Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 532.517

DOI: 10.34910/MCE.124.11

Digital models for retrospective analysis of the structure of currents in the Neva Bay

D.K. Zotov ✉, ***G.L. Kozinetc, P.V. Kozinets, P.V. Chernov*** , ***V.L. Badenko***

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

✉ *zotovdk@gmail.com*

Keywords: Neva Bay, Neva River, fairway, water area, hydrodynamic problem, finite element method, boundary conditions, anthropogenic impact, digital models, shallow water equation, velocity field, water exchange, hydrological regime

Abstract. The Neva Bay is a body of water located between the delta of the Neva River and Kotlin Island. The goal of the study was to develop a method for numerical modeling of the shallow water equation in the Neva Bay, based on the finite element method. To achieve this goal, we solved a number of tasks. First, we selected characteristic periods in the history of the Neva Bay and formed numerical modeling options while determining boundary conditions. Secondly, we determined the geometric characteristics of the computational domain for modeling options and formed a finite element mesh for each of the options. Then, we found a numerical solution of hydrodynamic problems in terms of determining values of current velocity vectors. Finally, we conducted a comparative analysis of the results of solving the hydrodynamic problem of the structure of currents in the Neva Bay in different periods of history. The changes in the velocity field occurred because of the construction of the fairway and the dams for the Complex of flood protection structures (CFPS) in St. Petersburg. Today there is practically no water flow south of the Sea Canal. Water exchange between the Neva Bay and the Gulf of Finland is carried out due to culvert structures in the northern part of the CFPS and navigation facilities. The average flow of the Neva River during the calculation period did not change and was about 2500 m^3/s (depends on the water level in Lake Ladoga); an increase in speeds occurs north of the Sea Canal.

Funding: The research was supported by the Russian Science Foundation grant No. 23-19-20062, https://rscf.ru/project/23-19-20062/, and the St. Petersburg Science Foundation grant No. 23-19-20062.

Citation: Zotov, D.K., Kozinetc, G.L., Kozinets, P.V., Chernov, V., Badenko, V.L. Digital models for retrospective analysis of the structure of currents in the Neva Bay. Magazine of Civil Engineering. 2023. Article no. 12411. DOI: 10.34910/MCE.124.11

1. *Introduction*

The Neva Bay is in the eastern part of the Gulf of Finland and is its shallowest part, where the full-flowing Neva River has an average flow of about 2500 m^3/sec [1–3]. Historically, this water area, starting from the 18th century, was subject to anthropogenic impact and its geometric parameters changed, and to date the area of the water surface is about 329 km^2, and the depths do not exceed 5–6 m [4–6]. The strongest impact on the hydrological regime of the Neva Bay was exerted by the construction of the Complex of Flood Protection Structures of St. Petersburg (CFPS), which was completed in 2011 and turned Neva Bay into a “technogenic lagoon”, a kind of internal marine area of the metropolis [2, 7–9].

The Neva Bay has been the subject of practical and theoretical research since the 18th century [10]. Special attention has always been paid to the study of the causes of the Neva floods, their development, and consequences [11–13]. It should be noted that many field observations and theoretical studies were carried out based on various hydrodynamic models, which were constantly modernized to improve the quality of forecasts [6, 14–16]. At the same time, the methods and instrumental support for field observations were constantly improved during numerous expeditionary studies using the latest instruments and remote sensing data – satellite images [3, 4, 17]. Many publications have been devoted to environmental problems and their connection with changes in anthropogenic load [2–4, 7–9, 17, 18]. Scientists were also interested in the impact of currently observed climate changes on the hydrodynamics of the Neva Bay [2, 17, 19]. It should be noted that all researchers highlighted the importance of retrospective analysis of changes in the structure of currents to identify trends and make forecasts, but such an analysis was not systematically carried out. Such retrospective studies are always carried out using numerical models, but due to the lack of detailed information about the modeling features, they are difficult to replicate.

In the world you can find estuaries that are to some extent similar to the Neva Bay and which raise similar problems related to sedimentation characteristics and changes in the ecological situation for the worse [20–24]. Typically, estuaries are studied in highly urbanized regions. The accumulation of bottom sediments in river mouths is being studied, which usually has a serious impact on the ecological state of the water area. The publications provide a series of hydrographic and bathymetric studies analyzing currents, sediment transport and morphological processes at the river mouth. Simulation results of sediment flow and circulation across seasons are typically studied using time series collected from hydrographic surveys. In addition, many authors use retrospective analysis to analyze trends in changes in hydrological conditions [25–27].

Thus, researchers of hydrodynamic phenomena in estuaries emphasize the importance of retrospective analysis of changes in the structure of currents for making forecasts and calibrating computational models; the task remains relevant. Most researchers use the “shallow water” model when modeling currents in estuaries [28–32]. At the same time, researchers recommend using the finite element method for estuaries that have the same complex configuration of the computational domain as in the Neva Bay [31–33].

