Методи досліджень

Research methods

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APPLICATION OF REMOTE SENSING DATA
AND NORMALIZED DIFFERENCE TURBIDITY INDEX (NDTI)
TO DETERMINE THE GEOMORPHOLOGY OF FLOODED COASTS

This publication is devoted to studying the geomorphological features of the seafloor on the northwestern Black Sea shelf (within the Dnipro Estuary) utilizing remote sensing data processing methodologies. Based on a range of geological evidence, the present-day morphology of the northwestern Black Sea shelf represents a continuation of the late Pleistocene subaerial coastal plain, which was incised by fluvial valleys and subsequently modified and partially leveled by a multi-phase marine transgression that persists to the present day. In coastal regions, seafloor geomorphology is primarily defined by inundated terraces and relict shorelines, which are of significant interest to geologists, ecologists, and archaeologists alike. When direct access to water bodies is restricted, remote sensing provides the most effective means of studying inundated shorelines. This study utilizes satellite observations from the Sentinel-2 mission, applying spectral band combinations based on the Normalized Difference Turbidity Index (NDTI) derived index for assessing water turbidity and transparency. By applying specialized image-processing techniques to satellite data, we reconstructed the position of the former coastline within the Dnipro Estuary, now submerged. The results were validated against bathymetric maps. This approach can be recommended for investigations of seafloor geomorphology, coastal geoecological processes, and enhancing the accuracy of locating ancient settlements.

***Keywords**: coast, remote sensing, multispectral data, northwestern Black Sea shelf, water surface, Normalized Difference Turbidity Index (NDTI).*

Introduction

The geomorphological study of the seabed and coastal areas on the northwestern shelf of the Black Sea has employed several complementary methods. These include lithostratigraphic analysis, which uses data on the composition of rocks from seabed drilling followed by mapping [1]; mineralogical analysis of coastal-zone minerals [5]; paleontological investigation of fossilized remains of terrestrial and marine flora and fauna [4, 6]; and archaeological methods involving hydroacoustic surveys of seabed topography and

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underwater artifacts [2]. However, these approaches demand direct access to the study area. Because access to much of the Ukrainian sector of the Black Sea shelf is restricted, an alternative method is required-one that enables observation without physical presence. In this context, remote sensing provides an effective means of monitoring changes in the water surface and seabed from a distance.

This study investigates the geomorphology of the coastal area of the estuary by identifying submerged coastlines and terraces at the current stage of the Black Sea's geological development. To solve this problem, it was necessary to determine the data and the method of its processing. To study changes in water surfaces, researchers use multispectral remote sensing data and apply formulas of various water-normalized indices: These include the Normalized Difference Water Index (NDWI) [10], the Modified Normalized Difference Water Index (MNDWI), the Normalized Difference Moisture Index (NDMI), the Water Ratio Index (WRI), the Automated Water Extraction Index (AWEI) [11, 18], and the Normalized Difference Turbidity Index (NDTI) [13]. To study water surfaces using SAR radar data, VH polarization or the VH-to-VV ratio is used [17].

The object of this study is the Dnipro Estuary on the northwestern shelf of the Black Sea (Fig. 1), with a focus on identifying shorelines submerged at depths of 2—3 meters.

Archaeologists have recorded approximately one hundred archaeological settlements within the northwestern Black Sea shelf and its coastal areas [2]. The sea transgression process observed in recent centuries has led to significant flooding of the coastline. The coastal structures built as protective fortifications along the shore ended up underwater. Over time, these structures turn into sandy material that partially erodes and then completely disappears, leaving no trace of the flooded coastline. The presence and accumulation of this material enable researchers to identify historical sites using hydroacoustic and other methods. The presence of sandy material at shallow depths of up to two to three meters, provided the water is relatively clear and the weather is favorable, allows identification of past coastlines underwater using processed optical data from satellite images. Therefore, multispectral data from the European Space Agency's Sentinel-2 mission was used, as it is available for download in the public domain.

