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Sources of Uncertainty and Problems of Increasing the Accuracy of Flow Assesment for the Transboundary Narva River

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***Abstract* – The water regime of the transboundary Narva River has always been constantly addressed by the hydrometeorological community. For many years, at the interstate level (the Russian Federation and the Republic of Estonia), there has been a discussion about the accuracy of flow assessment and the correctness of the methods applicable for these purposes. In some years, the discrepancies between the estimates of the average annual water discharge obtained by the Estonian and Russian sides reach values of 20-27%. Sustainable, reliable water use requires updating approaches and achieving greater unambiguity in the flow assessment. In the presented article, various sources of uncertainty in the Narva river flow assessment as hydrodynamic, seasonal factors and imperfection of existing methods are considered.**

Keywords – water discharge, flow assessment methods, transboundary river, hydroelectric power station (HEPS)

I. BRIEF DESCRIPTION OF THE CHARACTERISTICS OF THE NARVA RIVER

The Narva river receives its water from Lake Peipsi and flows into the Baltic Sea through the Narva reservoir and hydroelectric power station (HEPS) and has a length of 76.2km, mean annual runoff about 384m^3/s and the catchment area of 56 200 km^2, located within the territories of three countries (Figure 1 [1]). The width is on average 200-300 m, however, downstream of the Narva HEPS up to 390 m, and the greatest width is observed in the upper reaches of the Verkhovsky Island - about 900 m. The prevailing depth is 3-4 m, in places up to 6 m, below the hydroelectric power station - up to 11 m, before the mouth - up to 15 m. The fall of the river is 30 m and is unevenly distributed: 19% (4-7.5 m) of which falls on the Narva HGS and 16% (5 m) on the Omutskie rapids.

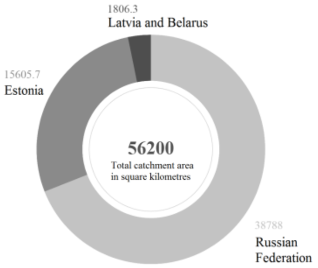

Fig. 1. The Narva catchment area distribution by countries (in square kilometres). [1]

The Narva River, taking on the task of measuring the runoff on the Narva River is initially quite difficult due to the regulation of the flow by the Narva reservoir and the hydroelectric power station on the one hand, and the wind-induced backwater phenomena from the Narva Bay.

II. HYDROLOGICAL MONITORING IN THE STUDY AREA

Hydrological monitoring in the catchment area of the Narva river is performed by national hydrometeorological services (and private network gauges) of two countries - the Russian Federation and the Republic of Estonia. The location of the stations is indicated in Figure 2.

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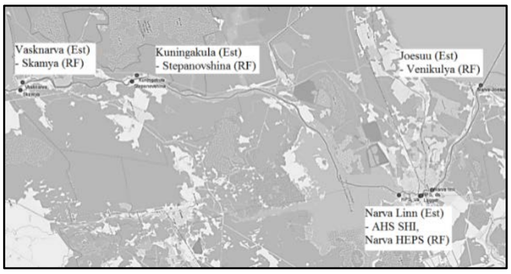
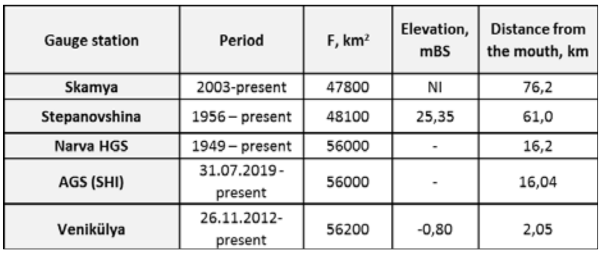


Fig. 2. Hydrological monitoring gauge stations network of Russian Federation and Republic of Estonia.

