16 ECONOMIC EFFECTIVENESS OF RESERVOIRS

Reservoirs are a part of the economic potential of any country, and as they are capital investment constructions they must be evaluated as such. An objective measure is to determine how they help to raise industrial productivity, which is done with the help of *quantitative economic indices*. Some capital investment consequences can only be estimated *qualitatively* and not quantitatively. However, the qualitative evaluation is of great importance for reservoirs. Intangible effects can lead to a choice of an alternative, which is less effective economically, but more advantageous socially.

16.1 EVALUATION OF THE EFFECTIVENESS OF RESERVOIRS

The same needs can often be met by different (alternative) measures. The most effective option is determined by a comparison of technical and economic indices of all implementable and interchangeable options. The needs can be met by various resources or by a different exploitation of the same resource. All losses and benefits must be taken into account.

How the water demand from a certain source is met depends on the natural conditions and on the parameters of a reservoir, i.e., its dimensions and methods of operation. These are derived from a synthesis of technical and economic calculations, including quantitative indices and qualitative characteristics.

The *effectiveness of capital investments* is determined by a complex comparative analysis of all decisive factors which influence the demands and effect of the capital investments.

Characteristic for reservoirs and dams is

- long service life,
- relationship with other branches of the economy and with the human environment,
- functions in large and complicated systems,
- multi-purpose use,
- possibility of construction in stages.

These characteristics influence the evaluation of their effectiveness; the methods used are:

- evaluation of alternatives by the method of comparative effectiveness,
- evaluation by the method of total effectiveness,
- evaluation of the alternatives by the method of decision analysis.

Basic terms

The *effectiveness of a capital investment* is the sum of the effects by which the investment contributes to the optimal structure of the material-technical foundation of a society and the meeting of that society's needs.

Economic effectiveness is the relationship between the summary economic demands and the economic effects created by them.

Intangible effectiveness reflects the influence of capital investments on cultural and social needs, and the improvement of the environment.

The *effects of the investment* are the economic and intangible results arising from its construction.

The *demand of the capital investment* is the sum of the demands on all sources and services in the non-economic sphere which are connected with the acquisition and operations of the basic tools.

Investment costs are the sum of the costs covered by capital investments and operation resources made in connection with the construction.

Direct investment costs are costs included in the capital investment.

Derived investment costs are the costs connected with the acquisition of the capital investment, which will be administered by other investors and must be made in the construction of the given capital investment.

Indirect investment costs are the costs that must be made in connection with the construction under consideration in other branches, to ensure the operation of the construction.

16.1.1 Evaluation of the effectiveness of reservoir construction by the method of comparative (relative) effectiveness

The *method of comparative effectiveness* should be used for the comparison of alternatives, which qualitatively and quantitatively fulfil the same aims at the same time, and are therefore interchangeable. Economically the most effective option is the one that has the *smallest sum of annuity or transferred costs*, which serve as evaluation criteria.

The index of transferred costs P transfers OMR (operation, maintenance and repair) and investment costs to a form that can be added up by one of the following methods:

(a) $$P = k_n J + P_p \overset{!}{=} \min \qquad (16.1)$$

where P is the transferred costs of the ith alternative
J – investment costs of the ith alternative
P_p – OMR costs of the ith alternative
k_n – standard coefficient of economic efficiency of investments (e.g., $k_n = 0.1$).

This method should be used if the construction time is short (about 1 year) and if the OMR costs are constant throughout the service life.

(b) $$P_T = k_n PV(J) + P_p \overset{!}{=} \min \qquad (16.2)$$

where P_T is the modified index of transferred costs

$PV(J)$ – the present value of investment costs and whereby

$$PV(J) = \sum_{j=1}^{T_c} J_j r^{(T_{cp}-j)} + \sum_{T=-T_{cp}+1}^{T_s} J_T r^{-T} \tag{16.3}$$

T_{cp} – construction time prior to the start of operations,

T_s – time of the service life of the capital investment in years,

T_c – construction time in years,

J_T – investment (j-th year of construction) costs in the T-th year of operation,

T – years of operation,

j – years of construction,

r – standard time factor (e.g., $r = 1.1$) $r = 1 + d$; d is the discount factor.

This modified method should be used for options with different construction times T_c or with different distributions J in the respective construction years, expressed on the time axis of years of operations. It is presumed that the OMR costs of the options are constant during the service life, or at least that they change in the same way.

(c) $$P_a = k_f[PV(J) + PV(P_o)] = DM(J) + DM(P_o) \overset{!}{=} \min \tag{16.4}$$

where P_a are the annuity costs during the service life,

P_o – OMR costs,

DM – discount mean in terms of the relationships,

$$DM(J) = k_f\, PV(J) \tag{16.5}$$

$$DM(P_o) = k_f\, PV(P_o) \tag{16.6}$$

k_f – coefficient of economic efficiency of investments (capital recovery factor), which is a function of r and T_s in terms of

$$k_f = \frac{r^{T_s}(r-1)}{r^{T_s}-1} = \frac{1}{\sum_{T=1}^{T_s} r^{-T}} \tag{16.7}$$

Values k_f for $r = 1.06$ and 1.1 for various T_s values can be found in Table 16.1.

This modified method should be applied if the options (alternatives) differ not only in their investment and OMR costs, which change in different ways with time, but also as to their service life.

Note 1. Provisions of the Czech Ministry of Investments prescribe uniform values of the standard time factor and efficiency coefficient: $r = 1.1$; $k_n = 0.1$; k_f = capital recovery factor for $r = 1.1$ and the respective time T_s.

Table 16.1 Values k_f for various values T with $r = 1.06$ and 1.1

T_s [years]	k_f for r 1.06	1.1	T_s [years]	k_f for r 1.06	1.1	T_s [years]	k_f for r 1.06	1.1
1	1.060 00	1.100 00	15	0.102 96	0.131 47	50	0.063 44	0.100 86
2	0.545 44	0.576 19	20	0.087 19	0.117 46	60	0.061 88	0.100 33
3	0.374 11	0.402 12	25	0.078 23	0.110 17	70	0.061 03	0.100 13
4	0.288 59	0.315 47	30	0.072 65	0.106 08	80	0.060 57	0.100 05
5	0.237 40	0.263 80	35	0.068 97	0.103 69	90	0.060 32	0.100 02
10	0.135 87	0.162 75	40	0.066 46	0.102 26	100	0.060 18	0.100 01

As reservoirs have an exceptionally long service life and are of great importance for the whole society, the Ministry of Water Management issued orders that for the comparison of the options the values should be: $r = 1.06$; $k_n = 0.06$; k_f = capital recovery factor for $r = 1.06$ and the respective time T_s.

Note 2. In the USSR methods for determining the economic efficiency of investments were adopted in 1969. According to these, the standard coefficient of economic efficiency of investments k_n is in the range of 0.10 to 0.33, i.e., the time to recover the costs is between 10 and 3 years. Zarubayev (1976) determined the following values:

Complex water management projects	0.10
Navigation	0.10–0.15
Irrigation	0.17–0.33
Drainage	0.11–0.25
Fish farming	0.17

It is recommended that a time factor be introduced, which for most water management projects is $\leq k_n$.

Method:

1. Investment and OMR costs are distributed over the respective years of a time series. If P_0 values are constant, they can be calculated for one year only; if they change in all options in the same way (only in relation to the value of the capital investment), they can be compared only for the final year; if P_0 increases annually by the same amount, the marginal flow factor Z_t should be introduced:

$$Z_t = \sum_{m=1}^{t} r^{-m} = \frac{(r^t - 1) - t(r - 1)}{r^t(r - 1)^2} \tag{16.8}$$

2. The characteristics of the differences between the options is estimated, and a criterion selected; the values are calculated from equation (16.1) to (16.7).

3. The costs in the respective years are multiplied by the respective investment-rate factor; they are added for every option and the difference between those sums is determined.

Evaluation of the results

Economically, the most expedient is that option which has the minimum sum of transferred or annuity costs. However, when choosing the optimal option secondary economic as well as intangible factors must also be taken into consideration. It must also be borne in mind that investment and OMR costs can be flexible.

If the effect of interchangeable options differs only slightly (up to 5%), the specific costs (transferred or annuity) are calculated per unit of production (amount of water or energy supplied annually).

Table 16.2 Economic comparison of two alternatives of a reservoir with dam

Index		Number of workers greater	Number of workers smaller
Total investment cost J (mil. Kčs), where J is divided into the years		400	600
of construction 1978		50	100
1979		100	150
1980		100	150
1981		100	150
1982		50	50
Number of workers		400	100
Average annual wage (Kčs yr^{-1})		30 000	32 000
Life span (years)		80	70
Discounted investment costs (mil. Kčs)			
Year of construction:	Factor r^t:		
1978	1.262 48	63.12	126.25
1979	1.191 02	119.20	178.65
1980	1.134 60	113.46	170.19
1981	1.060 00	106.00	159.00
1982	1.000 00	50.00	50.00
		451.68	684.09
OMR costs (mil. Kčs yr^{-1}):			
wages		12.00	3.20
electricity		4.00	5.00
maintenance, etc.		3.00	4.00
Annuity with capital recovery factor:	$k_{f,70} = 0.061\,03$	–	41.75
	$k_{f,80} = 0.060\,57$	27.36	–
Total costs (mil. Kčs yr^{-1})		46.36	53.95

Problem 16.1

The more advantageous of two alternative reservoirs with dams which differ greatly in their need for manpower during the construction is to be selected. The saving in manpower is balanced by higher costs for machinery and the resulting higher wages for skilled workers.

It is presumed that both options have the same utility and therefore only their respective costs are compared differently. Calculations are given in Table 16.2.

The results of the comparison show that the machinery was very expensive so that the option with a greater need for manpower would be the cheaper of the two. Even if the service life of both the options were $T_s = 80$ years, the result would change slightly more in favour of the "machinery" option.

With a total of capital investment for the second option of $J = 500$ mil. Kčs, equally distributed over the years of construction and with the same OMR costs, the costs come to a total of 46.60 mil. Kčs yr^{-1}, so that the first and the second option are practically equal. When using a higher standard value, $r = 1.1$, the first option without the introduction of new technology, would be more expedient.

16.1.2 Evaluation of the effectiveness of reservoir construction by the method of total (absolute) effectiveness

The method of total effectiveness is used to evaluate the economic effectiveness of the final choice derived by the method of comparative effectiveness (Section 16.1.1) or in estimating options with greatly differing effects which can be expressed in the form of costs and prices. This method is suitable to judge projects of

- single-purpose reservoirs for the supply of surface water or the production of electrical power,
- multi-purpose reservoirs,
- irrigation or flood control,
- supply of drinking water or utility water, including the resource, treatment, transport and distribution of the water.