In general, we can conclude that there is a gap in research that is focused on creating a methodology for implementing numerical modeling of currents in the Neva Bay for the purpose of conducting a retrospective analysis, and on the other hand, would make it possible to predict the development of the hydrological situation during various catastrophic phenomena.

The purpose of this work is to develop a method for numerical modeling of the shallow water equation in the Neva Bay based on the finite element method. To achieve this goal, the following tasks were solved:

- selection of characteristic periods in the history of the Neva Bay and the formation of numerical modeling options with the determination of boundary conditions;
- determination of geometric characteristics of the computational domain for modeling options;
- generation of a finite element mesh for each option;
- numerical solution of hydrodynamic problems in terms of determining the values of current velocity vectors;
- comparative analysis of the results of solving the hydrodynamic problem of the structure of currents in the Neva Bay in different periods of history.

2. Materials and Methods

When selecting characteristic periods for numerical modeling, the following criteria were used. Firstly, the timing of the construction of hydraulic structures, which significantly influenced the structure of currents in the Neva Bay. Such periods were defined as before and after the construction of the Sea Canal from Kronstadt to St. Petersburg [33], as well as before and after the commissioning of the CFPS [7]. For these periods, it was necessary to determine the availability of nautical charts for the selected periods. These maps can be obtained in scanned form from the Archive of the Navy, a branch of the Central Archive of the Ministry of Defense of the Russian Federation [34]. Also, in the Archive, you can obtain data on currents in the Neva Bay, which allows you to determine the boundary conditions for the direction and speed of the current.

The geometric characteristics of the computational area for modeling options are obtained thanks to map digitization using GIS technologies [35]. In this case, the calculation area was selected along the boundary of the currently existing CFPS dam.

A digital representation of the Neva Bay will allow us to move on to the next stage of constructing a finite element mesh. In this case, at the beginning, the finite element mesh was built automatically, and then it was manually optimized around islands and other inhomogeneities.

2.1. Methodology for numerical modeling of the Neva Bay reservoir

Numerical modeling was based on solving shallow water equations in the ANSYS environment in the following form [29]:

$$\frac{\partial h}{\partial t}+\frac{\partial hu_x}{\partial x}+\frac{\partial hu_y}{\partial y}=0; \tag{1}$$

$$\frac{\partial\left(hu_x\right)}{\partial t}+\frac{\partial}{\partial x}\left(hu_x^2+\frac{1}{2}gh^2\right)+\frac{\partial}{\partial y}\left(hu_xu_y\right)=h\left(f_x^{\nu}-g\frac{\partial b}{\partial x}\right)+f_x^s; \tag{2}$$

$$\frac{\partial\left(hu_y\right)}{\partial t}+\frac{\partial}{\partial x}\left(hu_xu_y\right)+\frac{\partial}{\partial y}\left(hu_y^2+\frac{1}{2}gh^2\right)=h\left(f_y^{\nu}-g\frac{\partial b}{\partial y}\right)+f_y^s. \tag{3}$$

In equations (1)–(3) the following notations are used (Fig. 1): $h\left(x, y, t\right)$ is the height of the water level, measured from the bottom surface, $b\left(x, y\right)$ is the bottom level, which is measured from the deep point, $u_x\left(x, y, t\right)$, $u_y\left(x, y, t\right)$ are components of the horizontal velocity vector, g is gravitational acceleration, $f_x^{\nu}\left(x, y, t\right)$, $f_y^{\nu}\left(x, y, t\right)$ are components of the vector of volumetric external force acting on the entire thickness of the water layer, $f_x^s\left(x, y, t\right)$, $f_y^s\left(x, y, t\right)$ are components of the surface external force vector, $\xi\left(x, y, t\right)=h\left(x, y, t\right)+b\left(x, y\right)$ is the water surface level, $h_0\left(x, y, t\right)$ is the height of the equilibrium water level, then the deviation from equilibrium value $\eta\left(x, y, t\right)=h_0\left(x, y\right)-h\left(x, y, t\right)$.

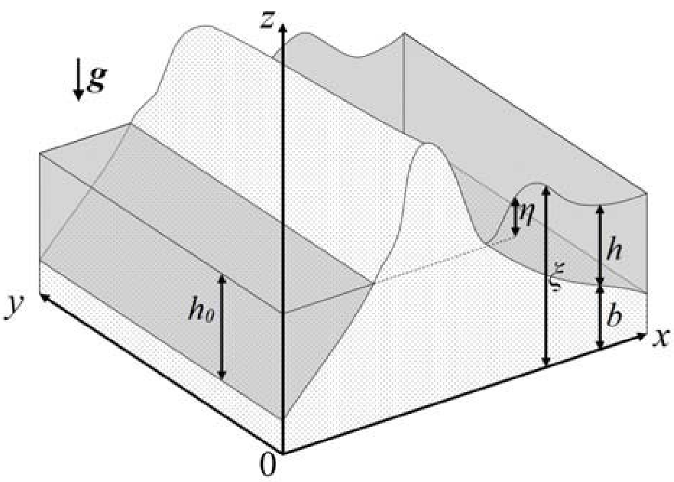

Figure 1. Input data for the shallow water equation.