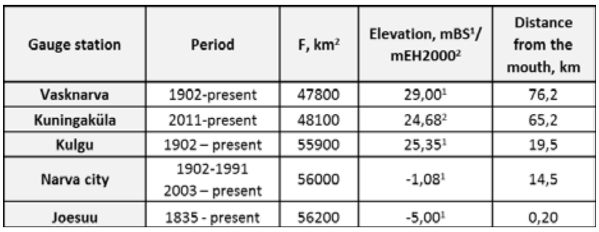
It should be noted that water discharge is measured only at the gauge station of the Narva river – Narva city (Est) and the Narva river - Narva HEPS (RF), at all other stations only the water level is monitored, Skamya and Venekyulya stations are departmental and access to data from them is quite limited. Nevertheless, potentially the two states have a good unified observation network, confined to important sections of the Narva River.

TABLE 1 RUSSIAN HYDROLOGICAL NETWORK [2]



Gauge station	Period	F, km^2	Elevation, mBS	Distance from the mouth, km
Skamya	2003-present	47800	NI	76,2
Stepanovshina	1956 – present	48100	25,35	61,0
Narva HGS	1949 – present	56000	-	16,2
AGS (SHI)	31.07.2019 - present	56000	-	16,04
Venikülya	26.11.2012- present	56200	-0,80	2,05

TABLE 2 ESTONIAN HYDROLOGICAL NETWORK [3]



Gauge station	Period	F, km^2	Elevation, mBS^1/ $mEH2000^2$	Distance from the mouth, km
Vasknarva	1902-present	47800	$29,00^1$	76,2
Kuningaküla	2011-present	48100	$24,68^2$	65,2
Kulgu	1902 – present	55900	$25,35^1$	19,5
Narva city	1902-1991 2003 – present	56000	$-1,08^1$	14,5
Joesuu	1835 - present	56200	$-5,00^1$	0,20

At the same time, the methods used to account the runoff fundamentally differ. Thus, on the Russian side flow assessment of the Narva River is carried out at the Narva hydroelectric generating station (HEPS) by hydraulic calculation (formula 1), summarizing flow through turbines ($Q_{turb.}$) and releases through the ice passes ($Q_{icepass}$), eelway (Q_{eelway}) and shields of the dam (Q_{dam}) [4]:

$$Q = Q_{turb.} + Q_{waste} = Q_{turb.} + Q_{icepass} + Q_{dam} + Q_{eelway} \tag{1}$$

Where:

$$Q_{icepass} = f(H_{HW}, \text{range of openning})$$

$$Q_{dam} = f(H_{HW}, \text{gates rise height})$$

$$Q_{eelway} = 0,5 - 1\frac{m^3}{s} daily$$

And H_{HW} – Narva HEPS headrace water level.

The water flow through the turbines, the assessment of which is the most vulnerable, is recalculated backward depending on the electrical capacity of a hydropower unit (N in kW), gross head of a hydroelectric power station (H in meters) and efficiency factor of a hydropower unit (η in %) values by formula 2 [4]:

$$Q_{turb.} = \frac{1000 * N}{H * \eta * g} \tag{2}$$

Where:

g - free fall acceleration, m/s^2.

In the Republic of Estonia, a gauge station the Narva river – Narva city (Linn) was opened in 2000, located 14.6 km from the mouth of the river. In the same year, measurements of water flow were started at the stream gauge of the gauge station.

Water level observations were automated in 2002. Hourly data of the water levels for the Narva river – Narva city gauge station is available from 01.01.2003 [3].

Discharges from 2000 to 2005 were measured from a boat.

Prior to 2006, discharges were measured on the «Druzhba» bridge using the «Neva» crane. Discharges were measured using the area velocity method, while the depths in the river cross section were measured using a measuring log line and the «Neva» crane, and the current velocities were measured on pivot points by integration method- using the «IST» mechanical river-based current meter.

Since 2006, water flow measurements have been started using acoustic Doppler current profiler (ADSP). Since 2012, a SonTek HydroBoard II profiler has been used.

Between 2000 and 2014, discharge was measured, covering the full cross section of the Narva River. Since 2015, only partial water discharges have been measured - on the Estonian side to the border line, which is situated approximately in the middle of the river.

Daily discharges for the Narva river – Linn gauge station were calculated only for the period 2003 – 2014.