The following conditions must be fulfilled:

- the capital investments must form an independent operational unit (otherwise the evaluation has to be extended to a set of functionally related investments),
- it must be possible to determine clearly all demands necessary to attain the required effect and to determine the entire effectivity of the investment,
- it must be possible to quantify the demands and effects in technical and monetary units in valid prices or their equivalents. Examples of the calculations for four alternatives are given in Table 16.3.

The most effective of the options I to IV is, according to the criterion of the maximum of the summary effect, option II. The optimum will be between options I–III. Figure 16.1 plots the relationships $SE = f(O_p)$ and $SE = f(J)$, which are similar. It is clear that the calculations of the four options do not suffice to determine the optimum, as four points still leave much licence as to their connection (see the dashed branches a, b and a', b').

It follows from line 24 of Table 16.3 that the locality of the reservoir is not very suitable, as with the chosen standards ($r = 1.06$) and with the price of water at 0.46 Kčs m^{-3}, $SE_{1.06}$ hardly reaches positive values. There is no doubt that with $r = 1.1$, $SE_{1.1}$ would be negative in all cases.

Table 16.3 Optimization of reservoir storage capacity for public water supply

Line	Index	Unit	Alternative I	II	III	IV
1	Yield O_p	$m^3 s^{-1}$	1.2	3.4	4.0	5.5
2	Water supply capacity	mil. $m^3 yr^{-1}$	37.84	94.61	126.15	173.45
3	Amount of water supplied during $T_s = 80$	mil. m^3	2872.48	4628.76	8731.30	11 546.65
3a	Average during one year	mil. $m^3 yr^{-1}$	34.06	57.86	109.14	144.33
	Benefits W for water supplied with price of water 0.46 Kčs · m^{-3}					
4	– 1st year	mil. Kčs yr^{-1}	4.60	4.60	4.60	4.60
5	– 6th year	mil. Kčs yr^{-1}	9.20	9.20	9.20	9.20
6	– 11th year	mil. Kčs yr^{-1}	–	23.00	23.00	23.00
7	final year	mil. Kčs yr^{-1}	17.41	43.52	58.03	79.79
8	(final year)	(year of operation)	(9)	(16)	(19)	(24)
	Present value of benefits $PV(W)$					
9	When $r = 0.6$	mil. Kčs	229.67	442.31	533.61	639.36
10	Discounted average of benefits	mil. Kčs yr^{-1}	13.91	26.79	32.32	38.73
11	Investment costs J	mil. Kčs	250	350	500	700
12	– direct costs	mil. Kčs	210	300	440	600
13	– derived costs	mil. Kčs	30	36	40	72
14	Construction period	years	4	5	5	6
15	Present value J $[PV(J)]$	mil. Kčs	274.05	407.27	583.99	834.13
16	Depreciation of direct costs (A)	mil. Kčs yr^{-1}	2.63	3.75	5.50	7.50
17	OMR costs (P_o)	mil. Kčs yr^{-1}	1.47	2.10	3.08	4.20
18	Total production costs (NV)	mil. Kčs yr^{-1}	4.10	5.85	8.58	11.70
19	Present value of P_o $[PV(P_o)]$	mil. Kčs	24.27	34.67	50.85	69.34
20	Annuity of $PV(J)$	mil. Kčs yr^{-1}	16.60	24.67	35.37	50.52
21	Annuity costs (NA)	mil. Kčs yr^{-1}	18.07	26.77	38.45	54.72
22	$PV(J) \cdot k_n$ (for $k_n = 0.1$)	mil. Kčs yr^{-1}	27.41	40.73	58.40	83.41
23	Transferred costs $PTV = k_n \cdot PV(J) + P_o$	mil. Kčs yr^{-1}	31.51	46.58	66.98	95.11
24	Total investment effect when $r = 1.06$ $SE = PV(W) - PV(J) - PV(P_o)$	mil. Kčs	−68.65	+0.37	−101.23	−264.11

Explanation to Table 16.3

line 2: is calculated from line 1 by multiplying by 31 536 000 s yr^{-1}

line 3: the actual amount supplied is calculated, i.e., up to the complete depletion of the reservoir's capacity (linear extrapolation between the years 1–6, 6–11 and 11–16) and then up to $T_s = 80$; full capacity

line 3a: from line 3 by dividing by $T_s = 80$

lines 4–7: the actual amount supplied is multiplied by the price of water 0.46 Kčs m^{-3}

Table 16.3 (continued)

line 8:	ordinal number of the year from the start of operations in which the reservoir capacity is fully exploited for the first time
line 9:	the actual annual incomes are converted to the present values by multiplying by r^{-t}
line 10:	from line 9 by dividing by z_t = 16.509 13 for T_s = 80
line 15:	direct costs (line 12) are distributed over the respective years of construction, updated to the start of operations and added to the derived costs
line 16:	from line 12 by multiplying by 0.0125
line 17:	from line 12 by multiplying by 0.007
line 19:	from line 17 by multiplying by z_t = 16.509 13 for T_s = 80
line 20:	from line 15 by multiplying by $k_{f.80}$ = 0.060 57
line 21:	from the sum of lines 15 and 19 by multiplying by $k_{f.80}$ = 0.060 57
line 23:	sum of lines 18 and 22

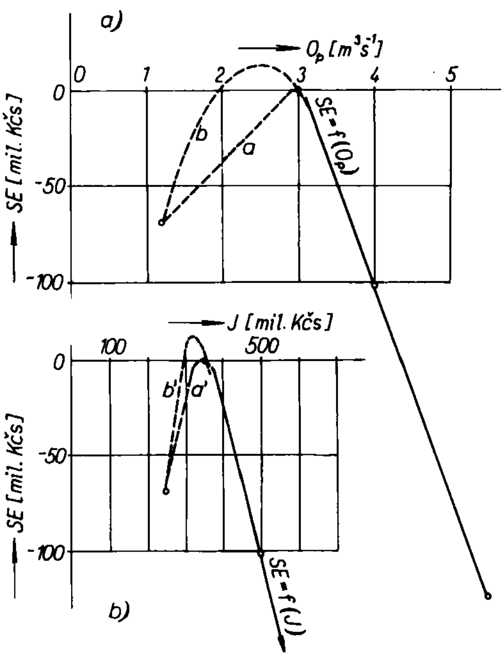


Fig. 16.1 Selection of optimal parameters of a reservoir from the graph of SE, (a) $SE = f(O_p)$; (b) $SE = f(J)$

As the capacity of the reservoirs differs greatly, the values of the specific indices of the respective options were calculated in Table 16.4. According to these, the best option is either II or III. According to all indices of specific costs the least suitable is option I, even though according to $SE_{1.06}$ it follows just after option II. In the given case all specific costs in the final year are lower for option II, while for the whole service life of a reservoir they are lower for option III. The differences are not as great as for SE.

If the reservoir is in an area with little water yield and therefore the price of the water is higher, optimization can be repeated for this higher price. If, for example, the price were double, the summary effect of option II would be 442.68 and of option III 432.38. It is clear that the optimum is between option II and III. After adding the secondary effects, the difference between the summary effects would further decrease to 455.11 and 449.29. If other reservoirs are to be built, the average discounted productivity of investment costs (using valid prices) is even lower and does not reach the *ARDJ* > 5% as in option III (see Table 16.5), it would be justified to recommend option III., especially if also used for power production.

Table 16.4 Specific indices for various reservoirs for water supply

Index	Unit	Alternative I	II	III	IV
Specific *J* for O_p	mil. Kčs $m^{-3} s^{+1}$	208.3	116.7	125.0	127.3
Specific *NV* for m^3 of water supplied in final year	hal m^{-3}	10.84	6.18	6.80	6.75
Specific *NV* for m^3 of average water supplied	hal m^{-3}	12.04	10.11	7.86	8.11
Specific annuity costs					
– for m^3 of water in final year	hal m^{-3}	45.32	28.30	30.48	31.55
– for m^3 of average water supplied	hal m^{-3}	50.35	46.27	35.23	37.91
Specific transfered costs					
– for m^3 of water in final year	hal m^{-3}	83.27	49.23	53.10	54.83
– for m^3 of average water supplied	hal m^{-3}	92.51	80.50	61.37	65.90

1 hal = 0.01 Kčs

Table 16.5 Comparison of gross productivity and mean annual discounted productivity

Index	Unit	Alternative I	II	III	IV
Gross productivity	%	6.38	11.83	10.99	10.80
Mean annual discounted productivity	%	4.54	6.06	5.01	4.14

Economic effectiveness of the optimal option

If we want to compare the advantages of two localities for reservoirs which are to supply water to the same region, we must find an optimal solution for every locality (Table 16.3 and 16.4) and for these we calculate the indices of the effectiveness of the investment

(a) The summary discounted productivity of investment costs $SRDJ$ is calculated from the equation

$$SRDJ = \frac{PV(W) - PV(P_o)}{PV(J)} \tag{16.9}$$

where PV is the present value: W – benefits; P_o – OMR costs; J – investment costs.

(b) The mean annual discounted productivity of investment costs $ARDJ$ is given by the relationship

$$ARDJ = \frac{100[DM(W) - DM(P_o)]}{PV(J)} = 100k_f \cdot SRDJ \tag{16.10}$$

where DM is the discouned mean; equation (16.5) and (16.6).

(c) The mean discounted (reproduction) productivity of direct costs P_d is given by

$$VRDP_d = \frac{100[DM(W) - DM(NP)]}{P_d} \tag{16.11}$$

(d) The rate of reproduction recovery TJR is given by

$$TJR = 100\frac{TJ}{T_s} \tag{16.12}$$

where TJ is the reproduction recovery in years.

Note: if the net benefit from the investment ($V = W - P_o$) is constant throughout the service life, then

$$TJ = \frac{J}{W_c - P_{oc}} \tag{16.13}$$

If the net benefit changes, the calculations have to be done in steps for the respective years (see Table 16.6).

