UDC 574
IRSTI 87.51.15
DOI 10.37238/1680-0761.2023.92(4).87

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REMOTE SENSING OF CHLOROPHYLL LEVELS IN OXBOW LAKES WITH VARIABLE WATER VOLUME IMPLEMENTED WITH SENTINEL-2

Annotation. *Although in an era of climate change and increasingly violent weather events, extreme events (flooding vs. desiccation) cannot be eliminated, and their management in river floodplains can significantly contribute. The article focuses on the role played by oxbow lakes in water accumulation and primary production using a section of the Ural River valley (western Kazakhstan) as an example. The level of water accumulation in these areas significantly changed between spring and summer. The area is also an important site of primary production. Chlorophyll-a can be used as a proxy for the amount of phytoplankton and is an important water quality parameter. This ecological formation in oxbow lakes causes selective absorption of light by chlorophyll-a pigment that can be identified by remote sensing of watercolor. Using satellite imagery has proven to be an excellent tool for assessing the potential of the floodplain and selecting sites of monitoring interest. In this way, it was pointed out that the role of river basins is to increase the resilience of the basin to climate and anthropogenic changes, as well as to increase water security, improve water quality, and enhance ecosystem services for society.*

Key words*: floodplain; water accumulation; primary production; climate change; Ural valley*

Introduction

Advances in the combination of transdisciplinary environmental sciences provide the backdrop for integrating two areas of water resources management: flood risk management or drought and sustainable floodplain management. Evidence shows that exposure of people and property to natural disasters has increased over the past decade [1-3]. There is a growing risk of impeding social progress, threatening health, well-being, employment opportunities, safety, water quality, and economic development [4]. Public institutions, scientists, and economic players must move toward a more comprehensive approach to disaster risk management [3].

Each natural river valley is characterized by an unregulated, meandering, or anastomosing river, rich in contiguous sites of varying depths and floodplains abundant with water, especially during high tides [5, 6]. Of this group, oxbow lakes, a transitional form between lotic and lentic ecosystems, seem particularly interesting. As a rule, they are characterized by a semicircular shape resulting from the riverbed's hydrodynamic (erosion-accumulation) processes. Oxbow lakes belong to water bodies, which, due to their specific origin, morphometry, and hydrodynamics, must be treated as separate types of aquatic ecosystems, unlike lakes of a different genesis, especially post-glacial [7, 8].

Climate change and the increasing frequency and intensity of extreme weather events such as floods, tornadoes, droughts, and drying up of streams and rivers [2], as well as the severe environmental degradation observed in many catchments and floodplains, have led to a reduction in the carrying capacity of the global system [9]. Satellite imagery can support management and decision-making to help reduce risks to human health and target field resources for water shortages or potentially harmful algal blooms (HABs) [10]. Within HABs, cyanobacterial (cyanoHAB) blooms are increasing in frequency, magnitude, and duration worldwide in freshwater [11, 12].

The Ural River, a transboundary water body flowing into the Caspian Sea and one of the major rivers in the basin, has been characterized in recent years by a sharp decline in groundwater levels and biological resources [13, 14]. This poses a serious challenge with the observed and projected climate changes. However, due to the highly meandering nature of the Ural River's channel, numerous floodplain lakes are observed in the river valley, which can serve as a reservoir of water and biodiversity (Fig. 1).

***Figure 1** – Ural River oxbow lakes filled with water in fall 2023.*

Our objectives in this work were to determine on a selected floodplain section of the Ural River valley: (i) the amount of water accumulated in spring and summer; (ii) changes in chlorophyll-a concentration (primary production level) using satellite data.

Materials and methods

The Ural River, the third longest river in Europe, is the traditional border between Europe and Asia. According to various sources, the river's total length varies from 2428 km to 2534 km. Its sources are located on the southeastern slopes of the Urals, at an altitude of 640 meters above sea level, and it flows through Russia and Kazakhstan to the Caspian Sea. The length of the Kazakhstan part of the main Ural stream is 1084 km. The total catchment area is about 220,000 square kilometers. The Ural River plays a unique role in the Caspian Sea basin [15], the region's only free-flowing river with an unregulated hydrological regime in the lower and middle reaches. It is rich in numerous oxbow lakes, only some of which are rich in water all year round and in which aquatic flora and fauna can exist permanently (Fig. 1). A small section of the valley in front of the town of Oral was selected for the study (Fig. 2).

