THE EFFECT OF RIVER CANALIZATION ON NAVIGATION*

By

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Introduction

The economical utilization of hydro power even in case of river stretches having flat slopes is on the one hand necessitated by increasing energy demands of individual countries and, on the other, facilitated by the development of technics. Therefore the canalization of water courses is rapidly gaining ground and so effects on navigation assume increased significance and interest. This effect manifests itself in the decrease of service and travelling time of the vessels, as well as in that of fuel consumption, further in some other various, generally favourable results. It is intended to denote the present study to questions of service and travelling time and to savings primarily in fuel, owing to the shortening of travelling time.

Chapter I

Objective

Some of the effects of river barrages on navigation have already been dealt with by E. Mosonyi in a previous study submitted to World Power Conference V. (Vienna, 1956.)[1] This first study presents a method based on approximate, as well as, on accurate mathematical computations, for the determination of the gain in navigation time and saving in fuel due to backwater effect. The equations derived in the study cited, refer to the particular case only of backwater effect of a river barrage extending exactly to the other barrage (the case of densely located river barrages, the so-called "tight" canalization). In the present study in contrast a mathematically accurate solution for barrages located arbitrarily is given, thus constituting the continuation, or rather, the generalization of the study mentioned before.

Reference to the first study the shortening of the introduction, as well as, the omission of the detailed discussion of mathematical operations is made possible.

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In the first place the effect of river barrages on navigation should be considered from that point of view, whether the watercourse is unimpededly and continuously navigable in its natural state or whether it is innavigable and/or secures only periodical navigation possibilities for the decisive vessel types.

In the present study only *waterways unimpededly and continuously navigable in their natural state* are being discussed with a view to advantages ensured by damming. Many operational advantages may be ascertained by means of raising the watersurface, the most important of which have already been enumerated in the previous study. *Herewith the gain of navigation time due to the decrease of the velocity of flow and the saving in fuel dependent therefrom* will be discussed in detail, those being the most substantial advantages originating from the effect of damming.

Conditions of the investigation and notations

In order to ensure the mathematical tractability of the objective predetermined, the following assumptions and approximations should be made use of:

1) The original hydraulic gradient (slope of natural water surface) between two consecutive river barrages of the canalized river is assumed to be as uniform, and/or may be equalized with sufficient accuracy.

2) Investigations are to be confined to the original low-water stage of the watercourse, backwater extending the farthest during these periods.

3) Backwater curves are parabolae of second degree with horizontal tangent. (An assumption allowing for safety.)

4) Further decrease in velocity owing to the increase of water surface area is neglected i. e. a bed of vertical banks is assumed. (An assumption allowing for safety.)

5) For computing waterdepths and mean velocities the riverbed is regarded as uniform i. e. a straight line parallel to the natural water surface line.

6) The distance and elevation of the barrages is arbitrary according to *Fig. 1.*

7) The total gain of time can be obtained by adding up the partial gains between the consecutive barrages.

The most common case met with is presented, when distance X between two river barrages is smaller than the backwater distance L of the barrage downstream (so-called overlapping river canalization). Introducing the notations used in *Fig. 2.*

J hydraulic gradient and average bedslope,
H elevation of the barrage from the original (natural) low-water surface,
h_0 original average low-water depth,
X distance of the barrages,
L backwater distance of the river barrage downstream,

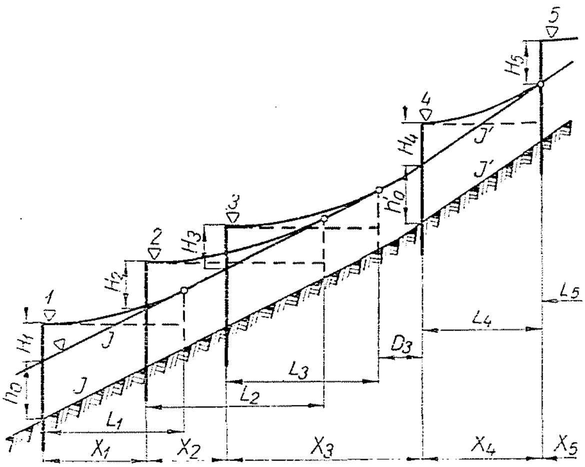

Fig. 1

y depth of the raised water surface as measured upstream at a distance x from the barrage downstream,
v_0 average value of the original velocity in the main current of the watercourse (line of swiftest flow),
c dead water travelling speed (of the vessel).

On basis of the foregoing it follows, that

$$L = 2H/J.$$

Basic relationships

The time required for travelling distance X *prior to damming*

upstream travel $$\tau_u = \frac{X}{c - v_0} \tag{1}$$

downstream travel $$\tau_d = \frac{X}{c + v_0} \tag{2}$$

and thus for a round (tour-retour) trip

$$\tau = \tau_u + \tau_d = X \frac{2\,c}{c^2 - v_0^2} \,. \tag{3}$$

It is expedient to relate any travelling time to the time required for distance 2 X on *dead-water surface*

$$t_0 = \frac{2\,X}{c} \,. \tag{4}$$

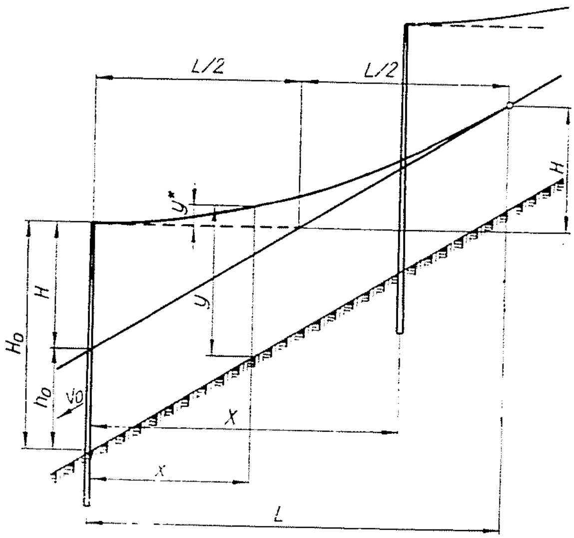

Fig. 2

Introducing the *velocity factor*

$$\beta = \frac{v_0}{c} \tag{5}$$

Eq. (3) may be rewritten

$$\tau = \frac{2\,X}{c} \left(\frac{c^2}{c^2 - v_0^2} \right) = t_0 \left(\frac{1}{1 - \beta^2} \right) \tag{6}$$

Since $\beta < 1$, thus $\tau > t_0$.

