Session OS2.1
EGU25-4089

Seasonal and inter-annual changes of structure and dynamics in the buoyant plume generated by the Dnipro-Buh estuary, Black Sea

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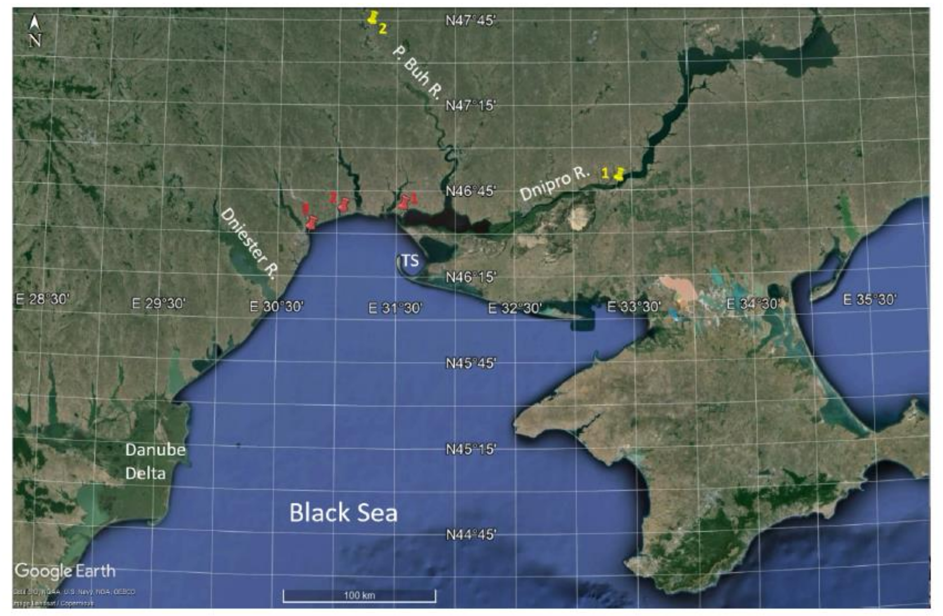
1

North-Western part of the Black Sea



1 - Ochakiv; 2 – Pivdenne; 3 – Odesa;
1 – Kakhovka HPP; 2 – Oleksandrivsk HPP

2

ABSTRACT

Based on long-term coastal hydrometeorological observations and oceanographic surveys, as well as satellite images, the average conditions, seasonal and interannual variability of integral water exchange and buoyant plume generation were studied for the Dnipro-Buh estuary (DBE).

Analysis of publications and available information showed that a simple Knudsen's box model can be adapted for the conditions of shallow non-tidal estuaries. Hydrodynamic dimensional and non-dimensional criteria that determine the nature and further behavior of plumes after their exit from the estuary into the open sea were considered. The application of the criteria for determining the nature of the plume for outflows from the DBE showed that on the exit of estuary plume of transitional waters is produced. It has a surface-advective nature, without the effect of friction in the bottom boundary layer, being driven by buoyancy and Coriolis forces, and is influenced by wind-wave mixing.

The main factor in the plume dynamics on the shallow waters are the wind currents, which contribute or hinder the spread of transitional waters along the coast to the right of the estuary mouth, or pushing them into the open sea and even turning them to the opposite. During the low-wind weather, the initial impulse of the river runoff plays the main role. This was especially evident in the situation of an abnormally large runoff volume after the explosion of the Kakhovka HPP on 06.06.2023. The consequences of its impact on the marine environment are shown according to a number of satellite images.

Using the mixture analysis method, the statistical structure was investigated and one-dimensional clustering of empirical salinity histograms at 3 shore stations in the vicinity of the DBE was performed. It has been found that salinity probability distributions can be approximated by a set of 2-3 Gaussian functions. These functions, as a rule, correspond to waters of river origin, marine origin, and intermediate waters as a result of the interaction of the first two. Seasonal changes of these water masses' mean values and standard deviations were obtained for each shore station.

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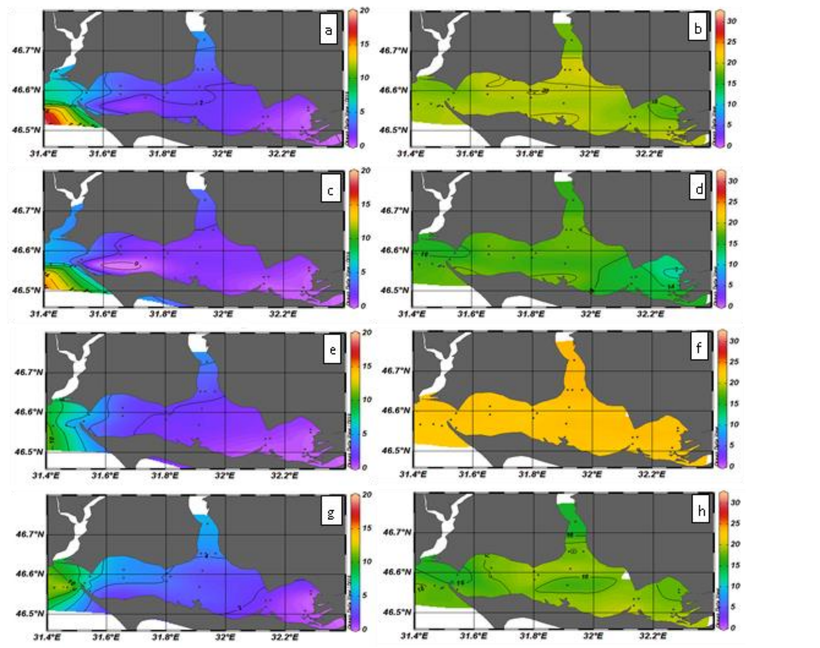
Average long-term distribution of water salinity, P.S.U., (a, c, e, g) and temperature, °C, (b, d, f, h) on the surface of the Dnieper-Bug estuary and the adjacent Black Sea area according to the monitoring data of the Hydrometeorological Service of Ukraine in 1992 – 2020: a, b – year (without winter); c, d – spring (March-May); e, f – summer (June-August); g, h – autumn (September-November)

