Roughness coefficient of the Instruch riverbed

N R Akhmedova[1*], *A S* Kochkareva[1], and *V A* Naumov[1]

[1]Institute of Fisheries and Aquaculture, Kaliningrad State Technical University, 1, Soviet Ave., Kaliningrad, 236022, Russia

Abstract. The article presents the results of improving the numerical method developed in [1-3] for calculating the roughness coefficient of the riverbed (RCOTR) to increase stability and using it to study the dependence of the RCOTR of the Instruch River on dimensionless complexes in different seasons.

1 Introduction

When processing the results of engineering and hydrological surveys, as well as when solving many other tasks (for example, calculation of the distribution of suspended impurities in a watercourse or the equilibrium of a fixed nets) it is necessary to determine the average flow velocity of the watercourse V. According to normative documents, the calculation is performed in the approximation of a uniform flow according to the Chezy formula:

$$V = C\cdot(R\cdot I)^{0.5} \tag{1}$$

Where I – slope of the water surface; R – hydraulic radius; C – Chezy coefficient.

According to the current regulatory documents, the Chezy coefficient at an average depth of a watercourse up to 5 m should be calculated according to the formula of N.N. Pavlovsky

$$C = R^y/n,\ y = 2.5\ n^{0.5} - 0.13 - 0.75\ R^{0.5}\cdot(n^{0.5} - 0.1) \tag{2}$$

Where n – the roughness coefficient of the riverbed (RCOTR).

Requirement [4] – RCOTR n in the formula (2) choose according to the descriptive characteristics of the settlement area given in the table by M.F. Sribny. The named tables for determining the RCOTR of watercourses have significant drawbacks, the main of which is a large range of values with the same description.

The issue of a reasonable choice of the RCOTR when performing hydraulic calculations is relevant, since the roughness of the riverbed significantly affects the dynamics of watercourses [5-12]. In [5], the results of studies are presented that show that the RCOTR tends to decrease with increasing flow and depth of water, and in a certain range it seems to

---

[*] Corresponding author: isfendi@mail.ru

remain constant. The authors of the work [5] confirm the need to evaluate the RCOTR by the method of field measurements.

The authors [6] tried to investigate the seasonal dynamics of the RCOTR on the basis of a one-dimensional hydraulic model. Four models of river sections were created based on a digital relief model with a height of 1 m and field measurements, in which seasonal RCOTR were calibrated and confirmed using sensor recording. The use of the seasonal roughness factor has improved the performance of the model, and the results are comparable to previous studies in the same field.

In the study [7], the formula for calculating the value of n was created on the basis of a statistical analysis of the estimated values of RCOTR according to the formula of Manning. The results showed that taking into account the dynamics of changes in n can improve the modeling of the flow of hydrological models, especially on slopes. In [8], a method was presented for determining the distribution functions of RCOTR along natural rivers based on modified optimization of random search and clustering (MRSOC). The results showed that using the proposed method, all changes in the value of n on the longitudinal sections of natural rivers can be estimated with sufficient accuracy, and equations for these changes can also be obtained.

In [9] presents the results of numerical simulation of surface water dynamics in the Volga-Akhtuba floodplain based on the system of Saint-Venant equations using a combined Lagrangian-Eulerian algorithm. On the example of the spring flood of 2011, the inapplicability of the hydrodynamic model with a constant value of the RCOTR was shown. The agreement of the numerical simulation results with the observation data at the hydroposts allowed us to obtain estimates of $n_{min} = 0.02$ and at the maximum of the water level in the Volga riverbed $n_{max} = 0.047$.

In the Russian State Hydrometeorological University (RSHU), on the example of about 500 rivers, a study was carried out of the dependence of the RCOTR on average depths $n=f(H)$ [10, 11]. Two main types of dependencies were identified. The first type includes the increasing functions of $f(h)$, characteristic of lowland rivers, the banks of which are intensively overgrown with shrubs and trees. Decreasing functions occur in rivers with well-developed non-overgrown riverbeds, which is more typical for mountain and one-and-a-half rivers (second type). In addition to the two main types of dependencies $f(H)$, intermediate dependencies are also possible. In particular, there are rivers where at first there is an increase in RCOTR with an increase in average flow depths, and then when their critical value n is reached, they decrease. The effect of the interaction of channel and floodplain flows on hydraulic resistances was studied: how will the RCOTR change with access to the floodplain [11].