Subsequent to damming the vessel travelling in water the velocity of which varies with distance x, thus the velocity of flow in the main current of the waterway is of sufficient accuracy

$$v = \frac{v_0 h_0}{y} \tag{7}$$

where

$$y = h_0 + H + y^* - J x \tag{8}$$

The rise y^* of the backwater curve may be expressed from the parabolic equation (H, L), substituting the correlated values as

$$y^* = \frac{H}{L^2} x^2 \tag{9}$$

herewith Eq. (8) assumes the following form

$$y = h_0 + H + \frac{H}{L^2} x^2 - J x . \tag{10}$$

Introducing notations $H/L^2 = a$ and $H_0 = h_0 + H$, Eq. (7) may be written

$$v = \frac{v_0 h_0}{h_0 + H + \frac{H}{L^2} x^2 - J x} = \frac{v_0 h_0}{H_0 + a x^2 - J x} . \tag{11}$$

The time required for travelling distance dx at any arbitrary point x, with velocity v pertaining to depth y

upstream $$d t_u = \frac{d x}{c - v} \tag{1*}$$

downstream $$d t_d = \frac{d x}{c + v} \tag{2*}$$

Determination of travelling time

In case of *upstream travel*, using Eqs. (1*) and (11)

$$d t_u = \frac{d x}{c - \frac{v_0 h_0}{a x^2 - J x + H_0}} = \frac{a x^2 - J x + H_0}{c a x^2 - c J x + c H_0 - v_0 h_0} dx \tag{12}$$

dissolved into partial fractions and integrated:

$$t_u = \int_0^X \frac{1}{c}\,\mathrm{d}x + \int_0^X \frac{\dfrac{v_0 h_0}{a c^2}}{x^2 - \dfrac{J}{a}x + \dfrac{c H_0 - v_0 h_0}{c a}}\,\mathrm{d}x\,.$$

Introducing notations

$$K = \frac{v_0 h_0}{a c^2} \qquad p = -\frac{J}{a} = -\frac{\dfrac{2H}{L}}{\dfrac{H}{L^2}} = -2L$$

and

$$q = \frac{c H_0 - v_0 h_0}{c a} \tag{13}$$

the integral becomes

$$t_u = \int_0^X \frac{1}{c}\,\mathrm{d}x + \int_0^X \frac{K}{x^2 + px + q}\,\mathrm{d}x\,. \tag{14}$$

Integrating we obtain

$$t_u = \frac{X}{c} + \left[\frac{2K}{\sqrt{4q - p^2}}\ \mathrm{arc\ tg}\ \frac{2x + p}{\sqrt{4q - p^2}}\right]_0^X \tag{15}$$

Introducing the *relative distance of river barrages*

$$\xi = \frac{X}{L} \leqslant 1 \tag{16}$$

the limit value X may be expressed by ξL. Using the relationships of Eq. (13)

$$4q - p^2 = 4L^2\left(\frac{h_0}{H} - \frac{h_0}{H}\cdot\frac{v_0}{c}\right)$$

and introducing the velocity factor given by Eq. (5)

$$\beta = \frac{v_0}{c}$$

and further the *damming factor*

$$\delta = \frac{h_0}{H} \tag{17}$$

we have

$$\sqrt{4\,q - p^2} = 2\,L \sqrt{\delta\,(1 - \beta)}\,. \tag{18}$$

Similarly according to the first relation of Eq. (13)

$$K = \frac{L^2}{c}\,\beta\,\delta\,. \tag{19}$$

Substituting Eqs. (18) and (19), the term in brackets of Eq. (15) become

at point $x = \xi\,L$

$$\frac{L}{c}\,\frac{\beta\,\delta}{\sqrt{\delta\,(1-\beta)}}\ \text{arc tg}\ \frac{\xi - 1}{\sqrt{\delta\,(1-\beta)}}$$

whereas at point $x = 0$

$$-\frac{L}{c}\,\frac{\beta\,\delta}{\sqrt{\delta\,(1-\beta)}}\ \text{arc tg}\ \frac{1}{\sqrt{\delta\,(1-\beta)}}\,.$$

Hence the total time of upstream travel

$$t_u = \frac{X}{c} + \frac{L}{c}\,\frac{\beta\,\delta}{\sqrt{\delta\,(1-\beta)}}\left[\text{arc tg}\ \frac{\xi-1}{\sqrt{\delta\,(1-\beta)}} + \text{arc tg}\ \frac{1}{\sqrt{\delta\,(1-\beta)}}\right]. \tag{20}$$

In order to determine the time of downstream travel consider Eqs. (2*) and (11). Thus

$$\mathrm{d}\,t_d = \frac{\mathrm{d}\,x}{c + \dfrac{v_0\,h_0}{a\,x^2 - J\,x + H_0}}\,. \tag{21}$$

Applying a mathematical procedure entirely similar to that previously described, the following symmetrical expression will be obtained for the total time of downstream travel:

$$t_d = \frac{X}{c} - \frac{L}{c}\,\frac{\beta\,\delta}{\sqrt{\delta\,(1+\beta)}}\left[\text{arc tg}\ \frac{\xi-1}{\sqrt{\delta\,(1+\beta)}} + \text{arc tg}\ \frac{1}{\sqrt{\delta\,(1+\beta)}}\right]. \tag{22}$$

To simplify the formulae let us introduce the following notations

$$\left.\begin{aligned} \varkappa &= \beta\,\delta \\ \mu &= \frac{1}{\sqrt{\delta\,(1-\beta)}} \\ \nu &= \frac{1}{\sqrt{\delta\,(1+\beta)}} \end{aligned}\right\} \qquad (23)$$

The time of upstream travel as computed from Eq. (20)

$$t_u = \frac{X}{c} + \frac{L}{c}\,\varkappa\,\mu\left[\operatorname{arc\,tg}\mu\,(\xi-1) + \operatorname{arc\,tg}\mu\right]. \qquad (24)$$

