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Evaluating the impact on wetlands following the destruction of the Kakhovka dam by analysis of vegetation index (NDVI) via high resolution satellite data.

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Evaluating the impact on wetlands following the destruction of the Kakhovka dam by analysis of vegetation index (NDVI) via high resolution satellite data.
Utvärdering av påverkan på våtmarker efter förstörelsen av Kakhovkadammen genom analys av vegetationsindex (NDVI) via högupplösta satellitdata.
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Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Analysis

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Abstract

The ongoing war in Ukraine has inflicted wide ranging environmental damages, each with their own set of consequences. The catastrophic failure of the Kakhovka Hydroelectric Dam on the 6th of June 2023 initiated a new cascade of environmental destruction, as hundreds of square kilometres were rapidly inundated, with hundreds more left dehydrated as the Kakhovka reservoir drained away. Within the affected region resided a large collection of Wetlands – complex ecosystems which are very sensitive to hydrological changes. With many of these wetlands protected under international treaty (the Ramsar agreements), the disaster has greatly disrupted their integrity by imposing a new set of hydrological conditions to the region.

This report analysed and compared changes to observed Normalised Difference Vegetation Index (NDVI) levels across the affected wetlands and general area in the months following the incident. The results indicate mean NDVI levels fell by between 35.4% to 43.5% during the summer of 2023 compared to reference values. However, NDVI levels saw great recovery to near normal levels by August for both the inundated region downstream of the dam and within the drained Kakhovka reservoir. Furthermore, NDVI levels across the former Reservoir have indicated the growth of new vegetation, which may form future wetlands. The analysis is complemented with a discussion of the results.

Key Words

Ukraine, Wetlands, Vegetation, RAMSAR, Ecosystem, Preservation, Russia-Ukraine, War, NDVI, Remote Sensing, GIS, Environment, Kakhovka Dam, Kakhovka Reservoir, Dnipro.

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1 Introduction.

Assessing the effects to the environment in active conflict zones is a major challenge (Machlis & Hanson, 2008). Since February 2022, Ukraine has been engaged in an armed conflict with the Russian Federation and has consequently suffered a variety of environmental damages which have yet to be properly quantified. Armed conflict should not distract from efforts to monitor the state of the environment. It is important to assess all environmental effects during this period as to begin to ascertain the extent of damages as well as to prepare plans for recovery and restoration, once the conflict between Russia and Ukraine ceases (United Nations Environment, 2022).

Wetlands are some of the world's most complex and valuable natural ecosystems, described as "an ecosystem transitional between aquatic and terrestrial ecosystems, where the water table is near the surface or where the surface is covered by shallow water" (Cowardin et al., 1979; Svirenko & Spirin, 1997). Being present on all continents and latitudes, wetlands cover an estimated global area of 1,280 million hectares in which large variations in their properties exist between different regions (Finlayson et al., 2005). They are responsible for various ecosystem processes, often correlated with high biodiversity by providing specialised habitats for a variety of species, including many threatened species (Finlayson et al., 2005). Ukraine is home to around 1 million hectares of wetlands, equivalent to 1.7% of total land surface (Stebelsky, 1993). Wetlands are of particular importance to the richness of the country's natural resources, which provide assets and support for agriculture and livestock, peat, minerals, and water (Svirenko & Spirin, 1997; Wang, 2024). Wetlands are vulnerable ecosystems and have experienced significant losses worldwide, particularly throughout the 20th century where around 50% of specific wetland types were destroyed across North America and Europe. This has occurred primarily due to drainage, conversion to agriculture, and infrastructure development (Finlayson et al., 2005). Because wetlands are of great scientific and ecological importance, it is imperative that the health of these ecosystems are monitored, and efforts made to preserve them (Finlayson et al., 2005; Mitsch & Gosselink, 1993; Rundquist et al., 2001).

There are several methods which can be used to assess wetlands (Cowardin et al., 1979). It can be difficult to assess the extent of wetlands and, given their large land area, it is not always economically or practically viable to conduct on-site surveying. This is particularly relevant during times of armed conflict, such as the one presently ongoing within Ukraine; the possibility of on-site field studies has largely become undesirable if not impossible in many parts of the country. A viable alternative method can be found through the use of Remote Sensing techniques. Whilst a variety of instruments and platforms can be utilised, Satellite Remote Sensing remains one of the most cost-effective options available, where synoptic, multispectral and temporal coverage of an area can be ascertained with relative ease (Rundquist et al., 2001).

The assessment of vegetation via remote sensing can be done with a vegetation index, which uses two or more spectral bands to help enhance the visual signal transmitted/reflected from underlying vegetation, while minimising solar irradiance and soil background effects. (Jackson & Huete, 1991). One of the most common vegetation indexes used to assess the health of vegetation is the Normalised Difference Vegetation Index (NDVI) (Rouse et al., 1974). The index is often used to help assess the density of vegetation (g m^{-2}) and its subsequent health, calculated by the reflectance of near-infrared (NIR) and red (RED) wavelengths (Ashok et al., 2021; Herring & Weier, 2000), as outlined in Equation 1. The reflectance of the RED band is used to assesses the absorption from photosynthesis, where productive vegetation reflects little.

NIR is suited for evaluating the density of vegetation, where dense conditions result in high reflection. The normalization of these two wavelength bands accounts for different illumination conditions whilst providing more effective delineation between bare soil, water, snow and vegetation.

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

Whilst NDVI does not directly measure a physical property of vegetation cover, it provides a convenient numerical value that can be used to monitor and compare an ecosystem's general state of health (Herring & Weier, 2000). NDVI results in a non-dimensional value range between 1 to -1, where 1 indicates dense and healthy vegetation, with decreasing values indicating decreasing vegetation, whilst everything below 0 indicates non-vegetated surfaces such as water, barren land, ice, snow or clouds (Jensen, 2009).

The Kakhovka Hydroelectric Power station was built in 1956 and situated on the Dnipro River next to Nova Kakhovka in Ukraine. It was the final dam before the mouth of the river at the Dnipro Delta, holding back the Kakhovka reservoir stretching 240 km northeast before meeting the Dnipro Hydroelectric Power station in the city of Zaporizhzhia. The reservoir was the largest in the country, covering an area of 2,155 km^2 and reserving 18.2 km^3 of water. Alongside power generation and irrigation, it also allowed shipping activities of grain, ore and metals, whilst also facilitating fish farming (mostly crucian carp, roach, bream, silver carp), (Vyshnevskyi et al., 2023; Vyshnevskyi, 2011). Within the confines of the Kakhovka reservoir to the Dnipro Delta resides a collection of sensitive wetlands. A portion of these wetlands are protected under the "Ramsar" convention on Wetlands of International Importance, totalling around 44,332.8 hectares (RSIS, 2016, 2017, 2022). These are outlined in Figure 1.

On June 6th, 2023, the Kakhovka Dam experienced a catastrophic breach, leading to the flooding of 83,000 ha at maximum extent downstream and the draining of the Kakhovka reservoir. (Spears et al., 2024). Initial reports indicated that the flooding period lasted several weeks, where estimates suggested a maximum extent of 83,000 ha was submerged between the 6 – 9th of June, with an overall flood extent of 53,000 ha (Spears et al., 2024). This has resulted in widespread environmental damages. According to Chen et al. (2024), wetlands have endured a brunt of the damage with their calculations suggesting out of a submerged area of 742.58 km^2, wetlands accounted for 539.84 km^2. Damage was not limited to downstream from the dam - across the Kakhovka reservoir, it is estimated that a total of 222.25 billion m^3 of water lost by July 7th, representing 97% of the reservoir’s capacity before the dam was destroyed and resulting in a huge area of the reservoir’s lake bed exposed (Chen et al., 2024).

