TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

COMPARISON AND ANALYSIS OF WATER DISCHARGE ESTIMATION METHODS FOR THE NARVA RIVER

NARVA JÕE VOOLUHULKADE HINDAMISMEETODITE VÕRDLUS JA ANALÜÜS

MASTER THESIS

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Tallinn 2020

(*On the reverse side of title page*)

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Department of Civil Engineering and Architecture

THESIS TASK

Student: Yaroslav Kobets 184544EABM (name, student code)

Study programme: EABM03/18, Environmental Engineering and Management (code and title)

main speciality: Master of Science in Engineering (MSc)

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Thesis topic:

(in English) Comparison and analysis of water discharge estimation methods for the Narva river

(in Estonian) Narva jõe vooluhulkade hindamismeetodite võrdlus ja analüüs

Thesis main objectives:

1. Gathering the data on the river Narva discharge from Estonia and Russia;
2. Analysing the data, methods used by both countries;
3. Giving solution/recommendations for reliable discharge estimation.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Data gathering	30.09.2019
2.	Data, methods analysing	20.12.2019
3.	Providing the outcome	30.04.2020

Language: English **Deadline for submission of thesis:** “.......”.................2020a

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PREFACE

The thesis topic was initiated by the supervisor of the work, PhD, Senior Lector, Alvina Reihan from Tallinn University of Technology. The study goes along with the NARVAWATMAN[1] project, which is conducted with the financial support of the Estonia – Russia Cross Border Cooperation Programme 2014-2020[2]. The project's main objective is to find a harmonized solution for the Narva river water discharge/pollution load estimation and provide the recommendations to HELCOM (Helsinki Commission).

The study focuses on the comparison and analysing existing and used techniques of the Narva river discharge estimation. It is aimed to find the harmonized solution which would suit both countries (Estonia and Russia) who share the most of its catchment area, the river itself and have fundamentally different approaches in discharge estimation.

Most of the thesis work was performed in Tallinn, Estonia with short trips to Narva city for the fieldwork and data gathering under the frames of the NARVAWATMAN project.

The data was provided by the contracting parties of the project: State Hydrological Institute of Russia and Environment Agency of the Republic of Estonia. Special thanks to hydrologist Anna Põrh (Environment Agency of the Republic of Estonia) for fast data providing.

Author expresses gratitude to Estonia – Russia Cross Border Cooperation Programme 2014-2020[2] for financial support that helped to conduct this research and bring his ideas to life.

Estonia-Russia Cross Border Cooperation Programme 2014-2020 aims to foster cross-border cooperation across the borders between the Republic of Estonia and the Russian Federation to promote socio-economic development in the regions on both sides of the common borders.

water discharge; rating curve; master thesis

[1] https://www.narvawatman.com

[2] https://www.estoniarussia.eu

List of abbreviations and symbols

ADCP - Acoustic Doppler Current Profiler;

ADP - Acoustic Doppler Profiler;

АНС, АГК, AGK – Automated Hydrological Complex (in Russian Автоматизированный Гидрологический Комплекс);

BK77, БСВ-77, BS – Baltic Height System;

BOB - Bothnian Bay

BY – Belarus;

CIS - Commonwealth of Independent States;

CP - contracting party;

EE – Estonia;

EH2000 – Amsterdam Height System (Amsterdam zero);

FI – Finland;

GUF – Gulf of Finland;

HELCOM – Helsinki Commission

HGS - Narva Hydroelectric Plant;

IGO - intergovernmental organization;

l.b. – left bank;

KAUR - Keskkonnaagentuur, Environment Agency of Republic of Estonia;

LV – Latvia;

MS - monitoring stations;

NAP - Normaal Amsterdams Peil, Amsterdam Ordnance Datum;

NO – Norway;

PLC – Pollution load compilation;

r.b. – right bank;

RU – Russia;

SE – Sweden;

SHI – State Hydrological Institute, St. Petersburg;

USSR – Union of Soviet Socialist Republics;

VAM - Velocity Area Method;

WMO – World Meteorological Organization;

The notions **Narva linn gauge, Narva gauge, Narva station** – are used interchangeably. The notions **Water level, stage** – are used interchangeably.

INTRODUCTION

It is believed that humankind exists on the planet Earth's surface for approximately 2,8 million years (the Hominidae family) [1] which is only 0,06% of the total Earth's age. The most revolutionary and incredible inventions were made during the last 100-150 years of our existence. That is just a tiny part of the entire humanity's age and needless to say – the Earth's. But already during those years of accelerating development, we altered and transformed our surroundings to such a great extent.

Therefore, nowadays the environmental issues are more getting at the front to prevent humanity from undoing itself. Our resources become scarce, and the air is hard to breathe, lots of animal species have already vanished. All is left in abundance is piles of waste, garbage and ash suffocating the land even more.

It's easy to say that water experiences the same changes. Still, unfortunately, the problem goes beyond scarcity and pollution because water is not only a resource but a habitat for various species people depend on. It is not just a resource we drink but a resource we use to produce food to eat and a vast amount of goods we consume. Water is used intensively in agriculture to grow crops, in the food industry, in the industrial process to produce computers, cars, etc., the list is almost infinite. Thus, we are highly dependent on that asset, and it is in our interests to preserve its quality and good state.

One of the ways for a good water quality maintaining is to perform hydrological monitoring, i.e. to assess water quantity and quality status regularly and pollution entering water bodies to find appropriate mitigating/preventive measures. Various organizations are established (e.g. HELCOM, Clean Water Fund, Clean Water Action, Pacific Institute, etc.), different policies are set up for that very purpose.

The present study is focused on hydrological quantity monitoring of the Narva river, on analysing its water discharge assessment methods and is aiming to improve it by underpinning drawbacks, providing recommendations to solve them or another technique for usage. The Narva river poses an additional challenge and is a matter of particular interest since it is a border river between Estonia and Russia (EU and non-EU country). The methods which are used by both countries are different, giving different numbers for one water body thus affecting consequent estimation of the pollution load which goes to the Gulf of Finland and the Baltic Sea.

In the study, the long-term data were analysed, existing methods for water discharge estimation were studied as well as various recommendations, e.g. from WMO (World Meteorological Organization) and HELCOM (Helsinki Commission). That was done to assess the current situation and to come up with the one ultimate harmonized solution for the river Narva water discharge assessment.

1. BACKGROUND

It is crucial to conduct constant hydrological monitoring to maintain good water quality and quantity of water bodies used by the population for various purposes (e.g. production, agriculture, drinking, recreation). Nowadays, it is not complex considering that various technological solutions are available and most of the countries (especially Estonia and other EU countries) follow the trends in the environment protection and sustainable use of freshwaters.

However, lots of water bodies are not located only in one country. For instance, many rivers are historically happened to go along different countries' borders. Needless to say, their basins go far beyond national boundaries. For such cases, further cooperation, agreements, and data exchange between the countries are required. Sometimes, an international organization for coordinating purposes is founded.

1.1 HELCOM

HELCOM – stands for Helsinki Commission. It is an intergovernmental organization (IGO), the Baltic Marine Environment Protection Commission which gathered together countries around the Baltic Sea (such as Denmark, Estonia, the European Union, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden). Its main goal is to provide a platform for regional level environmental policymaking for the marine environment of the Baltic Sea protection from all sources of pollution through intergovernmental cooperation. The convention covers the whole Sea area, inland waters included, as well as the seabed and monitoring the Baltic Sea catchment area to reduce land-based pollution. [2]

57° 44.43'N - the parallel of the Skaw in the Skagerrak which bounds the entrance to the Baltic Sea. The "Baltic Sea Area" is defined by Article 1 of the Convention as the Baltic Sea, the entrance to the Baltic Sea and the internal waters (Figure 1.1.1). [3]

In HELCOM Recommendation 37-38/1 "Waterborne pollution input assessment (PLC-WATER)" [4] is stated that HELCOM countries should report to the Commission an annual and periodical basis on the following data (quote):

"- Annually, total inputs of nutrients and hazardous substances to the sea should be reported by quantifying inputs from monitored rivers, unmonitored areas, and point sources discharging directly to the sea.

- Periodically (every six years unless otherwise decided by HELCOM), comprehensive waterborne pollution input assessment should be carried out to quantify, in addition to the total inputs to the sea (annual reporting), also waterborne discharges from point sources, losses from diffuse sources as well as natural background losses into inland surface waters within the Baltic Sea catchment area located within the borders of the Contracting Parties." [4, p. 10]

The riverine pollution calculation requires the reliable river discharge/runoff estimation because simply speaking the annual pollution load can be seen as (neglecting possible retention):

$$L_p^a = \int_0^{t_a} Q(t) C_p(t) dt \qquad (1)$$

Where:

L_{pa} – annual pollution load;

Q(t) – discharge [m_3/s] vs time;

C_p – concentration of a pollutant [mg/l] vs time;

t_a – period of the calculation (year).

Figure 1.1.1: Baltic Sea area [2]

Thus, reliable discharge/runoff estimation is essential for the precision of the pollution load estimation.

Considering mentioned above, Estonia and Russia are obliged to report to HELCOM annually and periodically on waterborne pollution inputs to the Baltic Sea from the Narva river and its catchment. Therefore, they need to be able to gather reliable data on discharges and contaminants concentrations of the river.

1.2 Transboundary and boundary rivers

The Baltic Sea catchment area is 1,73 million km2. Approximately 7% of that area is situated in non-HELCOM countries, but also a part of the catchment area within HELCOM countries contributes with transboundary river inputs to other HELCOM countries. [4].

As HELCOM PLC Water Guidelines define: the river is called **transboundary** if it crosses at least one country border and if it has its mouth reaching the Baltic Sea in one of the countries members of HELCOM. Such a river can cross more than one country, ether between countries members of HELCOM or from a country which is not a HELCOM member to one which is. Thus, river-borne pollution can be from one or more parties. A **border** river is a river with its outlet to the Baltic Sea at the border between two countries. For these rivers, the inputs to the Baltic Sea are divided between the states considering each country's share of the total input of pollution. [4]

Such type of rivers poses an additional challenge for pollution load assessment. For transboundary rivers country on whose territory the mouth of the river is located is obliged to proceed the measurements at the lowest monitoring station of the basin and report on the total inputs to the sea from monitored and unmonitored areas. The assessment and reporting on the revering inputs entering the sea from the border rivers should be coordinated and performed by countries sharing the border river, ensuring it is clear how the total load is allocated between them. [4]

In the presented study, the Narva river is considered and is classified by HELCOM as a border river. Therefore, the border rivers are of our particular interest. In Table *1.2.1* below, the border rivers' description can be seen.

There are only two rivers in the Baltic Sea catchment area, which are classified as border rivers – Narva (EE-RU) and Torne (SE-FI) – see Figure *1.2.1*. They have similar catchment area percentage distribution between the countries. However, in the case of the Torne river, the HELCOM country who is responsible for reporting is Sweden and proportions of the pollution load are agreed. On the other hand, in case of the Narva river, each country reports on its pollution load separately for its catchment area as they agreed. Therefore, the way they estimate their loads and discharge is essential and should be performed in such a way so the data could be comparable. Should be noticed that in the case of the Torne river, both countries are from EU which eases a lot the data exchange and cooperation, for instance with field works. It differs with Estonia and Russia.

Table 1.2.1: List of border rivers that should be taken into account in annual and periodical PLC reporting:

CP = Contracting Party, BY = Belarus, EE = Estonia, FI = Finland, LV = Latvia, NO = Norway, RU = Russia, SE = Sweden, BOB = Bothnian Bay, GUF = Gulf of Finland, MS = monitoring stations [4]

River name	**Border river between which CP's**	**CP to provide information and involved CP**	**Total catchment and proportion of catchment in involved countries**	**Monitoring station in CP and what is monitored**	**Expected available information in upstream country**	**Other comments**
Narva (GUF)	Border and transboundary river. LV to RU; EE and RU, BY	EE (own catchment) and RU (LV and RU catchment)	Total area: 58 126 km_2 EE: 30,2% LV: 6,3% RU: 63,0% BY: 0,5%	EE: 2 hydrochemical stations (7 km from mouth and outflow from Peipsi), 2 hydrological stations (20 km from mouth outflow from Peipsi) RU: chemical monitoring station -12 km from the mouth; hydrological - 16 km	LV: No hydrochemical surveillance monitoring stations with annual measurements; 1 hydrological – flow monitoring station (Zilupe – Pasiene)	RU to contact LV or to decide whether to take on LV input as part of RU inputs. No reporting/quantification of Belarussian inputs expected
Torne älv (BOB)	Border river between SE and FI	SE	Total area: 40 112 km_2 SE: 63,9% FI: 35,0% NO: 1,2%	SE: Chemical station at Mattila (approx. 7 km from an outlet). Hydrological station at Kukkolankoski (approx. 20 km from outlet) Fi:		It is agreed that 55% of the inputs of N and P entering the sea via the river is from SE and the remaining 45% from FI. Sweden reports the total inputs. Sweden includes Norwegian inputs in their net inputs

In 1997 based on mutual Estonian-Russian agreement on collaboration in the field of environment protection, the Joint Estonian-Russian Commission for the Protection and Rational Use of Transboundary Water Bodies was founded. Its main focus is on Narva river basin including the Lake Peipsi. According to the main provisions, contracting parties carry out hydrological monitoring by their own means on their territory. Monitoring data is opened for both countries, and the data exchange is proceeded according to the agreed program. [5] [6] However, experience shows that such interaction is not going as well as it is desired.

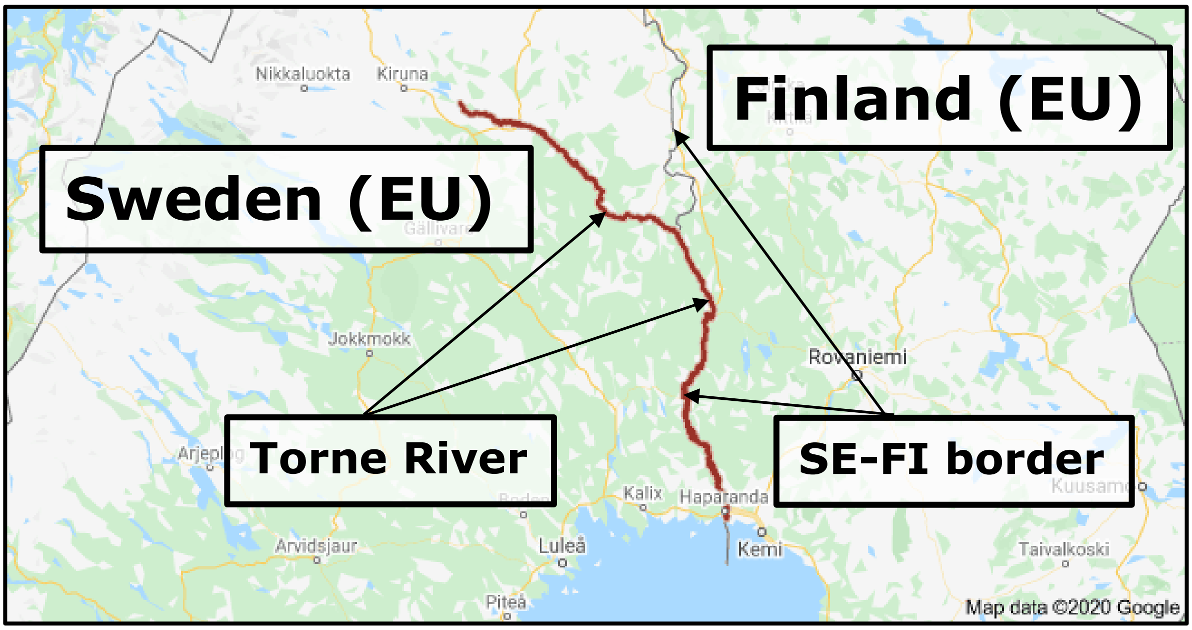


Figure 1.2.1: Torne river, GoogleMaps

The described situation leads to inconsistency, and a difference in pollution load estimation, particularly discharges, consequently affecting overall the Baltic Sea state assessment and the mitigating/preventing measures to be implemented.

2 STUDY AREA

2.1 The Narva river

The river Narva (Narova in Russian) is the river between Estonia and Russia with a border between countries going by its fairway. It has its source in the Lake Peipsi and its outlet (estuary) in the Gulf of Finland - one of 17 sub-areas into which the Baltic Sea is sub-divided. [7].

Most of the Estonian rivers have small slope and catchment area, and most have small length. They are uneven in a yearly runoff with small discharges during the dry periods. The Narva is an exception transporting the biggest amount of pollution to the Gulf of Finland. As was mentioned before its boundary character brings challenges for the river's indicators estimation. [8]

2.1.1 Pollution transported by the Narva river

Lots of pollutants are discharged to the Gulf of Finland with rivers and through the direct discharges from the coastal line settlements. [8] Its catchment area is located in Estonia, Finland and Russia. The biggest pollution load to the Gulf of Finland is from Russia (~80% of total amount) with its Neva River and the river catchment area 281 000 km2 and mean water flow $79,2*10^6$ m^3/a. Then, the Narva river has its "second place" with 56 200 km^2 of the basin area and mean water flow $10,9*10^6$ m^3/a. [8]

Table 2.1.1: River discharges of organic matter and nutrients into the Gulf of Finland by countries in 1982-1984 (t/a) [8]

	BOD_7	COD	Tot. N	NO3-N	Tot. P	PO4-P
Finland	*39 980*	*161 100*	*15 540*	*7 519*	*766,1*	*298,9*
Russia	*256 900*	*2 109 000*	*56 000*	*25 800*	*3480*	*1620*
Estonia	*57 800*	*560100*	*37 030*	*23 300*	*1 550*	*700*
The whole GUF drainage basin	***354 680***	***2 830 200***	***108 570***	***56 619***	***5 796***	***2 619***

The Narva River transports pollutants from the Lake Peipsi to the Gulf of Finland. Besides the Estonian discharges into the Lake Peipsi, the biggest river which is flowing there is the Russian river called Velikaya, which can be seen in Figure *2.1.3*. A load of nutrient and organic pollutions into the Gulf of Finland is much higher from the Russian side rather than from the Estonian side (Table *2.1.1*).

Nevertheless, according to the data of 2003 (Table *2.1.2*), Estonia makes a tangible contribution to the total Gulf of Finland pollution, the most of which it is from the Narva river and its catchment area. [8]

Table 2.1.2: Pollution loads from Estonia via rivers into the Gulf of Finland in 2003 [8]

	F	**W**	**BOD_7**	**NO_3**	**N_{tot}**	**PO_4**	**P_{tot}**
	km^2	**10^6 m^3/a**	**t/a**	**t/a**	**t/a**	**t/a**	**t/a**
Narva	56 200	9 209	21 032	1 311	5 245	230	530
Incl. load from the Estonian side into L. Peipsi	14 973	3 309	7 239	3 972	6 942	120	283
Other rivers	6 697	1 699	3 893	3 441	4 709	90	156
Unmonitored area	2 756	758	1 771	1 555	2 154	46,8	83,3

2.1.2 Hydromorphology

The river Narva takes its source from the Lake Peipsi (Chudskoe lake in Russian) nearby the Vasknarva village and flows into the Gulf of Finland by the gauge station Narva-Jõesuu. The river length is 77 km, the catchment area is 56 200 km^2 (17 200 km^2 in Estonia), the total level decline is 29,8 m, average slope is 0,39 ‰ as seen from Figure *2.1.1* and Table *2.1.3* below [9]:

Table 2.1.3: Change in the slope of the river by its length [9]

Distance from the river mouth, km	**Absolute level, m**	**Slope, %**
77,0	29,8	0,04
70,0	29,5	0,22
65,0	28,4	0,87
61,0	24,9	0,00
16,7	24,9	11,0
14,5	0,30	0,02
0,0	0,00	

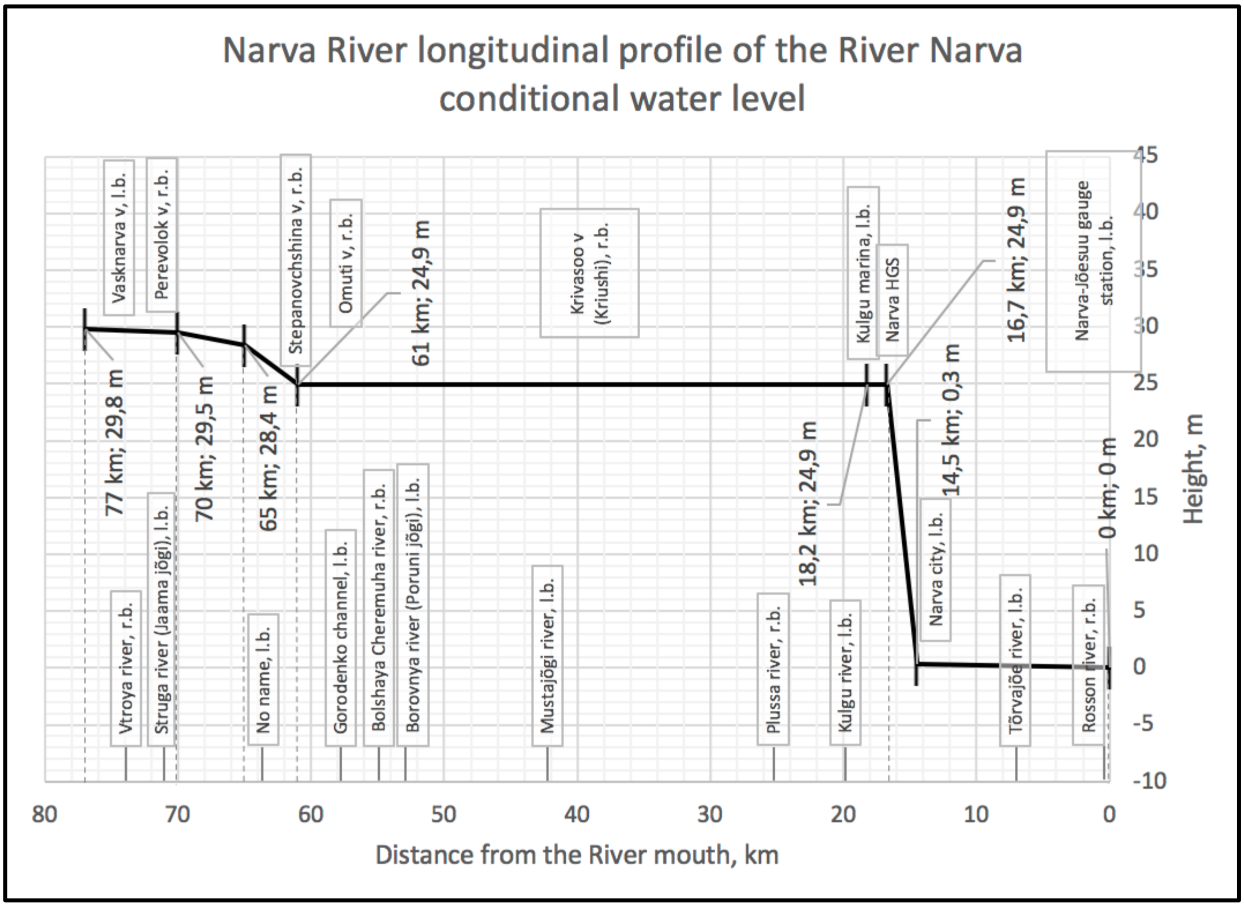


Figure 2.1.1: The Narva river longitudinal profile of the relative water level [9], made by author

The main tributaries of the Narva river [9]:

1. Vtroya river – right bank 74th km from the mouth of the river Narva, 16 km in length
2. Struga river (Jaama jõgi) – left bank 71st km from the mouth of the river Narva, 15 km in length
3. No name – left bank 64th km from the mouth of the river Narva, 14 km in length
4. Gorodenko channel – left bank 58th* km from the mouth of the river Narva, 21 km in length
5. Bolshaya Cheremuha river – right bank 55th* km from the mouth of the river Narva, 13 km in length
6. Borovnya river (Poruni jõgi) – left bank 53rd* km from the mouth of the river Narva, 10 km in length
7. Mustajõgi river – left bank 43rd* km from the mouth of the river Narva, 24 km in length

8. Plussa river – right bank 24th* km from the mouth of the river Narva, 281 km in length
9. Kulgu river – left bank 19th* km from the mouth of the river Narva, 19 km in length
10. Tõrvajõe river – left bank 7th km from the mouth of the river Narva, 16 km in length
11. Rosson river – right bank 0,51th* km from the mouth of the river Narva, 26 km in length

* Distances before the Narva reservoir creation

The width of the river Narva is approximately 200-300 m. The widest part is at its source 650 m. Not taking into account the Narva reservoir, which is several km in width, the river in its upper course is widest by Permisküla Island – 900 meters. Downstream from the Hydroelectric plant, it is mostly 300-400 m in width, sometimes going up to 600 m.