Sentinel- 2B is Europe's latest high-resolution, long-range multispectral imaging mission, incorporating MSI with 13 spectral channels in the visible/near-infrared (VNIR) and short-wave infrared (SWIR) spectrum, launched in December 2017. MSI has a spatial resolution of 10 meters and a 5-day re-visit period. The Sentinel mission provides good quality, high-resolution data in Levels 1B, 1C, and 2A. Level 1B products are radiometrically corrected images for upper atmosphere (TOA) radiation values and sensor geometry. Level 1C and 2A products are TOA and bottom-of-atmosphere reflections in cartographic geometry, respectively.

For the current analysis, the multispectral satellite datasets of Sentinel-2B MSI (S2-B) of wet and dry periods (April and July) during 2023 covering the study area were retrieved from the Copernicus Data Space Ecosystem (https://dataspace.copernicus.eu/) of the "European Space Agency" (ESA).

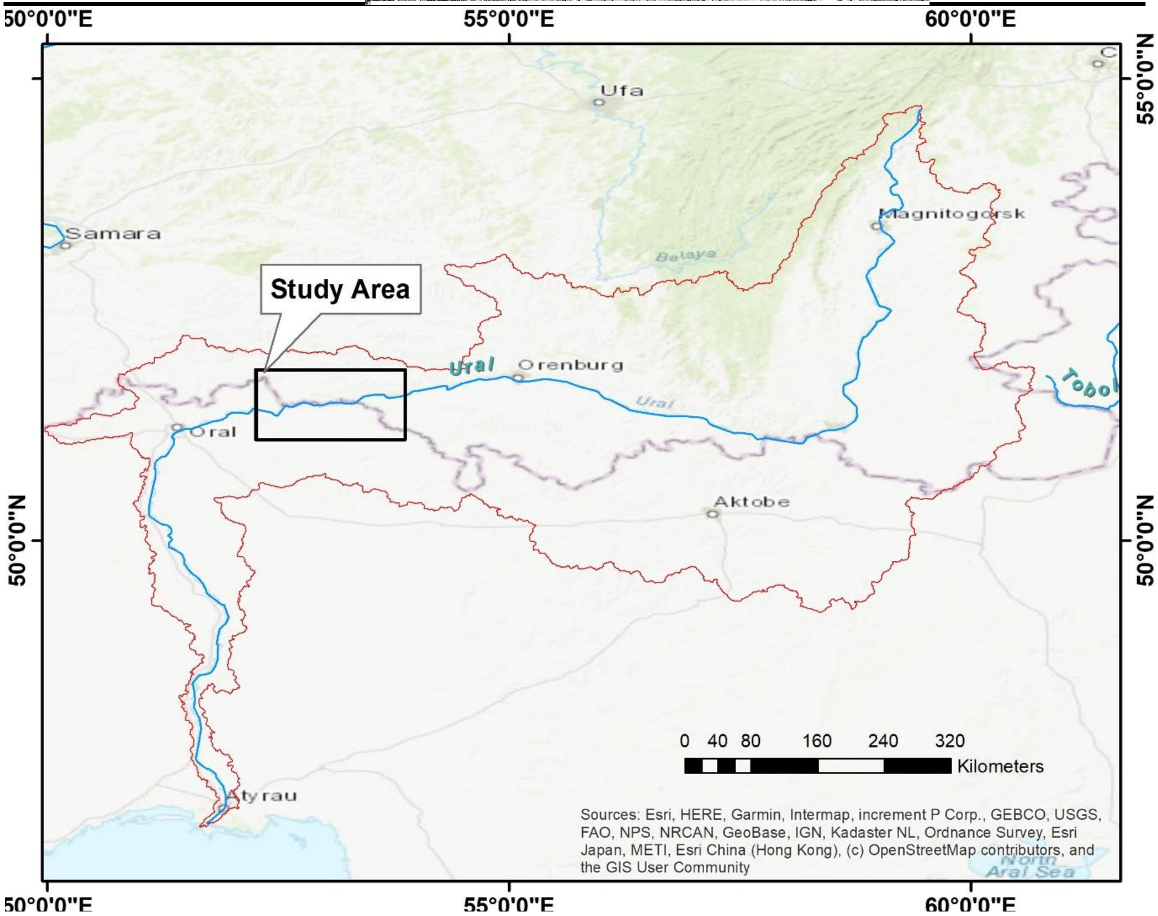

Figure 2 *– Location selected for the current study*

Table 1 – *Relevant specifics of the satellite datasets (S2-B) employed in the current investigation*