One of the well-known methods for numerically solving water flow equations for small reservoirs is the finite element method [36]. According to the basic idea of the finite element method, a continuous function is approximated by a set of piecewise continuous functions defined on a finite set of nodes in the domain under consideration. The problem solution area (a reservoir with its geometric characteristics) is divided into a finite number of elements according to the continuity condition. The main advantages of the method are the ease of approximation of boundaries when solving problems in the area of a reservoir of complex shape, since water elements can have a curvilinear shape and heterogeneous physical properties.

Calculation using the ANSYS Fluent package is carried out on a structured mesh containing 1,600,000 to 4,000,000 elements. The 1877 model does not have the Sea Channel, which, due to the small size area relative to the design area and the need to compact the grid, accounts for a significant part of the elements.

To adjust the FEM grid, the automatically generated finite element grid was manually adapted. After refining the grid, the basic size of which is 20 meters to 1 meter in places of sharp changes in depth.

Boundary conditions of the computational domain:

At the boundaries of the computational domain (bottom and shore), the flow rates are equal to 0.

This makes it possible to consider the influence on the structure of the current of the coastline of the Neva Bay, on which traditional no-flow condition (the normal projection of velocity to the solid boundary is zero). For the Neva River, the Chezy coefficient is 55, for deep sections (sea canal and fairways) 75, for the rest of the Neva Bay 45.

At the coastal boundaries, no-slip conditions on a solid surface (zero velocity vector) were used for velocities, and at the mouth of the Neva (in the branches) and along the CFPS boundary, known long-term values were used [10]. at the open border in the area of the Liteiny Bridge, the average annual flow rate (2500 m^3/s) in the Neva River was set. In the Neva Bay area, along the CFPS axis:

1. at the open boundary in the CFPS location area, the free water surface elevation was set ($h+b=const$);
2. on the open CFPS at the locations of navigation and culvert structures, the free water surface elevation was set ($h+b=const$) (Fig. 2).

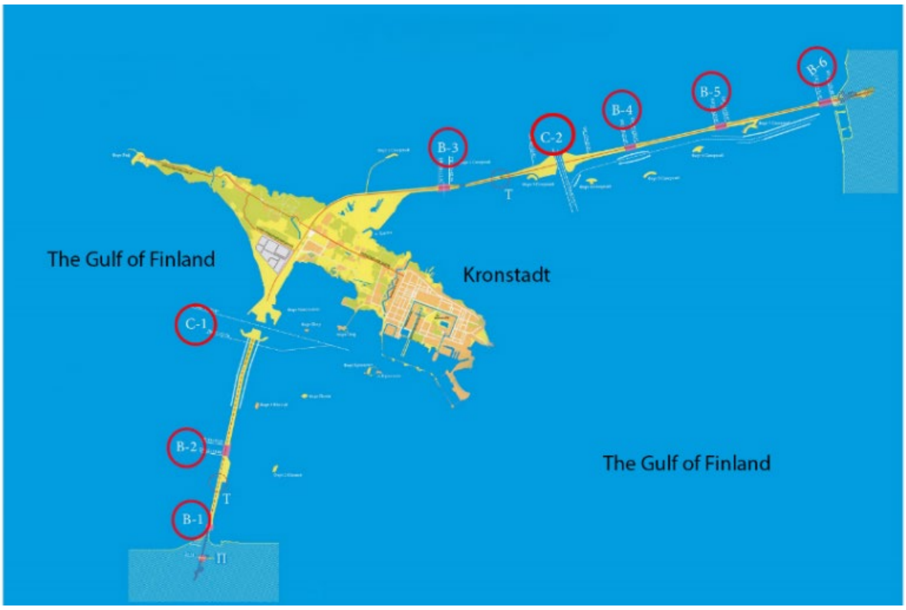

Figure 2. Scheme of the Protective Structures Complex.

Fig. 3–6 show, respectively, the results of calculations in the ANSYS Fluent (CFD) package of a finite element three-dimensional model of the Neva Bay with depth-averaged values of water flow velocities. The graphical image editor shows current velocity vectors and their numerical calculated values in m/sec.

A comparison of the results of numerical calculations and measurements shows that the values calculated on the finite element model are in good agreement with the measurement results, reproducing the maximum and minimum values of the flow parameters.

To model the Neva Bay reservoir, a three-dimensional 8-node fluid isoperimetric element (FLOW3D) was used. General description FLOW3D 8-node element for 3D problems for calculating water flow. Properties of fresh water: Dynamic viscosity VISC=1.005E^(-3) Pa·sec., Density DENS=1000 kg/m^3. The resulting values are the speed values displayed at each node. Numerical simulation results were obtained for four time periods.

The results present the structure of water flows in the form of velocity vectors.

