rivers examined, the K_i distribution coefficients are particularly interesting in the Varta River. In the lower stretch at the Gorzow Wielkopolski cross-section, $K_{i\ 10\%}$ coefficients remain at the same level (near 0.40) for five summer and autumn months and in winter they are about 0.50. From the point of view of using open cooling systems, this cross-section is the most suitable of the Polish rivers examined.

1.3.2. Magnitude and Distribution of Low Flows in European Rivers

In relation to their cooling capability, European rivers have been divided into two groups - medium and large. Large rivers can provide cooling water to open cycle power plants with capacities greater than 1,000MW; medium rivers provide cooling for open cycle plants with capacities up to 1,000MW.

TABLE 1.3. DISTRIBUTION OF Ki_{10} COEFFICIENT FOR EUROPEAN RIVERS

River	Cross Section	Months											
		XI	XII	I	II	III	IV	V	VI	VII	VII	IX	X
Vistula	Tyniec	0.29	0.36	0.38	0.37	0.82	0.66	0.47	0.35	0.38	0.35	0.29	0.33
Vistula	Jagodniki	0.32	0.35	0.34	0.39	0.82	0.68	0.43	0.41	0.35	0.34	0.28	0.29
Vistula	Szczucin	0.30	0.28	0.32	0.33	0.65	0.73	0.53	0.41	0.34	0.33	0.28	0.28
Vistula	Sandomierz	0.33	0.34	0.31	0.37	0.84	0.77	0.54	0.47	0.40	0.35	0.30	0.31
Vistula	Zawichost	0.33	0.36	0.34	0.34	0.83	0.76	0.47	0.44	0.38	0.33	0.28	0.28
Vistula	Pulawy	0.36	0.38	0.36	0.37	0.74	0.71	0.53	0.46	0.39	0.33	0.29	0.30
Vistula	Warsaw	0.38	0.41	0.39	0.39	0.75	0.75	0.55	0.48	0.39	0.35	0.30	0.33
Vistula	Plock	0.38	0.40	0.42	0.41	0.83	0.99	0.59	0.41	0.40	0.35	0.33	0.33
Vistula	Torun	0.42	0.41	0.45	0.45	0.74	0.90	0.60	0.42	0.40	0.37	0.34	0.35
Vistula	Tczew	0.43	0.44	0.48	0.45	0.79	0.97	0.66	0.49	0.43	0.39	0.37	0.38
San	Radomysl	0.24	0.31	0.27	0.37	0.75	0.69	0.38	0.31	0.21	0.22	0.19	0.19
Narew	Ostroleka	0.49	0.45	0.41	0.39	0.56	0.94	0.63	0.41	0.35	0.33	0.35	0.39
Oder	Scinawa	0.35	0.36	0.37	0.38	0.68	0.67	0.52	0.38	0.34	0.31	0.26	0.25
Oder	Nowa Sol	0.42	0.43	0.50	0.52	0.81	0.80	0.59	0.49	0.39	0.35	0.31	0.32
Oder	Cigacice	0.40	0.42	0.46	0.47	0.82	0.82	0.66	0.48	0.35	0.33	0.29	0.31

continued ...

Table 1.3 (cont)

River	Cross Section	Months											
		XI	XII	I	II	III	IV	V	VI	VII	VII	IX	X
Oder	Polacko	0.40	0.42	0.42	0.48	0.68	0.77	0.60	0.42	0.39	0.36	0.33	0.31
Oder	Slubice	0.43	0.43	0.47	0.50	0.75	0.79	0.66	0.38	0.40	0.37	0.32	0.34
Oder	Gozdowice	0.47	0.51	0.54	0.57	0.76	0.81	0.60	0.48	0.43	0.38	0.40	0.40
Varta	Poznan	0.39	0.62	0.56	0.35	0.75	0.71	0.47	0.33	0.29	0.26	0.26	0.31
Varta	Gorzow Wlk	0.49	0.59	0.58	0.58	0.87	0.85	0.63	0.44	0.41	0.41	0.43	0.45
Meric	Pazardzhik	0.20	0.16	0.25	0.30	0.45	0.32	0.42	0.13	0.03	0.01	0.01	0.13
Arda	Studen-Kadeneta	0.14	0.18	0.44	0.27	0.41	0.27	0.19	0.14	0.08	0.03	0.04	0.05
Dnieper	Kiev	0.30	0.26	0.33	0.32	0.36	1.31	1.47	0.61	0.40	0.34	0.32	0.34
Dnieper	Kremenshug	0.28	0.28	0.31	0.29	0.35	1.26	1.54	0.70	0.39	0.33	0.28	0.29
Dniester	Zaleszczyki	0.22	0.21	0.15	0.20	0.62	0.72	0.38	0.30	0.28	0.27	0.19	0.19
Neman	Kaunas	0.54	0.52	0.48	0.41	0.50	1.26	0.72	0.56	0.49	0.47	0.48	0 51
Neman	Smalininkai	0.68	0.50	0.48	0.39	0.48	1.28	0.71	0.46	0.43	0.38	0.40	0.42

continued ...

Table 1.3 (cont)

River	Cross Section	Months											
		XI	XII	I	II	III	IV	V	VI	VII	VII	IX	X
Daugave	Dvinsk	0.25	0.26	0.21	0.20	0.22	2.15	1.12	0.42	0.24	0.22	0.21	0.24
Daugave	Plavinskaja GES	0.26	0.27	0.22	0.20	0.21	2.12	1.10	0.44	0.25	0.21	0.20	0.25
Vltava	Modrany	0.29	0.31	0.35	0.36	0.55	0.58	0.42	0.34	0.29	0.20	0.25	0.30
Vah	Sala	0.33	0.37	0.31	0.29	0.68	0.87	0.67	0.59	0.40	0.33	0.30	0.26
Danube	Budapest	0.41	0.35	0.51	0.59	0.66	0.86	0.94	0.90	0.80	0.70	0.57	0.43
Danube	Orsova	0.48	0.48	0.42	0.50	0.72	0.90	0.82	0.71	0.60	0.47	0.38	0.28
Olt	Rimnieu-Vilcea	0.28	0.24	0.22	0.26	0.48	0.64	0.79	0.64	0.51	0.34	0.31	0.28
Siret	Rocaciuni	0.22	0.14	0.12	0.12	0.47	0.80	0.82	0.52	0.44	0.33	0.23	0.19
Bistrita	Bicaz	0.32	0.24	0.21	0.22	0.42	1.02	0.89	0.67	0.52	0.40	0.32	0.26
Seine	Paris	0.15	0.25	0.58	0.58	0.67	0.44	0.34	0.26	0.20	0.27	0.15	0.14
Garonne	Mas D'Agenais	0.28	0.35	0.47	0.52	0.54	0.52	0.51	0.38	0.20	0.12	0.14	0.15
Dorgogne	Dom(Cenac)	0.27	0.38	0.54	0.59	0.52	0.38	0.30	0.21	0.09	0.09	0.10	0.13
Loire	Montjean	0.25	0.43	0.63	0.73	0.61	0.47	0.31	0.28	0.18	0.13	0.13	0.15
Rhone	Beacaire	0.48	0.54	0.59	0.55	0.63	0.59	0.60	0.62	0.49	0.43	0.39	0.37
Rhine	Bale	0.46	0.43	0.44	0.39	0.52	0.66	0.82	1.07	0.90	0.78	0.62	0.48

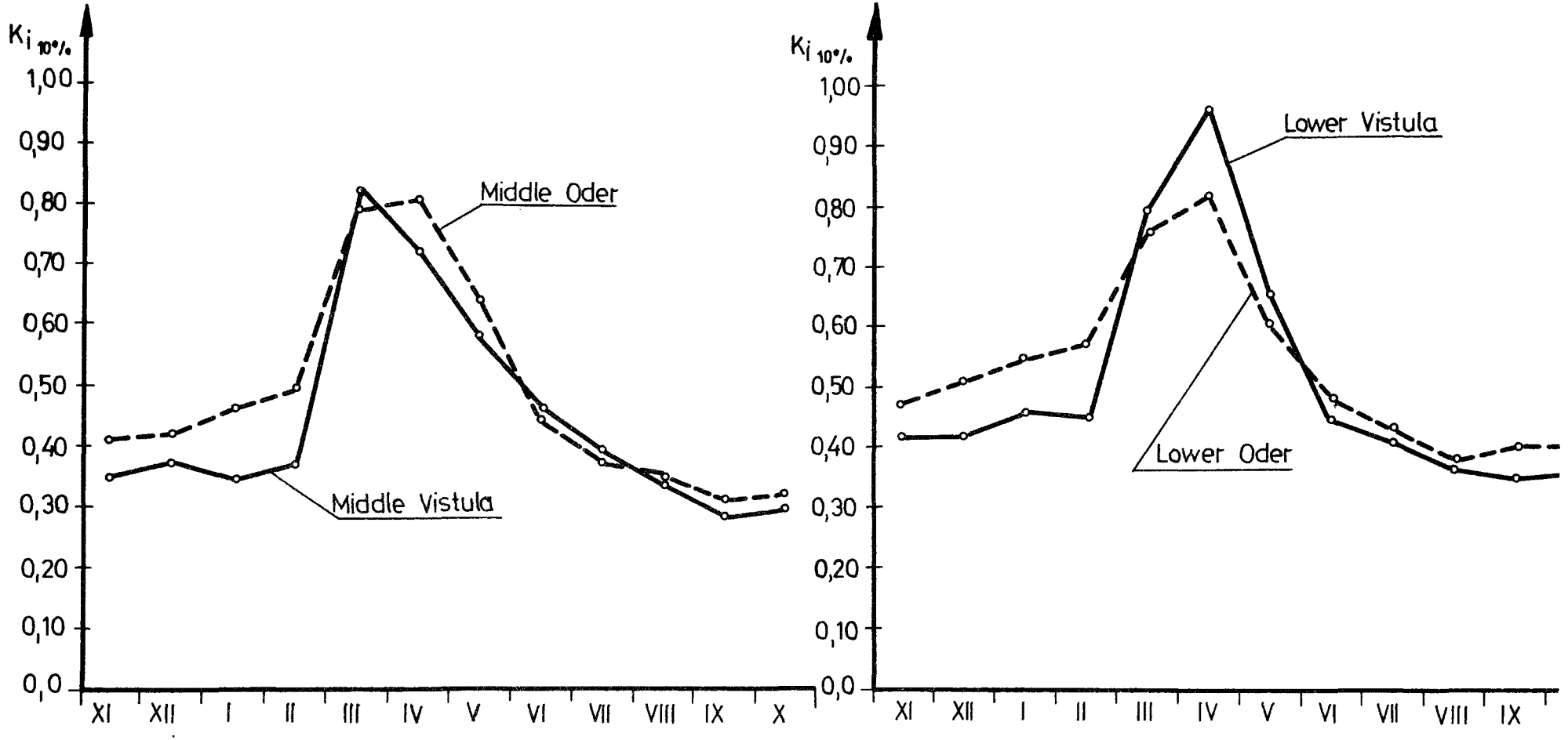


Fig. 1.2. Distribution of $K_{i\,10\%}$ coefficients on lower and middle Vistula and Oder

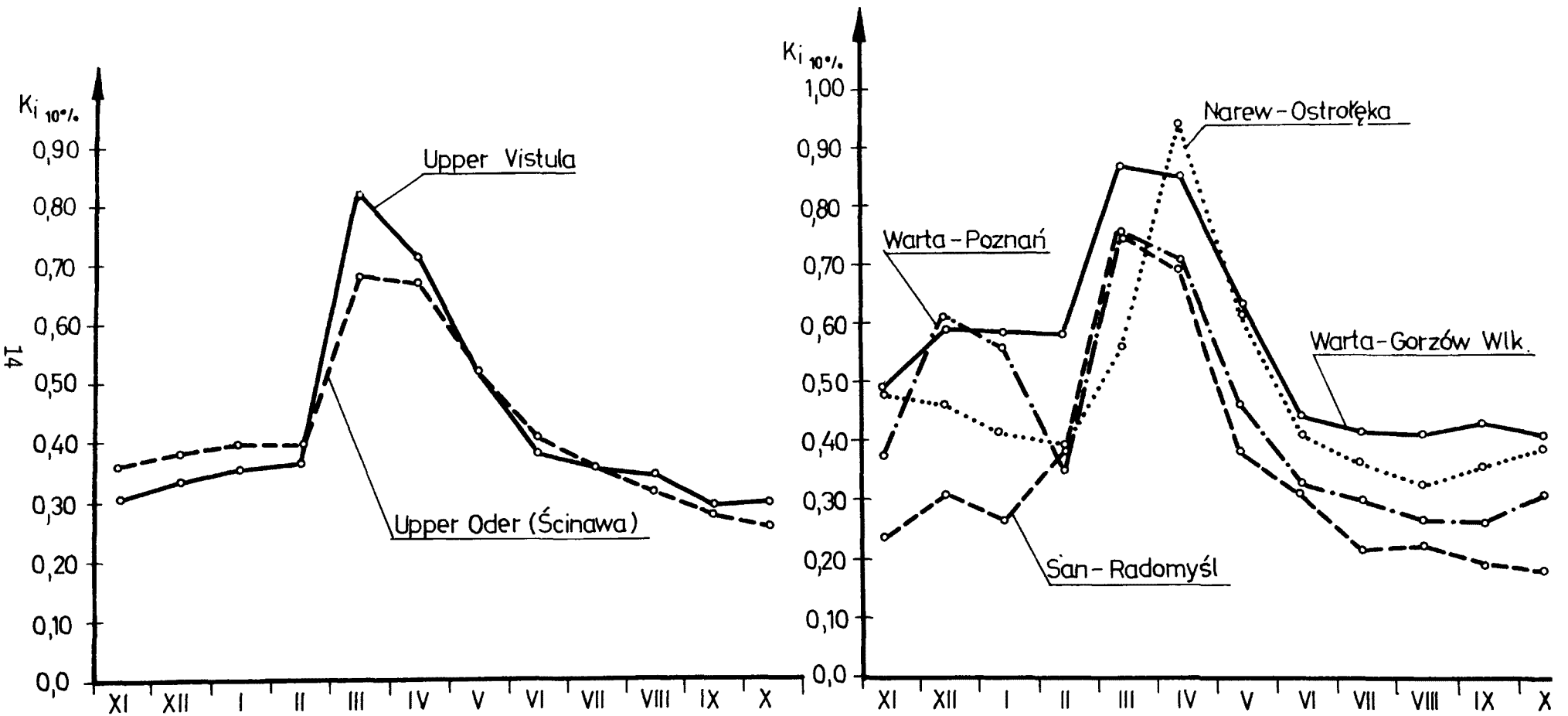


Fig.1.3. Distribution of $K_{i\,10\%}$ coefficients on Upper Vistula and Upper Oder and on San, Warta, Narew Rivers

The coefficients of distribution for the large European rivers are given in Figure 1.4. These results indicate that the variability of the coefficient of distribution $K_{i\ 10\%}$ depends on the individual character of the river. Coefficients $K_{i\ 10\%}$ may differ considerably in rivers flowing under similar geographical conditions. The Neman, Daugave, Rhine and Rhone, as well as the Danube, in its middle and lower stretches, are examples of significant differences of the coefficients of distribution $K_{i\ 10\%}$. The differences between distribution coefficients in the Vistula and Oder Rivers amount to 0.20 in winter and 0.10 in summer and autumn months. Slightly larger differences in coefficients of distribution $K_{i\ 10\%}$ occur in the medium size rivers. In Poland, these amount to 0.30 in winter and 0.20 in the summer critical period. The differences between coefficients of distribution discussed here include monthly magnitudes, critical periods when they occur within a year, and their duration. This indicates the need for individual analyses of the rivers.

1.4 Flow Shortages

The purpose of the analysis of flow shortages is to investigate the possibilities of low flow augmentation for power plant cooling systems. Flow shortage is the difference between the historical flow which is not exceeded 90% of the time and the required low flow (Q_r) with the defined control ratio, s:

$$s = \frac{Q_r}{Q} \tag{1.3}$$

where:

s = control ratio
Q_r = required low flow
Q = mean flow of many years

Flow shortages are calculated from historical data on a daily, weekly, or monthly basis. An analysis of flow shortages has been done for the Pulawy cross-section on the Vistula River. Observations of the flows in the years 1921-1973 were used. Separate calculations were carried out for monthly and daily flows, as well as for summer and winter flows. The months June through October are considered the summer period.

The duration of flow shortages determined on the basis of daily flows usually comprises a longer period than the basic period established on the basis of the monthly flows. This causes the volume of shortages determined on the basis of daily flows to be about 15% larger than the volume of shortages established on the basis of monthly flows. The calculated values are presented in Table 1.4.

1.5 Maximum Reliable Water Temperatures

If the river in question is used for cooling steam power plants, it is very important tat the duration of maximum temperatures is short. Natural temperatures exceeding 25°C rarely last more than a few days in Polish rivers.

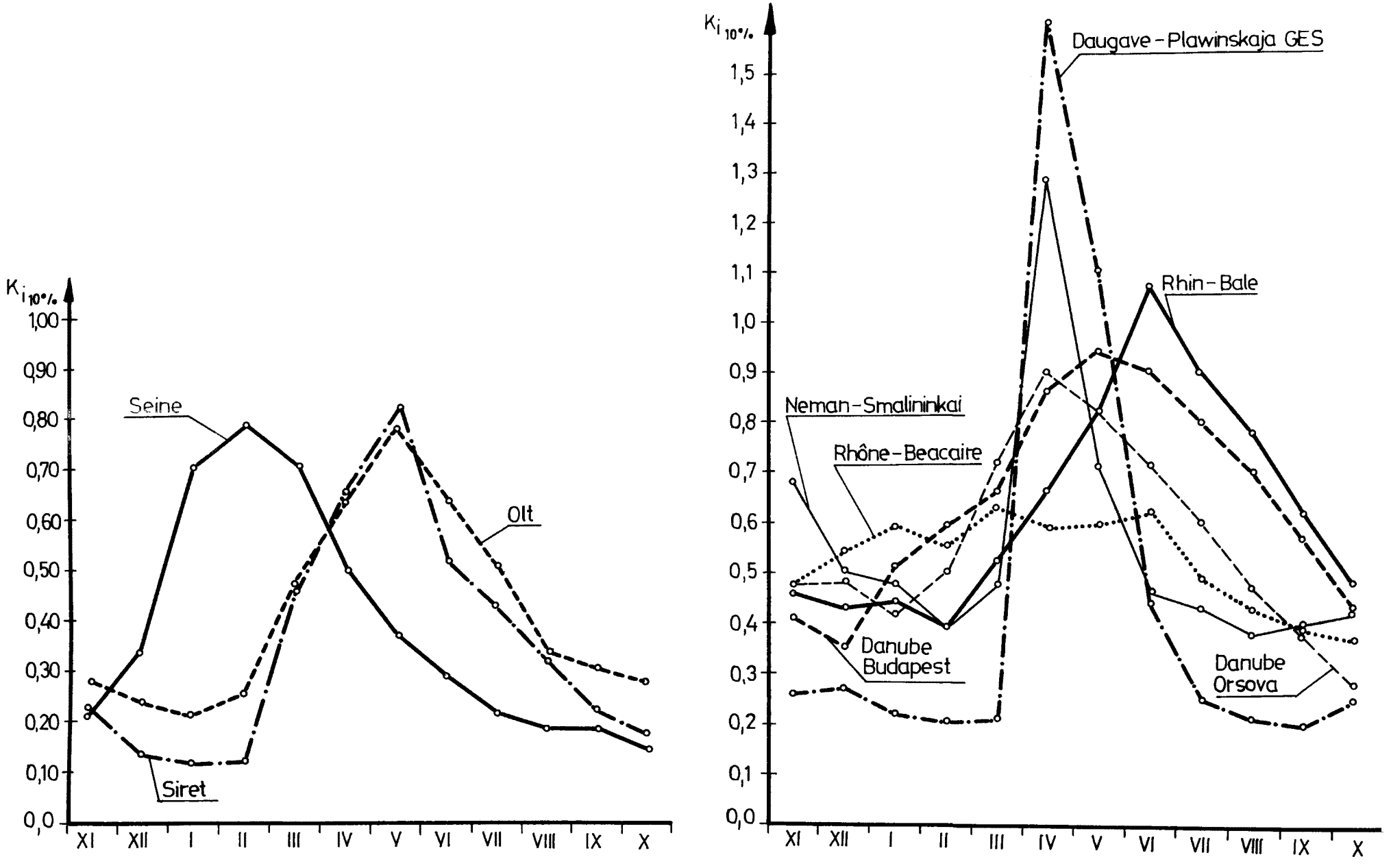


Fig. 14. Distribution of $K_{i\,10\%}$ coefficients on large and medium rivers.

TABLE 1.4. FLOW SHORTAGES FOR THE SUMMER WITH DIFFERENT CONTROL RATIOS, s, FOR p=90%

Control Ratio, s	The Sum of Monthly Shortages ($10 \times 10^6 m^3$)	The Sum of Daily Shortages ($10 \times 10^6 m^3$)	Coefficient of Increment*
0.30	34	37	1.09
0.35	135	156	1.16
0.40	260	300	1.15
0.45	392	450	1.15

* Coefficient of Increment is the ratio of daily flow shortages to monthly flow shortages.

During this period, rapid temperature changes of a few degrees Celsius may occur.

To establish a reliable water temperature for power plant cooling, temperatures which are not exceeded 95% of the period under investigation are proposed; such temperatures (t_{95}) should be calculated monthly. Calculations show (Gadkowski 1972) that reliable temperatures (t_{95}) are 1.0-2.0°C below extreme natural temperatures.

The concept of reliable temperatures was introduced to thermal analysis by other authors. Chauveau and Gras (1972) utilized this principle while analyzing open cycle cooling for steam power plants. Temperatures exceeded no more than 20 days of the year (t_{20_d}) were accepted as reliable. The difference between t_{max} and t_{20_d} in natural regimes is normally 2 to 3°C. In heated waters, the difference is greater and stays within the limits of 3 to 4°C.

Flinspach (1973), in thermal calculations of the Neckar River, assumes reliable temperatures as temperatures not exceeded 92.5% of the time in June, July and August. Reliable temperatures are 1.0°C less than the maximum temperatures in June and August and 3.0°C less in July.

In thermal calculations for the Rhine River (Arbeitsgemeinschaft 1971) the reliable temperature was assumed to be the mean temperature of the lowest low-flow period of 20 days duration for each year from 1947 to 1966. This reliable temperature exhibits the same characteristics as for the Neckar River.

Adoption of a reliable temperature lower than the maximum value is confirmed by the fact that measurements are usually made close to the river bank, and those shallow, slow flowing waters heat up more rapidly than the deeper mid-river waters. This phenomenon is reported by Cebotariev (1953), Zelazinski (1961), Hatfield (1965) and others.

2. Acceptable Temperature Increases in Free-Flowing Rivers

2.1 Variability of River Water Temperature

It is recognized that temperature changes caused by power plant operations can be of the same magnitude as temperature changes caused by a variety of natural phenomena. It is also recognized, however, that the power plant induced temperature increases are added to any natural changes, thus accentuating the increases. In any event it is instructive to review certain naturally-caused temperature changes.

Calculations show that temperatures of various rivers situated in the same climatic regions are different (Gadkowski 1976b). And, the larger the area under investigation, the greater the difference between temperatures taken simultaneously at different locations. This points to the opportunity for varying cooling water discharge temperatures for various power plants located within the area to accommodate these natural temperature variations.

In Poland, the differences between the summer mean monthly temperatures of many years amounts to about 4°C. Differences between extreme temperatures in the lower stretches of the Vistula and Oder Rivers are slightly smaller and amount to about 3.0°C in the Vistula and to about 1.2°C in the Oder (Gadkowski 1976a).

Maximum differences between the mean monthly values are much higher and in the summer amount to:

- for the whole area, about 6°C;
- for the lower stretches of the Vistula and Oder, between 4.0 and 5.5°C.