The time of downstream travel as computed from Eq. (22)

$$t_d = \frac{X}{c} - \frac{L}{c}\,\varkappa\,\nu\left[\operatorname{arc\,tg}\nu\,(\xi-1) + \operatorname{arc\,tg}\nu\right]. \qquad (25)$$

Thus the total time of a round (tour-retour) trip on a raised water surface may be expressed by the formula as follows:

$$t = \frac{2X}{c} + \frac{L}{c}\,\varkappa\left\{\mu\left[\operatorname{arc\,tg}\mu\,(\xi-1)+\operatorname{arc\,tg}\mu\right]-\nu\left[\operatorname{arc\,tg}\nu\,(\xi-1)+\operatorname{arc\,tg}\nu\right]\right\} \quad (26)$$

Since the value of the right hand side of the equation depends on the choice of three parameters i. e. on the quantities of ξ, β, δ, Eq. (26) may be written as

$$t = \frac{2X}{c} + \frac{L}{c}\,\Phi\,(\xi, \beta, \delta) \qquad (27)$$

where, in order to facilitate computations, the function Φ may be expediently used with reversed signs in the following form:

$$\Phi\,(\xi, \beta, \delta) = \varkappa\left\{\mu\left[\operatorname{arc\,tg}\mu - \operatorname{arc\,tg}\mu\,(1-\xi)\right] - \nu\left[\operatorname{arc\,tg}\nu - \operatorname{arc\,tg}\nu\,(1-\xi)\right]\right\}. \qquad (28)$$

Since $\xi \leq 1$, thus $(1-\xi)$ is positive or 0.

By expressing the dead-water travelling time $2X/c = 2\xi L/c = t_0$ as common factor from Eq. (27) the following simplified form is arrived at:

$$t = \frac{2X}{c}\left(1 + \frac{1}{2\xi}\,\Phi\right) = t_0\left(1 + \frac{1}{2\xi}\,\Phi\right) \qquad (29)$$

or substituting

$$\frac{1}{2\xi}\Phi = \lambda(\xi, \beta, \delta) \tag{30}$$

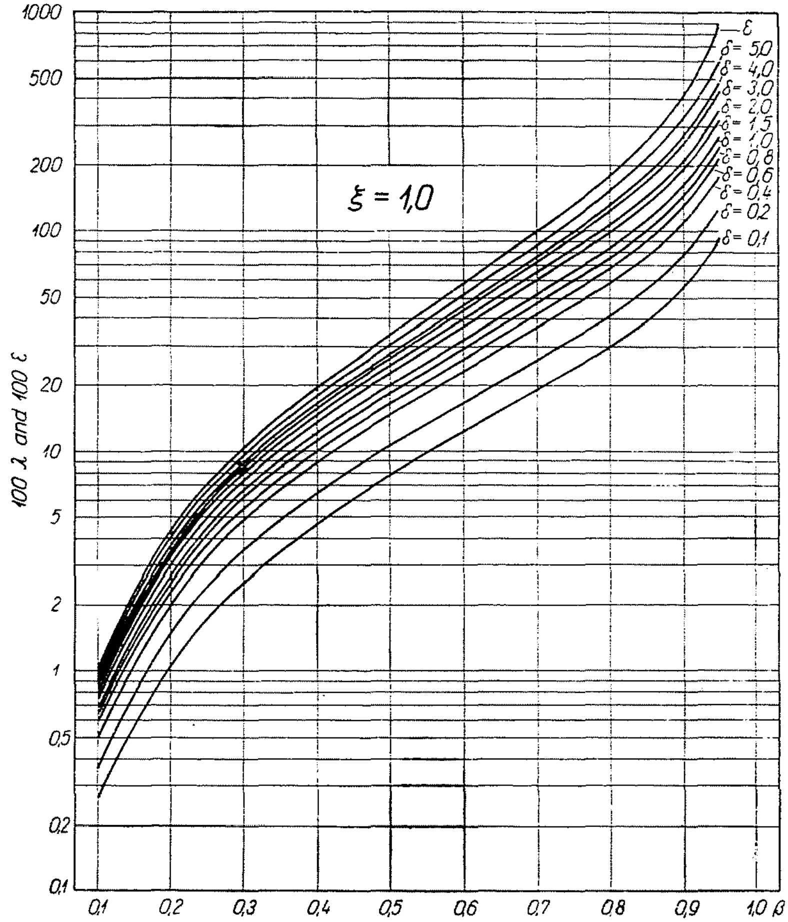

Fig. 3

we have

$$t = t_0 (1 + \lambda) . \tag{31}$$

Gain of time and saving in fuel

Combining Eqs. (6) and (31) and neglecting time losses, due to locking operation and further introducing notation

$$\varepsilon = \frac{\beta^2}{1 - \beta^2} \tag{32}$$

the gain of time is obtained as

$$\Delta t = t_0 \left(\frac{1}{1-\beta^2} - 1 - \lambda \right) = t_0 \left(\frac{\beta^2}{1-\beta^2} - \lambda \right) = t_0 (\varepsilon - \lambda) . \qquad (33)$$