(e) The demand on the indirect investments II is given by the relationship

$$II = \frac{P_{d,\,indirect}}{P_{d,\,direct}} \tag{16.14}$$

Problem 16.2

We use the values of option II in problem 16.1

(a) according to equation (16.9)

$$SRDJ = \frac{442.31 - 34.67}{402.27} = 1.0009 > 1$$

(b) According to equation (16.10)

$ARDJ = 100 \cdot 0.060\,57 \cdot 1.0009 = 6.063\% > 6\%$

Table 16.6 Calculations of reproduction recovery of reservoir *TJ* (problem 16.1, alternative II)

Year	Annual values (mil. Kčs yr^{-1})			Balance J (mil. Kčs)
	Benefits (W)	OMR costs (NP)	Net benefits ($W - NP$)	350.00
1	4.60	2.10	2.50	347.50
2	5.52	2.10	3.42	344.08
3	6.44	2.10	4.34	339.74
4	7.36	2.10	5.26	334.48
5	8.28	2.10	6.18	328.30
6	9.20	2.10	7.10	321.20
7	11.96	2.10	9.86	311.34
8	14.72	2.10	12.62	298.72
9	17.48	2.10	15.38	283.34
10	20.24	2.10	18.14	265.20
11	23.00	2.10	20.90	244.30
12	27.60	2.10	25.50	218.80
13	32.20	2.10	30.10	188.70
14	36.80	2.10	34.70	154.00
15	41.40	2.10	39.30	114.70
16	43.52	2.10	41.42	73.28
17	43.52	2.10	41.42	31.86
18	43.52	2.10	41.42	0

$$TJ = 17 + \frac{31.86}{41.42} = 17.77 \text{ year}$$

Let us compare *ARDJ* of all four options of problem 16.1 with the benefit-costs ratio which is given by the relationship

$$VJ = \frac{100(W_c - P_{o,c})}{J} \tag{16.15}$$

where index c denotes the values of the final year.

The results are given in Table 16.5. They clearly show that the benefit-costs ratio, calculated from the values of the final year, over-estimates the effectiveness of the investment, in our case quite substantially.

(c) According to equation (16.11):

$$VRDP_d = \frac{(442.31 - 34.67) \cdot 0.060\,57}{300} 100 = 8.23\%$$

(d) The reproduction recovery TJ (Table 16.6) is calculated and it comes to $TJ = 17.77$ years. Then according to equation (16.12)

$$TJR = 100\frac{17.77}{80} = 22.21\%$$

(e) According to equation (16.14):

$$II = \frac{36}{300} = 0.12$$

The role of secondary effects on the optimization of the capacity of a reservoir

Even a single-purpose reservoir can have favourable secondary effects which help to improve its total effect. Favourable effects can be, for example, recreational facilities, influence on the surrounding environment, new buildings which replace those in the inundated area, etc. Effects, however, can also be unfavourable, e.g., cold water downstream of a reservoir in summer, limitation of new constructions in the catchment of the reservoir.

Any secondary effects are estimated in valid prices or their equivalents from other branches. However, each case requires an individual analysis.

Table 16.7 Inclusion of secondary effects in the optimization of the water supply capacity

Line	Data	Unit	Alternative			
			I	II	III	IV
1	Presumed number of holiday-makers	thousand visitors / days per year	30	40	50	70
	Benefits from recreation facilities:					
2	– in final year (already 1st year)	mil. Kčs yr^{-1}	0.45	0.60	0.75	1.05
3	– present value of benefits	mil. Kčs	7.43	9.91	12.38	17.33
	Improvement of the state of buildings:					
4	– present value of benefits	mil. Kčs	5.0	7.0	10.0	15.0
5	– annual equivalent of benefit		0.30	0.42	0.61	0.91
6	Total present value of secondary effects	mil. Kčs	12.43	16.91	22.38	32.33
7	Total effect of investment including secondary effects	mil. Kčs	–56.22	17.28	–78.85	–231.78

Note: Line 7 is the sum of lines 6 and 24 of Table 16.3

Let us look at how the indices of the four options (I–IV) of our problem change, if we include in the calculations of the water supply and the income for water, secondary effects such as recreation facilities and the improvement of the present state of some buildings. (Tab. 16.7).

From line 7 in Table 16.7 one can see that the summary effect of the investment improved by including secondary effects; however, this did not change the order of the options. To cause any change, the secondary effects would have to be much more extensive and there would have to be a greater difference in the respective options.

16.1.3 Evaluation of alternatives of reservoirs by the method of decision analysis

Decision analysis is a method of selecting the optimal alternative; the decision must consider all economic as well as intangible effects. The process is a formal objective one; however, the evaluation of the respective aspects includes subjective judgements.

The decision process consists of

– the determination of the criteria to estimate the extent to which the required aim was reached,

– a simple evaluation of the options,

– a mutual comparison of the options,

– a weighted evaluation of the options.

This process results in the determination the hierarchic sequence of functions.

The criteria are to reflect the essential functions of a reservoir and should be independent of one another, i.e., they should not overlap. The criteria for reservoirs must express their costs, economic impacts, relationships with the environment and cultural monuments, conditions of construction, operational reliability, etc. The selection of the criteria is the most responsible stage of the decision-making process; it frequently has heuristic characteristics; it requires a creative approach and is specific for every reservoir.

Criteria that should be used in selecting an option

1. *Cost* criteria:

(a) investment

(b) OMR (operation, maintenance and repair)

Investment costs can be compared with the given financial limit as a whole or for a certain period.

2. *Performance* criteria:

(a) according to the quantity (amount of water supplied, hydro-power, navigation, flood control, etc.),

(b) according to the quality (reliability of water supply, water quality, etc.),

3. Criteria for the *influence on the human environment*:

(a) protection and creation of a natural environment (good and bad influence on the environment and respective measures, elimination of the fear of floods, flood damages or fear of lack of water, improvement or deterioration of sanitary conditions, etc.),

(b) exploitation for leisure time and water sports,

(c) confiscation of farm and forest land,

(d) moving of people living in the inundated area,

(e) protection of cultural and technical monuments.

4. Criteria of *economic efficiency*:

(a) the present value of investment costs and OMR costs or transferred costs (Sections 16.1.1 and 16.1.2);

(b) mean discounted reproduction productivity (Sections 16.1.1 and 16.1.2), if can be expressed in terms of money.

5. Criteria of *construction* which favourably or unfavourably affect the reservoir construction and are not reflected in the investment costs:

(a) construction time,

(b) conditions of foundations not determined by geological and geotechnical research,

(c) dependence of the construction on deliveries from abroad,

(d) requirement on the accuracy of work and technological discipline,

(e) difficulties of construction due to weather conditions, transport, lack of local manpower, topography of the building site, etc.,

(f) use of prefabs,

(g) utilization of the suppliers' resources.

6. Criteria of *operations*:

(a) reliability of operations and ability to overcome any breakdowns,

(b) maintenance and repairs,

(c) scope of limitations during reconstructions and repairs,

(d) influence of weather conditions on the reservoir's operations.

7. Criteria of *development*:

(a) harmony with other water-management projects,

(b) adaptability to future changes in the demands on a reservoir,

(c) conceptual reliability, i.e., ability to overcome breakdown situations in a system,

(d) extent and time consistency in the ulization of a reservoir.

8. *Other criteria*:

(a) conflicts of interests with other branches (use of fertilizers in farming, cattle breeding, etc.),

(b) state of readiness (territorial, planning, project, from the point of view of the supplier),

(c) international character of a reservoir, with the participation of other countries,

(d) defence,

(e) agreement with the political aims for the development of the region.

The criteria that are chosen, are those that best characterize the efficiency of the evaluated alternative. Those criteria which do not differentiate the alternatives can be eliminated from the evaluation.

Table 16.8 Simple and weighted estimation of two reservoirs

Criterion	Weight	Estimation of alternative I		Estimation of alternative II	
		simple	weighted	simple	weighted
1. investment costs	10	1	10	4	40
2. amount of water supplied	7	4	28	2	14
3. protection of the environment	8	4	32	5	40
4. recreation facilities	3	5	15	2	6
5. flood control	9	5	45	2	18
6. confiscation of land	5	3	15	2	10
7. people to be moved	4	2	8	5	20
8. economic effectiveness	11	4	44	3	33
9. time of construction	2	2	4	4	\
10. construction difficulties	1	2	2	3	3
11. agreement with water-management plans	12	5	60	2	24
12. competitive goals	6	2	12	4	24
score		39	275	38	240

Table 16.9 Comparison of the weight of the criteria in the Fuller triangle

2	3	4	5	6	7	8	9	10	11	12	Criterion	Number of advantages
1	1	1	1	1	1	8	1	1	11	1	1	9
	3	2	5	2	2	8	2	2	11	2	2	6
		3	5	3	3	8	3	3	11	3	3	7
			5	6	7	8	4	4	11	12	4	2
				5	5	8	5	5	11	5	5	8
					6	8	6	6	11	12	6	4
						8	7	7	11	12	7	3
							8	8	11	8	8	10
								9	11	12	9	1
									11	12	10	0
										11	11	11
											12	5

Problem

The water resources of an area are to be supplemented by a further resource of surface water. Two localities are considered and their utilizations optimized independently of each other. The most suitable locality should be determined. As the two reservoirs also have an extensive intangible impact, the decision analysis method is used.

Step 1: criteria are chosen (a total of 12), which best characterize the differences in the evaluated options and do not overlap (Table 16.8).

Step 2: a simple evaluation of the options is carried out, by giving each criterion a certain number of points on a scale, e.g., from 0 to 5, whereby 0 is the lowest evaluation and 5 the highest. By adding up these points a simple score is obtained for each option (Table 16.8). Evaluation by points is a matter of qualified estimation with a certain element of subjectivity. It is less serious to estimate one of the criteria incorrectly than to leave out an important criterion.

According to this simple score, option I appeared to be the more suitable; however, the difference of only one point is insignificant. From this estimation it is clear that two reservoirs are being compared, of which one is very large and the other much smaller. Even though the result of the comparison is uncertain, it draws attention to the most important criteria of the problem, mainly 1, 11 and some others.

Step 3: A mutual comparison of all the criteria is carried out with the help of the Fuller triangle (Table 16.9). The result of the estimation of two criteria is then written at the point of intersection of the line and column with the number of the compared pair of criteria, by writing down the number that is given preference. The preferences gained for each criterion are then added and their number written in the last column of the table with the respective number of the criterion. The number of preferences gained characterizes the weight of the criterion.

The greatest weight (11) was ascribed to broader water-management aims (criterion 11), followed by economic efficiency (10 for criterion 8), investment costs, etc. This estimation in pairs is also subject to personal opinions.

Step 4: Weighted estimation of the options is gained by the multiplication of their simple estimation (Table 16.8) by the weight of the respective criterion (Table 16.9) increased by one (to eliminate the possibility of zero weight). The sum of all the weighted values of the criteria of each option gives its weighted score; the bigger one determines the more favourable of the two options from the point of view of the criteria that were used (Tab. 16.8).

Option I proved to be the most advantageous by 35 points, i.e., by about 15%. The final decision will depend on the attitudes taken by various authorities concerning the decisive criteria 11, 8 and 1. Water-management authorities will prefer option I, with respect to criterion 11, while the authorities deciding the financial means will be inclined to support option II with respect to criterion 1.