The depth of the river Narva is 4-6 m on average with the deepest place at the mouth of the river – 15 m. The velocity of the stream is 1 m/s on average, going up to 3 m/s at rapids and down to 0,5 m/s at the lower course. The average discharge is 331 m^3/s at the source and 400 m^3/s at the mouth. The annual runoff is approximately 12,5 km^3 which is about a half of the Lake Peipsi. [10]

The river Narva catchment area is a plateau with a big amount of boggy lands and forests. The Lake Peipsi (Chudsko-Pskovskoe lake in Russian) is located in the middle of the basin representing 6% of its total territory. The average height of the catchment area is 20-30 m, excluding South-East part with 100 m average height. Wetland of the site is 35%, forest cover is 20%, lake cover is 8% with a total number of 1500 of lakes approximately. [9]

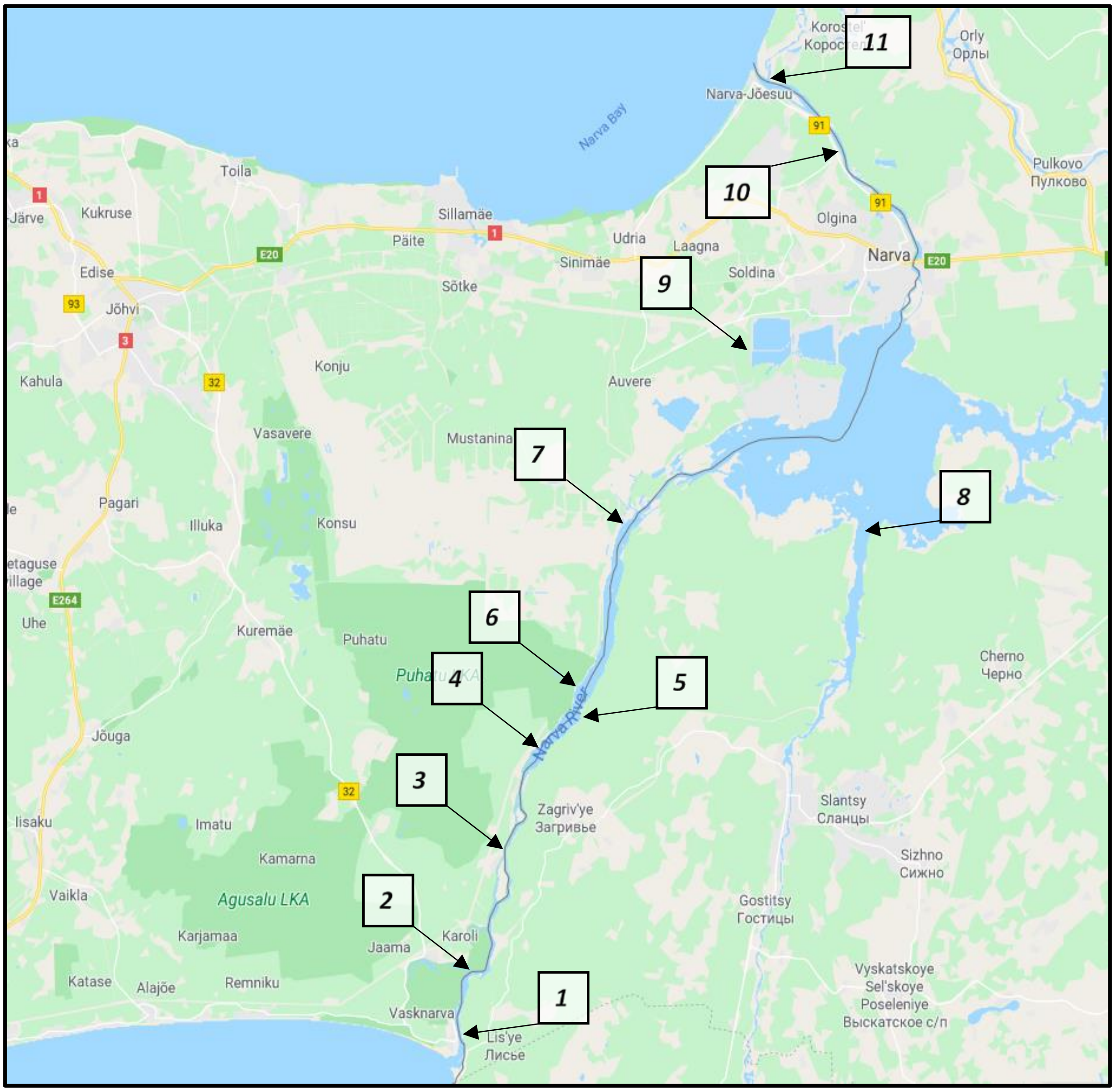


Figure 2.1.2: The Narva river tributaries, Google Maps

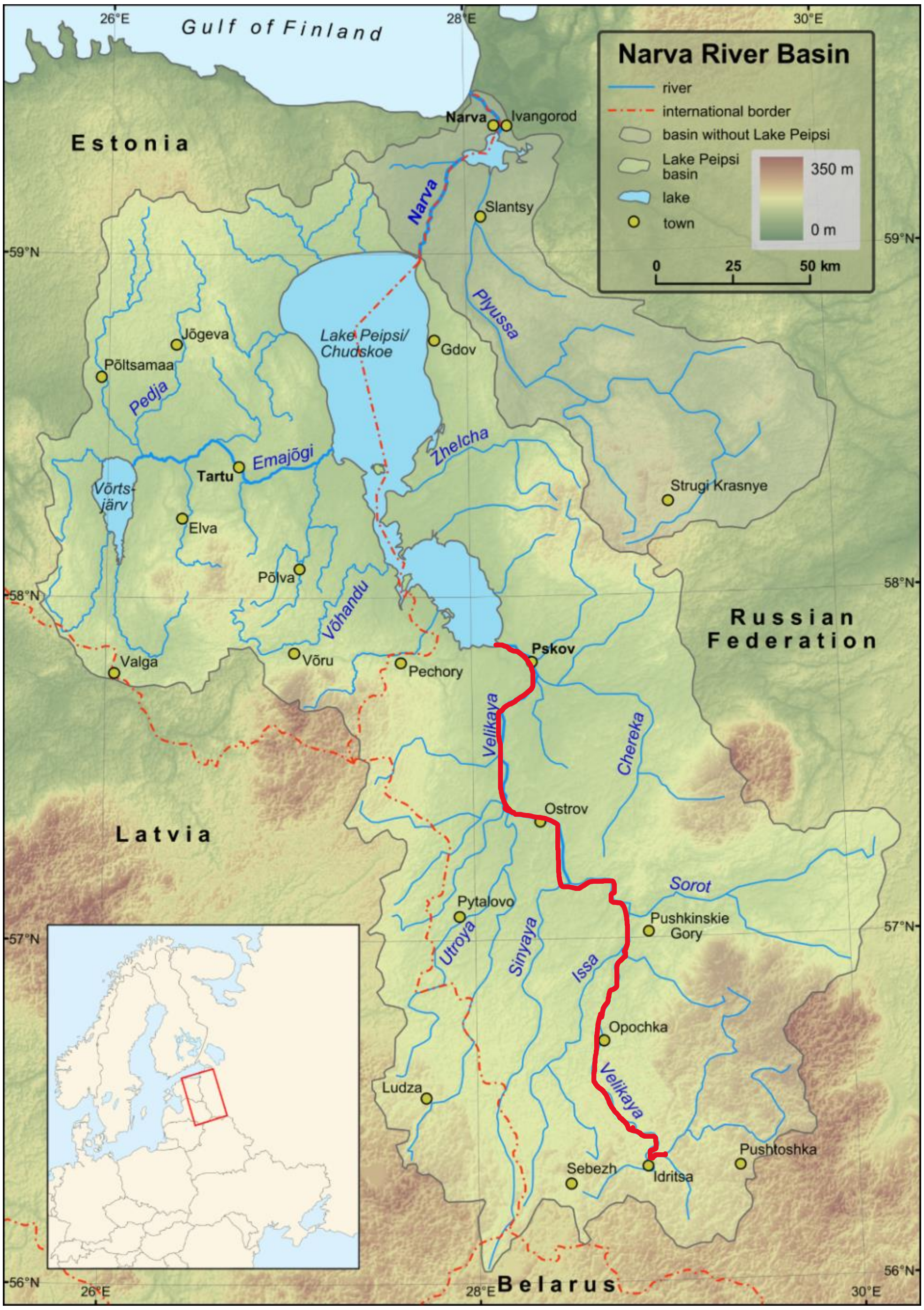


Figure 2.1.3: Narva river catchment area (river Velikaya marked with red) [11]

Narva river runoff upstream is regulated by the Lake Peipsi, downstream – by the Narva reservoir built in 1955 – 1956 years on the site of 18,2 – 61,0 km. Water level change downstream (before the Narva city) is affected by backwater effect from the sea. Higher stages here usually occur in August-September, lower in March-May. Upstream higher stages are seen in April-May during a spring flooding season, lower stages – in December. [9] The river is used for recreation, navigation and electro power generation on the Narva Hydro electro power plant operated on the right bank. [9]

The term “backwater” refers to a phenomenon when water velocity in a river course is slowed down aka “backed up” in comparison with the water usual conditions. Thus, areas with smaller or no flow are produced. Such effect tends to increase gauge height. [12]

2.1.3 Hydrological Monitoring

Hydrological observations in Estonia started in 1867 on Suur-Emajõgi in Tartu. But Narva is monitored only since 1902. [8] Discharge measurements began in 1902 with the start of studies for the establishment of the Pihkva-Tartu-Narva shipping lane. [10] In 1902 seven gauging stations were opened:

- the pumping station in Narva City;
- Kulgu Harbour;
- Krivasoo;
- Karjati;
- Perevolok;
- Omuti;
- Vasknarva.

Discharges were measured at Kulgu and Vasknarva. The other gauging stations were used for monitoring water stages and ice conditions. Additional monitoring site was opened downstream from the Narva bridge in 1907. Vasknarva measurements continued until 1909, but stages and runoff measurements continued there until 1918. They were restarted at the former gauging stations in 1920 because of the construction plans of the Narva Hydroelectric Plant. In 1921 the plant design was completed. After World War II observations were continued at the Kulgu Harbour and Vasknarva for waterpower utilization. [10]

The hydrological observation network was reorganized in 1955 because of the impoundment of the river Narva. It extended 38 kilometres upstream of the dam, as the submerged Krivasoo and Kulgu gauging posts were closed. Before the creation of the Narva reservoir, eight gauging stations were operating on the river. Discharge measurements were moved from the Kulgu Harbour to the headrace canal of the hydroelectric plant. Later the discharge was calculated by the amount of the power produced. At Stepanovshchina village a new gauging station was opened to serve as a reference point for Vasknarva. [10]

By 2010, there are three main operating hydrometric posts on the river Narva:

- Narva city (Narva linn) (opened in 2000) - #2 in the Figure *2.1.4*;
- Vasknarva (since 1902) - #5 in the Figure *2.1.4*;
- Narva-Jõesuu (opened in 1835) - #1 in Figure *2.1.4*.

The gauging station at Kulgu (#3 in Figure *2.1.4*) makes observations in the Narva reservoir. [10]

The Kuningaküla (#4 in the Figure *2.1.4*) hydrometric station was opened in 2011, located 58,0 km from the river mouth and operating as a water level measurement site. [13]

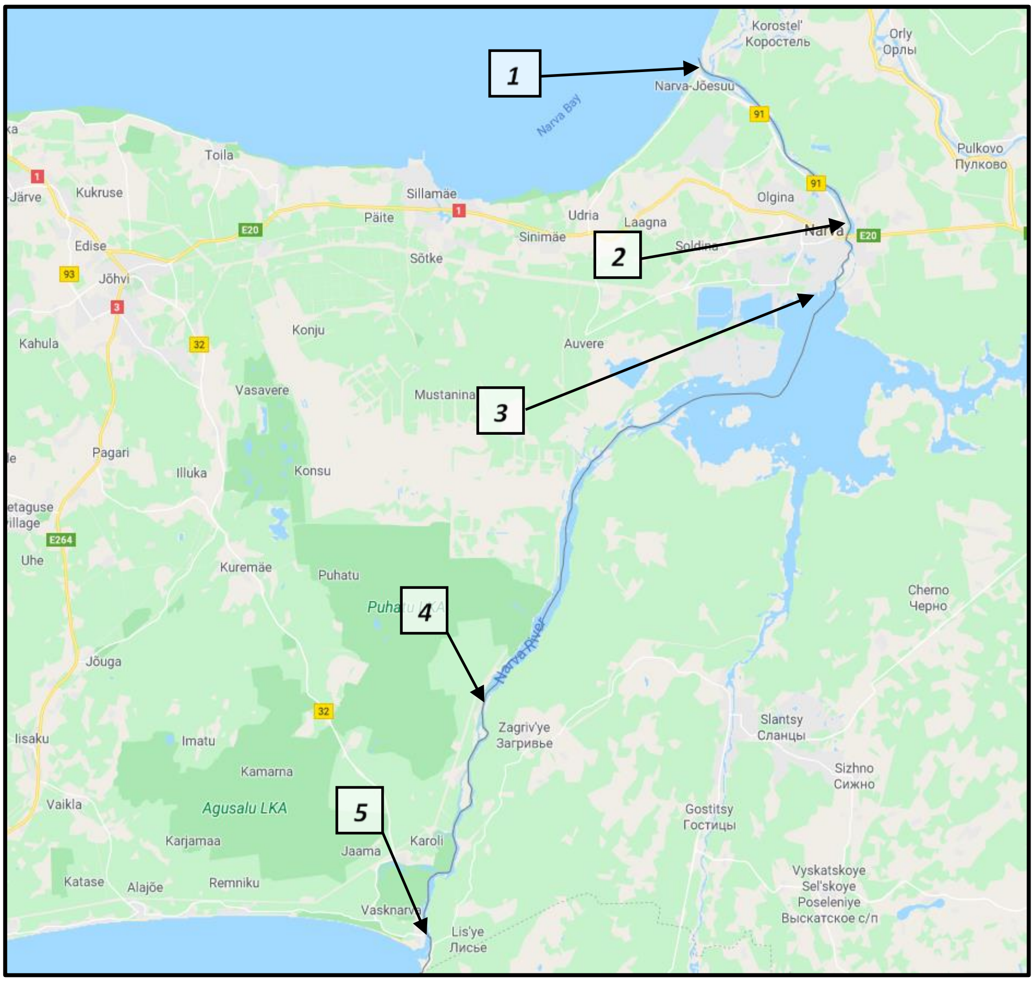


Figure 2.1.4: Hydrometric stations of the Narva river in Estonia, GoogleMaps

In the study for calculations, the data from Narva linn and Narva-Jõesuu was used. Their description can be seen in Table *2.1.4* below.

Table 2.1.4: Hydrometric stations description [14]

# on the map	Station	Characteristic
1	Narva-Jõesuu	**Location** Width: N 59 ° 28´06´´ Length: E 28 ° 02´33´´ Zero height of the station graph: -5.000 m (BS) Observations begin: 1899 (material preserved since 1908) The station was automated: 2010 Parameters to be measured and observed: • Water level • Water temperature
2	Narva linn	Ida-Viru county, Narva city, Narva port, Narva river **Location** Width: N 59 ° 22´58´´ Length: E 28 ° 12´24´´ Hydrometer Station Opening: 2000 Year of Automation: 2002 Distance from the mouth of the river: 14,6 km Basin area: 56 000 km 2 Zero height of the station graph: -0,90m EH2000 Parameters to be measured, observed and calculated: • Water level • Water temperature at the bottom of the river • Manually measured water temperature on surface water (0,10-0,5 m) during flow measurement • Flow rate, m^3/s (2-3 times a month; 5-6 times a month during high water periods) • Drainage (calculated) • Ice events (if present) during flow measurement • Description of aquatic vegetation (if any) during flow measurement

The period with the highest runoff in the river Narva was in 1923–1932, the highest discharge – 1323 m3/sec – occurred at Vasknarva on 12–15 May 1924. The lowest discharge – 26 m3/sec – was measured at the end of November 1971 and was caused by a bottom ice clog at the river source. [10]

2.1.4 Russian hydrometric station (АНС, АГК)

Recently under the frames of the NARVAWATMAN project new hydrometric gauge station was installed on the Russian side of the river (AHC – Automated Hydrological Complex, in Russian "АГК автоматизированный гидрологический комплекс"). The coordinates of the location are 59.370127; 28.210943 approximately 14,7 km from the mouth of the river right after the HGS dam (see Figure *2.1.5*). The available data is beneficial; however, its operation is planned only during the NARVAWATMAN project period until the end of 2021.

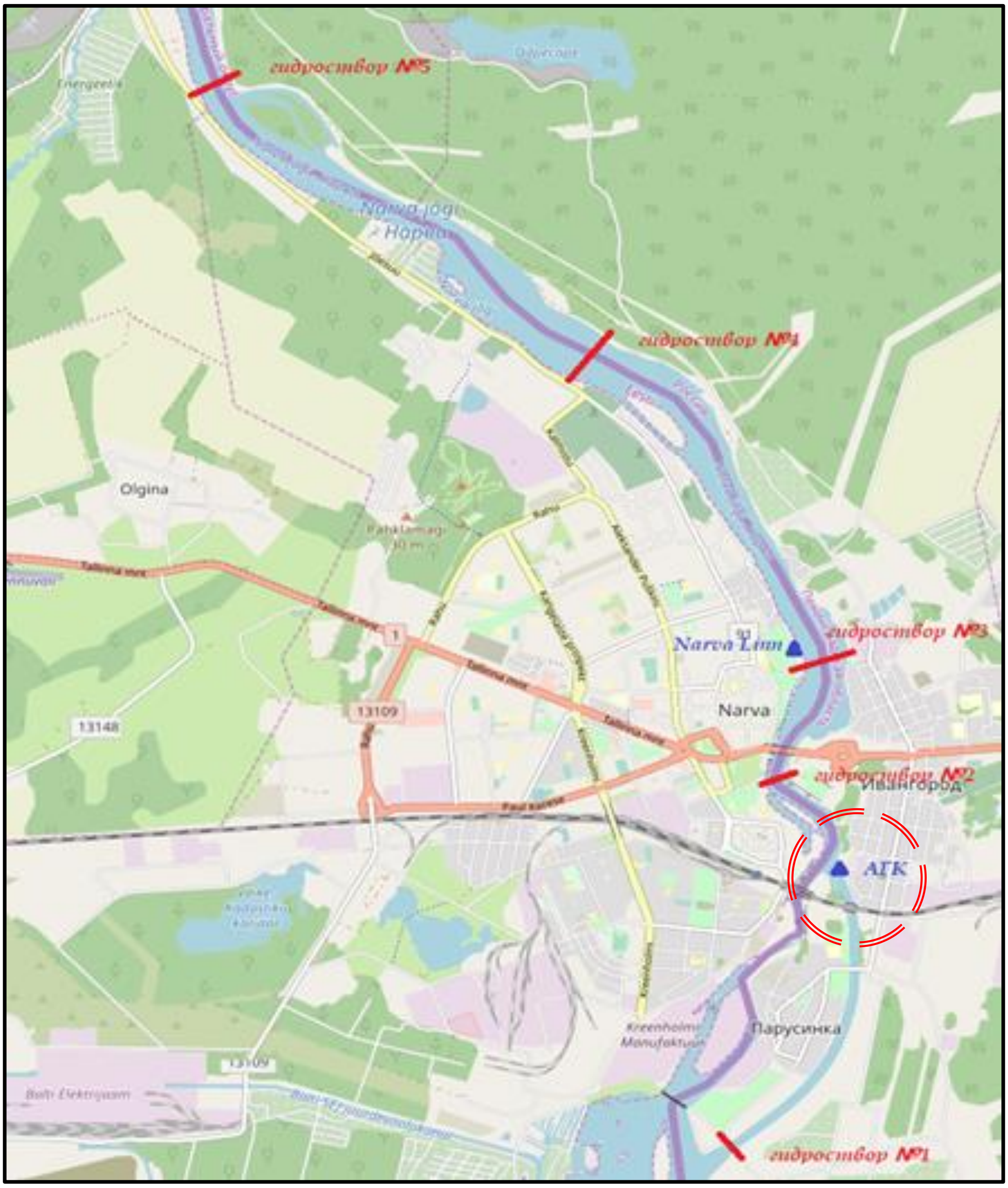


Figure 2.1.5: Automated hydrological complex location, marked as "АГК", provided by SHI

3 METHODS

3.1 Discharge estimation methods overview

According to the World Meteorological Organization (WMO) [15] [16] and HELCOM (Helsinki Commission) [4], there are several basic methods of the discharge estimation which will be examined further:

1. Discharge ratings using simple stage-discharge relations
2. Discharge ratings using the velocity index method
3. Discharge ratings using slope as a parameter
4. Linear interpolation

3.1.1 Discharge ratings using simple stage-discharge relations

Continuous records of discharge are calculated by applying derived discharge ratings to water level records. Those ratings can be simple or complex, but WMO considers the discharge ratings depending on the stage alone. [15] Of course, initially stage is the function of discharge which comprises a river profile, velocity, etc., but for the practical use this relation is considered in reverse. [17]

The common practice is that discharges are measured periodically in the field with the field worker registering a corresponding water level. Then, the measured discharges are plotted against the stages defining the rating curve. [15]

If the gauging station is new, it is recommended to perform several field measurements of the discharge to define the rating throughout of the whole water level range following periodic measurements either to confirm stability or to follow possible shifts in regime/ratings. [15]

If the water level-discharge relation is stable covering the whole range of water level, then there is no problem establishing the rating. On the other hand, a hydrologist can face a problem deriving the curve if there are no measurements for the upper part. In that case, the lower part of the curve should be extrapolated upwards. The principles which govern the shape of the rating curve should be examined beforehand for the hydrologist to decide whether the curve should be extrapolated as a straight line or with a concave eliminating possible extrapolating error. [15]

The extrapolation, of course, can be eliminated if the peaks discharges are known, or they are determined using indirect methods. If those discharges are not known, then some techniques of high stage-discharge estimation can be used. Sometimes, the curve lower part also needs extrapolation for that certain methods exist. [15]

Stage-discharge control – the physical element or set of elements which governs the stage-discharge relation used to convert record of the stage to a record of the discharge. Known types of control:

- Section control – specific cross-section downstream from the gauging station that governs the relation, can be natural such as sand bar, rock ledge, etc., or man-made such as a dam, a weir, a spillway etc.
- Channel control – set of parameters like channel size, shape, curvature, slope and channel roughness that controls the stage-discharge relation.
- Combination or compound controls – some relations are governed by a combination of the controls mentioned above. It usually occurs for a short range of stage between two types of control (section ad channel), that range is called a transition zone of ratings. [15]

Governing equations:

For section control, the relation of stage-discharge is governed by the weir/flume equation, which is in a very general form [15]:

$$Q = C_D B H^{\beta} \qquad (2)$$

Where:

Q [m3/s] – discharge;
C_D – coefficient of the discharge;
B [m] – cross-section width;
H [m] – hydraulic head;

β - is an exponent depending on the shape of the control (for example for V-shaped, β = 2.5 and for rectangular, β = 1.5).

For channel control, the relation of stage-discharge is governed by Manning or Chezy equation. The Manning equation is [15]:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad (3)$$

Where:

A [m2] – cross-section area;

R [m] – hydraulic radius;

S – is friction slope;

n – channel roughness

The Chezy equation [15]:

$$Q = CAR^{1/2}S^{1/2} \qquad (4)$$

Where:

C – the Chezy form of channel roughness.

These equations are usually used for gradual, uniform flow.

Then, plotting the rating curves (plotting discharge measurements against stage measurements) if possible, measurements from the previous times with high and low values should be presented to define the correct form of the curve and for the extrapolating purposes. [15]

3.1.2 Discharge ratings using the velocity index method

When variable backwater restricts the stage-discharge method, the velocity index method is used. [15] The index-velocity is defined as a time/range averaged velocity measured by a hydroacoustic meter. [18]

The method can be described in the following steps:

- A hydroacoustic current meter is constantly measuring velocity for a certain part of the channel;
- Near the current meter the cross-section is monitored to develop the relation between the cross-section and stage (stage-area rating);
- Discharge is measured with velocity index, stage recorded at the same time;
- the stage-area rating helps to derive the area A from the average stage S;
- The measured discharge is divided by the derived area A and thus mean velocity V for the discharge measurement is calculated;

- From every discharge, mean velocity V and index-velocity Vi are derived. Then the relation between V and Vi can be developed (velocity-index rating). Although, sometimes velocity also can be dependent on the stage;
- Then for the calculation of the discharge, the equation is used [15]:

$$Q = VA \qquad (5)$$

Where:

V [m/s] – velocity – is computed from the velocity-index rating;
A [m^2] – area of the cross-section – is computed from the stage-area rating;

The cross-section A used in this method doesn't have to be the same where the hydroacoustic meter is installed. [18]

3.1.3 Discharge ratings using slope as a parameter

In case of backwater or very unsteady flows at a gauging station, at a given stage, the energy slope is a variable. Thus, we cannot define the discharge rating by stage alone. This variable backwater usually is caused by a variable stage at a downstream confluence for a given discharge upstream or by downstream dam gates. In that case, the discharge depends on the stage and the slope of the energy gradient. The acceleration head has also to be considered if the stage change rate is great. [15]

WMO treats the unsteady flow situation in the chapter regarding the discharge rating method. The flow is of the natural flood wave where it has a stable wave profile moving down the channel. Such a wave is called "**uniformly progressive"** often produces loop ratings. Loop rating – is when the discharge for the same stage is greater when the stream is rising than when it's falling. [15]

The need for a slope as a parameter can be derived when investigating the rating procedures at the existing stations with similar conditions. Otherwise, the need is not apparent. Thus, a plot of a series of discharge measurements against middle and high stages can be useful for indicating the needed type of rating and if the additional gauging station is required for constant water-surface slope measurement. [15]

The location of gauges is based on the water-surface fall reach characteristics. The length of the reach should be that way so ordinary errors occurring in the stage determinations would cause no more than a minor error in the calculation the fall in the reach. The desirable fall is 0,15 m, although lesser numbers can provide good results. Channel reach should be uniform as possible in the reach. [15]

Changing discharge, variable backwater or both at the same time cause variable slopes affecting flows in open channels. For unsteady and gradually varied flows the differential equations below provide a general solution: [15]

$$\frac{Q^2}{K^2} = -\frac{\partial H}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \qquad (6)$$

$$\frac{Q}{x} = -B\frac{\partial h}{\partial t} \qquad (7)$$

Where:

Q [m3/s] – discharge;

K [m3/s] – conveyance of the cross-section;

H [m] – the total energy head;

x [m] – the distance along the channel;

g [m/s2] – the acceleration of gravity;

V [m/s] – the mean velocity;

t [s] – the time;

B [m] – the top width of the channel;

h [m] – is the water-surface elevation.

3.1.4 Linear interpolation

That method is a straightforward approach. According to the HELCOM guidelines, if the daily discharge Q_t (monitored or modelled) for particular day t is not known, it should be estimated using a linear interpolation method between days with available discharge value. [4] Thus, performing several field discharge measurements a year, we can make daily discharge estimation by using a linear interpolation method between known values of the measured discharges. However, we have to perform the field measurements in such a way to ensure a specific density of the points around the peaks and dips of the discharge curve to process the interpolation with low error.

4 ANALYSIS

4.1 Discharge measurements methods used now

4.1.1 Methods used in the Republic of Estonia

In Estonia daily discharges of the Narva river are assessed by monitoring daily water stages at the Narva linn gauge station located ca. 14,6 km from the river mouth. For the assessment, the simple stage-discharge relation is used to derive the rating curve. Since the stage is affected by the sea backwater, it is taken into account when establishing the curve because the plot points tend to be scattered. [19]

The measured discharge values are derived approximately once a month using VAM (Velocity Area Method) and ADCP (Acoustic Doppler Current Profiler). Until 2005 it was used for the whole cross-section. Width, depths and velocities measurements are done from moving boat as the river Narva is a large stream. [19]

The measurement is made by subdividing the stream cross-section into segments (i.e. sections, partial areas) measuring the depth and velocity in each vertical. Then, the total discharge can be computed by summing the products of the partial areas and corresponding average velocities. As expressed by the following equation [19]:

$$Q = \sum_{i=1}^{n} A_i \, v_i \qquad (8)$$

Where:

Q [m^3/s] – discharge;

A_i [m^2] – cross-section area, for the *i*th segment of the *n* segments into which the cross-section is divided;

v_i [m/s] – the corresponding mean velocity of the flow normal to the *i*th segment, or vertical.