Satellite	Sensor	Orbit		Spectral Bands	Spectral Signature	Wavelength (µm)	Resolution (m)
		Altitude	Inclination				
Sentinel 2B	**MSI** (Multispectral Instrument)	786 Km	98.62 °	Band 3	Green	0.55 – 0.58	10
				Band 4	Red	0.65 – 0.68	10
				Band 5	RE 1 (Red Edge 1)	0.70 – 0.73	10
				Band 6	RE 2 (Red Edge 2)	0.73 – 0.75	20
				Band 8	NIR (Near Infrared)	0.76 – 0.90	20
				Band 11	SWIR 1 (Shortwave Infrared 1)	1.54 – 1.68	20

Satellite data

Table 1 outlines the spectral bands of the S2-B datasets used in this investigation and their acquisition dates, resolutions, and wavelengths.

The raw satellite images were pre-processed using the Sentinel Application Platform (SNAP) tool and the Sen2Cor module for atmospheric, geometric, and radiometric adjustments before estimating spectral measurements to fulfill the current study's aim. After that, Sentinel-2 MSI datasets were converted to "top-of-atmosphere reflectance" values to rectify the bottom-of-atmosphere (BOA). Moreover, the S2-B spectral bands 1 (coastal and aerosol), 2 (blue), 7 (red edge 3), 9 (water vapor), 10 (SWIR - Cirrus), and 12 (SWIR-2) were omitted to extract the specific findings for the current study.

This study used spectral measurements to generate indices such as NDWI ("Normalized Difference Water Indies"), MNDWI ("Modified Normalized Difference Water Index"), NDMI ("Normalized Difference Moisture Index"), AWEI ("Automated Water Extraction Index") based on established algorithms mentioned in Table 2. These indices were incorporated into the workflow (Fig. 3) to effectively and accurately identify water pixels from non-water pixels by establishing threshold values. This method provides greater precision and accuracy in identifying water bodies and their changing extents from the wet season to the dry season in the Ural basin.

Table 2 – The algorithms applied for estimating the indices applied in the current investigation

Index	Algorithm	Reference
NDWI	$\frac{\text{Band 3} - \text{Band 8}}{\text{Band 3} + \text{Band 8}}$	[16]
MNDWI	$\frac{\text{Band 3} - \text{Band 11}}{\text{Band 3} + \text{Band 11}}$	[17]
NDMI	$\frac{\text{Band 8} - \text{Band 11}}{\text{Band 8} + \text{Band 11}}$	[18]
AWEI	$4 \times (\text{Band 3} - \text{Band 11}) - (0.25 \times \text{Band 8} + 2.75 \times \text{Band 11})$	[19]
CCI	$\frac{\text{Band 4}}{\text{Band 5}}$	[20]

Following that, the textures of shape and size of GLCM ("Grey-Level Co-occurrence Matrix") are applied for the final outlining of the areal extent of persistent water bodies during two considered periods across the research region, based on these remote sensing-based indices of water content extraction of two periods. Then, Using PCA ("Principal Component Analysis"), the high dimensionality of the GLCM output was efficiently reduced to a practical array of the aforementioned spectral bands [21]. Then, based on the finalized area of water bodies across the study area during two periods, the chlorophyll-a (Chl_a) concentration across the particular patches of water bodies was estimated. Hence, the index termed Chlorophyll Content Index (CCI) has been estimated using the spectral bands Red (Band 4) and RE1 (Band 5) of S2-B. Additionally, this index is commonly used in lakes as the slope between bands Red and RE1 is highly sensitive to alteration in the chlorophyll-a concentration, regardless of the applied atmospheric correction [21].