III. RIVER DISCHARGE DATA COMPARISON AND FIELD WORK RESULTS

Average monthly the Narva river – Narva city and Narva river – Narva HGS discharges comparison (m^3/s) from 2003 to 2014 (period of the full cross section measures by Estonian side) are given in table 3.

From the table 3 data analysis follows that in the period from 2004 to 2009, the relative discrepancies in the normal annual water discharges according to the data of the Narva river – Narva HEPS and Narva river – Narva city gauge stations do not exceed 6%, and in 2003 and 2010-2014 varied from 16 to 27%, while monthly data can vary by up to 45% (as in April 2010). For the 2019 and 2020 discrepancies amounts 19.8% and 11.5% resp.

TABLE 3 DISCREPANCY BETWEEN NORMAL ANNUAL DISCHARGES FOR NARVA RIVER – LINN AND NARVA RIVER – NARVA HGS GAUGE STATIONS [5]

Gauge station/ Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Narva HEPS	314	469	433	271	341	424
Narva city	392	488	459	287	351	441
Difference, m^3/s	-77	-18	-26	-16	-10	-17
Difference, %	-19.8	-3.8	-5.6	-5.6	-2.8	-3.8

Gauge station/ Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Narva HEPS	478	440	431	362	390	300
Narva Linn	495	573	514	435	486	411
Difference, m^3/s	-18	-133	-83	-73	-96	-110
Difference, %	-3.5	-23.2	-16.1	-16.8	-19.8	-26.8

Due to such a high discrepancy in the data obtained by both countries, with allowable errors about 10% for the flow accounting [6], and the importance of further reporting on this parameter (water discharge values) within Helcom (Baltic Marine Environment Protection Commission - Helsinki Commission) [7], additional studies were organized within the ER25 Narva WatMan project «Water Management of the Narva River: harmonization and sustention» [8] aimed at clarification of the flow assessment methodologies and develop common river discharge measurement and calculation methods in order to harmonize the flow estimation to make it comparable for Estonia and Russia.

Within the framework of the project joint river discharge measurements with further data processing and development of harmonized methodologies were performed. From the Russian side of the project the automated hydrological complex (AHC SHI) with a hydrostatic sensor was installed on the right bank of the Narva River, 260 m below the fence enclosing the territory of the Narva HEPS. The choice of this particular location for the sensor predetermined the further improvement of the quality of the Q = f (H) dependences, which cannot be called completely reliable in the gauge station of the city of Narva. During the first 3 periods of the project 53 water discharges (Figures 3-4 for 2019 and 2020 field seasons) in 5 discharge section lines were measured by researchers from the Russian side of the project and 13 – by Estonian researchers, 7 of them can be called a completely synchronous (with an accuracy of 10 minutes, which is important due to fast change of the Narva HEPS operation regimes) (Figure 5). Russian hydrologists used River Ray ADCP from Teledyne Inc. for moving vessel discharge measurements, Estonian - S5 and M9 ADCP from SonTek.

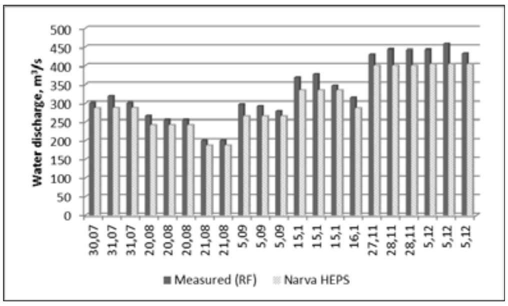


Fig. 3. 2019 field season measured (RF) discharges comparison.

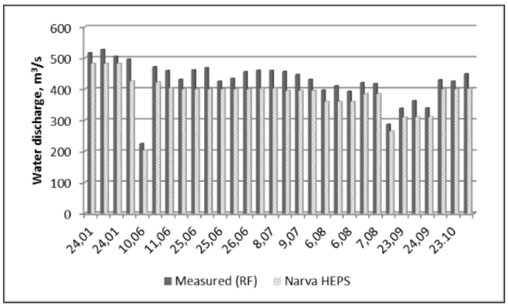


Fig. 4. 2020 field season measured (RF) discharges comparison.