The partially measured water discharges (only for the Estonian part of the river) are then multiplied by a coefficient that depends on the width of the river. [19]

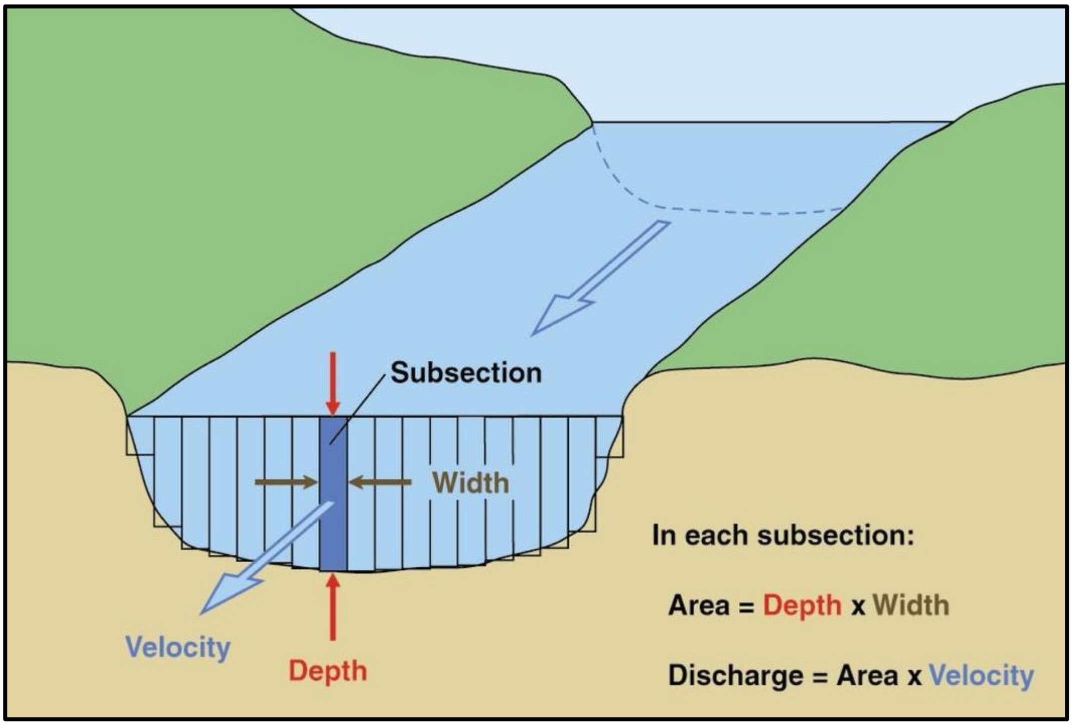


Figure 4.1.1: VAM discharge measurement and calculation [20]

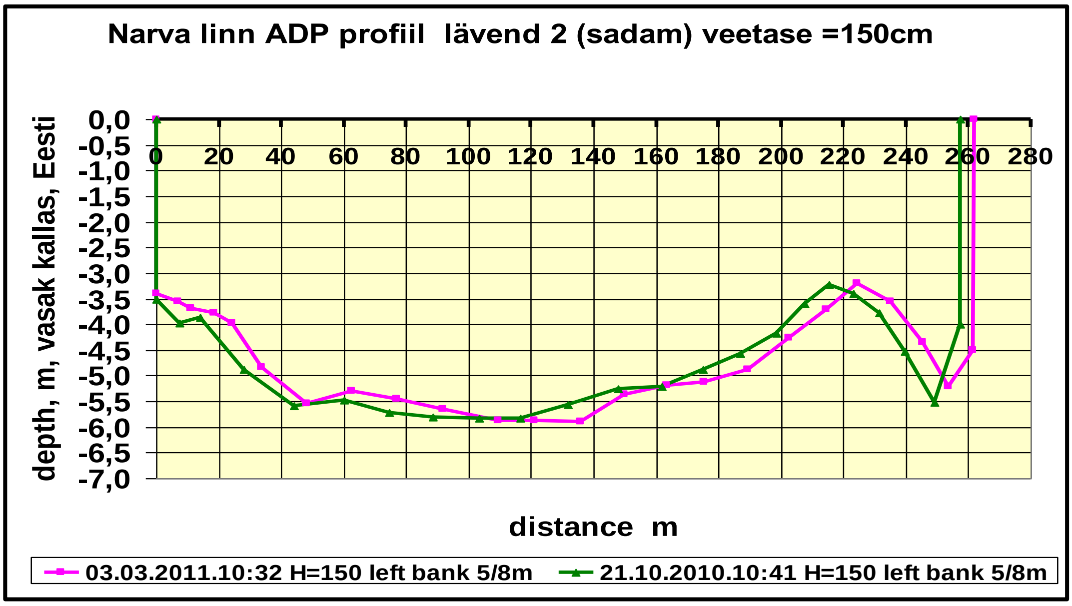


Figure 4.1.2: The Narva river full cross-section profile in 2010-2011 [19]

The device currently used is the SonTek HydroBoard II. The general work principle is based on the Doppler effect. The device sends a sound pulse into the water. It measures the difference in the frequency of the sound wave reflected by sediment particles, thus measuring the velocity of the water. [21]

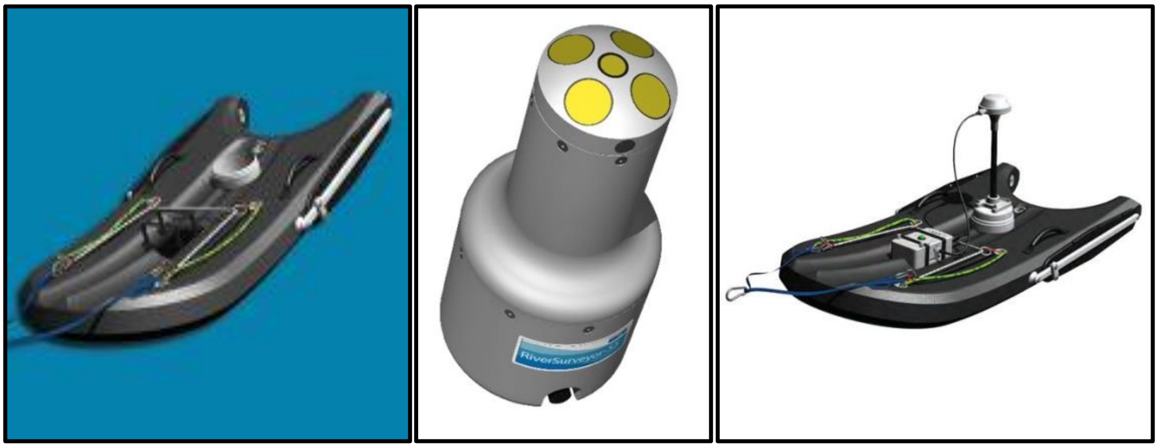


Figure 4.1.3: SonTek HydroBoard II [21]

Figure 4.1.4: Measurement sites, GoogleMaps

Site 1 – Hydrological monitoring station Narva linn (discharge measurements);
Site 2 – ca. 12 km from the river mouth (Chemical measurements);
Site 3 – ca. 6 km from the river mouth (Chemical measurements).

4.1.2 Methods used in the Russian Federation

In Russia daily discharges of the Narva river are assessed by using the data on the amount of the electricity produced by Narva Hydroelectric power plant or Narva Hydroelectric generation station (HGS). [10] [22]

The hydroelectric complex consists of three main structures: headwork, the derivation or supply channel and powerhouse with appurtenant structures. The water dam is located 18,2 km from the mouth of the river. The regulation of the water regime of the river Narva is carried out by the system of structures by water passing through the derivation channel and the spillway dyke. The power plant hydraulic performance is 760 m3/s. The total station capacity is 124,8 MW with a power factor 0,8. During floods, the factor can be increased to 0,9 with a station capacity increased to 140 MW. [22]

According to Application 6 "Instructions for water flow assessment at the Narva HGS (HGS-13)" to the «Standard operating procedure for the operation of hydraulic structures of the Narva HGS», the volume of water flow through the HGS site is determined by the following components:

- outflow through hydraulic components turbines when working in active mode and at idle;
- outflow through the dam;
- outflow through the ice dam;
- outflow through the eel way.

For the daily discharge estimation at the station, the following values are measured and recorded:

- hourly:
  - headwater level;
  - upstream water level;
  - tailwater level;
  - gross head of the HGS (the difference between upstream and tailwater levels).

- at "0" hours daily:
  - readings of electric meters for each generator;
  - readings of a turbine flow meter.

- at «9» hours daily:
  - drop on the clear bar of each unit;
  - discharge according to discharge indicator.

In addition to the listed above, the following is also recorded:

- the start and stop time of each unit and the duration of its operation per day;
- time, magnitude and duration of the opening of each of the dam gates and ice passes.

As a result of processing the obtained data, the following quantities are determined:

- average daily headwater level;
- average daily tailwater level;
- average gross head for the turbines operating time;
- average head losses in gates clear bar for the turbines operating time;
- average net head for the turbines operating time (the difference between gross head and drop on the clear bar);
- average daily turbine discharge;
- average daily dam and ice pass discharge;
- average daily eel way discharge;
- average daily tailwater discharge;
- average daily residual flow discharge of the HGS. [22]

Average daily turbine discharge, m3/s, determined by the formula [22]:

$$Q_{turb,\ avg} = \frac{\sum_1^3 V_{unit}}{T} = \frac{\sum_1^3 V_{unit}}{86400} \qquad (9)$$

Where:

V_{unit} [m3] – daily outflow through the unit (according to discharge indicator);
T=86 400 [s] – number of seconds per day. [22]

If the discharge indicator of any units is taken out of operation for repair or because of a malfunction, the discharge through the unit is determined by its general-purpose operating performance (curves). The information on the Russian discharge estimation method is taken from the Report on differences between Estonian and Russian methods and results of water runoff estimation, performed by the Russian party. [22]

Table 4.1.1: Comparison of hourly Narva HGS discharge data and measured discharges during the fieldworks in 2019 [22]

Date	Time	Site #	HGS discharge data Q_{TW}, m³/s	Measured discharge Q_m, m³/s	ΔQ, %
30.07.19	18:00	1	286	300	4,7
31.07.19	14:00	2	288	299	4,0
	15:00	1	288	301	4,7
20.08.19	17:00	3	261	254	-2,7
	18:00	2	237	254	7,2
	19:00	1	237	257	8,5
21.08.19	11:00	4	192	200	4,4
	13:00	5	191	201	5,1
5.09.19	10:00	3	263	264	0,3
	11:00	2	263	277	5,4
	12:00	1	263	271	3,1

The method gives a certain error as seen from Table *4.1.1* with HGS discharges and measured discharges from 2019. The error goes up to 9% and leads to a concern about the method reliability. Also, it should be mentioned that as any equipment HGS turbines tend to wear out and lose their efficiency, which affects the discharge measurement precision. [22]

4.1.3 Comparison of the methods used by both countries

As seen from the information in the sections above, two techniques are radically different. Estonia relies on the mathematical method of establishing discharge rating curve as recommended in various hydrological guidelines (WMO, etc.) while Russia solely relies on HGS data.

At first glance, it seems that in the case of Estonia discharge estimation, a lot of approximation takes place when making the curve. However, the Russian method leads to errors and mistakes due to equipment malfunctions and wear out, considering that the plant was built in the year 1955.

The long-term discharge values difference between those derived from Estonia and Russia varies from 346 m_3/s (12/26/2009) to 861 m_3/s (04/15/2010) approximately. [22]

Average monthly Narva river discharges from both side from 2003 to 2014 are given in Table *4.1.2* below. Maximum and minimum differences for each year are in red and blue colours respectively.

Table 4.1.2: Average monthly Narva river discharges comparison (m3/s) from both sides 2003 – 2014 [22]

Year	Gauge station	Month											
		1	2	3	4	5	6	7	8	9	10	11	12
2003	HGS	154	167	196	308	409	327	316	307	363	371	383	460
	Narva	280	297	255	330	400	443	405	441	468	525	396	456
	Difference	-127	-130	-58	-22	10	-117	-90	-134	-104	-154	-13	5
2004	HGS	356	401	442	716	557	493	495	396	434	409	445	482
	Narva	357	434	500	659	582	467	414	501	443	431	521	488
	Difference	-1	-34	-58	57	-25	26	81	-105	-9	-21	-76	-6
2005	HGS	480	416	415	636	649	601	435	384	321	308	314	246
	Narva	563	519	510	551	596	486	389	435	390	342	385	344
	Difference	-83	-104	-95	85	53	114	45	-50	-70	-35	-71	-97
2006	HGS	223	224	236	416	347	313	212	181	196	234	317	358
	Narva	237	241	251	465	344	320	265	193	183	244	336	366
	Difference	-14	-17	-15	-50	3	-8	-53	-12	13	-9	-19	-8
2007	HGS	414	339	490	489	483	369	284	251	234	239	244	257
	Narva	475	297	501	521	460	347	289	259	243	261	262	289
	Difference	-61	43	-11	-32	23	22	-5	-8	-9	-21	-18	-32
2008	HGS	213	330	459	626	523	409	332	336	425	410	482	544
	Narva	280	336	469	638	520	402	357	321	399	513	582	469
	Difference	-68	-6	-10	-12	3	7	-25	15	26	-103	-100	74
2009	HGS	439	427	412	654	517	481	435	382	378	462	564	584
	Narva	424	290	431	750	492	540	523	519	396	589	510	469
	Difference	15	136	-20	-96	25	-59	-88	-138	-18	-127	55	115
2010	HGS	432	411	411	449	674	427	468	414	417	401	417	355
	Narva	323	419	578	1000	783	712	597	542	443	501	579	409
	Difference	108	-9	-168	-550	-109	-286	-129	-128	-26	-100	-162	-54
2011	HGS	410	455	423	609	664	541	411	351	326	329	299	357
	Narva	460	479	472	818	679	581	550	408	392	456	420	450
	Difference	-50	-24	-49	-209	-15	-40	-139	-57	-66	-127	-121	-93
2012	HGS	245	200	328	448	549	479	398	340	330	342	378	303
	Narva	352	271	386	669	556	503	450	348	468	419	485	321
	Difference	-107	-71	-57	-221	-6	-25	-52	-8	-138	-77	-107	-18

Table 4.1.2 continued

Year	Gauge station	Month											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2013	HGS	388	401	384	378	415	528	431	376	312	309	374	381
	Narva	440	430	392	605	687	593	518	472	400	348	459	486
	Difference	-52	-29	-8	-228	-273	-65	-87	-95	-88	-39	-86	-105
2014	HGS	333	312	369	383	380	319	281	249	240	231	264	245
	Narva	476	405	488	512	423	366	342	340	337	418	446	364
	Difference	-143	-94	-119	-129	-43	-47	-61	-90	-97	-186	-182	-119

Table 4.1.3: Differences between typical annual Narva river discharges for Narva gauge station and HGS data [22]

Gauge station/ Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Narva HGS	314	469	433	271	341	424	478	440	431	362	390	300
Narva linn	392	488	459	287	351	441	495	573	514	435	486	411
Difference, m3/s	-77	-18	-26	-16	-10	-17	-18	-133	-83	-73	-96	-110
Difference, % (to Narva linn)	-19,8	-3,8	-5,6	-5,6	-2,8	-3,8	-3,5	-23,2	-16,1	-16,8	-19,8	-26,8

As seen from the data in Table *4.1.3*, the difference in discharges varies from 10 m3/s to 110 m3/s. That is approximately 3% up to almost 30%. During the process of making this study new data for the Narva linn discharges, and the HGS discharges for the year 2019 became available. The comparison is in Table *4.1.4* below.

Table 4.1.4: Average monthly Narva river discharges comparison (m3/s) from both sides 2019

Gauge/ Month 2019	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Narva HGS	227	260	398	464	359	287	233	209	218	254	419	436
Narva linn	417	370	473	367	451	341	301	228	236	386	319	346
Δ, m3/s	-191	-111	-75	97	-92	-55	-67	-19	-18	-133	101	90
Δ, % (to HGS)	-84,1%	-42,5%	-18,9%	20,8%	-25,7%	-19,1%	-28,8%	-9,2%	-8,4%	-52,4%	24,1%	20,7%

As seen, the difference in discharges is even bigger than in the previous analysis (2003-2014). It goes from 18 m3/s to 191 m3/s giving approximately from 8% to 84% discrepancy. Such difference poses big uncertainty since both countries report to

HELCOM on their own discharges and pollution loads that may differ up to 30% on average.

4.1.4 Height datum

An additional detail which should be addressed is a height datum. Height datum or vertical datum identifies the reference surface for determining the vertical position of various points such as water/sea stages, Earth elevation, i.e. it is potential value for the fundamental benchmark. In different countries and regions, different datums are used. [23]

In most Western European countries for defining a water level, Amsterdam Vertical Datum (aka Normaal Amsterdams Peil (NAP), Amsterdam Ordnance Datum) is used. Initially used in Prussia for Normalnull defining it then was used in other countries. [24]

On the other hand, Russia uses the Baltic Height System, which was established using the Kronstadt footstock zero. [25] [26] The system was used in Estonia before the Minister of the Environment of Estonia amended the Regulation on Geodetic System in 2017. It enabled Estonia to start using the Amsterdam Ordnance Datum (Normaal Amsterdams Peil NAP) as the height level measurements reference similarly to many other European countries. [27] Officially, beginning from January 2018, Estonia switches from the Baltic Height System (БСВ-77, BK77) to the new European Height System (EH2000, Amsterdam zero). Thus, the national weather system is making measurements in the new height system, including water/sea levels. [28]

Figure 4.1.5: Amsterdam Zero [29]

Figure 4.1.6: Kronstadt zero [30]

Reason for such a transfer is that most European countries, including Finland, Norway, Sweden, Latvia and Lithuania, closest to Estonia, use the European altitude system. Also, the Baltic Height System BK77 ages, due to its base on the planet parameters which appeared to be inaccurate. Moreover, by the year 2000, around 47% of the national elevation grid markings had been destroyed, making altitude base work extremely time-consuming and costly. When switching, absolute values in Estonia will increase by 15 – 24 cm approximately. [31]

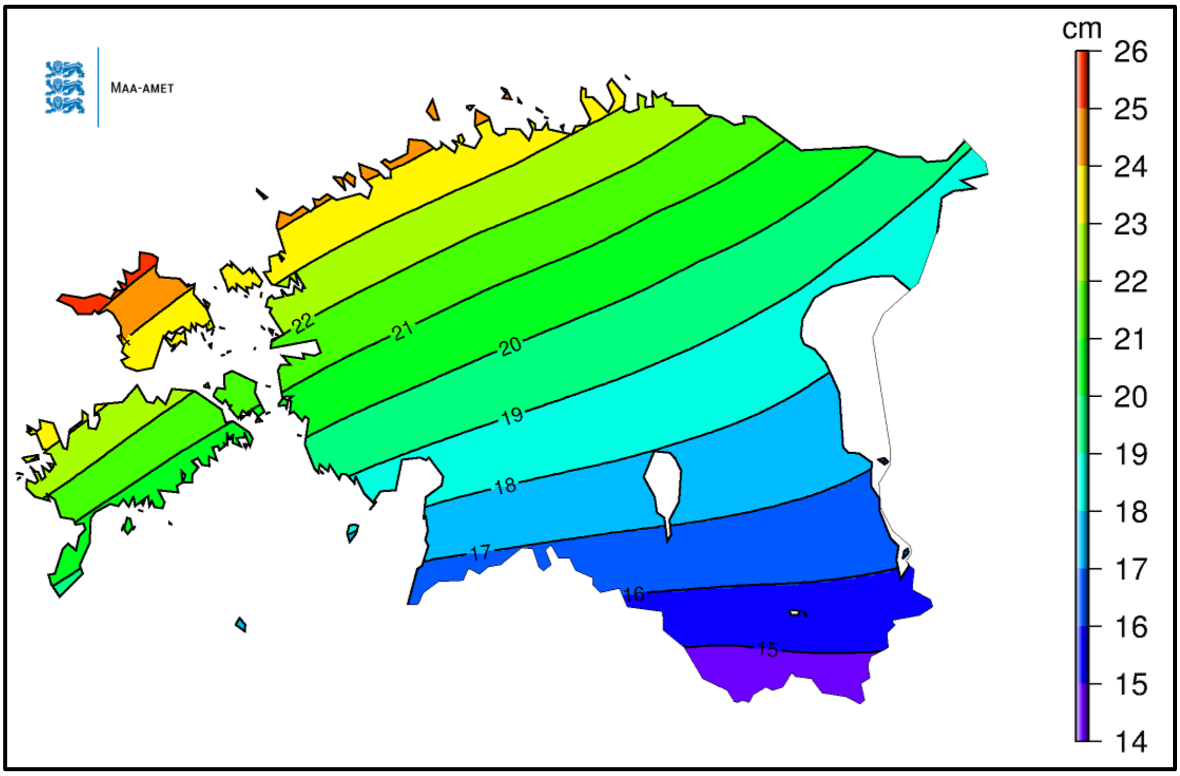


Figure 4.1.7: Differences added in Estonia to correct elevation value [31]

That should be taken into account when working with data to harmonize used methods since Russia still uses BK77. According to Figure *4.1.7*, the difference between Russian stages in BK77 and Estonian stages in EH 2000 will be approximately 18 cm (17,7 for the Narva linn gauge). When making calculations, it was decided to use EH 2000 as the primary height datum system.

4.2 Available data analysis

There are different data, including historical observations available for the Narva river and the catchment. The daily discharges, the measured discharges for several years and the recent stages and measured discharges will be considered in the chapter.

4.2.1 Daily discharges, historical observations.

Daily discharges for Vasknarva gauge station are available from 1903 to 2014 years, excluding periods: 01/01/1918 – 09/08/2020 and the year 1944.

Mean value is 331,3 m$_3$/s. The minimum discharge was on 22.11.1971 and equalled 25,8 m$_3$/s. The maximum happened on 12.05.1924 - 15.05.1924 and equals 1320 m$_3$/s. The numbers are consistent with that mentioned in chapter 2.1.3.

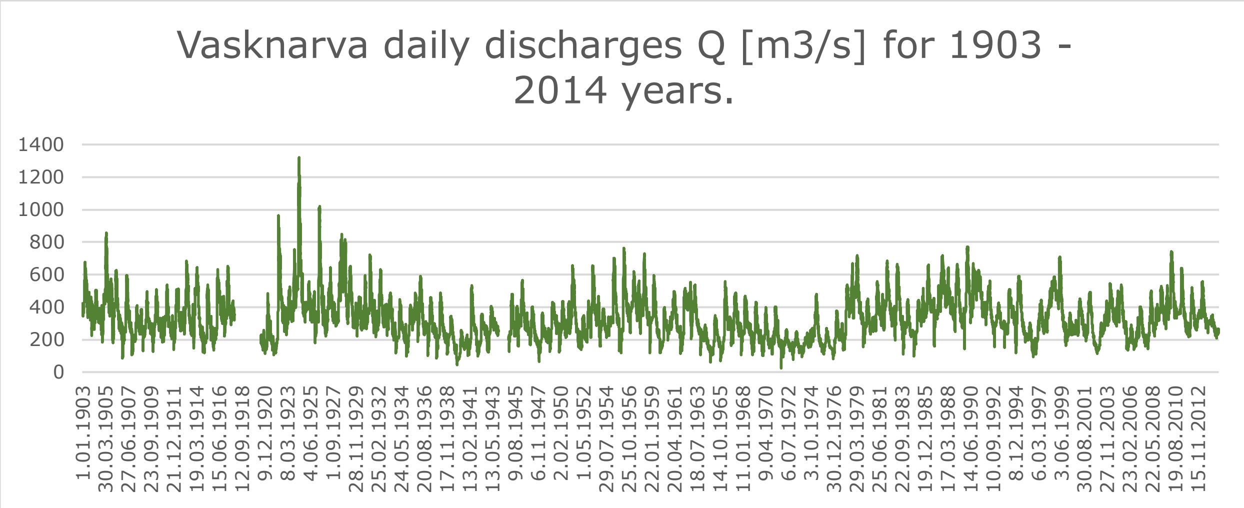


Figure 4.2.1: Vasknarva daily discharges, years 1903 – 2014

Daily discharges for Narva gauge station (Narva linn) are available from 2003 to 2014 years. Mean value is 444,2 m$_3$/s. The minimum discharge was on 21.01.2006 and equalled 84 m3/s. The maximum happened on 15.04.2010 and equalled 1280 m3/s.

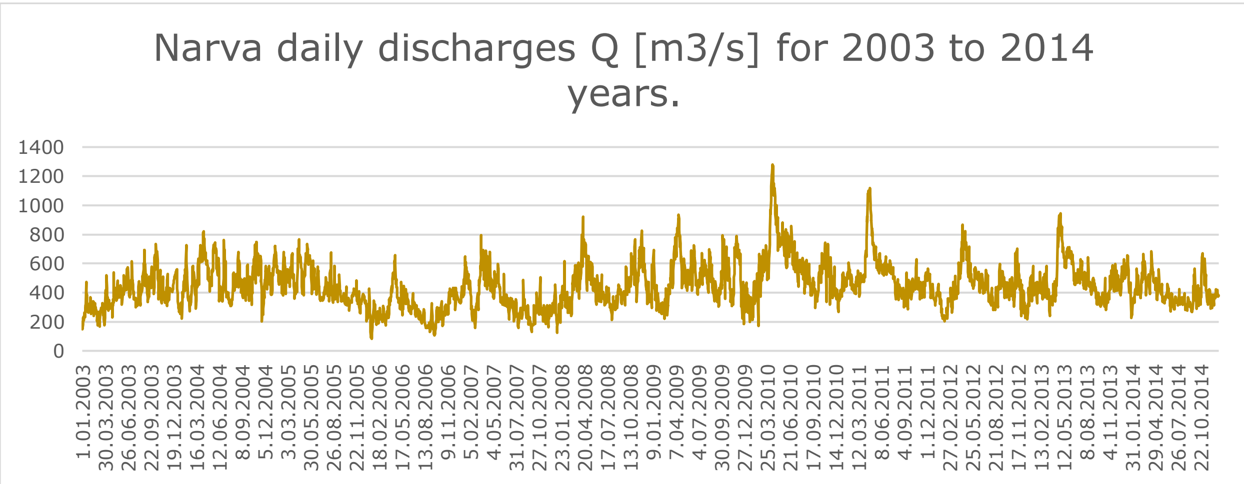


Figure 4.2.2: Narva daily discharges, years 2003 – 2014

Vasknarva and Narva daily discharges for 2003-2014 are plotted together on the graph in Figure *4.2.3*. As we can see, they follow the same pattern, although Vasknarva values are less extreme and the line is smoother. That can be explained by that the Narva river has a lot of tributaries before the Narva gauge station and Vasknarva station is located nearby the Lake Peipsi which has "regulative effect" on the data – that was mentioned in the chapter 2.1.2 - "Narva river runoff upstream is regulated by Lake Peipsi".

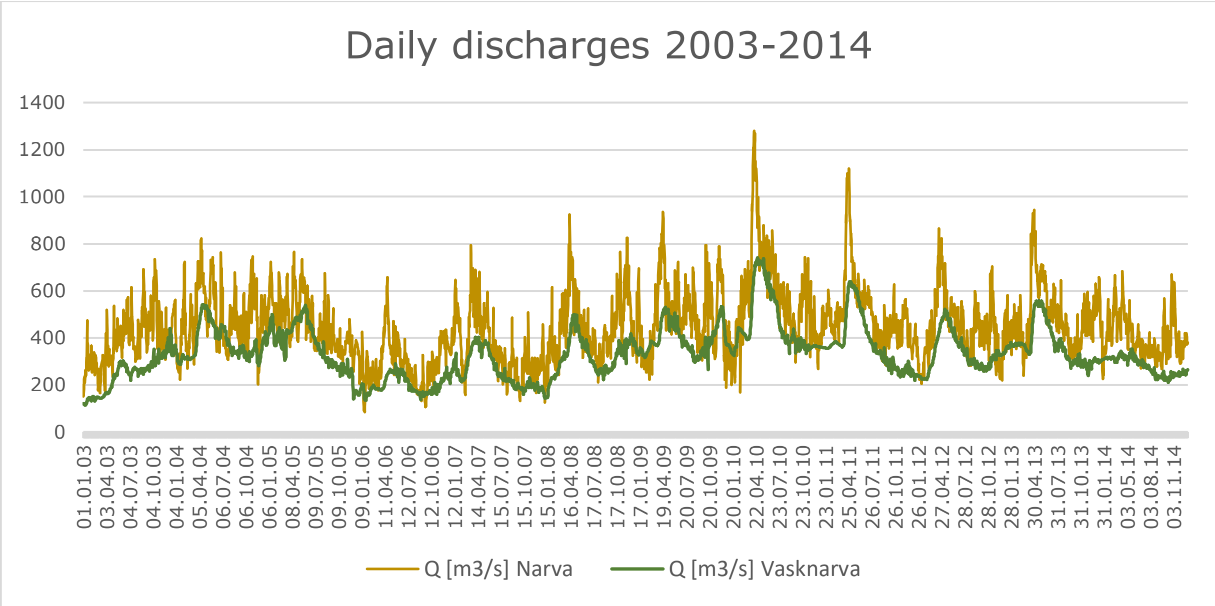


Figure 4.2.3: Narva and Vasknarva daily discharges, years 2003 – 2014

The daily discharges averaged to monthly numbers for the Narva city for years 2003-2014 were compiled together on one graph by each year to get a typical Narva river hydrograph. The graph can be seen in Figure *4.2.4* with a red line for the average daily discharges during a year representing the hydrograph.