Fig. 1. Overview map of depths on the northwestern Black Sea shelf showing changes based on data from [3]. The study area is highlighted in orange

Data and Research Methodology

To analyze changes in water bodies, researchers employ optical and radar satellite datasets, freely available from missions such as Sentinel-1 [12, 19], Sentinel-2 [7, 20], Landsat [8, 15], MODIS [9, 16], among others.

Multispectral data from the Sentinel-2 mission offer several advantages, most notably a spatial resolution of 10—20 m. In comparison, Landsat missions 1—5 and 7 provide a resolution of 30 m, while MODIS offers resolutions of 250, 500, and 1.000 m. In terms of temporal coverage, Landsat revisits every 16 days, MODIS every 1—2 days, and Sentinel-2 every 5 days, reduced to 2—3 days at mid-latitudes due to wide overlap. With respect to swath width, MODIS provides the largest coverage (2.330 km), followed by Sentinel-2 (290 km) and Landsat (185 km). Considering these parameters, Sentinel-2 imagery represents the most suitable dataset for monitoring individual water bodies, combining high spatial resolution with optimal temporal frequency and sufficient coverage.

A key limitation of optical satellite data is the dependence on weather conditions, as cloud, snow, or ice cover can substantially reduce surface visibility. To mitigate this constraint, only images with 0% cloud cover were selected for analysis.

Identifying submerged coastlines expressed in seafloor geomorphology requires consideration of the relative transparency of the water column as observed in satellite imagery. Seasonal and periodic increases in turbidity, primarily driven by vegetation growth and algal blooms, are particularly pronounced in shallow waters and can obscure detection. To minimize this effect, monitoring should be conducted during off-season periods, when plant-induced turbidity is absent.

The principal criterion for selecting imagery to accurately detect changes in the water surface is the choice of a monitoring period with atmospheric conditions comparable to summer but preceding planktonic and other vegetative blooms. For the northwestern sector of the Black Sea, including the Dnipro Estuary, the optimal observation window occurs in late spring (April-May) to early summer (June), depending on interannual variability.

Another challenge is the precise delineation of boundaries between aquatic and terrestrial environments, which is often affected by pixel blurring. This issue is typically addressed for specific study areas through additional stages of spatial data processing. In the present study, however, this factor is not critical, as the analysis is confined to a single water body.

The subsequent stage of the study involved selecting appropriate spectral band combinations and applying a formula for calculating the normalized difference index.

While indices such as NDWI are commonly applied to study the water surface, the present research focused on seafloor geomorphology. This required the use of an index with parameters sensitive to underwater changes under conditions of partial transparency. The most suitable choice is the NDTI, which is calculated using pixel values from the green (Green) and red (Red) spectral bands. NDTI quantifies water transparency-turbidity on a scale from —1 (high transparency) to +1 (high turbidity). Unlike indices associated with suspended sediment concentration, NDTI does not directly measure solid matter content and is therefore often applied in combination with other datasets to support comprehensive assessments of water quality.

Overall, the research methodology can be described as comprising several sequential stages:

Fig. 2. Map of the Dnipro Estuary derived from a Sentinel-2 true-color image. The numbered sections indicate coastal areas with archaeological settlements [2, 14]: *1* — Cape Bublikova; *2* — Stanislav, Zolotyi Mys settlement, and Hlyboka Prystan; *3* — Beikush settlement
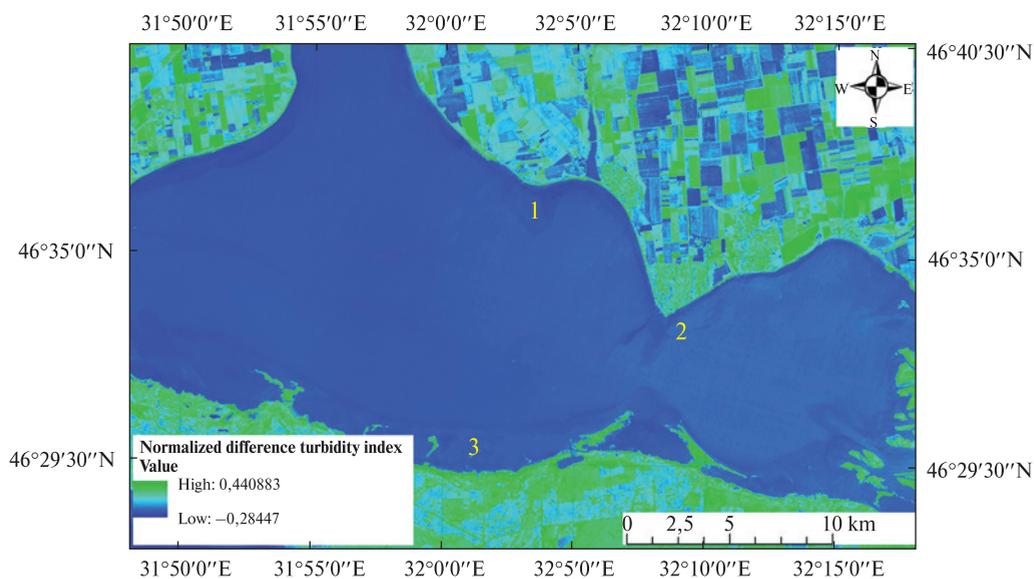

Fig. 3. NDTI map of the Dnipro Estuary derived from Sentinel-2 data (survey date: 9 April 2020). Numbered sections indicate coastal areas containing archaeological settlements (see legend in Fig. 2)

1. Selection of Earth observation data. This stage involves choosing imagery acquired under optimal weather conditions, with 0 % cloud cover and sufficient water column transparency (minimal surface disturbances, vegetation, or other interferences). Ensuring overall image quality is also a key consideration.