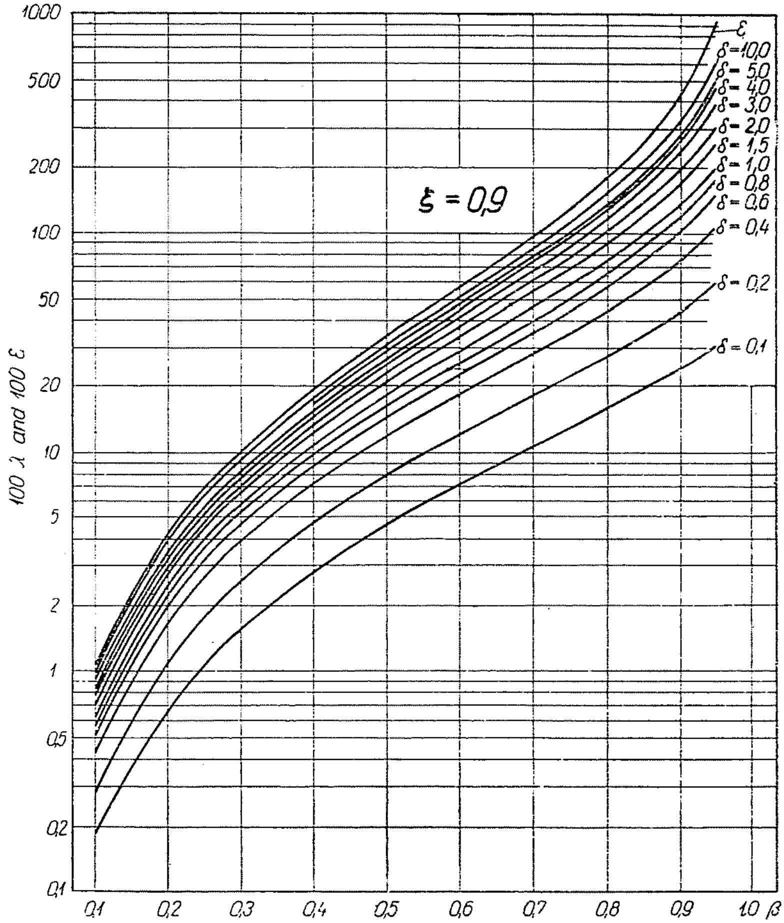

Fig. 4

It should be remarked, however, that for a single pool (between two barrages) of a canalized watercourse the resulting gain of time is obtained by subtracting the average locking time of one upstream and one downstream travel from the time determined by Eq. (33), thus

$$\Delta t_g = t_0 (\varepsilon - \lambda) - (t_u^* + t_d^*) . \qquad (34)$$

Charts given in *Figs. 3 to 10* will facilitate the quick solution of the above formulae, the use of which will be enlightened by an example in conclusion. The figures have been scaled to yield the 100 λ values. Rewriting namely Eq. (31) in the following form

$$100 \frac{t}{t_0} - 100 = 100 \lambda \, [\%] \qquad (35)$$

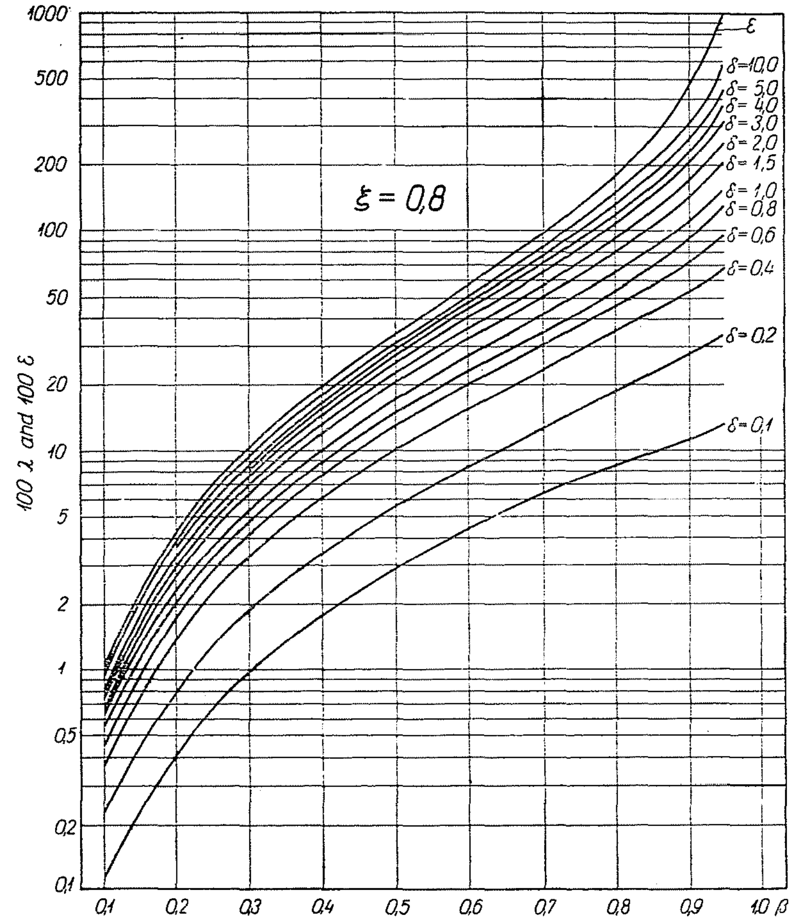

Fig. 5

the 100 λ values will obviously signify the increase of actual navigation time in per cent, above the dead-water travelling time (basic time). Each figure contains curves expressing $\varepsilon = \beta^2/(1 - \beta^2)$ as well, similarly in per cents. Any of thé figures will yield thus directly by two readings

$$100 (\varepsilon - \lambda) = 100 \frac{\Delta t}{t_0} \, [\%] \qquad (36)$$

i. e. the gain of time expressed by Eq. (33) in per cents of the basic time.

It has already been pointed out by the author in his study referred to that the gain of time in navigation is exceeded in significance, by the saving in fuel which may again be considered with sufficient accuracy as proportionate to Δt expressed by Eq. (33), showing a greater increase percentage. In some