A very interesting study was carried out in [12]. The accuracy of determining the RCOTR of lowland streams and rivers calculated in the reverse way was evaluated. The data of rivers of various sizes were used, the inter-boundary water flow rates of which vary from 0.06-0.07 (Polpe stream) to 900-1000 m^3/s (Oka river). The state of the rivers in the section of the hydrological alignment at the time of measurements is a free channel, ice phenomena and riverbed aquatic vegetation are absent. A number of important conclusions have been made. In particular, the error in the tabular evaluation of the RCOTR can be 100% or more; with different filling of the riverbed, the RCOTR can change several times.

The method for calculating NSR from measurement data, used in [12] and other works, is based on the Chezy formula with two simplifications:

- The hydraulic radius R is replaced by the average depth of the watercourse H.
- Instead of formula (2), the Manning approximation is used ($y=1/6$).

As a result of such simplifications, from (1), (2) the formula for calculating the RCOTR follows:

$$n = H^{2/3} I^{0,5} / V \tag{3}$$

Formula (3) is very convenient and does not require iterations. But nowhere is the error introduced by the accepted simplifications discussed.

In publications of recent years, studies of the dependence of RCOTR on dimensionless complexes have been carried out. Thus, in [13], the influence of the Froude numbers *Fr* and Reynolds *Re*, the slope of the water surface, the relative depth *h*:

$$Fr = V^2/(g \cdot H),\ \ Re = V \cdot H/\nu,\ h = H/B \tag{4}$$

Where g – acceleration of gravity, ν – coefficient of kinematic viscosity of water, B – width of the watercourse.

The change in the RCOTR of individual rivers during the year was studied in [1-3]. In [1], a close stochastic relationship was established between the RCOTR of the Krasnaya River (Tokarevka hydrological post) and the Froude number, which was approximated by the dependence:

$$n = n_0 \cdot + A \exp(-\alpha \cdot Fr) \tag{5}$$

Where *α, A, n0* – empirical constants that need to be found from observational data.

Formula (5) provided a very high determination index $R^2 = 0.959$. This means that 95.9% of the changes in the RCOTR of the Krasnaya River are explained by the variation of the Froude number and only 4.1% by other factors. Unfortunately, such a dependence of the RCOTR on one factor is quite a rare phenomenon. Dependence on several factors is more often realized.

In [1-3], a numerical method for calculating the RCOTR from measurement data was developed, which did not require the adoption of the above simplifications. However, it turned out to be unstable with a non-smooth transverse profile of the riverbed.

The purpose of this article is to improve this method to increase stability and to use it to study the dependence of the RCOTR of the Instruch River on dimensionless complexes in different seasons.

2 Materials and methods

The Instruch River flows completely through the territory of the Kaliningrad region, is a right tributary of the Pregolya River. The source of the river is located in the east of the Kaliningrad region, on the watershed of the Neman and Pregolya basins near the village of Pravdino in the Krasnoznamensky district. At the mouth, which is located in the city of Chernyakhovsk, the river Instruch merges with the river Angrapa and together they give rise to the river Pregolya. The length of the river is 101 kilometers, the basin area is 1250 km^2. In the upper reaches, the river first flows to the west, and after the village of Zabrodino turns southwest to the city of Chernyakhovsk. The shores are more often steep, sometimes steep, there are areas with gently sloping low swampy shores [14].

A hydropost (HP) is located on the river in the village of Ulyanovo (the former name is Kraupishken). According to the automated information system of the state monitoring of water bodies [15], the HP was opened on 01.01.1885 and is currently functioning; the zero mark of the HP of the Instruch river-Ulyanovo is 13.23 m in the Baltic system. The catchment area to the HP is 587 km^2, the distance from the source is 51 km, from the mouth is 50 km.

In the hydrological yearbooks for the years 1960-1966 [16-22], there are measurement data on the Instruch River (Ulyanovo HP). The measurements include the slope of the water surface required for calculations. The largest number of them – 71, was made in 1961. But the slopes of the water surface were not measured in all series. 49 complete series were selected. The results of these measurements are shown in Table 1 (columns 2 through 6).