Maximum differences between 24-hour values in the summer are considerable and range from 6 to 11°C.

Large temperature differences in the river may be caused by tributaries which have different water temperatures than the main stream. Usually such cases occur in rivers which are fed by glaciers or thermal sources. In European rivers, monthly temperature differences between the Rhone River and the Arve River reach 9°C (Table 2.1), but between the Rhone River and the La Saone River they are only 2.0 to 2.3°C (Remenieras 1972). Typically, temperature differences are large between upper and lower river stretches, particularly for rivers flowing from the mountains. In some cases, however, significant differences in the lower stretches of large rivers are observed. For example, in four cross-sections situated within a 145 km reach of the lower Rhone River (Serriers, Valence, Viviera Bagnols sur Ceze), the following differences of monthly river water temperatures between cross-sections were observed (Gadkowski 1976b):

TABLE 2.1. MONTHLY TEMPERATURE DIFFERENCES BETWEEN THE UPPER RHONE AND ARVE RIVERS

Month	1964	1970	1971	1972	1973	Average
Jan.	2.2	1.1	2.3	2.2	3.1	2.2
Feb.	1.4	0.7	0.7	0.9	1.9	1.0
Mar.	0.2	0.2	0.3	0.4	1.1	0.4
Apr.	0.4	0.4	0.7	0.9	0.8	0.6
May	0.7	1.0	2.0	3.2	1.5	1.6
June	1.9	6.1	2.5	3.6	5.6	3.9
July	7.0	4.7	7.3	7.0	7.0	6.6
Aug.	7.4	9.0	9.7	7.4	9.6	8.6
Sept.	7.5	5.6	7.3	6.2	8.1	6.9
Oct.	6.9	7.4	4.5	4.9		5.9
Nov.	3.3	3.0	4.0	6.0		4.1
Dec.	3.1	2.6	2.8	4.1		3.1

1970	1.8 to 4.4°C
1971	0.8 to 8.9°C
1972	0.1 to 6.4°C

Significant thermal changes may also be caused by discharges from storage reservoirs, e.g., warmer discharges during the winter and cooler discharges during the summer (May through August). The water discharged during the summer can be as much as 12°C cooler than the natural down-stream temperature (Cyberska 1975) and during the winter, 5 to 6°C warmer.

In summary, natural temperature changes do occur regionally and locally. In evaluating the range of these changes the following should be recognized:

- changes of 1.0°C are typical of changes in all river systems.
- changes of 4.0 to 8.0°C have been observed in the natural thermal system of some rivers.
- changes with 4.0 to 10.0°C can be caused by reservoir discharges.

2.2. Review of Temperature Increases Caused by Existing Steam Power Plants

2.2.1. Polish Steam Power Plants

Maximum temperatures recorded in Poland below power plants exceed 30°C. The highest, recorded over a long time period in Poland, occurred in the Vistula below the Skawina Power Plant in 1963 (Figures 2.1 and 2.2). It should be pointed out that in the summer of 1963, water temperatures in the thermal plume about 3 km downstream from the power plant were 34°C on several days and temperatures exceeding 30°C were recorded for 10 consecutive days from July 17 to 27. The maximum monthly temperature increase of the Vistula River in the period of power plant operation exceeded 5°C in the summer and 7°C in the winter (Table 2.2). A maximum temperature of 36°C, was recorded in the Nysa Luzycka River downstream from the Hirschfelde Power Plant (Stangenberg 1966). Very high water temperatures were also observed in the discharge of the Stalowa Wola Power Plant, which has a series cooling system. Waters discharged from the condensers installed at the first and second stage are used for cooling the third stage. The mean monthly water temperatures at the discharge of this power plant amounted to 43°C in the summer. Despite the considerable temperature rise, the maximum temperature of the river fell quite rapidly, and about 5 km downstream from the power plant, the maximum temperature increase in the heated plume was only about 3°C, while a mean value for the whole cross-section was only about 2°C.

The Kozienice Power Plant on the Vistula River is another example. In 1974, the temperatures below the discharge oscillated around 30°C from May 15 to September 15. Maximum temperatures were 32.5°C. Maximum natural temperatures the summer of 1974 in the region of the power plant intake were 21.0°C, with a 24-hour maximum of 22.5°C.

Discharge temperatures exceeding 35°C were also reported for the Patnow and Konin Power Plants (Figures 2.3 and 2.4).

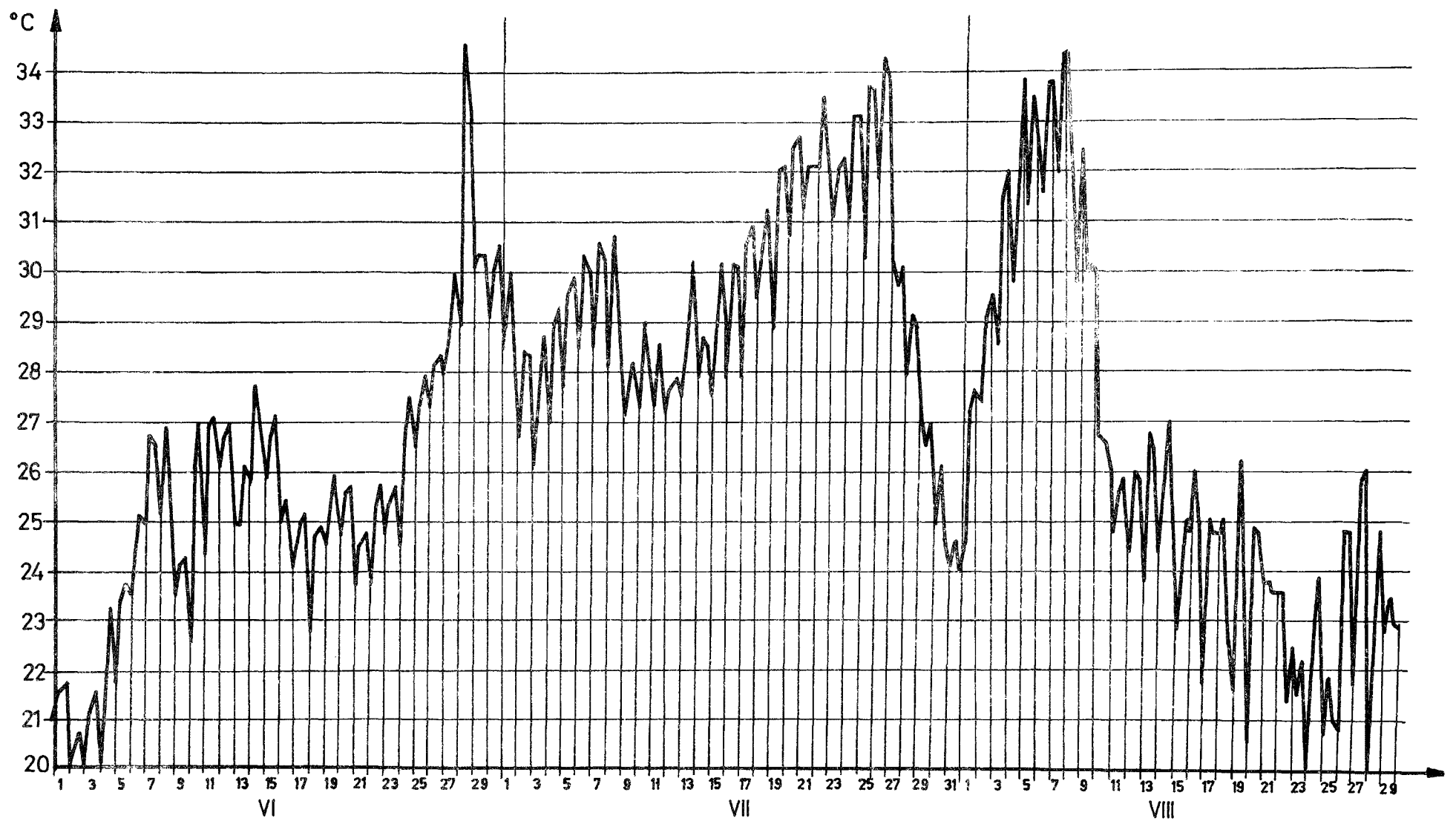


Fig. 2.1. Temperature distribution in the thermal plume below the Skawina power plant 1963 (temper. measurement at 7:00, 12:00 and 18:00)

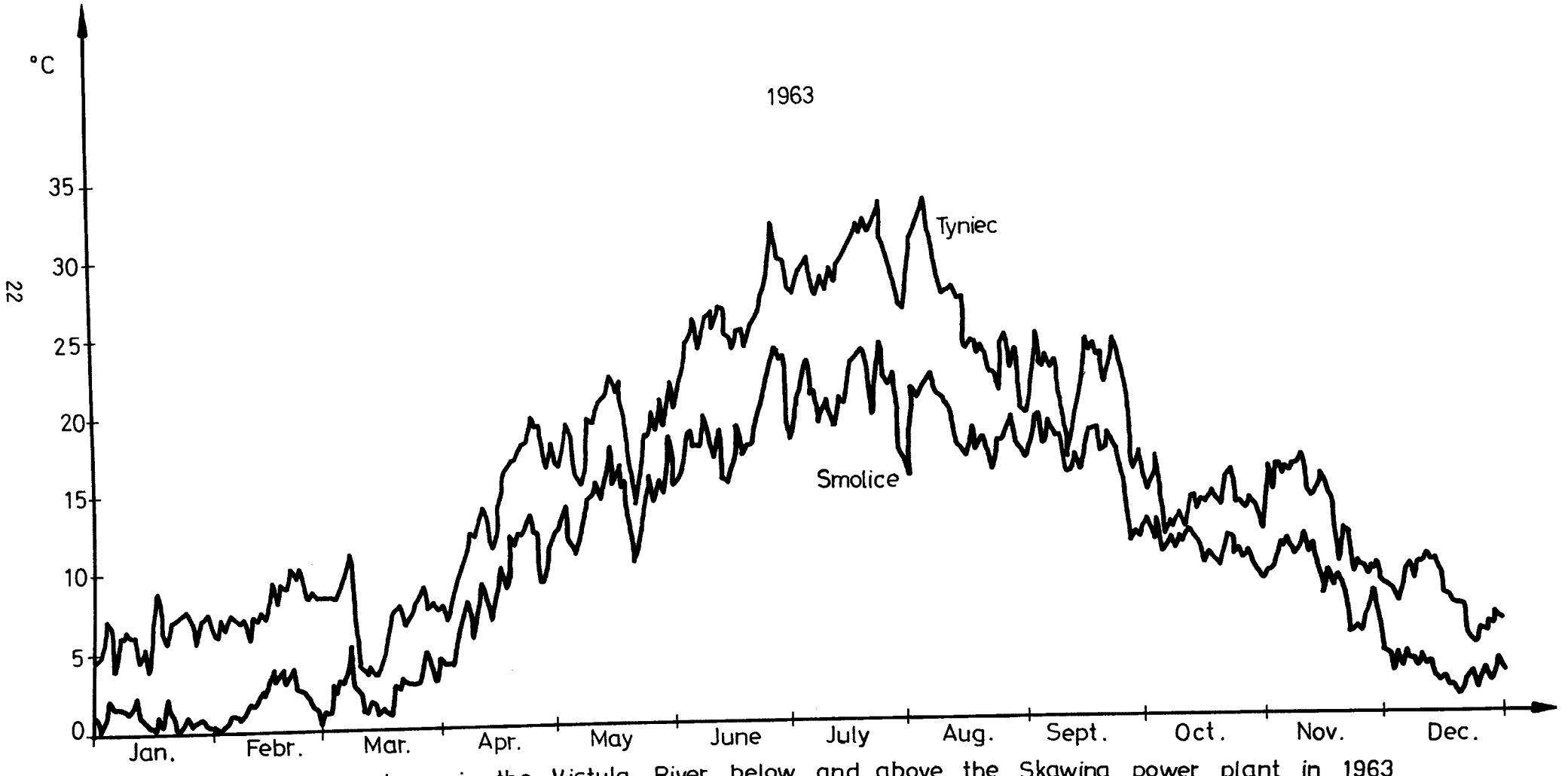


Fig. 2.2. Daily temperatures in the Vistula River below and above the Skawina power plant in 1963

TABLE 2.2. MONTHLY AVERAGE TEMPERATURE INCREASES IN THE VISTULA DOWNSTREAM FROM THE SKAWINA POWER PLANT, °C

Year	Months											
	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.
1961	2.36	1.78	3.06	1.65	1.58	1.74	2.78	2.16	3.36	1.79	5.57	4.81
1962	3.95	2.20	2.85	2.01	1.22	0.62	0.79	0.69	1.78	4.22	4.67	4.67
1963	3.45	3.46	4.63	5.06	1.04	1.47	1.46	2.55	4.65	4.92	2.47	1.20
1964	2.69	4.70	7.23	3.99	1.60	1.14	3.30	2.96	2.21	3.69	4.91	4.05
1965	1.98	2.46	2.89	2.98	1.01	1.48	1.19	0.73	1.52	2.02	3.17	3.58
1966	3.76	2.39	3.24	0.96	1.59	1.62	1.88	1.09	0.87	1.15	2.99	4.13
1967	3.28	2.11	3.15	1.19	1.10	1.59	1.99	1.47	3.46	3.64	3.28	3.98
1968	5.40	2.81	2.12	1.79	1.77	1.87	3.12	0.99	1.33	1.00	2.22	2.29
1969	3.25	4.29	4.68	2.46	2.49	1.84	3.42	2.45	1.50	2.30	3.84	4.56
1970	4.10	4.90	3.57	3.07	1.70	1.63	2.98	2.40	0.70	1.22	3.19	2.34
1971	1.93	2.16	2.20	1.93	1.41	2.23	2.28	2.16	1.61	4.72	3.84	3.87
1972	3.88	1.44	4.70	2.91	3.99	1.98	1.71	3.18	1.92	0.66	1.70	2.27
1973	3.03	2.94	4.05	1.71	1.31	1.70	2.54	3.08	1.83	2.44	3.69	3.63
max	5.40	4.90	7.23	5.06	3.99	2.23	3.42	3.18	4.65	4.92	5.57	4.81
ave.	3.31	2.90	3.72	2.44	1.68	1.61	2.07	1.99	2.06	2.60	3.50	3.49

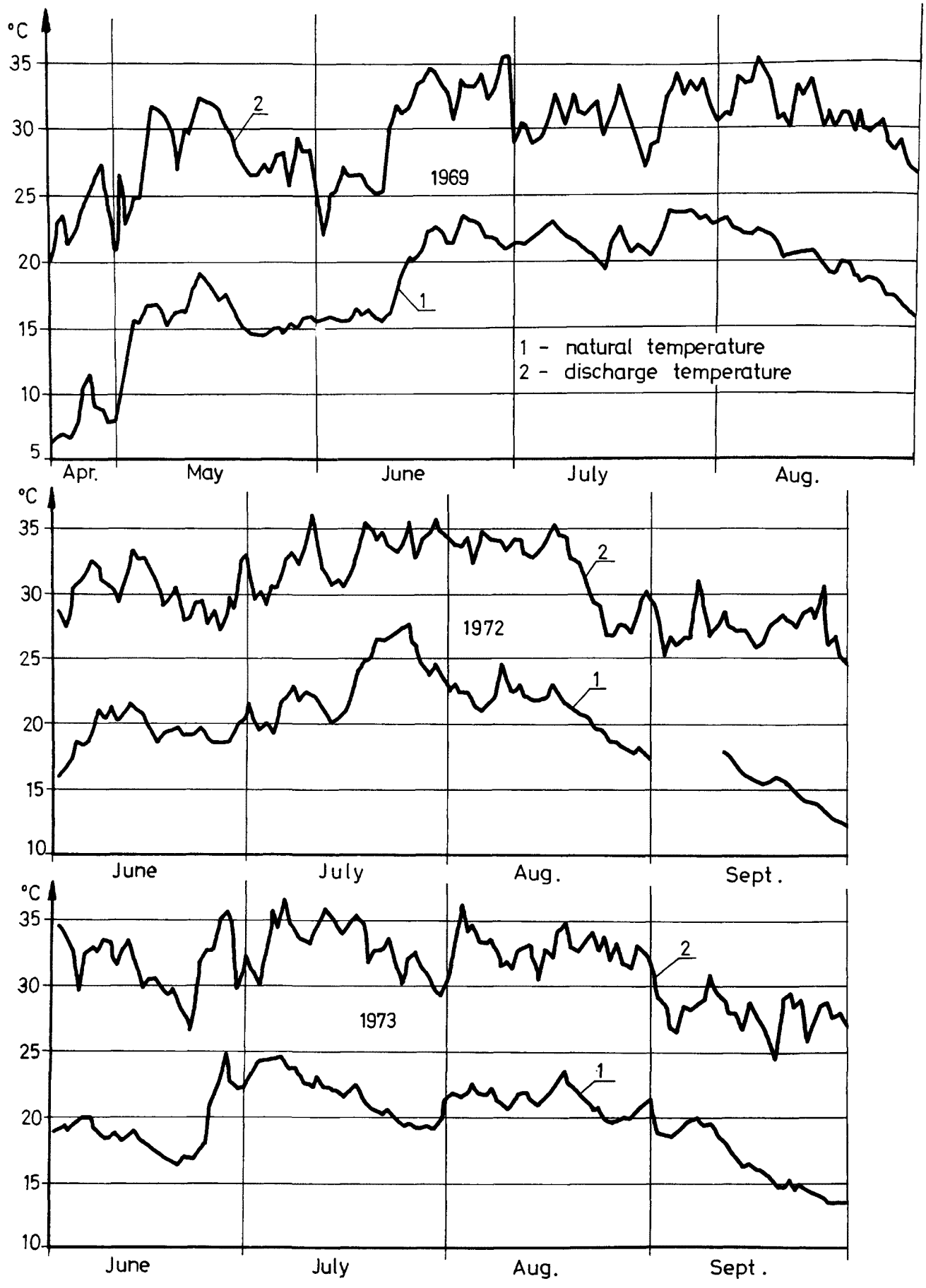


Fig. 2.3. Daily temperature changes in the cooling system in the Pątnów power plant

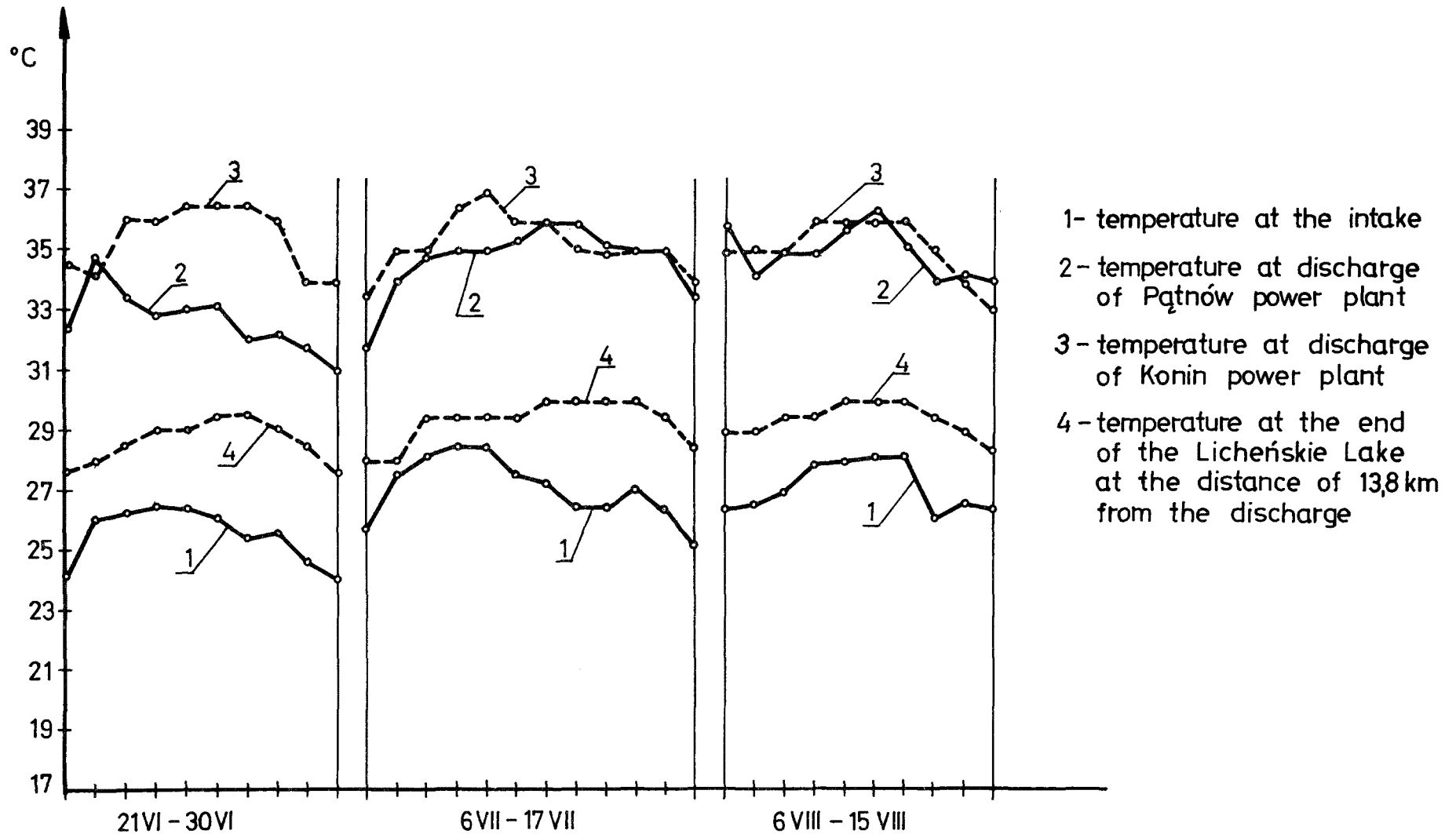


Fig. 2.4. Temperatures in cooling system of the Konin and Pątnów steam power plants in summer 1975

2.2.2 French Power Plants

Maximum discharge temperatures from French power plants are at the level of 30 to 35°C. Such temperatures were maintained for nearly 4 months during 1973 in the discharge of the Montreau Power Plant, and in July 1972 in the discharge of La Maxe Power Plant. The highest discharge temperatures occur downstream from the Blenod Power Plant. In summer they exceed 40°C, sometimes reaching 43°C. Average daily temperature increases in the La Moselle River downstream average about 10°C.

Downstream from other power plants, the maximum 24-hour temperature increase is smaller, and according to Chauveau (1972) amounts to:

Marne River downstream from the Vaires Power Plant in - 1964- 3.2°C
1967- 5.8°C
1971- 8.1°C

Oise River downstream form the Beautor Power Plant in - 1965- 8.9°C
1967-11.5°C
1971- 9.8°C

Oise River downstream from the Creil Power Plant in - 1964- 5.3°C

Gave du Pou River downstream from the Artix Power Plant in - 1971- 4.8°C

Loire River downstream from the Saint Laurent des Eaux Power Plant in - 1971- 4.8°C

Maximum monthly temperature increases for a number of French power plants are presented in Table 2.3.

The maximum monthly temperature increases below French power plants range from 3.0 to 10.0°C:

- temperature increases of 3.0 to 4.0°C occur from January to June,
- temperature increases of 4.5 to 5.5°C occur in July, August, November and December,
- temperature increases of 9.0 to 10.0°C occur in autumn months (September and October) when minimal flows appear in French rivers.

2.2.3 Other European Countries

Research carried out in Czechoslovakia (Kocakova 1976, Nauczno-Issliedovatelskij Institut Vodnogo Chozjaistva, 1976) showed significant temperature increases in the Morava River below the Godonin Power Plant and in the Oslava River below the Oslaviany Power Plant.