Ilyin, 2023a:



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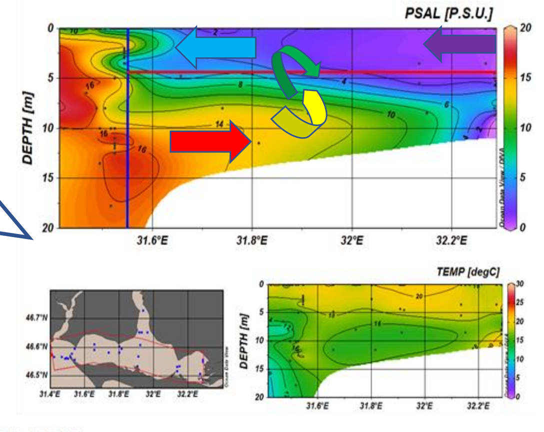
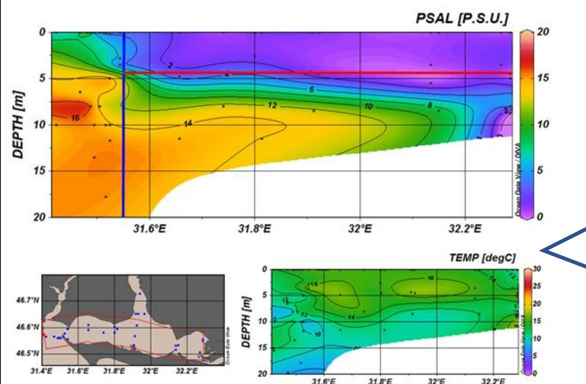
Ilyin, 2023a:

Vertical distribution of water salinity (upper) and temperature (bottom right) in the Dnipro estuary and adjacent region of the Black Sea by all observations data of 1992-2020



Vertical blue line – the Kinburn strait; Horizontal red line – mean depth of the Dnipro estuary



Vertical distribution of water salinity (upper) and temperature (bottom right) in the Dnipro estuary and adjacent region of the Black Sea by observations data of March-May of 1992-2020

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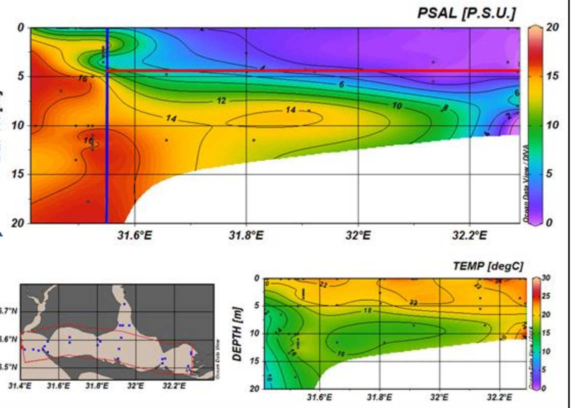
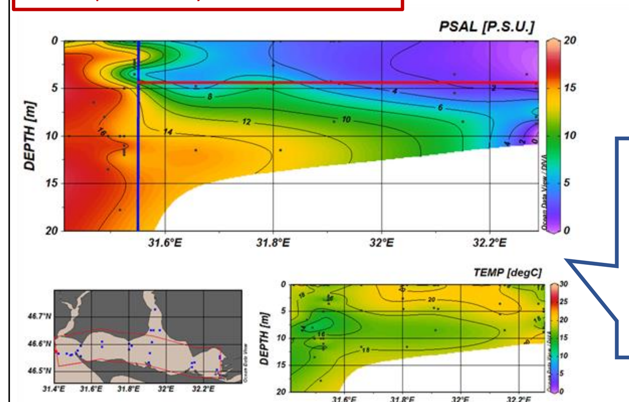
Vertical distribution of water salinity (upper) and temperature (bottom right) in the Dnipro estuary and adjacent region of the Black Sea by observations data of June-August 1992-2020



Vertical blue line – the Kinburn strait; Horizontal red line – mean depth of the Dnipro estuary



Vertical distribution of water salinity (upper) and temperature (bottom right) in the Dnipro estuary and adjacent region of the Black Sea by observations data of September-November 1992-2020

6

IndIndicators of the type and structure of the floating plume (Yankovsky & Chapmen, 1997):

- Плюм залишається прикріпленим до дна моря до глибини (м):

$$H_b = (2Q_{out}f/g')^{1/2}, \quad (1)$$

where $f = 2\omega \sin\varphi$ – Coriolis parameter (ω – Earth rotation frequency, s^{-1}; φ – latitude); $g' = g(\rho_0 - \rho)/\rho_0$ – reduced gravity; g – gravity acceleration, m/s²; $(\rho_0 - \rho)/\rho_0$ – relative water density anomaly or buoyancy (ρ – plume water density, kg/m³; ρ_0 – background seawater density); Q_{out} – volumetric transport of water flowing out of the strait.