To verify the results of calculations using the proposed model, data from field observations at the KZS in culverts B2, B6 were used. The average speed is 0.4 m/s. Which corresponds to the calculated data obtained from the model. The deviation of the calculated data and observational data is no more than 5 %, which makes it possible to confidently use this model for calculating flow rates. Fig. 3 shows velocity measurements at culvert B6. Field observations were carried out at a water level in Lake Ladoga (Petrokrepost) of 453 cm, which corresponds to the average flow in the Neva River equal to 2500 m^3/s [1].

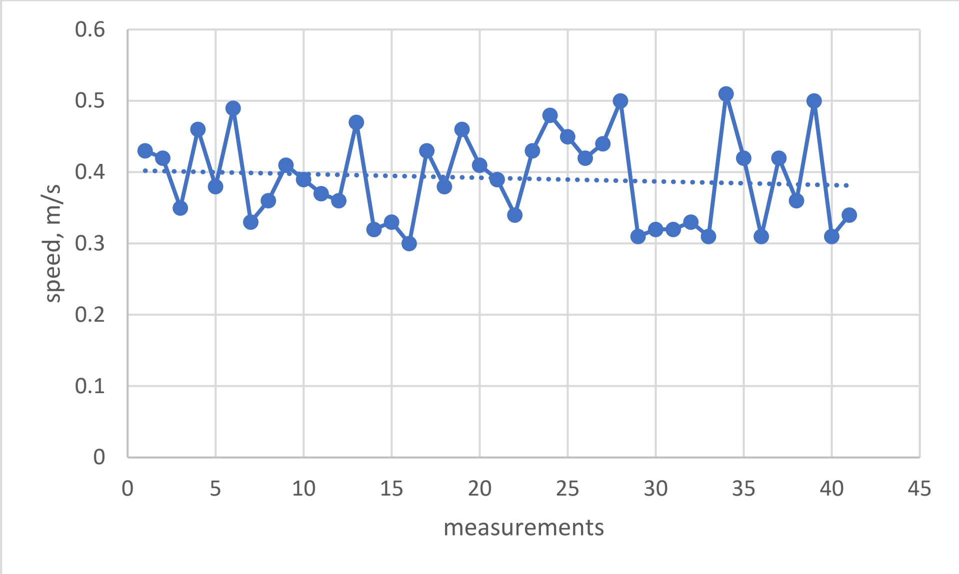

Figure 3. Velocity at culvert B6.

3. Results and Discussion

The solution to the problem is presented in the form of a field of velocities and streamlines of currents. The maximum speed at the water entry into the Neva Bay from the Neva River delta is set to 0.2 m/s. The speed in the Neva River ranges from 0.8 to 1.1 m/s.

Fig. 3 shows the calculated currents for 1877. The main current lines run from the north of Kotlin Island and from the south between Kotlin Island and Fort Kronshlot. The water speed in the Neva River delta is more than 0.6 m/s. Due to the high current speed (more than 0.6 m/s), a ravine formed between Kotlin Island and Fort Kronshlot, along which a historical fairway was formed. Velocities in the northern part of the Neva Bay between Kotlin Island and Lisiy Nos are distributed evenly and amount to 0.1 m/s. In the coastal zone there is practically no water flow.

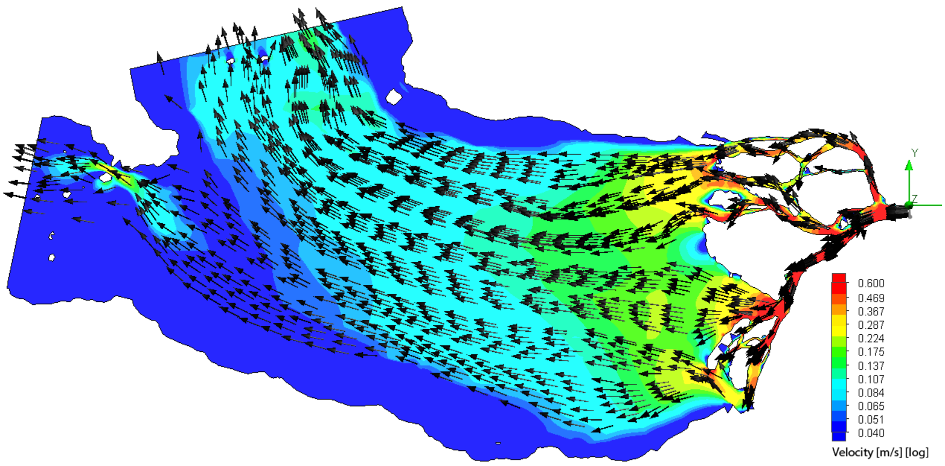

Figure 3. Velocity field and streamlines for the 1877 model.

Since 1877, construction began on the St. Petersburg Sea Canal, connecting the southern part of Kotlin Island and Gutuevsky Island and exiting through an artificial canal into the bed of the Bolshaya Neva. To protect the Sea Canal from silting, a sea canal dam was created, which had a significant impact on the currents, limiting the currents towards the southern part of the Neva Bay. The average values in this part of the Neva Bay have decreased and do not exceed 0.15 m/s. Currents from the northern part have not undergone significant changes and average 0.1 m/s; there is practically no current in the coastal zones. Fig. 4 shows the velocity field and streamline for the 1920 model.