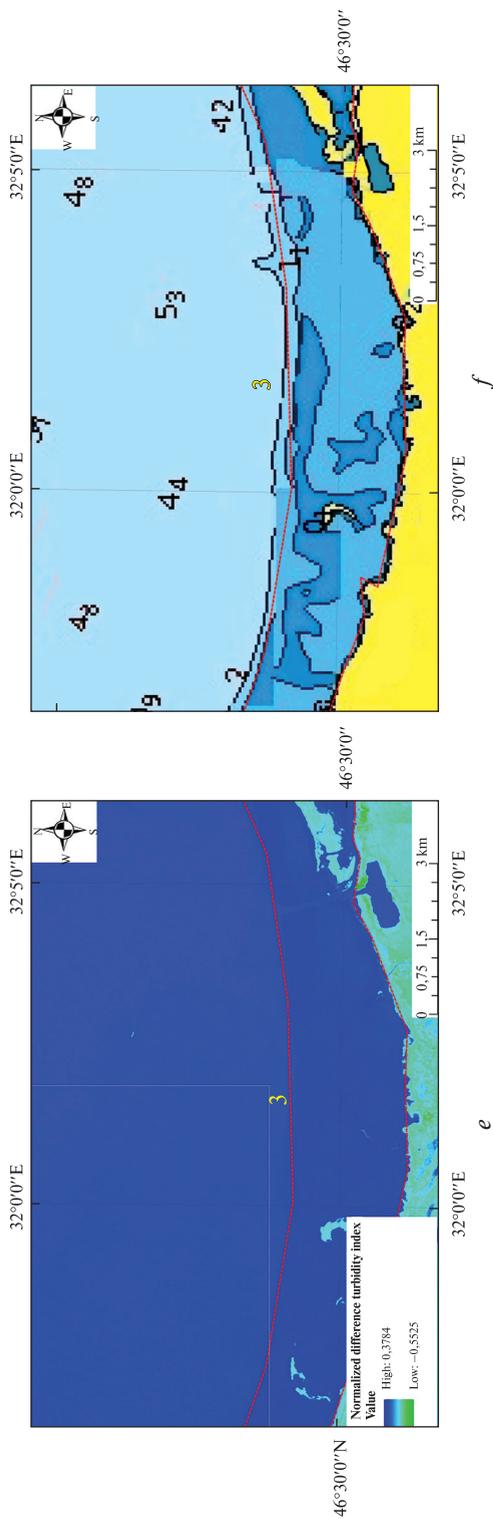2. Acquisition of data from the Copernicus Data Portal: https://browser.data-space.copernicus.eu/.
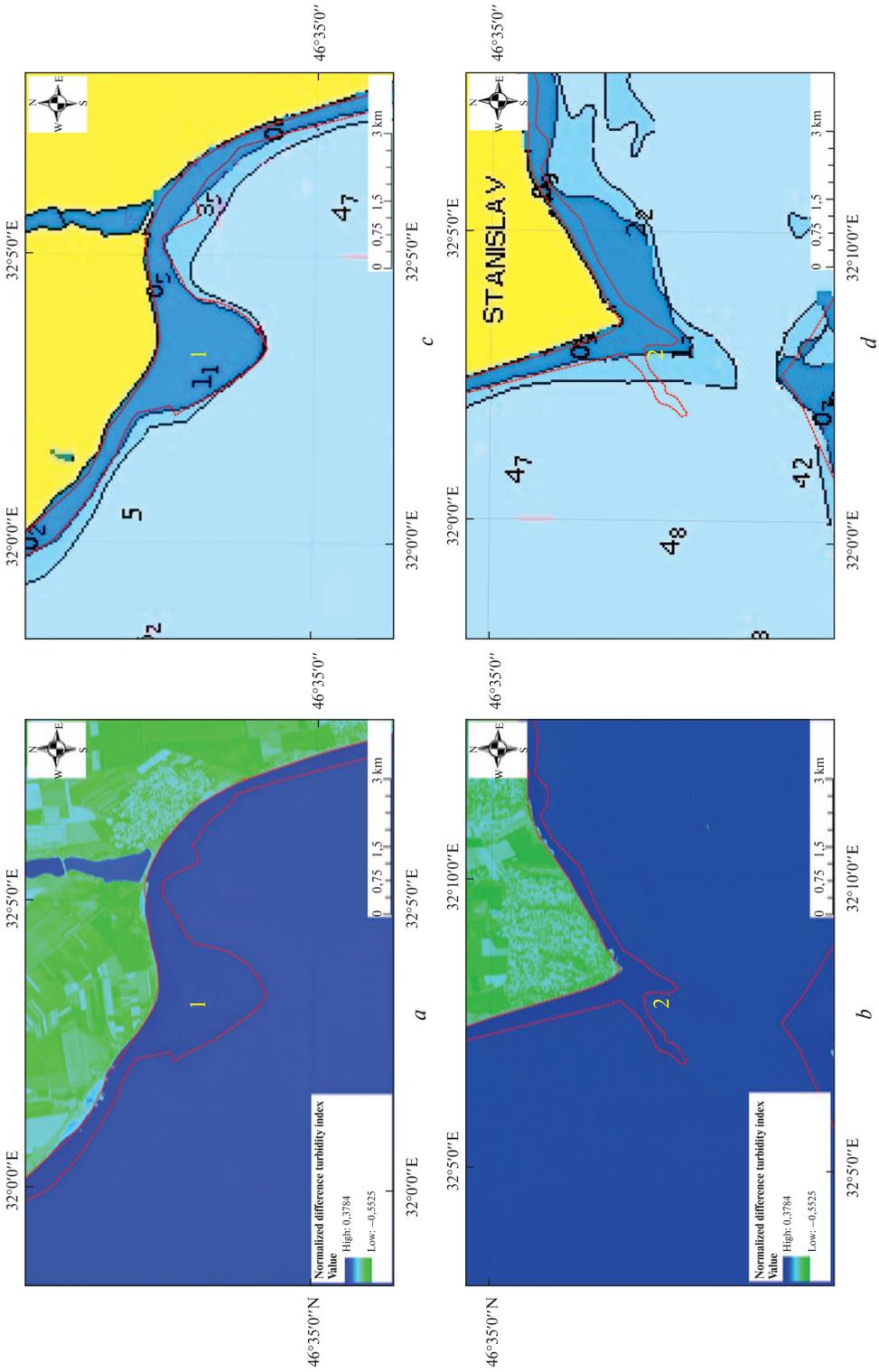
Fig. 4. NDTI-derived maps showing the submerged coastline near identified archaeological settlements within the Dnipro Estuary, constructed using Sentinel-2 data acquired on 9 April 2020 (*a, c, e*), and depth maps showing the identified submerged coastline (*b, d, f*): *a, b* — near Cape Bublikova (*1*); *c, d* — near Stanislav village and Zolotyi Mys settlement (*2*); *e, f* — near Beikush settlement (*3*)