Aim of Study:

The destruction of the dam has wide ranging ramifications, both in a humanitarian context and environmentally (Chen et al., 2024; Spears et al., 2024; Vyshnevskyi et al., 2023). Given that the event occurred less than a year ago, few studies have yet been published focusing on the specific effects to the wetlands of the effected region. This study aims to utilise high resolution satellite imagery in assessing to what extent NDVI levels have changed over wetlands across the Kakhovka reservoir and the Dnipro River Delta in the three months following the destruction of the Kakhovka dam. As a secondary objective, the study also aims to see whether vegetation has permeated across the former Kakhovka reservoir.

Expected outcome:

There has been an abrupt decrease in NDVI across all wetlands following the dam’s destruction when compared against previous years, whilst NDVI levels across the bed of the Kakhovka reservoir experiences little increase in comparison to reference levels.

2 Method.

2.1 Study Area

Two areas were defined as to distinguish between wetlands that were impacted from flooding and those that were impacted from the draining of the reservoir. The Dnipro River Delta, downstream of the Kakhovka dam was established as ‘Area 1’, whilst The Kakhovka Reservoir, between the Kakhovka dam and Dnipro Hydroelectric Station in Zaporizhzhia was defined as ‘Area 2’. These study areas are illustrated in Figure 1

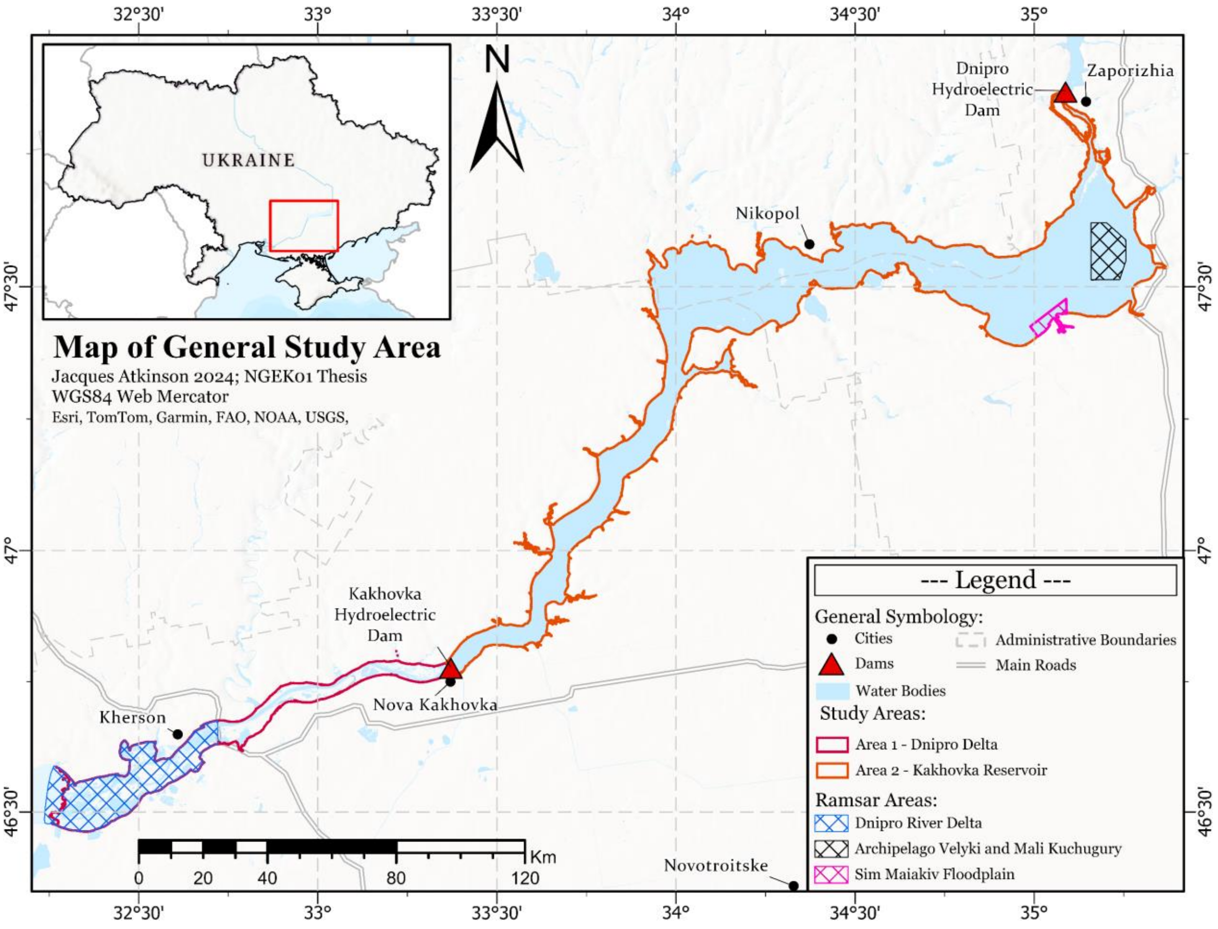

Figure 1: Map of Study Area constituents – Area 1 being downstream of the Kakhovka Dam, Area 2 being the reservoir.

Landcover was determined using the European Space Agency’s (ESA) ‘Worldcover’ dataset (Zanaga et al., 2022). Using version 2, the latest release from 2021, Worldcover combines Sentinel-1 synthetic-aperture radar measurements and Sentinel-2 data to attain a high-resolution (10m) global landcover dataset containing 11 classes. The product is “independently validated” through a comparison with the Copernicus Global Land Service Cover Layers (CGLS-LC) 100m dataset - achieving a global overall accuracy of 76.7% (Olofsson et al., 2012; Tsendbazar et al., 2022).

The processing of collected geodata was conducted using ESRI ArcGIS Pro v2.7.0. The raster land cover for the extent of the study area was reclassified to 2 classes: code 80 (Permanent waterbodies) and 90 (Herbaceous wetlands). Since other land classes did not relate to wetlands, these remaining land classes were reclassified into a new land class code of '1' as to better distinguish them from the more relevant land classes of 80 and 90. To spatially define the Areas 1 and 2 in a way suitable for data processing, a raster to polygon function was used to turn the reclassified raster file into a vector format. By manually identifying the banks of the main water bodies and river system, all areas surpassing these banks which did not include land code 80 and 90 were excluded. The Kakhovka Dam acted as the division between Area 1 and 2.

For Area 1, all secondary rivers feeding into the main delta were excluded from the study by splitting the land class polygon at the mouth of the secondary river. To suitably define the boundary of the study area close to the mouth of the delta, the boundaries of the Dnipro River Delta Ramsar protected area were used (RSIS, 2022). However, at the very mouth of the delta, the polygon was traced to include the surrounding islands without extending past into the Black Sea (consisting of only permanent water bodies). The resulting study polygon Area 1 was then buffered by 10m and is depicted in Figure 2, alongside the Ramsar boundary marked as Ramsar 1. A similar approach was used to define Area 2, however secondary river mouths were not excluded. Around the Zaporizhzhia Nuclear Power Station, the polygon excluded the cooling ponds and the surrounding wetlands in the southward direction. Ramsar boundaries of the Sim Maiakiv Floodplain (RSIS, 2016) and the Velyki & Mali Kuchugury Archipelago (RSIS, 2017) were combined to form a single polygon feature (collectively known as Ramsar 2) and incorporated into the study polygon. The study polygon was then buffered by 10m to compensate for any fringe spatial mismatch in the raster cells between the Worldcover dataset and the produced NDVI images – the resulting study area is depicted in Figure 3.