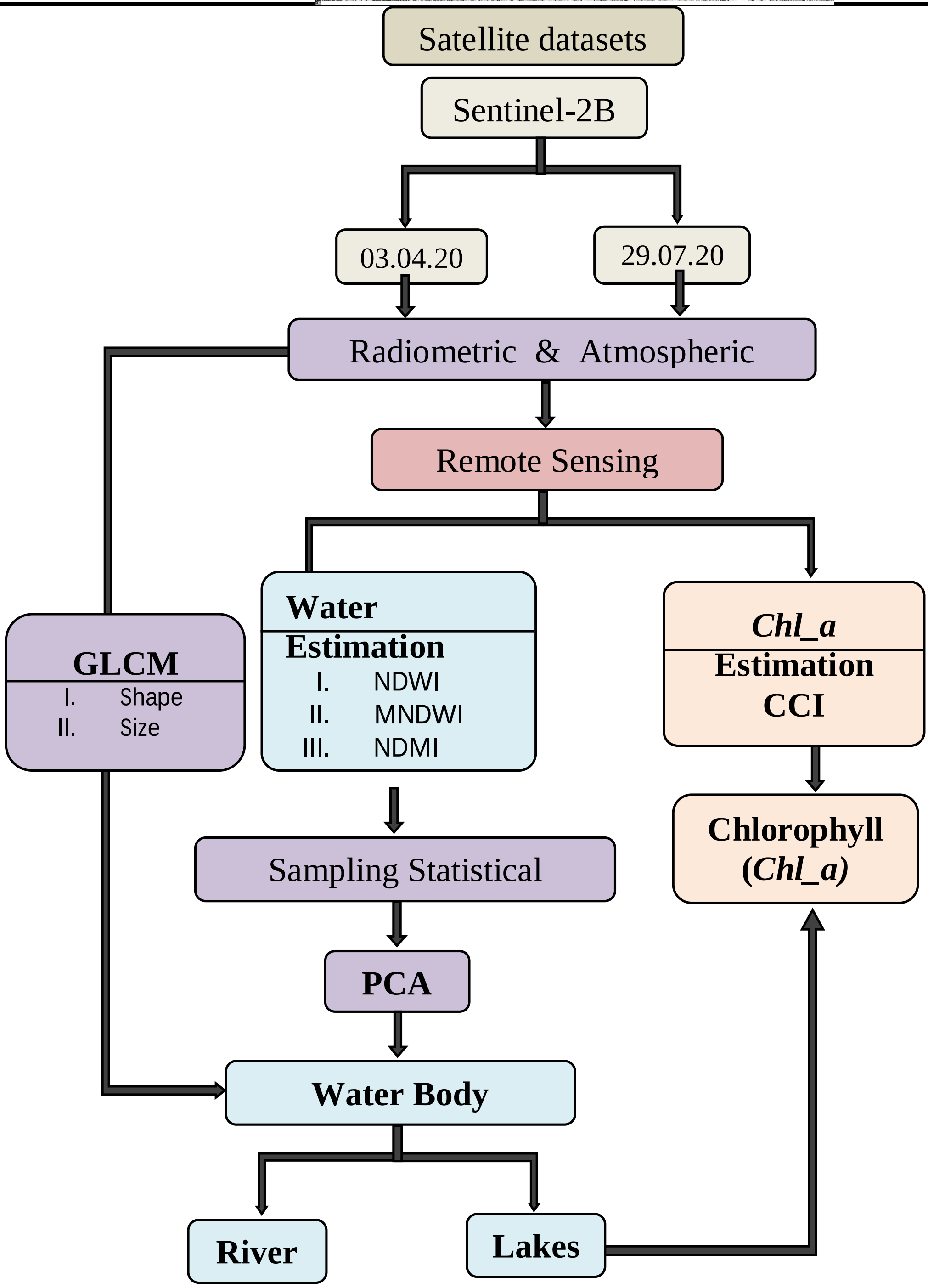

***Figure 3** – Work-flow used for the current investigation*

Results and discussion

Severe extreme events are prolonged droughts leading to water shortages, which could affect more than 65% of the world's human population by 2025 [22]. Currently, 40% of the world's population does not have enough water, and according to a UNESCO report, the amount of available water will be further reduced by about 30% in the next 20 years [23]. It is estimated that only about 2.5% of the world's water supply is freshwater, and less than 1% is potable water [24]. Extreme events such as catastrophic floods and prolonged droughts pose severe challenges to the long-term management of catchment-floodplain-river systems [4, 25, 26].

In the section of the Ural River valley selected for analysis, the presence of numerous left- and right-bank oxbow lakes was noted (Fig. 3). They were primarily filled with water in the spring, and a significant number of them were located at a considerable distance from the main channel of the river.

