Using of multiyear remote sensing data for the Neva Bay and the eastern Gulf of Finland for revealing peculiarities of anthropogenic impacts of hydro-technical facilities building and dredging on the coastal and water environment

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HISTORY OF USING REMOTE SENSING DATA FOR DETECTION OF ANTHROPOGENIC IMPACTS ON THE COASTAL AND WATER ENVIRONMENT OF THE NEVA BAY AND THE EASTERN GULF OF FINLAND

The presentation is devoted to the use of long-term remote sensing (RS) data for assessment of anthropogenic impacts on the coastal and water environment of the Neva Bay (NB) and the eastern part of the Gulf of Finland (EGOF), caused by construction of hydro-engineering facilities, operations for land reclamation, by dredging and underwater dumping. The study period includes past 40 years for which airborne and satellite data are available. Results of using long-term RS data sets for monitoring and studying coastal water environment, for estimation of levels of water contamination by suspended matter (SM), for revealing spatiotemporal variability of SM distribution under the influence of natural and anthropogenic factors, for studying features of surface water dynamics and of phytoplankton development, are discussed.

The archival and operational RS data used were obtained from different platforms and different sensors of optical, thermal and microwave ranges of electromagnetic spectrum. At present RS technologies offer large amount of spatial information from variety of sensors with middle, high and ultra-high spatial resolution, operating in different ranges of electromagnetic spectrum.
The NB of the Gulf of Finland - land reclamation

Operations for land reclamation of future urban territories in the coastal areas of the NB – period from the end of 1960’s till the early 1990’s years

Fragment of Landsat RGB composite image from 21.05.1976. The spring period characterizing by absence of hydro-technical operations (not started yet): 1 – background, relatively clean water; 2 – shallows viewed in conditions of low sea level and high water transparency; 3 – ice; 4 – water with ice fractions.

Photo obtained from space station “Soyuz-22” at 20.09.1976. Patterns of total suspended mater (TSM) distribution in the NB and the EGOF: 1 – background, relatively clean water; 2 – water contaminated by suspended sediments (SS) due to hydro-technical operations for land reclamation.
For this study have been used remote sensing data sets obtained for the Neva Bay and the eastern Gulf of Finland area from different satellite sensors during period since the middle of 70-s years of the past XX century till the resent time.

Landsat from 20.04.1978

RESURS-F from 24.05.1979
The Neva Bay of the Gulf of Finland
Land reclamation and
Construction of the Flood Protection Facility of St. Petersburg

1. Operations for land reclamation of future urban territories in the coastal areas of the NB – the period from the end of 1960’s till the early 1990’s years;

2. The first stage of the Flood Protection Barrier of Saint Petersburg construction (1979 to 1989).

3. The construction of the Flood Barrier was restarted only in 2003 and completed in August 2011.
Water of the NB and the EGOF contaminated by suspended matter due to land reclamation activity as can be seen from satellite images from 09.07.1981, A) RESURS-F, b) KATE-200: 1 – background, relatively clean water; 2 – water contaminated by suspended sediments. 3 – area with maximum level of water contamination.
Construction of the Flood Protection Facility of St. Petersburg (shortly – the Flood Barrier, or the Dam) over the Southern and Northern Gates of the NB has started in 1979. Active construction began in July 1981.

For flood level, + 5m

Flood map generated with GIS system owned and operated by “Morzashchita” – developed in co-operation with WL|Delft Hydraulics.
Bottom features of the Neva Bay revealed on RESURS-F satellite image from 06.05.1983. The spring period characterizing by absence of hydro-technical operations (not started yet), low sea level and unusual high for the NB estuary water transparency. So on the bottom can be detected shallows and fairways. On the image also the constructed part of the Dam (Д) and restricted areas with elevated level of SM (Вз) can be seen.
**Remotely sensed data sets used.** The remotely sensed data used are from airborne and different space borne systems of medium and high spatial resolution: "Meteor", "KOSMOS", "RESURS", “RESURS-F”, "OKEAN" (available in XX century), and from censor MODIS (Terra, Aqua) and LANDSAT satellite system. Another part of the data sets has obtained in course of aerial surveys. These are the air visual observations of the fields of suspended matter pollution, which usually were supported by the spectrometer transaction measurements from the same aircraft.