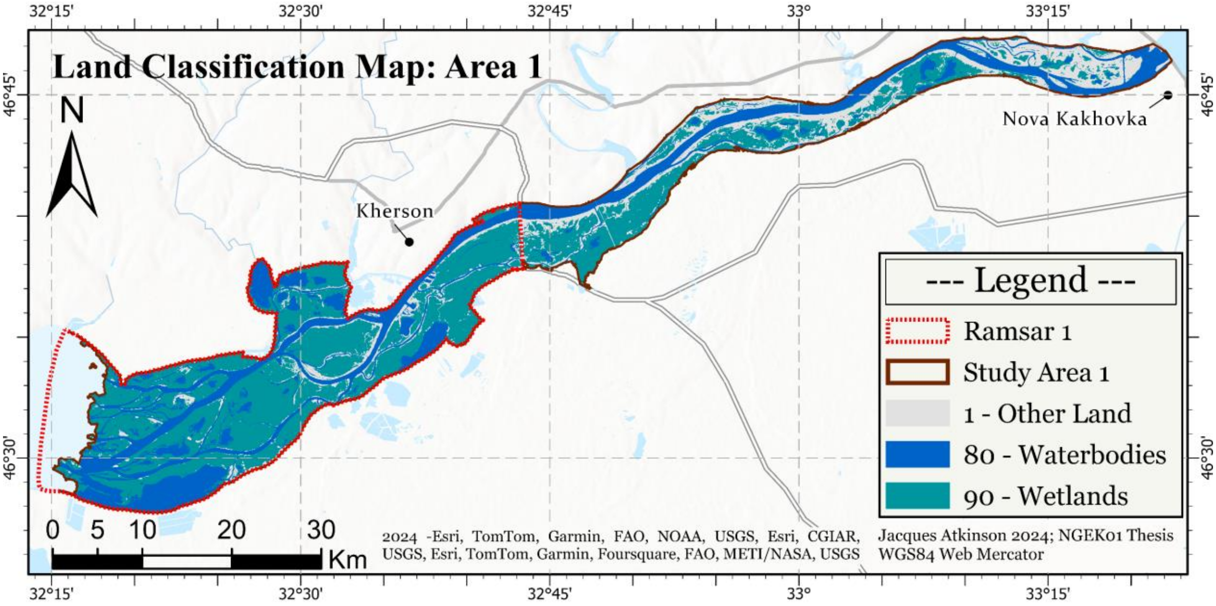

Figure 2: Map of Study Area 1 including 2021 Worldcover land classes and Ramsar boundaries.

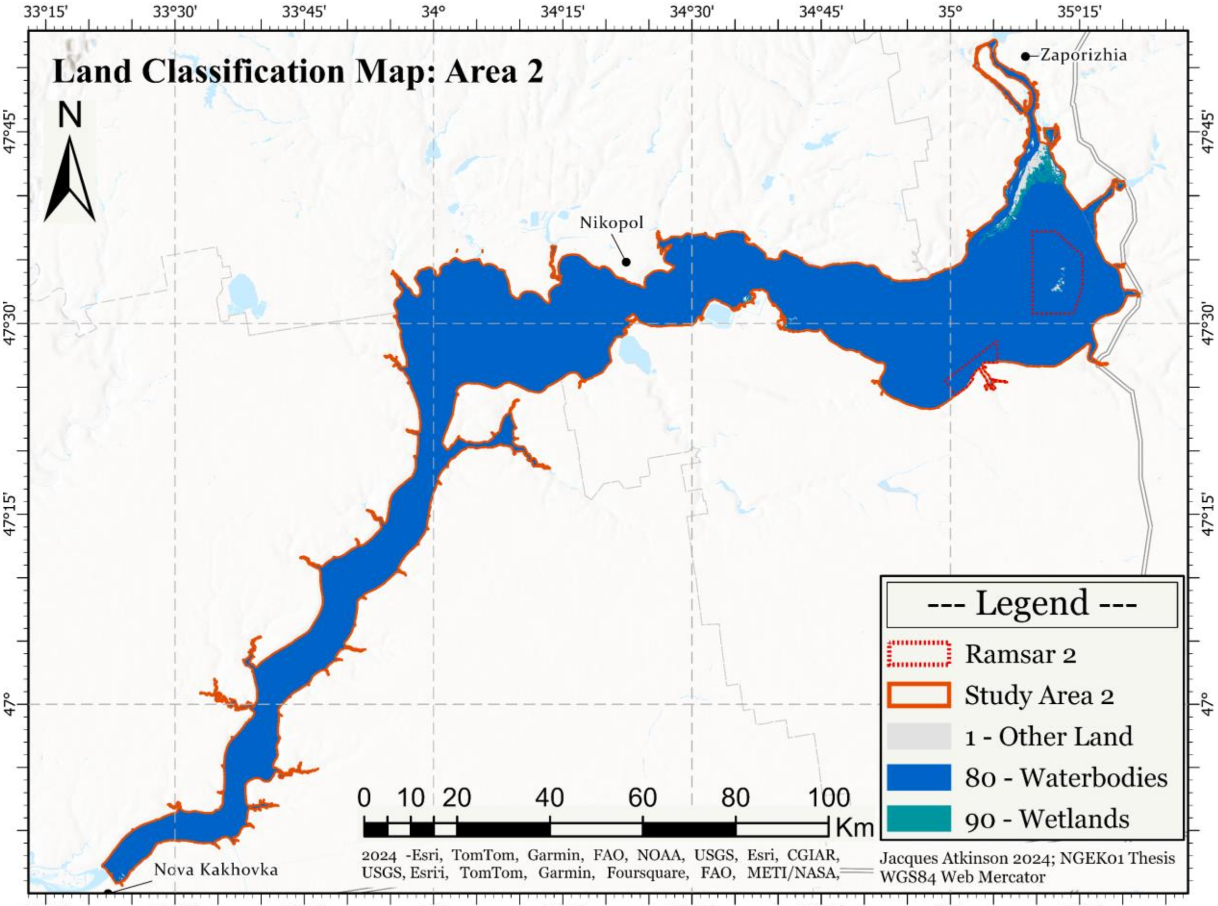

Figure 3: Map of Study Area 2 including 2021 Worldcover land classes and Ramsar boundaries.

2.2 Satellite Data

This investigation utilised the Harmonized Sentinel-2 Multi Spectrum Imagery Level A2 product, extracted using Google's Earth Engine data catalogue (Gorelick et al., 2017).
The product consists of 16 spectral bands, of which bands B4 (Red / 664 nm) and B8 (NIR / 832 nm) were extracted and used to calculate the NDVI image in accordance with Equation 1, with a pixel resolution of 10 meters. Images were collected for the months of June, July and August, for the years 2019 to 2023. When producing the NDVI coverage over the study area, a cloud mask was applied to filter out image artifacts and disturbances because of clouds. This was achieved using the QA60 band (60m) – a quality assurance bitmask containing various metrics including cloud shadow (Bit 10) and cloud cover (Bit 11). These cloud cover and cloud shadow masks are constructed via the Sentinel 2 Level 1C data product using three spectral bands. Blue visible light (Band 1 at 443 nm or Band 2 at 490 nm) and two shortwave infrared (SWIR) bands (B10 at 1375 nm together with Band 11 at 1610 nm or Band 12 at 2190 nm) (Coluzzi et al., 2018; ESA, n.d). Bit 10 and 11 were analysed so that across a period of a whole month within the extent of the study area, B4 and B8 pixels would only be used if the encompassing QA60 pixel recoded Bit 10 and Bit 11 to be 0 – indicating no cloud and no cloud shadow (Gorelick et al., 2017). The JavaScript Earth Engine code used to extract the raster dataset is attached in Appendix 1.