Evaluation of the method of decision analysis

The method has an objective part (formalized process) and a subjective part (selection and evaluation of criteria, simple evaluation of the options), which is an advantage, as well as a weakness, of this method.

The advantage is that the formal process is the same for everyone and that subjective estimation requires a more profound information about the respective options.

The weakness is that the objective rules need not necessarily reflect the proportions of the advantages correctly and that the results are greatly influenced by the subjective part. This influence can be limited by the proper choice of experts that can ensure a comprehensive view of all the elements evaluated. Where the opinions of experts differ, open discussion can clarify the reasons for the different opinions.

The main advantage of the decision analysis, however, is that it exceeds the limits of purely technical and economic estimations and that intangible factors can be introduced.

In spite of these advantages, decision analysis should not be expected to produce a final decision. However, those that are to make the decision will have valuable material on which to base it.

16.2 COST DISTRIBUTION OF MULTI-PURPOSE RESERVOIRS

Reservoirs usually serve several purposes and therefore investment and operation costs are divided among the respective uses (components of the water management complex). This is necessary to estimate the economic efficiency of every use of the reservoir correctly, to determine the technical and economic indices of the respective uses and to evaluate the whole system (water management, power, etc.).

There are many methods by which this complicated problem can be solved (Matlin, 1961; Shchavelev, 1961, 1966). It is not simple to distribute the investment and operation costs according to the respective uses according to their proper contribution to the national economy.

Interesting methods have been elaborated by the Leningrad Polytechnic Institute (LPI) and by the Ministry of Forestry and Water Management of Czechoslovakia—MLVH (1976).

16.2.1 The LPI method

The LPI method is based on the following conditions (Zarubayev, 1976):

1. The economic efficiency of a reservoir for the respective uses is determined by comparing the costs for two possible cases:

(a) for shared costs,

(b) for the realization of the most suitable interchangeable options, which would have the same effect.

2. The options compared must render the same production or services.

3. The economic efficiency of a reservoir for the respective users is determined on the basis of the time needed to repay the additional costs invested for this use, as compared to its alternative solution.

4. The costs of a multi-purpose reservoir are divided among the respective users in proportion to the economic efficiency of each use.

All investment costs for the basic parts of a reservoir are divided between joint costs and special costs. *Joint costs* serve several users: these include dams, reservoirs, large canals, etc. *Special costs* serve one user: lock chamber, building of the power plant, fish-passing facility, etc.

The efficiency of a reservoir is determined for every user by comparing the costs of two alternatives. For example, the efficiency of navigation compared with rail and road transport.

The comparison must be based on an extensive analysis of all natural, political, social, economic and technical factors. Other costs connected with a reservoir must also be taken into consideration, e.g., transfer of electrical power, transport of water, etc.

The repayment period T_i for the ith use is determined from the equation

$$T_i = \frac{(J_i + J_{is}) - J_{iz}}{P_{o,iz} - (P_{o,i} + P_{o,is})} \qquad (16.16)$$

where J_i are the investment costs of the ith use of the whole scheme,
J_{is} are the investment costs needed for the operation of the ith use,
J_{iz} are the investment costs of the interchangeable alternative for the ith use,
$P_{o,is}$; $P_{o,iz}$ are the OMR (operation, maintenance and repair) costs of the ith use of the whole scheme (other facilities needed for its operation; its interchangeable alternatives).

The repayment period of a whole scheme with n uses is

$$T = \frac{\sum_{i=1}^{n} (J_i + J_{is}) - \sum_{i=1}^{n} J_{iz}}{\sum_{i=1}^{n} P_{o,iz} - \sum_{i=1}^{n} (P_{o,i} + P_{o,is})} \qquad (16.17)$$

The index of transferred costs is frequently used as the minimum criterion

$$P = k_n J + P_p \overset{!}{=} \min \qquad \text{[equation (16.1)]}$$

If the investment costs are distributed unevenly over the respective years of construction and if the OMR costs change, equation 16.1 can take a more general form:

$$P_\tau = k_n \sum_{j=1}^{\tau} J_j r^{\tau - j} + \sum_{j=\tau_{op}}^{\tau} P_{p,j} r^{\tau - j} \qquad (16.18)$$

where τ is the year to which the costs are brought up to date (e.g., $\tau = T_s$),
τ_{op} is the year in which operations start;

Other symbols are as given for equations (16.1) to (16.7).

If we select for τ the year of the beginning of operations $\tau = \tau_{op} = T_c$, equation (16.18) can be written as equation (16.2).

For a multi-purpose reservoir with n uses, equation (16.18) will take the form of

$$P_\tau = \sum_{i=1}^{n} \sum_{j=1}^{\tau} (k_{n,i} J_{j,i} + P_{p,j,i}) r^{\tau - j} \tag{16.19}$$

The productivity of the reservoir can be derived from the relationship

$$SRDJ = \frac{PV(W) - PV(P_o)}{PV(J)} \qquad \text{[equation (16.9)]}$$

The costs can be distributed proportionally between the respective components of the whole complex:

1. according to technical indices (reservoir volume, amount of water supplied and used for individual purposes);
2. according to the scope of the contribution of each use;
3. according to the economic efficiency of the measures introduced for a certain use.

The third condition led to practical recommendations: Every ith use of the whole complex has the following investment costs J_i and OMR costs $P_{o,i}$:

$$J_i = J_{\text{joint}} \frac{P_{z,i} - P_{\text{spec},i}}{\sum P_z - \sum P_{\text{spec}}} + J_{\text{spec},i} \tag{16.20}$$

$$P_{o,i} = P_{o,\text{joint}} \frac{P_{z,i} - P_{\text{spec},i}}{\sum P_z - \sum P_{\text{spec}}} + P_{o,\text{spec},i} \tag{16.21}$$

where J_{joint} are the investment costs of joint structures and from among the special structures those parts that are under the joint costs,
$P_{o,\text{joint}}$ (or $P_{p,\text{joint}}$) – OMR costs,
$J_{\text{spec},i}$ – investment costs of special structures for the ith use,
$P_{o,\text{spec},i}$ (or $P_{p,\text{spec},i}$) – OMR costs,
$P_{y,i}$, $\sum P_z$ – the transferred costs of interchangeable structures of the ith use and of all the uses of the whole complex,
$P_{\text{spec},i}$, $\sum P_{\text{spec},i}$ – the transferred costs of special structures of the whole complex.

Transferred costs can be calculated from equation

$$P = k_n \sum_{j=1}^{T} J_j + \sum_{a=1}^{t} P_{o,a} \tag{16.22}$$

where T is the number of years,
j – the ordinal number of the year for the period T,
J_j – the increasing investment costs including the jth year,
$P_{o,a}$ – the variable OMR costs for the period from $a = 1$ to $a = t$ years.

As the respective components do not make full use of the whole complex at the same time, the indices of their efficiency also change with time, so that the value of the fraction in equations (16.20) and (16.21) is variable.

16.2.2 Directives issued by the Ministry of Forestry and Water Management of Czechoslovakia concerning the principles of evaluating the efficiency of investment for water management constructions and the distribution of costs of multi-purpose reservoirs

If the efficiency of the respective uses of a multi-purpose reservoir (MPR) has clearly been proved and its capacity has been optimized, then the overall efficiency does not have to be proved by distributing the costs over the respective uses.

The components of a multi-purpose reservoir can be divided into special and joint components. Investment and OMR costs for the special components are called special costs and concern only specific use. Investment and OMR costs of the joint components are called joint costs and these must be divided between the respective uses.

If a special component also has other functions (for instance if a lock chamber or the construction of a multi-purpose hydro-power plant replaces part of the impounding structure), then its special costs are decreased by the amount also serving other purposes; these costs are then included in the joint costs.

Cost distribution

To simplify this method, the term "summary costs, or SC" can be introduced. This is the sum of the present value of the investment and the respective OMR costs.

$$SC = PV(J) + PV(P_o) \tag{16.23}$$

Summary costs (SC) concern the whole reservoir, special components (SC_{spec}) and joint components (SC_{joint}).

1. Special investment and OMR costs of the respective uses and their present value, i.e., SC_{spec} are determined.

2. Joint investment and OMR costs and their present value, i.e., SC_{joint} are determined (the difference of the total costs and the special costs).

3. The efficiency of the respective uses is checked according to the special costs. If the SC_{spec} are higher than the present value of its performance or the present value of an interchangeable solution, the use of MPR is not effective and it is omitted.

4. The share of the summary costs of the whole MPR for the ith use, presuming the same discounted contribution WSD of the ith use and the whole MPR is determined, therefore

$$WSD = \frac{PV(W)}{SC} = \frac{PV(W_i)}{SC_i} = \text{const} \tag{16.24}$$

hence

$$SC_i = SC\frac{PV(W_i)}{PV(W)} \tag{16.25}$$

where $PV(W)$ or $PV(W_i)$ is the present value (PV) of the output of the whole MPR, or the output of the ith use,

SC or SC_i – the summary costs of the whole MPR, or of the ith use.

5. The share of the ith use in the summary joint costs is the difference of the summary costs for this use out of the total costs of the MPR and the summary costs of its special components are determined:

$$SC_{\text{joint},i} = SC_i - SC_{\text{spec},i} \tag{16.26}$$

6. The coefficient of the proportional distribution of the summary costs for the joint components among the respective uses is determined by

$$k_i = \frac{SC_{\text{joint},i}}{SC_{\text{joint}}} \tag{16.27}$$

which must fulfil the condition that

$$\sum_{i=1}^{n} k_i = 1.0 \tag{16.28}$$

7. The share of any part of the costs of the joint components for the ith use can be calculated with the coefficient k_i:

$$J_{\text{joint},i} = k_i J_{\text{joint}}$$
$$P_{\text{o,joint},i} = k_i P_{\text{o,joint}} \qquad \text{etc.}$$

8. The resulting costs of the ith use are calculated as the sum of the respective special costs and the share for these uses from among the joint costs:

$$J_i = J_{\text{spec},i} + J_{\text{joint},i}$$
$$P_{\text{o},i} = P_{\text{o,spec},i} + P_{\text{o,joint},i} \qquad \text{etc.}$$

This is valid for the costs in the respective years as well as for their present values and discounted means.

Note: The accuracy and objectiveness of the distribution of the costs of a multi-purpose reservoir among the respective uses is given mainly by the accuracy of economic measurements of its output and secondary effects, which must be expressed in monetary units as costs. If there are no value equivalents for significant secondary effect, they can be expressed with the help of investment and OMR costs of an interchangeable alternative; from these the annuity or transferred costs are calculated, or they can be determined by an agreement between the users of a multi-purpose reservoir.