- The surface manifestation of a cyclostrophic plume, or bulge, extends from the shore at a distance (m):

$$Y_s = 2Rd(3+F^2)/(2+F^2)^{1/2}, \quad (2)$$

where $Rd = (g'h_s)^{1/2}/f$ – baroclinic Rossby radius (m); $F = u_s/(g'h_s)^{1/2}$ – Frude number; $u_s = Q_{out}/(L_s h_s)$ – current velocity on the outlet from the estuary (in the strait); L_s, h_s – width and depth of the strait respectively.

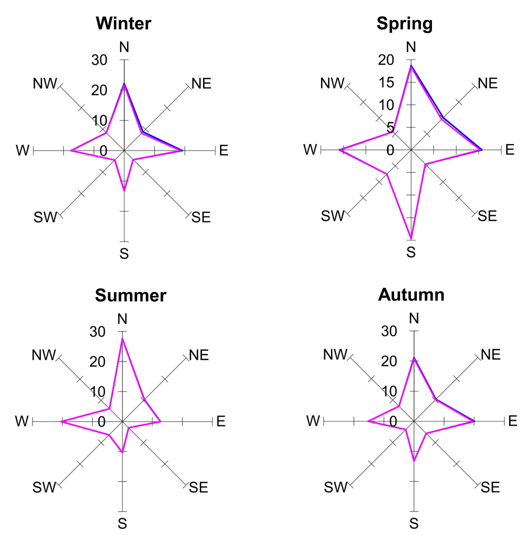
- It has been experimentally established that to estimate Q_{out} in the Kinburn Strait, a simple formula from the Knudsen model can be used (Ilyin, 2023a):

$$Q_{out} = Q_r(\rho_0 - \rho_r)/(\rho_0 - \rho), \quad (3)$$

where ρ_r – fresh water density; Q_r – riverine discharge, м³/с.

7

Average seasonal repeatability of wind directions at a speed of 1-10 m/s (pink line) and 1-20 m/s (purple line) according to observations of station Ochakov in 1991-2010: winter, spring (top) and summer, autumn (bottom)



Wind force Index (Whitney & Garvine, 2005):

$$W_s = u_w/u_s, \quad (4)$$

where $u_s = Q_{out}/(L_s h_s)$ – current speed, generated by buoyancy, see eq. (2); $u_w = 0{,}0265U$ – current speed, induced by wind U (Csanady, 1978)

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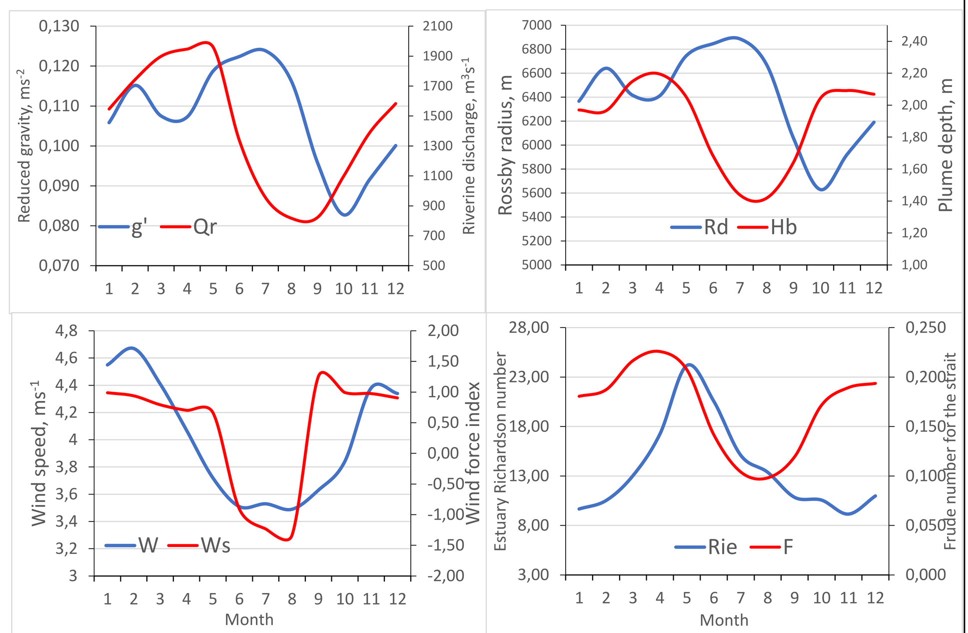
Ilyin, 2023a:

Seasonal changes of indicators of the structure and dynamics of the Dnipro-Buh estuary transitional waters according to observations of 1992-2020. On the charts, the blue curves refer to the left scales, the red curves to the right scales



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Conclusions from the analysis of monitoring data 1992-2020