Two NDVI images were produced for each individual month, one attaining maximum observed NDVI, and the other computing mean average NDVI over the entire one-month period. These images were then clipped by using the polygon templates for each assessment area. Finally, within the two study areas, the following parameters were extracted by mask, creating a new NDVI raster only including:

- Wetlands (land class 90)
- Wetlands and Permanent Water Bodies (land class 90 + 80)
- Ramsar Area (Sites within Area 2 were combined into one polygon set)
- Complete Area (Includes all land classes within Area 1 / Area 2)

Statistics were extracted from each raster via the histogram function - collecting mean, median and standard deviation values. This data was then compiled into Microsoft Excel version 2403, where further analysis was conducted. To adequately compare NDVI values for 2023 and determine the extent of changes to maximum and mean values compared to previous years, reference NDVI values were necessary. Reference NDVI was calculated by averaging NDVI values for June, July and August (for both mean and maximum terms) between 2019 and 2022, per individual study area and per the 4 study parameters.

Finally, to compare changes following the destruction against the calculated reference period, relative difference in NDVI in percentage terms was calculated (Kussul et al., 2022), as per Equation 2:

$$dNDVI_t = \frac{NDVI_{t+1} - NDVI_t}{NDVI_t} \times 100 \tag{2}$$

$dNDVI_t$ indicates the relative % difference of NDVI at time t, being the reference period. $NDVI_t$ indicates the NDVI prior to the dam's destruction. $NDVI_{t+1}$ indicates the NDVI value after the dam's destruction at point.

3 Results

A spreadsheet of the complete numerical results is attached as Appendix 2.

3.1 Geometric Areas

Table 1 shows the calculated area for each land class parameter and their share of total area corresponding to their respective study area. Of note, the Ramsar site within Area 1 (*) extends outside the boundary of the study polygon used to define Area 1, however statistics were still extracted for the whole Ramsar site. The Ramsar area included within the study polygon is 30559.96 hectares. (62.3% of Area 1)

Table 1. Total areas of studied parameters in Hectares (Land class codes in parentheses). Parameters highlighted in Red did not have their individual NDVI characteristics assessed.

	Wetlands (90)	Water Bodies (80)	Wetlands + Water Bodies (90+80)	Ramsar Area	Other Land (1)	Complete Area
Area 1	25942.3	15277.10	41219.43	34425.78	7803.9	49023.33
%	52.9%	31.2%	84.1%	70.2%*	15.9%	100.%
Area 2	2612.2	213385.99	215998.09	9888.14	2825.55	218823.64
%	1.2%	97.5%	98.7%	4.5%	1.3%	100.0%

3.2 NDVI across Wetlands

Area 1

Within Area 1, between 2019-2022 Wetlands under land class 90 experienced an average mean NDVI of 0.696 across all three summer months. In contrast, average mean NDVI in 2023 decrease by -43%, attaining an absolute average of 0.393. In maximum terms, the four-year reference period attained a maximum average of 0.797. For 2023, the value stood at 0.639 - a decrease of -20%. NDVI values per month are displayed in Figure 4A, with maximum observed values displayed in Figure 4B.

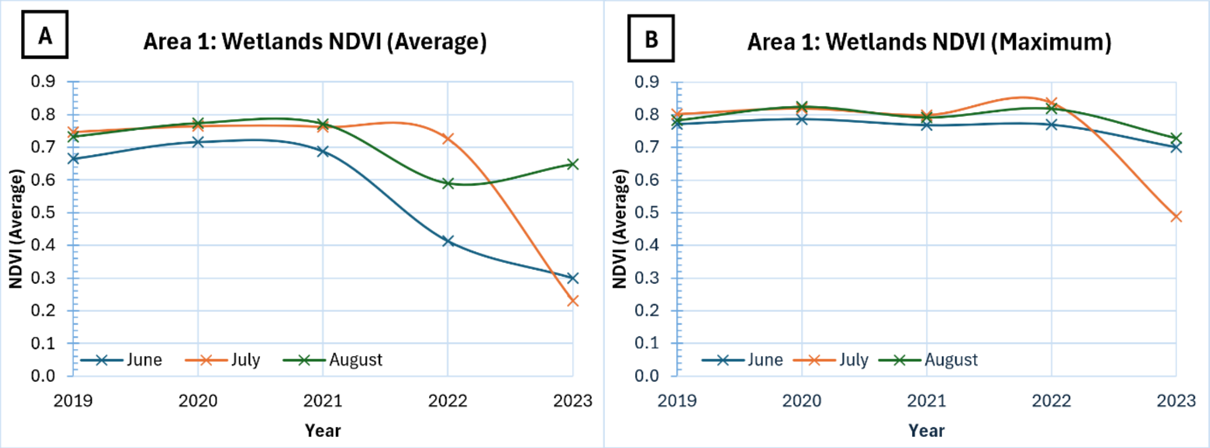

Figure 4: Monthly NDVI values per year across wetlands in Area 1. Mean average (A), Maximum (B).

Per month, the reference mean NDVI values for June, July and August stood at 0.621, 0.750 and 0.716 respectively. In 2023, mean values for June decreased by -52% (0.3), July by -69% (0.231). August saw an increase in NDVI (0.648) but remained -10% compared to the reference period. When looking at maximum NDVI, the reference average stood at 0.774, 0.814 and 0.805 for June, July and August respectively. For 2023, June only saw a small decrease of -9% (0.701) whilst July experienced a -40% drop (0.488). During August, a max NDVI of 0.728 was recorded corresponding to a -10% change from the reference.

Area 2

Within Area 2, the mean average for all summer months during the reference period stood at 0.635, whilst the maximum NDVI was averaged at 0.754. During 2023, mean NDVI decreased by -35% at 0.41. In maximum terms the average was 0.590, corresponding to a -22% decrease. Monthly results are displayed in Figure 5

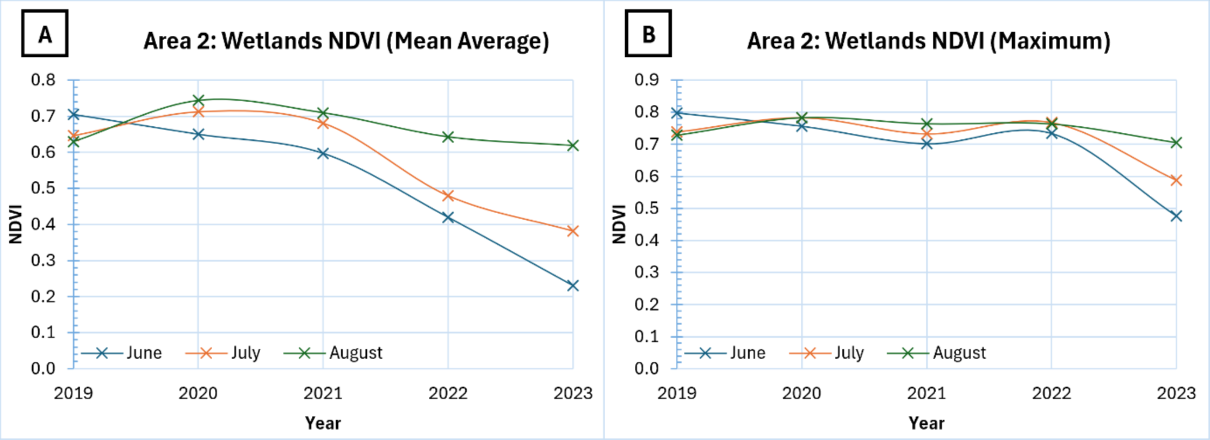

Figure 5: Monthly NDVI values per year across wetlands in Area 1. Mean average (A), Maximum (B)

In per-month terms, mean NDVI during the reference period stood at 0.593, 0.630 and 0.681 respectively. When compared to 2023, June experienced the largest decrease of -61% (0.231), compared to -39% (0.382) and -9% (0.619) for July and August respectively. In terms of maximum NDVI, respective reference values stood at 0.747, 0.756 and 0.76. In 2023, June experienced -36% (0.477), July -22% (0.588) whilst August only experienced a -7% decrease (0.705).