16.3 ECONOMIC SIGNIFICANCE OF THE RELIABILITY OF WATER SUPPLY AND FLOOD CONTROL

Output and services in water management have only a limited realiability. This reliability therefore determines the probability of satisfying the needs of the users completely, as far as water and the protection against the harmful consequences of water are concerned. This factor is important for any economic estimation of a reservoir. Even a small change in this rate can extensively change the basic parameters of a reservoir, as well as its costs and efficiency. To determine its optimal value is an economic problem that can be solved only by a very complex method and with the help of economic indices.

In water management the term "gauranteed" output has two values: the size of the output and its reliability, which is usually less than 100%. According to the type of reservoir, the economically justified values of the size and respective reliability concern, e.g.

- release from a reservoir to the river to increase the discharge,
- withdrawal of water from a reservoir for various purposes,
- output and production of hydro-power plants,
- all of these in a multi-purpose reservoir.

These parameters determine the size of a reservoir and are indispensable in any economic considerations.

16.3.1 Significance and variability of the reliability of water supply

Water-management balances presume that the need for water will be met in various degrees of reliability according to the damage that might be caused if the water is not supplied to the full amount. The rate of reliability of a full water supply is sometimes given by a *standard of design reliability* $P_{o\,des.}$; mostly as a share (%) of years in which the supply of water is ensured without any breakdowns. Data can be found in Section 4.4.

The higher the standard of the design reliability, the smaller the losses caused by the deficits of water, but the higher the costs for the utilization of the water resource (reservoir, conduits, etc.). The economic optimum for meeting the needs of the respective users is found by comparing these two consequences.

However, even an extensive economic analysis on the basis of which the standards for the supply of water are determined cannot accurately define all economic consequences.

One of the reasons is that the economic losses caused by the deficits of water are non-linear and differ greatly. A certain decrease in the supply of water or a short period in which no water is supplied at all need not lead to economic losses. Therefore the standard of reliability $P_{o\,des.}$ sometimes has two values of withdrawal: for the full need the standard is lower and for reduced withdrawal it is higher.

The time factor in the system water resource – user has an even greater effect on the reliability of water supply. The demand-supply relationships in the system vary with time. A new water resource (reservoir) is usually being built at a time when the reliability of water supply is lower than the standard or the economic optimum. During the development of the system and also during the construction and even the filling of a reservoir the reliability is decreased. When a reservoir is full, the reliability of water supply is usually higher than the standard and then gradually decreases up to the moment when the relationship presumed by the design between the yield of the water resources and the need for water is established.

Sudden changes in the system concern not only the water resources, but also the users if, e.g., a new factory is opened, or irrigation systems, housing estates, etc. are built.

Cooperation in a system helps to raise the output, or if the output remains the same the reliability is increased. A new resource which is not fully exploited can serve as a reserve in the system.

The reliability of developing dynamic systems should be investigated. Conditions in the second year and in the final target twelfth year after a new reservoir has been

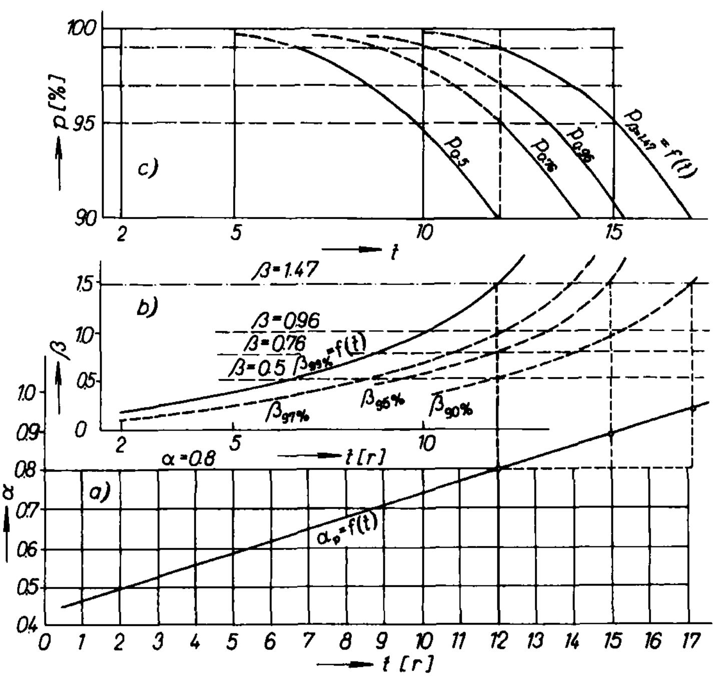


Fig. 16.2 Changes of reliability in time
(a) increase of water demand α_p in time and opening of a new resource $\alpha = 0.8$; (b) time pattern of volumes $\beta_z = f(t)$ needed to cover the demand α_p with various probabilities p; (c) time pattern of probability $p = f(t)$ for various β_z values

constructed to supply water to a certain region are plotted in Fig. 16.2. The time function of the demand on water is shown by the straight line $\alpha_p = f(t)$. In the second year $\alpha_p = 0.5$, but by constructing a reservoir with a relative storage capacity $\beta_z = 1.47$ a relative water supply of $\alpha = 0.8$ was ensured*); therefore when the new reservoir starts to operate the system has a surplus output of $\alpha - \alpha_p = 0.3$. To ensure the required $\alpha_p = 0.5$ in the second year, a reservoir with a storage capacity of $\beta_z = 0.22$, instead of $\beta_z = 1.47$, would suffice.

It follows that in constructing an over-year storage reservoir with full utilization of target parameters in the future it is not necessary to consider the moment that the reservoir is completely full as the beginning of operations, but rather the time when it is full enough to cover α_p; in our case a filling of $\beta = 0.22$ in the second year is enough to cover $\alpha_p = 0.5$ with a reliability of 99%.

Curve $\beta_{99\%} = f(t)$ in Fig. 16.2b determines the storage volume of the reservoir in relation to time t which is needed to cover $\alpha_p = f(t)$ from Fig. 16.2 with a 99% reliability. The difference up to the full volume $\beta_z = 1.47$ can be used to supplement the storage function in the system (if filled with water) or for better flood control (if left empty).

Let us consider how great the need is to introduce another source in the system in the final target twelfth year. The required α_p increases above the reservoir yield $\alpha = 0.8$ and can therefore be covered only with a smaller reliability. In the fourteenth year the reliability drops to 97%, in the fifteenth year to 95% and in the seventeenth year to 90%. With a linear increase of water demand (0.03α per year) the reliability of water supply drops from 99 to 90% if the construction of a new resource is postponed by 5 years. It is a matter of economy to find the optimum moment for building a new resource. Here it can be presumed that it is economically expedient temporarily to decrease the design reliability and to postpone operations of a new resource after the twelfth year.

Let us further consider whether it would not suffice to build a reservoir in the second year that would, in the final twelfth year ensure $\alpha_p = 0.8$, with a reliability of $p = 97\%$, as already long before that, a reliability of $p = 99\%$ is obtained. The relative volume of the storage capacity would be only $\beta_z = 0.96$, i.e., 65% $\beta_{99\%}$. Figure 16.2c shows the relationships of $p = f(t)$ for various volumes β_z. From the curve $p_{0.96} = f(t)$ one can see that a reservoir with a volume of $\beta = 0.96$ would ensure—from the beginning of operations in the second year until the tenth year—a reliable water supply of $p_{0.96} \geqq 99\%$, by the twelfth year it would decrease to 97% and with this it could ensure $\alpha = 0.8$ for the whole remaining life span. There is no doubt that eight years of fully covered operations with the required $p \geqq 99\%$ cannot balance the incomplete operations with $p = 97\%$ for the remaining life span.

*) For simplicity's sake the problem was solved with Svanidze's graphs (1964, p. 145) for $C_v = 0.4$; $C_s = 2C_v$; $r = 0.2$; $p = 99\%$.

However, if another resource is constructed in the twelfth year with a capacity of $\alpha > \alpha_{t-12}$, the reliability of the former reservoir could again temporarily be raised to the required value of 99%.

However, another factor that should be taken into consideration is the time-based reliability. In this case, the function $p = f(t)$ must be found, which does not encounter any difficulties. These difficulties increase if conclusions as to the optimization of the changes of the structure of the system in time are to be drawn, especially for extensive multi-purpose systems.

16.3.2 The relationship of reliability indices and economic factors

The most frequently used index of the reliability is the probability of the number of years with unlimited supply p_o [%] (Section 4.4); however, this index does not completely reflect losses or other difficulties caused by the deficits of water (energy). The number of failure years does not reflect the duration and the depth of the failure, nor the amount of deficit water or energy. The data p_o [%] do not reflect the percentage of economic losses out of the total production.

A more suitable index of the reliability of water or energy supply is an index based on failures in percentage in terms of their duration, as this is closer to the percentage of economic losses. However, there is no direct relationship between the duration of the inability to supply water or energy and economic losses. For the supply of the same volume a less severe, but longer failure is generally economically more favourable than a shorter, but more profound failure. The best way to express the design reliability is to use its probability characteristics in terms of the supplied water volume or energy. It is easier to find a relationship between the deficits of water or energy and social losses, than a relationship between the number or duration of failures. However, not even the volume of deficit water can clearly define the economic losses. If each unit of deficit water or energy leads to the same economic loss, then the value p_d is a parameter which accurately reflects the economic consequences. Mostly, however, a unit of deficit water or energy causes different economic losses, depending on whether it is a long, light failure or a short, heavy failure. The failure must then be characterized not only by the deficit volume, but also, e.g., by the depth of the failure.

The economic consequences of a unit of deficit water or energy also depend on the time of deficits. A deficit kilowatt-hour can cause different economic losses in winter or in summer; deficit cubic metres of water for irrigation have a different impact in various parts of the growing season, etc. The relationship between the data on the rate of reliability can only be determined by a more profound analysis; to express the rate of reliability as a percentage of water supply is justified only if the economic impact can clearly be determined.

If there are no suitable statistical-economic data on the basis of which the deficits expressed in technical units (in m^3, $m^3 s^{-1}$, kWh, kW) can be transferred to economic consequences, the simplest method to determine the rate of reliability in water management; e.g., p_o [%] can be used. However, here too, at least the approximate relationship between p_o, p_t and p_d should be known.

16.3.3 Relationship between the respective reliability indices

The relationship between the time-based reliability (p_t) and the occurrence-based reliability (p_o) is important. These values differ greatly, especially in reservoirs that hardly regulate their discharges; in that case $p_t > p_o$. In reservoirs with long-term regulation values, p_t and p_o will be close.