- The highest degree of DBE freshening and removal of transitional water from the Kinburn Strait is observed in spring, under conditions of increasing river runoff and prevailing winds from the east. At the same time, an increase in the frequency of the southerly wind contributes to the pressing of the plume to the coast of the NW Black Sea outside the estuary. In summer, the influence of sea waters on the DBE increases due to a decrease in river runoff and an increase in the frequency of the westerly wind. In autumn, the frequency of the westerly wind decreases and the number of cases of the easterly wind increases, but the water structure continues to change towards an increase in the salinity of the estuary water and the pressing of the primary transformation front (isohalines 10 ‰) to the Kinburn Strait.
- The application of the criteria for determining the nature of the plume for the outflow from the Dnipro-Buh estuary showed that the estuary produces a plume of transitional waters that have a surface-advective nature, being influenced by buoyancy, Coriolis, and wind-wave mixing forces, without the effect of friction in the bottom boundary layer.
- In average, on a long-term scale, the distance to which the plume spreads under the influence of buoyancy and Coriolis forces alone, even in summer, does not exceed half of the way to the Odessa Bay. The entry of transitional waters of the DBE there can only be facilitated by accompanying wind currents.
- The wind force index and wind roses indicate that the main factor in the summer dynamics of the plume is the wind and the currents generated by it, which prevent the spread of transitional waters to the west along the coast, pushing them towards the estuary and south of it.
- This does not deny the possibility of different plume behavior in specific years and months, according to synoptic variability of wind conditions.

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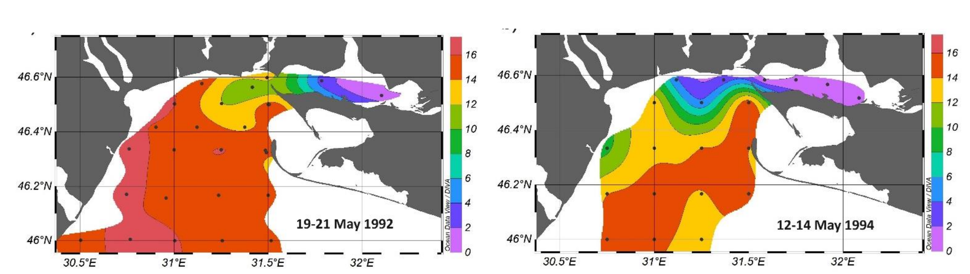
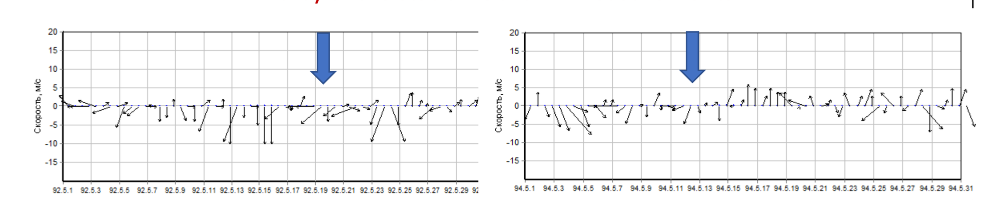
Yankovsky & Ilyin, CSR-2024:

Distribution of water salinity (PSU) on the NW Black Sea surface by r/v "Trepang" CTD-survey data, 19-21 May 1992. Q_r = 1283 m³/s (0,66 of Q mean val.)

Distribution of water salinity (PSU) on the NW Black Sea surface by r/v "Gidrooptik" CTD-survey data, 12-14 May 1994. Q_r = 3374 m³/s (1,72 of Q mean val.)



Wind by shore station Ochakiv measurements:



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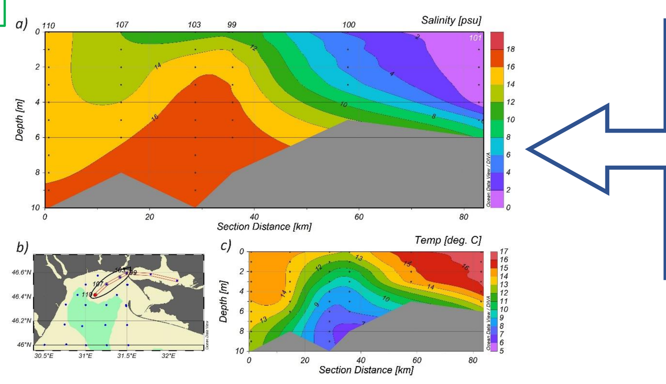
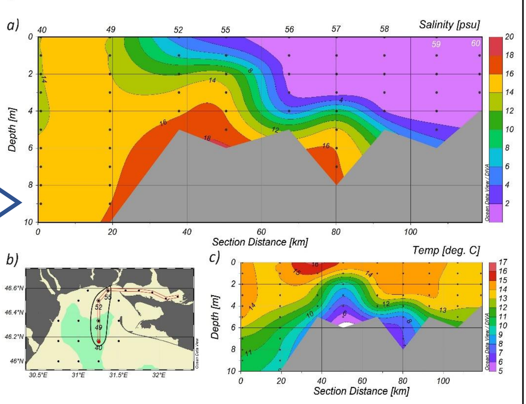


Vertical section of water salinity (a) and temperature (c) along the Dnipro estuary and transient water plume by CTD data of r/v "Trepang", 19-21 May 1992



Vertical section of water salinity (a) and temperature (c) along the Dnipro estuary and transient water plume by CTD data of r/v "Gidrooptik", 12-14 May 1994.