Mean temperature increases in the Morava were from 1.6 to 4.8°C in 1972 and in 1973, from 0.6 to 9.9°C. For the Oslaviany Power Plant water temperatures in the discharge channel were:

TABLE 2.3. MONTHLY AVERAGE MAXIMUM TEMPERATURE INCREASES AT FRENCH POWER PLANTS, °C

Power Plant	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Years
Saint-Ouen	1.49	1.38	1.28	0.71	0.93	0.58	0.88	1.44	1.63	2.00	2.01	1.91	1964-1973
Champagne sur Oise	3.35	2.88	2.44	1.19	1.85	2.20	1.45	1.92	3.31	3.39	3.97	3.72	1964-1973
Porcheville	2.11	1.70	1.32	0.60	0.92	1.33	0.83	1.43	2.10	3.04	3.10	2.57	1964-1973
Gennevilliers	1.71	1.33	1.21	0.60	0.60	0.51	0.60	0.70	1.41	2.10	2.32	2.24	1964-1973
Creil	2.1	2.0	1.9	1.6	1.4	1.2	1.3	2.5	3.8	3.9	4.6	3.8	1964-1973
Vaire sur Marne	3.50	2.50	3.65	1.23	1.80	2.40	1.65	2.10	3.40	3.90	5.86	7.04	1964-1973
Vitry	4.7	4.5	3.6	1.9	2.5	2.5	2.6	2.9	3.5	2.6	4.0	4.9	1964-1973
Saint Laurent des Eaux	4.3	2.1	1.5	1.0	1.3	1.6	2.2	2.3	3.0	2.5	5.1	3.4	1969, 1972 1973
Montereau	3.6	0.6	3.3	1.7	1.7	3.0	1.8	2.4	4.7	4.5	4.8	2.5	1971, 1972 1973
La Maxe	4.2	4.0	3.8	3.5	3.6	3.4	3.1	2.3	3.2	3.1	3.9	3.2	1972, 1973
Blenod	5.5	4.6	2.7	2.5	3.7	2.8	2.7	1.6	2.6	2.9	9.1	9.8	1971
Maximum	5.5	4.6	3.8	3.5	3.7	3.4	3.1	2.9	4.7	4.5	9.1	9.8	

Year	Temperature in the Discharge Channel	Summer Temperatures in the River 0.5 km Below the Discharge
1972	from 14.6 to 34.2°C	-
1973	from 18.5 to 36.8°C	33°C
1974	from 18.0 to 38.5°C	30 to 31°C

Temperature increases in the Neckar River in West Germany (Flinspach 1973), occur during critical conditions and amount to:

4.6°C - below the Altbach Power Plant
3.8°C - below the Marbach Power Plant
6.6°C - below the Heilbronn Power Plant
4.4°C - below the Obringheim Power Plant

2.3. Legal Limitations of Temperature for Open Cycle Cooling of Steam Power Plants.

An analysis of legal regulations indicates two different tendencies in the field of thermal limitations for open cycle cooling of steam power plants. One, there is a tendency to strengthen the limitations in a number of countries; yet permits issued for particular power plants often require deviations from these limitations.

In the regulations of different countries and in permits issued for specific plants, significant divergence concerning the reference point of admissible temperatures is found. For example, the following points are used in various regulations:

- in the discharge channel
- at the end of discharge channel
- in the thermal plume at some specified distance from the discharge point
- mean temperature in the river below discharge

Thermal standards of some European countries are presented for comparison in Table 2.4, and the required temperatures for Polish power plants are presented in Table 2.5.

The problem of thermal standards is the subject of long-term research in Comecon countries. In 1972 a plenary meeting of the Directors of Water Management of the Comecon countries took place in Warsaw during which a recommendation was approved to allow a 5°C increase in mixed river temperature over the temperature of the intake water. This recommendation was accepted by Polish, Czechoslovakian and Hungarian delegations. However, additional recommendations were included (SEV 1976):

- below the discharge, maintaining a zone of cold water one third the river's width,

TABLE 2.4. THERMAL STANDARDS IN SOME EUROPEAN COUNTRIES

Country	Temperature in the Discharge Channel	Temperature Downstream from the Discharge	Permissible Temperature Increment Downstream from Discharge
Poland		22°C or 26°C depending on the stream classification	If natural temperature exceed the temperature limits, a 2°C ΔT is allowed
Czechoslovakia			5°
Holland		32 - 37°C	
West Germany	30 - 33°C	28°C	3 - 5°C
Switzerland	30°C	25°C	
Hungary		30°C	
U.S.S.R.		For regions with cold water fish - 20°C in the summer and 5°C in the winter. For all other regions - 28°C in the summer and 8°C in the winter	

TABLE 2.5. PERMISSIBLE TEMPERATURE DECREASES AT POLISH POWER PLANTS

Power Plant	Receiving Stream	Class of Receiving Stream	Permissible Temperature in the Discharge Channel	Permissible Temperature in the Receiving Stream
1	2	3	4	5
Zeran Steam Power Plant	Vistula	I	35°C	not described
Siekierki Steam Power Plant	Vistula	I	35°C	Permissible temperature increase in the discharge, 10°C Temperature increment in the river downstream from the discharge, 2°C
Ostrokeka Power Plant	Narew	II	32°C	1 km downstream from the discharge after complete mixing, 28°C
Rybnik Power Plant	Reservoir on the Ruda River	unclassified	34°C	not described
Kozienice	Vistula	I	34°C	1 km downstream from the discharge after complete mixing: - at natural temperatures less than 26°C - permissible temperature, 26°C. - at natural temperatures greater than 26°C, permissible temperature increase is 2°C, but temperature must be lower than 29.6°C.

continued ...

Table 2.5 (cont.)

1	2	3	4	5
Stalowa Wola Power Plant	San	I	For river flow less than 30 m^3/s, 38.5°C For higher river flows, limitations are not described.	(not described)
Patnow and Konin Power Plants	Konin Lakes complex	I	34°C	In the northern part of Lichenskie Lake (13.8 km from the discharge) during the summer - 30°C for 80 hours - 33°C for 20 hours
Skawina Power Plant	Skawina River	I	Allowable	In the Skawinka River, 100 m downstream discharge, 30°C. In the Vistula River, 4 km downstream from the Skawina mouth, 26°C. In the Vistula River, 10 km downstream from the Skawina mouth, 22°C. Temperature increase after mixing in the Vistula, 6°C.

- limiting the temperature of water in lakes to 28°C (without specifying how to measure or define the limitation),

In France, three options are used to limit discharge water temperatures from power plants:

a. a temperature of 30°C at the discharge channel below power plant,

b. a temperature of 30°C related to the thermal plume in the cross-section specified in agreements with water management authorities,

c. a mean temperature of 30°C in the cross-section of the river below the discharge point.

The decisions and specifications regarding the selection of which option is used is made by regional water resources managers considering both river flow and biological quality.

In relation to existing French power plants, it is pointed out that in the Paris region, recognized as a protective zone, the interpretation presented in option "a" is obligatory. It applies to Champagne sur Oise, Porcheville, Vitry sur Sein and other power plants. In other regions, the interpretation is different, e.g. in the case of the La Maxe Power Plant, the mean temperature from four measuring points in the discharge from a preliminary cooling reservoir is the reference temperature. An interesting way to meet an imposed temperature limitation is found at Porcheville, where an additional quantity of water is pumped into the channel directly from the river. This "solution" allows an increase in the output of the plant. While appearing to meet the legal conditions of option "a", this method corresponds more closely to option "c" (Gadkowski, Tichenor, 1976).

In West Germany, the temperature limits are related to receiving water dissolved oxygen concentration. Use of combined cooling systems which provide aeration (e.g., sprays, cooling towers) allows higher discharge temperatures. An economic analysis has been carried out that indicates the advisability of modifying the present German standards. The new proposals are:

- admissible temperature rises in condensers of 15°C,

- admissible temperatures in the discharge channel of 35°C,

- admissible increase of river water temperature of 5°C.

The enforcement of these standards will be combined with simultaneous construction of water aeration equipment in power plants. The new standards have been temporarily accepted by the German water authorities and are under review for permanent approval.

In reviewing the above discussion of thermal regulations, it is emphasized that governmental entities often modify regulations; thus, the specific citations above may not be applicable at this date.

2.4. Impact of Heated Water on the Oxygen Balance in Receiving Water

Investigations of oxygen balance in water used for cooling purposes (Goubet 1967, Hawes 1970, Jensen 1974, Khalanski 1973, Dojlido 1976, Kiriak 1976, SEV 1976) show that when oxygen content in the intake water is high, there is a significant drop of oxygen content after the water passes through the cooling cycle of a power plant. In the case of low oxygen content in the intake water, it is enriched in oxygen after passing through the cooling cycle. Figure 2.5 illustrates this phenomenon. On the basis of published results, a regression equation was developed which relates change in oxygen concentration to intake oxygen concentration:

$$\Delta O_2 = A \sigma + B \qquad (2.1)$$

where:

ΔO_2 = change in oxygen content (mg O_2/dcm^3),

A and B = coefficients of regression equation,

σ = intake oxygen content or saturation

The coefficients for the above equation are presented in Table 2.6.

2.5. Impact of Heated Water on Fishes

Lethal temperatures have been determined for some cyprinides species existing in Poland (Table 2.7) (Horoszewicz 1976).

Comparisons show that under extreme river temperatures, critical conditions for fish may occur. In particular, this refers to power plant discharge channels and mixing zones. Practice shows, however, that if such zones don't cover the whole river cross-section, they are avoided by adult fish. To minimize the negative impact of extreme temperatures on fish, river water temperatures should not exceed 30°C and temperatures in discharge channels should not exceed 35°C.

2.6 Proposals for Permissible Temperatures

Permissible temperatures at three different reference points are proposed:

a. permissible discharge water temperature, 35°C

b. permissible temperatures downstream from the discharge, 30°C

c. Permissible temperature increment above the intake water temperature (natural):

   4°C in summer (June, July, August)
   5°C in September
   6°C during the rest of the year.

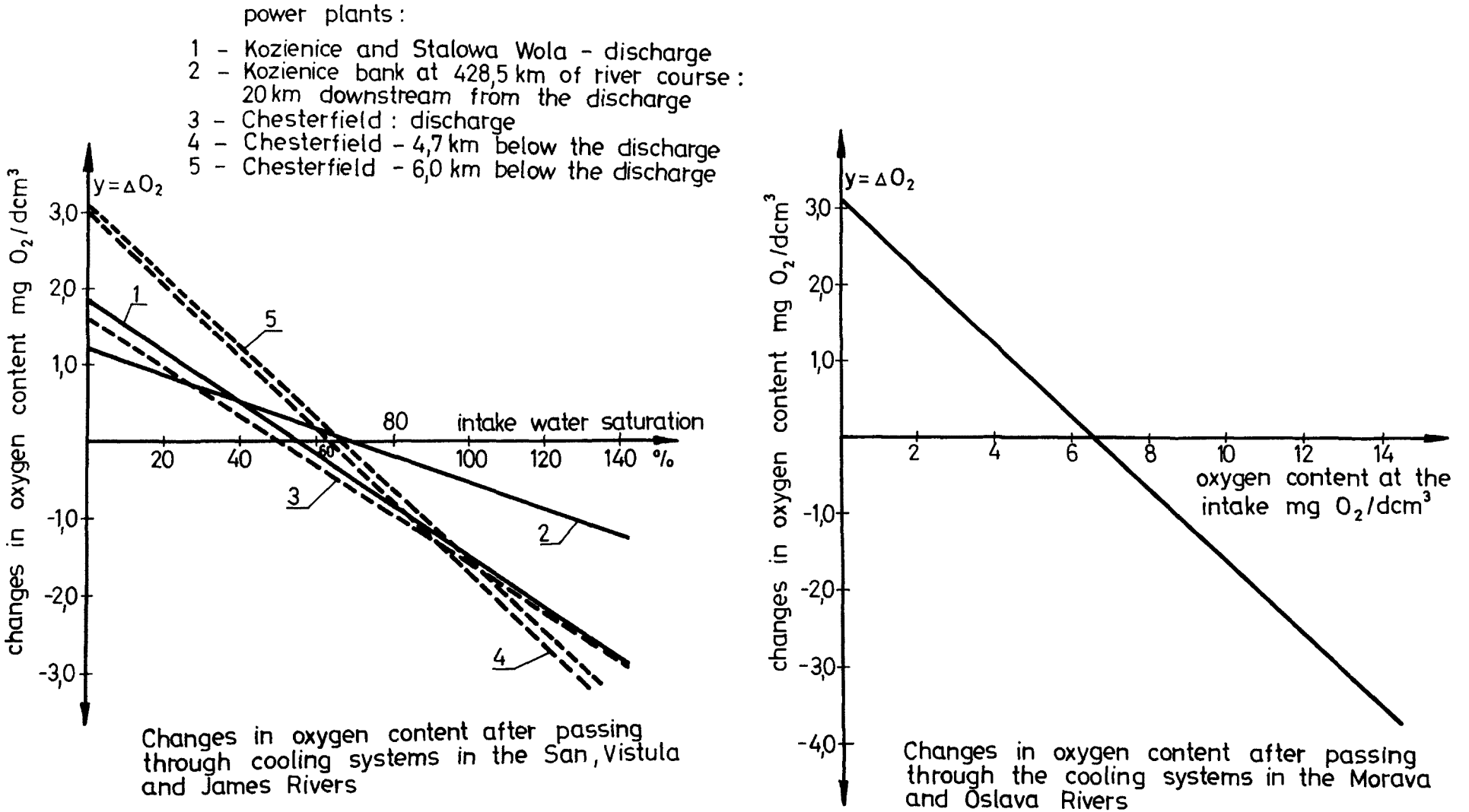


Fig. 2.5. Changes in oxygen content after passing through the cooling systems of steam power plants

TABLE 2.6. A, B, AND σ AT SELECTED LOCATIONS

No.	Place of Investigation	Reference Point	B	A	R (Correlation Coefficient)	σ	Number of Samples
1.	Discharge channel of the Kozienice and Stalowa Wola Power Plants	oxygen saturation, in %	1.837	-0.034	-0.504	0.879	51
2.	The left bank of Vistula River 2 km downstream from the discharge of the Kozienice Power Plant	"	1.260	-0.018	-0.539	0.483	35
3.	The Chesterfield Power Plant - discharge channel	"	1.623	-0.0323	-0.835	0.558	23
4.	The Chesterfield Power Plant 4.7 km downstream from the discharge	"	2.996	-0.0473	-0.798	0.960	117
5.	The Chesterfield Power Plant 60 km from the discharge	"	3.138	-0.0476	-0.788	0.931	87
6.	The Morava and Oslava Rivers	oxygen content, in mg/dem^3	3.122	-0.474	-0.863	0.839	62

TABLE 2.7. THE LETHAL TEMPERATURES OF CYPRINIDES, °C

Fish Species	Months					
	March	April	May	June	July	August
Abramis abrama		27.5 -28.5	30	31-33	33-34	31
Gobio-gobio		28	28.5			
Tinca tinca		31	32-34	33	34	
Scardinius erythrophthalmus		32	33			
Leuciscus cephalus				34	34	
Alburnus alburnus				33		
Leuciscus idus	27	28	28	29		
Gasterosteus aculeatus					29	
Rhodeus sericeus				31-32		
Carassius carassius						34-36
Carassius auratus gibelic	30	32	34	36	38-41	
Cyprinus carpio		26		36		
Ictalurus nebulosus		30-33	34		35-37	
Micropterus salmonides			28	32	34	33
Esox lucius				32-33		
Acerina cernua		28	31	34		
Perca fluviatilis	28	29	32	31	32	
Lucioperca lucroperca			29		34	34

3. Variability of Steam Power Plant Load

3.1. Introduction

Previous investigations (Dobrzanska 1963, Kopecki 1958, Kwiatkowski 1969) showed that electrical system load has a natural character. Important factors are climatic conditions, geographical situation, economic development of the country, and other factors. It is possible to identify distinct daily, weekly, and yearly cyclic changes in electrical system operations which seriously impact the load cycles of particular power plants.

The correlation between system load changes and power plant load changes depends on several energy system characteristics:

- variability of power demand during day, week, and year,
- mix of power in electrical systems (hydropower plants, pumped storage plants, gas turbine, fossil and nuclear steam power plants),
- regulation of operating schedules for hydro, pumped storage, gas turbine and steam power plants, utilizing both base and peaking load facilities,
- economic load distribution between different power plants, operating in a connected electrical system.

Taking into account the above dynamics and complexity of electrical system operation, emphasis was placed on analyzing plant operation on the basis of electrical system data. The analysis is supported by existing steam power plant production data.

The main aim of the analysis was to determine the average monthly coefficients of installed capacity utilization in power plants, depending on the expected time of their operation during the year. In these investigations, attention was also given to the relationship between power plant operating time, cooling system operating time, and daily load changes.

3.2. Daily Load Changes

To establish daily load changes of a steam power plant complex, an analysis was conducted on data from 11 power plants operating in the summers of 1972, 1973 and 1974.

Data were analyzed separately for two groups of power plants:

- all power plants operating with open cycle cooling systems,

- 6 large power plants operating with open cycle cooling systems.

Average load was described for holidays, days before and after holidays, and other working days. The range of changes in both groups of power plants was the same. For example, in Table 3.1, results of daily load changes in the second group of power plants are presented. The results obtained show that the load before and after holidays of this group of power plants is at the level of the average monthly load.

TABLE 3.1. DAILY LOAD CHANGES IN LARGE* POLISH STEAM POWER PLANTS WITH OPEN COOLING SYSTEMS (%).

Year	Month	Typical Working Day	Days Before and After Holidays	Holidays
1972	June	104	96	89
	July	116	82	80
	August	100	99	97
1973	June	101	97	85
	July	110	98	86
	August	107	99	92
1974	June	101	102	91
	July	105	99	89
	August	105	99	84
	Average	106	97	88

100% - Average monthly load

* including - Patnow - 1400 MW
Konin - 600 MW
Rybnik - 800 MW
Kozienice - 1600 MW
Stalowa Wola - 450 MW
Ostroleka - 600 MW

On typical working days it is 5 to 10% higher and during holidays it drops 10 to 15%. Larger load changes can occur in single power plants.

To characterize load changes for a single power plant, a plant of 550 MW capacity and 7,000 h operation time in the year was analyzed. Average monthly coefficients of power utilization (load factor) at the Skawina Power Plant were:

Month	1972	1973	1974
June	0.79	0.73	0.70
July	0.77	0.66	0.76
August	0.73	0.65	0.79

Additional data for the Skawina Plant are presented in Table 3.2 and Figure 3.1. These results show that daily load changes can be quite severe.

3.3. Steam Power Plant Operating Time

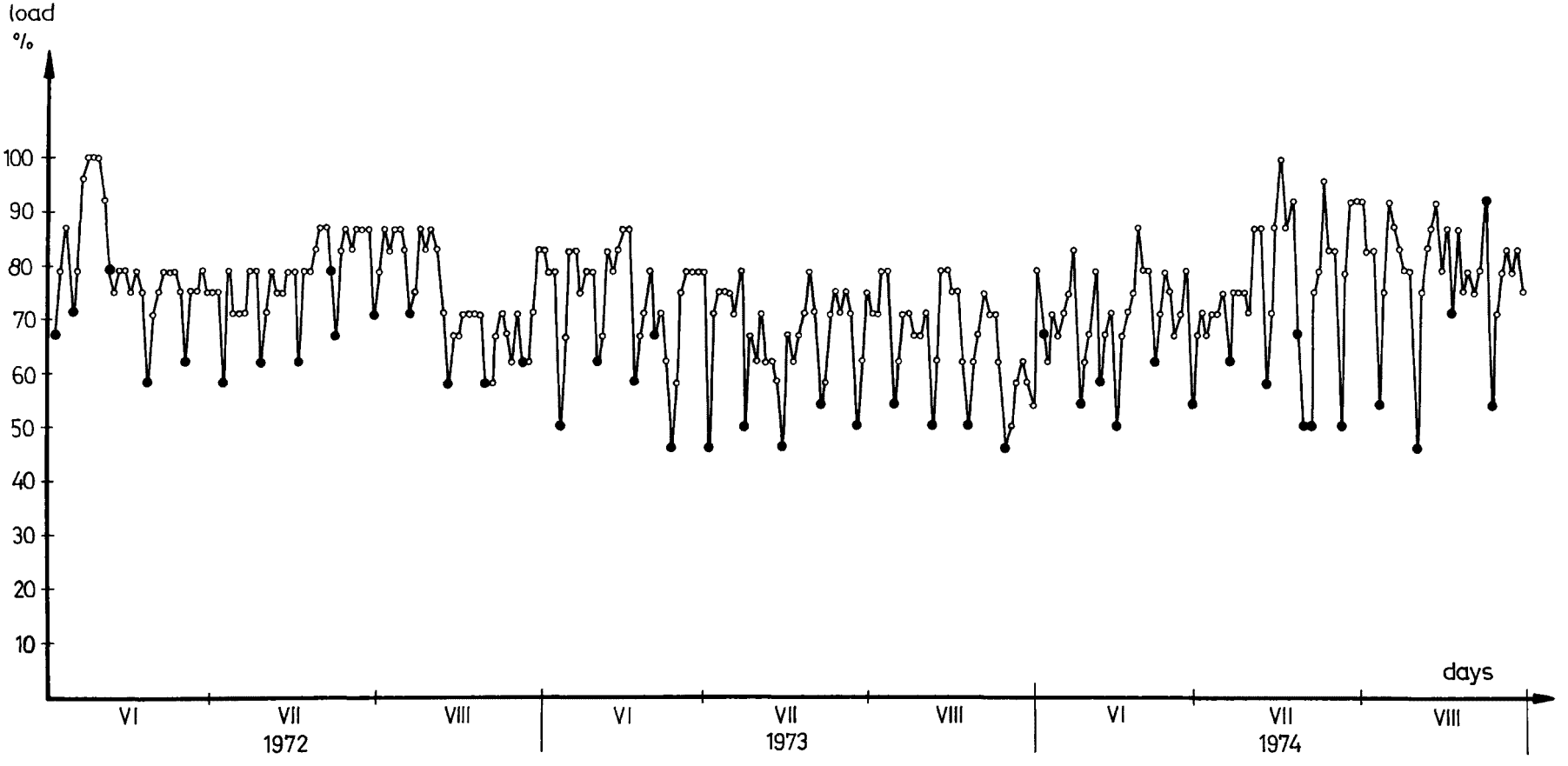
As shown in UNIPDE (Union Internationale des Production et Distributours d'Energie Electrique) papers and other references concerning load changes of electrical systems in countries situated in the middle latitudes, asymmetrical load distributions caused by geographical location appear during the year. For such load distributions, system load in corresponding months in the first and second half-years will be equal. Actually, a constant energy demand increment means that during the second half-year a higher demand is observed than in the first half-year. This increment is nearly constant and the mean for all world electrical systems is 7.2%. In Polish electrical systems, some load deformation is observed. It is caused by increased electric energy utilization for heating and other purposes, so the system load is higher in the first half-year. Comparing this trend to open cooling cycle operation, this corresponds with the period of increased water resources in the rivers.

Other factors which are not considered here may have significant impact on load distribution throughout a year. Electrical system load changes require high elasticity in electric energy production, thus quite a large part of the installed capacity in electrical systems is not utilized over an annual cycle. There is a rule in electric power system organizations that the total installed capacity in the system depends on the maximum peak load plus some reasonable reserve capacity (15-25%).

As a characteristic indicator of steam power plant operation, the annual full load operation time was used. The annual full load operation time equals the annual load factor times 8,760 hours per year. This indicator is provided to indicate yearly electric power production. Full load operation times of base load steam power plants in different countries are presented in Tables 3.3 and 3.4 (Zarzycki 1976).