For the relationship between the occurrence-based reliability of a real design low-flow year p_o and the design duration-based reliability of normal power supply $p_{t\,des.}$ Aivazian (1947) recommended the expression

$$p_o = 1 - \frac{1 - p_{t\,des.}}{\mu} \qquad (16.29)$$

where μ is the ratio of the total duration of the shortage period vs. the duration of these years.

Table 16.10 shows calculations of values p_o for $\mu = 0.20$ and for various $p_{t\,des.}$ values; it can be seen how greatly they change due to even small changes of $p_{t\,des.}$.

Table 16.10 Relationship between p_o and $p_{t\,des.}$ for $\mu = 0.2$ (according to V. G. Aivazian)

$p_{t\,des.}$ (%)	95	96	97	98	99	100
p_o (%)	75	80	85	90	95	100

According to the selected value of μ, the change of occurrence-based reliability p_o by Δp_o corresponds to the change of the reliability $p_{t\,des.}$ by $\Delta p_{t\,des.}$ derived from equation (16.29).

$$\Delta p_o = \frac{1}{\mu} \Delta p_{t\,des.} \qquad (16.30)$$

and therefore the change $\Delta p_{t\,des.} = 1\%$ corresponds to the change $\Delta p_o = 1/\mu$ [%]. From equation (16.30), but also from simple observations, it is clear that the values of $\Delta p_{t\,des.}$ and Δp_o differ more, the smaller the share of time falling within the range of the shortage period in low-water years, i.e., the smaller the value of μ. If μ is close to zero, Δp_t is also close to zero, but if $\mu = 1$ (i.e., if the shortage period includes the whole duration of the low-water years) $\Delta p_o = \Delta p_{t\,des.}$.

The relationships between occurrence-based reliability p_o, time-based reliability p_t and volume-based reliability p_d had been studied for 23 river sites in the Czech regions (Votruba and Broža, 1966, p. 286). Mean monthly discharges were used. Relationships were derived for current operations (without a storage capacity) as well as for various sizes of storage capacities up to $\beta_z = 1.0$. Relationships were calculated for the various degrees of release control for these capacities:

– dependence of time-based reliability on occurrence-based reliability $p_t = f(p_o)$;

– dependence of yield O_p on occurrence-based reliability $O_p = f(p_o)$;

– dependence of total water deficits $\Delta \sum O_p$ [mil. m^3] during the observation period on occurrence-based reliability $\Delta \sum O_p = f(p_o)$;

– dependence of relative water deficits $\Delta \sum O_p$ [%] on occurrence-based reliability $\Delta \sum O_p\,[\%] = f(p_o)$.

In all cases, uniform yield was considered.

(a) Relationship $p_t = f(p_o)$

Relationships $p_t = f(p_o)$ for various sizes of storage capacities A_z were drawn up for the respective sites. In Fig. 16.3 these relationships are shown for the Děčín site on the Labe. It can be seen that the values of p_t are much higher than the values of

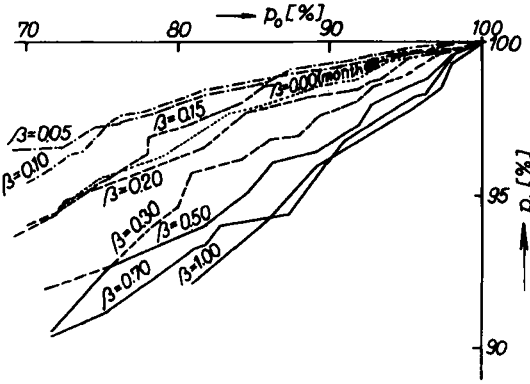


Fig. 16.3 Relationship between p_o and p_t at Děčín on the river Labe for different volumes β_z

p_o (especially for smaller reservoir volumes). With larger volumes, i.e., with over-year release control, p_t with p_o decline more rapidly. Also at the other sites the relationship between p_t and p_o is not very close and is greatly influenced by the reservoir volume.

Figure 16.4 plots the differences in relationships between O_p, p_o, p_t, p_d for current operations ($\beta_z = \emptyset$), derived from mean monthly discharges and from mean daily discharges in a 50-year series from the river Berounka at Křivoklát (1891–1940). Relationships $O_p = f(p_o)$ differ greatly, the relationship $p_d = f(p_t)$ is essentially identical within the studied range.

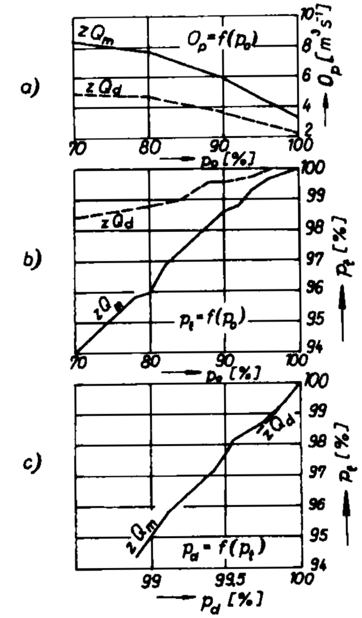


Fig. 16.4 Relationships between O_p, p_o, p_t, p_d at Křivoklát (1891–1940) for $\beta_z = 0$, derived from mean monthly and daily discharges

(b) Relationship $\sum O_p = f(p_t)$

Figure 16.5 plots the relationships $\sum O_p = f(p_t)$ for the storage capacity size $\beta_z =$ $= 0.30$ at seven studied sites using a complete observation series. The closeness of

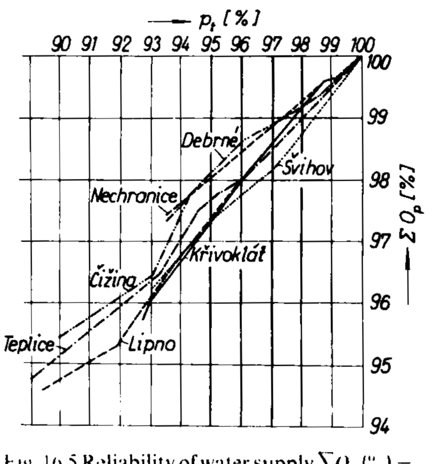


Fig. 16.5 Reliability of water supply $\sum O_p$ (%) = $= f(p)$ for $\beta_z = 0.3$

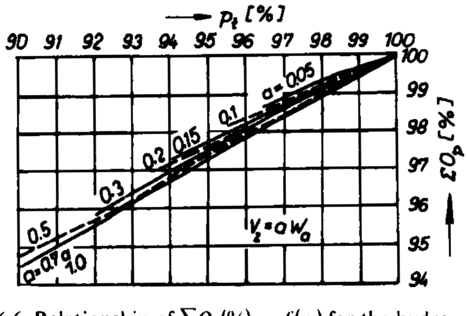


Fig. 16.6 Relationship of $\sum O_p(\%) = f(p_t)$ for the hydrological series at Děčín on the Labe (1851–1960)

the relationships is obvious; e.g., value O_p in the range of 97.3 to 98.1% corresponds to the value $p_t = 95\%$.

The relationship $\sum O_p = f(p_t)$ is close in the 110-year series at Děčín throughout the whole range of the different sizes of storage capacities ($\beta_z = 0.05 - 1.0$) (Fig. 16.6).

(c) Relationship $\sum O_p = f(p_o)$

Even though it is obvious that the relationships between $\sum O_p$ and p_o will be less close than between $\sum O_p$ and p_t, they were calculated because it is simple to determine the occurrence-based reliability p_o which is also most frequently used. Therefore it is advantageous to have a general idea of the values of $\sum O_p$ corresponding to the various values of p_o.

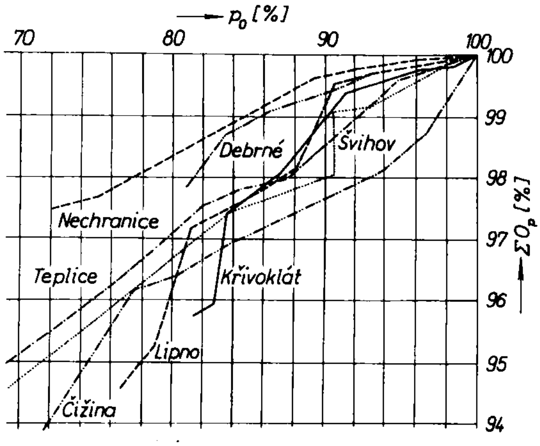


Fig. 16.7 Reliability of water supply $\sum O_p$ (%) $= f(p_o)$ for $\beta_z = 0.3$

Figure 16.7 plots the relationships $\sum O_p = f(p_o)$ for the storage capacity size $\beta_z = 0.30$ at the same 7 observed profiles. It can be observed that the relationships are less close than in Fig. 16.5.

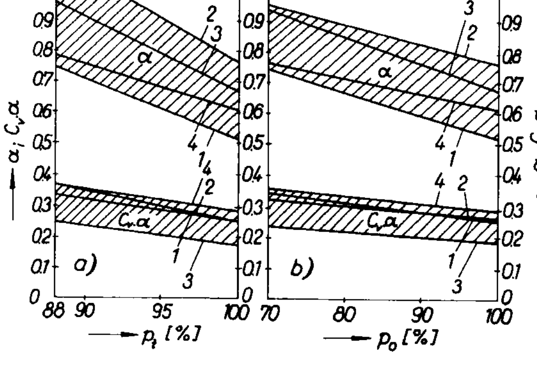


Fig. 16.8 Dependence of relative yield $\alpha = O_p/Q_a$ and product $C_v\alpha$ on reliability: (*a*) time based; (*b*) occurrence-based

(d) Relationship $O_p = f(p_t)$ and $O_p = f(p_o)$

The relationships in the period 1931 to 1960 at 15 river sites varied greatly. To make it easier to compare the results, relative yield $\alpha = O_p/Q_a$ was chosen instead of yield O_p. The limits of 15 relationships $\alpha = f(p_t)$ are plotted in Fig. 16.8a and in Fig. 16.8b the limits of 15 relationships $\alpha = f(p_o)$ for a volume of $\beta_z = 0.30$. It can be seen from the diagram that this volume can create the yield $O_p = (0.52 - 0.76) \cdot Q_a$, etc., with a 100% reliability (according to the observed period).