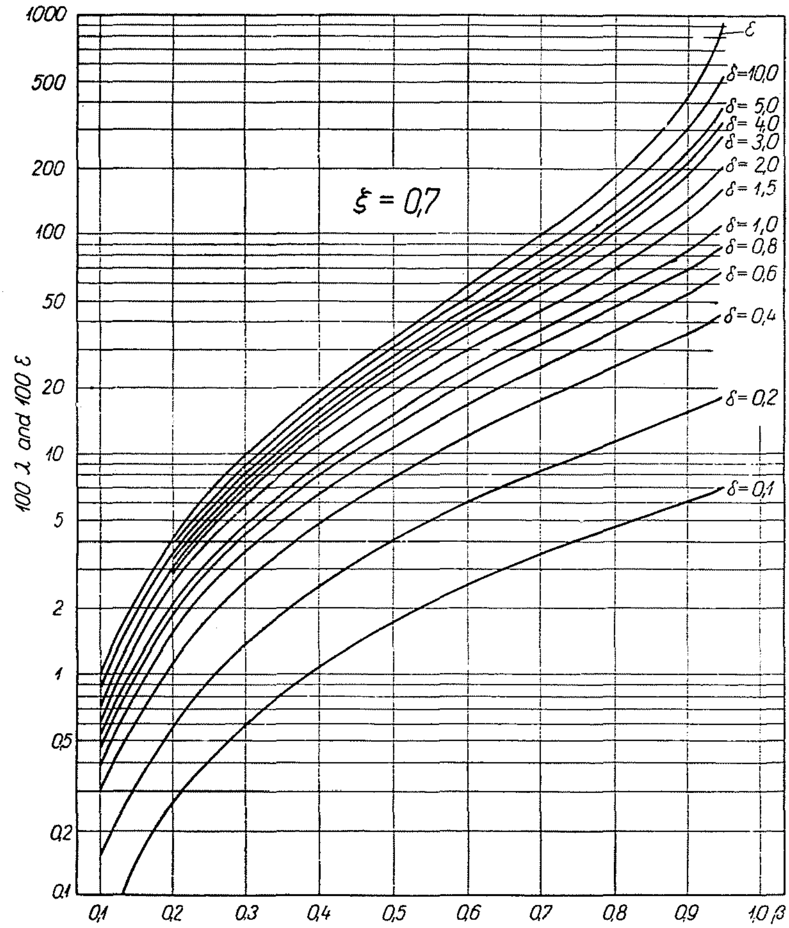

Fig. 6

instances $\Delta t_g < 0$, and thus a loss in service time may occur, yet this is offset by the saving in fuel, due to the gain in travelling time Δt.

For the sake of theoretical lucidity, the various concepts of time have been related in every case to dead-water basic time. From practical considerations, however, as basis of comparison not deadwater travelling time is taken mostly into account, the important features being

a) the saving in fuel in case of navigation on the raised water surface as compared to that on the original water surface,

b) the relative gain of time as compared to the service time on the original water surface.

In this sense the *relative saving in fuel* may be defined as the quotient of Eqs. (33) and (6), i. e.

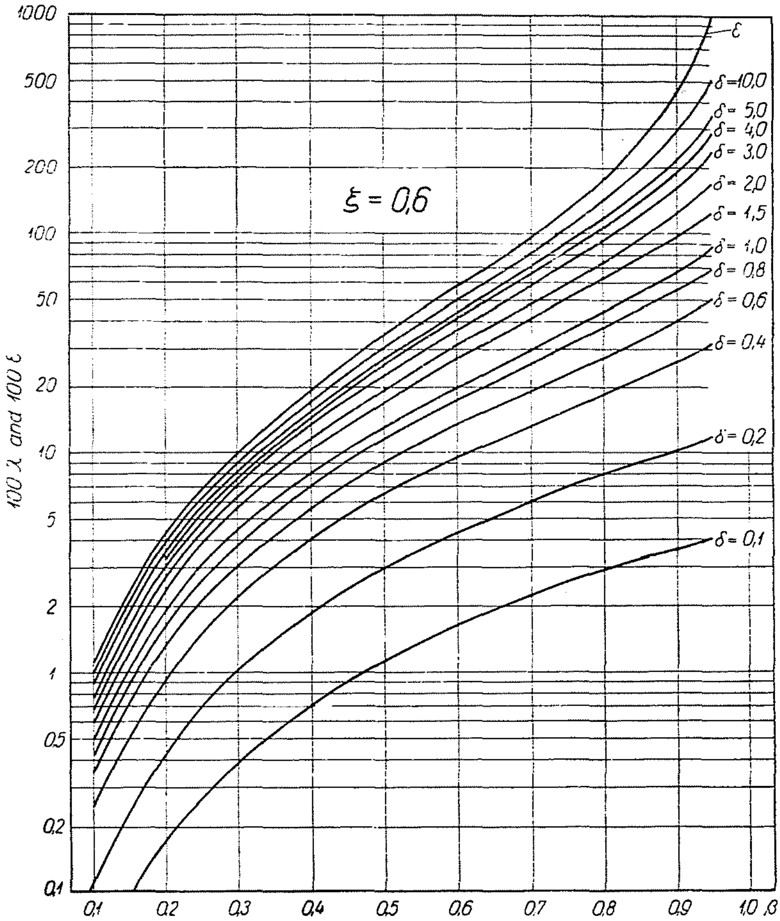

Fig. 7

$$\sigma_f\,\% = 100\,\frac{t_0\left(\dfrac{\beta^2}{1-\beta^2} - \lambda\right)}{t_0\left(\dfrac{1}{1-\beta^2}\right)} = (100 + 100\,\lambda)\,\beta^2 - 100\,\lambda \tag{37}$$

and the *relative resultant gain of time* as the quotient of Eqs. (34) and (6), i. e.

$$\sigma_t\,\% = (100 + 100\,\lambda)\,\beta^2 - 100\,\lambda - 100\,(1-\beta^2)\,\frac{t_u^* + t_d^*}{t_0} \tag{38}$$

respectively.

It should be noted that with the substitution $\xi = 1$ Eq. (26)applies to the special case where the upstream barrage is erected at the backwater limit of the downstream barrage (tight river canalization). The author's previous study referred to in the Introduction gives a solution for this particular case by the