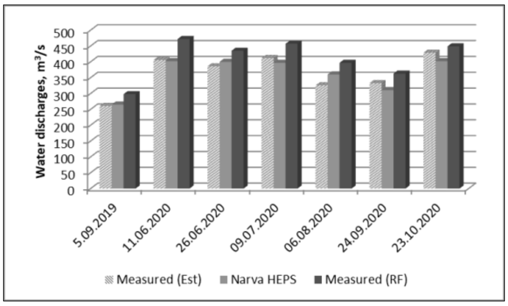


Fig. 5. Synchronous water discharge data.

The discrepancy between the values of water discharge through the hydroelectric units of the Narva HEPS relative to the measurements of the Russian side is on average 10.0%, the Estonian side - 5.87%. In the first case, discrepancy is systematic ($Q_{HEPS} < Q_{meas.RF}$). The maximum discrepancies between the water flow rates measured by the Russian side and those for the hydroelectric power station amounted to 17.3% (June 25, 2020), the Estonian side - 11.1% (November 7, 2019). These indicators show that flow assessment at hydroelectric power plants and direct measurements can be called generally reliable and intercomparable.

IV. SOURCES OF UNCERTAINTY AND SOLUTIONS FOR INCREASING THE ACCURACY OF FLOW ASSESSMENT OF THE NARVA RIVER

A. Wind-induced variable backwater effect and influence of HEPS releases waves to the water level regime of the Narva river

Problem: Backwater wind-induced phenomena have a significant impact on the water level regime of the Narva river at a distance of up to 20 km (to the tail water of the Narva HEPS), making rating curves unstable and unreliable. Discharge/stage points scattering could be caused by the combined effect of the wind and sea “pressure” [9]. This is especially true for the Narva city gauge station rating curve (Figure 6). When the Narva HEPS releases waves are superimposed during waste water discharges period, this effect becomes even more difficult.

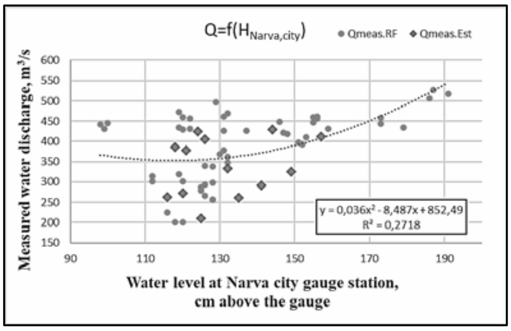


Fig. 6. Rating curve at Narva city gauge station.

Another water level regime influencer is a vertical immobile waves formation during the Narva HEPS releases. When water is released from the HEPS, a hydraulic jump is formed, which subsequently breaks on the downstream spillway apron (15 meters long rubblework). This process affects the level regime of the river, creating standing waves. Unfortunately, the accuracy and discreteness of the data obtained is not enough to unambiguously judge the impact of this factor at the moment.

Solution: Reliable determination of the period of influence of variable backwater. The critical number of the effective component of the wind power W^I (formula 3 [9]), which affects the level regime of the Narva river, should be established:

$$W^I = W * \cos(\beta_w + RV) \quad (3)$$

Where:

W^I - the effective component of the wind power vector (affects the effective surface);

W- the wind power vector;

β_w - the wind direction in °;

RV- rotation value (The number could be found from the map, as seen in Figure 6)

RV = 90° - 22.3° = 67.7° [9].

All the data on the wind should be processed to derive W^I for every hour using the derived angle value and then intercomparison with the wind speed with further analysis performed. Now this analysis is in deep analytical progress.

Even more important in this field is to choose correct locating for the water level gauge station to install. Consequently, the gauge station in the city of Narva is vulnerable to this phenomenon, and at the temporary gauge station AHC SHI and the level gauge at the Narva river HEPS, this influence, if any, is only insignificant. This is well illustrated by the dependence Q = f (H) for these stations (Figures 6-8).