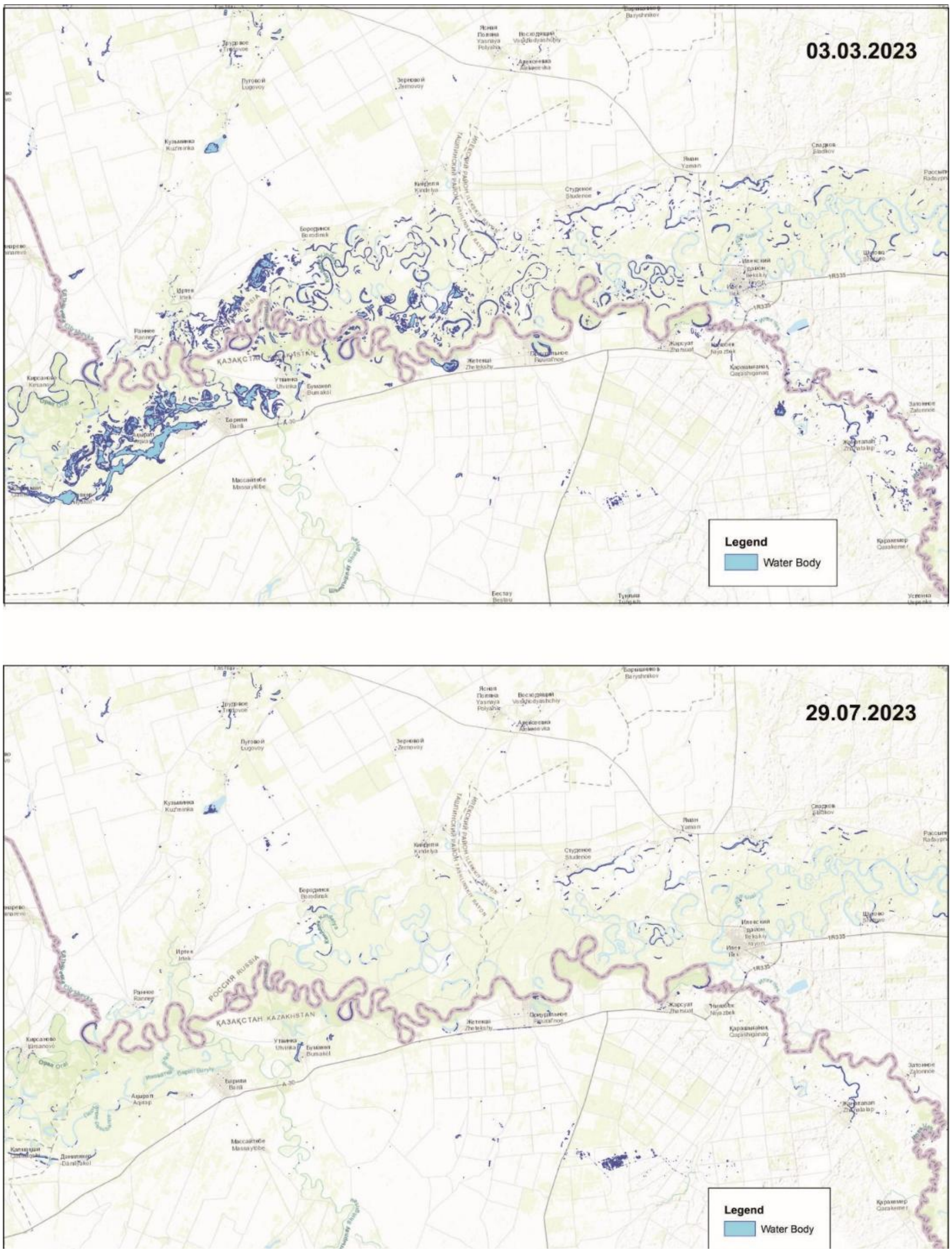

Figure 4 *– Distribution of water bodies on study area Ural river valley on spring and summer 2023 (Sentinel-2B)*

Based on satellite images in early spring, the area of water bodies (oxbow lakes) in the floodplain was determined to be almost 60 km^2. With the assumed average depth of these reservoirs at 2.5m during this period, the volume of accumulated water was determined at 0.1 km^3 (Table 3). At the peak of summer, there was a noticeable drying up and disappearance of the cover reservoirs. Their area and volume decreased by more than nine cartons relative to spring. Thus, the hydrobionts habitat in the Ural River valley was significantly reduced.