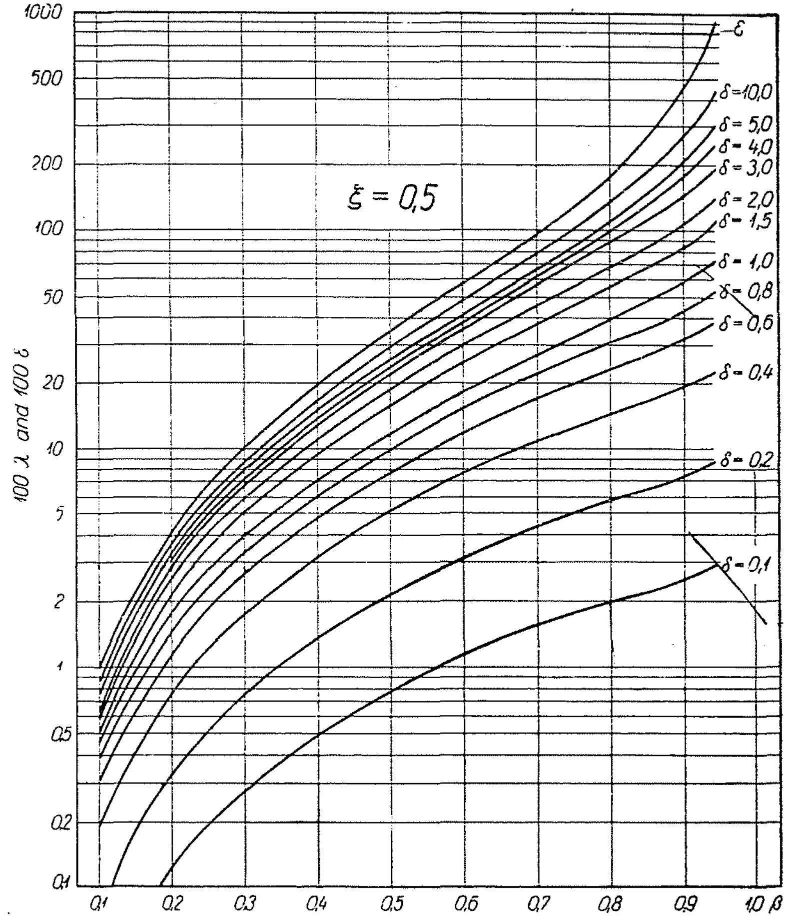

Fig. 8

formula derived also from Eq. (26) :

$$t_r = \frac{2L}{c} + \frac{L}{c} \varkappa (\mu \operatorname{arc tg} \mu - \nu \operatorname{arc tg} \nu) . \qquad (39)$$

In the case of the pool denoted by No. 3. in Fig. 1, navigation time consists of two parts : the decreased time on the reach affected by backwater L_3 and the unvaried time necessary on the reach with original water surface.

Varying river stages

With increasing discharges also velocity v_0 and consequently velocity factor β increase. This causes the gain of time to rapidly increase. The decrease

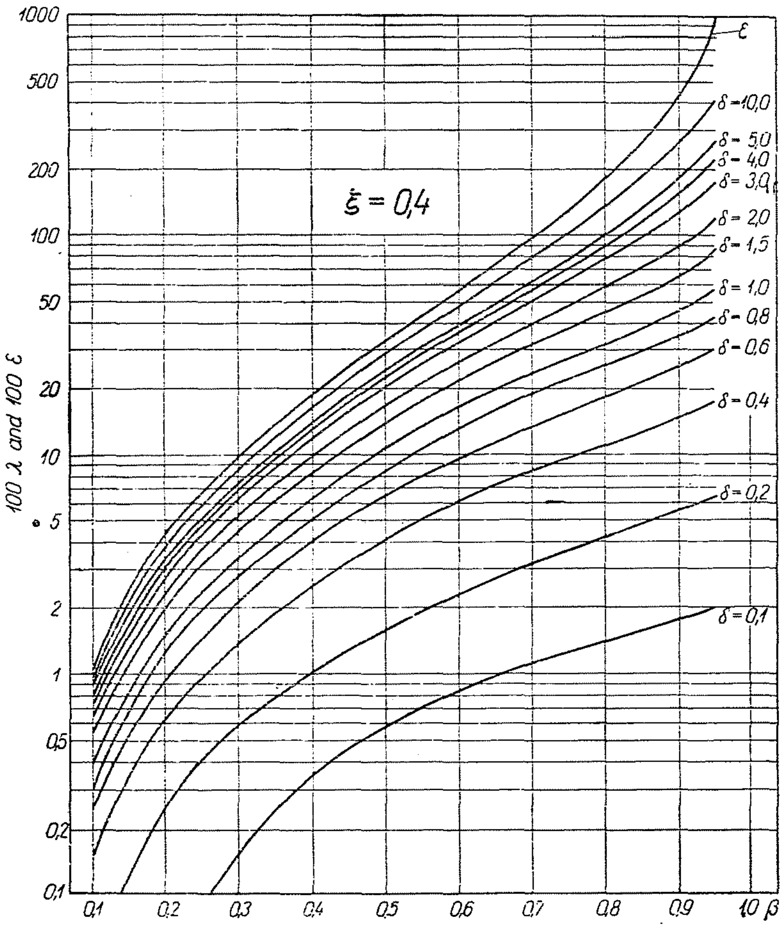

Fig. 9

of elevation H of the river barrage on the other hand affects the former in two respects adversely. The increase of damming factor δ and the decrease of backwater effect L act disadvantageously on the gain of time. The first mentioned effect is not counterbalanced in most instances by the latter, at least up to a certain value of H. Thus, in order to secure a complete survey of the problem

1) the gain of travelling time and saving in fuel, further
2) the resultant gain of time

relating to various discharges should be computed. The values obtained in this manner should be weighted and summed up to the average traffic volume pertaining to the various discharges that the results to be expected owing to the canalization of the waterway within a year could be properly evaluated.