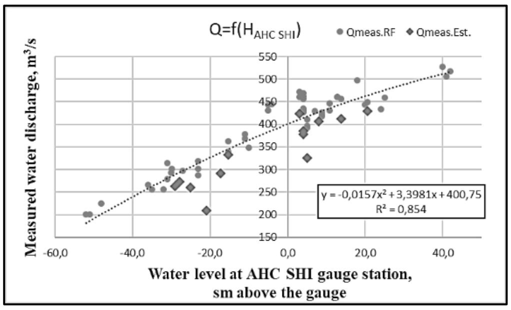


Fig. 7. Rating curve at AHC SHI gauge station.

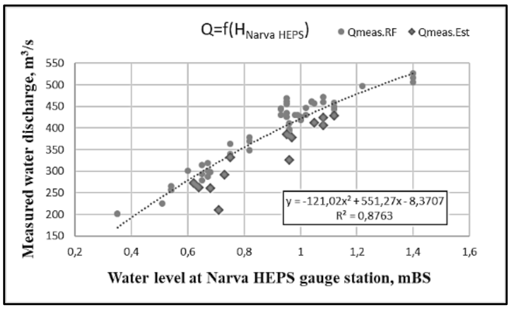


Fig. 8. Rating curve at the Narva river HEPS gauge station.

One of the best solutions to improve these dependences could be the adding of one more variable - the slope of the water surface. And such an attempt was undertaken by both sides of the ER25 project. Thus, Russian researchers obtained the best dependences according to the measurement data in terms of Q = f ($H_{\text{AHC SHI}}$, $I_{\text{AHC SHI – Narva city}}$) and Q = f ($H_{\text{Narva city}}$, $I_{\text{AHC SHI – Narva city}}$) (Figures 9-10).

The quality of the obtained dependences was assessed according to the characteristics of the series of relative deviations of the measured water discharges $Q_{\text{meas.}}$ from those calculated by the equations Q (H_{meas} ; I_{meas}) using formula 4:

$$\tilde{q}_{mes} = \frac{Q_{\text{meas}} - Q(H_{\text{meas}} I_{meas})}{Q(H_{\text{meas}} I_{meas})} \quad (4)$$

The mean square values $\sigma_{\tilde{q}}$ and mathematical mean value $m_{\tilde{q}}$ of relative regression residuals were estimated.

For the dependence shown in Figure 9 below, the equation is obtained:

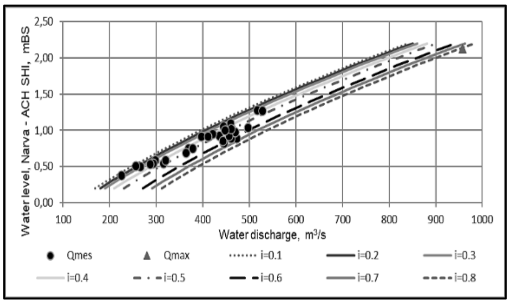


Fig. 9. Slope-and-level curve at AHC SHI gauge station.

$$\boldsymbol{Q(H_{AHC}, I_{AHC-Narva}) = 100.925 + 230.152H_{AHC} + }$$
$$\boldsymbol{+ 44.047H_{AHC}^2 + 203.682I_{AHC-Narva}}$$

With: $m_{\tilde{q}}= 0.00$, $\sigma_{\tilde{q}}=0.036$

For the dependence shown in Figure 10 below, the equation is obtained:

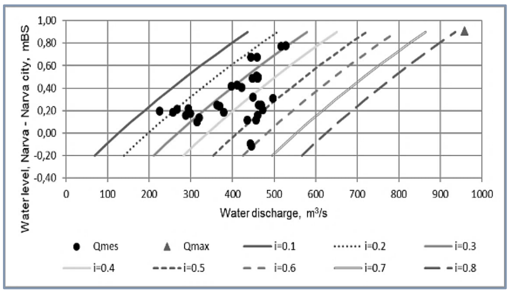


Fig. 10. Slope-and-level curve (RF) at the Narva city gauge station

$$\boldsymbol{Q(H_{Narva}, I_{AHC-Narva}) = 100.925 + 230.152H_{Narva} +}$$
$$\boldsymbol{+\,44.047H^2_{Narva} + 203.682I_{AHC-Narva}}$$