3.3 NDVI across Ramsar Areas

Ramsar 1
The Dnipro River Delta is protected under the Ramsar agreement within Area 1, as outlined in Figure 2. The NDVI analysis within this area included all land classes. The monthly results are displayed in Figure 6.

When averaging across all three summer months, the reference period obtained average mean NDVI of 0.394 and an average maximum NDVI of 0.518. In 2023, compared to the reference, the mean average NDVI decreased by -43% to 0.224, whilst the average maximum NDVI decreased by -18% to 0.426.

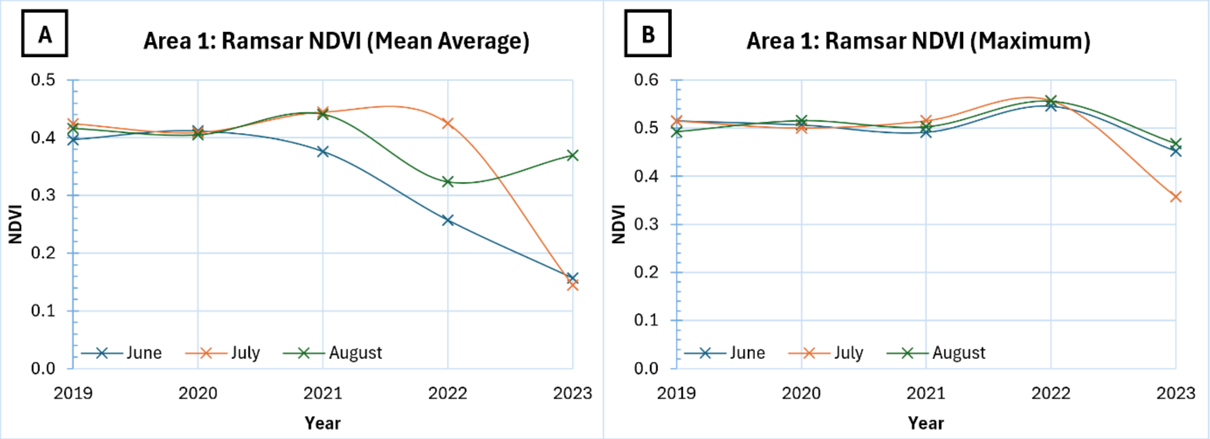

Figure 6: Monthly NDVI values per year across Ramsar protected areas within Area 1. Mean average (A), Maximum (B)

Averaged across monthly terms, obtained mean average NDVI stood at 0.36, 0.426, 0.397 for June, July and August respectively. In 2023, mean NDVI decreased respectively by -57% (0.157), -66% (0.144) and -7% (0.37). For maximum NDVI, the reference values were 0.515, 0.522 and 0.517 respectively. In 2023, maximum NDVI decreased by -12% for June (0.453), -32% (0.358) for July and -9% for August (0.468)

In respect to yearly variations, there is only a little variation in mean and maximum NDVI between 2019-2021, whilst 2020 experienced noticeably lower mean NDVI during months of June and August 2022. In 2023, mean NDVI in June continued to fall, (excluded 2022 as an outlier, it is observed that June 2023 reduced by -60%) with July experiencing a very large reduction. By contrast, August 2023 saw a 14.1% increase in mean NDVI when compared against 2022.

Ramsar 2

Within Area 2, the Ramsar areas encompassing the Sim Maiakiv Floodplain and Velyki & Mali Kuchugury Archipelago (outlined in Figure 3) obtained a reference period average mean of -0.113, with an average maximum NDVI of 0.049, across all summer months. For 2023, average mean NDVI rose to 0.145, whilst average maximum rose by +426% (0.256)

Monthly results are plotted in Figure 7.

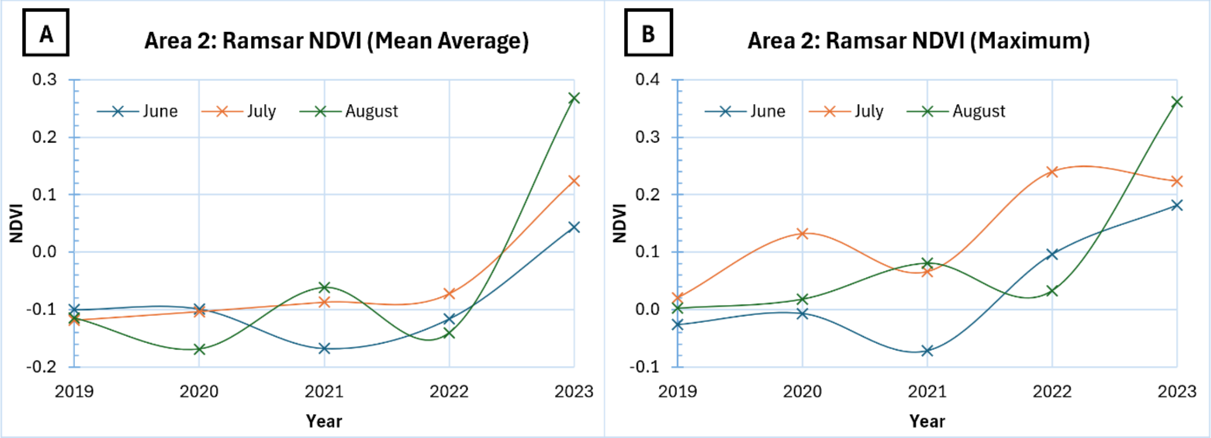

Figure 7: Monthly NDVI values per year across Ramsar protected areas within Area 2. Mean average (A), Maximum (B)

Per month, mean average NDVI was calculated at -0.12, -0.096 and -0.121 for June, July and August respectively. With the draining of the reservoir in 2023, mean NDVI rose into the positive, for all months, (0.044, 0.124 and 0.268 respectively). For maximum NDVI, the reference values were -0.002, 0.114 and 0.034 respectively. In 2023, maximums rose to 0.182 for June, 0.224 for July, whilst August experienced the largest increase to 0.362 (+977%)

3.4 NDVI across Wetlands + Permanent Waterbodies

Area 1

Calculation of NDVI across land class 80 and 90 combined for Area 1 resulted in a mean average of 0.414 and maximum average of 0.565 across the 2019-2020 reference period for all summer months. In 2023, mean average NDVI decreased by -46.7% to 0.221, with maximum NDVI falling by -20% to 0.449. Monthly terms are presented in Figure 8.

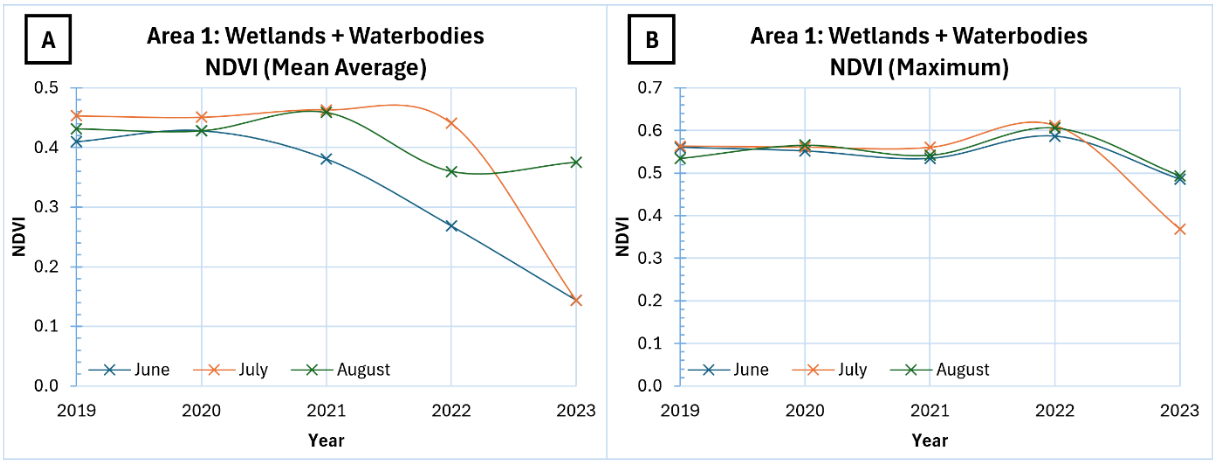

Figure 8: Monthly NDVI values per year across Wetlands and Permanent Waterbodies within Area 1. Mean average (A), Maximum (B)