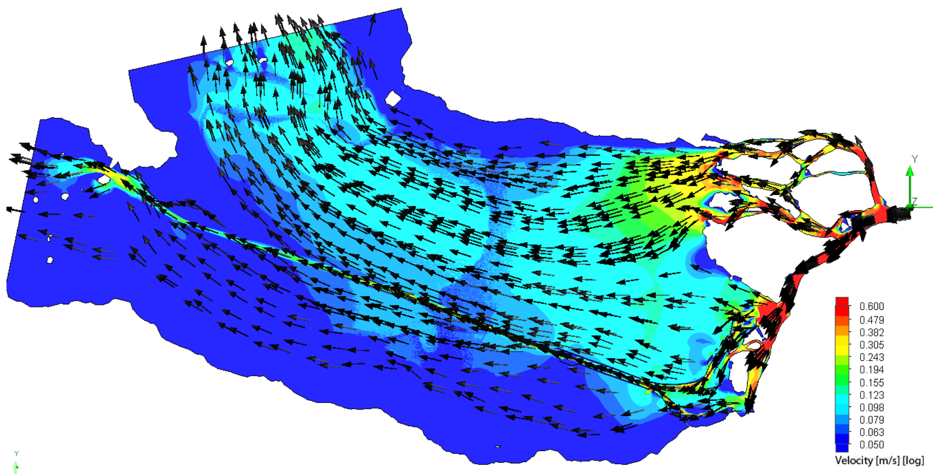

Figure 4. Velocity field and streamlines for the 1920 model.

Figure 5 shows the velocity field and streamline for the 1997 model. By 1997, the main work on filling the CFPS earthen dam was completed. For the passage of water, culverts B1-6 and navigation passages C1, C2 were left, and additional fairways were created, such as the fairway connecting navigation passage C2 with the Sea Canal, as well as the "Petrovsky Canal" connecting the Marine Canal with the Malaya Neva. Due to this, the currents became less uniform, and jets began to form in the flow with a higher speed of 0.11 m/s. Also, due to shallowing, the average current speed north of the Sea Channel increased, amounting to 0.15 m/s.

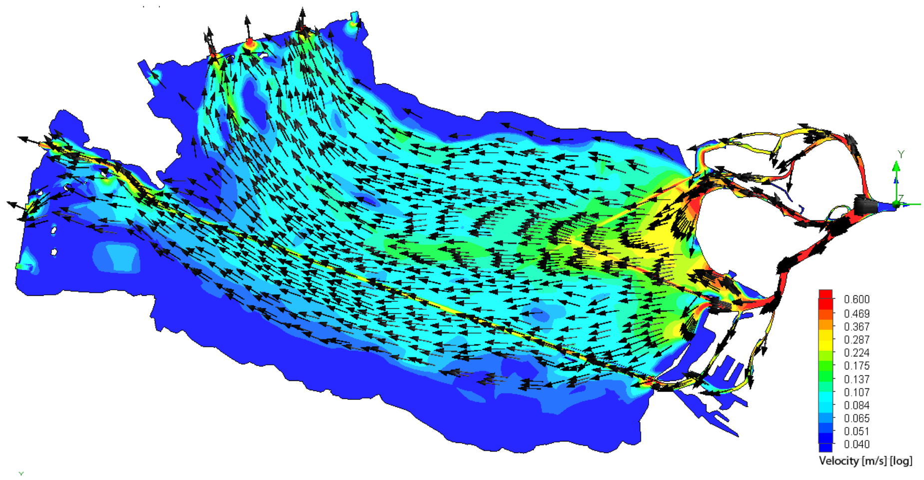

Figure 5. Velocity field and streamlines for the 1997 model.

Figure 6 shows the velocity field and streamline for the 2022 model. The 2022 model is characterized by the completion of the construction of all elements of the CFPS, the construction of the Western High-Speed Diameter (WHSD), and the elevation of ground levels in the western part of the Vasilievsky and Krestovsky Islands, as well as in the Lakhtinsky Razliv area. Due to the reasons described above and the significant shallowing of the Neva Bay, local average speeds increased north of the Sea Canal, and speeds around culverts B4-B6 increased. As a result, gullies began to form around culverts B4-B6 and navigation structures C2. The maximum water speeds through culverts and navigation structures are 0.4–0.6 m/s, which corresponds to field observations, so the average speed in the B-6 culvert is 0.4 m/s. Average speeds north of the Sea Channel increased and amounted to 0.15 m/s.