With: $m_{\tilde{q}}= 0.00$, $\sigma_{\tilde{q}}=0.048$

The equation of dependence Q = f (H_{Narva}, $I_{Narva\ city\text{-}Joesuu}$) is also obtained. The quality of the latter dependence turned out to be significantly worse:

With: $m_{\tilde{q}}= 0.00$, $\sigma_{\tilde{q}}=0.164$

Estonian researchers used WMO techniques [10] and developed dependence (Figure 11):

$$\boldsymbol{Q_m = 1.6 * 10^{-17}[\frac{(H_{Narva} + 540)^{7.45}}{(H_{Narva} + 11.065)^{0.5}}](H - H_{Joesuu})^{0.5}}$$

Using this technique also gives better results compared to using the regular rating curve, but quite limited in the lower part of the curves (which deform in disagreement with the hydraulic physical entity).

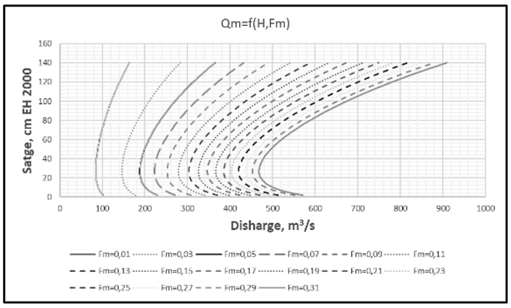


Fig. 11. Slope-and-level curve (Est.) at the Narva city gauge station.

Uncertainties of the flow assessment on the above-described dependencies have several sources:

1 - outside of the range of measuring water discharge and slopes of the water surface, the dependences were obtained by calculation and not confirmed by in-situ data;

2 - random water discharge errors caused by the use of ADSP as a measuring tool (for more details look at subchapter E);

3 - errors in determining the slopes of the water surface at the gauge stations.

The results of the studies performed show that the methodology for assessing water discharge at the Narva city gauge station should be based on reliable observation data of water slopes.

B. Reverse currents during the period of low water levels and discharges through the Narva HEPS

Problem: Water discharge assessment in conditions of negative slopes of the water surface in the section from Narva HEPS to Narva-Joesuu remains as a big problem. This phenomenon is due, as a rule, to the complete or partly shutdown of the operation of the turbines of the hydroelectric power station. At such conditions, reverse currents can occur, and water discharges, in certain surface layers, can be negative. Often, the maximum discrepancies in the data are confined to periods with negative or very low slopes of the water surface

Solution: An analysis of the observational data for slopes for the period from 01.01.2019 to 31.12.2020 (and to 16.06.2020 for the AHC SHI gauge) shows that very low slopes of the water surface are observed in the Narva city gauge station - Narva-Joesuu section (table 4). In 85% of cases, they do not exceed 0.015 ppm.

The uncertainty of the data on the slopes should not exceed 10-15%, which means that the error in determining the difference in water levels at the gauges limiting the sections should not exceed 2-3 cm. Under the existing conditions of the level regime of the Narva River at the estuary, this is a difficult task. Slopes are more reliably determined on the section AHC SHI - Narva city and AHC SHI - Narva-Joesuu, the values of which in most cases have values an order of magnitude higher than on the section Narva city - Narva-Joesuu.

TABLE 4 WATER SURFACE SLOPES DATA ANALYSIS

Section	Section lenght, km	Slop using avg. daily data ‰		Slop using avg. hourly data ‰		Number of hours with negative slopes	
		min	max	min	max	2019	2020
AHC - Joesuu	15.84	0.008	0.105	-0.0099	0.122	26	2
AHC - Narva city	1.54	0.01	0.106	-0.151	0.989	119	6
Narva city - Joesuu	14.3	0.00014	0.03526	-0.0173	0.0434	30	107

For a reliable assessment of the slopes of the water surface, it is necessary to organize additional automated water level gauges above and below the Narva city gauge station. At the same time, the issue of determining representative locations for their placement must be resolved. Thus, in the section between Narva HEPS and the Narva city, the AHC should be located outside the zone of possible formation of vertical immobile waves.