**Complementary concomitant data used.** In correspondence with available remotely sensed data sets the relevant series of hydro-meteorological network data, including the historical information for several days before space borne monitoring, and conventional in-situ data (hydro-chemical, hydro-biological, hydro-physical) for period under review have been stored and used in analysis. For a large part of remotely sensed imagery the quasi-synchronous ship borne measurements of different water parameters, including the transparency and total suspended matter concentrations are available.

**Knowledge-based data used.** A priori knowledge-based information such as maps of bottom topography, geomorphologic maps, existing knowledge about typical current fields and other parameters, characterizing the bottom sediments tape and size composition, optical properties of the water masses occurring in the region, relations between water parameters, data about upwelling phenomena and about anthropogenic sources of pollution were collected as well.
Methods applied for remote sensing data interpretation.

Calibration of remotely sensed data has made using in-situ measurements at the network stations of *Secchi* depths (transparency) and/or the values of the sediments concentration.

On satellite images of the NB and the EGOF of the 1980’s years period, in accordance with the methods developed six water classes have been distinguished with the following ranges of TSM concentration (see fig.):

1) lower than 10 g/m³ (for relatively clean background water);
2) 10 to 15 g/m³ (for water with very low level of contamination);
3) 15 to 20 g/m³ (for low level case);
4) 20 to 25 g/m³ (for mediate level);
5) 25 to 60 g/m³ (for high level);
6) more than 60 g/m³ (very high level of water contamination).

The last (6 range) corresponds to saturation effect for the commonly used spectral channels.

**Schematic maps of TSM concentrations (g/m³) in the NB and the EGOF, compiled from RS data. In both cases – stable outflow hydro-meteorological situation, low changeable winds and slow oscillations of the sea level.**
Methods applied.

Classification of contaminated zones in the NB and the EGOF using remote sensing methods – degree of contamination, Secchi depth and concentrations

<table>
<thead>
<tr>
<th>Class/zone No.</th>
<th>Degree of contamination</th>
<th>Secchi depth, m</th>
<th>Concentration of particulate matter, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Relatively clean waters,</td>
<td>&gt; 1.0</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>2</td>
<td>Very low</td>
<td>0.7–1.0</td>
<td>10–15</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>0.5–0.7</td>
<td>15–20</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>0.4–0.5</td>
<td>20–25</td>
</tr>
<tr>
<td>5</td>
<td>High</td>
<td>0.2–0.4</td>
<td>25–60</td>
</tr>
<tr>
<td>6</td>
<td>Very high</td>
<td>&lt; 0.2</td>
<td>&gt; 60</td>
</tr>
<tr>
<td>7</td>
<td>Super High</td>
<td>&lt; 0.1</td>
<td>60–1000 (and higher)</td>
</tr>
</tbody>
</table>

Identification of zones with super high degree of water contamination by PSM, with concentration values from 60 to 1000 mg/L as revealed from near-infrared spectral range, canal 5, Landsat-8 from 27.07.2014 (colors within 8 grades of brightness scale - from 128 to 255 units).

TSM in the EGOF from RGB image (canals 432), Landsat-8 from 27.07.2014: 1- background clean waters; 2- very low contaminations; 3- low; 4- moderate; 5- high; 6- very high; 7- phytoplankton. Hydro-meteorological situation – calm weather; low sea level, -27 cm by BS. Water stratification, upwelling.
LANDSAT image from 08.08.1986 – unusual dynamics of water flows, for the stage of the Dam construction when the Northern Gates of the NB were almost closed: 1 – water contaminated by suspended sediments; 2 – cianobacteria bloom; 3 – background, relatively clean water.
Features of water dynamics at different stages of the Dam construction

Superposition of different time satellite images:
Resource-F/KATE-200 – from 08.08.1986 with ratio of flows through Northern and Southern Gates of the NB become 26% and 74%, respectively, and Resource-F/KFA-1000 – from 12.07.1989 with ratio of flows of 58% to 42%. From the image can be seen the features of water dynamics traced by suspended sediments (SS): the red tones refer to 1986 case and the green – to 1989. The first (1986) represents unusual dynamics of water flows, for the stage of the Dam construction when the Northern Gates of the NB were almost closed.
In the early 1990’s, after 15 years of hydro-technical works, the Barrier construction was suspended, at that time approximately 40% of the construction works were already completed. It occurred due to coincidence of drastic political and economical changes in the country and the authoritative but incorrect conclusion, supported by public opinion, that namely the Flood Barrier was the main source of the poor ecological state of the NB. As a result, the financing of the Dam construction was stopped.