Table 1. The results of observations and calculations of the characteristics of the Instruch River in 1961.

No.	Q	ω	B	Hm	I	$10^3 \cdot Fr$	$10^2 \cdot h$	$10^{-5} \cdot \mathrm{Re}$	n
	m^3/s	m^2	m	m	‰	-	-	-	-
1	7.69	34.8	26.2	1.93	0.056	3.75	5.07	2.93	0.0417
2	5.83	23.8	26.2	1.52	0.056	6.74	3.47	2.24	0.0286
3	14.3	51.2	26.2	2.53	0.12	4.07	7.46	5.46	0.0662
4	11.7	44.8	26.2	2.34	0.056	4.07	6.53	4.47	0.0432
5	7.97	37.2	26.2	2.03	0.056	3.30	5.42	3.04	0.0457
6	10.3	42.9	26.2	2.24	0.067	3.59	6.25	3.93	0.0498
7	6.07	29.2	26.2	1.75	0.056	3.96	4.25	2.32	0.0396
8	4.45	25.5	26.2	1.57	0.089	3.19	3.71	1.70	0.0520
9	6.35	30.8	26.2	1.81	0.056	3.69	4.49	2.42	0.0415
10	8.38	43.1	26.2	2.22	0.067	2.34	6.28	3.20	0.0621
11	7.57	35.7	26.2	1.94	0.056	3.37	5.20	2.89	0.0438
12	4.98	24.1	26.2	1.51	0.056	4.74	3.51	1.90	0.0336
13	3.97	16.3	22.0	1.22	0.033	8.17	3.37	1.80	0.0184
14	2.16	6.88	18.2	0.75	0.10	26.6	2.08	1.19	0.0170
15	1.27	3.36	9.70	0.55	0.17	42.1	3.57	1.31	0.0149
16	1.16	2.74	9.40	0.47	0.14	62.7	3.10	1.23	0.0113
17	0.66	1.90	9.10	0.38	0.13	59.0	2.29	0.725	0.0114
18	2.10	10.3	19.5	0.93	0.13	8.03	2.71	1.08	0.0328
19	3.41	21.7	26.2	1.43	0.078	3.04	3.16	1.30	0.0488
20	5.60	30.2	26.2	1.77	0.067	3.04	4.40	2.14	0.0494
21	15.6	48.4	26.2	2.46	0.089	5.77	7.05	5.97	0.0463
22	13.4	49.6	26.2	2.51	0.089	3.93	7.23	5.11	0.0577
23	8.31	41.3	26.2	2.17	0.056	2.62	6.02	3.17	0.0528
24	4.26	23.5	26.2	1.50	0.10	3.74	3.42	1.63	0.0504
25	1.78	10.9	20.0	0.97	0.067	4.99	2.73	0.890	0.0308
26	1.59	4.88	16.5	0.66	0.130	36.6	1.79	0.964	0.0169
27	0.64	2.06	9.10	0.39	0.120	43.5	2.49	0.703	0.0123
28	0.37	1.18	6.0	0.3	0.110	48.3	3.28	0.601	0.0104
29	0.45	1.81	8.70	0.38	0.110	33.3	2.39	0.517	0.0141
30	1.26	4.83	14.0	0.64	0.130	20.1	2.46	0.899	0.0201
31	0.56	2.42	9.20	0.44	0.160	20.8	2.86	0.609	0.0190
32	0.30	1.03	5.50	0.3	0.110	46.2	3.41	0.545	0.0108
33	0.22	1.09	5.50	0.29	0.100	21.0	3.62	0.401	0.0137
34	1.0	2.62	9.20	0.46	0.170	52.2	3.10	1.08	0.0132
35	2.90	9.89	19.2	0.94	0.110	17.0	2.68	1.51	0.0221
36	3.42	16.8	22.8	1.28	0.089	5.74	3.23	1.49	0.0364
37	4.84	26.6	26.2	1.64	0.078	3.33	3.88	1.85	0.0494
38	6.58	32.7	26.2	1.85	0.067	3.31	4.76	2.51	0.0480
39	4.41	23.5	26.2	1.51	0.067	4.01	3.42	1.68	0.0403
40	3.58	15.7	21.8	1.21	0.067	7.37	33.0	1.64	0.0272
41	3.70	12.2	19.8	1.04	0.078	15.2	31.1	1.87	0.0198
42	7.40	39.8	26.2	2.14	0.029	2.32	58.0	2.82	0.0397
43	12.0	46.5	26.2	2.41	0.078	2.83	67.7	4.58	0.0541
44	6.09	26.7	26.2	1.63	0.056	5.21	38.9	2.32	0.0331
45	4.0	13.4	20.5	1.1	0.056	13.9	31.9	1.95	0.0179
46	1.04	2.67	9.20	0.44	0.110	53.3	31.5	1.13	0.0105
47	0.66	1.95	9.20	0.36	0.120	55.2	23.0	0.717	0.0109
48	0.65	1.77	9.20	0.40	0.110	71.5	20.9	0.706	0.0105
49	15.4	51.6	26.2	2.58	0.089	4.61	7.52	5.88	0.0530