Table 3 *– Information on the area and volume of oxbow lakes of the studied floodplain of the Ural River in spring and summer 2023 (Sentinel-2B)*

Water bodies area on floodplain		
	Area (km^2)	Volume (km^3)
03 March 2023	56.6	0.113
29 July 2023	6.0	0.012

The Ural River (on the territory of the Republic of Kazakhstan - the Zhayik River) is an inter-zonal river whose landscape and climatic conditions are incredibly diverse. Climatic changes lead to decreased water runoff, changes in the proportion of recharge sources, chemical composition, and water mineralization. The contrast between mineralization and mineral composition intensifies as the dryness of the territory increases [14].

Regardless of the distinguished hydrodynamic types of oxbow lakes that favor the occurrence of a particular hydration formation, these reservoirs are important ecological centers (so-called "hot spots") at the scale of the river valley or even the region, providing diverse habitats for numerous representatives of flora and fauna [27-30]. The interdependence between the riverbed and the valley is expressed in complex functions such as production, decomposition, and consumption, which are determined by systematic surges and water table fluctuations [31]. The size and length of the connection between the river and the oxbow lakes determine the development of phytoplankton in the oxbow lakes [32]. Many authors report the dominance of chlorophytes, euglenoids, dinoflagellates, and cyanobacteria during the free flow of river water [33-34]. However, diatoms, cyanobacteria, chlorophyta, and Chara were dominant at low water levels in Lake Mallaköy [35]. Unfortunately, the remote sensing techniques used in this study did not allow us to isolate information on the concentration of individual phytoplankton groups.

In spring, a significant concentration of chlorophyll a was observed in oxbow lakes of the Ural River, which indicates the value of phytoplankton primary production. Interestingly, these results did not apply only to oxbow lakes near the riverbed but also to those far from it. This may indicate the extensive impact of the river. Analysis of satellite images did not indicate that phytoplankton activity affected only oxbow lakes with regular morphological form (typical moon shape) but also more extensive floodplains (Fig. 5A). In early spring, the water-rich floodplains of the valley play an essential role in maintaining high biodiversity. During this period, the riverbed is not washed and is silted up, and the amount of dissolved oxygen decreases, leading to ichthyofauna damage [14]. The lack of human influence in the form of regulation of hydrological conditions is a factor that implies natural valley processes during this period. Unfortunately, the summer period with high temperatures increases transpiration. It dries out most of the floodplain lakes (Fig. 5B). In summer, eutrophication of the water is observed, leading to a deterioration of the oxygen regime. The water "blooms" and oxybionts invertebrates are almost absent on the river bottom and in the dry floodplains [14].

The current ecohydrological state in the lower reaches of the Ural River draining into the Caspian Sea is influenced by natural and anthropogenic factors [36]. The Caspian Plain belongs to an area of chloride salinity, so the soils in the catchment area contain highly soluble chlorides. This leads to increased mineralization and increased chloride content not only in groundwater but also in surface water. Groundwater plays a significant role in recharging the river valley during periods of low water levels when water inflow from the surface of the catchment area decreases or completely ceases.