3. Processing of the acquired data using the open-source GIS platform SNAP (https://step.esa.int/main/download/snap-download/). Georeference the data and generate raster images using water index formulas. Subsequently, classify the object types and, if required, perform post-classification refinement and vectorization.

4. Mapping, compilation, and design of the resulting maps.

5. Analysis of the processed data and interpretation of the results.

The northwestern Black Sea coast hosts approximately 200 archaeological sites, with remains located along the shores of water bodies or submerged underwater. Archaeological studies have identified more than ten ancient settlements and fortified sites dating from the 5th century BCE to the 3rd century CE within the coastal areas of the Dnipro Estuary. Notable examples include the hillfort settlements of Zolotyi Mys (1st — 3rd century CE) and Hlyboka Prystan (corresponding to the peak period of the Olbia state), as well as the Tyagin fortress (14th — 16th century CE), situated approximately 60 km upstream of the Dnipro Estuary [2]. However, some settlements that were in the coastal zone in the past are now underwater. Accurate identification of such objects is necessary to study them. To continue the research, Sentinel-2 satellite images from the last three years were monitored, and the optimal image, Product S2B_MSI1CL, from April 9, 2020, was selected. The map in the visible range (Fig. 2) shows traces of the flooded coastline or terraces of the Dnieper Estuary in pixel contrast. The numbers indicate sections of the coastline with archaeological settlements, according to data [2].

Cape Bublikova (Fig. 3, mark 1) is considered the probable location of the Temple of Demetra. The Beikush settlement (Fig. 3, mark 3) lies at the confluence of the Berezan and Beikush estuaries, approximately 8 km west of Ochakiv. According to [2], the area also contains the ancient settlements of Geroyske-1 (3rd — 4th century BCE) and Geroyske-2 (1st — 3rd century CE).

Results and Their Discussion

Analyzing Sentinel-2 data from recent years, we selected an image from April 9, 2020 (product S2B_MSI1CL) and constructed an NDTI raster using the formula:

$$NDTI = (B_{RED} - B_{GREEN}) / (B_{RED} + B_{GREEN}),$$

where B_{RED} — red spectral band, B_{GREEN} — green spectral band.

As a result, a map of the Dnieper Estuary of the northwestern shelf of the Black Sea was constructed using the NDTI formula with the red and green spectral ranges (Fig. 3). Flooded shores were identified by pixel contrast.

As a result, paleoshorelines within the Dnieper Estuary on the northwestern shelf of the Black Sea were identified using the NDTI. This complements the information obtained in previous stages of the study using water indices.

According to preliminary studies, the NDWI and MNDWI models, as well as the NDTI map, identified a coastline in pixel contrast. The processed images show a sharp change in pixels, which is explained by changes in the depth and transparency of the surface layer of water. These changes are recorded as the past coastline.