One of the improvements of the calculation method is to obtain an analytical dependence of the hydraulic radius on the maximum depth of the watercourse H_m in the considered river alignment. The most reliable data from the array of measurements is the area of the living section of the watercourse as a function of depth $\omega=f\omega(Hm)$. Therefore, we choose it as the base function, and not the dependence of B on H_m, which often has low accuracy. As the subsequent analysis showed, sufficient approximation accuracy is obtained by using a 4th-order polynomial:

$$f_\omega(H_m) = a_1\, H_m + a_2\, (H_m)^2 + a_3\, (H_m)^3 + a_4\, (H_m)^4 \tag{6}$$

Where are the coefficients $a_1,\ a_2,\ a_3$ are selected by the least squares method. Note that in the formula (6) $a_0 = 0$, since this should be done $f_\omega(0)=0$.

The derivative of (6) gives an approximation of the dependence of the width of the watercourse on the greatest depth

$$B= \varphi(H_m) = a_1 + 2a_2\, H_m + 3a_3\, (H_m)^2 + 4a_4\, (H_m)^3 \tag{7}$$

The found function φ allows you to calculate the wetted perimeter:

$$\chi = f_\chi\left(H_m\right) = \varphi(0) + \int_0^{H_m} \left(1 + \varphi p(H)^2\right)^{0,5} dH \tag{8}$$

Where $\varphi p(H)$ is the derivative of $\varphi(H)$ by H.

Approximation expression for hydraulic radius:

$$R=f_R(H_m) =f_\omega(H_m)/f_\chi(H_m) \tag{9}$$

We substitute expressions (2), (9) into (1), and then take the logarithm of both parts of the resulting equality:

$$(2.5\, n^{0.5}–0.13–0.75\, f_R(H_m)^{0.5}\cdot(n^{0.5}–0.1))\cdot ln\ (f_R(H_m)) – ln(n) = ln(V) – 0.5(ln(f_R(H_m) + ln(I)) \tag{10}$$

We substitute the set of measured values into equation (10): the average velocity V, the water surface slope I, and the greatest (in cross section) depth of the watercourse H_m. Solving the equation obtained by the numerical method, we find the value n. corresponding to the set of measured values. This procedure is repeated for each set of measurements.

3 Results and Discussion

For formula (6), coefficient values were obtained, for example, for 1961 (according to Table 1) $a_1 = –0.428$ m; $a_2 = 14.30$; $a_3 = –2.473$ m^{-1}; $a_4 = –0.003797$ m^{-2}. As can be seen from Figure 1, the approximation error according to (6) is very small.

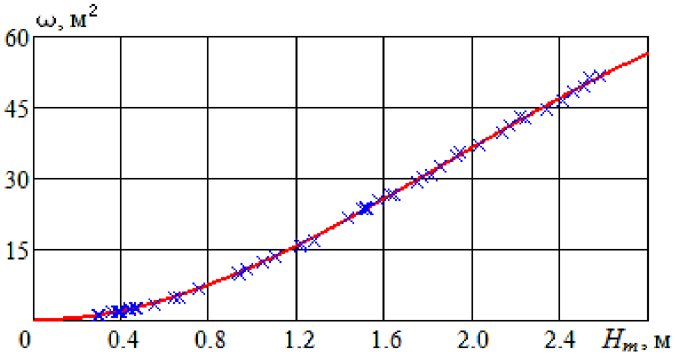


Fig. 1. Dependence of the area of the living section of the Instruch River on the greatest depth in 1961. Points - according to observations, line - calculation by formula (6).