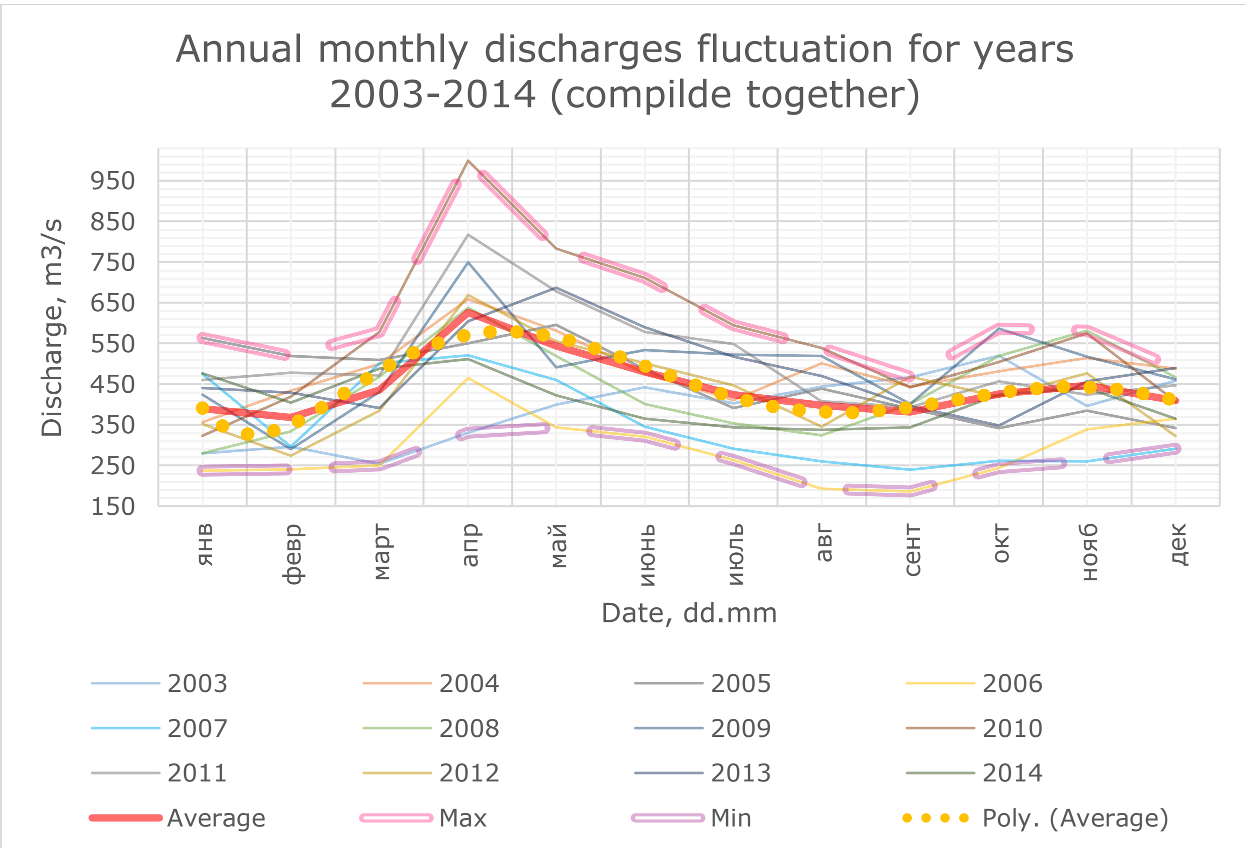


Figure 4.2.4: Monthly discharges fluctuation for years 2003-2014 (compiled together)

After the data analysing, we can conclude that the hydrograph (line average) has:

- two peaks - 724,08 m3/s on 19.04 and smaller 480,75 m3/s on 28.10 representing high discharge in spring after the ice melt and the period of the ice formation respectively;
- two dips - 333,67 m3/s on 23.02 and bigger 346,67 on 11.09 representing baseflow in winter after the ice formation and low flow in autumn respectively.

4.2.2 Measured discharges.

Measured discharges for Vasknarava are available from 1995 to 2010. For Narva - from 2000 to 2018 and from recent 2019 when they were measured under the NARVAWATMAN project. In this chapter only measured discharges for Narva will be considered. Discharges in Narva were measured on average 17 times per year. The minimum discharge measured was on 21.09.2006 and equalled 94,2 m3/s. The maximum discharge measured was on 22.04.2010 and equalled 1268 m3/s. Figure *4.2.5* with the measured discharges plotted against the corresponsive stages can be seen below.

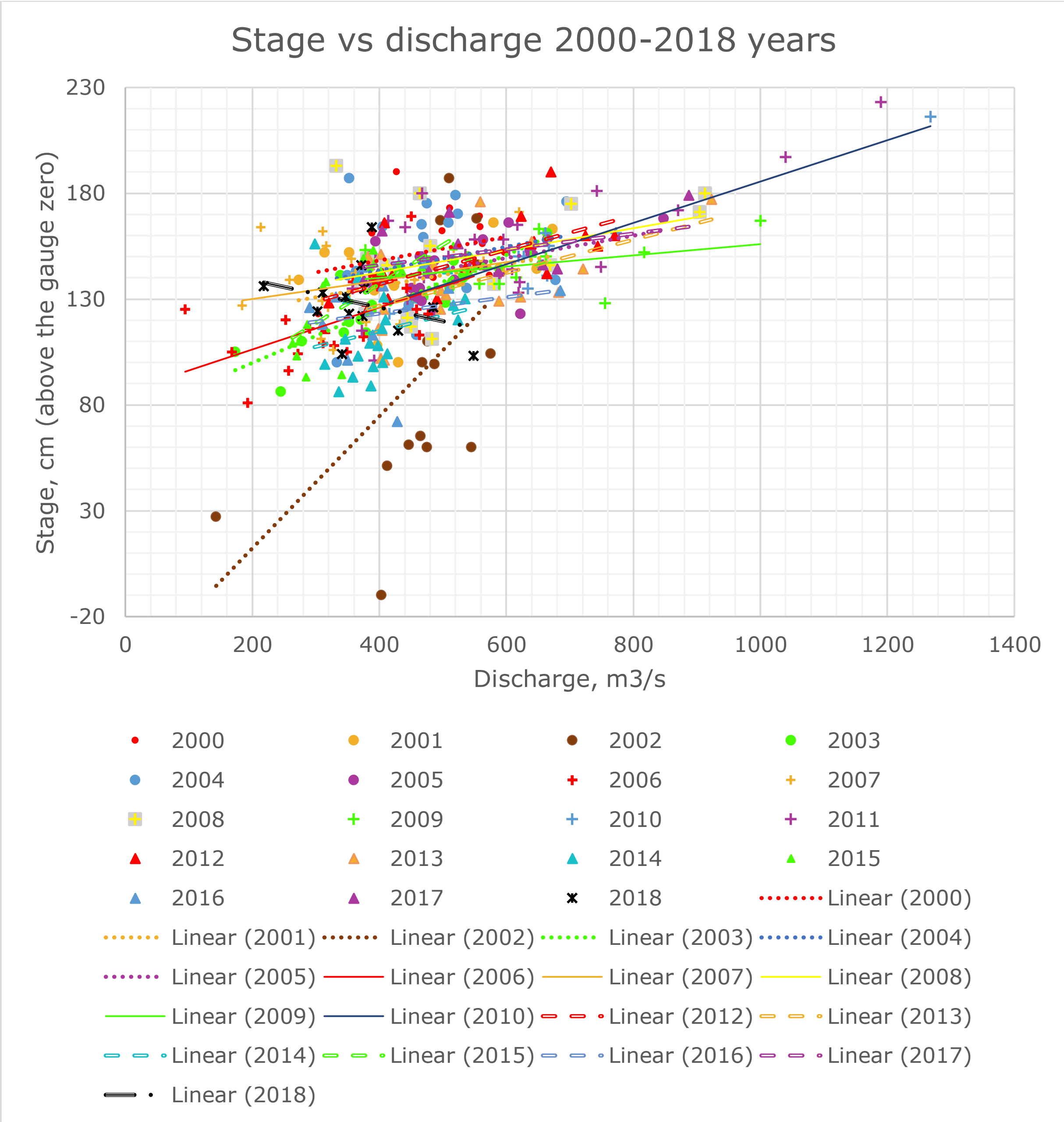


Figure 4.2.5: Measured discharges for the Narva gauge station for the period 2000-2018 years

As we can see, the pattern is approximately the same. However, the points are very scattered, which could be a result of a backwater effect and unsteady flow due to the Gulf of Finland or Sea influence and Narva HGS operation. More scattering occurs for stages less than 150 cm (above the gauge zero).

4.2.3 Recent measured discharges

Under the framework of the NARVAWATMAN project, discharges were measured from Russian and Estonian sides in 2019 and at the beginning of 2020. The results can be seen in Table *4.2.1*.

Table 4.2.1: Discharges measured under the framework of the NARVAWATMAN project

#	Date	Site #	Stage above the gauge zero, cm (Narva linn)	Stage, m BS (Narva linn)	Stage, cm EH2000 (Narva linn)	AHC, m BS	AHC, cm EH2000	Discharge, m3/s	Area F, m2	Mean stream velocity, m/s
Russian Measurements										
1	30/07/2019	1	115	0,073	25			300	400	0,75
2	31/07/2019	1	124	0,163	34	0,59	76,7	301	401	0,75
3	31/07/2019	2	122	0,143	32	0,59	76,7	299	286	1,05
4	20/08/2019	1	129	0,213	39	0,54	71,7	257	404	0,64
5	20/08/2019	2	127	0,193	37	0,51	68,7	254	280	0,91
6	20/08/2019	3	126	0,183	36	0,50	67,7	254	1165	0,22
7	20/08/2019	4	121	0,133	31	0,34	51,7	200	1363	0,15
8	21/08/2019	5	121	0,133	31	0,35	52,7	201	1073	0,19
9	05/09/2019	1	129	0,213	39	0,56	73,7	271	386	0,70
10	05/09/2019	2	130	0,223	40	0,55	72,7	277	273	1,01
11	05/09/2019	3	135	0,273	45	0,58	75,7	264	1156	0,23
12	15/10/2019	1	129	0,213	39	0,76	93,7	341	388	0,88
13	15/10/2019	2	127	0,193	37	0,75	92,7	352	285	1,24
14	15/10/2019	3	126	0,183	36	0,75	92,7	345	1171	0,29
15	16/10/2019	3	109	0,013	19	0,55	72,7	303	1149	0,26
16	27/11/2019	1	98	-0,097	8	0,81	98,7	419	397	1,06
17	28/11/2019	2	99	-0,087	9	0,86	103,7	423	343	1,23
18	28/11/2019	3	100	-0,077	10	0,86	103,7	422	1102	0,38
19	05/12/2019	1	177	0,693	87	1,09	126,7	422	386	1,09
20	05/12/2019	2	176	0,683	86	1,10	127,7	433	316	1,37
21	05/12/2019	3	171	0,633	81	1,07	124,7	422	1302	0,32
22	24/01/2020	1	183	0,753	93	1,27	144,7	507	402	1,26
23	24/01/2020	2	186	0,783	96	1,27	144,7	510	322	1,58
24	24/01/2020	3	187	0,793	97	1,28	145,7	507	1323	0,38
Estonian Measurements										
1	17/07/2019	3	141	0,333	51			292	1123	0,26
2	31/07/2019	3	120	0,123	30	0,59	76,7	273	1050	0,26
3	21/08/2019	3	125	0,173	35	0,38	55,7	210	1105	0,19
4	05/09/2019	3	135	0,273	45	0,58	75,7	261	1135	0,23
5	16/10/2019	3	116	0,083	26	0,55	72,7	263	1096	0,24
6	07/11/2019	3	121	0,133	31	0,90	107,7	378	1112	0,34

The measurement sites' locations can be seen in Figure *2.1.5*. They marked as "гидроствор №" followed by the site's number. The sites' numbers and their descriptions are in Table *4.2.2*.

Table 4.2.2: Measurement sites

River sites		
#	Name	Location
1	Channel	Derivation channel
2	Fort	Upstream Narva linn gauge station
3	Narva marina	Narva linn gauge
4	Garages	12km from the mouth of the river
5	Tower	6 km from the mouth of the river

In Table *4.2.1*, the measured discharges, stages for the Narva linn gauge station and Russian AHC stages are given at the same time. The discharges performed by both countries were plotted first against Narva linn gauge stages and then against AHC stages.

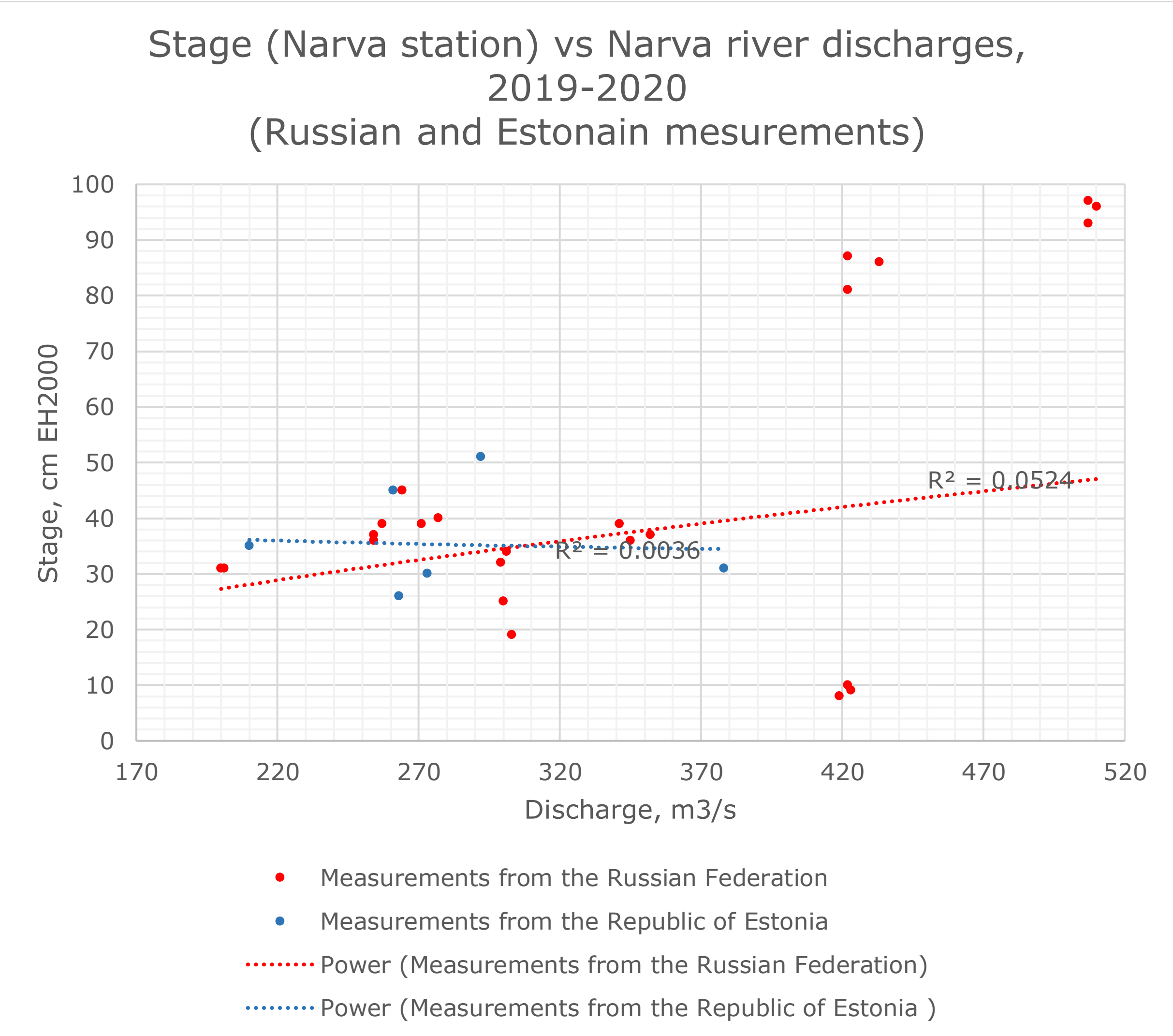


Figure 4.2.6: Narva river discharges vs stage (Narva station), 2019-2020

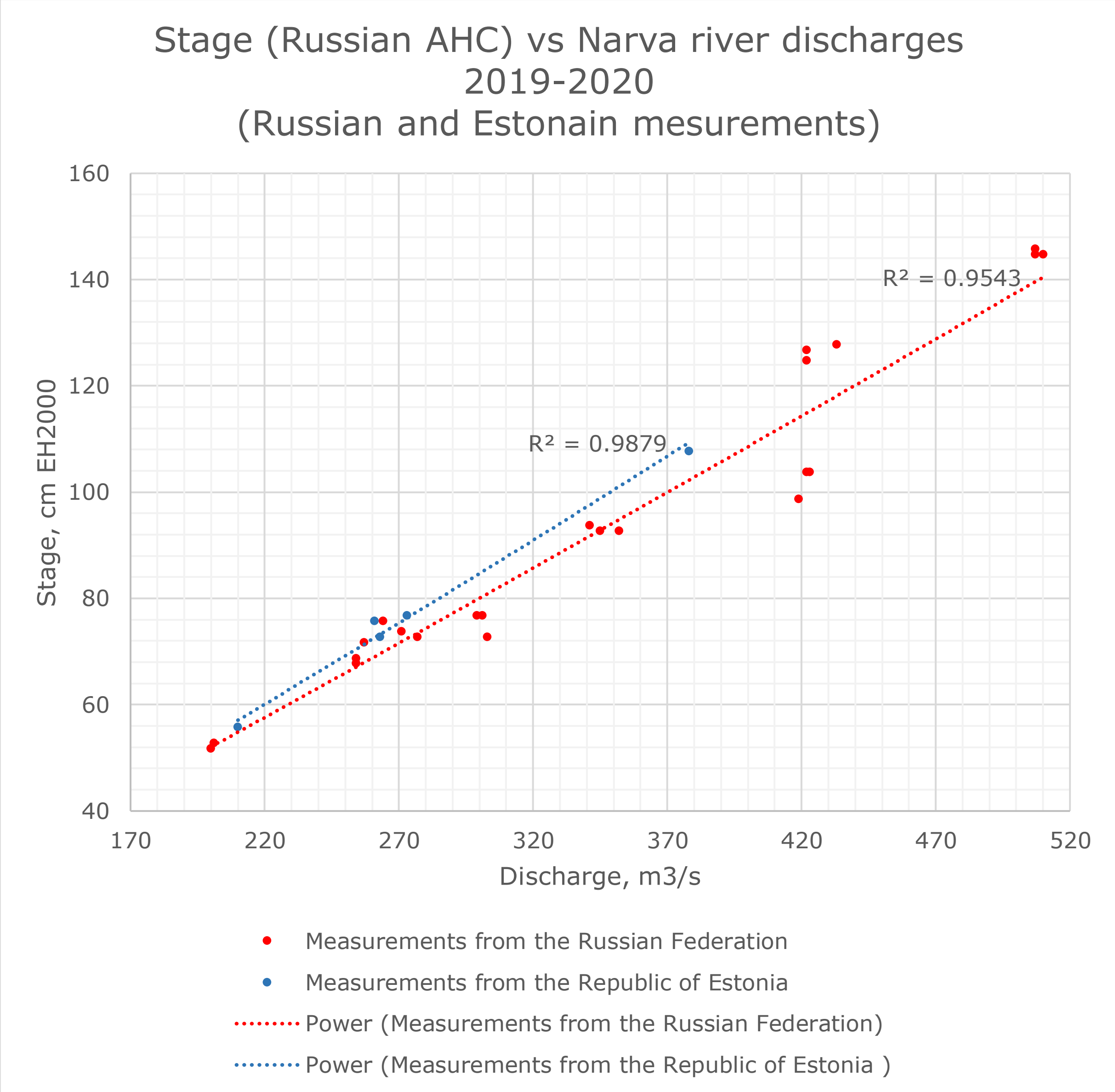


Figure 4.2.7: Narva river discharges vs stage (Russian AHC), 2019 - 2020

The graph with the discharges vs stages of the Russian AHC (Figure *4.2.7*) clearly shows higher dependence rather than with those plotted against Narva linn stages. That happens because of the backwater effect and the Narva river unsteadiness. Since the AHC stages measurements are performed at HGS channel, the values are very sensitive to rapid changes in discharge due to HGS operation. While, after reaching the Narva linn gauge station, these effects tend to blur because the river width increases and interfering with wind and backwater occurs.

In Figure *4.2.6* (the measured discharges against the Narva linn stages), we can highlight three extreme points for 27.11-28.11.2020 with relatively low stages and high discharges:

- Point 1 - 8 cm EH 2000, 419 m^3/s;
- Point 2 - 9 cm EH 2000, 423 m^3/s;
- Point 3 - 10 cm EH 2000, 422 m^3/s.

Despite that these values seem to be off, they are consistent with historical observations and data. As it was mentioned in the chapter 2.1.2 lower stages are seen in December (the end of November in our case) and as seen in the Figure *4.2.4* peaks in discharges occur in April-May (higher peak) and October-November (lower peak). The same point can be seen for measured discharges in 2002 – Point 6.12.02 with the stage -10 cm above the gauge zero, the discharge 403 m^3/s. The author supposes that it can be explained that in late November, the Gulf of Finland or backwater effect tends to be very small, and the Narva river flow is not affected by the sea.

The measured discharges also were compared with average daily discharges from the Narva HGS and daily discharges calculated by Environment Agency of the Republic of Estonia (KAUR, Keskkonnaagentuur)[3]. Should be noted that measured discharges present numbers for particular time point on a specific day, on the other hand, HGS data and data from Environment Agency are averaged for that particular day. Nevertheless, the HGS data is less than the measured values as seen from Figure *4.2.8* below. Especially on 24.01.2020, it has a rapid drop to almost a third of the measured value. Numbers from Environment Agency (marked as "Discharge KAUR") are generally closer to the measured discharges (values for 24/01/2020 are absent in Figure *4.2.8*). However, the Environment Agency values are almost twice smaller than those from the Narva HGS and the measured ones for those three points – 27-28.11.2019.

From the mentioned above, we can conclude that the method used by the Environment Agency doesn't take the backwater effect and the flow unsteadiness into account. At the same time, the Narva HGS data is generally lower than measured values what casts doubt on the Russian discharge estimation reliability, especially considering significant difference on 24.01.2020.

[3] https://www.keskkonnaagentuur.ee/en

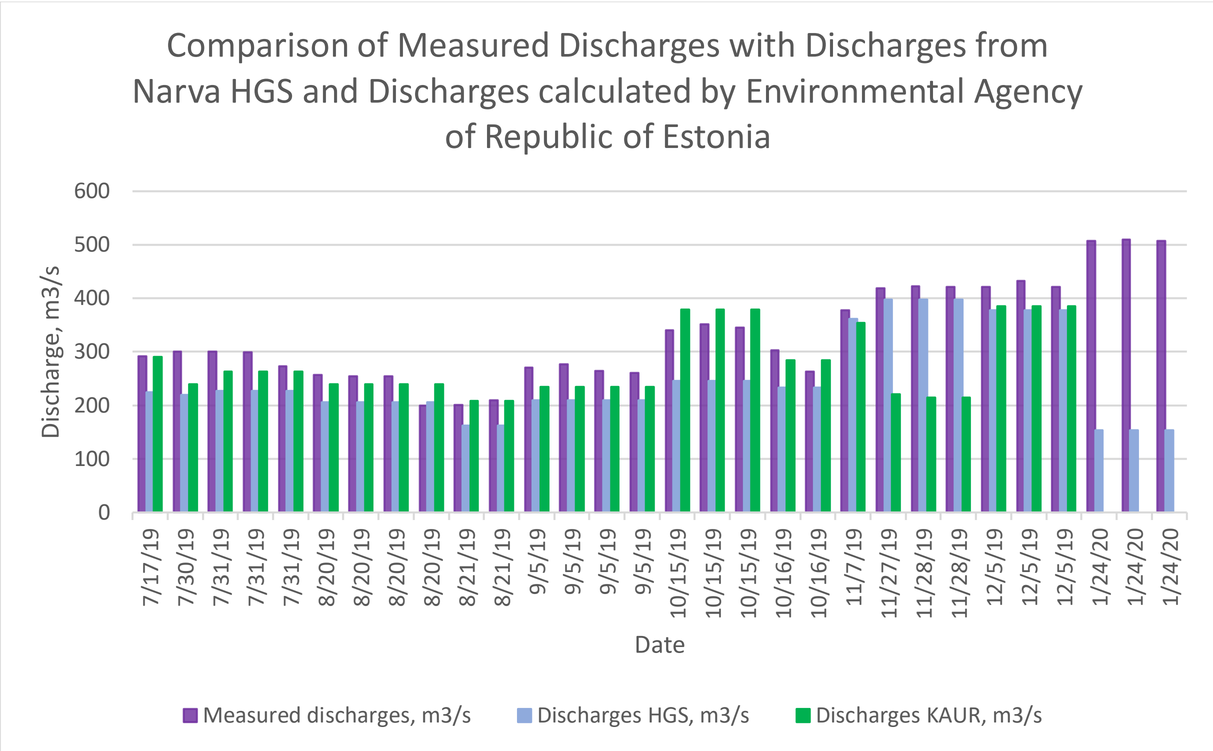


Figure 4.2.8: Comparison of measured discharges with discharges from Narva HGS and discharges calculated by the Environmental Agency of the Republic of Estonia for various dates in 2019-2020

4.2.4 Wind, sea & stages

It is supposed that the backwater effect responsible for discharge/stage points scattering could be caused by the combined effect of the wind and sea "pressure". Hourly sea levels, wind power and direction at the Narva-Jõesuu gauge station, Narva linn gauge station stages and Russian AHC stages were gathered. Then the study seeks to analyse them and justify if such a combined effect worth consideration and if they affect opting of the Narva river harmonized discharge estimation method.

The hourly data on wind, sea level and Narva linn gauge station was provided by the Estonian Environmental Agency (KAUR, Keskkonnaagentuur)[4] for the period from 1.01.2019 to 5.03.2020.

To assess how sea levels and river stages are affected by the wind, its direction should be considered. When the wind blows towards the gauge making the levels rise higher

[4] https://www.keskkonnaagentuur.ee/en

wind power produces higher rises, while the same power blowing in the opposite direction decreases the levels. [26]

The data on the wind is presented as the wind direction in degrees and the wind power in m/s. The greatest effect of the wind to the sea level will be in case of the wind blowing perpendicular to the Sea coastline. Let’s call it the effective surface and suggest that it lies along the EW (East-West). Then we get four cases of the wind direction, as seen from Figure *4.2.9* below:

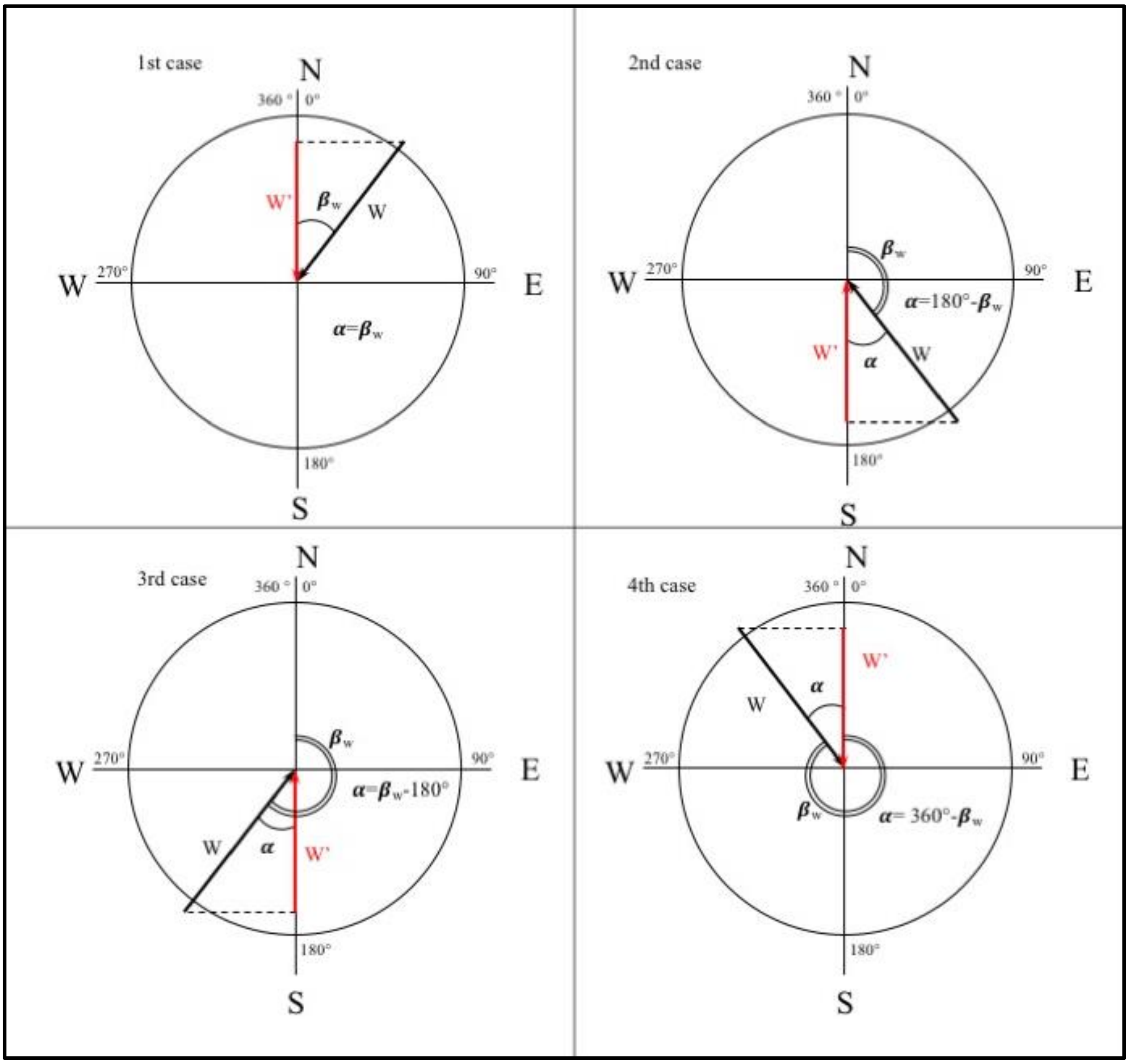


Figure 4.2.9: Four cases of the wind direction

Where:

W [m/s] – the wind power vector;

W' [m/s] – the effective component of the wind power vector (affects the effective surface);

$\boldsymbol{\beta}_w$ [°] – the wind direction.