Dynamic of benthos in the Neva Bay

Creation of storm-surge barrier have caused:
- redistribution of macrozoobenthos along the Neva Bay
- decrease of abundance and biomass.
During the examined part of 40-years period that belongs to the past XX century in the NB and the EGOF the following large scale hydro-technical activity were conducted:

1) operations for land reclamation of future urban territories in the coastal areas of the NB – a period from the end of 1960’s till the early 1990’s years;
2) the first stage of the Flood Protection Barrier of Saint Petersburg construction – from 1979 till 1989.

In the early 1990’s, after 15 years of hydro-technical works, the Barrier construction was suspended, at that time approximately 40% of the construction works were already completed.
Anthropogenic impacts on the coastal and water environment of the NB and EGOF during XXI Century

For the period of about 10 years (from 1993 till 2004) in the region under investigation the relatively “calm situation” related to them economical development can be detected.

Namely, begins from the early 1990s and coincides with the crisis in agriculture and industry at the same time in the Neva Bay (NB) was interrupted/finished the dredging activity for ground filling. As a result through time considerable amelioration of waters quality parameters have been settled and natural for the NB, level of variations of TSM concentrations were in range from 5 to 25 g/m3 has been established.

A new stage of essential anthropogenic impacts of hydro-technical facilities building, land reclamation, dredging operations and under water dumping on the coastal and water environment of the NB and EGOF began in early 2000’s:

1. The second stage of the Barrier construction after interruption (restarted in 2003 and finished in 2011);
2. The construction of the port of Ust’-Luga started in 2003;
3. The large Sea Façade of Saint-Petersburg Project realized from 2006 to 2008 years, with more active phase of dredging in 2006 to 2007;
4. The large Project for construction of the multipurpose maritime transshipment port complex (MMTPC) of Bronka, the period of implementation – 2011 - 2015, the more active dredging activity was observed from 2013 to 2015 years.
The second stage of the Barrier construction after interruption restarted in 2003 and finished in 2011

On the picture Vessels traffic-gate C1 (200 meters wide) is closed – during the official opening of the Barrier on 22 August 2011

Patterns of suspended sediments distribution in the eastern Gulf of Finland registered from LANDSAT-5 20.08.2011. In the EGOF can be detected phytoplankton blooms, water stratification, and upwelling event. Sediments re-suspension happens in the Neva Bay under wind-wave action – winds of eastern directions up to 8-10m/s; low sea level, -20 cm BS. Behind the water gates of the Dam mushroom eddies forms.
The Project «Sea Façade of the St. Petersburg» implementation

According Project plan volumes of dredging in the NB were as:

- for 2005 г. – 1 230 000 м³,
- for 2006 г. – 12 150 000 м³,
- for 2007 г. – more than 8 000 000 м³

Period – before the project «Sea Façade of the St. Petersburg» implementation started (for father ecological impact assessment this will be consider as Period 1).

Satellite image of the NB and the EGOF obtained from sensor MODIS 10.08.2004.
Variability of hydro-physical fields in the EGOF caused by influence of natural and anthropogenic factors. These scenarios were chosen from Data Base created as a result of satellite ecological monitoring during implementation of the Project “The Sea Façade”. Period 2 – 2005-2008.
Levels of contamination.
Concentrations of suspended matter:
1 – very high,
2 – high,
3 – medium,
4 – low,
5 – oil pollution,
6 – shallows,
7 – passenger terminal – under construction,
8 – background waters of the Neva Bay (with TSM concentration 7-8 mg/l).