Fig. 2. HP Ulyanovo on the river Instruch: the position of the measuring rail on the bridge support. Photo of the authors during the summer-autumn low water period (08.10.2022).

The peculiarity of the Ulyanovo HP is that the measuring rail is placed on the support of the bridge over the Instruch River (Figure 2), therefore, the width of the river along the water edge does not exceed the maximum value equal to the distance between the supports (B_{max} = 26.2 m). This value is reached at a depth of approximately H_0 = 1.58 m.

The relationship between the width of the river and the maximum depth will be obtained, taking into account the vertical support, using formula (7):

$$B = \begin{cases} \varphi(H_m), & H_m < H_0; \\ B_{max}, & H_m \geq H_0. \end{cases} \tag{11}$$

On Figure 3 shows observational data not only for 1961, but also for 1960. The noticeable scatter of points at $H_m < H_0$ is most likely due to the low accuracy of determining the width of the river.

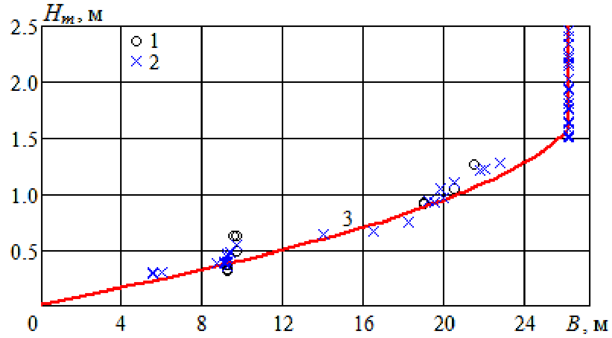


Fig. 3. Relationship between the maximum depth and width of the Instruch River (HP Ulyanovo).

Points - according to observational data: 1 - 1960, 2 - 1961 Line 3 - calculation by formula (11)

Using (8), (9), we calculate the wetted perimeter and hydraulic radius, which is plotted in Figure 4. At first glance, according to Figure 4, the calculated values of the hydraulic radius R_i do not differ much from the measured average depths of the Instruch River H_i. Let us calculate the relative error of such a replacement (Figure 5):

$$\varepsilon_i = 100\cdot(H_i/f_R(H_{mi}) - 1) \tag{12}$$

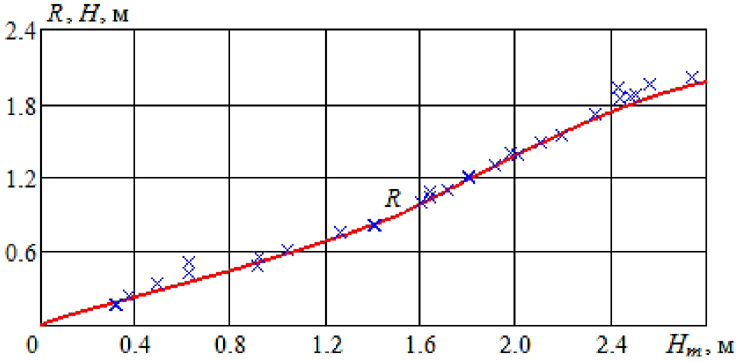
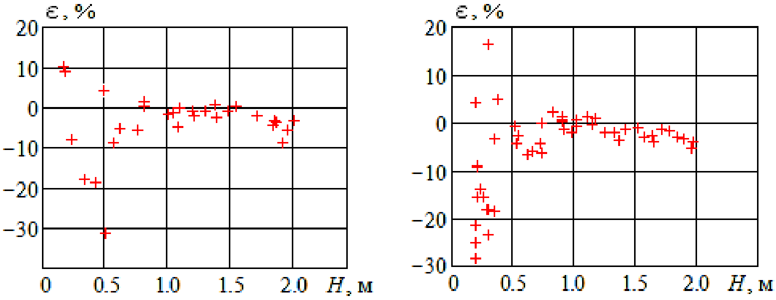


Fig. 4. Comparison of the measurement data of the average depth of the Instruch River in 1961 (points) with the result of calculating the hydraulic radius – line.