In any of the presented cases, the effective wind power W' equals:

$$W' = W\cos\alpha \quad (10)$$

Then, for the first case:

$$cos\,\alpha = cos\,\beta_w \quad (11)$$

For the second case:

$$\cos\alpha = \cos(180° - \beta_w) = \cos 180° \cos\beta_w + \sin 180° \sin\beta_w = \cos\beta_w \quad (12)$$

For the third case:

$$\cos\alpha = \cos(\beta_w - 180°) = \cos\beta_w \cos 180° + \sin\beta_w \sin 180° = \cos\beta_w \quad (13)$$

For the fourth case:

$$\cos\alpha = \cos(360° - \beta_w) = \cos 360° \cos\beta_w + \sin 360° \sin\beta_w = \cos\beta_w \quad (14)$$

Thus:

$$W' = W\cos\beta_w \quad (15)$$

Because the Narva-Jõesuu coastline "tilted" left, we should as well tilt left our effective surface by adding the rotation value to $\boldsymbol{\beta}_w$. The number could be found from the map, as seen in Figure *4.2.10* below:

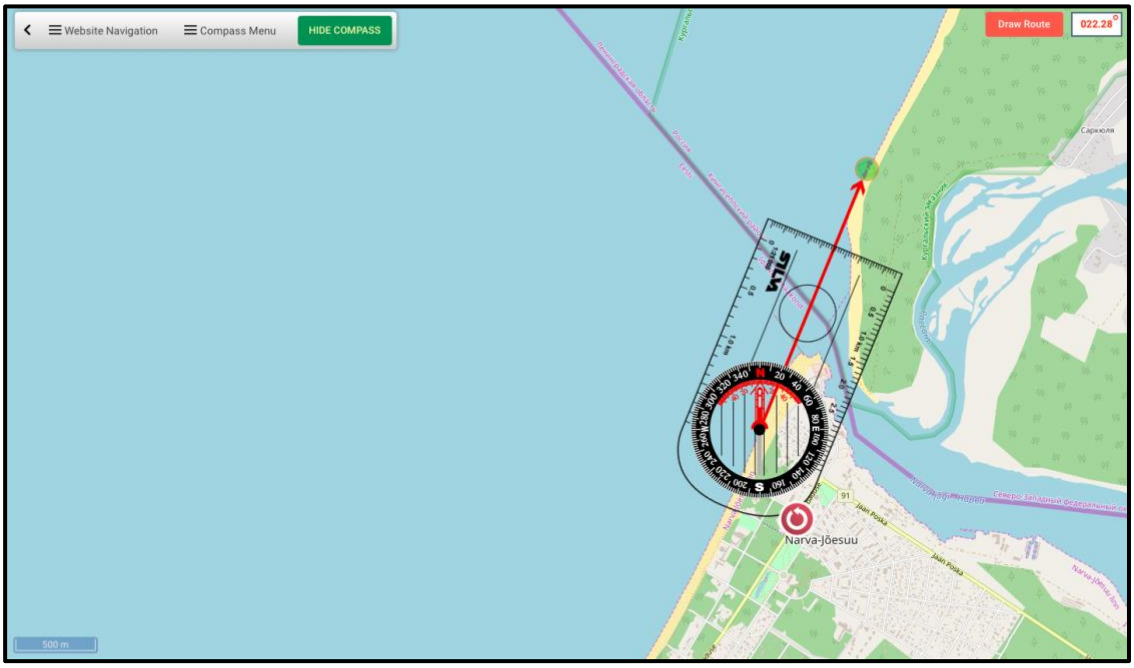


Figure 4.2.10: Narva-Jõesuu coastline angle, https://osmcompass.com/

That value is 90°-22,3°=67,7°. All the data on the wind was processed to derive W' for every hour using the derived angle value.

All the data was compiled on one graph to analyse the effect. Since the amount of numbers is vast, the graph is produced for a small representative period from 25.10.2019 to 10.12.2019. It can be seen in Figure *4.2.12*. The wind which increases the levels has a positive value while the one which decreases has a negative. These values are shown as purple and red bars respectively on the graph. The wind effect on the sea and Narva stage can be seen.

However, the dependence is complex and not linear, plus, the AHC data has rather even rapid peaks which represent working cycles of the HGS. Those peaks have a certain correlation with Narva linn stage peaks. Thus, we can suppose that Narva linn stage is regulated by three factors: wind, sea backwater and HGS work with complex non-linear co-dependency, which makes it difficult to define it mathematically. Moreover, as was mentioned before, the riverbed before the Narva linn gauge station is wider than the channel after the HGS outlet. Thus, the rapid discharge change won't have the same drastic effect on the Narva linn stage as it has on the AHC stage. Plus, there is a small area on the left of the channel, which can act as a buffer zone, smoothing stage changes for Narva linn gauge (Figure *4.2.11*). Therefore, the author suggests that another way should be used to assess the backwater effect rather than just trying to establish the dependence between the mentioned variables. Although, making such kind of graphs can be handy to adjust the scattered points when establishing simple stage-discharge relation as it is used now in Estonia (chapter 4.1.1). Should be noticed that AHC has a plateau approximately in the middle of the considered period. Most probably, it can be just a mistake of the measurements.

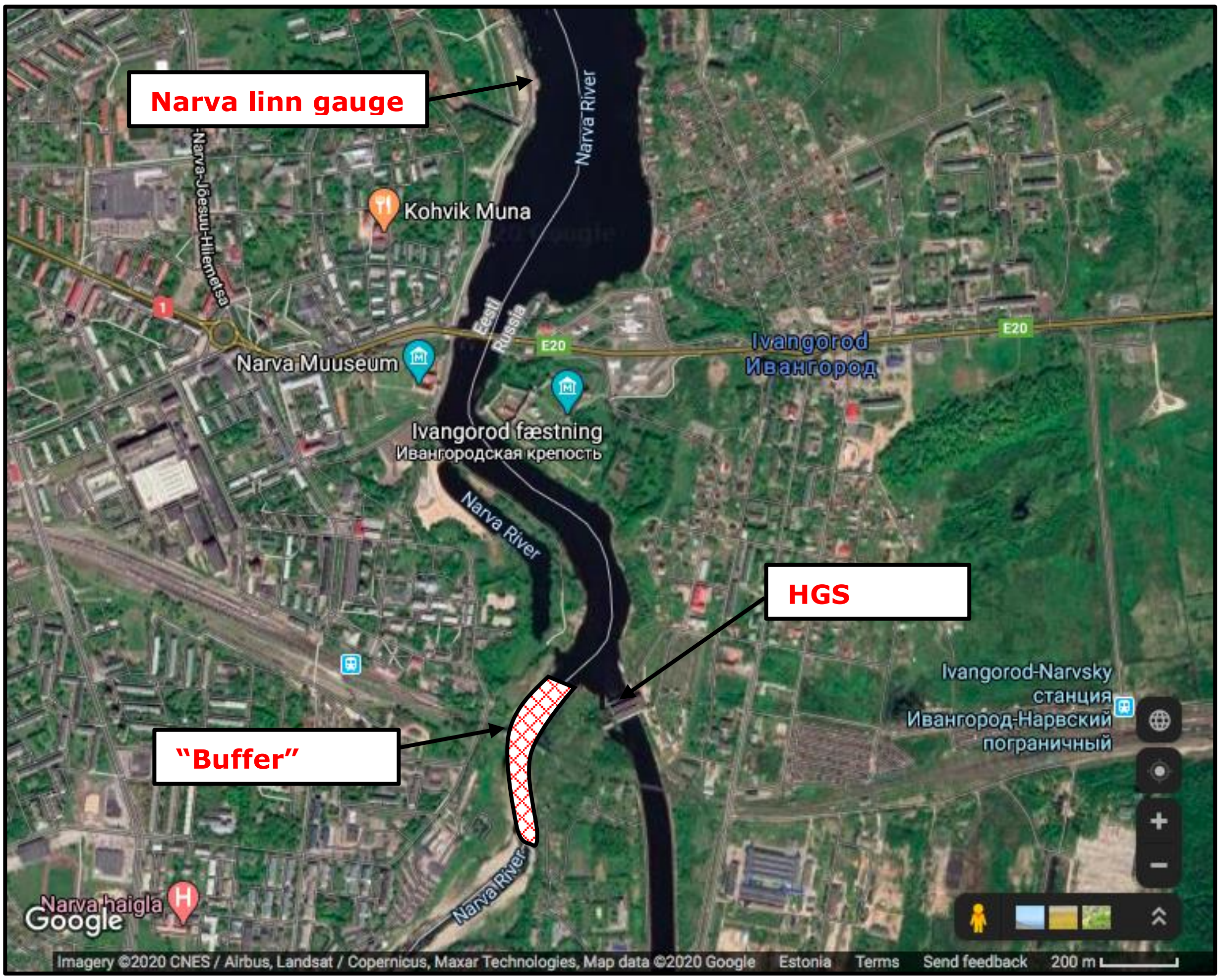


Figure 4.2.11: HGS outlet, Narva linn gauge, buffer zone, GoogleMaps

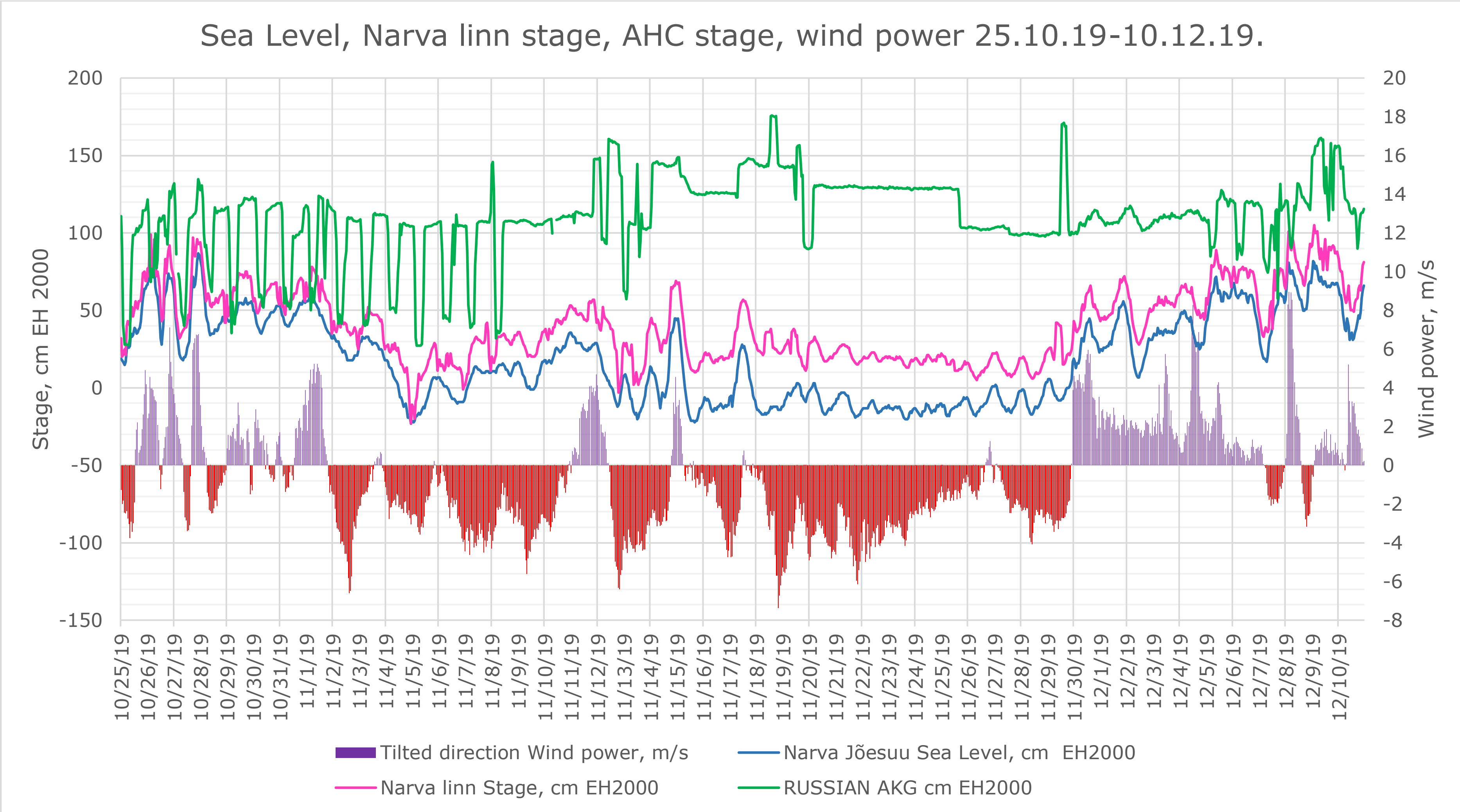


Figure 4.2.12: Sea Level, Narva linn stage, AHC stage, wind power 25.10.19 - 10.12.19

4.3 Harmonized discharge estimation method

4.3.1 Choice of the method for the Narva river discharge estimation

Observing the methods of discharge estimation mentioned in chapter 3.1, we can conclude that:

1. Discharge ratings using simple stage-discharge relations – the technique is currently used by Estonia. However, it has a drawback in the present case since Narva linn stages are highly affected by the backwater effect and unsteady flow due to the HGS work. Thus, the points on the graph stage vs discharge are scattered as was seen before making establishing the rating curve rather problematic and errors may appear as it was shown in the chapter 4.2.3, the Figure *4.2.8*. Although the AHC stages show good correlation, the gauge station will be operating only during a short period of the NARVAWATMAN project work, making it impossible to use it in the long run.
2. Discharge ratings using the velocity index method – the method is recommended for usage when variable backwater restricts stage/discharge relations. It may be a good option in the case of the Narva river. Still, unfortunately, it requires a hydroacoustic current meter to measure velocity for a certain part of the channel constantly. Such equipment is not in operation on the Narva river.
3. Discharge ratings using slope as a parameter – the method is recommended when backwater or very unsteady flows at a gauging station exists. It was said that this variable backwater usually is caused by a variable stage at a downstream confluence for a given discharge upstream or by downstream dam gates. We can consider the mouth of the river and the river Rosson located near the "confluences". Then, Narva linn gauge is considered as the base gauge and Narva-Jõesuu as the auxiliary one.
4. Linear interpolation can be an option in case of a rather big amount of the discharge field measurements data available. The reason is that as seen from the Narva river hydrograph in Figure *4.2.4* for the Narva linn gauge, it has two defined peaks per year and two defined dips per year. The density of the measurements around those extreme points should be as such to allow the interpolation to be quite precise. Besides, the hydrograph takes into account average monthly discharges, that is why the curve looks rather smooth. But if we take into account the average daily discharges, the fluctuation of the curve gets much higher, as seen from Figure *4.2.3* where daily Narva river discharges

are plotted for eleven years. Such fluctuation requires even bigger filed measurement density to provide the allowable precision of the discharge estimation. As we know, on average discharges are measured 17 times a year which is not enough.

4.3.2 The Narva river discharge estimation process

It appears that the best option is to use discharge ratings using slope as a parameter as the Narva river discharge estimation method. Narva linn gauge station is considered as the base gauge, Narva-Jõesuu as the auxiliary one. Their data are used to calculate the fall. WMO gives a detailed description of how to use the method which was followed further [15]:

All discharge measurements were plotted using stages at the base gauge as ordinates and discharges, Q_m, as abscissa, and the measured fall, F_m, was noted beside each plotted point. See Figure *4.3.1* below.

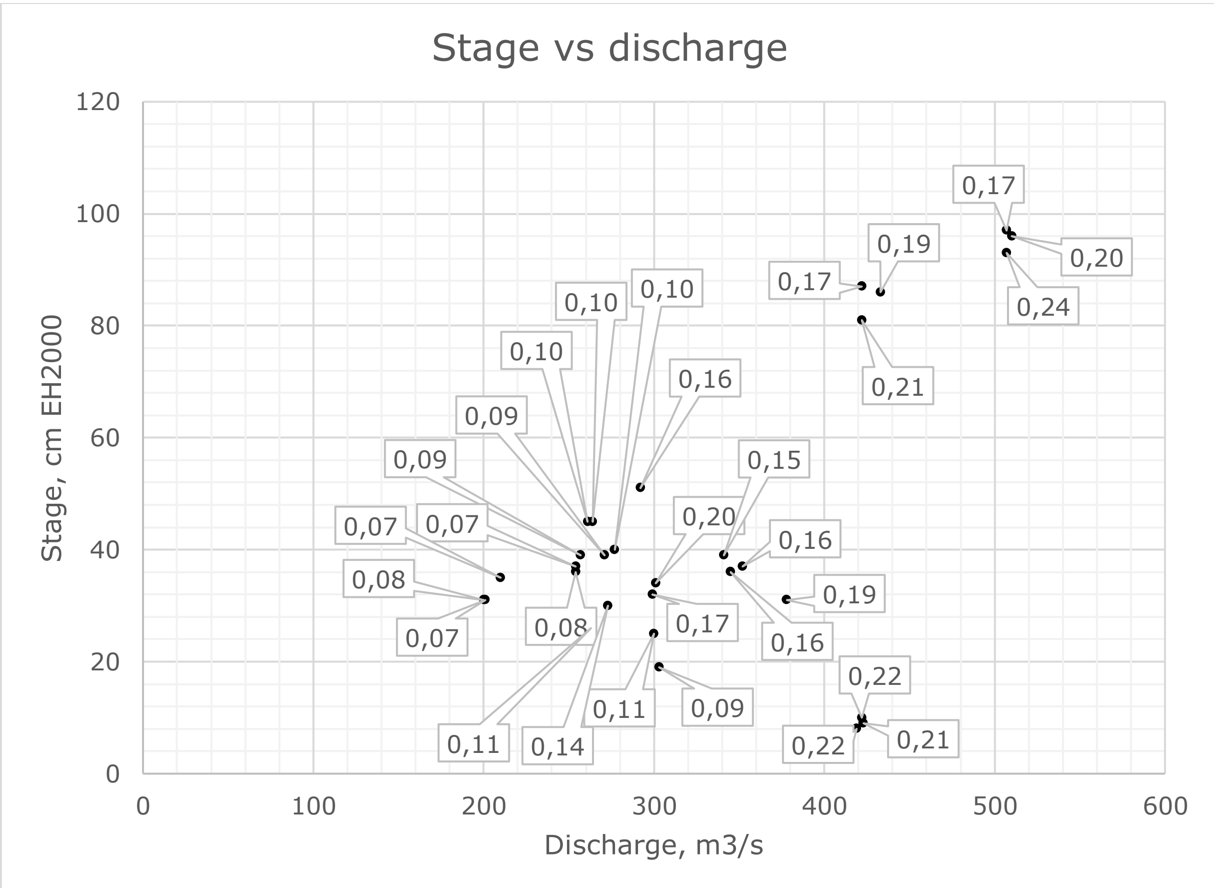


Figure 4.3.1: Stage at the base gauge (Narva linn) vs measured discharge

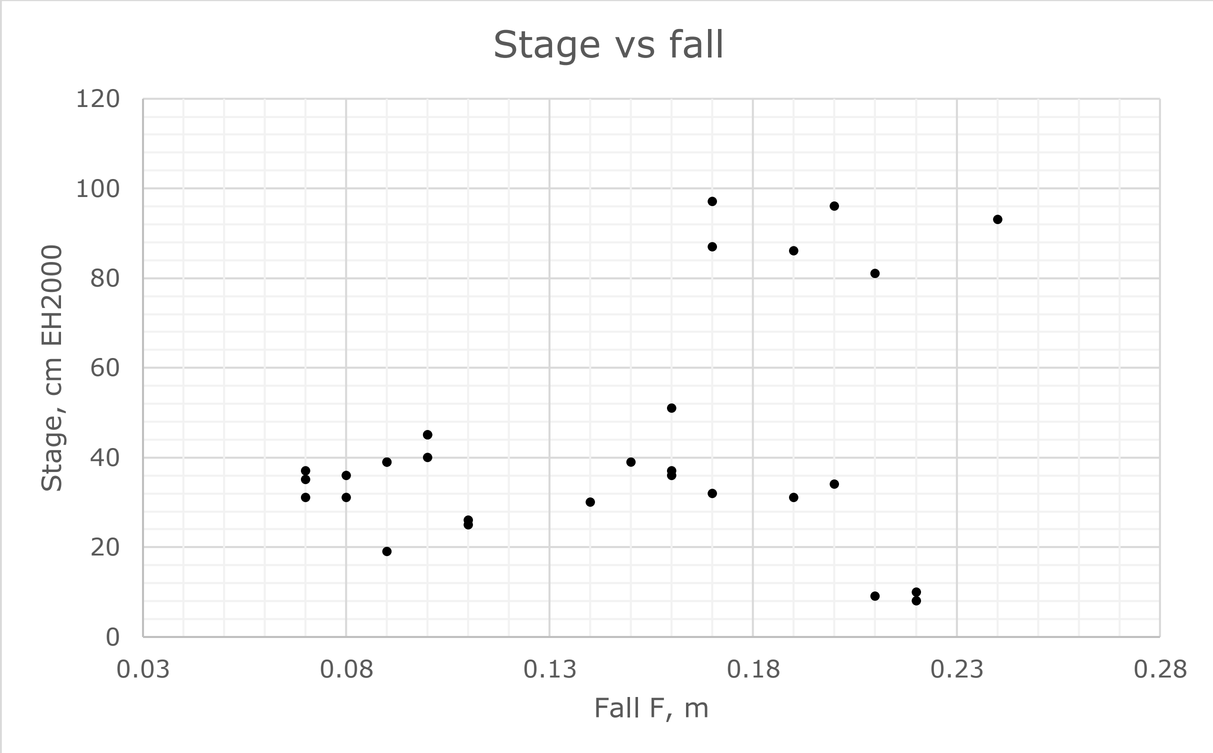


Figure 4.3.2: Stage vs fall

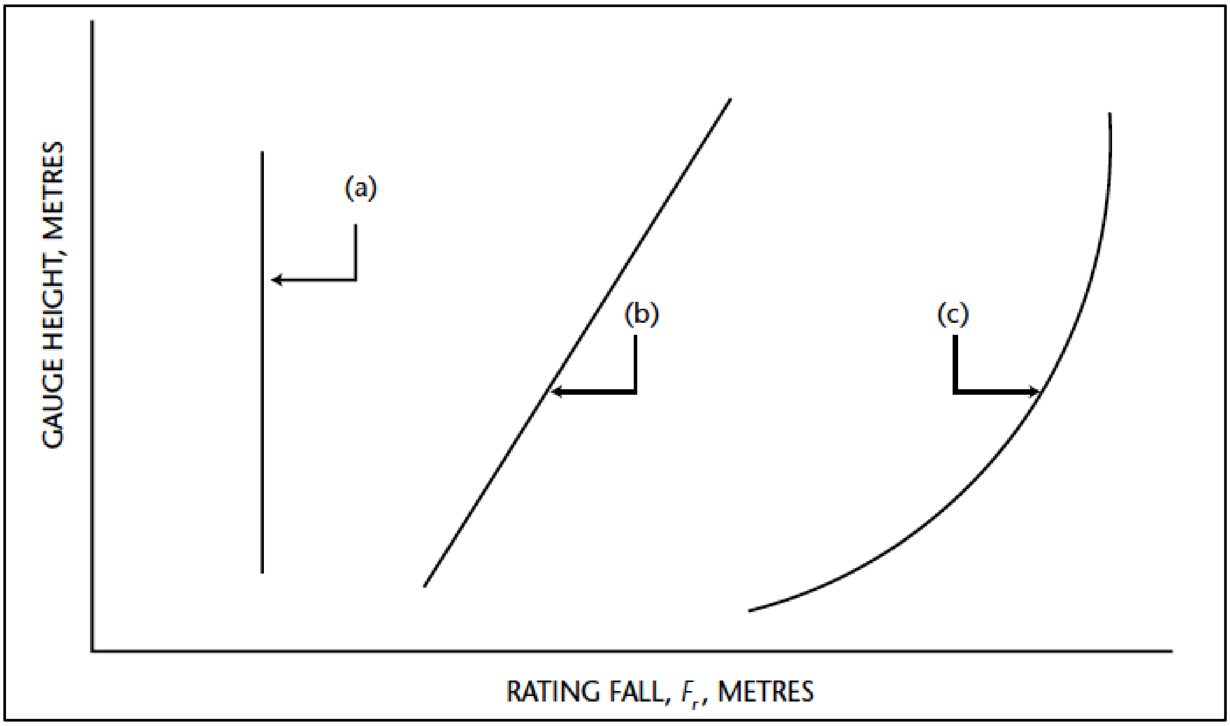


Figure 4.3.3: Possible stage-fall relation [15]:
a – no relation; b – linear; c – complex.

Measured fall, F_m, for each discharge measurement was plotted against the stage at the base gauge, using the stage as the ordinate. See Figure *4.3.2*. WMO states [15] that there could be no dependence between stage and fall, it can be linear or complex; the examples can be seen in Figure *4.3.3*. It was supposed that the points are scattered due to some measurement errors, and the relation is linear. However, such linkage is not perfectly clear.

Then, we fit a Q_r rating curve to the stage-discharge plot in and another F_r rating-fall curve to the stage-fall plot. For that, linear regression in the Microsoft Excel software was used, producing a straight line. For fitting Q_r rating curve, the power type equation for stage-discharge relation [32] [33] was used:

$$Q = C(H - a)^{\beta} \quad (16)$$

Where:

C – constant;

H [cm] – stage;

a [cm] – constant.

To estimate "a" it was considered that it should indicate that the discharge equals zero when the stage in EH 2000 system reaches the bottom of the river. Constant "a" was derived from the Narva river cross-section profile at the Narva linn gauge station which can be seen in Figure *4.1.2*, and it equals -540 cm EH 2000 approximately.