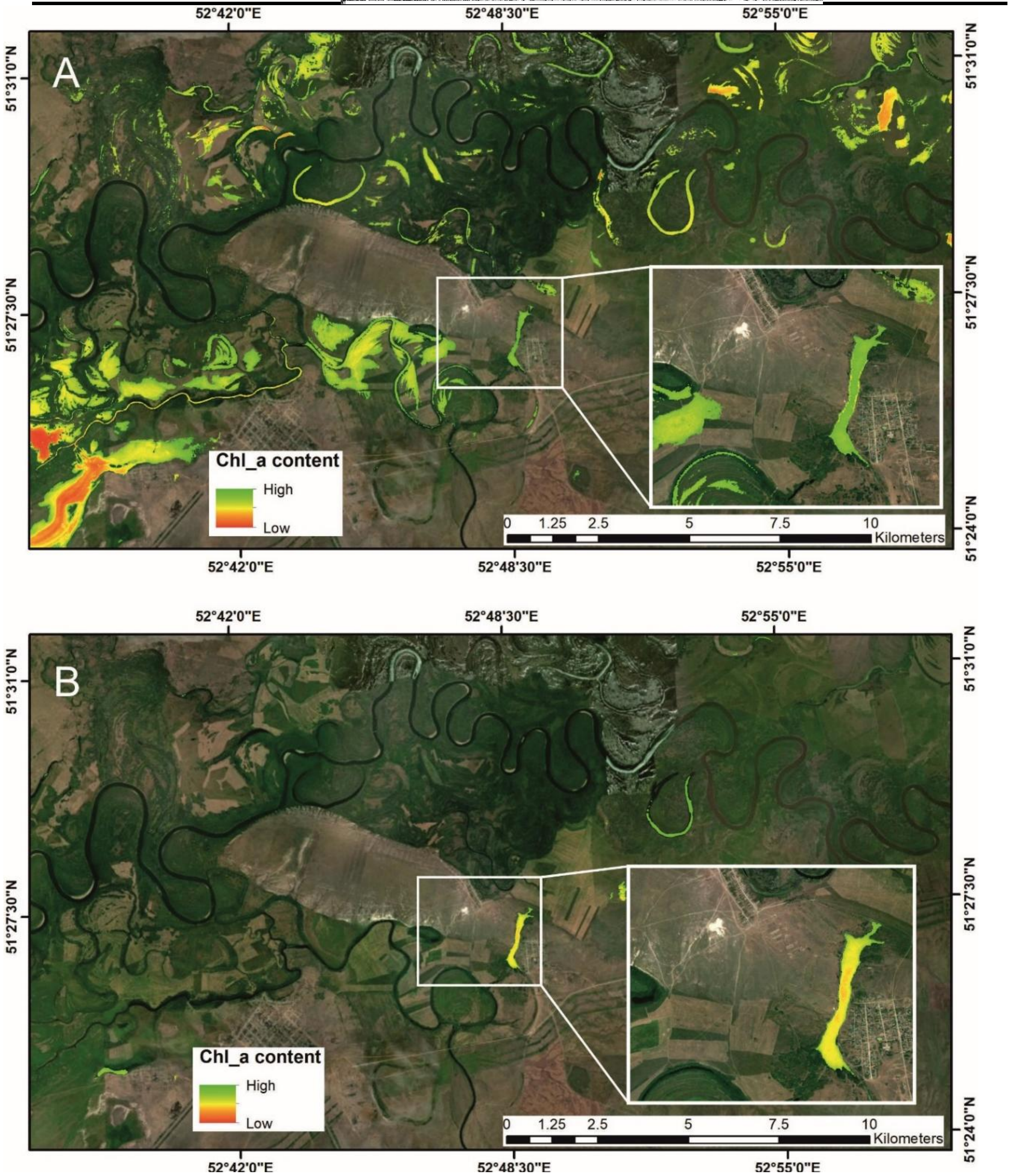

***Figure 5** – Concentration of chlorophyll-a (=primary production) in study area Ural river valley on (A) spring and (B) summer 2023*

Recorded annual average air temperatures in Kazakhstan over the 1971-2021 period show a marked increase from 5.3°C (1971-80) to 7.0°C (2011-21). In March, the average temperature increase was from -5.0°C (1971-80) to -3.1°C (2011-21), and in July, from 22.3°C to 24.0°C in the corresponding decades [37].

In the selected area of the Ural River Valley, thanks to the application of remote sensing techniques, it was possible to select one reservoir abundant in both spring and autumn, in which the concentration of chl-a was maintained (Fig. 5). It is possible to observe the current amount of primary production and also its changes in subsequent years.

The concept of the relationship of aquatic valley ecosystems with the river, in terms of the exchange of matter, energy, and aquatic organisms through the medium of water, was pioneered by Amoros et al. [27, 38]. On the other hand, Tockner et al. [39] showed that water chemistry and organism assemblages (biotic communities) are directly related to water levels, reflecting the hydrological connection during periods of low water levels. Organic matter accumulated in aquatic ecosystems in the floodplain terraces is not available to river organisms. At the same time, the rapid increase in the amount of water in rivers has a devastating effect on their biocoenoses, eliminating most representatives of aquatic flora and fauna in the riverbed, and their only reservoirs are small water bodies located in the floodplain terraces [40].