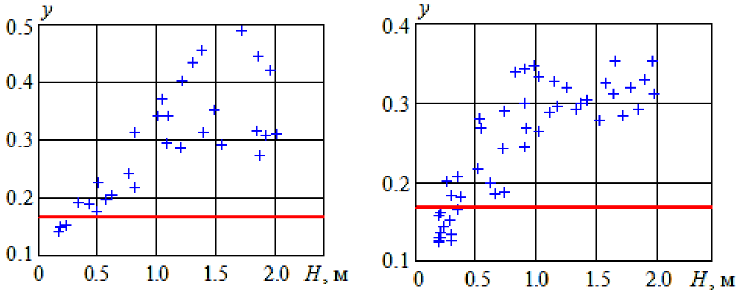


a b

Fig. 5. Relative error when replacing the hydraulic radius with the average depth of the Instruch River: *a* – 1960; *b* - 1961.

According to figure 5 shows that at a depth of less than 0,5 m, the relative error ε increases and can reach 30%. With such values of ε, the use of the average depth instead of the hydraulic radius can lead to a large calculation error. Therefore, we do not use the first simplification further. The results of solving (10) by the numerical method according to the data of 1961 are listed in the last column of table 1.

Let us discuss the possibility of applying the second simplification. According to fig. 6 it can be seen that the value of y calculated by the Pavlovsky formula at great depths can exceed the Manning value by several times. Only at shallow depths are they more or less close.



a b

Fig. 6. Auxiliary parameter in the Chezy formula for the Instruch river. Points – calculation according to measurement data and Pavlovsky formula, line – Manning approximation (y = 1/6): a – 1960; b - 1961.

Before constructing a regression model, let us estimate, with the help of pair correlation coefficients (PCC), the tightness of the stochastic relationship between the measured and calculated values, including dimensionless complexes. Previously, a close stochastic relationship between the RCOTR and the reciprocal of the Froude number was established. Therefore, we will use the Fr^{-1}. argument in the model. In table 2 PCC values above the main diagonal were obtained according to the data of 1960, below - 1961.

Table 2. Pair correlation coefficients.

	n	**ω**	***H***	***V***	***I***	Fr^{-1}	***h***	***Re***
n	1	0.762	0.753	–0.690	0.029	0.875	0.663	0.367
ω	0.906	1	0.995	–0.348	–0.274	0.625	0.885	0.833
H	0.904	0.998	1	–0.309	–0.235	0.605	0.924	0.854
V	–0.616	–0.426	–0.392	1	0.320	–0.852	–0.155	0.203
I	–0.504	–0.601	–0.577	0.624	1	–0.278	–0.020	–0.112
Fr^{-1}	0.908	0.835	0.813	–0.744	–0.691	1	0.490	0.137
h	0.788	0.926	0.941	–0.215	–0.409	0.672	1	0.844
Re	0.761	0.927	0.942	–0.113	–0.398	0.579	0.941	1

Of the dimensional quantities, the average depth and cross-sectional area have the greatest influence on the RCOTR. But between ω and H, the relationship, almost linear functional, one of these factors can be excluded from consideration. This is due to the fact that most of the measurements were performed at the maximum value of the width B_{max}. A noticeable negative correlation between the average speed of the RCOTR; PCC is slightly less than the significant level.

As for the previously studied rivers [1-3], the closest stochastic relationship is between the RCOTR and Fr^{-1}. The next most important dimensionless complexes are relative depth and Reynolds numbers. Moreover, according to the data of 1961, the PCC of these complexes and RCOTR are close, and according to 1960, the PCC of n and Re are noticeably lower. Even weaker is the stochastic relationship between RCOTR and velocity; according to 1960 data, $r = 0.029$.