Then equation was transformed to make it possible to use linear interpolation as follows:

$$\ln Q = \ln C(H - a)^{\beta} \quad (17)$$

$$\ln Q = \ln C + \ln(H - a)^{\beta} \quad (18)$$

$$\ln Q = \beta \ln(H - a) + \ln C \quad (19)$$

The curves and lnQ=f(ln(H-a)) line can be seen further:

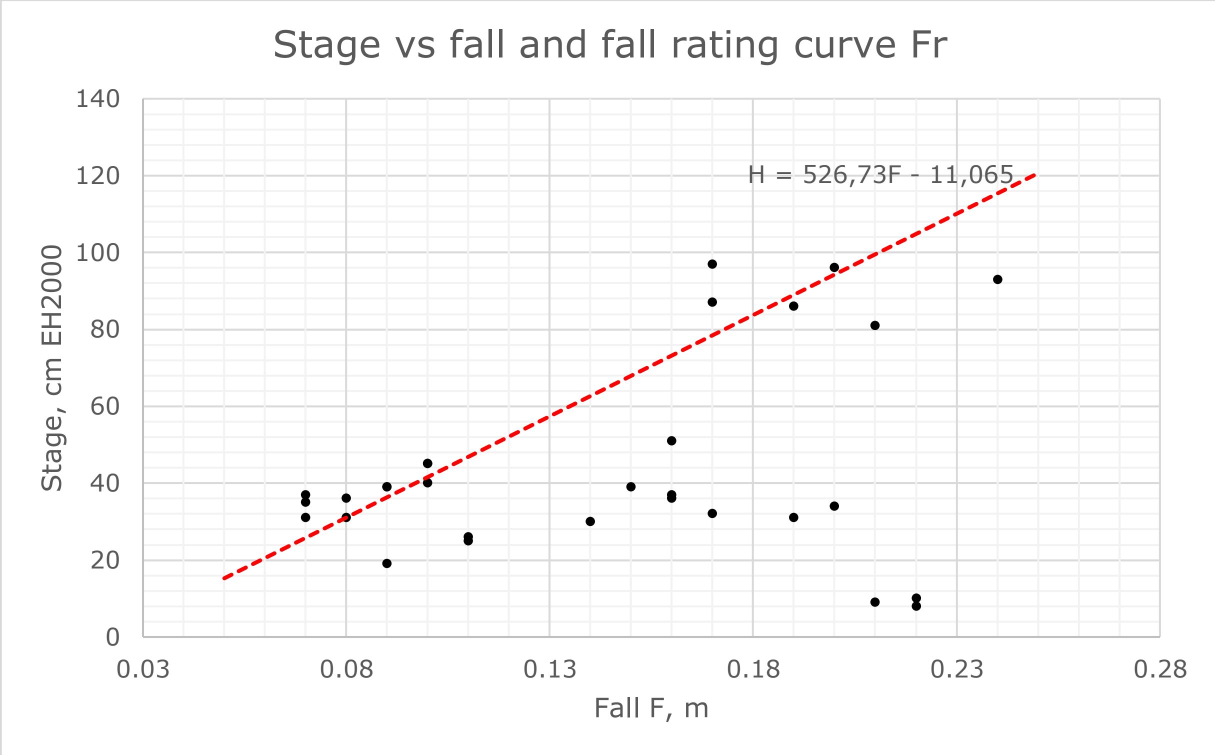


Figure 4.3.4: Stage vs fall and fall rating curve F_r

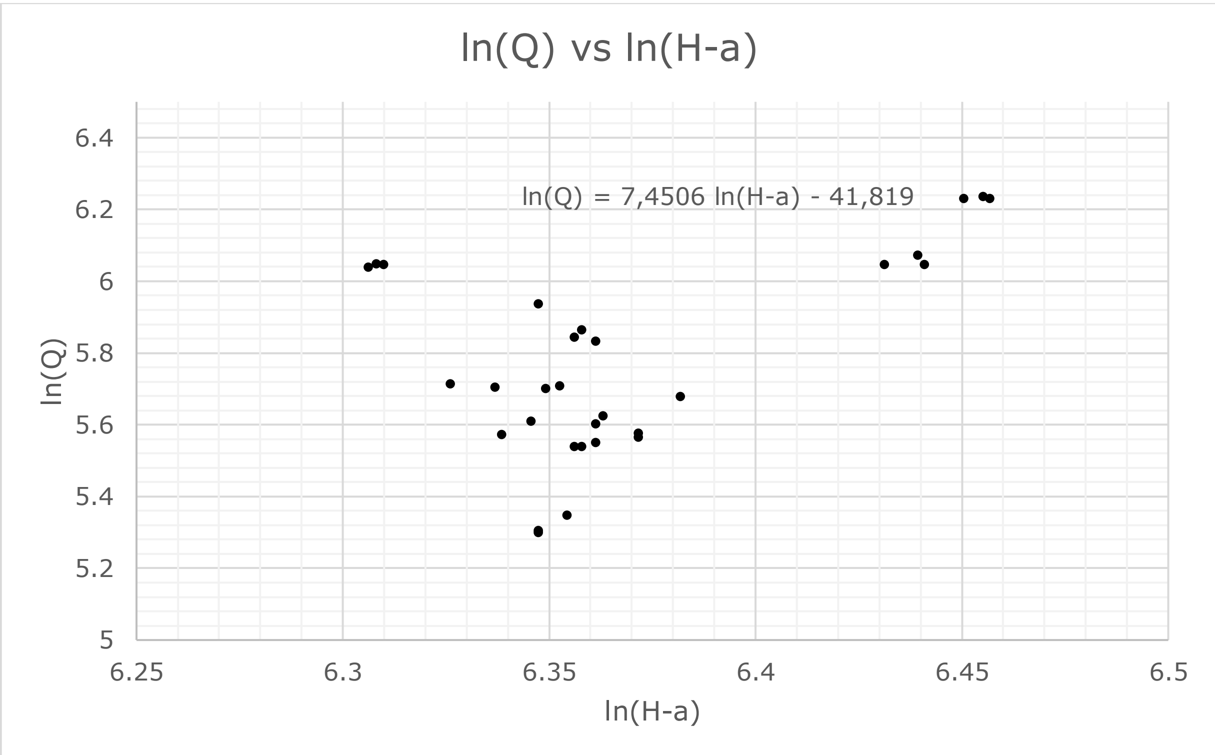


Figure 4.3.5: lnQ=f(ln(h-a))

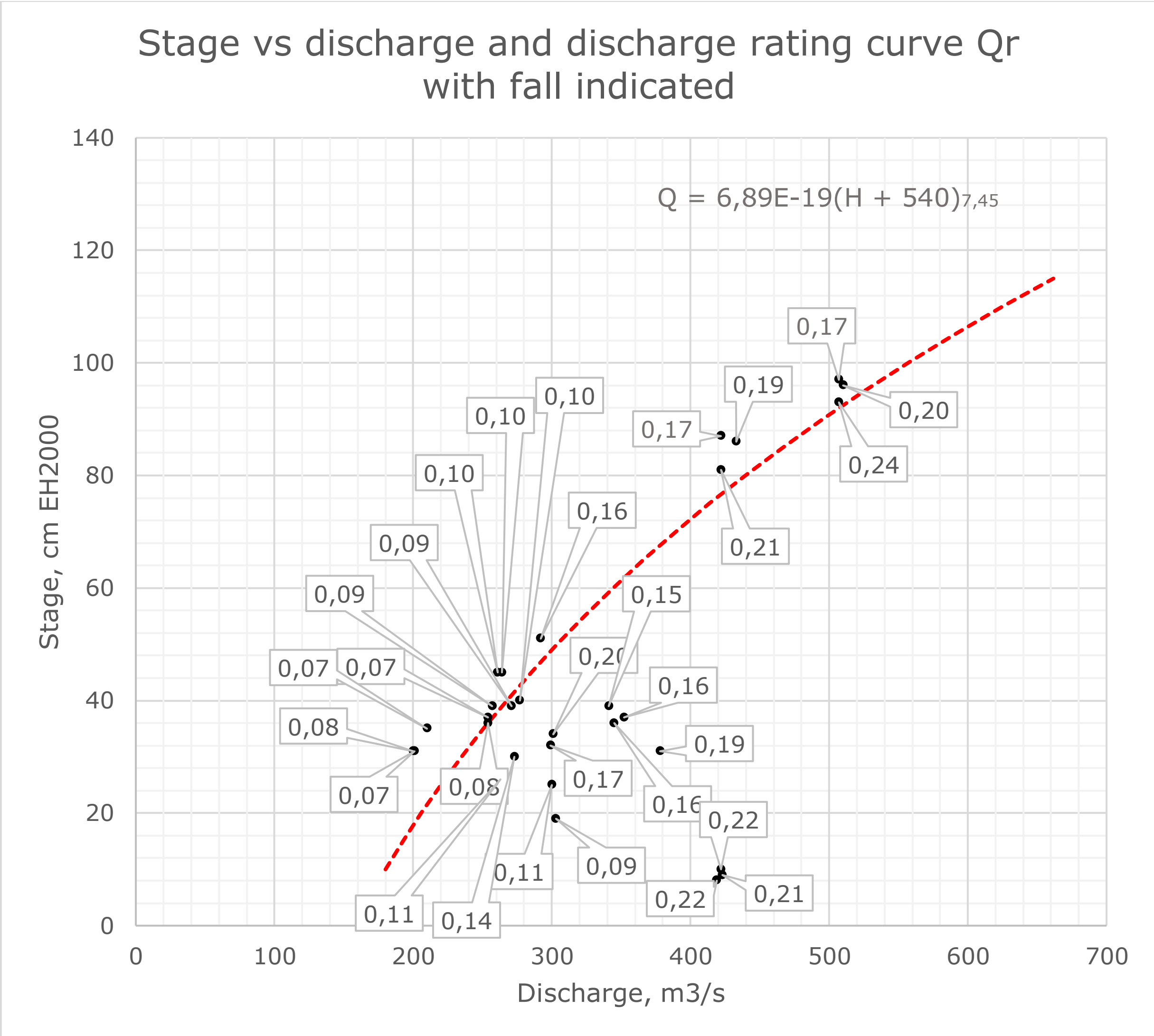


Figure 4.3.6: Stage vs discharge and discharge rating curve Q_r with fall indicated

Derived governing equations are respectively:

$$H = 526{,}73F - 11{,}065 \quad (20)$$

$$\ln Q = 7{,}4506 \ln(H - a) - 41{,}819 \quad (21)$$

$$Q = 6{,}89 \cdot 10^{-19}(H + 540)^{7{,}45} \quad (22)$$

However, it should be noted that the relation is not ideal, considering that due to some technicalities, there were now field measurements of discharges in spring when the highest discharges occur.

Then from the curve values of Q_r and F_r corresponding to the stage of each discharge measurement, were obtained, and the ratios Q_m/Q_r and F_m/F_r for each discharge measurement were computed. The graph with Q_m/Q_r as ordinate against F_m/F_r as abscissa was plotted with the curve $Q_m/Q_r = (F_m/F_r)0.5$ drawn.

It is said in the WMO [15] that Q_r and F_r curves should be adjusted, so the revised values of Q_r and F_r in ratios Q_m/Q_r and F_m/F_r will make scattered points fit the $Q_m/Q_r = (F_m/F_r)_{0,5}$ curve. Exponents 0,4, 0,45, 0,55 also can be considered. All adjustments were made beforehand in Microsoft Excel. The computed data can be seen in Table *4.3.1*. The exponent 0.5 was used eventually.

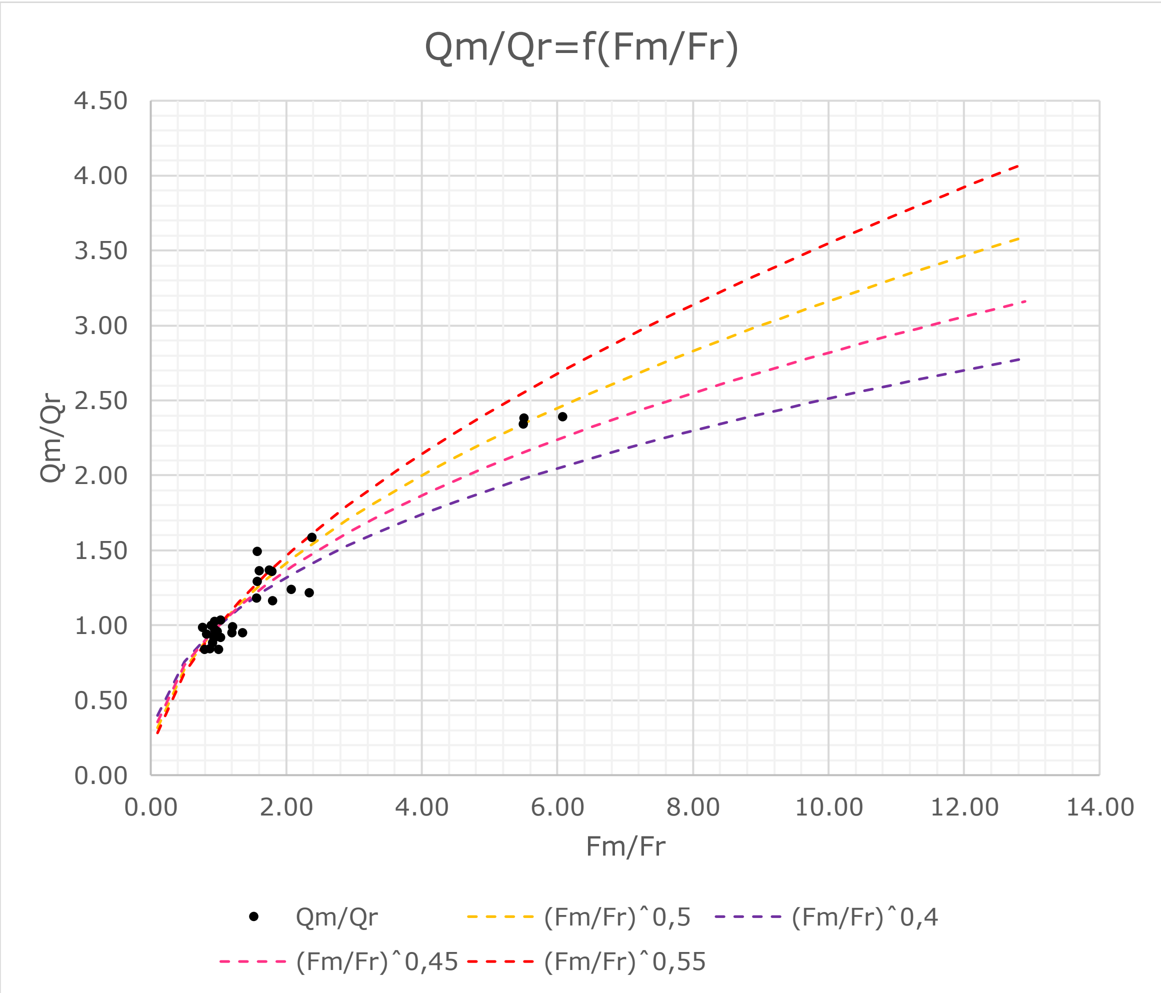


Figure 4.3.7: $Q_m/Q_r=f(F_m/F_r)$ curves and Q_m/Q_r vs F_m/F_r point

Table 4.3.1: Data used for fall/stage/discharge curves establishing

Measurements from the Russian Federation											
#	**Date**	**Stage above the gauge zero, cm (Narva linn)**	**Stage, m BS (Narva linn)**	**Stage, cm EH2000 (Narva linn)**	**Q_m, m3/s**	**Stage, cm EH2000 (Narva-Jõesuu)**	**Fall F, m**	**Qr, m3/s**	**Fr**	**Qm/Qr**	**Fm/Fr**
1	30/07/2019	115	0,073	25	300	14	0,11	219,99	0,07	1,36	1,61
2	31/07/2019	124	0,163	34	301	14	0,2	247,48	0,09	1,22	2,34
3	31/07/2019	122	0,143	32	299	15	0,17	241,13	0,08	1,24	2,08
4	20/08/2019	129	0,213	39	257	30	0,09	264,00	0,10	0,97	0,95
5	20/08/2019	127	0,193	37	254	30	0,07	257,28	0,09	0,99	0,77
6	20/08/2019	126	0,183	36	254	28	0,08	253,98	0,09	1,00	0,90
7	20/08/2019	121	0,133	31	200	23	0,08	238,01	0,08	0,84	1,00
8	21/08/2019	121	0,133	31	201	24	0,07	238,01	0,08	0,84	0,88
9	05/09/2019	129	0,213	39	271	30	0,09	264,00	0,10	1,03	0,95
10	05/09/2019	130	0,223	40	277	30	0,1	267,42	0,10	1,04	1,03
11	05/09/2019	135	0,273	45	264	35	0,1	285,08	0,11	0,93	0,94
12	15/10/2019	129	0,213	39	341	24	0,15	264,00	0,10	1,29	1,58
13	15/10/2019	127	0,193	37	352	21	0,16	257,28	0,09	1,37	1,75
14	15/10/2019	126	0,183	36	345	20	0,16	253,98	0,09	1,36	1,79
15	16/10/2019	109	0,013	19	303	10	0,09	203,17	0,06	1,49	1,58
16	27/11/2019	98	-0,097	8	419	-14	0,22	175,21	0,04	2,39	6,08
17	28/11/2019	99	-0,087	9	423	-12	0,21	177,60	0,04	2,38	5,51
18	28/11/2019	100	-0,077	10	422	-12	0,22	180,03	0,04	2,34	5,50
19	05/12/2019	177	0,693	87	422	70	0,17	477,88	0,19	0,88	0,91
20	05/12/2019	176	0,683	86	433	67	0,19	472,23	0,18	0,92	1,03

Table 4.3.1 continued 1

Measurements from the Russian Federation											
#	**Date**	**Stage above the gauge zero, cm (Narva linn)**	**Stage, mBS (Narva linn)**	**Stage, cm EH2000 (Narva linn)**	**Q_m, m3/s**	**Stage, cm EH2000 (Narva-Jõesuu)**	**Fall F, m**	**Qr, m3/s**	**Fr**	**Qm/Qr**	**Fm/Fr**
21	05/12/2019	171	0,633	81	422	60	0,21	444,84	0,17	0,95	1,20
22	24/01/2020	183	0,753	93	507	69	0,24	513,02	0,20	0,99	1,21
23	24/01/2020	186	0,783	96	510	76	0,2	531,41	0,20	0,96	0,98
24	24/01/2020	187	0,793	97	507	80	0,17	537,67	0,21	0,94	0,83
Measurements from the Republic of Estonia											
#	**Date**	**Stage above the gauge zero, cm (Narva linn)**	**Stage, mBS (Narva linn)**	**Stage, cm EH2000 (Narva linn)**	**Q_m, m3/s**	**Stage, cm EH2000 (Narva-Jõesuu)**	**Fall F, m**	**Qr, m3/s**	**Fr**	**Qm/Qr**	**Fm/Fr**
1	17/07/2019	141	0,333	51	292	35	0,16	307,60	0,12	0,95	1,36
2	31/07/2019	120	0,123	30	273	16	0,14	234,92	0,08	1,16	1,80
3	21/08/2019	125	0,173	35	210	28	0,07	250,71	0,09	0,84	0,80
4	05/09/2019	135	0,273	45	261	35	0,1	285,08	0,11	0,92	0,94
5	16/10/2019	116	0,083	26	263	15	0,11	222,91	0,07	1,18	1,56
6	07/11/2019	121	0,133	31	378	12	0,19	238,01	0,08	1,59	2,38

As mentioned in the WMO manual [15], after all adjustments, all curves should be smooth and fit scattered plotted points. That was achieved here. For further daily discharge estimation, one should read the stage F_m (measured fall), H (stage at the Narva linn gauge) and corresponding F_r and Q_r from the derived curves mentioned above. Then for deriving the discharge number Q_m, the following formula is used:

$$Q_m = \left(\frac{Q_r}{F_r^{0,5}}\right)\left(F_m^{0,5}\right) \qquad (23)$$

After substituting our data for F_r and Q_r curves:

$$Q_m = \left(\frac{6{,}98 \cdot 10^{-19}(H+540)^{7{,}45}}{\left(\frac{H+11{,}065}{526{,}73}\right)^{0{,}5}}\right)\left(F_m^{0,5}\right) \qquad (24)$$

Or:

$$Q_m = 1{,}6 \cdot 10^{-17}\left[\frac{(H+540)^{7{,}45}}{(H+11{,}065)^{0{,}5}}\right]\left(H - H_{Jõesuu}\right)^{0{,}5} \qquad (25)$$

Where:

$H_{Jõesuu}$ [cm EH 2000] – water level at the Narva-Jõesuu gauge station.

Fall-stage-discharge relation also can be presented in a graphical form, as seen in Figure *4.3.8* below:

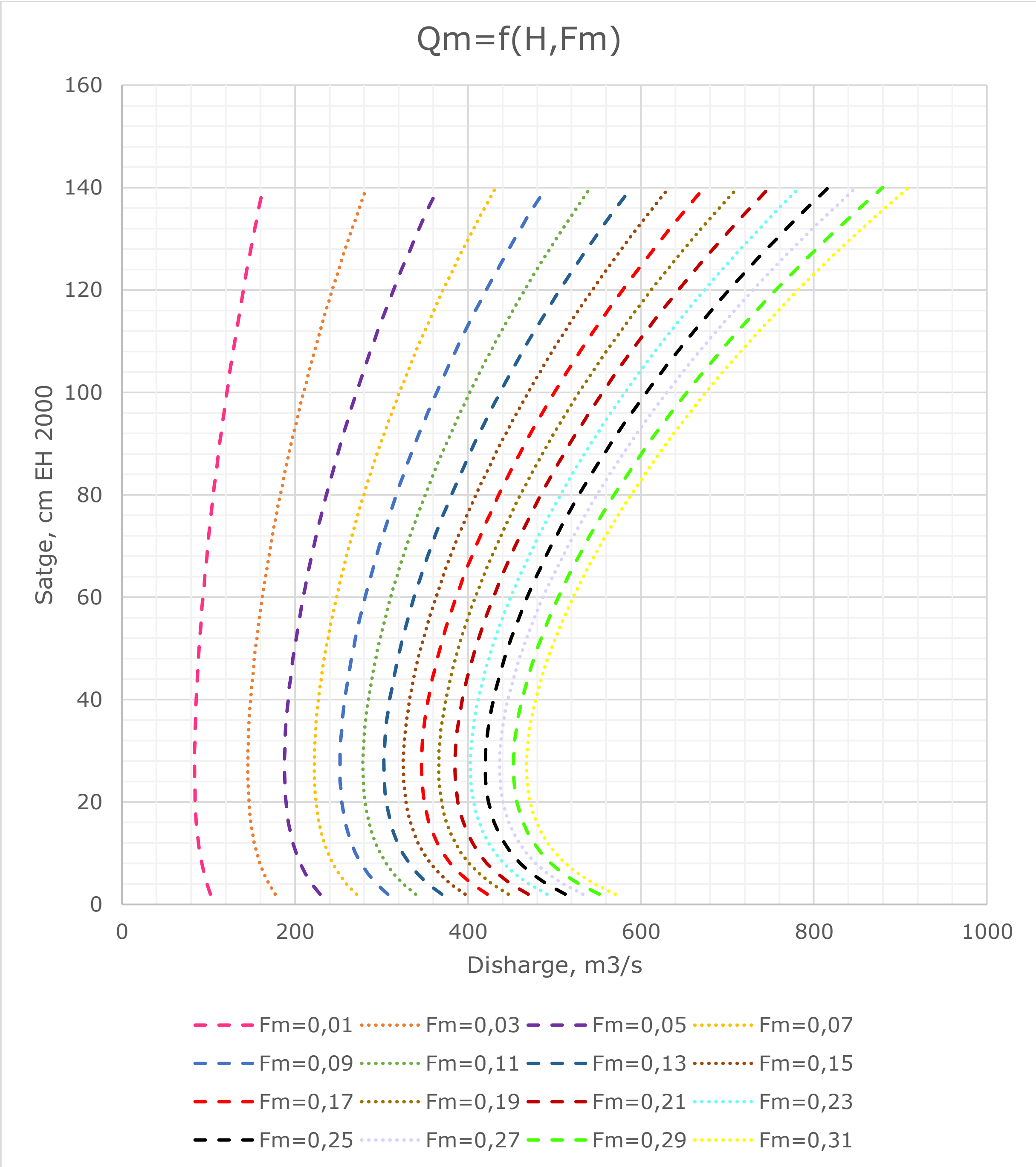


Figure 4.3.8: Stage vs discharge for various falls

5 Results

Discharge ratings using slope as a parameter was used as the method for the river Narva discharge estimation. The equation (26) was derived, and the graph in Figure *4.3.8* was produced. Comparison of the methods for the Narva river discharge estimation can be seen in Figure *5.1.2* below.

The daily discharge for all methods generally follows the historical average (hydrograph) plotted with historical daily means. However, the values for the used method (discharge ratings using slope as a parameter) follow the HGS data being a little higher at the same time. Also, it has a defined peak at the end of April, which is in consent with the historical average. The data for the three methods also were compared to the measured discharges. The comparison can be seen below in Figure *5.1.1*

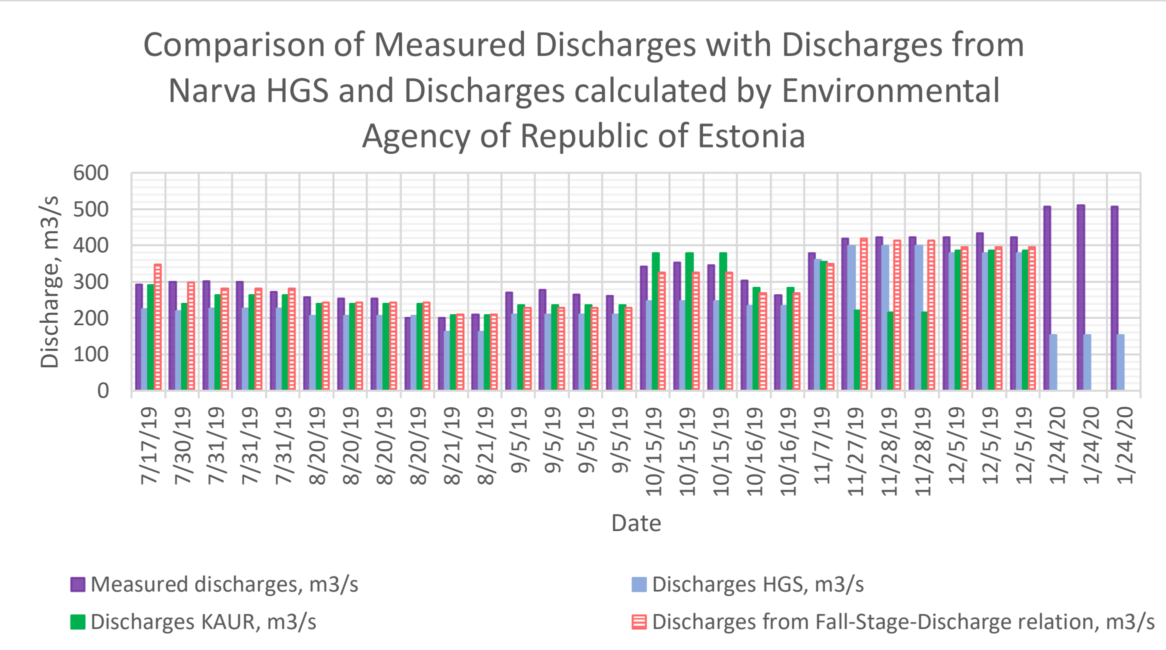


Figure 5.1.1: Comparison of measured discharges with discharges from Narva HGS and discharges calculated by the Environmental Agency of the Republic of Estonia

From the comparison, we can see that the discharges derived from the method used in the study are closer to the measured in 2019 (there are no calculated discharges for 2020 in Estonia). Moreover, they are in consent with the discharges measured in 27-28.11.2019, where backwater effect seems to be low and high discharges occur with very low stages as was discussed in chapter 4.2.3.