Monthly mean NDVI across the reference period was calculated as 0.372, 0.452 and 0.419, for June July and August respectively. During 2023, mean NDVI of 0.143 (-61.4%), 0.144 (-68.2%) and 0.375 (-10.6%) was attained. Maximum NDVI throughout the reference period were very consistent across all three months, with values at 0.558, 0.574 and 0.562. In 2023, levels fell to 0.485 (-13%) for June, 0.368 (-36%) for July and 0.494 (-12%) for August.

Area 2

Within Area 2, it is important to consider the results in the context that the wetlands and waterbodies parameter was almost entirely waterbodies, as per Table 1. Here, a general mean NDVI of -0.113 across all summer months during the 2019-2022 reference period. General maximum NDVI was calculated at 0.086. For 2023, mean NDVI was recorded to be 0.085, whilst general maximum NDVI rose by 165% to 0.227. Monthly values are displayed in Figure 9.

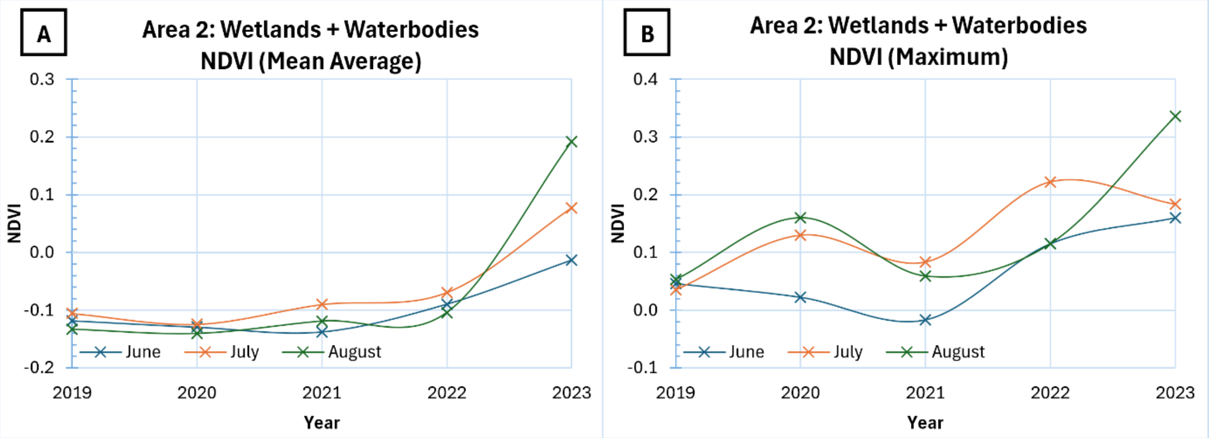

Figure 9: Monthly NDVI values per year across Wetlands and Permanent Waterbodies within Area 2. Mean average (A), Maximum (B)

When looking at monthly variations, mean NDVI during June, July and August was relatively consistent with each other, standing at -0.119, -0.097 and -0.124 respectively throughout the reference period. By contrast, 2023 saw increases to Average NDVI into positive values, calculated at -0.013, 0.077 and 0.192 respectively. For maximum NDVI, reference values attained were 0.042, 0.118 and 0.097 respectively. In 2023, June saw a maximum average of 0.160 (+283%), July at 0.183 (+56%) and August at 0.336 (+247%)

3.5 NDVI across Complete Areas

Complete Area 1

Across all land classes within Area 1, the three summer months experienced mean average NDVI levels of 0.462 and a maximum average of 0.606 during the reference period. During 2023, mean average NDVI decreased by -42.8% to 0.264, with maximum NDVI falling by -19% to 0.494.

Monthly NDVI per year is depicted in Figure 10.

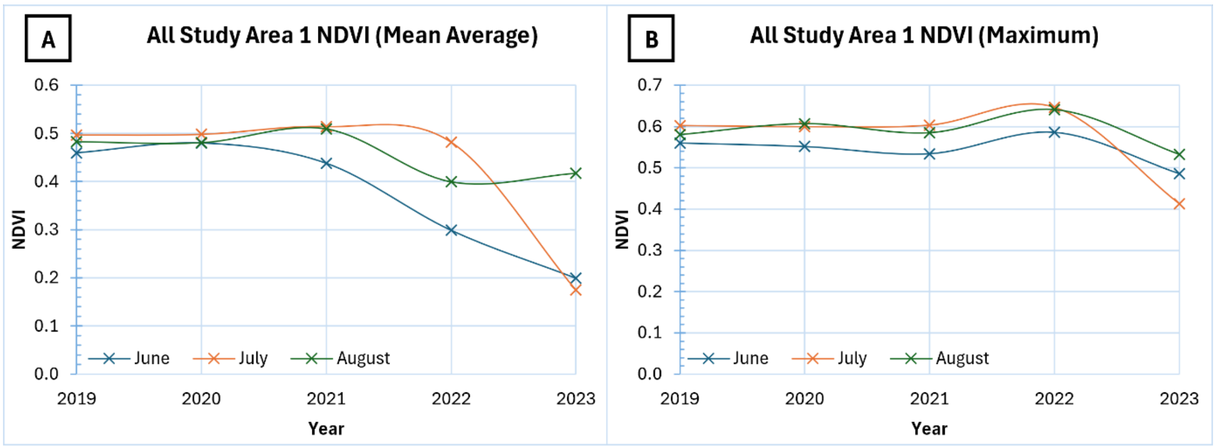

Figure 10: Monthly NDVI values per year across for the entirety of Study Area 1. Mean average (A), Maximum (B)

In monthly terms, mean NDVI through the reference period saw observed averages of 0.372, 0.452 and 0.419 for June, July and August respectively. During 2023, mean NDVI decreased to 0.143 during June (-61.4%), 0.144 for July (-68.2%) and 0.375 for August (-10.6%). In respect to maximum NDVI, the reference period attained values of 0.558, 0.574 and 0.562 respectively. For 2023, June, July and August observed maximum NDVI levels of 0.485 (-13%), 0.368 (-36%) and 0.494 (-12.2%). A visual aid to help display the spatial distribution of changes to NDVI across Area 1 is displayed in Figure 11.