Regression models of the first and second order for the two most significant factors:

$$n = c_{10} + c_{11}/Fr + c_{12}\,h \tag{13}$$

$$n = c_{20} + c_{21}/Fr + c_{22}\,h + c_{23}/F^2 + c_{24}\,h^2 + c_{25}\,h/F \tag{14}$$

The values of the empirical coefficients found by the least squares method according to the data of 1961: $c_{10} = 0.00313$; $c_{11} = 9.168{\cdot}10^{-5}$; $c_{12} = 0.343$; $c_{20} = 0.0285$; $c_{21} = 2.169{\cdot}10^{-4}$; $c_{22} = -1.251$; $c_{23} = -1.336{\cdot}10^{-7}$; $c_{24} = 18.379$; $c_{25} = -0.00136$.

According to Table 3, the index of determination of the second-order model with one argument is 0.870; with two arguments - 0.947. However, already the first-order model with two arguments (13) gives a good approximation

Table 3. Approximation error estimate.

Arguments	Model order	ε (%)	R^2
Fr	1	19.6	0.824
Fr	2	16.5	0.870
Fr, *h*	1	15.4	0.906
Fr, *h*	2	12.9	0.947

On Figure 7 calculated curves were obtained according to the data of 1961. The experimental points for both 1961 and 1960, shown in figure 6 are in quite satisfactory agreement with the calculated curves. As well as points for other (1962-66) years not shown here.

Large Froude numbers in Figure 7 correspond to low water (shallow depths). Thus, in order to calculate the minimum flow rates, it is necessary to recommend a well-defined value of the RCOTR of the Instruch River (Ulyanovo HP): n = 0.010. Whereas there is no such unambiguity for calculating the maximum flow rates. The value of n is in the range (0.04; 0.08) depending on the relative depth values.

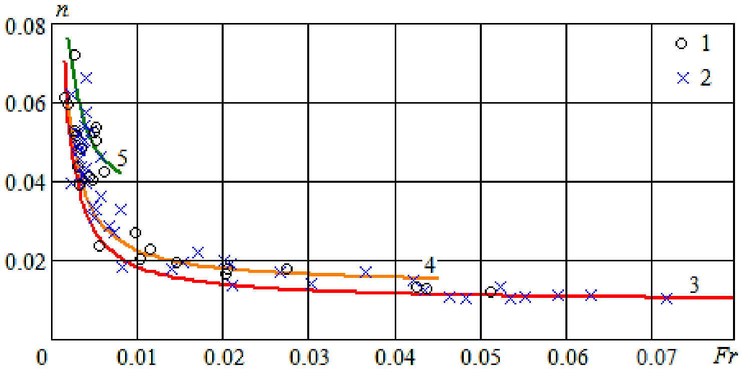


Fig. 7. Dependence of the RCOTR of the Instruch River on the Froude numbers. Points - according to observational data: 1 - 1960, 2 - 1961; lines are the results of calculation by formula (1): 3 - at h = 0.018; 4 – h = 0.03; 5 - h = 0.08.

4 Conclusion

The rationale for RCOTR when performing hydraulic calculations is relevant, since it is one of the most important indicators that characterizes the resistance of the channel to flow and affects the flow rate. Currently, as a rule, the roughness value is taken from the visual characteristics of the channel, which is subjective and can lead to significant errors in the calculations.

When determining the RCOTR from field measurements, a calculation method is used that is based on the Chezy formula with two simplifications: when calculating the Chezy coefficient C, the Manning approximation is used; the hydraulic radius R is replaced by the mean watercourse depth H.

For the alignment of the Instruch River (HP Ulyanovo) determined the relative error of replacing the value of the hydraulic radius R_i by the average depths of the river. It has been established that at a depth of less than 0.5 m, the relative error ε increases and can reach 30%. With such values of ε, the use of the average depth instead of the hydraulic radius can lead to a large calculation error.

When studying the possibility of using the second simplification for hydraulic calculations on the Instruch River (HP Ulyanovo) found that the value of y, calculated by the Pavlovsky formula at great depths, can be several times greater than the Manning value.

Calculation methods have established a close stochastic relationship between RCOTR and Fr^{-1}.