The discrepancy of the values from the three methods against the measured discharges was calculated. It can be seen in Table *5.1.1* below.

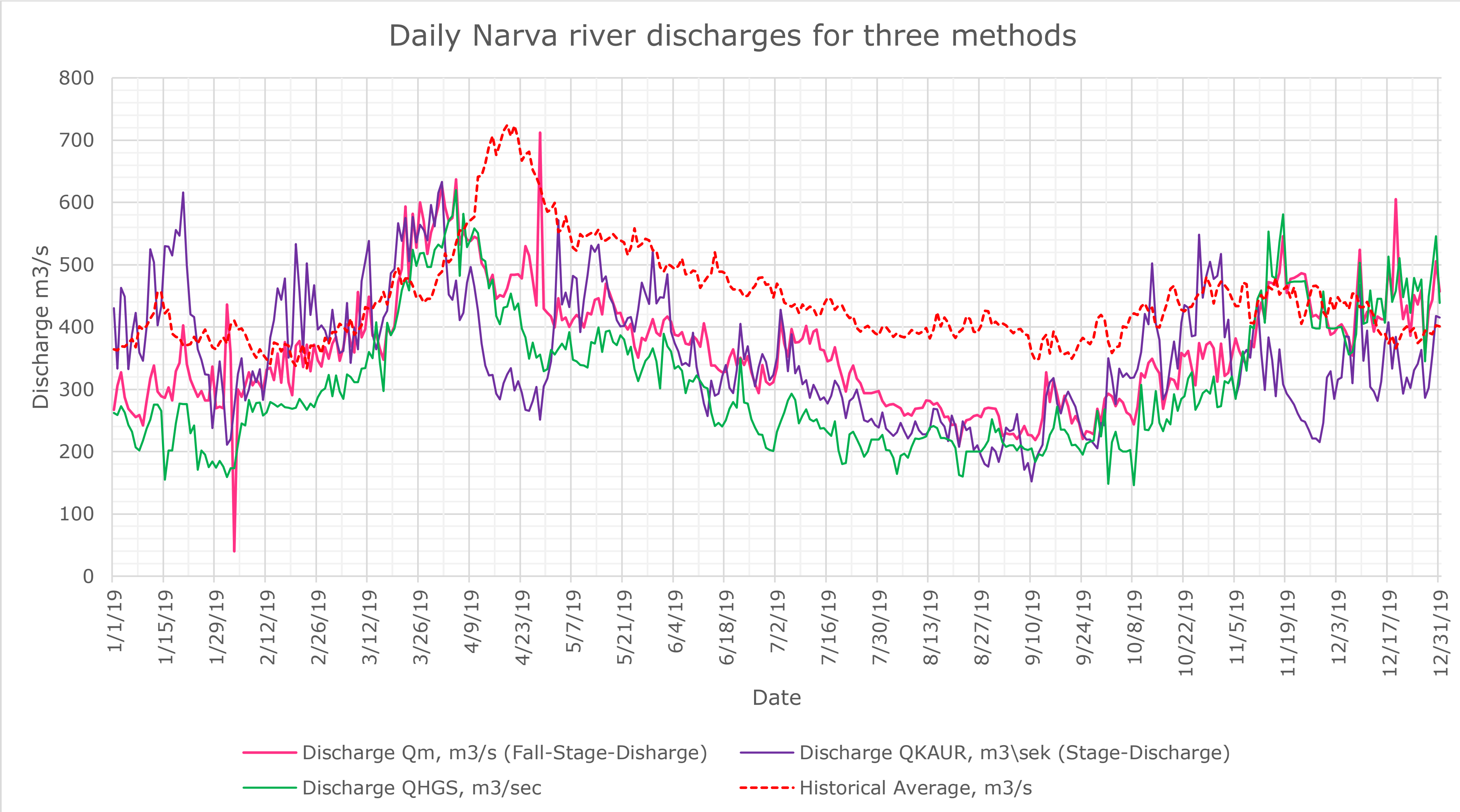


Figure 5.1.2: Daily Narva river discharges for three methods

Table 5.1.1: Discrepancy of the values of the methods against the measured discharges in 2019

Date	ΔQHGS, %	ΔQKAUR, %	ΔQm, %
17/07/2019	22,95%	0,68%	19,11%
30/07/2019	27,00%	20,33%	0,99%
31/07/2019	24,58%	12,62%	6,59%
31/07/2019	24,08%	12,04%	5,96%
31/07/2019	16,85%	3,66%	3,00%
20/08/2019	19,84%	6,61%	5,33%
20/08/2019	18,90%	5,51%	4,21%
20/08/2019	18,90%	5,51%	4,21%
20/08/2019	3,00%	20,00%	21,65%
21/08/2019	19,40%	-3,48%	4,63%
21/08/2019	22,86%	0,95%	0,14%
05/09/2019	22,51%	13,28%	15,67%
05/09/2019	24,19%	15,16%	17,50%
05/09/2019	20,45%	10,98%	13,43%
05/09/2019	19,54%	9,96%	12,44%
15/10/2019	27,86%	11,14%	4,48%
15/10/2019	30,11%	7,67%	7,46%
15/10/2019	28,70%	9,86%	5,58%
16/10/2019	23,10%	6,27%	11,44%
16/10/2019	11,41%	7,98%	2,03%
07/11/2019	4,50%	6,35%	7,76%
27/11/2019	5,01%	47,26%	0,13%
28/11/2019	5,91%	49,17%	2,30%
28/11/2019	5,69%	49,05%	2,07%
05/12/2019	10,43%	8,77%	6,60%
05/12/2019	12,70%	11,09%	8,97%
05/12/2019	10,43%	8,77%	6,60%
Average	**17,81%**	**13,23%**	**7,42%**

As seen from Table *5.1.1*, the method of discharge ratings using slope as a parameter used in the study shows the least average contradiction towards the measured discharge values comparing to the others method used by Estonia and Russia.

Using average daily discharge for three methods total Narva river runoff was calculated for the 2019 year and can be seen in Table *5.1.2* below. The deeper shade in the cells indicates the highest/middle/lowest runoff of a month.

Table 5.1.2: Narva river runoff in 2019 for the three methods

Month	**Runoff Kaur, km3**	**Runoff HGS, km3**	**Runoff Analysis, km3**
Jan	1,118	0,607	0,795
Feb	0,896	0,628	0,787
Mar	1,266	1,065	1,198
Apr	0,952	1,203	1,336
May	1,209	0,962	1,103
Jun	0,885	0,743	0,926
Jul	0,805	0,625	0,921
Aug	0,611	0,559	0,703
Sep	0,612	0,565	0,649
Oct	1,035	0,679	0,848
Nov	0,826	1,087	1,095
Dec	0,926	1,168	1,154
2019 Year	**11,141**	**9,891**	**11,513**

As seen, the HGS provides the lowest runoff, KAUR data give the number in the middle, while the used method provides the highest number that is closer to the average number of 12,5 km^3 as was mentioned in the chapter 2.1.2. [10]

6 Additional analysis of the rating using slope as a parameter as a method and its justification

The applied method of discharge rating using slope as a parameter showed good results. However, as was mentioned before, the study doesn't include measurements in Spring when the highest discharges usually occur, and the stage/fall relation doesn't seem to be clear. Daily stages for Narva linn gauge station were plotted against corresponding fall in 2019. The graph is in

Figure *6.1.1*. As we see, rather great points scattering is presented. Thus, adopting a linear relation may be a reason for errors.

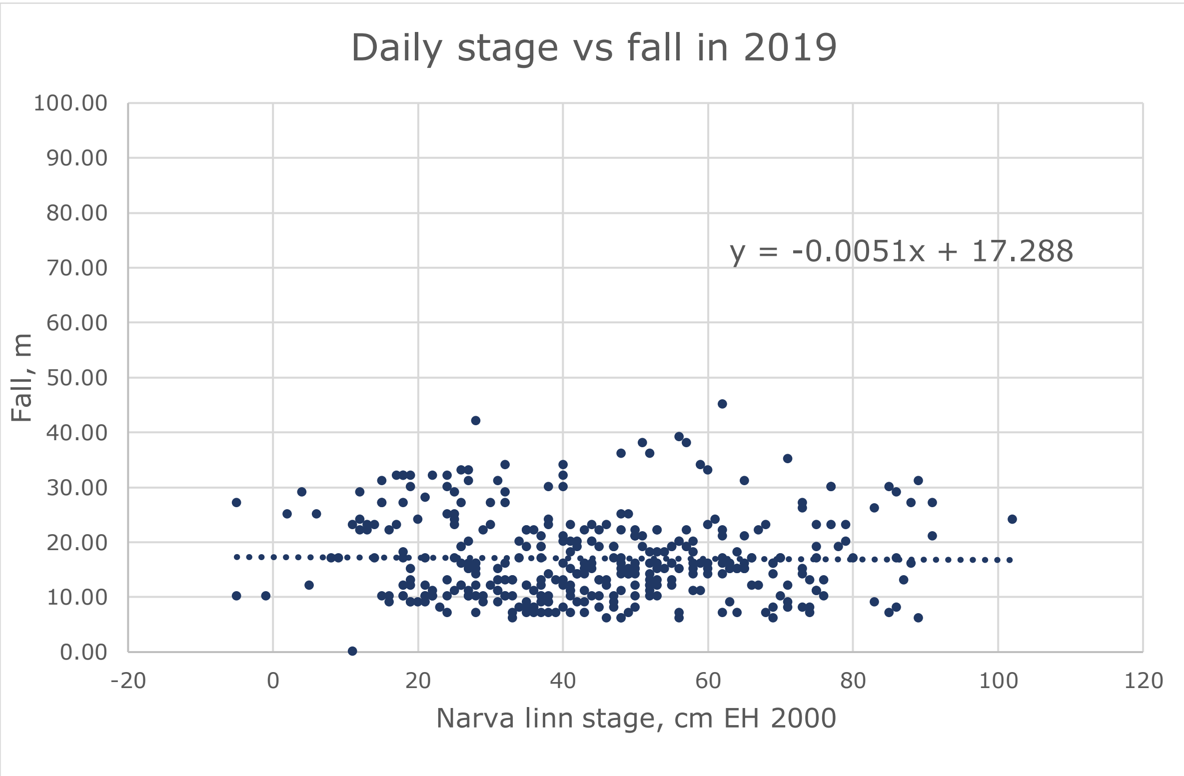


Figure 6.1.1: Daily stage vs fall in 2019

To justify the usage of the method of discharge rating using slope as a parameter, additional analysis was performed. It was suggested that different periods have different stage/fall relations.

The graph where daily stages of the Narva linn gauge are plotted against the daily stages of the Narva-Jõesuu gauge station was made in

Figure *6.1.2*. As can be seen, the relation between the stages on average is linear and is represented by equation (26):

$$H_J = 1{,}0051H - 17{,}288 \qquad (26)$$

Where:

H_J – Narva-Jõesuu stage [cm EH 2000];

H – Narva linn stage [cm EH 2000].

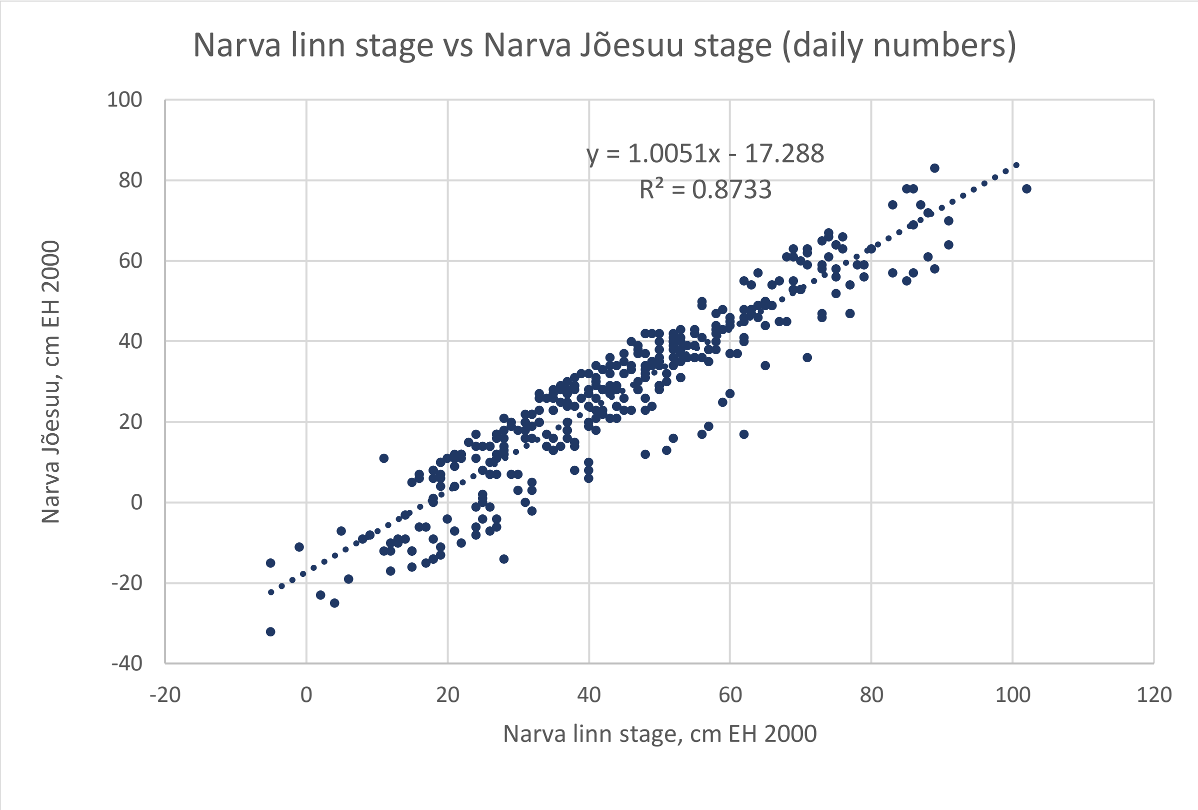


Figure 6.1.2: Narva linn stage vs Narva Jõesuu stage

From such relation, we can derive that on the average the fall is 17,288 cm. The coefficient 1,0051 says that there is almost no relation between the fall and the stage. However, that is not entirely true, as we expect that the fall/stage function will change depending on the time interval considered. To choose the intervals, daily stages for both gauges, wind power were plotted together for 2019 and can be seen in Figure *6.1.3*.

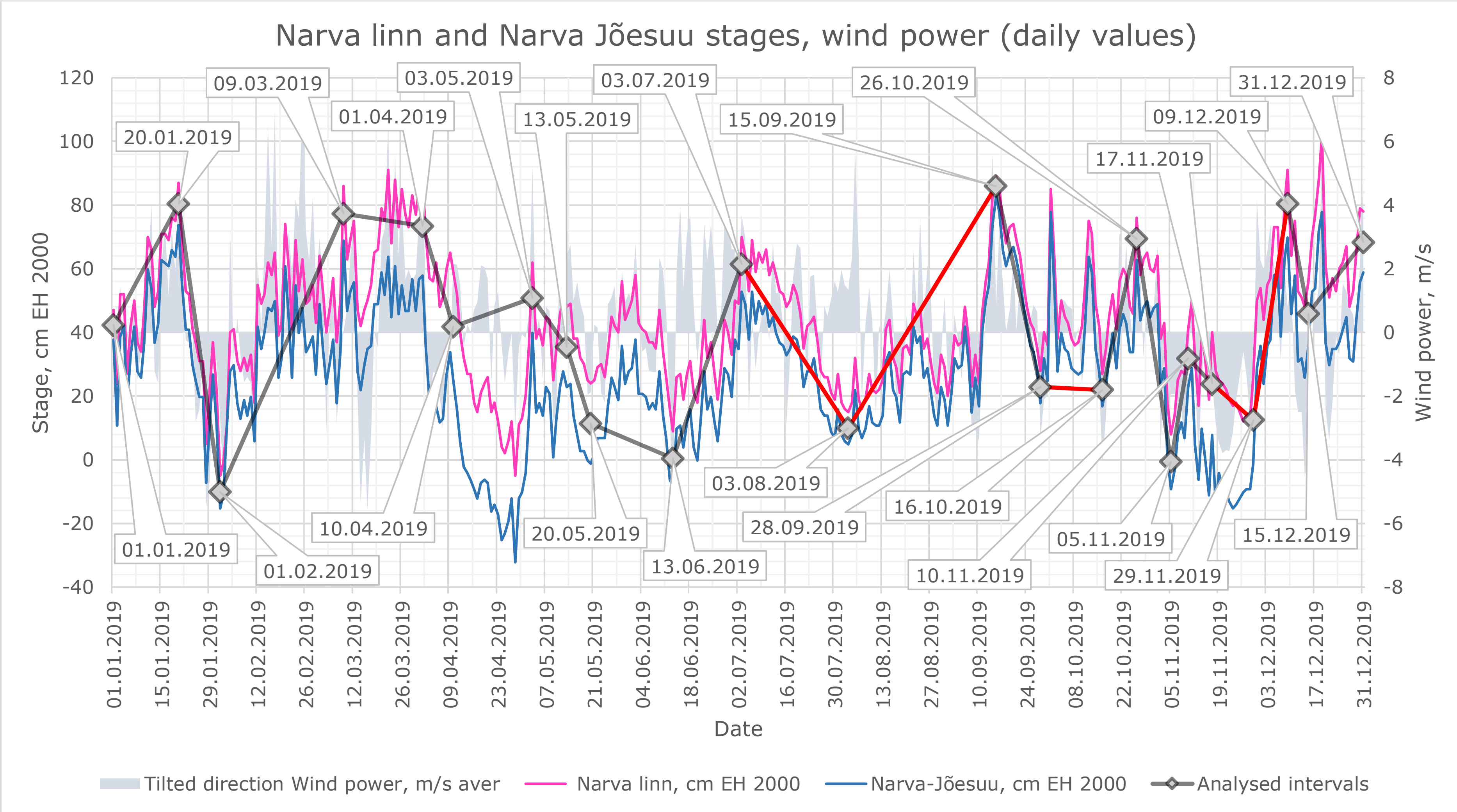


Figure 6.1.3: Narva linn and Narva Jõesuu stages, wind power (daily values)

When choosing the intervals, the periods of relative stages descending and ascending served as a guide. Intervals with measured discharges presented are marked in red. Moreover, when plotted, some periods were reconsidered according to their Narva linn stage-Narva-Jõesuu stage points scattering. To support the choices of the intervals, the backwater effect was assessed. The backwater approximated reach was calculated by the formula [34]:

$$L_b = {}^{k\Delta H_m}/_{Io} \qquad (27)$$

Where:

L_b – the backwater reach from the mouth of the river [km];

ΔH_s – sea level rise [m];

I_0 – water surface slope before the rise [‰];

k – constant, usually appears to be from 1,8 to 2,2.

For calculations it was suggested, that k equals 2, the average fall is 17,288 cm was excepted as "normal". Thus, the sea rise was computed as a difference between the average fall and the fall at the time of calculation. The slope was calculated, taking into account that the distance from the Narva linn gauge is 14,6 km. The reach was calculated for daily stages in 2019 and plotted, as seen in Figure *6.1.4*.

The threshold of 14,6 km, when the effect reaches Narva linn gauge was marked as a red line. On the other hand, sea level drops produced negative values of the reach. It was considered that in such case the sea backwater effect is negative or there is no "pressure" from the sea, which affects the stages. Such a case is still considered a backwater effect. [33] If the backwater effect reach is equal or less than - 14,6 km, it was suggested that such "no sea pressure event" reaches the Narva linn gauge.

As seen from the graph, periods with positive values of the reach exceeding 14,6 km happened twice – at the beginning of February and the middle of September representing phases of lowest discharges with high stages according to the Narva river hydrograph. On the other hand, negative values happened at the beginning of April and the end of November, which are the periods of highest discharges with low stages. That means that the absence of the backwater has a greater influence than its presence since that's what tends to scatter the points of stage/discharge plot.

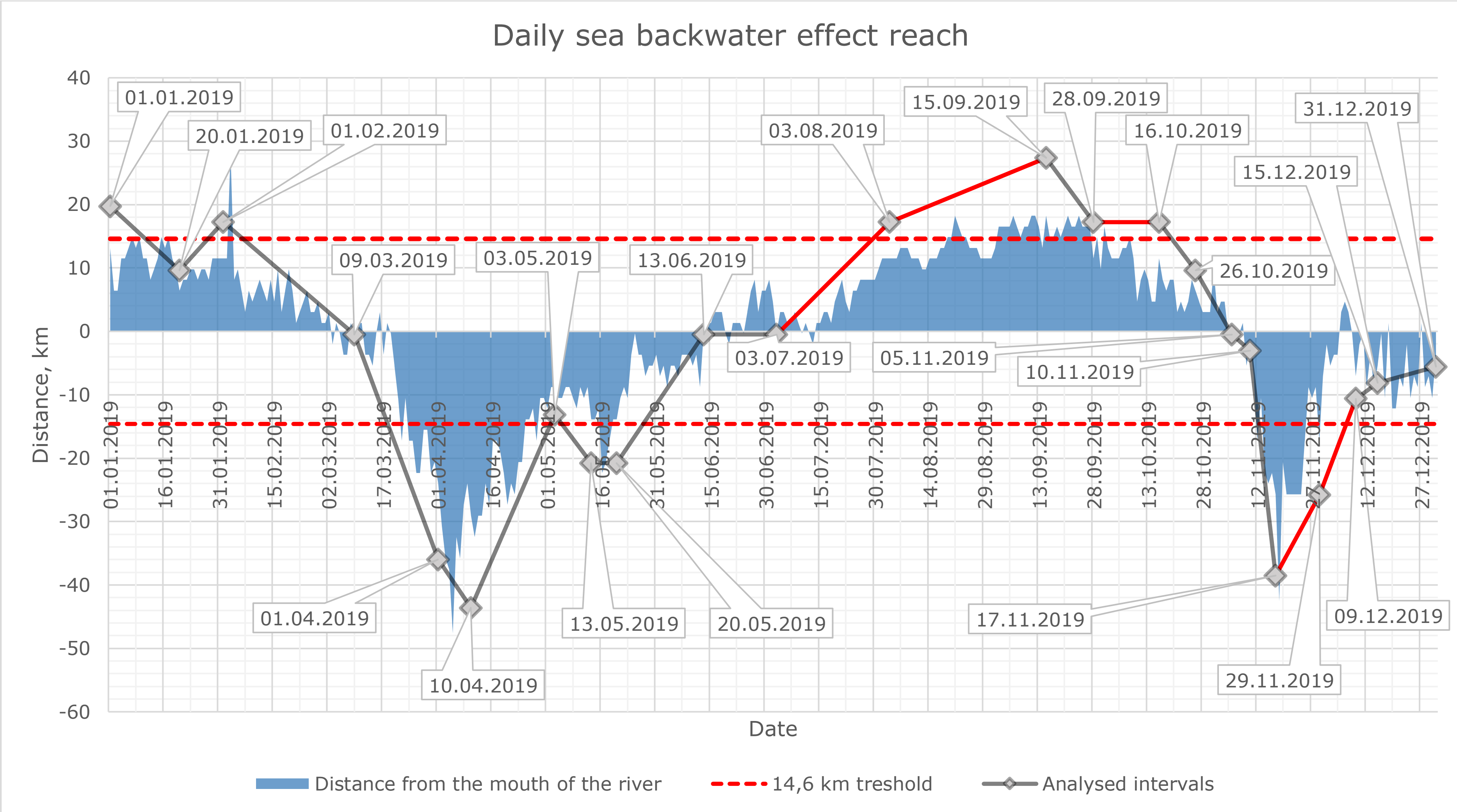


Figure 6.1.4: Daily sea backwater effect reach

If the Narva linn stage/Narva-Jõesuu stage relation is linear with the k coefficient of the linear relation is not zero, it can be stated that fall/stage relation is linear two. Because linear Narva linn stage/Narva-Jõesuu stage relation is:

$$H_J = kH + b \quad (28)$$

Where:

H_J – Narva-Jõesuu stage [cm EH 2000];

H – Narva linn stage [cm EH 2000];

k, b – constants of a linear relation.