Taking into account full load operation times of fossil fueled power plants, it is possible to divide them into three groups:

Annual Full Load Operation Time	Group of countries
4,000 to 5,000 hours	Czechoslovakia, Belgium Spain, West Germany, USA.
5,000 hours	Poland, USSR
5,500 to 6,000 hours	Rumania, East Germany



• Sundays and holidays

Fig. 3.1. Daily load in power plant of yearly operation time T = 7000 hours

TABLE 3.2. FREQUENCY OF MAXIMUM DAILY LOAD IN A POWER PLANT WITH T = 7000 h OPERATION TIME

Daily Load %	1972			1973			1974			Sum of cases	
	June	July	August	June	July	August	June	July	August	Number	%
100	3							1		4	1.4
96	1							1		2	2.1
92	1							3	4	8	5.0
87	1	6	5	2			1	4	3	22	13.0
83		2	6	4			1		6	19	19.9

TABLE 3.3. TIME OF FULL LOAD INSTALLED CAPACITY IN SOME COUNTRIES (HOURS)

Country	Years				
	1967	1968	1969	1970	1971
	Conventional Power Plants				
Poland	5005	5164	5037	5025	4780
Czechoslovakia	4221	4377	4627	4446	
East Germany	5605	5937	5897	5638	
Romania	5613	5884	5540	5485	
U.S.S.R.	5226	5116	5098	4965	
Belgium	3741	3997	4383	4620	4608
France	4410	3948	4279	4060	4531
Spain	4027	4052	3419	4127	
West Germany	4067	4464	4888	4793	
U.S.A.	4514	4629	4673	-	
	Nuclear Power Plants				
East Germany	4657	5600	6071	6014	
U.S.S.R.	1622	2092	5442	-	
England (CEGB)	6220	6323	6023		
France	3938	3510	3245	3730	4455
Spain	3376	5110	5571		
West Germany	3651	2004	5314	5843	

TABLE 3.4. EXPECTED TIME OF FULL LOAD INSTALLED CAPACITY FOR NUCLEAR POWER PLANTS IN SOME COUNTRIES (HOURS)

Country	Years				
	1980	1985	1990	1995	2000
Bulgaria	5500	6000	7125	6917	6842
Hungary	6818	6914	6959	7000	7000
West Germany	7000	6666	6333	6000	6000
Czechoslovakia	7058	7037	7016	6818	6479
Yugoslavia	5583	5555	6071	6417	6364
Austria	6500	5900	5400	-	-
Belgium	7000	6800	6600	-	-
Denmark	7080	7070	6460	-	-
West Germany	5275	-	5300	-	-
Switzerland	7037	6889	6923	6333	5917
Sweden	6570	6440	5600	5625	5580
Canada	4872	-	6242	6230	6250
Japan	6963	6916	6910	6470	6895
India	7242	7407	7456	7466	7483
Australia	6000	6000	6000	-	4868

Table 3.4 provides projected full load operating time data for nuclear power plants up to the year 2000. In many countries it is expected that in the future, nuclear plant full load operating time will be prolonged up to 7,000 hours. The problem of power systems operating time for conventional and nuclear power plants should be considered separately. For example, referring to Table 3.4, the high power plant full load operating time in India is caused by the expected constant energy utilization for irrigation purposes. Similarly high values in Switzerland are caused by the electric power system structure which includes substantial hydropower. To cover basic energy demands, Switzerland is building nuclear power plants instead of fossil-fueled plants.

Data on Polish power plants indicate that the full load time also depends upon the type of cooling system used (Table 3.5). These results show that in the Polish electrical system power plants operating with open cooling systems have higher load factors than those operating with closed cooling systems. The Polish Board of Energetics has predicted full load operating times for various sized units through 1990 (Table 3.6).

3.4 Monthly Coefficients of Installed Capacity Utilization

In previous investigations of open cycle cooling systems, the distribution of monthly power plant utilization has been inadequately treated. Problems of monthly production are acknowledged as important, and in this report they are analyzed using different calculation methods such as:

a. statistical analysis of production changes,
b. repairs schedule,
c. cosine model,
d. BETA distribution model.

3.4.1. Statistical Analysis of Production Changes

The statistical analysis of production changes was carried out by the Polish Energetic Board (Zarzycki 1976). It was established that a reasonable period for characterizing operating conditions of large steam power plants was the period after 1967; thus, the statistical data from 1967-1973 were used. Results of the analysis are presented in Table 3.7 and Figure 3.2. Differences between average, maximum and minimum values are not large (Figure 3.2), and the range of these differences is nearly constant during the whole year. In addition, the Energetic Board conducted analyses which showed that monthly coefficients of capacity utilization will be at the present level up to 1980 and will drop slightly thereafter (Table 3.8).

3.4.2. Repairs Schedule

The analysis of power plant unit repair schedules allows the evaluation of power production during the year and the possibility of shifting part of the load of power plants operating with open cooling systems to power plants operating with closed cooling systems. Polish power plants are down for repair an average of 7.4% of the time.

TABLE 3.5. TIME OF FULL LOAD CAPACITY IN POLISH POWER PLANTS, UNITS OF 120 AND 200 MW (hours).

Year	Power Plant With Open Cooling System	Power Plant With Closed Cooling System	Average for both Groups
1964	4,467	5,258	5,150
1965	5,438	5,468	5,453
1966	5,666	5,488	5,517
1967	5,694	5,599	5,617
1968	6,531	5,291	5,610
1969	6,248	5,486	5,726
1970	6,160	5,287	5,565
1971	5,816	5,365	5,492
1972	5,955	5,775	5,884
1973	5,926	6,070	6,016
Average	6,050	5,553	5,692

TABLE 3.6. EXPECTED TIME OF FULL LOAD INSTALLED CAPACITY FOR POLISH POWER PLANTS IN 1980, 1985, AND 1990.

Size of Unit	Year	Cooling System		Average for Both Groups
		Open	Closed	
120-200 MW	1980	6,000	5,500	5,760
	1985	5,830	5,350	5,606
	1990	5,340	4,900	5,135
360-500 MW	1980	-	4,900	4,900
	1985	5,800	5,200	5,314
	1990	6,100	5,600	5,657
Nuclear Units 440-500 MW	1980	-	-	-
	1985	5,400	-	5,400
	1990	6,100	5,600	6,000
Total	1980	6,000	5,388	5,675
	1985	5,799	5,269	5,487
	1990	5,688	5,387	5,505

TABLE 3.7. INSTALLED CAPACITY UTILIZATION COEFFICIENTS FOR LARGE POWER PLANTS, 1967-1973 (%)

Months	Power Plants With Open Cooling Systems		Power Plants With Closed Cooling Systems		Average for Both Groups	
	Average	Minimum* / Maximum	Average	Minimum / Maximum	Average	Minimum / Maximum
January	71.5	63.7 / 74.4	69.2	63.5 / 76.6	70.0	64.1 / 74.1
February	71.5	55.6 / 79.5	68.4	61.7 / 73.4	69.6	64.2 / 73.6
March	71.7	63.1 / 79.3	65.8	60.0 / 72.3	67.6	63.9 / 72.8
April	67.7	60.8 / 78.3	61.5	57.9 / 65.1	62.9	59.5 / 65.0
May	69.6	60.3 / 86.6	60.0	57.1 / 64.1	62.2	59.0 / 64.9
June	69.0	62.9 / 78.6	55.9	45.4 / 62.9	59.5	51.5 / 63.1
July	59.9	53.7 / 66.1	54.4	47.0 / 61.5	55.7	51.6 / 60.3
August	57.2	51.9 / 68.5	57.1	51.0 / 64.7	57.2	54.1 / 62.7
September	69.0	66.8 / 72.5	60.4	51.1 / 67.3	63.0	57.5 / 69.1
October	72.4	59.8 / 79.8	66.5	61.9 / 70.9	68.4	65.0 / 73.3
November	73.3	59.7 / 83.8	70.2	62.2 / 76.5	71.1	63.3 / 75.6
December	75.1	70.4 / 86.0	70.4	69.8 / 75.4	71.7	68.8 / 74.7

* $\frac{\text{Minimum}}{\text{Maximum}} = \frac{\text{minimum monthly value}}{\text{maximum monthly value}}$

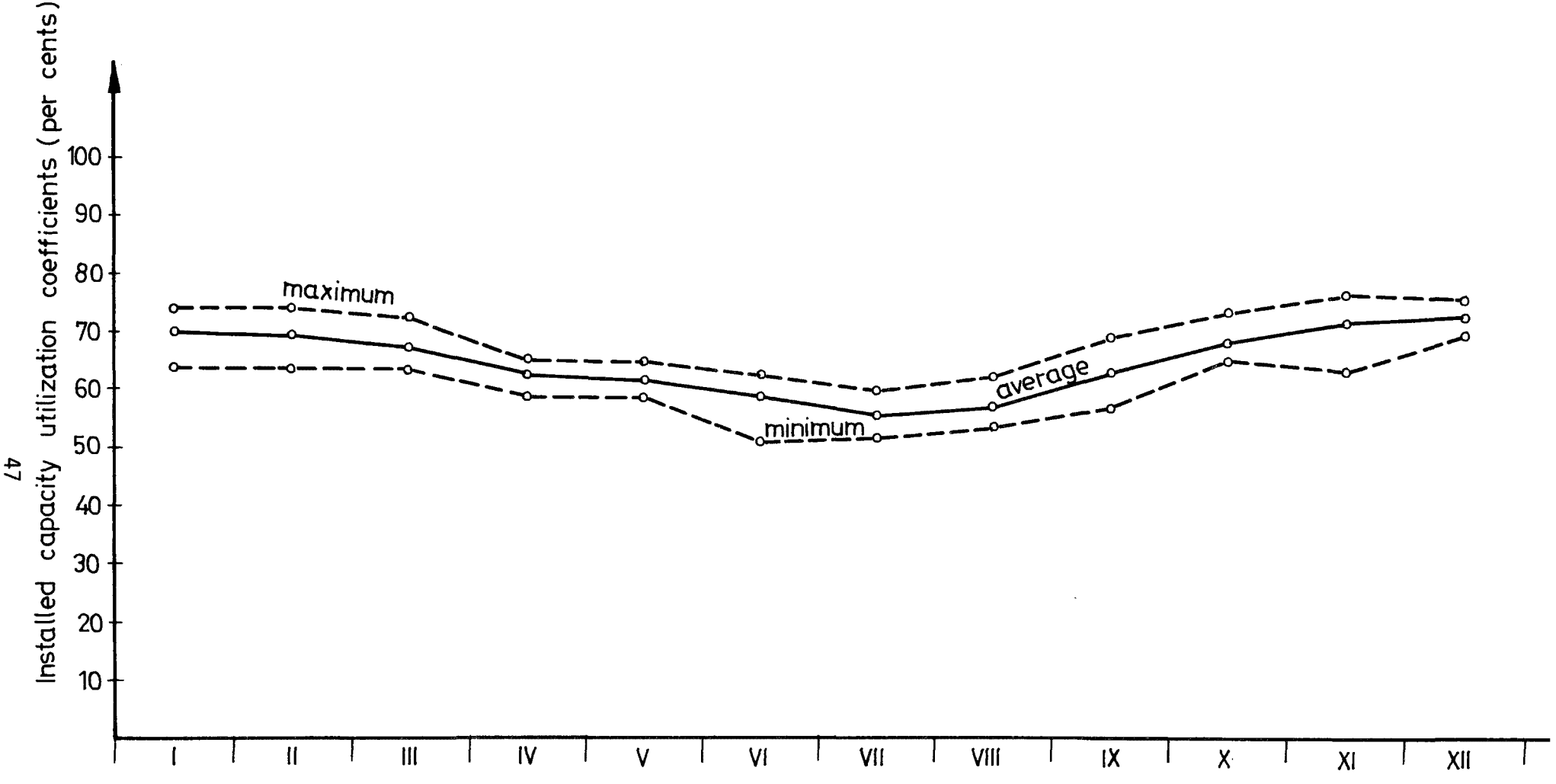


Fig. 3.2. Average real coefficients of installed capacity utilization in Polish multiunit steam power plants in period 1967 – 1973

TABLE 3.8. EXPECTED INSTALLED CAPACITY UTILIZATION COEFFICIENTS FOR STEAM POWER PLANTS (%)

Month	Average For Period 1967-1973	1980	1985	1990
January	70.0	68.9	66.8	66.9
February	69.6	69.3	67.1	67.2
March	67.6	67.2	65.0	65.0
April	62.9	63.1	61.1	61.1
May	62.2	63.1	60.8	60.8
June	59.5	60.8	58.3	58.3
July	55.7	55.7	53.8	54.1
August	57.2	57.5	55.6	55.7
September	63.0	63.1	60.6	61.1
October	68.4	67.8	65.6	65.9
November	71.1	69.8	68.0	68.4
December	71.7	70.8	68.8	69.3

The Energetics Board investigated 3 variations of repair schedules of power plant units operating with open cooling systems:

- basic variation - presently existing repair schedule
- maximum variation - assumes all units are repaired within a 3 month period,
- optimum variation - assumes repairs on two units in one power plant can occur simultaneously.

The optimum variation takes into account the possibility of optimal organization of repair brigades and equipment necessary for repairs (cranes, repair fields, etc.). The optimum variation was designed to allow load shifting between two groups of power plants (with closed and open cooling systems) without additional investment inputs. Monthly indicators of capacity decreases due to repairs are presented in Table 3.9. These values show that by changing repair schedules it is possible to reduce, in the summer period, the mean load of power plants operating with open cooling system by about 5% of installed capacity (i.e., the difference between the basic and optimum variations).

3.4.3. Cosine Model

3.4.3.1. Analysis of Calculation Method

The cosine model analysis of steam power plant operations was conducted using data from 1958-1968. The air of the investigation was to describe the maximum monthly average coefficients of installed capacity utilization in power plants at an assumed probability of occurrence in relation to power plant operating time throughout the year.

TABLE 3.9. MONTHLY INDICATORS OF CAPACITY DECREASES DUE TO REPAIRS (%)

Month	Basic Variation	Maximum Variation	Optimum Variation	Disposable Capacity*
January	-	-	-	100
February	1.1	0.4	-	100
March	6.0	-	-	100
April	5.2	-	-	100
May	6.8	0.4	6.8	93.2
June	18.4	27.2	24.6	75.4
July	19.6	32.6	26.7	73.3
August	21.9	28.6	25.2	74.8
September	9.6	0.4	5.6	94.4
October	0.3	-	-	100
November	-	-	-	100
December	-	-	-	100

* assumes Optimum Variation

As the basis of the calculations, the following trigonometric function was used, which describes the monthly average coefficient of power utlization:

$$g_{imax} = (f_i + \Delta f_i)\ (b + a \cos \alpha) \qquad (3.1)$$

where:

g_{imax} = monthly average maximum coefficient of installed capacity utilization in a steam power plant at the assumed probability of occurrence,

a = function of b, of the form, $a=xb + yb^2$, where x and y are constants,

b = yearly average coefficient of installed capacity utilization, where

$$b = \frac{T_o}{8{,}760} = 1.14\ T_o\ 10^{-4}\ (\%) \qquad (3.2)$$

T_o = annual full load operating time, hrs,

f_i = monthly average correction coefficient,

Δf_i = correction coefficient defining the relationship between the g_{imax} value and the assumed probability of excess,

α = angle designated by the function of month, i,

$$\alpha = (2i - 1) \frac{\pi}{12}$$

The base data included the installed capacity of specific power plants and the monthly gross production (MWh). At the same time, monthly average coefficients of installed capacity utilization in particular years and power plants were described. These coefficients were calculated using the formula:

$$g_i = \frac{A}{P_o h} 100 \qquad (3.3)$$

where:

g_i = monthly average coefficient of installed capacity utilization %.

A = monthly gross production, MWh.

P_o = installed capacity in a particular month, MW.

h = number of hours in the month.

Power plant operating time during the year depends on different factors such as breakdowns, planned and unplanned repairs, system load changes, etc.. Therefore, for each power plant, monthly average coefficients of capacity utilization for the whole period under investigation were calculated. These coefficients eliminate to a remarkable degree the details of power plant operation, while exhibiting the seasonal nature of their operation. To calculate these coefficients, only full years were considered, excluding the first year of operation, when operating rules are different than for established plants. Calculated coefficients were the basis for future calculations and analyes.

Coefficients of installed capacity utilization were computed using the assumed trigonometric model according to formula:

$$g_i' = b + a \cos \alpha \qquad (3.4)$$

The comparison of real and calculated values by equation 3.4 was done using the least squares method. At the given 12 monthly g_i values, the regression curve was defined by equation 3.4. Deviation of the calculated values g_i' from the actual values g_i is given by:

$$\Delta g_i = g_i - g_i' = g_i - b - a \cos \alpha \qquad (3.5)$$

$$\text{where, } a = \frac{\sum_{i-1}^{12} g_i \cos \alpha}{6} \qquad (3.6)$$

$$\text{and, } b = \frac{\sum_{i-1}^{12} g_i}{12} \tag{3.7}$$

a and b are defined as:

a = yearly oscillation amplitude,

b = sinusoid ordinate,

The next steps include the calculation of:

a) ordinate of points on regression curve using equation 3.4

b) sum of squares $(g_i - g_i')^2$ (3.8)

c) sum of squares $(g_i - \bar{g}_i)^2$ (3.9)

d) $$\bar{g}_i = \frac{\sum_{i-1}^{12} g_i}{12} \tag{3.10}$$

e) correlation indicator:

$$\rho = \sqrt{1 - \frac{\sum_{i=1}^{12} (g_i - g_i)^2}{\sum_{i=1}^{12} (g_i - g_{imax})^2}} \tag{3.11}$$

f) standard deviation of real monthly average g_i values from their calculated values g_i':

$$\delta = \sqrt{\frac{\sum_{i=1}^{12} (g_i - g_i)^2}{12}} \tag{3.12}$$

Differences between real coefficients g_i and coefficients g_i' are called deviation coefficients.

The magnitudes of deviation coefficients are:

± 1% from real values - 37.4% of cases investigated
± 2% from real values - 67.8% of cases investigated
± 3% from real values - 83.8% of cases investigated

The small deviations obtained in the analysis show that monthly average coefficients of installed capacity utilization for particular power plants are similar to those assumed in equation 3.4.

3.4.3.2. Amplitude of Yearly Changes of g_i Coefficients

Using values obtained from equations 3.6 and 3.7 by the least squares method, the correlation between function "a" and "b" was determined [a = f(b)]. As a result, the following quadratic equation was obtained:

$$a' = 0.134b - 0.0008\ b^2 \tag{3.13}$$

On the basis of the new values of "a" from equation 3.13, the capacity utilization coefficients were calculated again:

$$g_i'' = b + a' \cos \alpha \tag{3.14}$$

Further analysis refers to installed capacity utilization coefficients calculated on the basis of equation 3.14.

3.4.3.3. Designation of Correction Coefficient, f_i

Coefficient f_i is a correction of the assumed trigonometric model adopting it to actual power plant operations. Coefficient f_i equals the average f_i' individual coefficients designated separately for each month for the investigated power plants. Only the years when the power plant operated during a complete annual cycle were used. Individual correction coefficients f_i' were obtained from equation:

$$f_i' = \frac{g_i}{g_i''} = \frac{T_s}{T_r} \tag{3.15}$$

where:

g_i = monthly average real coefficient of installed capacity utilization (from the equation 3.3),

g_i'' - theoretical coefficient of capacity utilization (from equation 3.14),

T_s - yearly average of full load power plant capacity utilization time (h/year),

T_r - time of full load power plant utilization in the year under investigation (h/year).

Final values of f_i were calculated for particular months using equation:

$$f_i = \frac{\sum_{i=1}^{132} f_i'}{132} \qquad (3.16)$$

Values of f_i are given below:

Jan - .0990	May - 0.972	Sept - 1.012
Feb - 1.008	June - 1.003	Oct - 1.007
Mar - 1.005	July - 0.999	Nov - 1.013
Apr - 0.971	Aug - 1.011	Dec - 0.997

The calculated f_i coefficients are nearly all equal to 1, which confirms the conclusion that under average conditions the installed capacity utilization coefficients are similar to the assumed model presented by equation 3.14.

3.4.3.4. Designation of Δf_i Coefficient

The difference $f_i' - f_i$ is the Δf_i coefficient. Values of these differences, called f_i deviations, were investigated for 132 cases. To describe the probable values of Δf_i, it was assumed that deviations are random variables of the continuous type and normally distributed. Assuming the distribution is centralized around f_i values, the probability of deviations may be calculated from using a Gaussian (normal) distribution according to the following equation:

$$\Delta f_i = \sigma \; \Phi \left(\frac{\Delta f_i}{\sigma} \right)_p \qquad (3.17)$$

In equation 3.17, σ is the standard deviation and for particular months it is:

Jan - 0.119	May - 0.127	Sept - 0.095
Feb - 0.124	June - 0.139	Oct - 0.090
Mar - 0.109	July - 0.117	Nov - 0.094
Apr - 0.098	Aug - 0.113	Dec - 0.099

$\Phi \left(\frac{\Delta f_i}{\sigma} \right)$ = number of standard deviations from mean (f_i) such that ($f_i' + f_i$) will not be exceeded p % of the time.

Values of Δf_i for a given probability are presented in Table 3.10.

3.4.3.5. Analysis Summary

The analysis discussed above shows that the assumed trigonometric model of installed capacity utilization in steam power plants gives results similar to actual data.

Monthly average f_i coefficients are nearly equal to 1. The additional coefficient $g_{i\max}$ allows one to establish monthly average maximum coefficients of installed capacity utilization in steam power plants which will not be ex-

TABLE 3.10. VALUES OF Δf_i

No.	Probability %	Φ (P)	$\frac{\Delta f_i}{\sigma}$ p	Standard Deviation (σ)											
				(Jan)	(Feb)	(Mar)	(Apr)	(May)	(June)	(July)	(Aug)	(Sep)	(Oct)	(Nov)	(Dec)
				0.119	0.124	0.109	0.098	0.127	0.139	0.117	0.113	0.095	0.090	0.094	0.099
1	80.0	1.28		0.152	0.159	0.139	0.125	0.162	0.178	0.150	0.145	0.122	0.115	0.120	0.127
2	82.0	1.34		0.159	0.166	0.146	0.131	0.170	0.186	0.157	0.151	0.127	0.120	0.126	0.133
3	85.0	1.44		0.171	0.178	0.157	0.141	0.183	0.200	0.168	0.163	0.137	0.129	0.135	0.143
4	86.0	1.48		0.176	0.183	0.161	0.145	0.188	0.206	0.173	0.167	0.141	0.133	0.139	0.147
5	87.0	1.51		0.181	0.168	0.164	0.148	0.192	0.210	0.177	0.171	0.143	0.136	0.142	0.150
6	88.0	1.55		0.186	0.193	0.169	0.152	0.197	0.215	0.181	0.175	0.147	0.139	0.146	0.153
7	89.0	1.60		0.190	0.198	0.174	0.157	0.203	0.222	0.187	0.181	0.152	0.144	0.150	0.158
8	90.0	1.64		0.196	0.205	0.179	0.161	0.208	0.228	0.192	0.185	0.156	0.147	0.154	0.162
9	91.0	1.70		0.202	0.211	0.189	0.167	0.216	0.236	0.199	0.192	0.161	0.153	0.160	0.168
10	92.0	1.75		0.208	0.217	0.191	0.171	0.222	0.243	0.205	0.198	0.166	0.157	0.165	0.173
11	93.0	1.81		0.215	0.224	0.197	0.177	0.230	0.251	0.212	0.204	0.172	0.163	0.170	0.179
12	94.0	1.88		0.224	0.233	0.205	0.184	0.239	0.261	0.220	0.212	0.179	0.168	0.177	0.186
13	95.0	1.96		0.233	0.243	0.214	0.192	0.249	0.272	0.229	0.221	0.186	0.176	0.184	0.194
14	96.0	2.05		0.244	0.254	0.223	0.201	0.260	0.285	0.240	0.232	0.195	0.184	0.193	0.203
15	97.0	2.17		0.258	0.264	0.236	0.213	0.275	0.302	0.254	0.245	0.206	0.195	0.204	0.215
16	50.0	0.674		0.080	0.083	0.073	0.066	0.085	0.094	0.079	0.076	0.064	0.060	0.063	0.067

ceeded at a given probability. The probability given in this analysis was determined for cases equal to and smaller than calculated, occurring once in 10 years. For example, in Table 3.11 monthly average coefficients in percent of installed capacity for power plants of different full-load operating times (T) and different probabilities are presented. These values were calculated using equation 3.1.