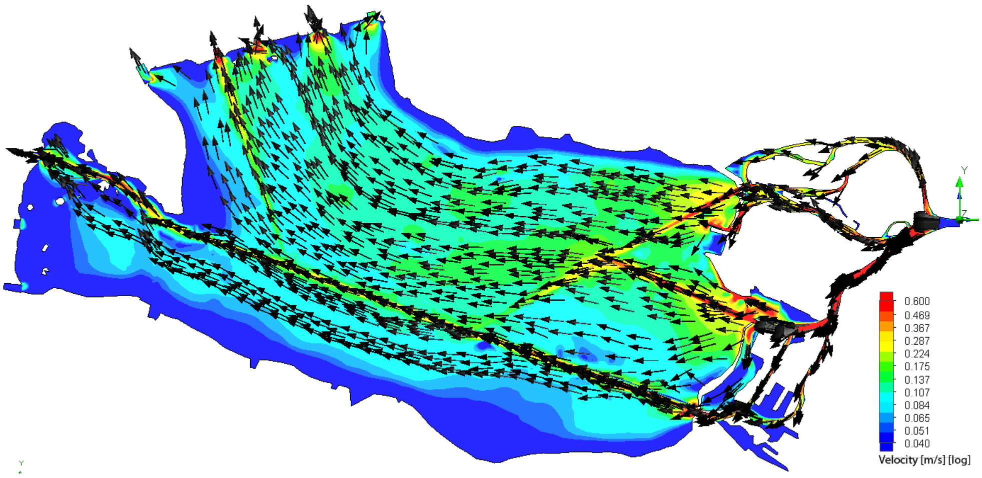

Figure 6. Velocity field and streamlines for the 2022 model.

4. Conclusion

We developed a method for numerical modeling of the shallow water equation in Neva Bay based on which a solution to the hydrodynamic problem was performed for 4 characteristic dates in the history of Neva Bay. As a result of solving hydrodynamic problems, the velocity fields and streamlines of water flows were determined, and an analysis of the results obtained was performed. As a result of solving the problem, the following conclusions were drawn:

1. Changes in the velocity field occurred due to works on the fairway and the construction of dams of the CFPS, which contributed to the shallowing of the Neva Bay water area.
2. Today there is almost no water flow south of the Sea Canal. Water exchange between the Neva Bay and the Gulf of Finland is carried out due to culverts in the northern part of the CFPS and shipping facilities; average speeds are 0.6 m/s.
3. Since the average flow of the Neva River during the calculation period has not changed and is 2500 m^3/s, an increase in speeds occurs north of the Sea Canal; the maximum speeds in the center of the Neva Bay are 0.2 m/s.
4. Due to changes in currents, the formation of local high-speed flows towards culverts is observed.

References

1. Nezhikhovskiy, R.A. Reka Neva i Nevskaya guba [The Neva River and Neva Bay]. Leningrad: Gidrometeoizdat, 1981. 112 p. (rus)
2. Ryabchuk, D.V., Nesterova, E.N., Zhamoida V.A., Kotilainen A., Vallius G., Sukhacheva L.L., Spiridonov M.A. Dinamika sedimentatsionnykh protsessov v Nevskoy gube (Finskiy zaliv) pod vozdeystviyem tekhnogennykh faktorov [Dynamics of sedimentation processes in the Neva Bay (Gulf of Finland) under the influence of technogenic factors]. Uchenyye zapiski Rossiyskogo gosudarstvennogo gidrometeorologicheskogo universiteta. 2014. No. 35. Pp. 102–118. (rus)
3. Shilin, M.B., Sychev, V.I., Mikheev, V.L., Istomin, Y.P., Lednova, Yu.A., Luk'yanov, S.V., Abramov, V.M. Results of investigations of the Neva Bay technosphere at RSHU. Gidrometeorologiya i ekologiya. 2020. 60. Pp. 351–370. DOI: 10.33933/2074-2762-2020-60-351-370 (rus)
4. Kovaleva, O.A., Ryabchuk, D.V., Sergeyev, A.Yu., Budanov, L.M. Monitoring razvitiya beregovykh protsessov vostochnoy chasti Finskogo zaliva pod vliyaniyem prirodnykh i tekhnogennykh faktorov [Monitoring the development of coastal processes in the eastern part of the Gulf of Finland under the influence of natural and man-made factors]. Morya Rossii: God nauki i tekhnologiy v RF-Desyatiletiye nauk ob okeane OON [Conference proceedings]. Sevastopol, 2021. Pp. 408–409. (rus)
5. Leontyev, I.O., Ryabchuk, D.V., Spiridonov, M.A., Kurennoi, D.N. The coastal profile in the Eastern Gulf of Finland: the results of a survey and the reconstruction of the evolution in the late Holocene. Okeanologiya. 2010. 50(6). Pp. 1034–1044. (rus)
6. Voltsinger, N.Ye., Zolnikov, A.V., Klevanny, K.A., Preobrazhensky, L.Yu. Calculation of the hydrological regime of the Neva inlet. Meteorologiya i gidrologiya. 1990. 1. Pp. 70–77. (rus)
7. Mikhaylenko, R.R. Saint-Petersburg flood prevention facility complex as a techno-natural system for integrated management of water resources: its social, economical and environmental benefits. Biosfera. 2015. 7(1). Pp. 1–25.
8. Rodionov, V.Z. Kompleks zashchitnykh sooruzheniy Sankt-Peterburga ot navodneniy: istoriya i ekologicheskiye problem [Complex of protective structures of St. Petersburg from floods: history and environmental problems]. Regionalnaya ekologiya. 2016. 4. Pp. 13–23. (rus)
9. Rumyantsev, V., Kondrat'yev, S., Pozdnyakov, Sh., Ryabchenko, V., Basova, S., Shmakova, M. Osnovnyye faktory, opredelyayushchiye funktsionirovaniye vodnoy sistemy Ladozhskoye ozero—reka Neva—Nevskaya guba—vostochnaya chast Finskogo zaliva v sovremennykh usloviyakh [The main factors determining the functioning of the water system Lake Ladoga—Neva River—Neva Bay—eastern part of the Gulf of Finland in modern conditions]. Proceedings of the Russian Geographical Society. 2012. 144(2). Pp. 55–69. (rus)
10. Nezhikhovskiy, R.A. Voprosy gidrologii r. Nevy i Nevskoy guby. [Issues of hydrology of the river. Neva and Neva Bay]. Leningrad: Gidrometizdat, 1988. 108 p.