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Yankovsky & Ilyin, CSR-2024:

- Transport of buoyant water within the plume is sustained by both its inherent dynamics (presumably geostrophic), and by external forcing, associated predominantly with the wind stress. In order to assess a relative role of the inherent plume dynamics, we estimate a geostrophic transport of freshwater around the bulge and compare it to freshwater discharge feeding the plume.
- Geostrophic balance is considered to represent the leading-order dynamics in the unforced far field of a plume, and the freshwater transport in the far field should match closely the freshwater discharge if the plume is in near-stationary conditions.
- The net geostrophic transport depends on the difference of buoyancy characteristics in the center of the plume and outside (ambient shelf water), which are both resolved.
- Since the water column is continuously stratified without a well-defined interface between the plume and ambient shelf waters, we estimate the depth of buoyant layer h following Arneborg et al. (2007) as:

$$h = \frac{2\int_{-D}^{0}(\rho_0-\rho)z\,dz}{\int_{-D}^{0}(\rho_0-\rho)\,dz} \quad (5),$$

where $\rho(z)$ is the seawater density and ρ_0 is the reference density, which is a maximum (near bottom) value at each station, D is the water depth, and the vertical coordinate z points upward.

- We also estimate the equivalent freshwater layer depth h_f as:

$$h_f = \int_{-D}^{0}\frac{s_r-s}{s_r}dz \quad (6),$$

where s_r=17 is the reference salinity representing ambient water on the shelf.

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Table 1. Plume characteristics derived from hydrographic surveys in 1992 and 1994: h [m] is the buoyant layer depth from (5), h_f [m] is the equivalent freshwater layer depth from (6), Q_g [m³s⁻¹] is the freshwater geostrophic transport from (8), positive eastward.

Survey 1992

Station	h	h_f	Q_g
99	1.47	0.54	
			108
103	2.99	0.95	
			136
107	4.01	1.39	
			-296
110	10.21	0.98	

Survey 1994

Station	h	h_f	Q_g
55	1.60	1.77	
			-65
52	1.67	1.94	
			-769
49	8.43	1.38	
			508
40	10.80	1.91	

The freshwater layer is deeper in 1994 (Table 1), which is consistent with higher freshwater discharge in that year. Interestingly, h_f does not decrease with the offshore distance: even though the salinity anomaly of the buoyant layer decreases, its depth increases, so that the freshwater content remains roughly the same.

- Baroclinic geostrophic velocity is calculated by integrating the thermal wind shear equation upward from the reference level. As a reference level for a pair of stations, we select the closest to h grid point (typically, below h) at the inshore station. The thermal wind shear is:

$$\frac{\partial u_g}{\partial z} = \frac{g}{f\rho}\frac{\partial \rho}{\partial y} \quad (7)$$

Here, u_g is the geostrophic velocity component normal to the transect (positive upstream/ eastward) and g is the acceleration due to gravity. Freshwater transport by a geostrophic current is:

$$Q_g = \int_{-h}^{0} u_g \frac{s_r-s}{s_r}dz \quad (8)$$

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To better assess the role of wind in the evolution of the Dnipro-Buh plume, we will quantify a relative contribution of the buoyancy and wind forcing in the coastal current formation by using the sea level data. We start with buoyant outflow, which, in the absence of other forcing agents, should form a geostrophic coastal current propagating alongshore. If the buoyancy is conserved, the maximum depth h_b of this current can be defined from (1) (Yankovsky and Chapman, 1997). Assuming that the average salinity of the buoyancy current is s_p and the density is a function of salinity only, the volumetric transport of the buoyancy current Q and its associated reduced gravity g' can be defined as:

$$Q = \frac{Q_r s_r}{\Delta s} \quad \text{and} \quad g' = \frac{g\gamma\Delta s}{\rho_0} \quad (9),$$

where $\Delta s = s_r - s_p$ and Q_r is the river discharge feeding the plume. Q is defined as:

$$Q = \frac{1}{2}h_b\int_{-L_p}^{0}\bar{u}\,dy = \frac{1}{4}h_b\int_{-L_p}^{0}u_s\,dy \quad (10)$$

Here $\bar{u}$ and u_s are depth-averaged and surface velocity x-components, respectively; x- and y-axes point east- and northward, zonal coastline is at y=0, and L_p is the plume width. Lastly, u_s is in geostrophic balance $u_s = -\frac{g}{f}\frac{\partial\eta}{\partial y}$, where η is the free surface perturbation, $\eta = \eta_0$ (y=0) and η = 0 (y=$-L_p$). Substituting the expression for u_s into (10), integrating and assuming westward Q yields:

$$\eta_0 = \frac{4Qf}{gh_b} = \sqrt{\frac{8Q_r f\gamma s_r}{g\rho_0}} \quad (11)$$

Expression (11) is the scale for the free surface perturbation at the coast if the geostrophic coastal current was formed and carried all discharged water downstream along the coast.

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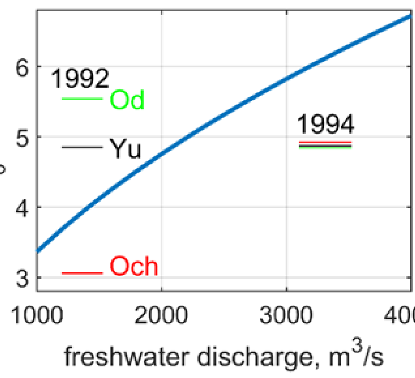

Estimate of a coastal sea level perturbation associated with the geostrophic buoyancy current (heavy blue line) and the observed sea level standard deviations at Ochakiv (red), Yuzhniy (black), and Odesa (green) shown over the freshwater discharge range for a corresponding year.