Period 2 (2005-2008)
Period 2 (2005-2008) – implementation of the Project “The Sea Façade of the St. Petersburg”

a) Quick Bird image of the Neva Bay from 08.08.2007 – the spot of water contamination by suspended sediments;
b) Relative values of water radiances in channel-2 (for 16 intervals);
c) MODIS/Aqua image, also from 08.08.2007, shows the large scale of SS dispersion (located away from license areas for sediment dumping);
d) Results of cluster analysis of the polluted water area on the Quick Bird image (a):
   1 - 6 subareas with different values of sediments concentrations: 1 – minimum amount of suspended sediments, 6 – maximum values in the spot of illegal underwater deposition (illegal dumping site), S – sewage plum from waste-pipes, T – new terminal (under construction).
Scenario of fine-grained SS distribution in the EGOF for the late autumn conditions

Period 2
(2005-2008)

Aqua/MODIS from 14.11.2007

Levels of water concentration by suspended matter:
1 – maximal (very high);
2 – high;
3 – medium;
4 – low;
5 – clouds;
6 – shadows from clouds.
Late autumn. Winter aspect of the area study. Distribution of fine suspended sediments after the dredging activity in the Neva Bay was already stopped due to ice conditions. Scenario was chosen from satellite Data Base for the EGoF (ecological monitoring during implementation of the Project “The Sea Façade of the St. Petersburg” has been conducted by NIIKAM using MODIS satellite images).
Inter-annual Zebra mussel biomass \((g/m^2)\) dynamics, Satellite data and relative periods

Sources of variations are unclear, recruitment is irregular (Orlova, Panov, 2004)

Quasi-stable state of population with annual recruitment and elimination of settled juveniles and old specimens
Examples adjusting a high variability in hydro-physical fields of the EGOF RS data for 2011-2013 years

Optical in-homogeneity in the EGOF obtained from MODIS 21.06.2012. Winds WSW direction 7 - 11 m/s. Wind shadows behind the isles. Sediments re-suspension in the Neva Bay

Period 3, after dredging stopped (2009-2013)

Patterns of suspended sediments distribution in the dam area of the EGOF at 20.08.2011. LANDSAT-5/TM. Eastern wind, 5 - 10 m/s. Low sea level, -17 cm BS. Re-suspension of sediments in the Neva Bay

Results of continuous satellite monitoring of the NB and eastern EGOF, implemented on the basis of censor MODIS data with medium spatial resolution (250m), show that the observed in 2006-2009 anthropogenic impact on the NB and the EGOF was caused mainly by dredging and ground disposal during implementation of large project «Sea Facade of Saint Petersburg». The extremely high level of water pollution by SM was detected in 2006-2007. Obtained results were compared with our previous investigations for period since middle of the 1970s till 2005. We can concluded that volumes of hydro-technical engineering and scales of pollution identified from satellite images for these years exceed observed earlier, caused by dredging operations for ground filling of urban territories (during the 1970s – 1980s years).
The multipurpose maritime transshipment port complex (MMTPC) “Bronka”

According the plan of Project “Bronka” entire volume of dredging in the NB during 2013-2015 period was estimated as $29,300,000$ m$^3$.

Results of modeling assessment of expected increase of water turbidity in the NB and EGOF due to dredging activity during construction of planned the seaport “Bronka” according to EAI.
1 – very high level of water contamination by SM nearby settlements Lomonosovo and Bronka; 2 – zones with a high degree of pollution; 3 – medium degree of pollution; 4 – plums of SM nearby the Terminal; 5 – plume of turbid waters in the area of the bridge under construction; 6 – contaminated water coming from the river; 7 – inflow of brackish waters from the EGOF throw the sea channel; 8 – upwelling water; 9 – clouds; 10 – the shadows from clouds; 11 – plum of turbid waters coming from the lake Sestroretsky Razliv.

Landsat-8 synthesized image (channels 432) from 21.10.2013.