11. Zakharchuk, Ye.A., Tikhonova, N.A., Sukhachev, V.N. Spatial structure and propagation of the Neva flood waves. Meteorologiya i gidrologiya 2020. 4. Pp. 42–53. (rus)
12. Ivanov, S.V., Visheratin, A.A., Nasonov, D.A., Boukhanovsky, A.V. Method of reconstruction of extreme natural phenomena of low frequency for improvement of Saint Petersburg flood-prevention facility. Izvestiya vysshikh uchebnykh zavedeniy. Priborostroenie. 2014. 57(12). Pp. 68–70. (rus)
13. Andreyev, P.N., Liberman, Yu.M., Mostamandi, S. Kompleks morskikh gidrodinamicheskikh modeley v Sankt-Peterburgskom TsGMS-R [Complex of marine hydrodynamic models in the St. Petersburg Central Hydrodynamics Center-R]. SOI Proceedings. 2011. 213. Pp. 74–79. (rus)
14. Martyanov, S.D., Ryabchenko, V.A. Simulation of the Resuspension and Transport of Bottom Sediments in the Neva Bay Using a 3D Circulation Model. Fundamental and Applied Hydrophysics. 2013. 6(4). Pp. 32–43. (rus)
15. Vinogradov, M.V., Tikhonova, N.A., Zakharchuk, Ye.A. Long-term variations of the Baltic sea level in the second half of the 20th - beginning of the 21st century. Gidrometeorologiya i fizika atmosfery: sovremennyye dostizheniya i tendentsii razvitiya [Conference Proceedings]. St. Petersburg, 2023. Pp. 91–95. (rus)
16. Klevannyy, K.A., Kolesov, A.M., Mostamandi, M.S.V. Predicting the floods in St. Petersburg and the eastern part of the Gulf of Finland under conditions of operation of the flood prevention facility complex. Meteorologiya i gidrologiya. 2015. 2. Pp. 61–70. (rus)
17. Sergeev, A.Yu., Ryabchuk, D.V., Nosevich, E.S., Prishchepenko, D.V., Zhamoida, V.A., Piskarev-Vasiliev, A.L., Elkina, D.V., Bashirova, L.D., Ponomarenko, E.P., Budanov, L.M., Grigoriev, A.G. Evolution of sedimentation environment of postglacial basins in the Eastern Gulf of Finland during the holocene under the changing climate. Okeanologiya. 2022. 62(3). Pp. 466–484. (rus)
18. Shilin, M.B., Zhigulsky, V.A., Bobylev, N.G., Ahmad, A., Lednova, J.A., Don, S. Development a complex of compensation measures to reduce the negative impact of port Bronka construction on the south coast of Nevskaya lip. Natural and Technical Sciences. 2020. 3. Pp. 178–188. DOI: 10.25633/ETN.2020.03.11 (rus)
19. Pavlovskiy, A.A., Menzhulin, G.V. Dynamics of St. Petersburg flooding and its changes during different climatic periods. Vestnik Sankt-Peterburgskogo Universiteta, Seriya Geologiya i Geografiya. 2010. 2010(2). Pp. 71–83. (rus)
20. Wu, W., Wang, L., Lei, X., Zheng, Y., Wei, J., Mao, X.-zh. Sustainable estuarine governance based on artificial island scheme for a highly anthropogenic influenced Shenzhen Bay, China. Journal of Hydrology. 2023. 616. 128784. DOI: 10.1016/j.jhydrol.2022.128784
21. Zhou, Y., Wang, L., Zhou, Y., Mao, X.-zh. Eutrophication control strategies for highly anthropogenic influenced coastal waters. Science of the Total Environment. 2020. 705. 135760. DOI: 10.1016/j.scitotenv.2019.135760
22. Xiao, Y., Wu, Zh., Cai, H., Tang, H. Suspended sediment dynamics in a well-mixed estuary: The role of high suspended sediment concentration (SSC) from the adjacent sea area. Estuarine, Coastal and Shelf Science. 2018. 209. Pp. 191–204. DOI: 10.1016/j.ecss.2018.05.018
23. dos Santos, V.H.M., da Silva Dias, F.J., Dottori, M., Torres, A.R., Santos, R.L., Soares, R. de A., Ribeiro, J.C.M., Serejo, J.H.F., Lima, H.P., Azevedo, I.H.R. Investigation of physical properties and suspended particulate matter discharge in a macrotidal estuary at the Amazon-semiarid transition zone. Regional Studies in Marine Science. 2023. 67. 103194. DOI: 10.1016/j.rsma.2023.103194