Then:

$$-H_J = -kH - b \quad (29)$$

$$H - H_J = H - kH - b \quad (30)$$

$$F = H(1-k) - b \quad (31)$$

$$F = Hk' + b' \quad (32)$$

Where:

F – fall [cm];

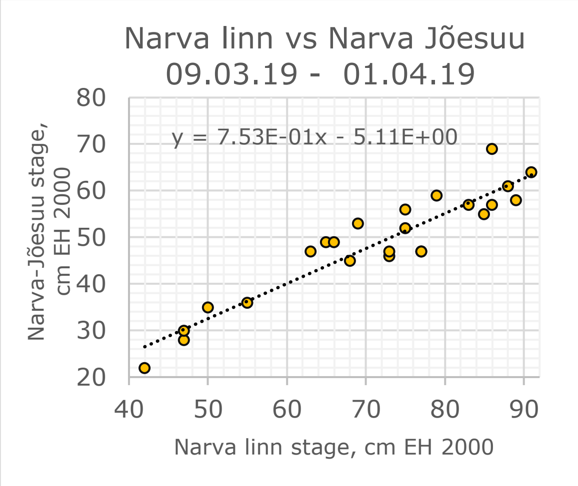
H – Narva linn stage [cm EH 2000];

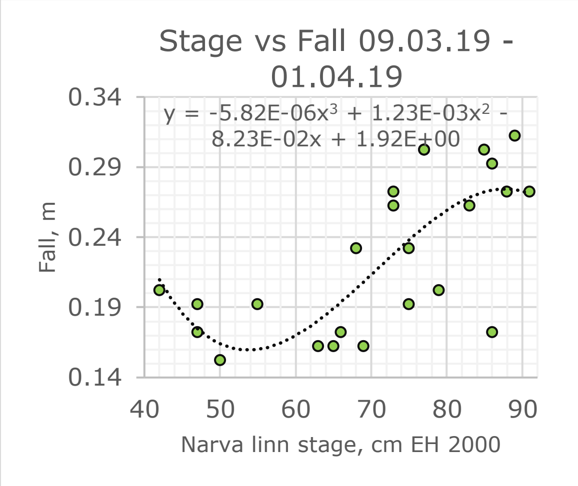
k', b' – constants of linear relation:

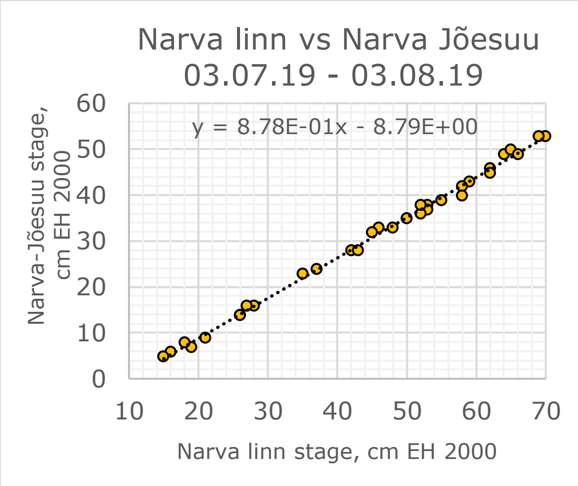
$$k' = (1-k)[cm] = \frac{(1-k)}{100}[m] \quad (33)$$

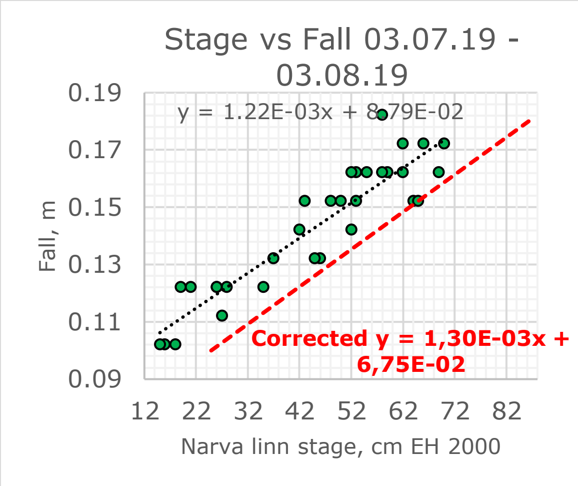
$$b' = -b[cm] = \frac{-b}{100}[m] \quad (34)$$

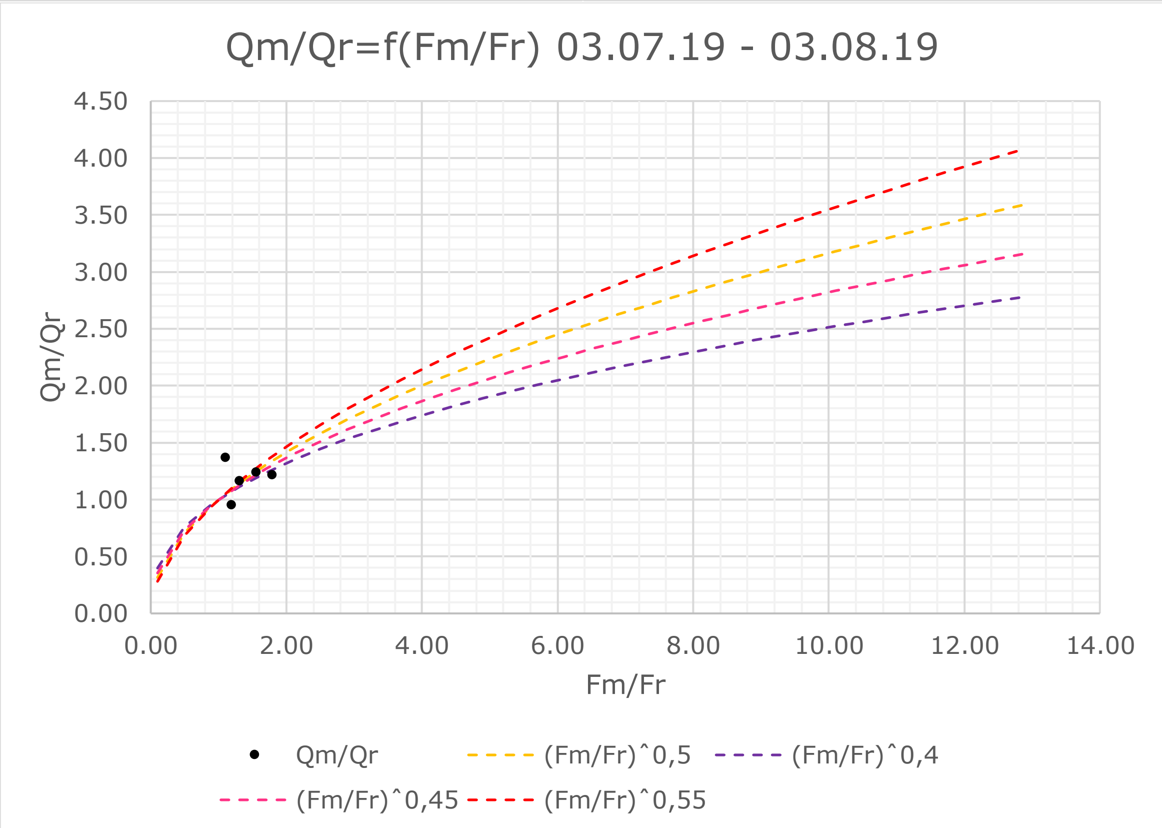
Thus, linear Narva linn stage/Narva-Jõesuu stage relation leads to linear fall/stage relation. Using that graphs of Narva linn stage/Narva-Jõesuu and fall/ Narva linn stage for chosen intervals were produced. Should be noted, that sometimes when the points were scattered, it was suggested that the relation is more complex. It happened in the periods of high discharges with low stages (negative backwater effect reaching Narva-linn gauge). Further, some links (with measured discharges presented) were corrected so that the points would fit the $Q_m/Q_r=(F_m/F_r)_{0,5}$ as WMO states in its guidelines and as it was done in the chapter 4.3.2 of the study. Qr curve from the chapter 4.3.2 was used. Some of the representative graphs produced can be seen below in Figure *6.1.5*, (due to a big amount of data, these graphs were named as one Figure).


Narva linn vs Narva Jõesuu 09.03.19 - 01.04.19
y = 7.53E-01x - 5.11E+00
Narva-Jõesuu stage, cm EH 2000
Narva linn stage, cm EH 2000


Stage vs Fall 09.03.19 - 01.04.19
y = -5.82E-06x³ + 1.23E-03x² - 8.23E-02x + 1.92E+00
Fall, m
Narva linn stage, cm EH 2000


Narva linn vs Narva Jõesuu 03.07.19 - 03.08.19
y = 8.78E-01x - 8.79E+00
Narva-Jõesuu stage, cm EH 2000
Narva linn stage, cm EH 2000


Stage vs Fall 03.07.19 - 03.08.19
y = 1.22E-03x + 8.79E-02
Corrected y = 1,30E-03x + 6,75E-02
Fall, m
Narva linn stage, cm EH 2000


Qm/Qr=f(Fm/Fr) 03.07.19 - 03.08.19
Qm/Qr
Fm/Fr
Qm/Qr
(Fm/Fr)ˆ0,5
(Fm/Fr)ˆ0,4
(Fm/Fr)ˆ0,45
(Fm/Fr)ˆ0,55

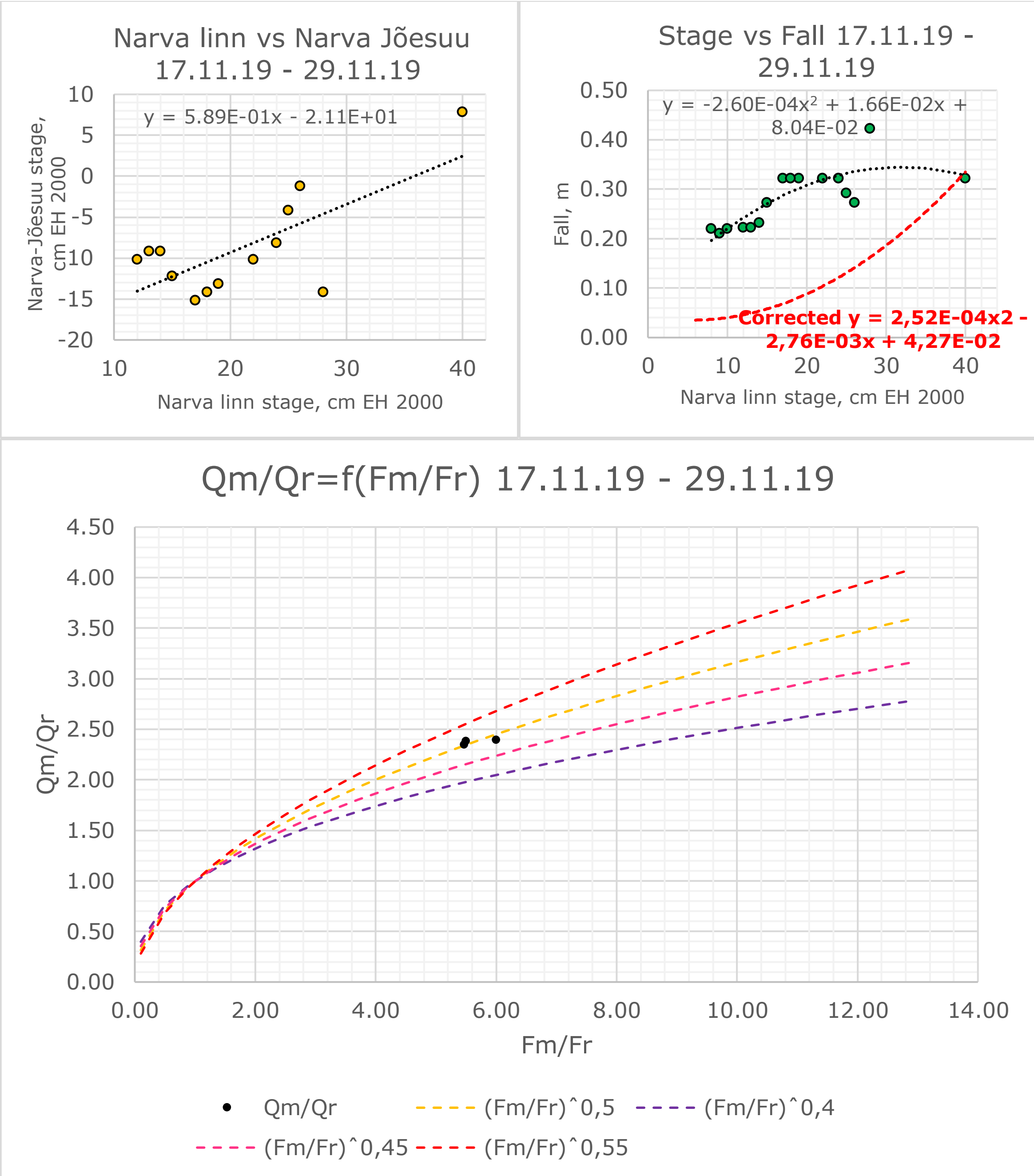


Figure 6.1.5: Calculations for the set of intervals in 2019 (set of figures)

As seen from Figure *6.1.5*, some relations were excepted as non-linear, due to $H_J(H)$ points scattering. Should be noted, that in the interval 17.11.19 - 29.11.19, fitting points into $Q_m/Q_r=(F_m/F_r)_{0,5}$ graph was rather problematic, that is why function H(F) is so off the plotted points.

Using derived relations, new values for daily discharges in 2019 were produced. Then they were plotted on the graph with values derived from HGS, KAUR and method for discharge rating using slope as a parameter implemented earlier (with linear stage/fall relation for a whole year). The results can be seen in Figure *6.1.6* below.

Unfortunately, the daily discharges are off the main trend, having low values at the end of April and the end of November, where they are supposed to have maximum values. The total annual runoff for that method is 9,427 km_3, which is even less than the runoff from the technique used by Russia (HGS).

That shows that the discharge is not fully covered by individual interval stage/fall relations, especially for periods of high discharges when the sea backwater effect is at a minimum. Also, that can be explained that Q_r curve in $Q_m/Q_r=(F_m/F_r)_{0,5}$ relation is not suitable for such minimum backwater intervals and should be derived separately, as it seems that there is another curve for such conditions. Indeed, if we look at the graph in Figure *4.3.5* we see that the points under rather normal conditions lay on one line, while minimum backwater points seem to line on the other separate line, representing the different Q_r curve. Unfortunately, low field measurement density doesn’t allow us to do so.

It can be concluded, that the method of discharge estimation using slope as a parameter previously used in the chapter 4.3.2 provides the best result, giving an "adjustment effect" on fall and stage values for the periods of high discharges with the sea backwater effect at its minimum and taking into account the change in Q_r curve for such periods.

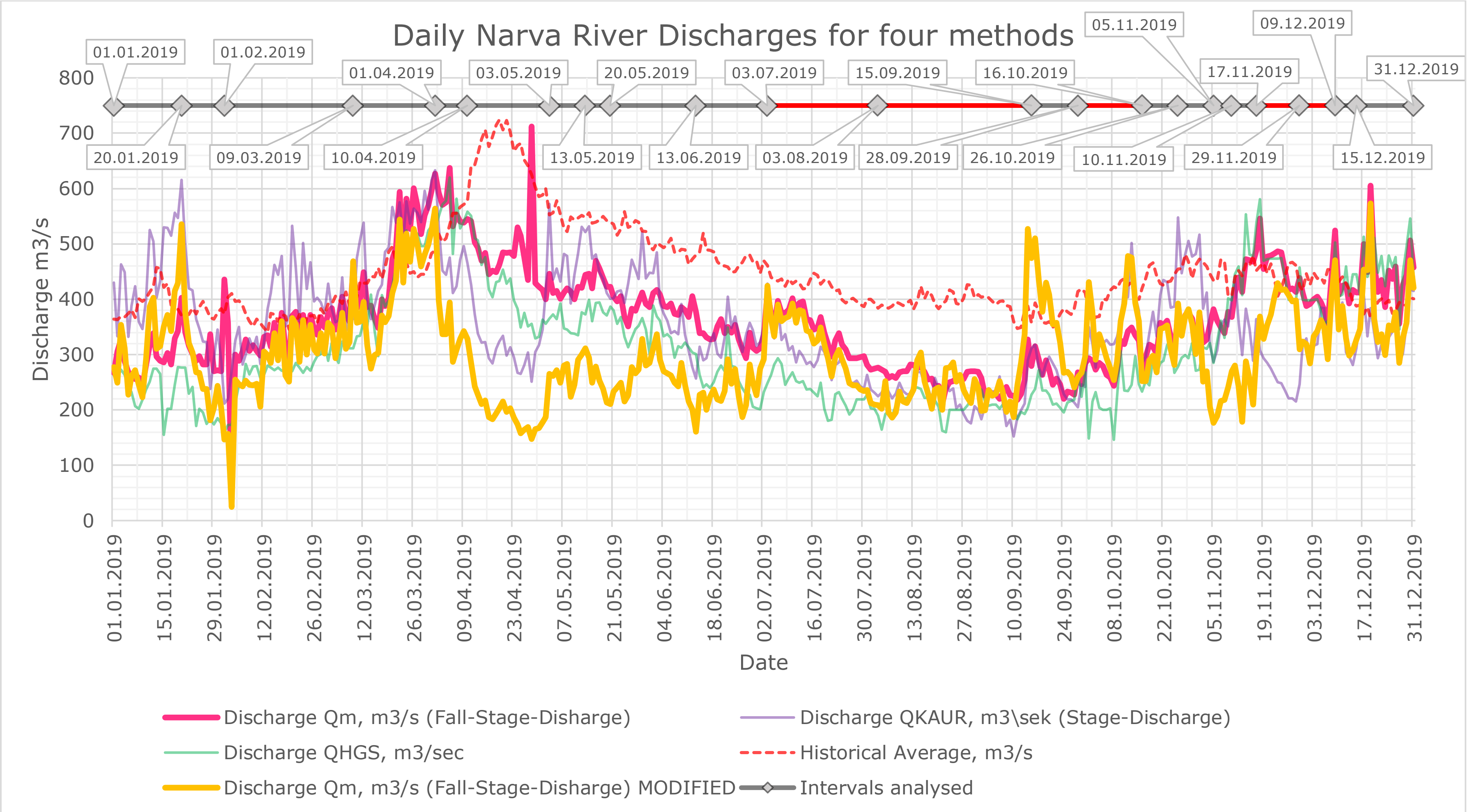


Figure 6.1.6: Daily Narva River Discharges for four methods

7 Discussion

As concluded in the previous chapters, the method used in the present study namely discharge ratings using slope as a parameter proves to be a good common alternative to the existing techniques for the Narva river discharge estimation used by Estonia and Russia. Nevertheless, there are issues to be addressed, along with certain recommendations to be provided.

First and the most important recommendation is to increase the international cooperation and the intercountry data exchange to make the future analysis more holistic and precise. It would be useful because the Narva river case is rather complicated due to cumulative effect of the Lake Peipsi, HGS, the sea, the reservoir and especially considering that the river and the Lake Peipsi which is the source are divided between the countries all along the way. Plus, the river has various tributaries on both banks, i.e. different sides of the government border.

The discharge ratings using slope as a parameter method showed the reduction of the error against the measured discharge values in comparison with other methods currently used by the countries. However, it should be noted that maybe the fall is not the function of the stage, there might be other factors affecting its values, and the relation might be more complex rather just linear. That should be considered in the future when applying the method. For instance, the Narva river right bank tributary the river Rosson is known sometimes to flow in the reverse direction from - its mouth located in the river Luga (Russian Federation) to its source in the river Narva. That usually happens when the Luga river water level is much higher due to the spring flood season. [35] That may affect the Narva-Jõesuu stages and thus the fall. Moreover, the measured discharges start available only since 17.07.2019, missing an essential period of the year March-April when the highest discharges can occur. Thus, they are not included in the analysis and the deriving of the mathematical relation, making the relation not as complex as it should be. Therefore, it is recommended to use more field data evenly distributed throughout the year.

Another option for the discharge estimation is to leave the AHC gauge operating after the NARVAWATMAN project ends because it showed high correlation with the measured discharges and could be used for the daily discharge estimation using simple stage-discharge rating.

If the HGS data will be used further for the daily discharge estimation, the author recommends examining the HGS equipment in order to find out what causes the difference with the measured values and maybe it will be possible to come with the solution either for the equipment upgrade or for developing some coefficient to correct the HGS data approximating it to the measured numbers. It is also possible to use the existing HGS data with current stage-discharge rating used by Estonia to find their co-dependency and develop other methods approximating theoretical values to measured ones.

Considering the study findings, the author suggests that the best technique for the Narva river discharge estimation would be discharge ratings using the velocity index method. The author thinks the technique could be the most precise since it is evident that when we have high stages with low discharges and vice versa, it is the velocity which is the main variable. From the Narva river profiles created with the field measurements of the discharges under the NARVAWATMAN project, we see that the velocity throughout the water volume is rather even for three measurement sites (Figure *7.1.1*, Figure *7.1.2*, Figure *7.1.3*). That allows us to use an arbitrary point in this cross-section, for constant index velocity measuring by which we can judge the mean stream velocity.

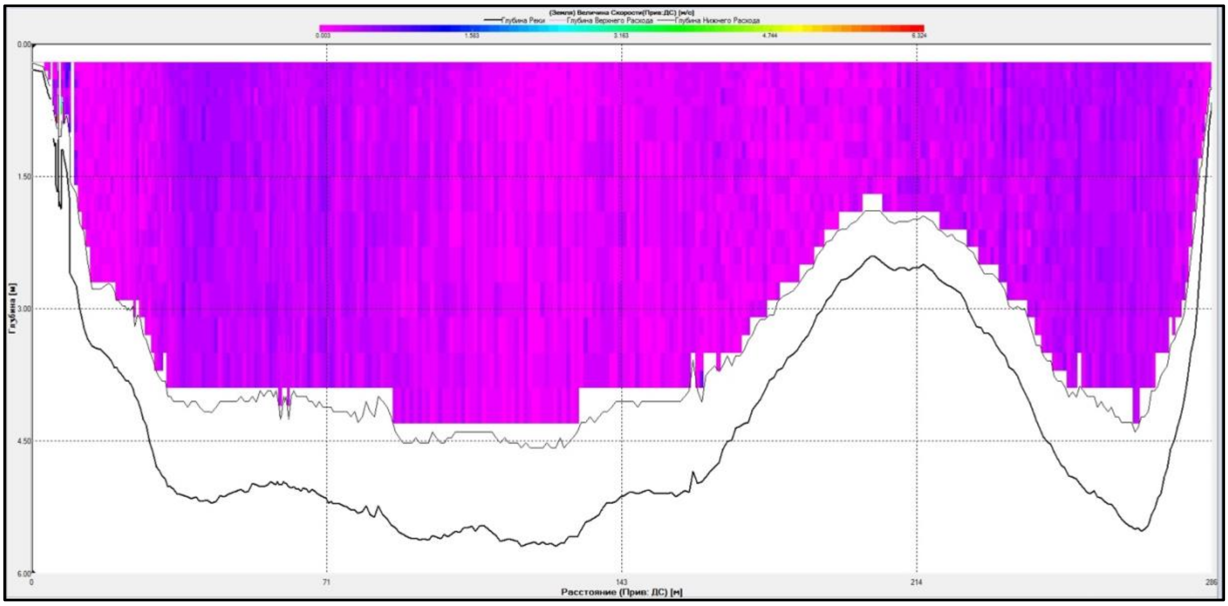


Figure 7.1.1: The river Narva cross-section profile of the Narva marina (Narva linn gauge) measurement site

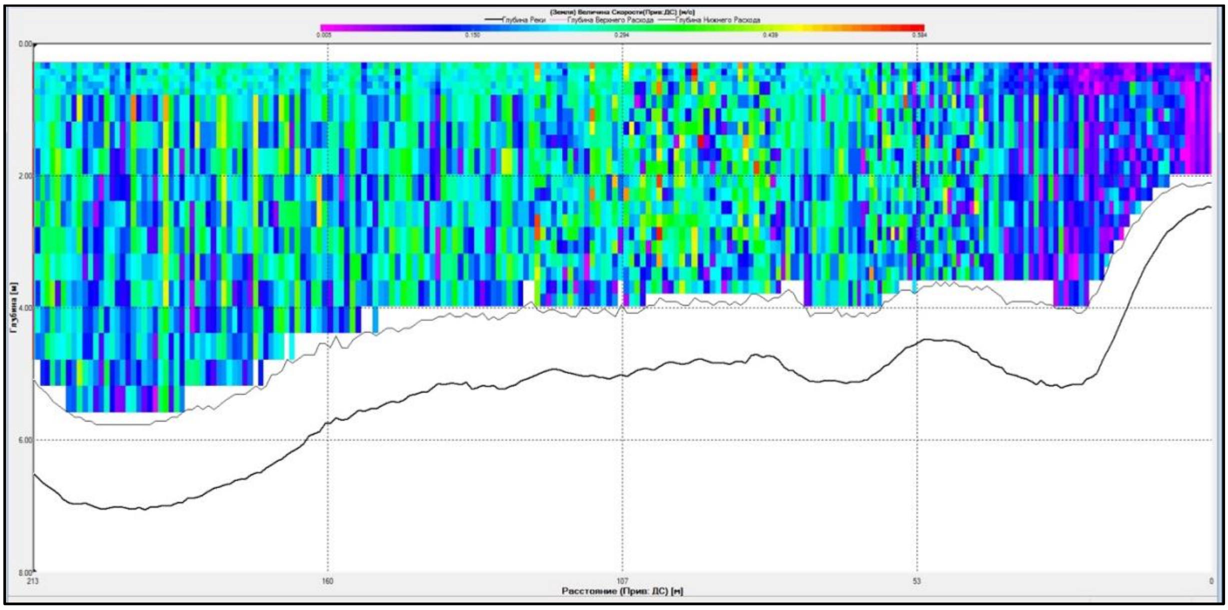


Figure 7.1.2: The river Narva cross-section profile of the tower measurement site

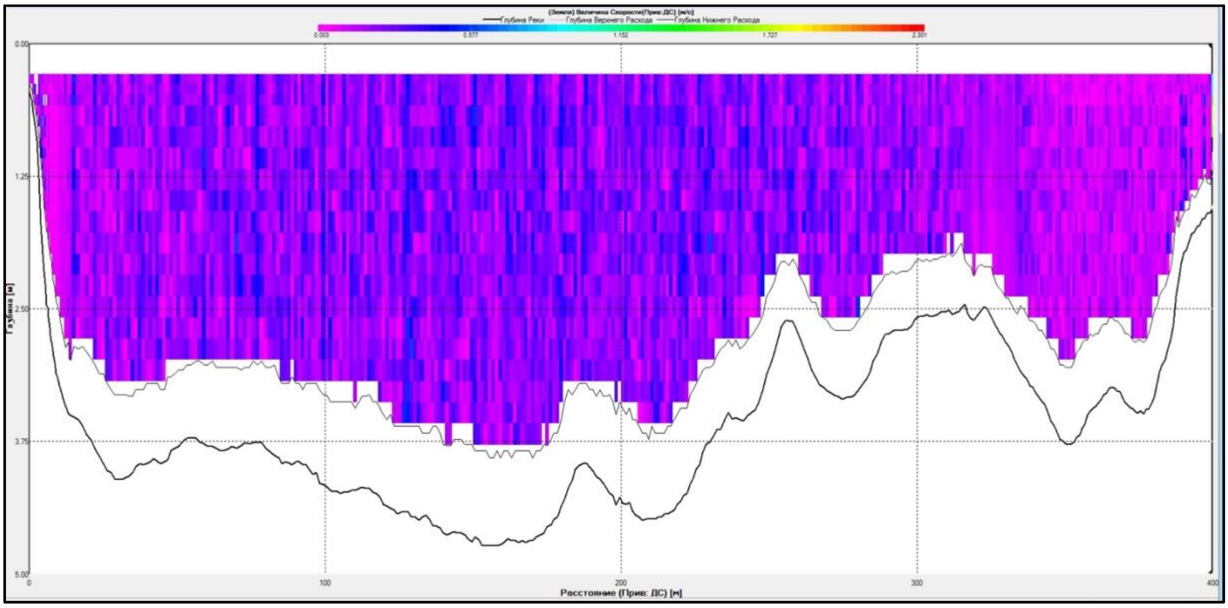


Figure 7.1.3: The river Narva cross-section profile of the garages measurement site

However, an additional study should be conducted for assessing the economic and environmental feasibility, since the requires the installation of the additional equipment for the index velocity measuring.

8 Conclusion

The applied method of discharge rating using slope as a parameter showed its feasibility along with simplicity and low error against the real measured values in comparison to the other methods currently in use. It can be implemented as a harmonized method for the river Narva discharge estimation suitable for both countries. Although it was recommended to use the velocity index method as the best option, while the necessary equipment is not yet installed, the discharge rating using slope as a parameter is the most suitable so far.

Moreover, since annual pollution load is calculated through the discharge numbers and the rating using slope as a parameter showed the least error, the pollution load estimation also is expected to be the least.

The proposed methods for the river discharge estimation will help to eliminate such data discrepancy between Estonia and Russia and provide more precise and comparable data for HELCOM on the river runoffs and pollution load.

SUMMARY

The main objectives of the study were gathering the data on the transboundary Narva river and analysing it along with the methods used nowadays by Estonia And Russian Federation for the river discharge estimation. It was necessary to outline flaws and differences and find the harmonised solution for the Narva river discharge estimation that can be more reliable and precise rather than the existed techniques/methods. The analysis was done in the frame of NARVAWATMAN project, supported by the Estonia – Russia Cross Border Cooperation Programme 2014-2020.[5]

The HELCOM was introduced and emphasising that in comparison with other contracting parties obliged to report on their riverine and airborne pollution entering the Baltic Sea, Estonia and Russia provide data on the river Narva pollution load coming into the Gulf of Finland separately. It makes the case unique since there are no other countries following the same way of reporting on the border water objects.

Furthermore, it was underpinned that the Narva river case is rather problematic for the discharge assessment: its flow is regulated by the Lake Peipsi (where the river has its source), the Narva Hydroelectric Power Plant (Narva HGS) and the Baltic Sea, along with the backwater effect which tends to scatter the points of stage vs discharge graph.

Historical available values for daily Narva river discharges were analysed providing typical hydrograph showing that the fluctuations are rather high, making it impossible to use simple interpolation for instance.

Data on the methods for the Narva river discharge estimation used by the countries were thoroughly studied. As a result, it was found that the difference in numbers between the two techniques is significant. Moreover, there is a big difference when these values were compared to the field discharge measurements done simultaneously by the countries.

In order to solve the issue, different recommendations from WMO for rivers discharge estimations under various conditions were examined. The proposed method for the Narva river discharge estimation - discharge rating using surface slope as a parameter - was chosen for usage along with providing its justification and the explanation why the other methods are less eligible in that case. Steps provided by WMO were followed to derive the stage-fall-discharge relation.

[5] https://www.estoniarussia.eu

As an outcome, the method was applied for the Narva river, daily discharges for 2019 were calculated by the derived formula, and the results were provided outlining the advantages of such way of the water discharge estimation. To try another option for reliable discharge assessment and make improvements in the future, it was recommended to leave the AHC gauge on the Russian side in operation after the end of the NARVAWATMAN project. Also, it was suggested to examine the Narva HGS equipment to figure out the reason for the difference in data it produces or to use the discharge ratings using the velocity index method (considered the best option).

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Appendix 1 List of Figures

Appendix 2 List of tables