3.4.4. BETA Distribution Model

In the BETA model, as with the cosine model of power plant operation, an installed capacity utilization coefficient was assumed to be the ratio of production to installed capacity. The installed capacity utilization coefficient was assumed to be a random variable with a discrete time parameter, considering power plant operation in monthly periods. Also, it was assumed that the installed capacity utilization coefficients in a particular month are independent variables, W_i, i= 1, 2, ... 12. Therefore, power plant load determination is reduced to:

- assumption of the probability distribution of the variables W_i where, i = 1, 2, 3, ...
- estimation of distribution coefficients,
- distribution function tabulation for particular variables,

It was assumed that W_i variables (i= 1, 2, ... 12) have a log-normal double limited distribution. Minimum specification is zero and maximum specification is 1 (100% installed capacity utilization).

A distribution which may be applied under such specifications is the so-called BETA distribution iwth 0 and 100% specifications. The definition of the density function of this distribution is:

$$f(x) = \frac{w^{p-1}(1-w)^{q-1}}{\int_0^1 x^{p-1}(1-x)^{q-1}\,dx} \qquad \text{for } 0 < w < 1 \qquad (3.18)$$

$$(p > 0,\ q < 0) \qquad \text{for } w \leq 0 \text{ or } w > 1 \qquad (3.19)$$

An estimation of the p and q parameters may be done using the moment method. From equations:

$$\bar{w} = \frac{p}{p+q} \qquad (3.20)$$

$$\sigma^2_w = \frac{pq}{(p+q)^2\,(p+q+1)^2} \qquad (3.21)$$

After their conversion, the following equations are obtained:

TABLE 3.11. MONTHLY AVERAGE INSTALLED UTILIZATION COEFFICIENTS, g_{imax} (%), VARIOUS OPERATION TIMES, T/h/year

%	Jan.	Febr.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
						T = 5000 h/year						
50	61.327	61.127	58.675	54.154	52.014	52.365	52.155	54.101	56.440	58.792	61.430	61.947
75	66.283	66.160	62.937	57.834	56.562	57.271	56.279	58.167	60.009	62.295	65.251	65.912
85	71.290	71.921	67.840	62.017	61.806	62.805	60.925	62.823	64.081	66.323	69.617	70.619
90	73.469	73.559	69.125	63.133	63.144	64.267	62.178	64.000	65.140	67.374	70.769	71.790
95	75.761	75.863	71.169	64.862	65.338	66.564	64.110	65.927	66.814	69.067	72.588	73.779
97	77.310	77.137	72.453	66.033	66.729	68.130	65.415	67.211	67.929	70.176	73.801	75.080
						T = 6000 h/year						
50	72.996	72.907	70.247	65.142	62.847	63.443	63.190	65.369	67.893	70.387	73.268	73.512
75	78.894	78.910	75.350	69.570	68.343	69.388	68.187	70.283	72.187	74.581	77.825	78.452
85	85.604	85.781	81.221	74.602	74.680	76.093	73.816	75.908	77.084	79.404	83.032	84.056
90	87.447	87.734	82.759	75.944	76.296	77.864	75.334	77.331	78.359	80.662	84.407	85.456
95	90.175	90.482	85.206	78.023	78.947	80.647	77.675	79.659	80.371	82.689	86.577	87.816
97	92.019	92.001	86.743	79.432	80.628	82.545	79.256	81.210	81.713	84.017	88.023	89.364
						T = 7000 h/year						
50	84.465	84.538	81.765	76.183	73.822	74.721	74.423	76.784	79.399	81.927	84.957	85.062
75	91.290	91.499	87.704	81.361	80.278	81.724	80.309	82.556	84.421	86.809	90.241	90.778
85	99.054	99.466	94.538	87.245	87.721	89.621	86.939	89.164	90.448	92.423	96.279	97.262
90	101.187	101.731	96.328	88.814	89.620	91.707	88.727	90.835	91.639	93.887	97.873	98.883
95	104.344	104.918	99.175	91.247	92.734	94.985	91.483	93.569	93.993	96.246	100.389	101.614
97	106.447	106.679	100.965	92.894	94.708	97.220	93.346	95.392	95.562	97.792	102.066	103.405

$$p = \frac{\bar{w}\,(\bar{w} - \bar{w}^2 - \sigma^2_w)}{\sigma^2_w} \tag{3.22}$$

$$q = \frac{(1 - \bar{w})\,(\bar{w} - \bar{w}^2 - \sigma^2_w)}{\sigma^2_w} \tag{3.23}$$

where $\bar{w}$ and σ^2_w are calculated on the basis of n-elements sequence of trials as:

$$\bar{w} = \frac{\sum_{i=1}^{n} w_i}{n} \tag{3.24}$$

$$\sigma^2_w = \frac{\sum_{i=1}^{n} (w_i - w)^2}{n} \tag{3.25}$$

Moreover, for the BETA distribution there is the following formula for model value (distribution maximum density):

$$w_{mod} = \frac{1 - p}{2 - p - q} \tag{3.26}$$

The distribution function is given by the equation:

$$F(x) = P(W<w) = \int_0^w f(x)dx = \frac{\int_0^w x^{p-1}(1-x)^{q-1}dx}{\int_0^1 x^{p-1}(1-x)^{q-1}dx} \tag{3.27}$$

The hypothesis that the variables W_i, i=1, 2, ... 12 have BETA distribution was verified by the Kolmogorov test, where the maximum difference D_{max}, is found between the empirical and theoretical distribution functions, and then it is investigated whether the condition

$$\lambda = \sqrt{n}\ D_{max} < \lambda o\ (\alpha) \text{ is met,} \tag{3.28}$$

where α is the assumed confidence level and λ_o is a Kolmogorov-Smirnov distribution function (Kaczmarek 1970). In all the investigated cases, the Kolmogorov test gave positive results (i.e., there was no basis to reject the assumed hypothesis).

The results of computations for heavily-utilized Polish power plants are presented in Table 3.12 (columns 3 and 4).

3.5. Summary of Analysis of Monthly Installed Capacity Utilization Coefficients

The analysis cover multi-unit power plants; that is, power plants equipped with at least four units. The choice of models, as well as particular calculations and values, refer only to Polish power plants operating in a connected electrical power system. There was a lack of statistical data to enable selection of a mathematical model for load changes in other electrical systems.

Referring to the Polish electrical power system, there was also lack of data describing installed capacity utilization coefficients in three-unit plants. In the case of two-unit power plants, constant full load operation is assumed for the purpose of cooling system design. In these power plants, load changes are not systematic and can fluctuate widely.

The purpose of the analysis was to determine the maximum reliable installed capacity utilization coefficients which are the basis for open cycle cooling system designs. These reliable coefficients are larger than the average values for those power plants investigated.

The results of analysis using three compututional techniques are presented in Table 3.12 and in Figure 3.3.

The results obtained from monthly modular coefficients of the BETA distribution and the probable coefficients of the cosine model indicate good agreement between them.

During summer months (June, July and August), the calculated coefficients correspond to available capacity in compliance with the optimum repair schedules. The agreement of the results obtained shows that the models correspond to real conditions. For practical purposes, we propose the selection of the cosine model and coefficients for power plant operation time of 6,000 h/year with a 90% probability that the value will not be exceeded.

TABLE 3.12. COMPARISION OF INSTALLED CAPACITY UTILIZATION MONTHLY COEFFICIENTS OBTAINED BY DIFFERENT METHODS OF COMPUTATION

Month	Disposable capacity taking into account repairs in power plants with open cooling systems	Utilization of power plants taken from computations using the BETA distribution		Coefficient from cosine model	
		Average	Mode	T = 600 h p = 90%	T = 6500 h p = 75%
Jan.	100	81.16	86.62	87.45	85.12
Febr.	100	81.11	87.37	87.73	85.22
Mar.	100	75.73	80.04	82.76	81.53
Apr.	100	71.80	74.34	75.94	75.46
May	93.2	71.88	74.36	76.30	74.29
June	75.4	70.90	74.34	77.86	75.53
July	73.3	72.30	75.34	75.33	74.22
Aug.	74.8	72.64	75.74	77.33	76.40
Sept.	94.4	76.16	80.19	78.36	78.30
Oct.	100	76.65	81.36	80.66	80.70
Nov.	100	79.45	85.11	84.41	84.05
Dec.	100	79.85	85.94	85.46	84.64

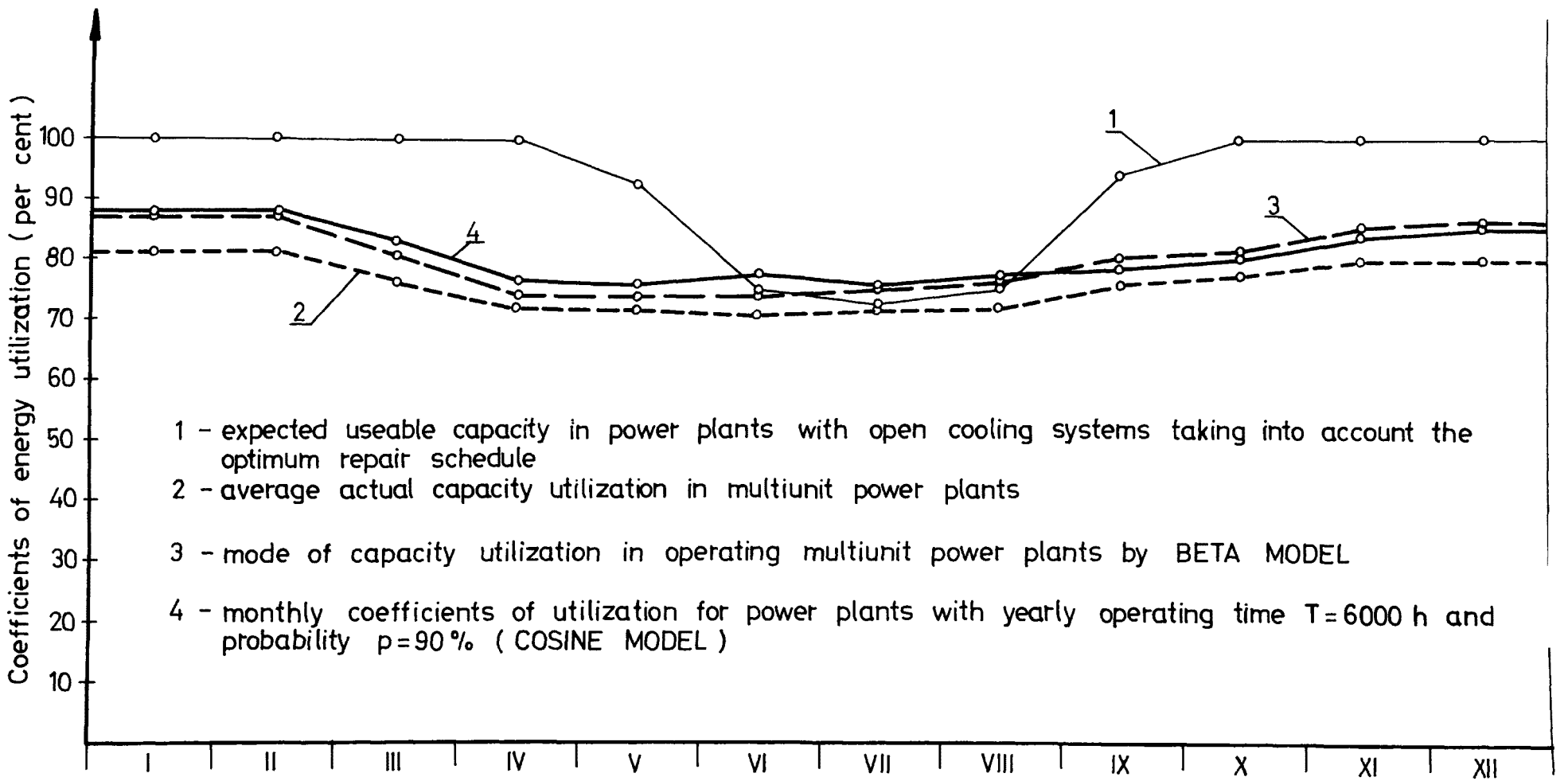


Fig. 3.3. Comparison of real and calculated coefficients of installed capacity utilization in power plants in Polish energetic systems

4. Power Plant Capacity and its Relation to Temperature Increases Downstream from the Discharge

4.1. Power Plant Capacity

From the standpoint of limiting temperature increases in the receiving water, the capacity of a power plant operation with an open cooling system can be determined by:

$$P \cdot g_{ki} \cdot C_k = Q \cdot \delta ti \cdot K_i \cdot \rho \cdot c \cdot 3600 \qquad (4.1)$$

where:

P = power plant installed capacity, (MW),

g_{ki} = monthly average coefficient of installed capacity utilization under critical conditions (p=90%),

C_k = waste heat discharged from the power plant in the cooling water (Kcal/kWh),

c = specific heat of water, (kcal/kg/°C),

ρ = density of water, (kg/l),

Q = mean yearly river flow, (m^3/s),

K_i = distribution coefficient, describing the ratio of low monthly flow (p=10%) to the mean yearly flow,

δt_i = acceptable increase in mixed river temperature (assuming no heat loss to the atmosphere) under critical conditions for month i. Acording to the Section 2.6, the following values of δt_i are used for Polish rivers:

Jan - 6°C	May - 6°C	Sept - 5°C
Feb - 6°C	June - 4°C	Oct - 6°C
Mar - 6°C	July - 4°C	Nov - 6°C
Apr - 6°C	Aug - 4°C	Dec - 6°C

After transformation, equation 4.1 is as follows:

$$P = \frac{Q \cdot K_i \cdot \delta t_i \cdot c \cdot \rho}{g_{ki} \cdot C_k} \qquad (4.2)$$

For conventional power plants, C_k is about 1200 kcal/kWh, which corresponds to a thermal efficiency of ∿ 34%; thus the above equation is as follows:

$$P = \frac{3 \cdot Q \cdot K_i \cdot \delta t_i \cdot \rho \cdot c}{g_{ki}} \tag{4.3}$$

Calculations of the capacities of power plants with open cycle cooling are presented in Table 4.1. These data show that in most cases August is the month when installed capacity should be limited. There are some cases, however, when capacity limitations occur in other months. For example, at the Skawina Power Plant, the permissible minimum installed capacity is in November. This is because the regulation of permissible temperature increases in the Vistula River downstream from the discharge limits the increase to 6°C year round. Also, on the Danube and Dniester Rivers, capacity limitations occur during the winter months. In particular cases, values close to the August criterio noccur during the period from June through September. It is worth noting that the calculation results are similar to the capacities of power plants already constructed. A comparison of capacities calculated here with capacities of operating power plants is presented below:

Cross-section	Permissible Capacity Calculated for Critical Period (MW)	Power Plant	Installed Capacity (MW)
Vistula-Tyniec	420-550	Skawina	550
Vistula-Szczucin	1260-1320	Pokaniec	1000
Vistula-Pulawy	2300	Kozienice	2100
Narew-Ostroleka	550-600	Ostroleka	600
San-Radomysl	450-490	Stalowa-Wola	450

The Skawina power plant was built in the early 1950's with a combined cooling system, and the calculations presented here confirm the correctness of that decision. In the calculations for the Skawina power plant, a C_k value of 1600 kcal/kWh was used on the basis of operating data. Calculations were also conducted for the French power plant Vitry sur Seine. They show convergence between results obtained by calculation and the installed capacity as in the case of Polish power plants. Permissible calculated capacity for Vitry sur Seine power plant ranges from 975 to 1100 MW, and the installed capacity for this power plant is 1,000 MW.

4.2. Mixed Temperature Increases Downstream from Power Plants

Transforming equation 4.1, a formula describing completely mixed temperature increases downstream from the discharge under critical conditions, assuming no heat loss to the atmosphere, is obtained:

TABLE 4.1. CALCULATION OF INSTALLED CAPACITY WITH OPEN CYCLE COOLING IN POLISH RIVERS

Month	g_{ki}	K_i Coefficients					Installed Capacity (MW)				
		Vistula-Tyniec	Vistula-Szczucin	Vistula-Pulawy	Narew-Ostroleka	San-Radomysl	Vistula-Tyniec*	Vistula-Szczucin	Vistula-Pulawy	Narew-Ostroleka	San-Radomysl
Jan.	0.874	0.38	0.32	0.36	0.41	0.27	533	1615	3340	900	750
Febr.	0.877	0.37	0.33	0.37	0.39	0.37	518	1670	3420	860	1020
March	0.828	0.82	0.65	0.74	0.56	0.75	1215	3800	7340	1300	2170
April	0.759	0.66	0.73	0.71	0.94	0.69	1065	4260	7580	2380	2210
May	0.763	0.47	0.53	0.53	0.63	0.38	750	3080	5630	1590	1210
June	0.779	0.35	0.41	0.46	0.41	0.31	551	1550	3190	680	640
July	0.753	0.38	0.34	0.39	0.35	0.21	619	1340	2800	600	450
Aug.	0.773	0.35	0.33	0.33	0.33	0.22	551	1260	2300	550	455
Sept.	0.784	0.29	0.28	0.29	0.35	0.19	490	1320	2500	720	490
Oct.	0.807	0.33	0.28	0.30	0.39	0.19	499	1540	3010	890	570
Nov.	0.844	0.29	0.30	0.36	0.49	0.24	420	1570	3450	1120	690
Dec.	0.855	0.36	0.28	0.38	0.45	0.31	518	1450	3600	1010	880

* For this cross-section a C_k value of 1600 K cal/KWh was used to account for the combined cooling system of the Skawina Power Plant.

$$\delta t_i = \frac{P \cdot g_{ki} \cdot C_k}{3600 \cdot Q \cdot K_i \cdot c \cdot \rho} \tag{4.4}$$

for average conditions:

$$\delta t_{mi} = \frac{P \cdot \bar{g}_i \cdot C_k}{3600 \cdot \mu_i \; Q \cdot K_{mi} \cdot c \cdot \rho} \tag{4.5}$$

where: $K_{mi} = \frac{Q_i}{Q}$

Q_i = average monthly long-term flow

μ_i = median flows coefficients, $\left| \frac{Q_{i\ 50\%}}{Q_i} \right|$

$Q_{i50\%}$ = monthly flow with a probability of p=50%

$\bar{g}_i$ = monthly coefficient of installed capacity utilization under average conditions (p=50%),

Formula 4.5 can be simplified as:

$$\delta t_{mi} = \frac{P \cdot \bar{g}_i C_k}{3600 \cdot Q_{i50\%} \cdot c \cdot \rho} \tag{4.6}$$

Calculated values for the Skawina power plant (Table 4.2) show good agreement with measured values of heating for average conditions. But measured temperature increases under critical conditions are up to 2.8°C lower than the calculated values. This difference is probably due to atmospheric heat losses and may be treated as a safety factor.

4.3. *Discharge Design*

Discharge designs are based on the biological premise that small areas of thermal impact are more desirable than large areas. The impact of thermal discharges on water temperature distribution was investigated on the Vistula River below the Kozienice Power Plant and on the Narew River below the Ostroleka Power Plant. In addition, laboratory investigations were conducted using a hydraulic model.

4.3.1. Field Investigations

Some results of the field investigations are presented in Tables 4.3 and 4.4. For the purpose of these studies, the 0.1°C isotherm was used to delineate the thermal plume. Data on plume width and capacity (i.e., % of river flow in the plume) were then compiled. The value of % of river flow in the plume is used as a measure of mixing.

TABLE 4.2. THE COMPARISON OF CALCULATED vs. MEASURED TEMPERATURE INCREMENTS IN THE VISTULA RIVER DOWNSTREAM FROM THE SKAWINA POWER PLANT

Month	g_{ki} (1)	$\bar{g}_i$ (2)	Km_i	μi	K_i	Temperature increment under average conditions (°C)		Temperature increment under critical conditions (°C)	
						Calculated	Measured	Calculated	Measured
Nov.	0.844	0.849	0.822	0.804	0.29	3.36	3.31	7.84	5.4
Dec.	0.855	0.851	0.804	0.849	0.36	3.36	2.90	6.40	5.0
Jan.	0.874	0.845	0.802	0.879	0.38	3.12	3.72	6.20	7.2
Febr.	0.877	0.845	0.991	0.889	0.37	2.58	2.44	6.38	5.1
March	0.828	0.818	1.415	0.481	0.82	1.58	1.68	2.72	2.4
April	0.759	0.762	1.353	0.936	0.66	1.61	1.61	3.09	2.2
May	0.763	0.738	1.044	0.876	0.47	2.17	2.07	4.37	3.4
June	0.779	0.747	1.014	0.744	0.35	2.65	1.99	5.99	3.2
July	0.753	0.744	1.163	0.796	0.38	2.17	2.06	5.34	4.6
Aug.	0.773	0.768	1.009	0.851	0.35	2.93	2.60	5.95	4.9
Sept.	0.784	0.794	0.750	0.779	0.29	3.66	3.50	7.28	5.6
Oct.	0.807	0.819	0.819	0.740	0.33	3.63	3.49	6.59	4.8

(1) For 6000 hrs/year at the 90% level.
(2) For 7000 hrs/year at the 50% level.

TABLE 4.3. FIELD INVESTIGATION RESULTS IN THE VISTULA RIVER DOWNSTREAM FROM THE KOZIENICE POWER PLANT

Date	Intake		Distance 300 m			Distance 1000 m			Distance 9100 m			Distance 12.800 m			Distance 35.500 m		
	Q_p m^3/s	p%	Q_c%	B_c	B_c%	Q_c%	B_c	B_c%	Q_c%	B_c	B_c%	Q_c%	B_c	B_c%	Q_c	B_c	B_c%
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
April 26-27, 1973	4.77	1.0	33	99	25.3	34	160	41.0	34	168	38.0	-	-	-	-	-	-
May 7-9, 1973	13.1	3.0	16	50	12.7	40	75	19.5	32	150	26.3	-	-	-	-	-	-
May 17-18, 1973	14.6	4.2	38	122	31.1	64	115	31.5	90	355	75.5	-	-	-	-	-	-
July 17-18, 1973	19.6	3.3	44	105	26.9	21	90	21.4	50	280	53.5	-	-	-	-	-	-
July 26-27, 1976	15.1	2.5	17	102	33.3	40	140	33.3	52	210	41.6	59	260	58.4	-	-	-
August 6-7, 1973	15.0	2.7	38	106	28.3	24	150	35.7	84	408	71.9	77	305	69.6	-	-	-
April 3-4, 1974	25.4	8.6	53	105	19.9	71	216	63.1	69	409	77.9	92	490	98.0	-	-	-
April 17-18, 1974	25.1	12.5	76	148	47.4	82	220	62.8	45	254	71.7	50	252	55.3	100	400	100
May 2-3, 1974	19.3	6.3	53	130	41.8	75	188	53.2	90	252	54.7	53	256	63.7	66	245	74.7
July 24-25, 1974	28.2	2.6	42	140	28.0	30	172	42.0	76	315	62.2	-	-	-	53	207	50.7
August 5-7, 1974	35.4	6.7	87	180	67.4	90	380	90.4	92	380	76.3	88	360	81.8	91	335	80.1
August 19-21, 1974	40.6	7.3	83	235	60.2	80	365	84.1	58	320	64.2	77	260	59.8	55	380	86.7
May 5-7, 1975	43.1	6.3	-	-	-	74	250	59.1	(62)	(395)	(83.1)	100	449	100	100	393	100
May 21-24, 1975	49.5	9.5	79	140	54.4	55	223	54.5	-	-	-	90	382	85.4	100	390	100
August 5-7, 1975	52.9	8.0	41	109	25.7	45	190	44.8	-	-	-	70	233	52.0	100	392	100
August 19-22, 1975	52.5	12.1	64	97	51.3	87	339	86.9	(76)	(363)	(74.8)	100	416	100	100	396	100
Sept. 2-5, 1975	53.4	13.1	53	95	38.5	63	210	50.7	(85)	(273)	(55.0)	84	386	85.6	100	364	100

Qp - cooling water flow m^3/s, p - percent of river flow

Qc - per cent of thermal plume downstream from the discharge as per cent of total river flow

Bc - thermal plume width, m

Bc % - thermal plume width in relation to river bed width, %

( ) - at a distance of 4,000 m

TABLE 4.4. FIELD INVESTIGATION RESULTS IN THE VISTULA RIVER 1000 m FROM THE DISCHARGE OF THE KOZIENICE POWER PLANT

Date	Q_p (m^3/s)	P (%)	B_c (m)	B_c (%)	Q_c (%)
April 18, 1973	11.2	2.0	70	18	29
May 29, 1973	15.0	5.0	55	18	29
June 12, 1973	12.2	1.4	80	20	28
June 26, 1973	14.2	4.0	85	24	34
August 21, 1973	20.7	8.0	150	38	47
Nov. 16, 1973	11.4	4.5	225	54	49
Jan. 31, 1974	17.4	2.7	300	72	75
Febr. 21, 1974	13.7	2.1	380	90	85
March 14, 1974	15.8	5.6	220	57	49
May 29, 1974	41.2	6.6	190	45	28
July 12, 1974	32.0	4.0	210	50	29
Sept. 24, 1974	41.2	18.0	385	91	95
Oct. 10, 1974	37.6	2.8	210	48	25
Dec. 4, 1974	10.6	1.2	320	75	68
Dec. 19, 1974	11.2	1.4	310	72	67
April 9, 1975	27.5	3.8	215	38	46
June 3, 1975	57.2	9.0	255	60	63
June 17, 1975	46.2	6.0	192	45	50
Sept. 27, 1975	45.8	11.3	107	55	62

Investigations on the Narew River were carried out below the Ostroleka Power Plant. At this location, a large river meander causes complete mixing of the thermal plume. On the Vistula River investigations were conducted below the Kozienice Power Plant. During the investigations, vertical temperature homogeneity at the distance of 300 m downstream from the discharge was observed; further downstream some stratification occurred.