Hydro-physical fields distribution in the EGOF. Wind of West directions 2 m/Ps, low sea level, -20 cm BS.
Scenarios of SS from dredging distribution in EGOF under the influence of natural and anthropogenic factors revealed from censor MODIS for 2014 year. The port “Bronka” construction is implemented in the south-eastern part of the Neva Bay.

a) 15.05.2014, calm weather, sea level –8 cm by BS, stratification and upwelling can be observed; b) 15.06.2014, decreasing sea level situation, NE winds; c) 27.07.2014 intensification of dredging activity, water stratification, upwelling, NW winds, high level of SS can be detected even along the northern coast of EGOF; 

d) 11.07.2014, stratification, NE winds 3-4 m/sec, low sea level (–15 cm by BS); 
e) 27.07.2014, stratification, upwelling, calm weather, low sea level (–27 cm by BS); 
f) 16.09.2014, stratification, upwelling, NE winds.
Scenarios of SS distribution in EGOF under the influence of natural and anthropogenic factors revealed from censor MODIS for 2015 year

a) — image from 11.04.2015, NW winds 4–5 m/sec, sea level 10 cm by BS, stratification, upwelling, spring development of phytoplankton;
b) — from 08.05.2015, SW wind 5–6 m/sec, sea level - 2 cm by BS, stratification, upwelling;
c) — from 15.05.2015, NW wind 4–5 m/sec, level - 28 cm by BS, stratification, upwelling; turbid water can be detected along the coast of the Kurortny District;
d) — from 25.05.2014, W-SW wind, 1–3 m/sec, level — 10 cm by BS, stratification, upwelling; peculiarity of suspended matter distribution in the southern part of the NB evidences the intrusion of salt waters along the Sea Channel;
e) — from 06.06.2015, SW wind, 4 m/sec, level 26 cm by BS, stratification, upwelling;
f) — from 07.06.2015, W winds, 6 m/sec, level 58 cm by BS, stratification upwelling.
Identification of super high degree of water contamination by SM

The spot of water contaminated by suspended matter in the vicinity of seaport “Bronka” construction site as revealed from composite Landsat-8 image (channels 432) from 04.05.2015.

Identification of zones with super high degree of contamination of the NB and the EGOF by SM, with concentration values from 60 to 1000 mg/L as revealed from near-infrared spectral range data, channel 5 of the Landsat-8 from 04.05.2015 (colors within 8 lower grades of brightness scale — from 128 to 255 units). Land is masked.
From results of fisheries monitoring carried out in by GosNIO RKH in 2011, 2013, 2014 in the biota of the construction area of the port “Bronka” essential changes (most pronounced in 2014) were marked /Susloparova et al., 2015/:

• The ecological state of the aquatic environment worsened due to increasing the concentration of suspended mater, 376.0 mg/l at the surface and to 1830.0 mg/l at the bottom.
• The water transparency decreased to 0.03-0.10 m.
• The abundance of fish feed base has also decreased.
• The number of benthic invertebrates species decreased in 1.5 times from June to October 2014.
• Stocks of feed zoobenthos (for fish) decreased from 5.52 to 2.97 g/m2.
• The impact on the fish had a cumulative prolonged character.
• The change in bio-productivity of the area was caused by the loss of the spawning grounds and pastures because of exclusion productive section of the bay for the port territory.
Conclusion
As a result of our study conducted on the basis of multiyear RS data during the examined four decades can be distinguished 3 periods characterized by aggravation of ecological state of the NB and the EGOF:

1. **The first** one lasted since the middle 1970’s till the early 1990’s, when large scale operations for land reclamation of urban territories were being conducted in the shallows of the NB.

2. **The second** period begins from the early 1990’s and goes on till early 2000’s; this coincides with the crisis in agriculture and industry; at the same time the activity for the land reclamation in the NB was cancelled. As a result, considerable amelioration of ecological situation and improving of waters quality parameters can be observed.

3. **The third period** started from early 2000’s and involved 4 large projects:
   - the next stage of the Barrier construction (restarted after interruption in 2003 and finished in 2011);
   - the port of “Ust’ Luga” construction (2003 – 2014);
   - the large Project “Sea Façade of Saint-Petersburg” realization (2006 – 2008);
   - the large Project for construction of the port “Bronka” (2011 – 2015).
Due to the fact that in the NB and the EGOF in nearest future is expected a realization of a new large-scale hydro-technical projects, it is necessary to take measures for harmonization of needs for economical development and environment protection.
Thank you for your attention!