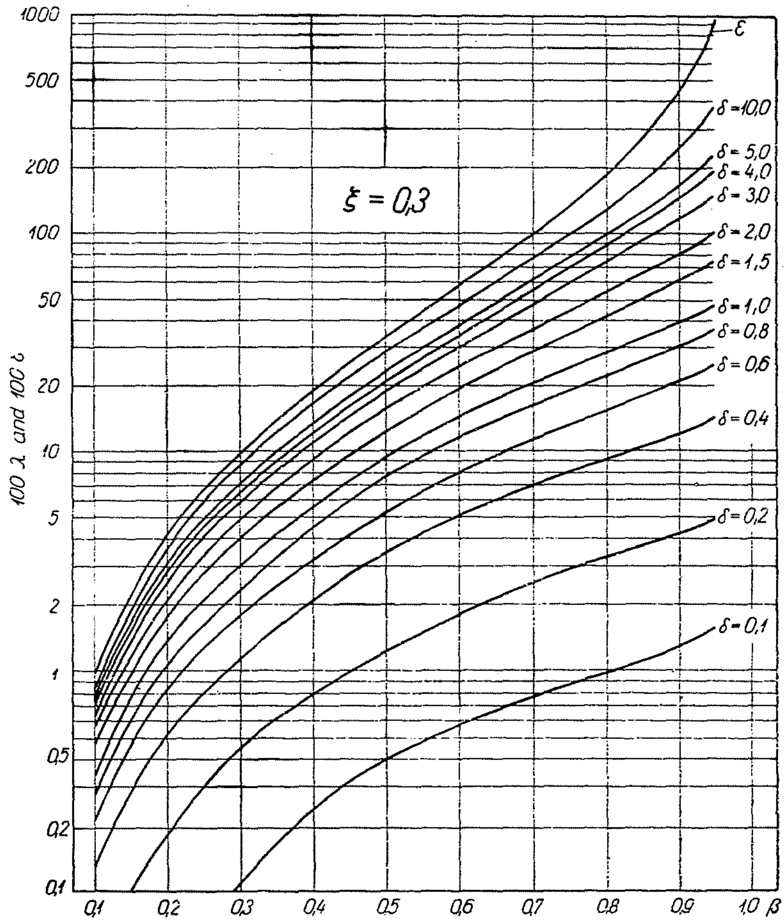

Fig. 10

In order to simplify computations it is advisable to construct auxiliary diagrams on which the gain of time and the saving in fuel falling to one pool are plotted against discharge or against the original natural river stage :

$$\Delta t = f(h_0) \quad \text{and} \quad \Delta t_g = f(h_0)$$
$$\sigma_f \% = f(h_0) \quad \text{and} \quad \sigma_t \% = f(h_0) \qquad (40)$$

respectively.

Table

Examples for the calculation of gain of time according to E. Mosonyi's equations

No	Stage	h_0	$H = H_0 - h_0$	$\delta = \frac{h_0}{H}$	v_0	$\beta = \frac{v_0}{c}$	$100\,\varepsilon$	$\frac{2X}{c}$	$\varepsilon\frac{2X}{c}$	$L = \frac{2H}{J}$	$L < X$: $D = X - L$	$L < X$: $\frac{2D}{c}$	$L < X$: $\varepsilon\frac{2D}{c}$	$L < X$: $\frac{2L}{c}$	$L > X$: $\xi = \frac{X}{L}$	$L > X$: $100\,\lambda$ for interpolation	$100\,\lambda$	$L < X$: $\lambda\frac{2L}{c}$	$\vartheta = \varepsilon\frac{2D}{c} + \lambda\frac{2L}{c}$ if $L < X$ / $\vartheta = \lambda\frac{2X}{c}$ if $L > X$	$\Delta t = \varepsilon\frac{2X}{c} - \vartheta$	$\Delta t_g = \Delta t - (t_u^* - t_d^*)$	p weight	$p\,\varepsilon\frac{2X}{c}$	$p\,\Delta t$	$\tau_x = \frac{2X}{c}(1+\varepsilon)$	$t_x = \frac{2X}{c} + \vartheta$	$\sigma_t = \frac{100\,\Delta t}{\tau_x}$	$\sigma_t = \frac{100\,\Delta t_g}{\tau_x}$
	cm	m	m	—	km/h	—	%	hours	hours	km	km	hours	hours	hours	—	%	%	hours	hours	hours	hours	—	hours	hours	hours	hours	%	%
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Example No. 1.																												
$J = 0{,}09‰$, $x = 120$ km, $H_0 = 10$ m, $c = 12$ km/h, $(t_u^* + t_d^*) = 1$ hour																												
1	100	3	7	0,429	2,48	0,207	4,55	20,0	0,91	155,4	—	—	—	—	0,771	1,50	1,41	—	0,28	0,63	—0,37	0,158	0,144	0,100	20,91	20,28	3,02	—1,77
2	200	4	6	0,670	3,13	261	7,60		1,52	133,2	—	—	—	—	0,900	—	3,6	—	0,72	0,80	—0,20	0,436	0,663	0,349	21,52	20,72	3,71	—0,93
3	300	5	5	1,0	4,10	342	13,6		2,72	111,0	9,0	1,50	0,20	18,5	1	—	8,3	1,54	1,74	0,98	—0,02	0,319	0,868	0,313	22,72	21,74	4,31	—0,09
4	400	6	4	1,5	5,40	450	25,7		5,14	88,8	31,2	5,20	1,34	14,8	1	—	11,1	2,53	3,87	1,27	+0,27	0,074	0,380	0,094	25,14	23,87	5,03	+1,08
5	500	7	3	2,33	6,67	555	44,8		8,96	66,6	53,4	8,90	3,99	11,1	1	—	33,0	3,66	7,65	1,31	+0,31	0,010	0,090	0,013	28,96	27,65	4,53	+1,07
6	600	8	2	4,0	8,17	680	88,0		17,6	44,4	75,6	12,60	11,09	7,4	1	—	69,0	5,11	16,20	1,40	+0,40	0,003	0,053	0,004	37,6	36,20	3,71	+0,61
Weighted average values:																					—0,13	1,000	2,198	0,873	22,20	23,07	3,79	—0,58
$J = 0{,}09‰$, $x = 120$ km, $H_0 = 10$ m, $c = 10$ km/h, $(t_u^* + t_d^*) = 1$ hour																												
1	100	3	7	0,429	2,48	0,248	6,80	24,0	1,63	155,4	—	—	—	—	0,771	2,22	2,10	—	0,50	1,19	+0,13	0,158	0,258	0,179	25,63	24,50	4,39	+0,51
2	200	4	6	0,670	3,13	313	11,2		2,69	133,2	—	—	—	—	0,900	—	5,3	—	1,27	1,42	+0,42	0,436	1,174	0,620	26,69	25,27	5,31	+1,57
3	300	5	5	1,0	4,10	410	20,5		4,92	111,0	9,0	1,80	0,37	22,2	1	—	12,4	2,75	3,12	1,80	+0,30	0,319	1,566	0,572	28,92	27,12	6,15	+2,77
4	400	6	4	1,5	5,40	540	41,2		9,89	88,8	31,2	6,24	2,57	17,76	1	—	27,0	4,80	7,37	2,52	+1,50	0,074	0,732	0,186	33,89	31,37	7,47	+4,49
5	500	7	3	2,33	6,67	667	83,0		19,92	66,6	53,4	10,68	8,86	13,32	1	—	57,0	7,59	16,45	3,47	+2,47	0,010	0,199	0,035	43,92	40,45	7,91	+5,63
6	600	8	2	4,0	8,17	817	200,0		48,00	44,4	75,6	15,12	30,24	8,88	1	—	142,0	12,61	42,85	5,15	+4,15	0,003	0,144	0,015	72,00	66,85	7,17	+5,77
Weighted average values:																					+0,607	1,000	4,073	1,607	28,07	26,46	5,71	+2,16
Example No. 2.																												
$J = 0{,}25‰$, $x = 60$ km, $H_0 = 13$ m, $c = 10$ km/h, $(t_u^* + t_d^*) = 1$ hour																												
		3	10	03	9,0	0,9	426	11,2	47,8	80	—	—	—	—	0,75	—	61,4	—	6,81	40,9	39,9	—	—	—	59,0	18,08	69,3	67,9
$J = 0{,}25‰$, $x = 60$ km, $H_0 = 13$ m, $c = 12$ km/h, $(t_u^* + t_d^*) = 1$ hour																												
		3	10	0,3	9,0	0,75	128,6	9,33	12,0	80	—	—	—	—	0,75	—	36,5	—	3,40	8,6	7,6	—	—	—	21,33	12,73	40,3	35,6