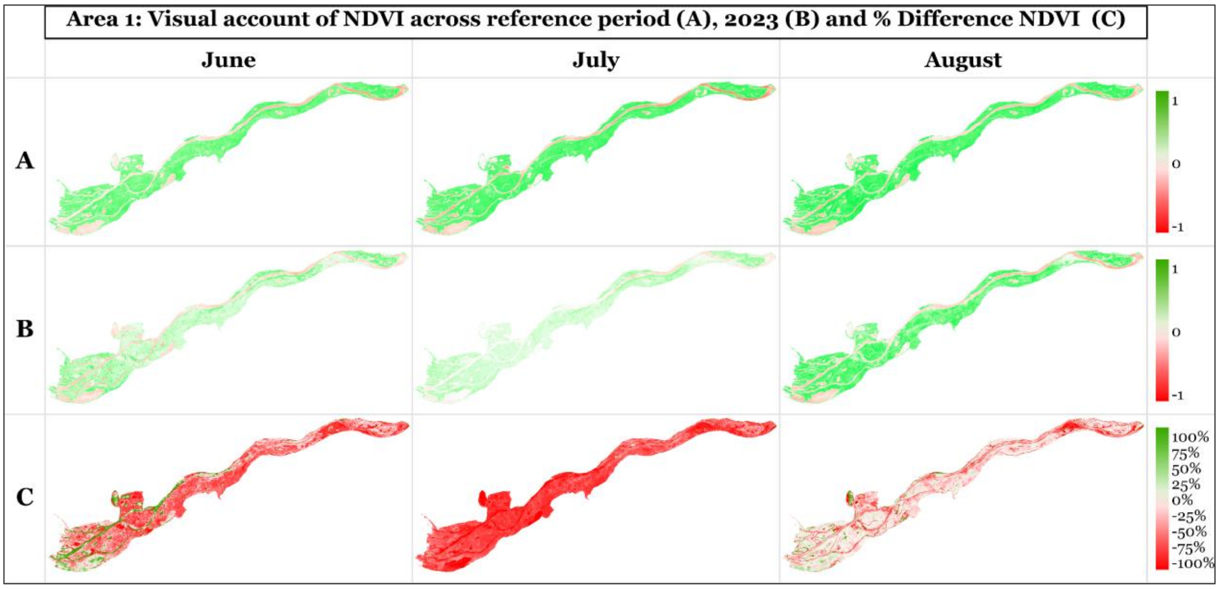

Figure 11: Monthly visual representation of mean NDVI levels during the reference period (A) and 2023 (B), alongside with % $dNDVI_t$ (C) for Area 1.

Complete Area 2

When analysing all land classes across Area 2, the reference period for all three months experienced a mean average NDVI of -0.103. For 2023, this rose to 0.091. For maximum NDVI, the reference period attained an average value of 0.094 whilst in 2023 this rose to 0.233 (+147%). Monthly NDVI per year is depicted in Figure 12.

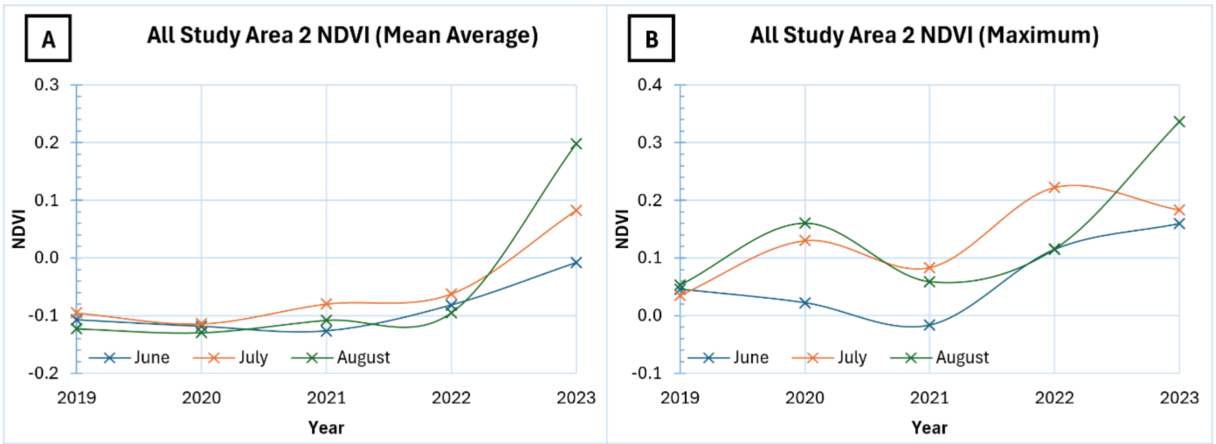

Figure 12: Monthly NDVI values per year across for the entirety of Study Area 2. Mean average (A), Maximum (B)

Across monthly terms, mean NDVI throughout the reference period saw an average of -0.109, -0.088 and -0.114 for months June, July and August respectively. During 2023, mean averages rose to -0.008, 0.082 and 0.198 respectively. For maximum NDVI, the reference period attained levels at 0.051, 0.126 and 0.106 respectively. For 2023, max NDVI for June rose by +226% to 0.168, July saw a +51% increase to 0.19 and August experienced +223% higher maximum at 0.341. A visual aid to help display the spatial distribution of changes to NDVI across Area 2 is displayed in Figure 13.

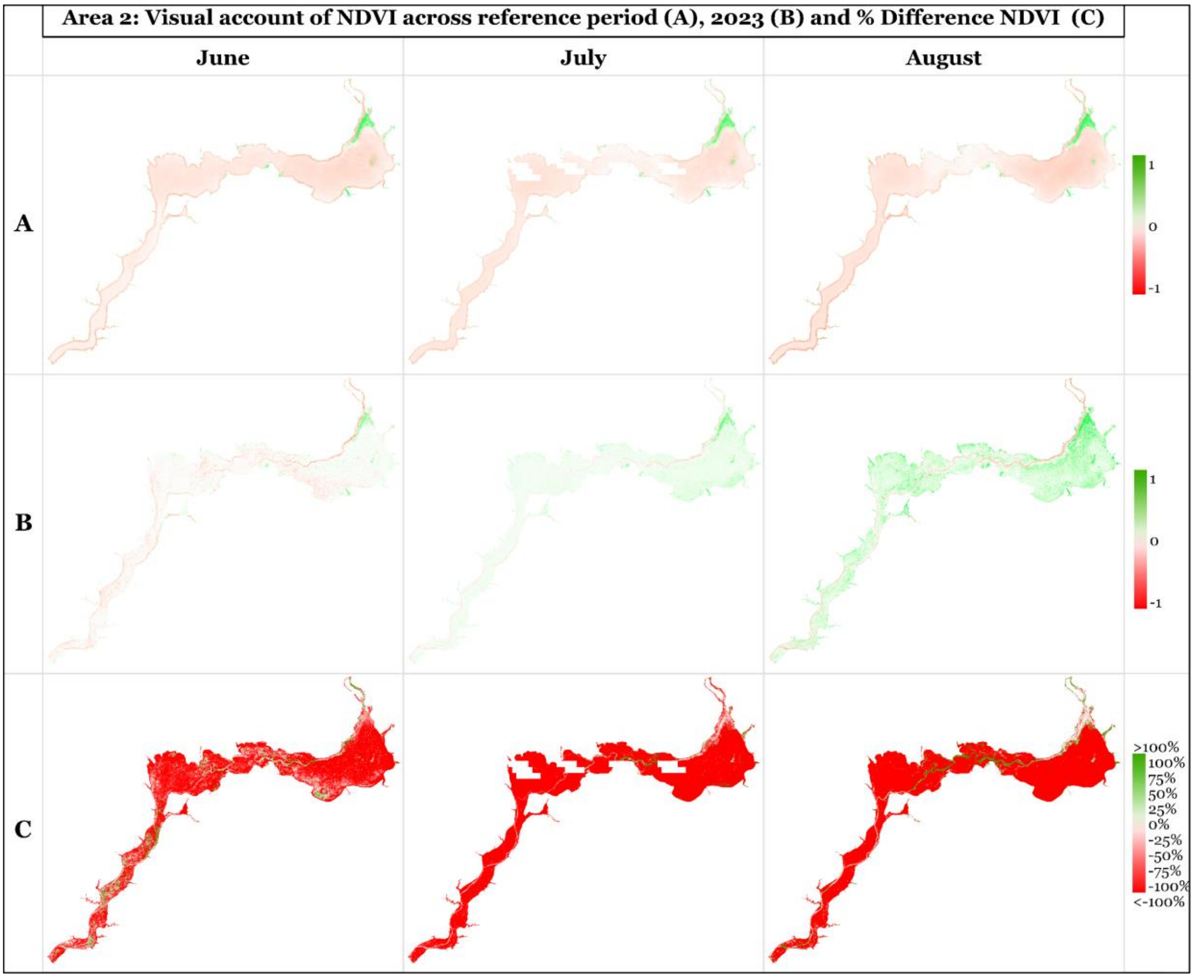

Figure 13: Monthly visual representation of mean NDVI levels during the reference period (A) and 2023 (B), alongside with % $dNDVI_t$ (C) for Area 2.