During both surveys the Dnipro-Buh plume was observed under light wind conditions such that the plume dynamics should dominate the wind-induced sea level setup and corresponding barotropic transport. Under this scenario, our estimates indicate that only a fraction of total freshwater discharge was transported downstream in geostrophic buoyancy driven current around the bulge. A significant amount of freshwater was contained in the bottom layer which likely propagated in the opposite, upstream direction, as deduced from the thermal wind shear reversal. Also, due to a coarse spatial resolution of both surveys, the role of subemeso- and meso-scale processes in freshwater transport is unknown. Lastly, the analyzed surveys did not extend eastward from the mouth's longitude (except for the estuary itself) and hence the freshwater content in that part of NWS is unknown. To better illustrate the pathways of the Dnipro-Buh freshwater outflow, in the next subsection we consider a set of satellite images obtained under similar conditions of spring freshet, with a variety of wind and discharge patterns, which demonstrate a bi-modal spreading of the Dnipro-Buh river plume.

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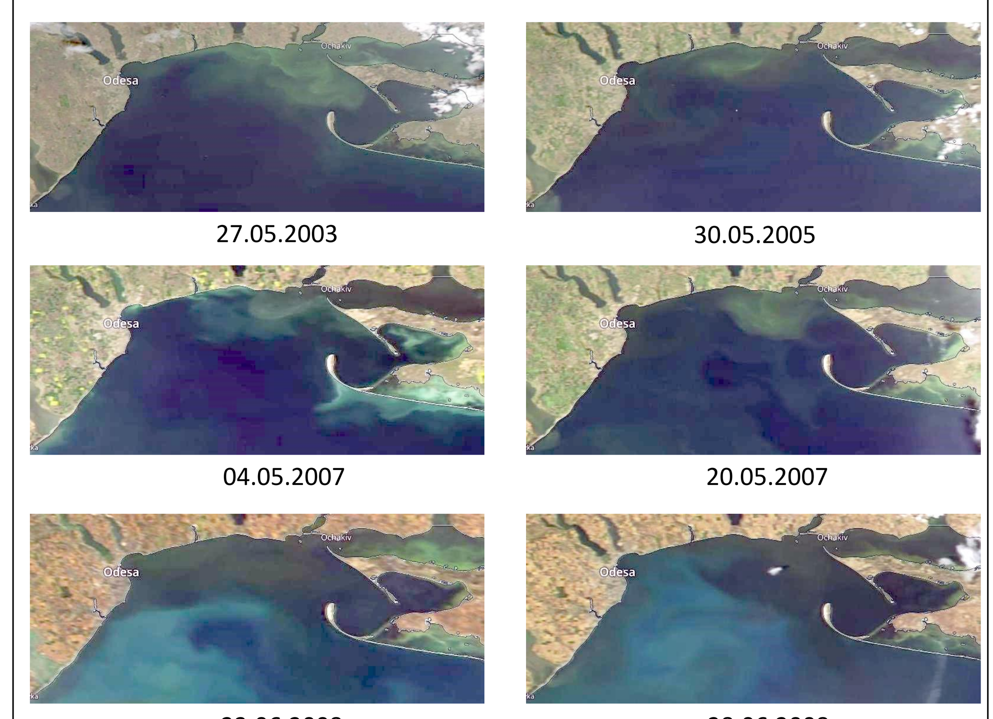
MODIS enhanced natural color images of NW Black Sea



27.05.2003 | 30.05.2005
04.05.2007 | 20.05.2007
23.06.2008 | 28.06.2008

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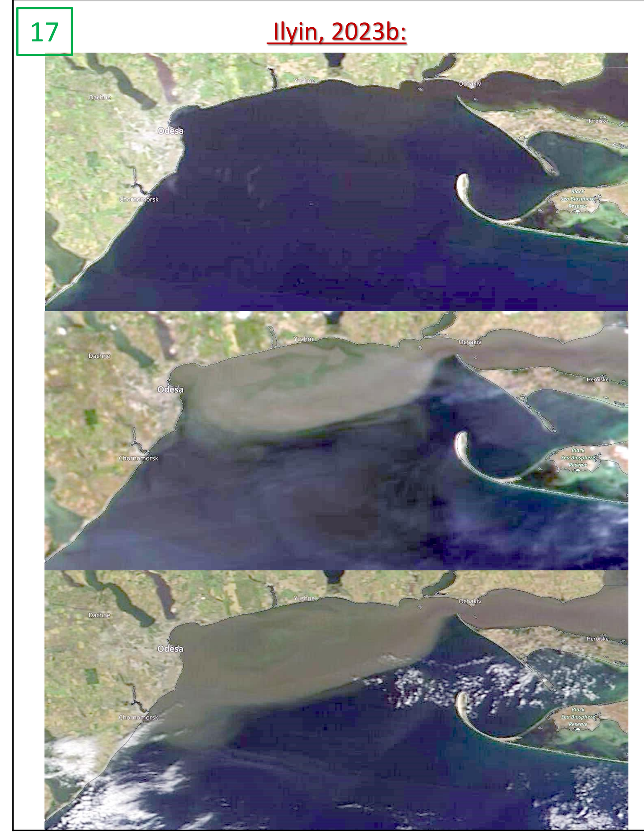
Ilyin, 2023b:



Satellite images of the northern region of the NW Black Sea in natural colors, from top to bottom (UTC time):
05.06.23, 08:18, MODIS/Terra;
09.06.23, 10:46, VIIRS/NOAA-20;
10.06.23, 11:06, MODIS/Aqua

→ According to data from 07.06, the average velocity of sediment flow through the riverbed and estuary was 122 cm/s.