24. Torres-Marchena, C.A., Flores, R.P., Aiken, C.M. Impacts of training wall construction on littoral sedimentation under seasonal flow variability and sea-level rise: A case study of the Magdalena River (Colombia)ю Coastal Engineering. 2023. 183. 104306. DOI: 10.1016/j.coastaleng.2023.104306
25. do Carmo, J.S.A. The changing paradigm of coastal management: The Portuguese case. Science of the Total Environment. 2019. 695. 133807. DOI: 10.1016/j.scitotenv.2019.133807
26. Pye, K., Blott, S.J. The geomorphology of UK estuaries: the role of geological controls, antecedent conditions and human activities. Estuarine, Coastal and Shelf Science. 2014. 150. Pp. 196–214. DOI: 10.1016/j.ecss.2014.05.014
27. Schrijvershof, R.A., van Maren, D.S., Torfs, P.J.J.F., Hoitink, A.J.F. A Synthetic Spring-Neap Tidal Cycle for Long-Term Morphodynamic Models. Journal of Geophysical Research: Earth Surface. 2023. 128(3). e2022JF006799. DOI: 10.1029/2022JF006799
28. Klimovich, V.I., Voronkov, O.K., Davidenko, V.M., Ivanov, S.N. Alkali-activated slag binders from rock-wool production wastes. Magazine of Civil Engineering. 2018. 82(6). Pp. 228–242. DOI: 10.18720/MCE.82.21.
29. Bulatov, O.V., Yelizarova, T.G. Regularized shallow water equations for numerical simulation of flows with a moving shoreline. Computational Mathematics and Mathematical Physics. 2016. 56(4). Pp. 665–684. (rus)
30. Ivanov, A.V. Computer complex for modelling of sea currents using regularized shallow water equations. Mathematical Models and Computer Simulations. 2021. 33(10). Pp. 109–128. DOI: 10.20948/mm-2021-10-08
31. Behzadi, F., Newman III, J.C. An exact source-term balancing scheme on the finite element solution of shallow water equations. Computer Methods in Applied Mechanics and Engineering. 2020. 359. 112662. DOI: 10.1016/j.cma.2019.112662
32. Heniche, M., Secretan, Y., Boudreau, P., Leclerc, M. A two-dimensional finite element drying-wetting shallow water model for rivers and estuaries. Advances in Water Resources. 2000. 23(4). Pp. 359–372. DOI: 10.1016/S0309-1708(99)00031-7
33. Dikiy, D.I., Sokolov, A.N., Chubarenko, B.V., Artem'yeva, V.D. Metodika opredeleniya optimalnogo podkhoda k chislennomu modelirovaniyu techeniy v pribrezhnykh lagunakh dlya ekologicheskikh prilozheniy [Methodology for determining the optimal approach to numerical modeling of currents in coastal lagoons for environmental applications]. Information and Space. 2018. 2. Pp. 117–125. (rus)
34. Kurnosova, O.B. 130 years anniversary of opening the seaway channel from Kronshtadt to St. Petersburg. Shipbuilding. 2015. 3. Pp. 86–89. (rus)
35. Korshunov, E.L., Rupasov, A.I. Archive of the navy - branch of the central archive of the Ministry of defense of the Russian Federation: stages of history. Herald of an Archivist. 2018. 3. Pp. 915–925.
36. Nikonorov, A., Badenko, V.L. Flood events dynamics estimation methodology in a GIS environment. Magazine of Civil Engineering. 2021. 101(1). Article no. 10110. DOI: 10.34910/MCE.101.10
37. Kozinec, G.L. Generalization of the Methodology of Studying the Durability of Segmental Gates. Power Technology and Engineering. 2018. 52(4). Pp. 395–399.

Information about authors

Dmitry Zotov,
E-mail: zotovdk@gmail.com

Galina Kozinetc, *Doctor of Technical Sciences*
E-mail: kozinets_gl@spbstu.ru

Pavel Kozinets,
E-mail: pavelstrenger@gmail.com

Petr Chernov,
ORCID: https://orcid.org/0000-0003-0267-1505
E-mail: PchelkaDragpet@mail.ru

Vladimir Badenko, *Doctor of Technical Sciences*
ORCID: https://orcid.org/0000-0002-3054-1786
E-mail: vbadenko@gmail.com

Received 25.08.2023. Approved after reviewing 26.11.2023. Accepted 30.11.2023.