According to the results of processing field studies, it is possible to recommend the value of the RCOTR of the Instruch River (HP Ulyanovo) n = 0.010 when calculating the minimum flow. To calculate the maximum discharges, the value n of the Instruch River (HP Ulyanovo) is in the range (0.04; 0.08) depending on the values of the relative depth.

Acknowledgement

The work was financially supported by the Russian Science Foundation and the Government of the Kaliningrad Region within the framework of the scientific project No. 22-27-20016.

References

1. Bulletin of science and education of the North-West of Russia, http://vestnik-nauki.ru/wp-content/uploads/2018/08/2018-N3-Naumov.pdf
2. V.A. Naumov, Analysis of the variability of the roughness coefficient of the riverbed according to the measurement data given in the hydrological yearbooks, Bulletin of the educational and methodological association for education in the field of environmental management and water use, **14**, 50-55 (2019)
3. N.R. Akhmedova, V.A. Naumov, Influence of the change in the roughness coefficient of the channel on the maximum calculated levels of a small watercourse in a given section (on the example of the Nelma River), Bulletin of the Engineering School of the Far Eastern Federal University, **4**, **49**, 74–80 (2021)
4. Determination of the main calculated hydrological characteristics. Approved for use as a regulatory document by the Decree of the Gosstroy of Russia No. 218. Code of rules COR 33-101-2003 (2003)
5. J.S. Kim, C.J. Lee, W. Kim, Y.J. Kim, Roughness coefficient and its uncertainty in gravel-bed river Water Science and Engineering, **3**, **2**, 217-232 (2010)

6. S. Song, B. Schmalz, Y.P. Xu, N. Fohrer, Seasonality of roughness – the indicator of annual river flow resistance condition in a lowland catchment, Water Resources Management, **31**, **11**, 3299-3312 (2017)
7. A. Ye, Z. Zhou, J. You, F. Ma, Q. Duan, Dynamic Manning's roughness coefficients for hydrological modelling in basins, Hydrology Research, **49**, **5**, 1379–1395 (2018)
8. M. Attari, M. Taherian, S.M. Hosseini, S.B. Niazmand, M. Jeiroodi, A. Mohammadian, A simple and robust method for identifying the distribution functions of Manning's roughness coefficient along a natural river, Journal of Hydrology, **595**, 125680 (2020)
9. A.V. Pisarev, S.S. Khrapov, E.O. Agofonnikova, A.V. Khoperskov, Numerical model of surface water dynamics in the Volga channel: estimation of the roughness coefficient, Bulletin of the Udmurt University, **1**, 114-130 (2013)
10. N.B. Baryshnikov, Hydraulic resistance of riverbeds: a textbook (RSHU Publishing House, St. Petersburg, 2003)
11. N.B. Baryshnikov, M.S. Dregval, P.P. Ovseyko, E.S. Subbotina, Impact of the effect of the interaction of channel and floodplain flows on the hydraulic resistance of channels and floodplains, Scientific notes of the Russian State Humanitarian University, **41**, 55-62 (2015)
12. A.J. Vinogradov, T.A. Vinogradova, V.A. Obyazov, M.M. Kadatskaya, Estimation of the value of the roughness coefficient. Hydrosphere, Hazardous processes and phenomena ,**1**, **4**, 462-476 (2019)
13. S.S. Dash, K.K. Khatua, P.K. Mohanty, Factors influencing the prediction of resistance in meandering channel, Int. Journal of Scientific and Engineering Research, **4**, **5**, 63-66 (2013)
14. Scheme for the integrated use and protection of water bodies in the Neman River basin and the rivers of the Baltic Sea basin (Russian part in the Kaliningrad region). Approved by order of the Neva-Ladoga BVU of the Federal Agency for Water Resources No. 171, http://www.nord-west-water.ru/activities/ndv/page-2/
15. Automated information system for state monitoring of water bodies, https://gmvo.skniivh.ru/
16. Hydrological Yearbook, Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1960)
17. Hydrological Yearbook, Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1961)
18. Hydrological Yearbook, Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1962)
19. Hydrological Yearbook,Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1963)
20. Hydrological Yearbook, Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1964)
21. Hydrological Yearbook, Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1965)
22. Hydrological Yearbook, Baltic Sea Basin 1963 (Gidrometeoizdat, Leningrad, 1966)