The results for the Vistula River show that the temperature distribution downstream from the discharge is subject to random dynamic changes. Taking into account the variability of the thermal plume distribution average values obtained in particular cross-sections of the Vistula River were obtained:

Distance From the Discharge (m)	Flow Capacity Q_c (%)	Width B_c (m)	Width B_c (%)
300	51.1	123	37.0
1000	59.5	205	51.4
9100	66.3	302	61.8
12800	78.3	337	67.5

These average values show that with increasing distance from the discharge, the thermal plume capacity and width increase. A comparison of average mixin g coefficients (Q_c,%) obtained in field investigations with those obtained in laboratory tests (Europejskaja ... 1969) shows similar results.

Comparison of the results of field and laboratory investigations for an average intake flow of 6.4% of the river flow is presented below:

Distance From the Discharge (m)	Average Field Mixing Coeff. (%)	Mixing Coeff. From Lab. Investigations (%)
300	51.1	42.0
1,000	59.5	53.0
9,100	66.3	82.0
12,800	78.3	86.0

The project investigations show that particularly intensive mixing takes place in the near-discharge field at a distance of 50 to 300 m downstream from the discharge. Within this zone, the thermal plume capacity, Q_c, increased by a factor of 8 and the maximum temperatures decreased 6°C. The zone of inten-

sive mixing is at the same distance (50 to 300) in the Vistula and Narew Rivers (Figure 4.1).

Four winter surveys show that mixing intensity during the winter is greater, but the number of investigations is too low to establish more specific relationships. Further field results are presented in Figures 4.2 and 4.3. These figures show that after the zone of intensive mixing, cooling in the river is slow, amounting to about 1°C in 35 km. This distance is confirmed by previous studies (Gadkowski 1970), where, using Dobrowolski's results (1967), it was shown that for similar intake percentages at the Stalowa Wola power plant, total cooling distance under low river flows is 34 km and under average flows about 86 km. Similar results have been obtained for the Lea River, England (Gameson, et al. 1959) and Mikyska's elaboration (1964).

4.3.2. Model Investigations

Model investigations of heated waters discharged to free flowing rivers were conducted at different values of the following elements:

- distance from the intake to the discharge, L
- angle of the discharge, β
- discharge channel width, b

A schematic of the model is presented in Figure 4.4.

Changes of particular elements were within the range of:

- maximum distance L, up to 10B.
- angle of the discharge β from /4 to /2,
- discharge channel width b, from 0.3B to 0.7B, where B is the river width.

The purpose of the studies was to describe the impact of the discharge design on the thermal plume structure in the near-field and to establish the analytical relationship describing plume axis development.

The investigations covered the range of geometric, dynamic and thermal parameters at Polish steam power plant cooling systems. Intake flows in the range of 10-100% of the river flow were used. Investigations of different distances between the intake and discharge show that the location of the water intake has a decisive impact on the velocity field between intake and discharge. This impact is small at L=5B, but at L=1 to 2B, which is common for open cooling system design, this impact is very distinct. It is characterized by irregular flow velocity distribution with decreased velocity at the bank opposite the discharge and in some cases in a small area close to the discharge.

The discharge angle has an important impact on the thermal plume structure (Figure 4.5) For a small discharge angle, the thermal plume is close to

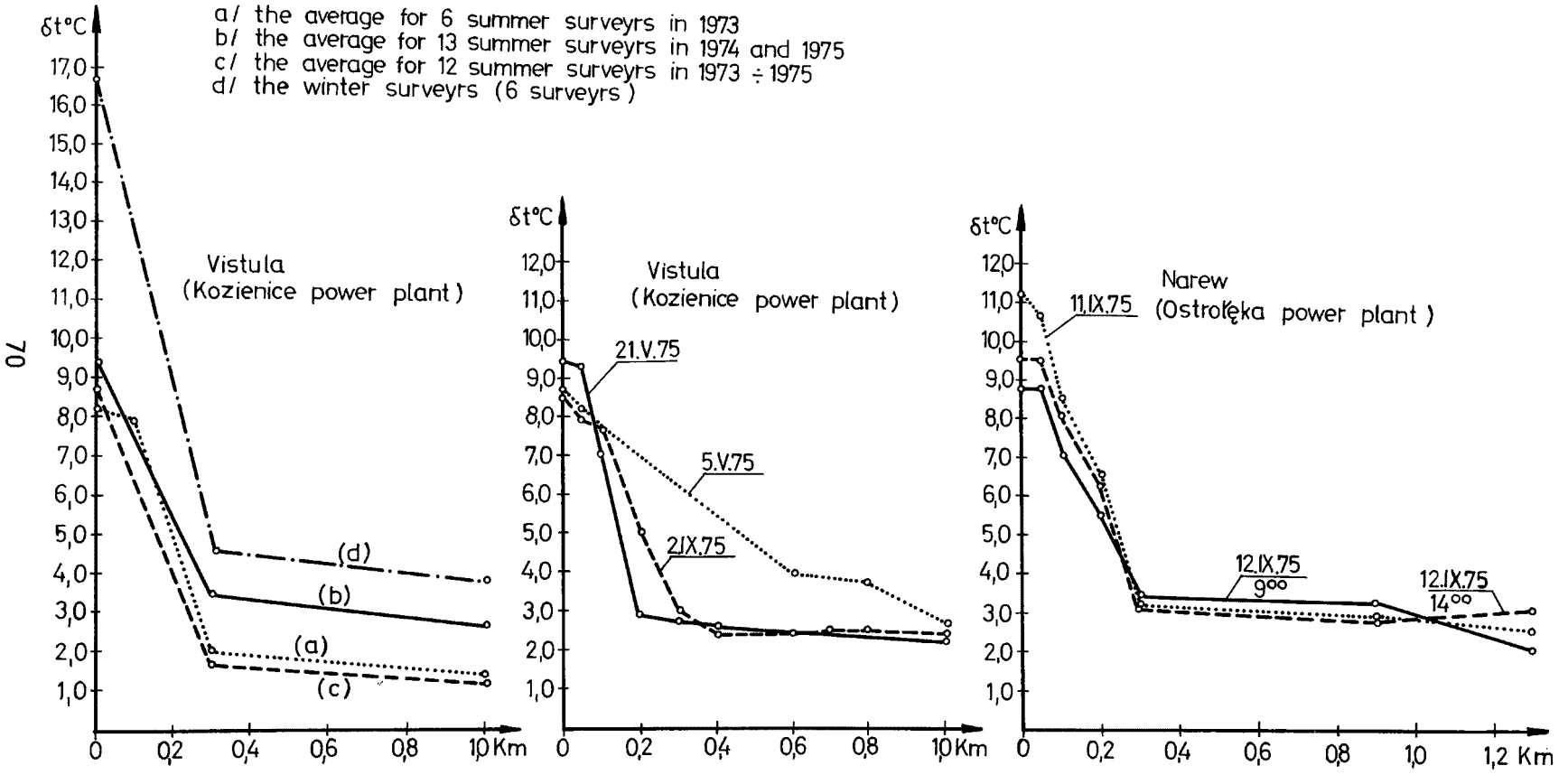


Fig. 4.1. The maximum temperature decrease in the discharge zone below the Kozienice and Ostrołęka power plants

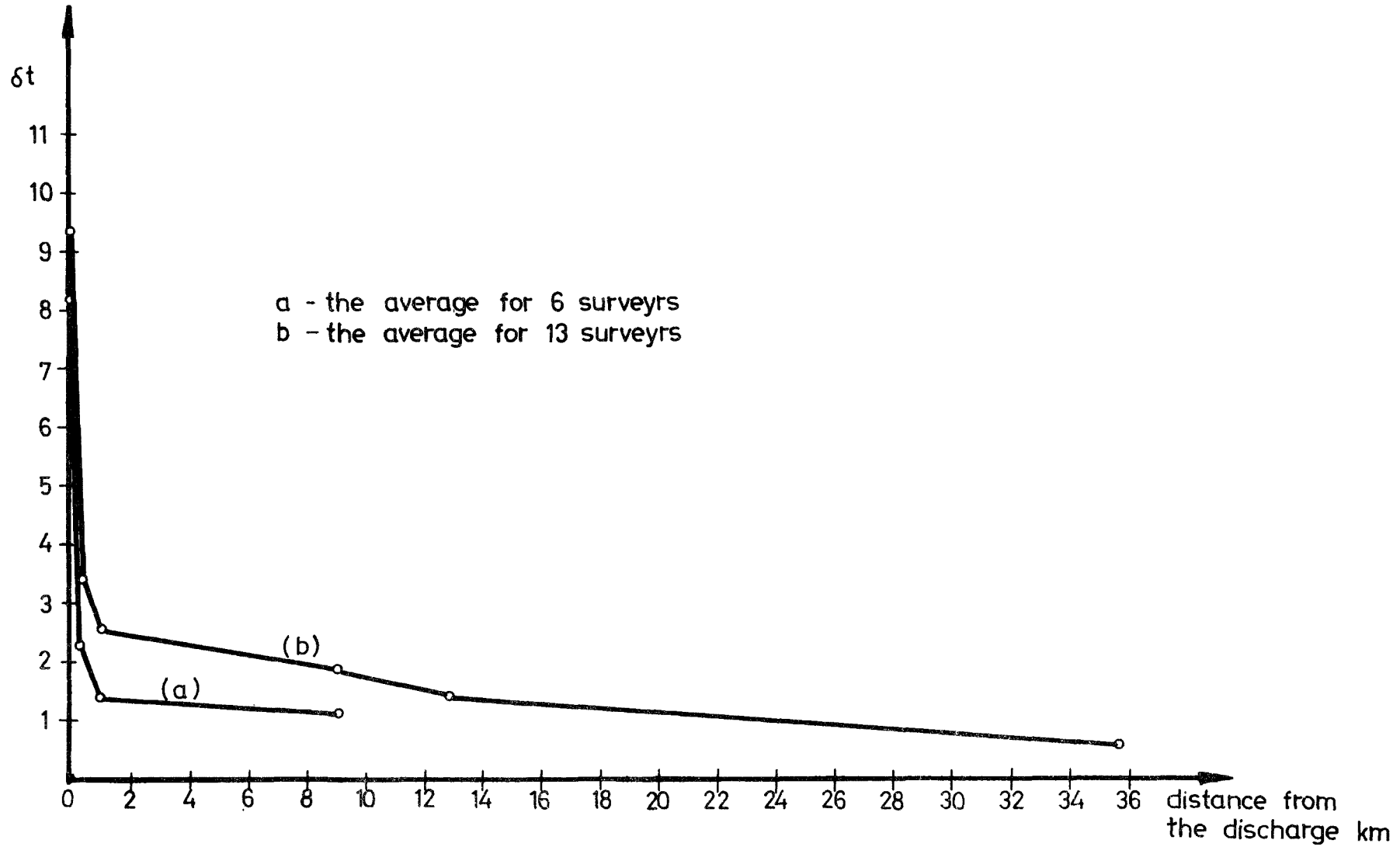


Fig. 4.2. The maximum temperature decrease at a longer distance below the discharge from the Kozienice power plant

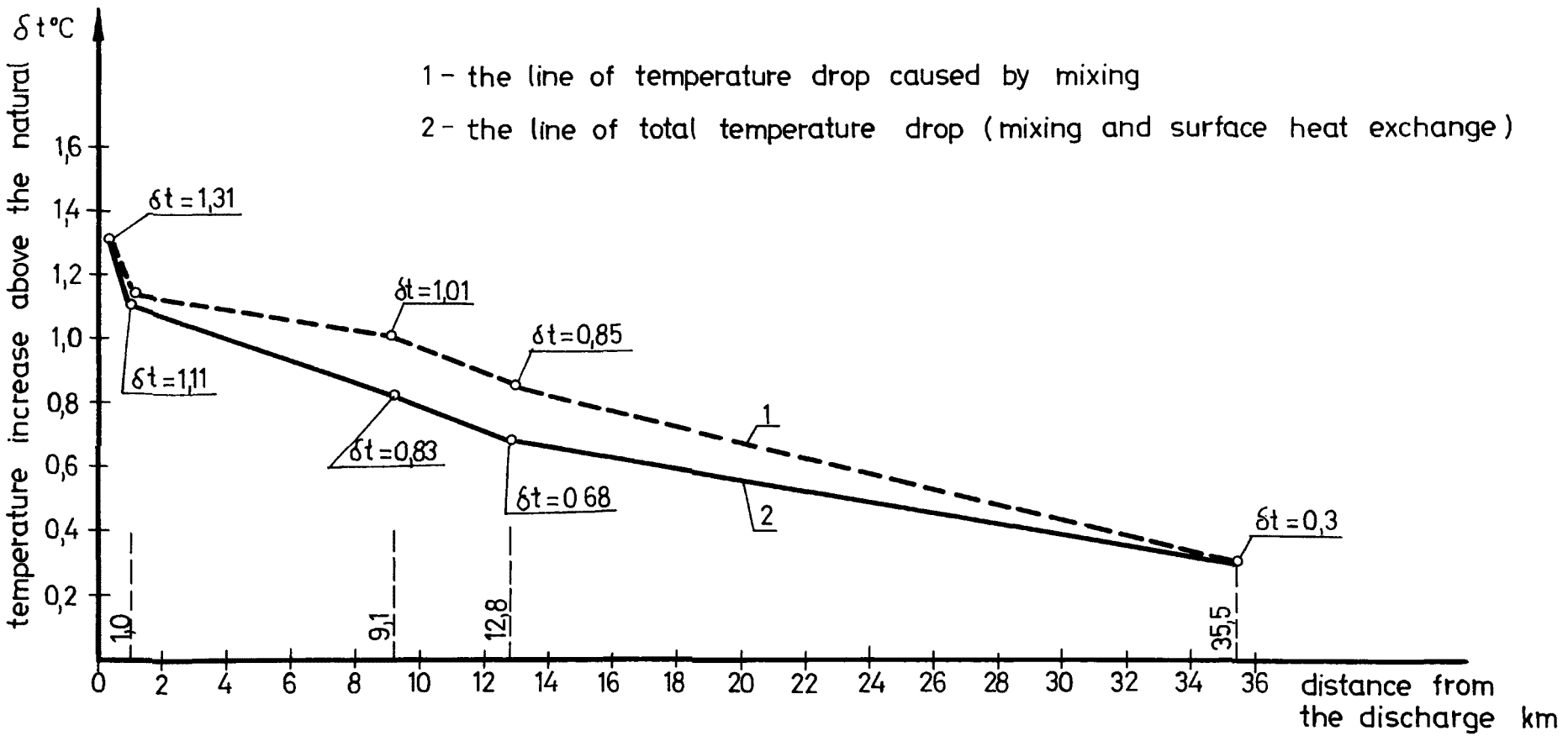


Fig. 4.3. Average maximum temperature drop in the thermal plume below the Kozienice power plant

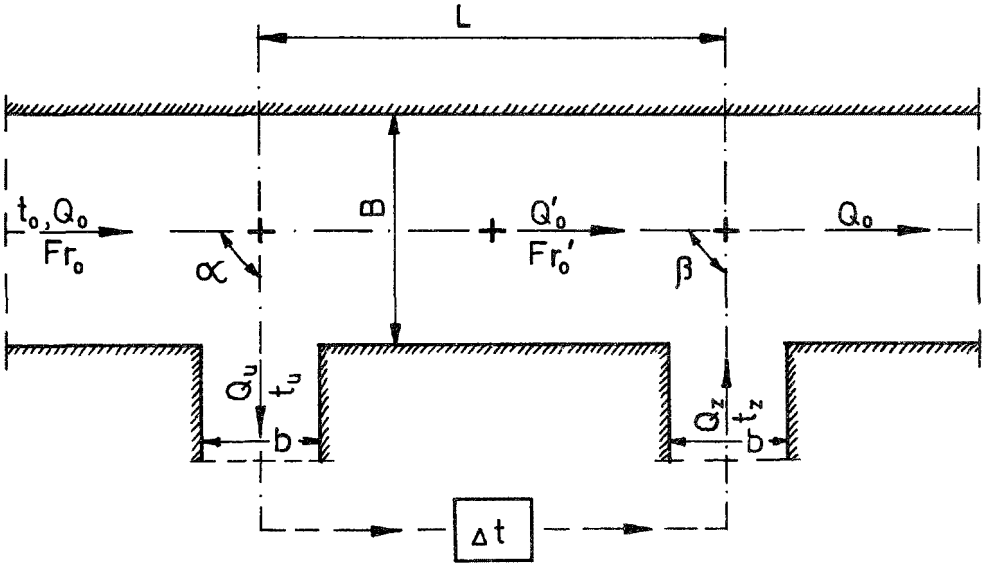


Fig. 4.4. Scheme of model

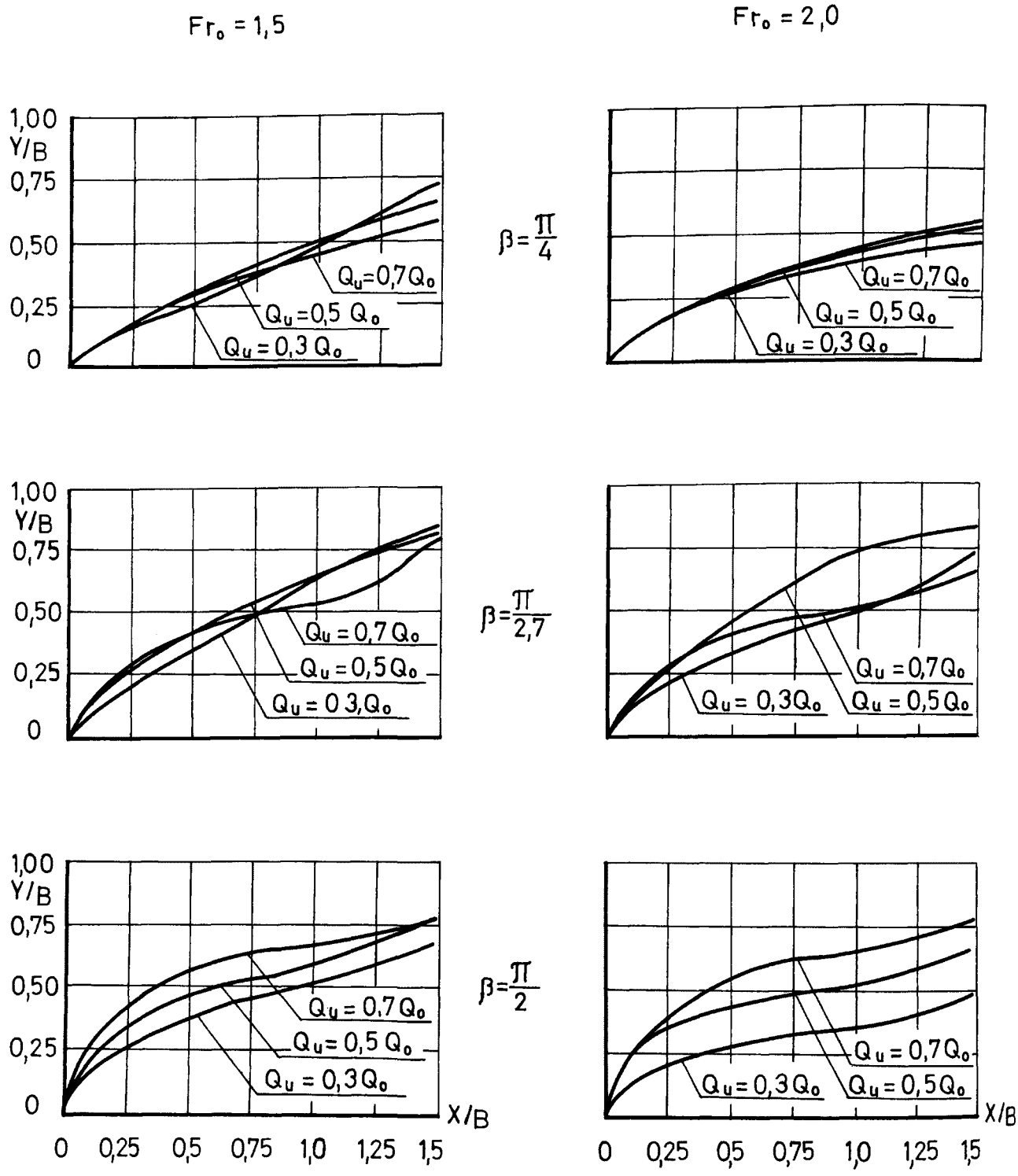


Fig. 4.5. Arrangement of discharged jet axes with regard to changes of outlet angle β for b/B = 0,5

the discharge bank and the effect of the relative discharge value (Q_u/Q_o) on plume axis development is small. When the discharge angle is smaller than 67° ($\pi/2.67$), the gradient of temperature decrease ($\delta t/\delta L$) drops and the distance to the cross-section where the thermal plume covers the whole river width increases. Changes of discharge channel width in the range of 0.3 to 0.7B effect the thermal plume axis development by altering the discharge dynamics, particularly when L > 2B. The results of the investigation of different angles of the discharge channels were analyzed using the least-square method. Computation shows that plume axis position in the zone of free discharge may be described by the function:

$$y = 0.272\ x^{0.465}\ Fr_0^{-0.159}\ \beta^{0.411}(v_o'/v_z)^{-0.384} \qquad (4.7)$$

in a rectangular co-ordinated system with the center situated on the axis of the mouth of discharge channel and the x axis colinear with discharge bank.

Fr_o = discharge densimetric Froude number

β = angle of the discharge,

v_o' = average flow velocity in the river between the intake and discharge,

v_z = average velocity in the discharge cross-section

The model investigations show that in order to keep horizontal stratification in the river, the angle of the discharge channel should be in the range of 45 to 65° in relation to the river axis, and discharge velocities should be low in comparison with river flow velocities upstream from the discharge, $v_z \leq 0.5v_o'$.