In the next stage of the study, a detailed analysis was performed on three areas of the Dnieper Estuary, and the identified flooded coastline was plotted. To verify the results, a comparative analysis was performed by plotting the identified flooded coastline on a depth map (Fig. 4, *a—f*).

The submerged coastline identified using NDTI was overlaid on a detailed bathymetric map (see Fig. 4). The resulting delineation closely follows the isobaths, with pronounced depth transitions at 2—3 m, demonstrating the effectiveness of multispectral data and the water turbidity/transparency index for investigating shallow coastal areas. Adhering to specific criteria for satellite image processing enables this method to be applied remotely, representing a clear advantage over traditional field-based approaches under these conditions.

The presented method can be applied by meeting certain criteria for the sequence of processing space images. This is an absolute advantage over other methods in these conditions because it eliminates the need to be directly at the research site.

Concluding Remarks

The primary objective of this study was to identify an optimal method for detecting submerged shorelines without the need for direct on-site access, using the Dnipro Estuary on the northwestern Black Sea shelf as a case study. Multispectral remote sensing data were employed to achieve this goal. While optical data is subject to limitations — including weather conditions, seasonal variations in water clarity and surface characteristics, and challenges in distinguishing underwater features — these constraints were addressed through the development of a specific algorithm for the application and processing of remote sensing imagery, as presented in this study.

Using multispectral Sentinel-2 imagery, we identified the submerged coastline of the Dnipro Estuary, including areas corresponding to known archaeological settlements and potential locations of additional flooded sites. The coastline was delineated based on pixel contrast at depths of 2—3 m, employing the NDTI to assess water transparency and turbidity.

This method is recommended for investigating seafloor geomorphology at shallow depths (up to 3 m) under conditions of moderate water transparency, as well as for mapping water bodies, coastal zones, and continental shelf areas. It is also suitable for studying sites with submerged archaeological remains -primarily composed of sandy material — and for monitoring environmental aspects of the marine environment, such as increases in seafloor sediment accumulation observable in satellite imagery.

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ЗАСТОСУВАННЯ ДАНИХ ДИСТАНЦІЙНОГО ЗОНДУВАННЯ ТА НОРМАЛІЗОВАНОГО ІНДЕКСУ КАЛАМУТНОСТІ (NDTI) ДЛЯ ВИЗНАЧЕННЯ ГЕОМОРФОЛОГІЇ ЗАТОПЛЕНИХ БЕРЕГІВ

Публікація присвячена дослідженню геоморфології дна прибережної зони на ділянці північно-західного шельфу Чорного моря (в межах Дніпровського лиману) за допомогою методу обробки даних дистанційного зондування Землі. Сучасний рельєф північно-західного шельфу Чорного моря, за різними даними, успадкований від пізньоплейстоценового субаерального рельєфу приморської рівнини, розчленованої річковими долинами, і у подальшому згладжено в ході багатоетапної трансгресії моря, яка продовжується і в наш час. В прибережних зонах геоморфологія дна представлена затопленими терасами або берегами минулих часів, які вивчають вчені-геологи, екологи, археологи. В умовах обмеженого доступу до водного обєкту, оптимальним методом дослідження затоплених берегів є застосування даних космічних технологій. В представленій статті використані супутникові дані місії Sentinel-2 з комбінаціями спектральних діапазонів за формулою індексу каламутності/прозорості води (NDTI). Використовуючи певну технологію обробки космічних знімків, вдалося визначити розташування берегової лінії минулих часів в межах Дніпровського лиману, яка в наш час знаходиться під водою. Верифікацію отриманих результатів було виконано за допомогою карти глибин. Визначену методику можна рекомендувати для вивчення: геоморфології дна, геоекологічних процесів прибережних зон, для уточнення пошуку місць давніх поселень.

Ключові слова: берег, дистанційне зондування Землі, мультиспектральні дані, північно-західний шельф Чорного моря, індекс каламутності/прозорості води NDTI.