In the computation according to traffic, not the net tonnage, but of course the quality of the goods transported and/or the cost of transportation should be taken as decisive.

Examples

In order to ensure better conspicuity, the examples will be given in tabulated form.

Example 1. On a river with a slope of $J = 0{,}00009$ (9 cm per km) two river barrages have been built from one another at a distance of 120 km. For the time conditions of navigation between the two barrages, the data of the downstream barrage are to be considered: the raised water surface is 7 m above the lowest water level, the depth of the latter is 3 m. The up- and downstream locking time amounts to 1 hour. The values of mean velocity v_0 are derived from an assumed stage-discharge curve consistent with natural conditions. The results of computations are the following: travelling time prior to damming (C. 26), travelling time subsequent to damming (C. 27), gain of travelling time (C. 31), relative saving in fuel (C. 28), gain of service time — in some instances with low river stages loss of time — (C. 22), relative resultant gain of time — eventually loss of time — (C. 29.). The computations have been performed in regard to six different river stages for two different vessel speeds; $c = 10$ km per hour and $c = 12$ km per hour. With analogy based on the regime of the Danube, relative frequencies pertaining to the original river stages are given in Column 23. Taking these frequencies into account, the results have been weighted, and thus the weighted mean values indicated in the last row of the computations, were obtained. The saving in fuel pertaining to the speed of 12 km per hour will be 3,8 per cent, whereas that for the speed of 10 km per hour will be 5,7 per cent.; in the first case a negligible small loss, whereas in the second case a gain of 36 minutes (weighted value) can be ascertained.

Example 2. On a river with relatively high velocity of flow and with a slope of $J = 0{,}00025$ (25 cm per km) near to each other, high river barrages are installed: $h_0 = 3$ m, $H = 10$ m, $X = 60$ km, $v_0 = 9$ km per hour. With a dead-water speed of 10 km per hour the saving in fuel will be 69 per cent, and that in case of 12 km per hour dead-water speed will be 40 per cent. Also here a considerable gain of service time may be noted: 40 hours (68 per cent) and 7,6 hours (36 per cent) respectively.

The above examples refer to fairly extreme cases.

For the construction of the curves, as well as for performing the computations of the examples, the author wishes to express his gratitude to Mr. József Szepessy.

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Summary

In the study th effect of river barrages with regard to navigation for water courses navigable in their natural state unimpededly and continuously, is being discussed. It does not deal with all the consequencies of river canalization, but only with some of the more significant advantages ensured by backwater effect. The author wishes to support the economical features of the run-of-river hydroelectric power plants installed for the sake of multi-purpose utilization and mainly for power generation.

I. *The gain of time and the relative saving in fuel.* By damming navigation achieves savings both in *travelling time* and in approximately proportionate fuel consumption. For the mathematical solution of the problem some assumptions should be made: the riverbed is regular, the original natural water surface and the riverbed are uniform and parallel, the backwater curve is a parabola of second degree. With these assumptions the gain of travelling time to be achieved may be accurately determined theoretically for any headwater elevation.

The gain of time achieved within a round (tour-retour) trip between two river-barrages will be given by Eq. (26) in case of backwater extending from the downstream barrage up to the upstream barrage i. e. if the tailwater of the upstream barrage is raised. In that particular case, when the limit of backwater effect falls within the section of the upstream barrage also Eq. (26) or the simplified Eq. (39) derived therefrom may be used ($\xi = 1$). If backwater effect does not extend to the upstream barrage, then, according to Eqs. (26) and (39) respectively, gain of time may be achieved on the raised stretch, where as farther towards the upstream barrage travelling time remains unvaried.

The saving in fuel may be taken as approximately proportionate to the gain in travelling time. *Relative saving in fuel* is determined by Eq. (37).

The saving obtainable in *service time* should be determined by subtracting the average locking time according to Eq. (34), whereas the relative gain of time is given by Eq. (38). It may occur, however, that in spite of the savings in travelling time and fuel consumption, no gain will be achieved in service time or, as the case may be, it will be increased.

The computation and the final formulae contain three dimensionless parameters:

β = *velocity factor*

δ = *damming factor*

ξ = *relative distance* of the riverbarrages.

The accompanying charts furnish correlations between percentual gain of travelling time and the parameters mentioned.

The method of computation as well as the use of charts is enlightened in conclusion by examples. The examples draw attention to the fact which can also be deduced theoretically that the gain of travelling time pertaining to higher discharges will be considerably greater in most cases, than that pertaining to lower discharges, in spite of the fact, that backwater effect with mean or maximum discharges extends only to a short distance.

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