5. Combined Cooling Systems and Flow Augmentation

5.1. Review of Combined Cooling Systems and Flow Augmentation for Power Plants

Combined cooling systems are designed for two purposes:

- to enable power station operation in times of water shortage,
- to regulate the discharge of waste heat to the receiving water.

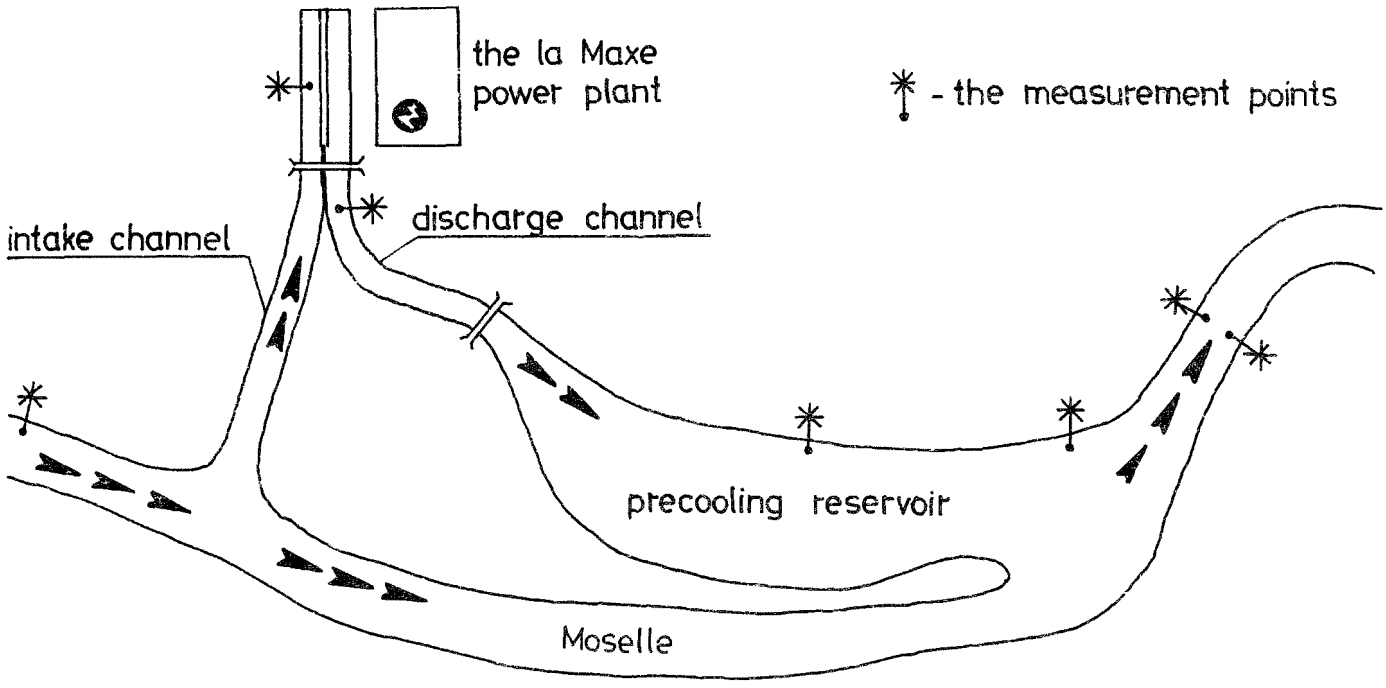
The Blenod power station (Gras, et al. 1969, 1971) (Figure 5.1) was one of the first power stations to artificially augment low flows. This power station has four units of 250 MW and was built in the period 1963-1969. Total water demand for the cooling system of the Blenod power plant amounts to $40m^3/s$ from the Moselle river. Annual mean flow in the river equals $130m^3/s$; but in the mean year, flows smaller than $40m^3/s$ occur for 158 days. Minimum flows appear in September and October and, at p=10%, amount to $19m^3/s$. Much smaller flows have been noted also, e.g. minimum 24-hour flows recorded in 1972 amounted to (EdF 1971, 1973):

$9.0m^3/s$ - in July
$11.5m^3/s$ - in August
$4.3m^3/s$ - in September
$7.1m^3/s$ - in October

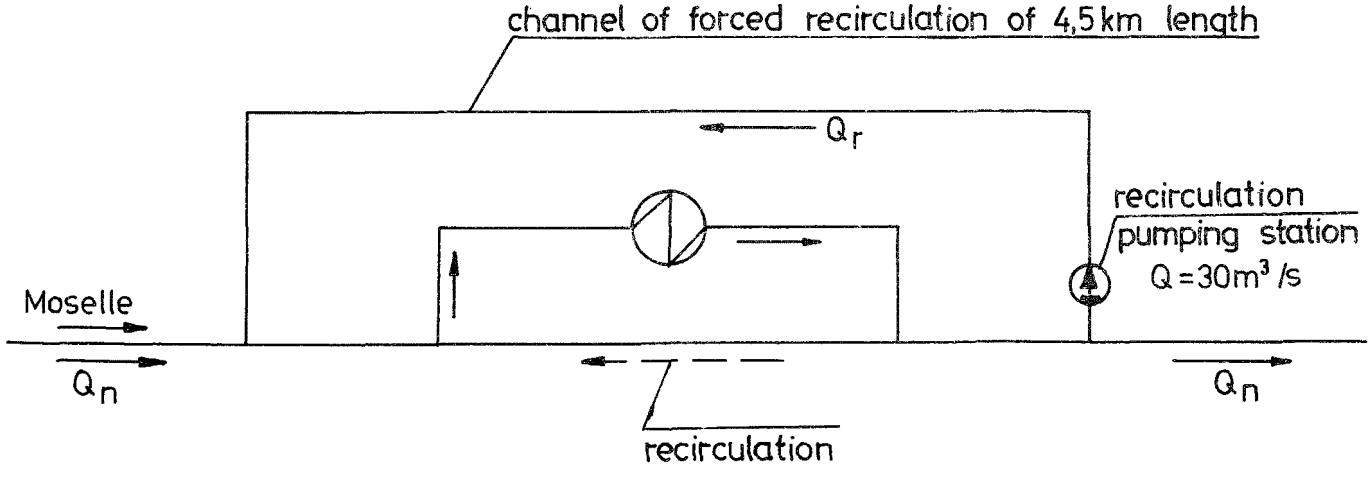
Initially, water shortages were supplemented by recirculation of the water discharged to the river, but this proved to be inefficient. Later, water was taken from below the power plant and pumped through channels to the Moselle above the power plant. The maximum discharge of pumped water was $30m^3/s$. This recirculation circuit is 100 hectares in surface area and, thus, also provides a cooling function. In 1971, La Maxe power plant (two units of 250 MW power) was built (EdF 1973) 50 km below the Blenod power plant. A precooling reservoir of 72 hectares (Figure 5.1) was built on the discharge channel of La Maxe power plant to secure water temperature regulation. The results of work on this reservoir are presented in Section 5.6 of this report.

Combined cooling to overcome water shortages was used at the nuclear power plant of Neckerwesthein located on the Neckar River (Flinspach 1973). This 900 MW power plant began operation in 1976; its water demand amounts to $40m^3/s$, while minimum flows in the Neckar River are about $20m^3/s$.

Combined cooling systems are being increasingly used to regulate discharge temperatures. Many power plants utilizing this solution are under operation in different countries. The 550 MW Polish power plant at Skawina, built in 1957, is the oldest one. Other large power plants using combined cooling circuits include the American power plants: Chesterfield, Dresden,



The scheme of precooling reservoir of the la Maxe power plant



The scheme of recirculation in the Blenod power plant

Fig .5.1. French power plant cooling systems

Monticello, Allen S. King, Browns Ferry and others; and West German power plants: Biblis, Neckarwesthein, Grundrenmingen and others. The majority of these plants utilize mechanical draft cooling towers for thermal energy dissipation, but other solutions could include:

- natural draft cooling towers,
- spray equipment,
- discharge channels and cooling ponds.

5.2. Assumptions Used in Analyses.

Taking into consideration solutions utilized in practice and results of studies, combined cooling circuits can be divided into three categories:

- parallel,
- hybrid,
- combined parallel/hybrid.

Parallel circuits employ cooling devices for a portion of total cooling waterflow and cool it in a closed loop. Such parallel circuits are normally used to overcome water shortages. Cost is the decisive factor in the selection of parallel circuits.

Hybrid circuits use cooling devices for the cooling water flow prior to discharge, but the open cycle is maintained. Hybrid circuits are usually used to maintain temperature conditions in the receiving water. Economical aspects and efficiency of thermal energy dissipation are decisive factors in the selection of hybrid technologies. The remainder of this analysis, is a discussion of hybrid technologies.

5.3. Determination of Hybrid Circuit Capacities

Using equation 4.1 it should be noted that alterations of power output during a year depend upon the mutual relationships between:

- admissible temperature increase, δt_i,
- distribution coefficients, K_i
- coefficients of power utilization, g_i

This dependency can be defined as:

$$P = f \quad \frac{\delta t_i \cdot K_i}{g_i} \tag{5.1}$$

or $P - f(m)$ (5.2)

where:

$$m = \frac{\delta t_i \cdot K_i}{g_i}$$

The "m" expression is called the coefficient of open circuit variation. "m" coefficients for selected rover cross-sections are presented in Table 5.1

These results indicate that:

- in the majority of cases, the month of August is the critical period from the point of view of power plants with open cycle cooling systems,
- the value of the "m" coefficient depends on character of the river. In the cases investigated, minimum "m" coefficients range between 0.67 for the Loire River and 2.62 for the Danube,
- based on "m" coefficient values, the rivers can be divided into 3 groups:
  a) rivers characterized by low "m" coefficients within the limits of 0.67 to 1.12, including the Loire, Seine, San and Dniester Rivers.
  b) rivers characterized by "m" coefficients within the limits of 1.71 to 2.12, including the Vistula, Oder, Warta and Narew Rivers.
  c) rivers characterized by high "m" coefficients exceeding 2.6, represented by the Danube.

In addition, Table 5.1 indicates that a high stability of the "m" coefficient occurs along the Vistula River.

Another important factor is the "m" coefficient variation during the year. Based on the rivers investigated, it can be shown that variations of "m" can proceed in a rapid, medium or slow manner. Rapid variations of "m" take place in the Loire River. On this river, if an increase in cooling system capacity is needed, hybrid circuits can be employed for relatively short periods of time, e.g., only 3 months, if we want to increase total cooling capacity about 70% (e.g., for "m" coefficient ranging from 0.67 to 1.11). Slow variations of "m" appear in the Vistula at Szczucin. In this case, employment of hybrid circuits to dissipate an additional 30% ("m" coefficient ranges from 1.71 to 2.26) of the waste heat are required for 8 months of the year. A medium example case is the Warta at Gorzow, where an additional 60% of the waste heat has to be dissipated during a 4 month period ("m" from 2.12 to 3.35) and 90% of the waste heat has to be dissipated for 7 months of the year. Data on the % cooling vs. time of cooling are contained in Table 5.2.

TABLE 5.1. COEFFICIENT OF OPEN COOLING SYSTEM VARIATION, m

	Vistula				Oder	Warta	Narew	San	Seine	Loire	Danube	Dniester
	Tyniec	Szczucin	Palawy	Plock	Slubice	Gorzów	Ostroleka	Radomyśl	Paris	Montjean	Budapest	Zaleszczyki
Jan.	2.61	2.20	2.26.	2.88	3.23	3.98	2.81	1.85	3.98	4.32	3.50	1.03
Febr.	2.53	2.26	2.53	2.80	3.42	3.97	2.67	2.53	3.97	4.99	4.04	1.37
March	5.94	4.71	5.36	6.01	5.43	6.30	4.06	5.43	4.85	4.42	4.78	.4.49
April	5.21	5.77	5.61	7.82	6.25	6.72	7.43	5.45	3.48	3.71	6.82	5.72
May	3.70	4.17	4.17	4.64	5.19	4.95	4.95	3.00	2.67	2.44	7.39	2.97
June	1.80	2.10	2.36	2.10	1.95	2.26	2.10	1.59	1.33	1.44	4.63	1.54
July	2.02	1.81	2.07	2.12	2.12	2.18	1.86	1.12	1.06	0.96	4.25	1.51
August	1.81	1.71	1.71	1.81	1.91	2.12	1.71	1.14	0.88	0.67	3.62	1.40
Sept.	1.85	1.78	1.85	2.10	2.04	2.74	2.23	1.21	0.96	0.83	3.63	1.19
Oct.	2.45	2.08	2.23	2.45	2.53	3.35	2.90	1.41	1.04	1.11	3.16	1.46
Nov.	2.06	2.13	2.56	2.70	3.06	3.48	3.48	1.71	1.07	1.78	2.90	1.59
Dec.	2.53	1.96	2.67	2.80	3.02	4.14	3.15	2.17	1.75	3.02	2.62	1.47

TABLE 5.2. DEPENDENCE OF HYBRID COOLING SYSTEM OPERATION TIME ON HYBRID CIRCUIT SIZE (in % of Open Cooling System Size)

Hybrid Cooling System Operation Time (months)	Hybrid Circuit Size (%)											
	Vistula				Oder	Warta	Narew	San	Seine	Loire	Danube	Dniester
	Tyniec	Szczucin	Palawy	Plock	Slubice	Gorzów	Ostroleka	Radomyśl	Paris	Montjean	Budapest	Zaleszczyki
1	--	--	10	15	--	--	10	--	10	20	10	15
2	--	--	20	15	10	10	20	10	20	40	20	30
3	15	15	30	15	10	30	30	30	20	70	30	40
4	15	25	30	35	30	60	60	40	20		40	40
5	40	25	40	40	60	60	60	50	50		40	40
6	40	25	50	55	60	90	70	70	100		50	50
7	40	30	50	55	70	90	80	90			60	50
8	40	30	50	55	80	90	100				80	50

5.4. Economic Aspects of Combined Cooling Circuits

Costs of combined cooling circuits have been compared with marginal costs for open cooling circuits (in Poland) (Gadkowski 1972b). Marginal costs were calculated by considering investment costs and operating costs of open and closed circuits. Equation 5.3 allows one to define the economically justified costs that can be paid for the open cooling circuit together with the equipment for combined cooling, so that the total costs of a closed cycle circuit shall not be exceeded.

$$Igr = \frac{Iz\left(1 + \frac{bz \cdot r}{2}\right) + T \cdot \Delta K_z}{1 + \frac{bo \cdot r}{2}} \qquad (5.3)$$

where:

Igr = marginal cost for combined cooling circuit (zl*/kW),

Iz = mean capital cost for closed cycle cooling circuit (zl/kW),

ΔK_z = difference between mean operating costs (depreciation excluded) of closed and open cooling circuits (zl/kW),

T = period of recoupment of capital cost (12.5 years for Poland),

bz = mean time of power plant construction with closed cycle cooling circuit (assumed 5 years in Poland),

bo = mean time of power plant construction with open cycle cooling circuit (assumed 6 years in Poland), and

r = interest rate (8%).

Based on cost indicators for Polish price levels of 1965, Gadkowski (1972b) calculated: Iz = 410 zl/kW, ΔK_z = 30.5 zl/kW.

Calculations for combined cooling, not considering increase of fuel prices, gives:

Igr = 704 zl/kW - this equals 16.0% of total power plant capital cost.

For open cycle cooling circuits, this cost indicator amounts to 5.1%; thus 16.0 - 5.1 = 10.9% is a marginal indicator of additional equipment for combined cooling circuits. In current prices, this indicator (10.9%) amounts to about 1,100 zl/kW of installed capacity.

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* zl = zloty, the unit of currency in Poland.

Analyses on the following aspects were carried out:

- increase of open cycle cooling possibilities by augmentation of low flows,
- cooling in discharge channels and reservoirs,
- utilization of mechanical draft cooling towers.

5.5 Increase of Open Cycle Cooling Possibilities by Augmentation of Low Flows

Regulation of low flows by releases from upstream reservoirs is frequently utilized in water management practices on many rivers. In some cases, such low flow augmentation allows significant increases in natural low flows. The Willamette River in the USA and the Seine River in France are examples of successful low flow augmentation programs.

Utilizing methods described in Chapters 1 and 4, the economic aspects of cooling capability increases in the Pulawy cross-section of the Vistula River were analyzed based on augmentation of low flows. Assuming K=0.35; 0.40; 0.45, the flow shortages and increase of reservoir flows are presented in Table 5.3. The calculated marginal benefits due to the increase in open cycle cooling for power plants were compared with the capital costs of reservoir storage and with the social costs of increased water flows. Capital costs of storage were calculated based on the reduction of total capital costs of reservoir and hydraulic construction, as well as the costs of flood control.

It was assumed that flood control occurred over 4 months; in the remaining 8 months, the whole usable reservoir capacity is utilized for low flow augmentation.

Investment costs of augmentation capacity (I_w) were calculated according to the equation:

$$Iw = \frac{Ig \times 8 + Uw \times Ig \times 4}{12} = \frac{Ig\ (2 + Uw)}{3} \qquad (5.4)$$

where:

Ig = capital cost of reservoir construction,

Uw = share of augmentation capacity of the usable capacity, %.

Based on economic indicators accepted by Hydroprojekt in the "Vistula" Plan and comparing cost indicators with price levels from 1976, the indicators of investment cost obtained on storage of disposable resources amounts to 11.5 zl/m^3.

In Poland, social costs of flow increases are based on operating costs and on the cost of capital (Ministerztwo 1975). The purpose of the interest cost is to encourage rational water use. Social costs of water flow increase, Ko, amount to:

TABLE 5.3. COOLING SYSTEM PARAMETERS IN RELATION TO RATE OF FLOW AUGMENTATION IN THE PULAWY CROSS-SECTION

Rate of flow augmentation	Flow shortages, 10^6 m^3	Increment of cooling system %	Increment of operating time of open cooling system, months	Total operating time of open cooling system, months	Capacity increment in power plant MW	Marginal costs of increment of open cooling system size, 10^6 zl
0.35	156	6	1	1	138	151.8
0.40	300	21	2	3	483	531.3
0.45	450	36	4	6	828	910.8

Table 5.4. ECONOMICS OF COOLING SYSTEM SIZE FLOW AUGMENTATION IN THE PULAWY CROSS-SECTION

Rate of flow augmentation	Marginal costs of increment of open cooling system size, 10^6 zl	Investment costs of water storage, 10^6 zl	Social costs of flow increment, 10^6 zl
0.35	151.8	1794	187.2
0.40	531.3	3450	360.0
0.45	910.8	5175	540.0

$$Ko = \frac{Ke + Iw \times 8}{L} \qquad (5.5)$$

where:

Ke = reservoir operating cost,

Iw = as in equation 5.4,

L = period of reservoir utilization (assumed L=100 years).

Individual social costs of flow increase in 1976 prices are 1. 2 zl/m^3.

The comparative cost summary presented in Table 5.4 indicates that the social costs of flow increase, are smaller than the marginal costs of open cycle cooling increase. Investment costs of storage are too high to justify reservoir construction only for the demand of power plant cooling. The calculations indicate that for construction of reservoirs for complex regulation of low flows, a proper share of power plant output should be recognized as a form of compensation for increases in river cooling capability. On the investigated sections of the upper and middle Vistula, an increase of flow can be utilized by the following four power plants:

Opatowiec - in area of the Danajec tributary,

Polaniec - below the Nida tributary,

Zamosc - below the San tributary,

Pulawy - above the Wieprz tributary.

5.6. Cooling in Discharge Channels and Precooling Reservoirs

Precooling reservoirs can be used as supplemental cooling facilities for once-through plants or those using the surfaces of natural lakes or artificial reservoirs for cooling. Under some conditions, the precooling reservoirs can be combined with discharge channels and/or with artificial spawning channels to reduce overall costs.

Examples of supplemental cooling systems include the following:

(1) At the Dresden power plant in the USA (Units 2 and 3 - 2x809 MW), discharge channels with cooling sprays provide supplementary cooling for an artificial cooling reservoir.

(2) At the Chesterfield power plant in the USA (Units 4, 5 and 6 with a capacity 972 MW), water is discharged to an old riverbed of the James River (channel Farrar Gut of 6 km length) (Jensen 1974); supplemental spray cooling is also employed.

(3) La Maxe power plant - 2 x 250 MW (France), discharges water to the Moselle River via a reservoir of 72 hectares. This precooling

reservoir is 3,245 m long, with a maximum width of 350 m and a mean depth of 1.60 m. The time of water flow through the reservoir is 12 hours.

A precooling reservoir of 73 hectares and depth of 2 to 3.5 m was built for cooling system of the Patnow and Konin power plants in Poland. The basic cooling system of these power plants is a complex of 5 natural lakes. The precooling reservoir is supplementary to the circuit for two additional units of 2 x 200 MW capacity. The water from the precooling reservoir is discharged to a complex of fishing lakes of 185 hectares. This solution secured proper cooling for the power plants and simultaneous utilization of heat release for beneficial purposes (i.e. fishing).

Areas of precooling reservoirs can be defined by:

$$F = \frac{A}{w\ \overline{\delta t}} \qquad (5.6)$$

where:

F = cooling area surface

A = thermal energy dissipation by the precooling reservoir

w = coefficient of surface heat exchange

$\overline{\delta t}$ = difference between the mean temperature in the precooling reservoir and natural water temperature, (°C)

Assuming that:

- natural temperature is 25°C (t_n)
- temperature rise in the condenser is 8°C
- amount of heat discharged to the cooling system, C_k = 1200 kcal/kWh
- coefficient of surface heat exchange according to the results of research at the Konin lakes and Rybnik reservoir (Gadkowski 1976b):

$$w = 16.2 + 0.2 \cdot t_n \qquad \text{kcal/m}^2\text{/h/°C} \qquad (5.7)$$

The solution of equations 5.6 and 5.7 for various values of t_n provides the following results for the precooling reservoir:

Comparison of results for the La Maxe reservoir calculated according to equation 5.7 (Figure 5.2.) indicates that intensity of surface heat exchange in the La Maxe reservoir is, in the summer period, about 15% higher than in the reservoir circuits in the complex of Konin Lakes and in the Rybnik reservoir. This difference can be explained by climatic and regional differences.