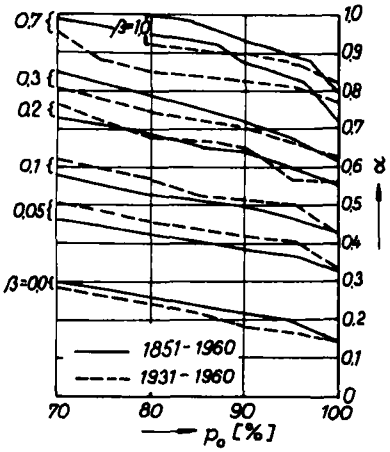


Fig. 16.9 Relationship $\alpha = f(p_o)$ for a 30-year and 110-year series of the Labe at Děčín

To show the influence of the variation coefficient on the value O_p, the limits of relationships $C_v\alpha = f(p_t)$ and $C_v\alpha = f(p_o)$ were plotted in the same figures for the same 15 sites. The decisive 4 sites were given the numbers 1 to 4. It can be seen that the influence of C_v on the rearrangement of the curves is quite extensive; the curves that were limits in the relationships for $\alpha(1.2)$ are included in the relationships for $C_v\alpha$ among the remaining curves and the other curves (3.4) shift to the edge of the family of curves.

For a better comprehension of the relationship between the 30-year series and the 110-year series, the relationship $\alpha = f(p_o)$ has been plotted in Fig. 16.9, derived from mean monthly discharge at Děčín for the two series. With current operations ($\beta_z = \emptyset$) the two relationships are very close; the 30-year series has less favourable results in the whole range of p_o (70–100%). The 110-year series gives the worse results with small β_z (0.05–0.15). With $\beta_z = 0.2$ the values of α of the two curves intersect and with $\beta_z = 0.3$ in the range $p_o = 98$ to 100% less favourable is the 110-year series and for $p_o < 98\%$ the 30-year series.

The relationships between the values of α, β_z, p_t and p_o for the 110-year series of mean monthly discharges of the river Labe at Děčín (1851–1960) are given in Fig. 16.10. Fig. 16.10a shows the relationship $\beta_z = f(\alpha, p_t)$ and Fig. 16.10b shows the relationship $\beta_z = f(\alpha, p_0)$. The smooth continuous curves pass through the empirical points with great accuracy. From these it is possible to read any of the three values (α, β_z, p_t) or (α, β_z, p_0) if two of them are given. The values of β_z determine the total relative storage capacity of a reservoir, derived from mean monthly discharges. The variation coefficient of mean annual discharges of the 110-year series of Labe at Děčín is $C_v = 0.293$.

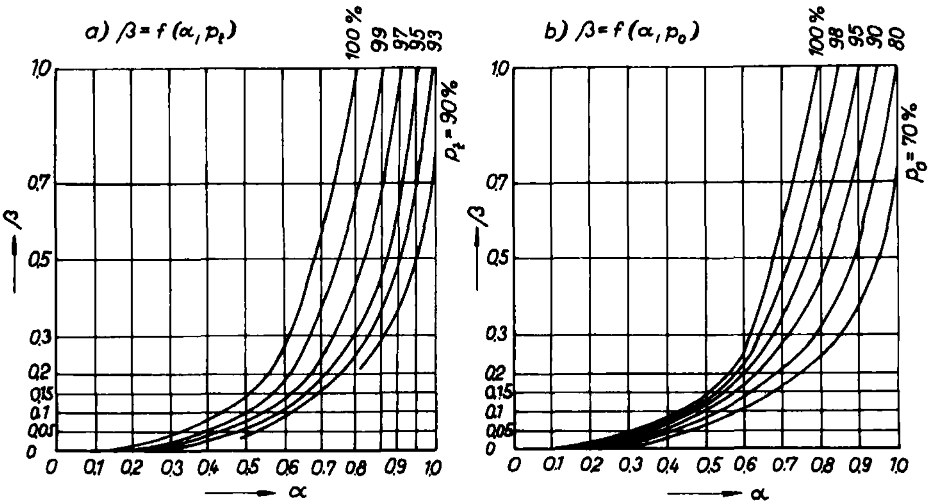


Fig. 16.10 Relationship between β_z, α, p_t, p_0 for a 110-year series of the Labe at Děčín (1851–1960)

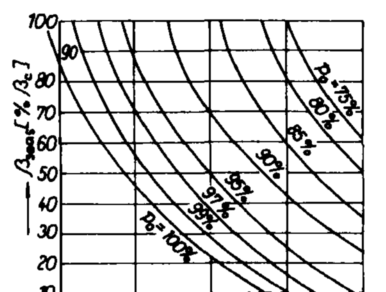


Fig. 16.11 Relationship $\beta_{seas.} = f(\alpha)$ in % β_c with $p_0 =$ = const. for a natural series of the Labe at Děčín (1851–1960)

An idea of the size of the seasonal component of a reservoir volume with over-year release control can be obtained from Fig. 16.11. Plotted here are the curves $\beta_{seas.} =$ $= f(\alpha)$ for several values $p_0 =$ const., derived from a real 110-year series from the river Labe at Děčín. The curves for $p_0 = 76$–90% pass through the empirical points with great accuracy; the curves for $p_0 = 95$–100% were smoothed mainly in the interval around $\alpha \doteq 0.7$. It can be seen that the seasonal component drops below

10% β_z only with high α and p_o values, i.e., with a very long-term release control with a great reliability of the yield.

The relationships derived from the Děčín series offer an idea of the studied parameters (O_p, α, p_o, p_t, β_z) under similar hydrological conditions.

16.3.4 Reliability of water supply in various branches of water management

Reliability of water supply for irrigation

The former relationships between the various rates of reliability were valid for a constant yield in the year. Relationships between various expressions for the realiability of water supply for irrigation were studied at the Czech Technical University, presuming that the irrigation withdrawal O_p^v is constant for the whole growing period and that in the non-growing period $O_p' = Q_{355d}$. In the three cases that were studied (the rivers Čižina, Lužnice, Metuje) the following essential differences could be found as compared to reliability with a constant yield O_p:

(a) Relationship $\quad p_t = f(p_o)$:

Time-based reliability decreases with a decrease of p_o more slowly than with an all-year constant O_p.

(b) Relationship $\quad \sum O_p = f(p_t)$

A close correlation relationship, found with an all-year constant O_p, is preserved if withdrawal is confined to the growing period.

(c) Relationship $\quad \sum O_p = f(p_o)$

The limits of the correlation relations for various sizes of β_z are roughly the same as with all-year O_p = const; however, the ratio dp_d/dp_o decreases with the increasing size of β_z; with all-year withdrawal this ratio increases (Fig. 16.12). This can be explained by the fact that large reservoirs ensure a large total withdrawal $\sum_c O_p$ and

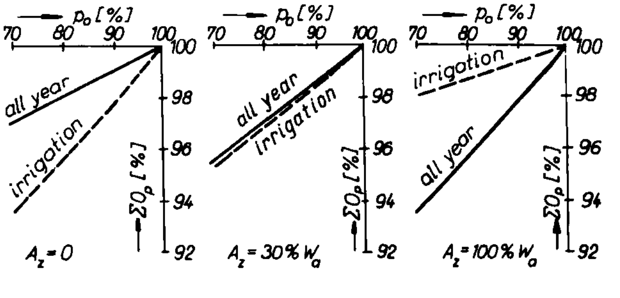


Fig. 16.12 Relationship between volume-based reliability and occurrence-based reliability p_o at Pilař on the river Lužnice (1931 to 1960): (*a*) for all-year constant withdrawal; (*b*), (*c*) – for constant irrigation withdrawal (April to September)

if the reservoirs fail to supply water in a certain year the relative deficits only in the growing season are smaller which can affect $\sum O_p$, expressed in percentage.

In determining the optimal rate of reliable water supply from a reservoir for irrigation, it is considered that the demand is constant every year (in dry regions) or varies, year by year, depending on the weather conditions (supplementary irrigation).

The first case is a simpler one; we determine the respective annual irrigation-water demand and look for an economically justified reservoir volume. For the respective years of the hydrological series we determine the necessary storage capacities V_z, which form a statistical sample of random quantities. From the exceedance curve of storage capacities we choose several V_z values with various probabilities of exceedance, and for these we find the economic effectiveness (Sections 16.1 and 16.2).

In complicated weather and hydrological conditions the following method can be applied to determine the optimum reliability of irrigation water supply:

(a) We determine the irrigation water demand for a real series of weather conditions. For every month of the series we calculate the total irrigation demand in $m^3\,ha^{-1}$ ($1\,mm = 10\,m^3\,ha^{-1}$) using the model of irrigation water requirements (Kos, 1982) based on the monthly time series of meteorological factors (temperature, relative humidity, sunshine duration, wind velocity and precipitation) and water surpluses in the previous month (from winter precipitations). By multiplying this by the irrigated area, we obtain the irrigation demand on the water resource.

(b) The solution is based on a series of mean monthly discharges of the water resource. Other water users and the minimum maintained discharge downstream of the dam must be considered. Instead of discharges in $m^3\,s^{-1}$, module coefficients of monthly discharges $k_m = Q_m/Q_a$ can be used. Several sizes of storage capacities V_z or relative capacities β_z are chosen and the deficits of water in m^3 (or %) are determined, as well as the resulting irrigation reliability in terms of water supply p_d and in terms of time-based reliability p_t and occurrence-based reliability p_o.

(c) An economic analysis determines the optimal rate of water supply reliability. For the respective storage capacities β_z, fixed and operational costs of the water resource are determined, as well as the economic effectiveness of each alternative. The resultant values determine the most effective β_{opt} and the corresponding p_d^{opt}, p_t^{opt}, p_o^{opt}.

If the irrigated area is not given and if its optimal size is to be determined with regard to a given water resource, a more general approach should be used. A unit water resource $Q_a = 1$ is chosen and several sizes of irrigated areas S_{ir} are ranged with the respective sizes of storage capacity ($\beta_z = 0.10, 20, 30\% \ldots$), for which p_d, p_t, and p_o are determined. For each β_z various relationships between the quantities S_{ir}, p_d, p_t and p_o can then be plotted. By solving the economic effectiveness of several options with different S_{ir} for every β_z we obtain the dependence of the effectiveness on a form of reliability (p_d, p_t, p_o) and from the closeness of the relationships we obtain the most advantageous of these technical parameters as indices of the economic effectiveness, for which the standard reliability values should be determined.

This procedure can be applied to real series as well as to synthetic series.

Reliability of water supply for households and industry

Water demand is increasingly covered by reservoirs and to ensure optimal reliability of the water supply is most important today. It is difficult to estimate the economic consequences of the water shortages, particularly in heterogeneous public water supply systems and, besides the economic effects, intangible impacts are also serious. Therefore the design rate of public water supply reliability is usually set by estimated standard values ($p_o = 95$–99%).

The question of reliability of water supply for households, industry and agriculture is all the more complicated, because it also concerns the water quality. Water temperature, demands for clean water downstream of a dam, etc., can influence the amount of water to be withdrawn or released.

Water supplied to households should be of the best quality and should always be available for reasons other than economic.