Conclusion

In summary, the results indicate that changes in hydrological conditions in the studied floodplain of the Ural River affect habitat conditions—consequently, the abundance of phytoplankton changes. Thanks to remote sensing techniques, a significant increase in phytoplankton biomass assessed as chl-a concentration was observed during spring floods; summer droughts significantly reduced the number of oxbow lakes and phytoplankton development. Based on the available images from the Santinel-2B satellite, one site rich in water and phytoplankton throughout the year was selected. It can be a model site for studying the productivity of oxbow lakes in a selected section of the valley. Given the ongoing climate change, which inevitably leads to hydrological changes in rivers and their valleys, there is a need for regular monitoring of oxbow lakes biocenosis in the form of in situ studies and remote sensing techniques.

Acknowledgement

This manuscript was possible thanks to the support of the Ministry of Science and Higher Education of the Republic of Kazakhstan within the framework of the project "On approval of the plan of distribution of the number of foreign scientists to engage in teaching activities in higher and postgraduate educational institutions".

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ДИСТАНЦИОННОЕ ИЗМЕРЕНИЕ УРОВНЯ ХЛОРОФИЛЛА В СТАРИЦАХ С ПЕРЕМЕННЫМ ОБЪЕМОМ ВОДЫ, РЕАЛИЗОВАННОЕ С ПОМОЩЬЮ SENTINEL-2

Аннотация. *Хотя в эпоху изменения климата и все более жестоких погодных явлений экстремальные явления (наводнения или высыхание) не могут быть устранены, и управление ими в поймах рек может внести значительный вклад. В статье основное внимание уделяется роли старицких озер в накоплении воды и первичном производстве на примере участка долины реки Урал (Западный Казахстан). Уровень накопления воды в этих* *районах значительно менялся в период с весны по лето. Этот район также является важным местом первичного производства. Хлорофилл-а может использоваться в качестве показателя количества фитопланктона и является важным параметром качества воды. Это экологическое образование в старицах вызывает избирательное поглощение света хлорофиллом - пигментом, который можно идентифицировать с помощью дистанционного зондирования акварели. Использование спутниковых снимков зарекомендовало себя как отличный инструмент для оценки потенциала поймы и выбора участков, представляющих интерес для мониторинга. Таким образом, было отмечено, что роль речных бассейнов заключается в повышении устойчивости бассейна к климатическим и антропогенным изменениям, а также в повышении водной безопасности, улучшении качества воды и расширении экосистемных услуг для общества.*

Ключевые слова: *пойма; накопление воды; первичное производство; изменение климата; Уральская долина.*

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SENTINEL-2 КӨМЕГІМЕН ЖҮЗЕГЕ АСЫРЫЛАТЫН ӨЗГЕРМЕЛІ СУ КӨЛЕМІ БАР ЕСКІ АРНАЛАРДАҒЫ ХЛОРОФИЛЛ ДЕҢГЕЙІН ҚАШЫҚТЫҚТАН ӨЛШЕУ

Аннотация. *Климаттың өзгеруі және ауа-райының қатыгездігі дәуірінде экстремалды құбылыстарды (су тасқыны немесе кептіру) жою мүмкін болмаса да, оларды жайылмаларда басқару айтарлықтай үлес қоса алады. Мақалада Жайық өзені алқабының (Батыс Қазақстан) учаскесінің мысалында судың жинақталуы мен бастапқы өндірістегі ескі көлдердің рөліне баса назар аударылады. Бұл аудандарда судың жинақталу деңгейі көктемнен жазға дейін айтарлықтай өзгерді. Бұл аймақ сонымен қатар негізгі өндірістің маңызды орны болып табылады. Хлорофилл-а фитопланктон мөлшерінің көрсеткіші ретінде пайдаланылуы мүмкін және су сапасының маңызды параметрі болып табылады. Ескі арналардағы бұл экологиялық формация жарықтың хлорофиллге селективті сіңуін тудырады, оны акварельді қашықтықтан зондтау арқылы анықтауға болады. Спутниктік суреттерді пайдалану Жайылманың әлеуетін бағалаудың және бақылауға қызығушылық тудыратын сайттарды таңдаудың тамаша құралы ретінде өзін дәлелдеді. Осылайша, өзен бассейндерінің рөлі бассейннің климаттық және антропогендік өзгерістерге төзімділігін арттыру, сондай-ақ су қауіпсіздігін арттыру, су сапасын жақсарту және қоғам үшін экожүйе қызметтерін кеңейту болып табылады.*

Кілт сөздер: *жайылма; судың жиналуы; бастапқы өндіріс; климаттың өзгеруі; Жайық алқабы.*