→ According to data from 09.06, the average speed of the current on the sea surface at the leading front of the turbidity plume was 55 cm/s in light wind weather!

→ As of 10.06, the plume of turbid waters had increased in width to 20-29 km.

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Average long-term monthly and annual estimates of the dynamics and structure of the plume (Ilyin, 2023a) as well as indicators of anomalous discharge after the explosion of the Kakhovka HPP dam (the last row)

Month	Q_{out}, m³/s	g', m/s²	u_s, cm/s	F	Rd, km	H_b, m	Y_s, km
1	1938	0,106	12,2	0,181	6,366	1,97	27,084
2	2096	0,115	13,2	0,187	6,641	1,96	28,257
3	2344	0,107	14,7	0,217	6,416	2,15	27,326
4	2440	0,107	15,3	0,226	6,409	2,20	27,309
5	2359	0,119	14,8	0,207	6,745	2,05	28,719
6	1636	0,122	10,3	0,142	6,846	1,68	29,093
7	1208	0,124	7,6	0,104	6,886	1,44	29,242
8	1102	0,116	6,9	0,098	6,670	1,42	28,322
9	1219	0,096	7,7	0,119	6,058	1,64	25,731
10	1628	0,083	10,2	0,172	5,630	2,04	23,943
11	1891	0,092	11,9	0,189	5,923	2,09	25,204
12	2021	0,100	12,7	0,194	6,191	2,07	26,348
Year	1823	0,107	11,7	0,169	6,398	1,89	27,215
6-9 06.2023	20495	0,133	128,8	1,706	7,124	5,73	38,01

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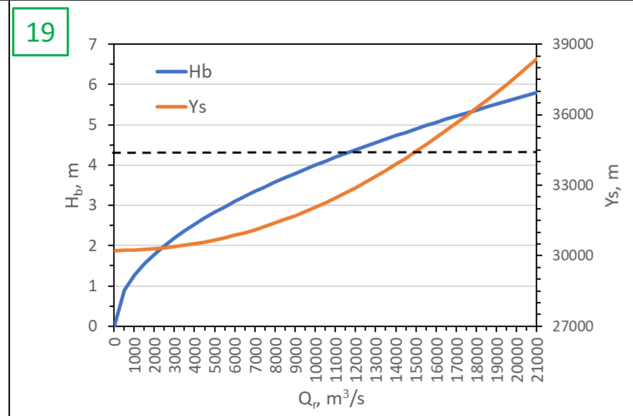

Dependence of the plume depth H_b and the distance of the plume seaward expansion Y_s on the riverine discharge Q_r according to the theory of Yankovsky & Chapman (1997).

Dash line – average depth of the Kinburn Strait 4,4 m

Quantitative indicators of the riverine water dynamics in the sea at the first stage of its expansion were calculated based on the assessment of the average water discharge for 3 days after the dam explosion. It was concluded that the abnormal discharges of the Dnipro river (20.5 thousand m³/s) produce an unusual mode of the riverine water dynamics in the sea, namely, the supercritical flow from the Kinburn Strait and the formation of a buoyant plume that interacts with the bottom at a depth of no more than 6 m. According to satellite observations, the plume of turbid riverine waters moved on the shelf at a speed of more than 50 cm/s and quickly reached the Odesa Bay, forming an anticyclonic eddy structure, which later increased to more than 40 km in diameter. As a first approximation, it is accepted that in 3 days after the dam explosion, about 700 tons of dissolved inorganic phosphorus and more than 1,000 tons of dissolved inorganic nitrogen entered the Black Sea (Ilyin, 2022; 2023b). Such an unusually large amount of nutrients could obviously cause the explosive reproduction (blooming) of phytoplankton.

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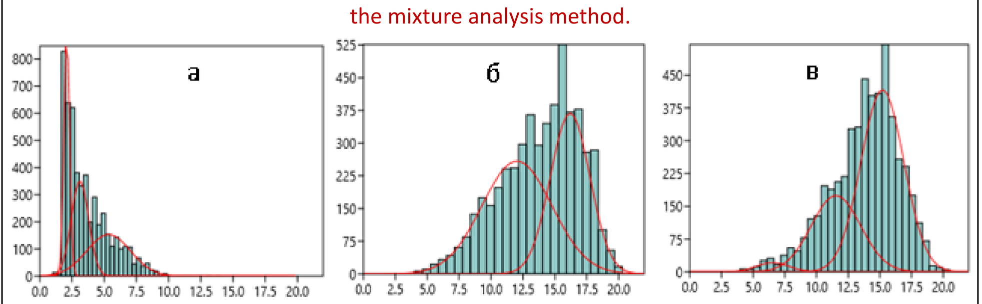
Ilyin, 2024:

Manifestations of the interaction of river and marine waters in the statistical structure of salinity by the observations data at coastal stations of Ukraine

Time series of water salinity observations from 1997 to 2010 at marine hydrometeorological stations on the northern coast of the Northwestern Black Sea from the mouth of the Dnipro-Buh Estuary (Kinburn Strait) to the Gulf of Odesa are analyzed. Empirical probability distribution functions of salinity were constructed for the Ochakiv, Pivdenny and Odesa-port stations for all months and year as a whole. Using the mixture analysis method, one-dimensional clustering of empirical salinity histograms is performed under the assumption that they consist of several normal distribution functions, each of which represents a separate water mass and is characterized by its own indicators - the average value, standard deviation and share (proportion) in the general distribution (mixture).