C. The problem of the influence of the discreteness of the obtained data on the accuracy of the flow characteristics

Problem: Uncertainties that arise when calculating water discharge at HEPS are largely due to the choice of the method for calculating the average daily water discharge Fundamentally little differing from one another, methods of determining the average daily water discharge can be used.

The first most accurate way is that for each hour of the day, electrical capacity of a hydropower unit N (kW), gross head of a hydroelectric power station H (m) are determined. According to these data, using the operational characteristic, according to the formula (1), the water discharge for each hour Q_h (m^3/s) is calculating. Average daily discharge is defined as:

$$Q_{\text{avg.daily}} = \frac{\sum_1^{24} Q_{\text{hourly using F.1}}}{24} \qquad (5)$$

When using the second method, the average daily electrical capacity of a hydropower unit $N_{\text{avg.daily}}$ (or hydraulic units, if the calculation is carried out for all hydraulic turbines at once) is determined by the formula 6:

$$N_{\text{avg.daily}} = \frac{Э}{24} \qquad (6)$$

Where:

Э - generation of electricity by a hydraulic unit (all hydraulic units) for a calculated time interval (day), kWh.

Based on the data of individual measurements of the levels of the headwaters and tailwaters, the average working gross head per day is determined. For the obtained average values of capacity N and gross head H according to the flow characteristic of the hydraulic unit, the average daily water discharge through the hydraulic turbines is calculating.

The second method gives satisfactory results only with a uniform round-the-clock load of the hydraulic units.

If during the day the hydraulic unit was stopped or operated in the synchronous compensator mode, then the determination of the average daily load by dividing the output by 24 hours will inevitably lead to a decrease in the average daily load and, consequently, the flow rate. The error will be the greater, the less the hydraulic unit was in operation. For example, when a hydraulic unit is stopped for only 1 hour, the average daily flow rate determined by the second method will be reduced by 1/24 part, or 4%.

For more reliable flow assessment at hydroelectric power plants, it is necessary that under the conditions of daily regulation, only the first method of calculating the average daily water discharge is used and the values of the operating characteristics of the turbines are regularly updated. This is required by the regulatory documents of the Russian Joint-Stock Company of Energy and Electrification [11].

Solution: measure all of the described above characteristics with a discreteness of no more than 1 hour for further calculations of water discharge and use the first daily averaging approach (formula 5).

D. Accuracy of the flow assessment by Narva HEPS

Problem: systematic discrepancies between the measured water discharges and calculated at the HEPS within 10%. In this case, the reasonable question is - which of the estimates is true? The measured ADCP flow discharges have objective errors (subchapter E), and flow assessment at HEPS has always been recognized as the most reliable method in turbulent conditions. In-depth measurements (including pulsation flow velocities measurements) carried out in 1989 by SHI researchers [12] at the headrace revealed only a small (<5%) systematic negative ($Q_{\text{meas.}}>Q_{\text{HEPS}}$) discrepancy between the water discharges measured by traditional flow metering instruments and an ultrasonic unit and calculated by HEPS. Such a low discrepancies indicate the high quality of flow metering at hydroelectric power plants.

Solution: new calibration of a hydroelectric power plant is an expensive procedure in which Narva HEPS itself cannot be interested, as a water discharge in comparison with electricity generation is not a main value. The accuracy obtained at the moment can be considered high.

E. Moving vessel ADCP as a water discharge instrument

Problem: random errors in water flow measurement by moving-vessel ADCP, two main reasons for which are: (1) the boat's speed exceeding while measuring the current velocities in this section; (2) inaccurate determination of the distance to the left bank when moving the Q-boat; (3) boat displacement due to high turbulence and related inaccuracies in the determination of the cross-section characteristics.

Solution: under these conditions, none of the modern measuring instruments can operate correctly. Accuracy can be increased by using river bank-based immersible ADCP (solution of the first problem). The second and third problems can be solved by good post-processing of the measurement data. To solve the 3rd problems, there are special software solutions described in [13].

CONCLUSION

The problems discussed in this article can be consider as a case study in the field of flow assessment in conditions of turbulence and variable backwater effects at medium and large rivers.

Acknowledgements

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