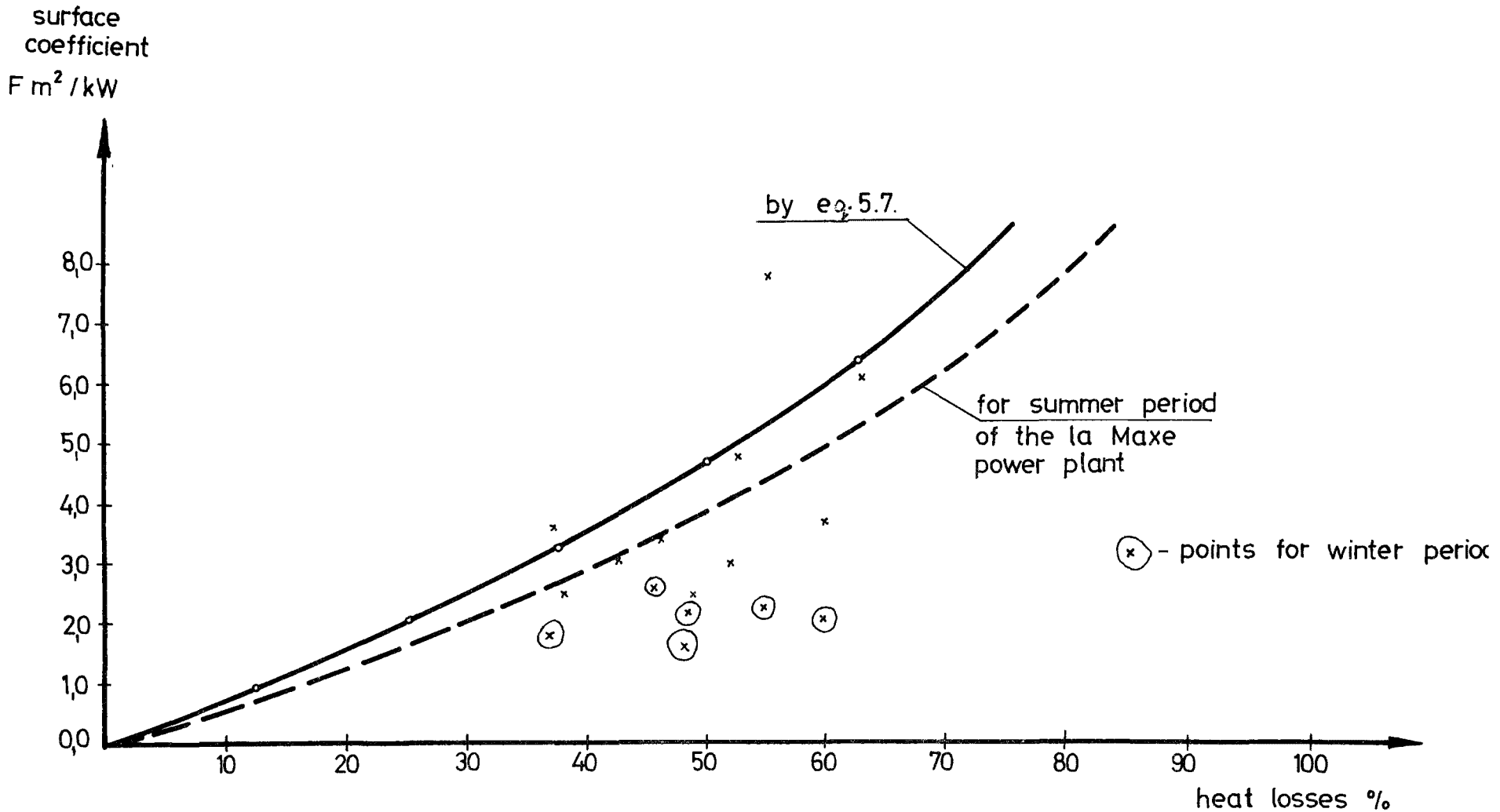

Fig. 5.2. Heat losses in precooling reservoirs

Temperature drop through precooling reservoir, °C	1	2	3	4	5
Heat dissipated, %	12.5	25.0	37.5	50.0	62.5
Cooling surface, sq. m/kW	0.94	2.02	3.26	4.72	6.43
Investment cost, % of power plant construction	1.15	2.46	3.48	5.76	7.84

A detailed analysis of the preliminary cooling system for the Patnow II power plant was conducted, including field measurements in the discharge channel of Patnow power plant (Figure 5.3).

Five measurement cross-sections were placed on this channed:

- point A - situated 100 m below power plant outfall,
- point B - situated 150 m above first overflow to Goslawskie Lake,
- point C - 200 m below last overflow,
- point D - 580 m downstream from point C,
- point E - about 100 m above the connection of the Konin power plant discharge channel with the Patnow power plant discharge channel.

The research was carried out in two annual measurement surveys in 1975 and 1976.

In 1975 the research included temperature measurements from boats. Six measurement series were executed in this period; their results are presented in Figure 5.4.

Lack of consistent cooling is observed for the overflow to Goskawski Lake (i.e., between section B and C). It can be assumed that this phenomenon appears due to turbulent water overflow to the lake which causes intensive evaporation and convective heat exchange between the water and atmosphere.

The results obtained during the 1975 surveys indicate that cooling on the whole length of the channel, excluding the B-C section, is linear in character. This permitted measurements made in 1976 over a short section to represent the whole channel length. Therefore, further measurements were made only on the A-B section but with an increased number of samples.

In December 1975, four thermistor instruments were installed in cross-sections A and B and in an additional cross-section, A' situated at a distance

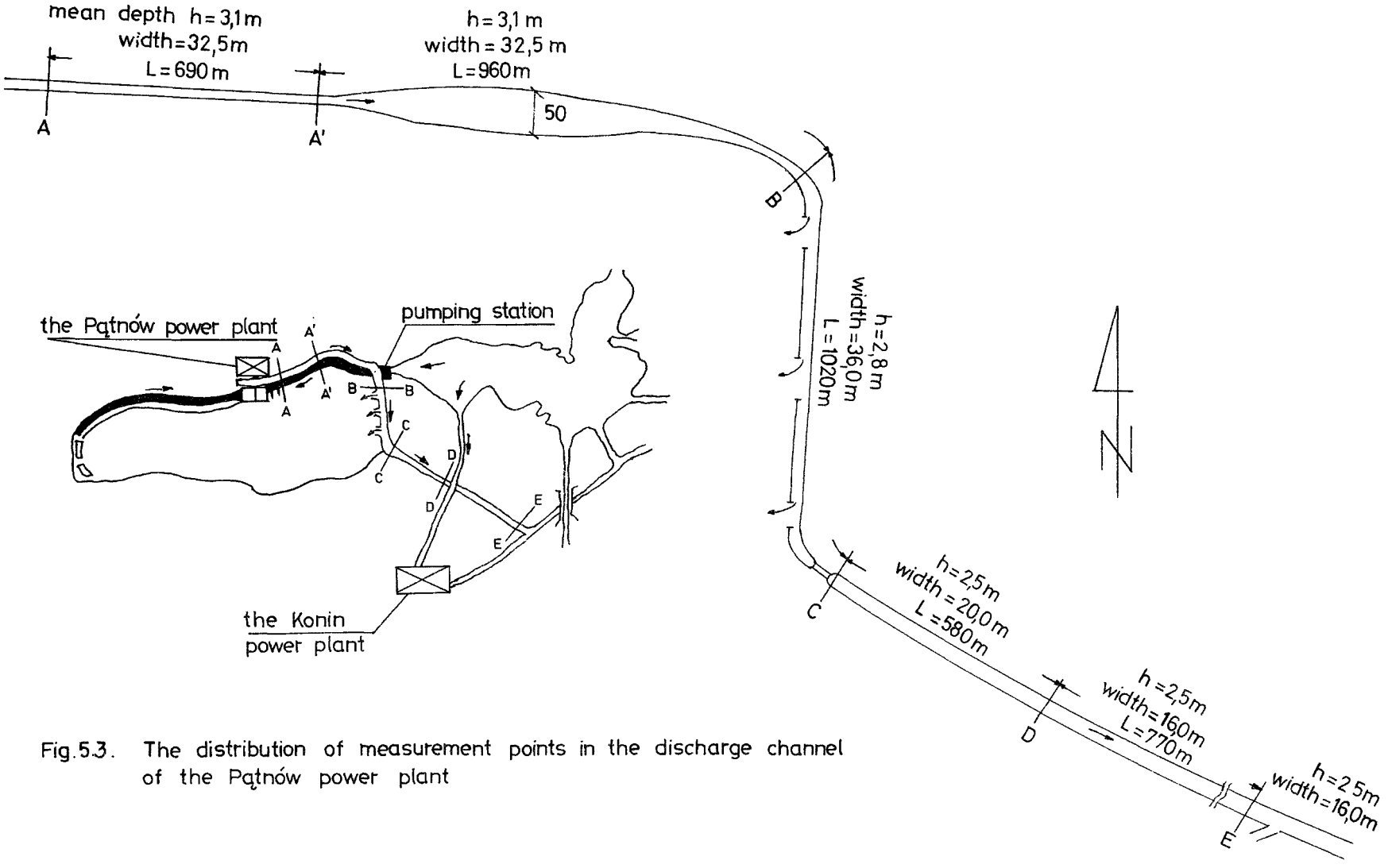

Fig.5.3. The distribution of measurement points in the discharge channel of the Pątnów power plant

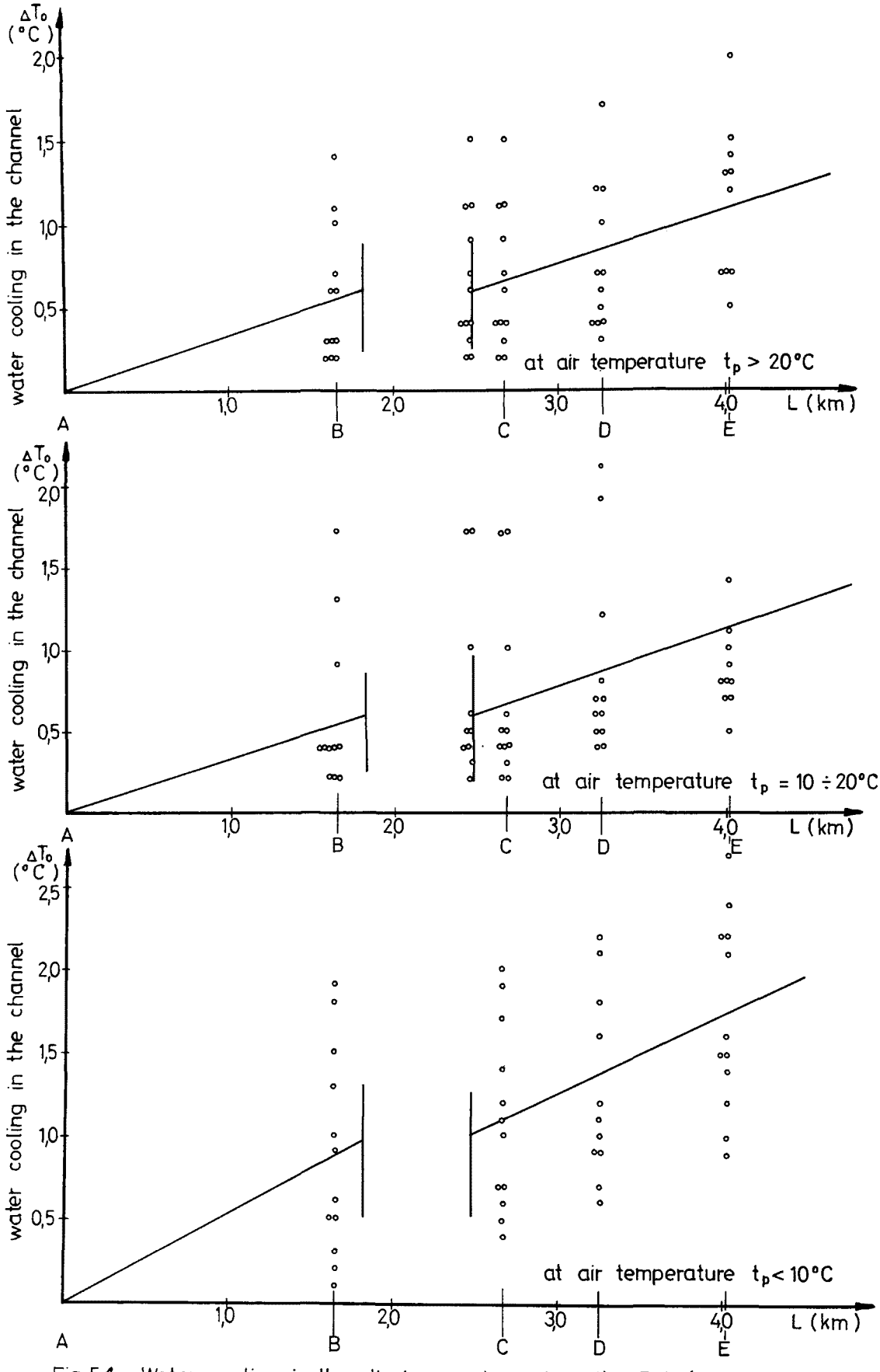

Fig. 54. Water cooling in the discharge channel of the Pątnów power plant – surveys in 1975

of 690 m from cross-section A. At points A and A', the detectors were installed at the surface, at mid-depth and at the bottom in 3 plumb lines, 1 detector each, for a total of 9 thermistors. At point B, a total of six detectors were installed in two plumb-lines.

The measurements of 1976 were executed three times in a 24-hour period. Because of power plant load alterations, some measurements were discarded. Only results obtained at stabilized power plant power outputs were accepted for analysis.

About 288 measurements were used in the subsequent data analysis. The mean values of the results indicate that in the case of the Patnow power plant, with a mean channel width of 150 m and a mean depth of about 3.0 m, the intensity of water cooling in the channel may be described using the equation 5.8:

$$\delta t = e^{-(a\ tn + b)} \tag{5.8}$$

where:

δt = indicator of water cooling at the distance of 1 km of the channel reduced to the difference of 1°C between temperature of discharge water and natural water temperature,

tn = natural water temperature, °C,

a,b = coefficients

$$a = 0.0235$$
$$b = 3.0713$$

The correlation coefficient of the curve obtained from the equation is low and equals 0.31. The distribution of measurement points and the fitted curve are presented in Figure 5.5 and show the large variability of the water cooling effect in the channel.

Assuming a water temperature increase in the power plant of 8°C, it is possible to describe the water cooling intensity as (δt):

at $tn = 20°C$, $\delta t = 0.232$ °C/1km
$th = 25°C$, $\delta t = 0.208$ °C/1km

Therefore under summer conditions, a distance of 4.5 to 5.0 km of channel length is required for a 1°C drop in temperature.

Unit costs for 1 km of the discharge channel, by analogy to the Dolna Odra power plant, may be assumed to be 0.26% of total investment costs. The cost of the discharge channel necessary to cool the water by 1°C will thus range from 1.17 to 1.3%. It is worth noting that costs of the discharge channel as well as the costs of precooling reservoirs can vary widely depending on local conditions and methods of construction.

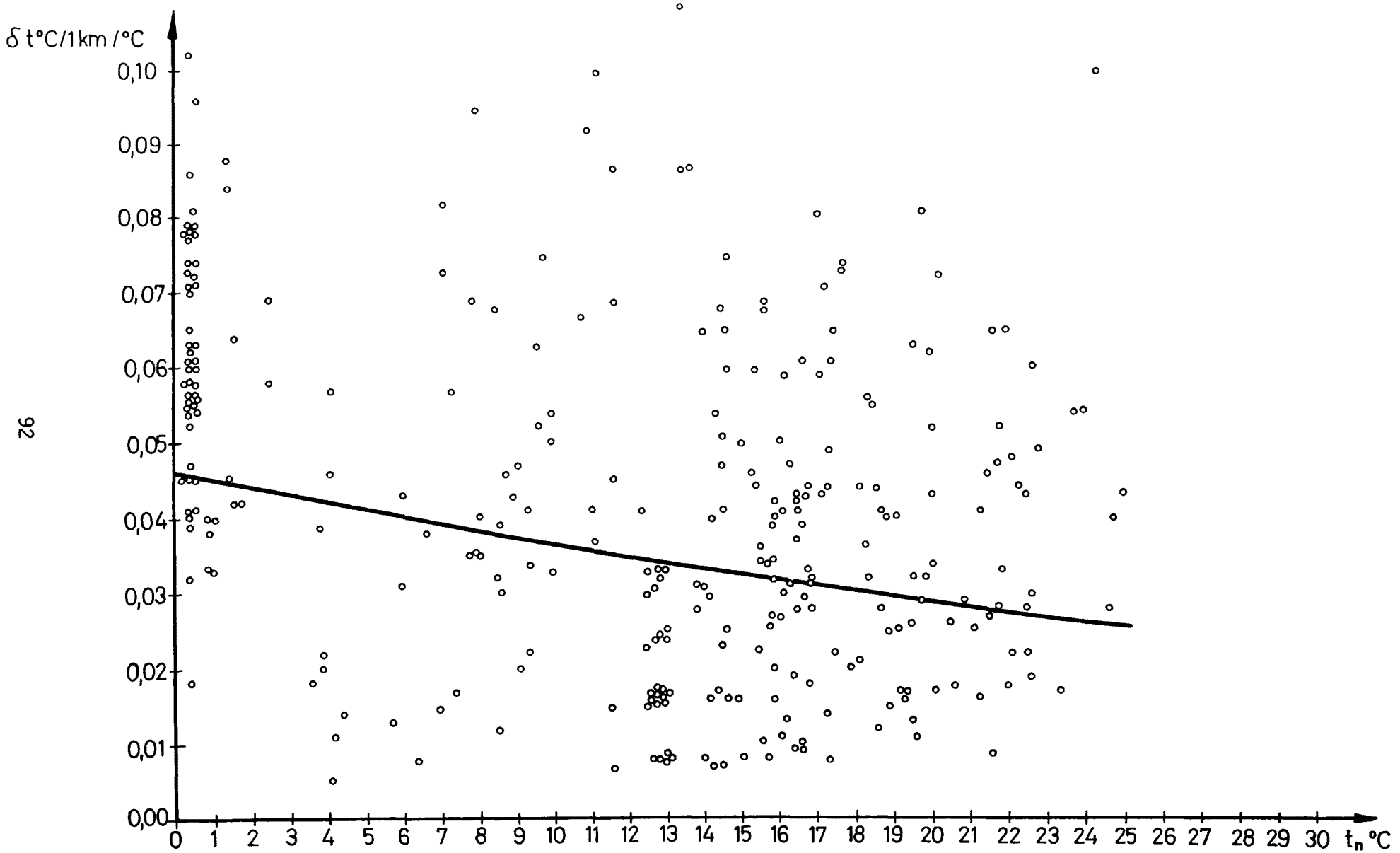

Fig. 5.5. Indicator of water cooling in the discharge channel of the Pątnów power plant t°C/1km/°C

5.7. Utilization of Mechanical Draft Cooling Towers

Utilization of mechanical draft cooling towers in hybrid installations of combined cooling circuits is a recognized solution. It derives from both economic and thermal aspects.

The thermal balance of hybrid circuits using cooling towers can be defined as:

$$tn + \Delta t - \Delta t_H - \sigma_H = \sigma_p \tag{5.9}$$

where:

tn = intake water temperature,

Δt = temperature rise in the condenser,

Δt_H = cooling range, difference between intake temperature and discharge temperature from the cooling tower (in the majority of hybrid cases, $\Delta t_H < \Delta t$),

σ_H = approach - difference between the discharge water temperature and the wet bulb temperature,

σ_p = wet bulb temperature.

As calculations indicate (Gadkowski 1972a), a significant role is played by the approach in determining the costs and size of the cooling tower. In general, the larger the approach, the smaller the cooling tower. Normally, approaches less than 3°C are not designed.

In an earlier paper (Gadkowski 1969), a proposal for hybrid installations using mechanical draft cooling towers was suggested as follows:

$$tn + 2\Delta t - \Delta t_H - \sigma'_H = \sigma_p \tag{5.10}$$

$$\sigma'_H = \sigma_H + \Delta t \tag{5.11}$$

A modified scheme for hybrid installations involves a two-fold temperature rise of the cooling water through the condenser. In this way a significant increase of approach is obtained. Calculations indicate that this modified scheme of hybrid installations allows a decrease by nearly half of the costs of mechanical draft cooling towers in Poland. Such a scheme is employed in the cooling circuit of the Polaniec power plant, presently under construction.

6. Summary

In this report, methods for determining capacities of open-cycle and hybrid power plant cooling systems are presented. Hybrid cooling systems are ones which combine once-through cooling systems with additional cooling devices to reduce a part of waste heat load to obtain an acceptable temperature increase in the receiving water.

The report provides detailed analyses of these main elements:

- hydrological conditions required for once-through power plant cooling systems,
- guidelines, standards and regulations which are obligatory in various countries,
- water temperature and temperature increases downstream from the discharges of existing power plants.

Based on the results of these analyses, it is concluded that once-through cooling system capacity depends on:

- hydrological characteristics of the river,
- acceptable temperature increase downstream from discharge,
- power plant capacity factor variability.

On the basis of various analyses of reliable flows for evaluating cooling systems operating conditions, low monthly flows with a probability of occurrence p=90% are assumed reliable.

Analyses of water temperatures occurring downstream from the discharge of power plants and the impact of heated water on the oxygen balance in the receiving water as well as impact on fisheries were used to develop the following acceptable temperatures for Poland:

1. acceptable discharge water temperatures, 35°C
2. acceptable mixed temperatures downstream from the discharges, 30°C
3. acceptable temperature increase over the intake water temperature, 4°C to 6°C, depending on the season of the year.

To maintain the free migration of fish, discharge configurations which guarantee a horizontally stratified temperature distribution in the receiving

water downstream from the discharge should be applied. Model investigations show that such horizontal stratification can be obtained when the angle of the discharge channel is in the range of 45 to 65° in relation to the river axis and when the discharge velocity is about half of the river flow velocity upstream from the discharge.

Monthly average power plant capacity factor values are defined by:

$g_i = (f_i + \Delta f_i)\ (b + 0.134\ b \cos\alpha - .008b^2 \cos\alpha)$

g_i = maximum monthly average capacity factor at the assumed probability of occurrence

b = annual mean capacity factor

f_i = mean monthly correction coefficient

Δf_i = correction coefficient defining the relationship between the g_i value and the assumed probability level

α = angle designated by the function of a month:

$$\alpha = \frac{2i - 1}{12}\ \pi$$

For practical purposes, coefficients for power plants with an operating time of 6,000 h/year at a 90% probability were assumed. These values for individual months and applied to power plants in Poland are listed below:

Jan. - 87.45	July - 75.33
Feb. - 87.73	Aug. - 77.33
Mar. - 82.76	Sep. - 78.36
Apr. - 75.94	Oct. - 80.66
May - 76.30	Nov. - 84.41
June - 77.86	Dec. - 85.46

From the standpoint of waste heat balance, the installed capacity of a power plant with open cooling can be determined by:

$$P \cdot g_{ki} \cdot C_k = Q \cdot Ki_{10\ \%}\ \delta t_i \cdot \rho \cdot c \cdot 3600$$

where:

P = power plant installed capacity (MW)

g_{ki} = monthly average capacity factor for p=90%

C_k = waste heat discharged from the power plant in the cooling water (Kcal/kWh)

c = specific heat of water (kcal/kg/°C)

ρ = density of water (Kg/l)

Q = mean annual river flow (m^3/s)

$K_{i\ 10\%}$ = distribution coefficient, describing the ratio for low monthly flow (p=10%) to the mean annual flow.

δt_i = acceptable increase in mixed river temperature under critical conditions for month i.

7. Conclusions

As a result of the analyses conducted during this project, the following conclusions are made:

1. Considering the variability in both river flow and steam power plant load factors, the installed capacity of open cycle cooling systems in Poland can be increased by about 25% without installation of supplemental cooling.

2. If the installed capacity of Polish power plants must be increased by more than 25%, the best technical solution is hybrid cooling systems with mechanical draft cooling towers and double-pass condensers.

3. For single power plants, modest increases in capacity (e.g., 20%) over once-through systems can be economically obtained via open cycle systems with pre-cooling reservoirs and spray systems.*

4. The economic analysis indicates that low flow augmentation using upstream storage reservoirs is too expensive when used solely for stream temperature control and can be applied only when a comprehensive water management strategy is developed.

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* The author is aware of the difficulties encountered with spray system operation in the USA. The use of spray systems in Poland would be predicated on resolution of these operating problems.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

The report describes analytical, laboratory, and field research conducted to optimize the use of rivers, specifically in Poland, for once-through cooling of steam electric power plants. Maximum discharge and receiving water temperatures, based on biological criteria, are coupled with natural flow and temperature variations to determine acceptable flow/temperature regimes for streams over an annual cycle. Controllable variables, such as repair schedules, reserve capacity, power plant size, hybrid cooling system size and operation, and low flow augmentation via reservoirs, are evaluated as mechanisms to modify electrical power output. The acceptable temperature/flow regimes in streams are then compared to various power system configurations and schedules to optimize the annual generation of electric power. The following conclusions are reached, relative to Polish conditions:

-- The installed capacity of open cycle cooling sytems can be increased by about 25% without installing supplemental cooling.

-- For increases greater than 25%, mechanical draft cooling towers and double pass condensers operated in a hybrid, open cycle is the most economical solution.

-- Low flow augmentation for power plant cooling via upstream reservoirs is economical only when used in a comprehensive water management plan.

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