Annual salinity histograms according to data from the stations Ochakov (a), Pivdenne (б) and Odesa-port (в). The horizontal axis is water salinity (PSU), the vertical axis is the number of cases (observations). The red lines are normal probability distribution functions extracted by the mixture analysis method.



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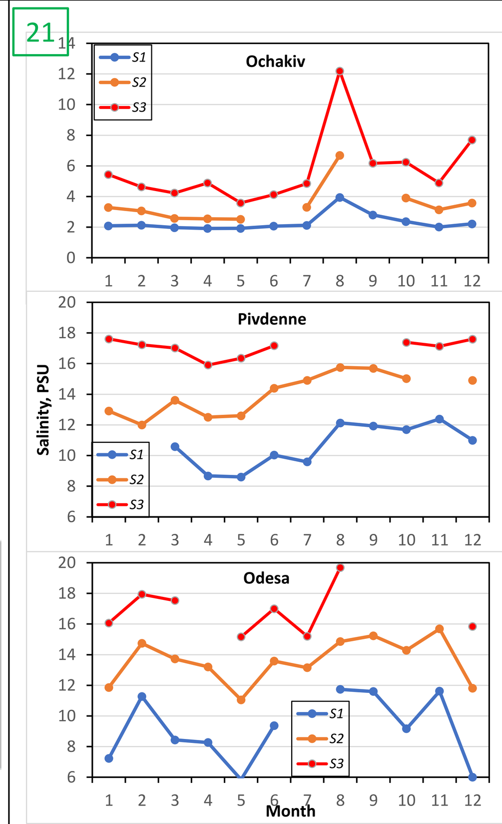

Seasonal changes of mixture components salinity – riverine (S_1), intermediate (S_2) and marine (S_3) waters by observations data of 1997-2010 on shore stations Ochakiv, Pivdenne and Odesa-port (Ilyin, 2024)

Experimentally, taking into account the peculiarities of the water dynamics in the northern part of the Northwestern Black Sea shelf, it was established that salinity histograms can be approximated by a set of 2-3 Gaussian functions. These functions, as a rule, correspond to waters of riverine origin, marine origin and intermediate waters as a result of the interaction of the first two. The approximation parameters (mean values, standard deviation and proportion in the mixture) vary in space depending on the distance to the source of desalination or salinization, as well as in time in accordance with the seasonal variability of the processes of supply and interaction of water masses on the North-Western Black Sea shelf.

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Overall results:

- Based on hydrometeorological data, oceanographic surveys and satellite observations, the average multi-year conditions, seasonal and interannual variability of the nature of the spread of the transitional water plume after leaving the Dnieper-Bug estuary were studied.
- According to satellite observations, the spread of the anomalous removal of water from the Dnieper estuary in the Black Sea after the collapse of the Kakhovka HPP dam was analyzed.
- Using the mixture analysis method, one-dimensional clustering of empirical salinity histograms based on coastal station data was performed, and the spatial and seasonal variability of the indicators - the average value, standard deviation and share (proportion) in the general distribution (mixture) was studied.

References:

- Ilyin, Yu.P. (2022). Average long-term values and variability of water, salt and dissolved nutrient flows in the system of the Dnieper-Bug estuary. Meteorology. Hydrology. Environmental monitoring, 2. 71-80. DOI: 10.15407/Meteorology2022.02.071. [In Ukrainian]
- Ilyin, Yu.P. (2023a). Average condition and seasonal variability of the structure and dynamics of transitional waters in the Dnieper-Bug estuary region. Ukrainian Hydrometeorological Journal, 32. 63-79. DOI: 10.31481/uhmj.32.2023.05 [In Ukrainian]
- Ilyin, Yu. (2023b). Spreading of the extreme water discharge from the Dnipro-Buh estuary into the Black Sea in June 2023 by satellite observations data. Meteorology. Hydrology. Environmental monitoring, 2(4). 62-74. DOI: 10.15407/Meteorology2023.04.062 [In Ukrainian]
- Ilyin, Yu.P. (2024). Manifestation of the interaction of riverine and marine waters in the statistical structure of salinity by the observations data at coastal stations of Ukraine. Meteorology. Hydrology. Environmental monitoring, 2(6). 72-79. DOI: 10.15407/Meteorology2024.06.072
- Yankovsky, A.E., Chapman, D.C. (1997). A simple theory for the fate of buoyant coastal discharges. J. Phys. Oceanogr. 27, 1386–1401.
- Yankovsky, A.E., Ilyin, Y.P. (2024). The Dnipro-Buh plume: A tale of high-volume freshwater discharge in a non-tidal sea. Continental Shelf Research, 282. 105345. 10 pp. DOI: 10.1016/j.csr.2024.105345