Thermal power plants require a high rate of reliability. Experience with industrial plants shows that economic losses are not directly proportional to the deficits of water. When the optimal withdrawal is decreased only slightly (frequently to about 80 to 95%) economic losses are small; the losses increase more rapidly due to a greater decrease of withdrawal when the plant is unable to function properly. Numerous short water-supply failures have a different economic impact from a continuous longer failure of the same depth.

When looking for the optimal rate of water-supply reliability for industrial plants (and other users), the following method can be used:

(a) We determine the relationship

$$Z = f(O) \tag{16.31}$$

where Z is the economic loss per unit of time caused by the deficits of water,
O – water withdrawn per unit of time.

With optimal withdrawal $O = O_{opt}$ $Z = 0$, and with $O = O_0$ $Z = Z_{max}$ (the plant has to be closed for lack of water).

(b) Hydrological series (natural or synthetic) are applied to determine the water-supply failures; these are expressed as a function of the volume V_{fail} and duration t_{fail} and then the respective economic losses Z are determined; therefore $Z = f(V_{fail}, t_{fail})$. If release is subject to rules and schedules, the possibilities are investigated of how to prolong the failure advantageously, to t'_{fail} and losses $Z' = f(V_{fail}, t'_{fail})$ smaller than losses Z are introduced in the solution.

(c) From an economic analysis of several options concerning the cost of a reservoir and the respective losses in the industry, the optimal reliability of water supply p_d is found together with the instructions for the operation rules.

Reliability of water for hydro-power plants

Standards that ensure a reliable output for hydro-power plants are usually derived from experience. The water power plants often cooperate with the thermal power plants in the power system. The reliability of the power supply is determined by the power system and therefore the reliability of the hydro-power plants is given by the standards.

The relationship between the reliability of release and the energy and output of a hydro-power plant cannot be defined clearly, as the head also affects the output. Figure 16.13 gives the relationship between the mean annual discharges Q_r and the annual power production at the Křivoklát site on the river Berounka using the installation of a hydro-power plant for a 120-day discharge and a maximum head of $H_{max} = 7.63$ m.

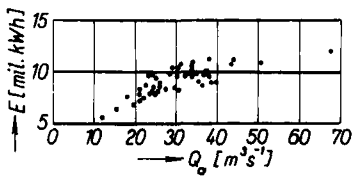


Fig. 16.13 Relationship between Q_r and annual power generation E at Křivoklát (1891 to 1940)

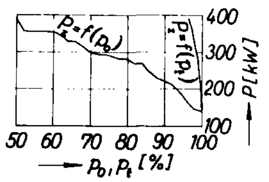


Fig. 16.14 Output reliability of a base-load hydro-power plant in the Křivoklát site

Figure 16.14 shows the relationship of a reliable output P_z and the occurrence-based reliability p_o and time-based reliability p_t for the same hydro-power plant. $p_t > 96\%$ corresponds to the reliability $p_o = 50\%$. For power plants the index of time-based reliability is more suitable.

Reliability of augmented discharges for navigation

Inland waterways are part of a transport system, but also of a water-management complex; these bounds with two branches should not be overlooked in any economic estimations. All the various aspects of navigation have been dealt with in specialized books (Čábelka, 1963, 1976 and others). Navigation can be replaced by other means of transport and its economic effect should be compared with the effect of those other means.

Reservoirs can supply water for canals or augment water stages on natural or trained rivers. Any effective augmentation of water stages requires a great augmentation of discharges and therefore large reservoir volumes. Navigation can benefit from release control for other purposes (e.g., flood control, power plants); it uses water, but does not consume it.

To determine the optimal reliability of water release from reservoirs to augment water stages for navigation, the following method can be used:

(a) We determine the economic losses on a water-way caused by low water stages under natural conditions making it impossible to use the stream for navigation throughout the year. This loss equals zero if the streams are navigable for fully-loaded vessels throughout the year. Losses are caused if navigation has to be interrupted due to low water stages or floods, etc. Calculations are based on loaded cargo and number of trips. Operation costs are only reduced slightly if navigation has to be interrupted (saving of fuel).

If streams became unnavigable other means of transport have to be used, e.g., railways. From the difference between the transport costs of boats and railways the losses can be calculated for every ton that is transported and from these the total losses. The values of the total annual losses make up a statistical sample from which the necessary statistical characteristics can be derived mainly mean annual economic losses.

(b) For an augmented discharge that provides for uninterrupted navigability, and for some other selected values of augmented discharges Q_p which ensure partial navigability, we determine the necessary volumes of storage capacities.

(c) We select several smaller values of storage capacities V_z and ascertain for the same augmented discharges as in (b), the rate of reliability of the augmented discharge and the mean annual losses Z. It is best to use the time-based reliability p_t. For every selected value of augmented discharge, we ascertain the relationships $p_t = f(V_z)$, $Z = f(V_z)$ and $Z = f(p_t)$.

(d) We calculate the annual operation costs P_0 for the construction of the respective storage volumes V_z and construct the relationship $P_0 = f(V_z)$. By comparing this with the relationship $Z = f(V_z)$ and $p_t = f(V_z)$, we can determine the economically optimal values of V_z and p_t.

Influence of the limited length of hydrological series on the reliability values

In a long hydrological series less favourable low-flow periods can be expected than in a short series. However, it is not possible to ascribe lower values to the reliability values from shorter series than from longer series.

To find out which periods are decisive for the water supply from different volumes of storage capacities, we constructed, for all the observed sites, graphs of the necessary sizes of storage capacities for any required augmented discharges O_p for the 10 to 15 driest periods out of the whole hydrological series and similar graphs for the 110-year hydrological series 1851 to 1960 at Děčín on the Labe.

If we presume that there is an analogy between the river Labe at Děčín and other rivers as far as low-flow periods are concerned, it is possible to consider the driest period of the last forty years as the decisive period of the last hundred years. Therefore it can be said that the last forty-year period has a greater weight than would correspond to the number of years.

16.3.5 Relationship between flood characteristics and economic losses

Flood-control measures are introduced to eliminate losses caused by floods. Besides direct damage to land and houses, floods cause indirect losses, e.g., interruption of transport or power supply, etc. The flood-control effect of a reservoir is designed with an economically justified measure of reliability.

Economic losses caused by floods are determined by a detailed study of the flood plain and from older recordings of extensive floods. The best data for the relationship between flood characteristics and economic losses are a time series of floods during the observation period, in which each flood is characterized by technical parameters and by the extent of the damage it caused.

For economic estimation of the flood-control effect of a reservoir it is advantageous to use the relationship between economic losses and one of the flood characteristics (maximum discharge, flood volume, etc.). Most frequently, economic losses depend on the maximum flood discharge $Z = f(Q_{max})$.

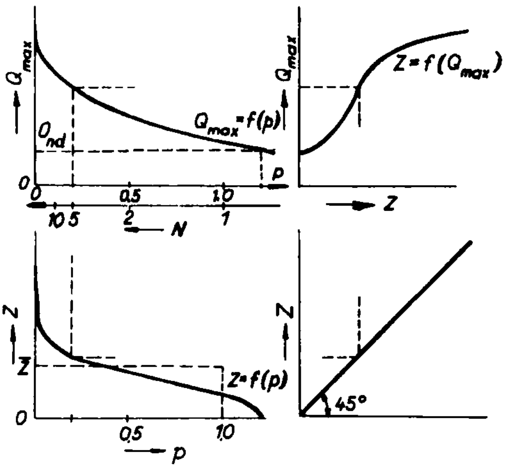
The basic economic index of the extent of flood damage is the mean annual economic loss $\bar{Z}$, given by the relationship

$$\bar{Z} = \int_{N=N_{nd}}^{N\to\infty} \frac{Z(N)}{N} \mathrm{d}N \qquad (16.32)$$

where N is the probable time of exceeding flood discharges. With regard to the general pattern of the curve $Z = f(N)$ the value $\bar{Z}$ can be suitably determined graphically.

The exceedance curve of maximum flood discharges is drawn by plotting probabilities of exceeding $p = 1/N$ on the abscissa and the corresponding values of maximum discharges on the ordinate. Using the relationship $Z = f(Q_{max})$, the exceedance curve of economic losses is determined (Fig. 16.15). The area defined by the axes of the coordinates and the curve $Z = f(p)$ is transferred to a rectangle with a base equal to 1, i.e., from $p = 1/N = 0$ to $p = 1$, the height of which on the ordinate is the mean annual economic loss.

Flood-control reservoirs help to diminish economic losses. The mean annual benefit is given by the difference between the mean annual economic loss before and after the construction of a reservoir. Floods that are held completely by a reservoir and do not exceed a non-damaging discharge do not cause any losses; losses are caused by floods not held by reservoirs or only partly held. We construct their exceedance curve and ascertain the mean annual economic loss $\bar{Z}_1$ after the construction of a reservoir in the same way as above (Fig. 16.16). The economic loss



◀ Fig. 16.15 Determination of the exceedance curve of economic losses and mean annual losses caused by floods

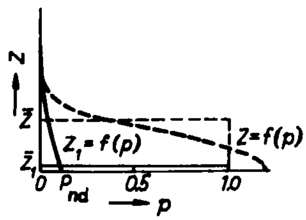


Fig. 16.16 Determination of the reduction of losses due to the flood control effect of a reservoir

equals zero at point $P_{nd} = 1/N_{nd}$, where N_{nd} is the probable time of exceeding a non-damaging discharge. Also plotted in the diagram are the original exceedance curve of economic losses $Z = f(p)$ and the mean annual loss $\bar{Z}$. The difference between the losses $\bar{Z}$ and $\bar{Z}_1$ is the mean annual benefit of the flood-control effect of a reservoir.

For further economic estimations the utility of the flood-control effect on the active storage capacity, the flood-control capacity and surcharge capacity must be determined. The solution is similar, but should be carried out in stages. First we determine the exceedance curve of economic losses for the active storage capacity and the respective mean annual losses. Then we consider the effect of the surcharge capacity and finally the effect of the flood-control capacity. Special attention should be paid to the surcharge. If it is expedient to build an ungated spillway in a storage reservoir, the reservoir has a surcharge capacity which is given by the need to make the whole construction safe. The costs for this capacity are shared by the users of the active storage capacity. If the surcharge capacity is also used for flood control the cost remains the same, as the size of this capacity is given by the standards that ensure the safety of the reservoir which are always more demanding than flood control standards; it is, however, possible to include an adequate share of these costs in the flood-control costs.

The flood-control effect of the active storage capacity is estimated in a similar way. Here, however, extra costs have to be considered that are introduced to raise the effect of the active storage capacity, e.g., costs for forecasting services, etc.