4 Discussion

4.1 Main Findings

When comparing NDVI across the different spatial areas, the general observed pattern across Area 1 indicates generally reduced mean NDVI during 2023 across all assessed parameters. The month of August experiences the smallest disparity to the reference mean NDVI – indicating signs of initial recovery to vegetation within all parameters. Area 2 experiences increased NDVI in mean and maximum terms across all assessed parameters, except over wetland areas.

Wetlands

Within Area 1, wetlands classified under land class code 90 experience very similar mean NDVI values during the months of June and July 2023, as seen in Figure 4A. This is followed by a large recovery of NDVI during the month of August at more than double the mean value of June/July. This recovery, whilst the value remains lower than the reference period for the month of August, did exceed levels recorded during 2022 by 9.9%. A similar observation is made with maximum NDVI, where June and August remained within a 10% deviation from their respective reference values. With respect to high maximum values for June 2023, this is likely a result of the Earth Engine code selecting satellite images taken before Dams' destruction on June 6th.

Wetlands in Area 2 experienced similar fluctuations in NDVI as seen within Area 1, with June and July experiencing large decreases to mean and maximum NDVI levels during 2023 compared to the reference period, as seen in Figure 5. However, the decrease during July was not as profound as that observed in Area 1 for both mean and maximum terms. This difference may have been because of two different hydrological conditions, where Area 1 saw NDVI levels drop as a result of water inundating large parts of wetlands (Chen et al., 2024). As flooding receded during June, lower NDVI levels may have ensued during July because of physical damage to vegetation - with mean values around 0.23 comparable to values expected for shrub and bushland, indicating very sparse vegetation density. Within Area 2, the lowest NDVI were observed during June, thereafter mean values increased by +65% in July. This might be because of a sudden decrease in water levels leaving wetlands to dry out quite suddenly, resulting in lower NDVI levels for June. However, this raises questions as the water table would still have been higher compared to July, in which improved NDVI levels were attained. Other reasons may thus be responsible for this and lie outside the scope of this study. Nevertheless, the month of August also sees a return to levels comparable to the reference for the area.

Between the two study Areas, NDVI values across wetlands were almost identical to each other during August 2023, where Area 1 experienced marginally higher NDVI values by +4.6% and +3.2% in mean and max terms respectively compared to Area 2. This coincides to previous years where Area 1's wetlands have appeared slightly greener than Area 2. This is likely because the wetlands of Area 2 are more spatially distributed over a larger area, and thus may have less cohesive NDVI levels because of different ecological and climatic conditions. In any regard, the wetlands are sensitive to hydrological conditions, to better understand their physical state of health, it would be necessary to use NDVI / land change metrics in conjunction to hydrological data (Sosnowski et al., 2016), which this study lacks. These early indications show that wetlands across both areas are recovering in a similar fashion - with NDVI unexpectedly recovering to nearly reference levels by August. This suggests that photosynthetic activity and vegetation density have returned to 'normal' reference levels within only a few months, however this does not mean the character of the vegetation has completely been preserved. It is possible that less resilient species have succumbed to the stresses with greater consequence than others that have perhaps been replaced by other vegetation which more easily settles. Such risks are particularly important to evaluate within the Ramsar sites since they were established with the aim to preserve the biodiversity of wetlands. Because of limits relating to image resolution and vegetation concealing underlying vegetation and microflora, such an assessment would be very difficult to achieve adequality via remote sensing and thus would require a physical visit to the wetlands.

Ramsar Areas

Shifting focus to Ramsar protected areas, the Dnipro Delta in Area 1 experienced very similar variations to NDVI as was observed with just wetlands, although general NDVI levels are comparatively lower by 0.3 to 0.4. This is most likely due to the Ramsar site including large amounts of permanent water bodies as part of the masking polygon. The Ramsar site also experienced a recovery in NDVI close to reference values for the month of August, with mean NDVI for 2023 exceeding levels observed in 2022 by +9.9%, whilst max NDVI remained marginally lower than the reference. General NDVI levels observed in Ramsar 1 were very similar to those for the complete Area 1. Ramsar sites in Area 2 were combined for the purposes of this study to save time when processing the NDVI image sets. Both polygon sets included large areas of permanent water bodies with comparatively minuscule amount of wetland according to the Worldcover dataset. This is reflected in the very low reference NDVI values that are comparable to levels attained for the whole study area. Post the dam's destruction, mean NDVI levels experienced substantial increases into positive values, with values rising as the summer progressed. This effect also occurred amongst the other parameters within Area 2, however Ramsar 2 experienced slightly higher mean and maximum NDVI levels compared to the complete area by roughly +0.06 across 2023. Since the Ramsar areas contain various land classes, including permanent water bodies, it is likely that not all landcover types behave or recover in the same way following the flooding in Area 1, or the draining of the reservoir in Area 2. To better assess this, it would be necessary to extract each individually land class within both areas and analyse them individually. This would be particularly relevant for Area 2 as NDVI between wetlands and water bodies react very differently to the effect of the reservoir draining. This approach should be adopted to improve any future study on this matter.

Complete study area / Wetlands and Waterbodies

Very similar NDVI values were observed when comparing against wetlands and waterbodies (90+80) were and the complete study area. In Area 1, subtle differences were more apparent due to the greater presence of other land types within the whole study area, resulting in recorded NDVI being slightly higher in value than those for wetlands and waterbodies combined. This was likely caused from the fact that the majority of other land types consisted of Tree cover under land class code 10 (Tsendbazar et al., 2022). Nevertheless, variations were only ±0.05 in mean and maximum terms, hence the presence of other land classes did not greatly skew the overall result since they accounted for a proportionally very small area with likely similar NDVI levels as to wetlands themselves. There were no meaningful differences between the two parameters for Area 2, where values were almost identical as seen in Figure 9 and 11. This is due to only being 2.5% of land classified as something other than permanent water bodies. Within Area 2, like in Ramsar 2, 2023 saw NDVI levels rise to positive values – something that did not occur anytime during the reference period. However, NDVI levels would still be considered low, even with the highest NDVI levels recorded during August being comparable to that expected from shrubland.

General Remarks
The emergence of positive NDVI values over wetlands and waterbodies in Area 2 indicates that vegetation began to colonise exposed land in the former Kakhovka reservoir as early as June. Nevertheless, research by Kuzemko et al. (2024) suggests that the emergence of vegetation could have been facilitated thanks to a nutrient-rich substrate, aided by high soil moisture content and the presence of a seed bank already buried within the soil from before the dam. Preliminary reports also warn that emerging vegetation might be dominated by invasive species which could outcompete native vegetation (Vyshnevskyi et al., 2023). If these trends continue in the future and subject to correct ecological and hydrological conditions, this newly established vegetation may be the formation of new wetlands compatible with definitions such as those outlined by Cowardin et al. (1979).

Overall, despite wetlands across both areas showing indication of stresses after the dam was destroyed, the rise in NDVI levels during August to the degree observed provides encouraging signs that underlying vegetation was in recovery by the end of the 2023 summer period. That said, it is important to reiterate that NDVI does not evaluate all physical properties of vegetation and thus further investigations will be necessary to properly ascertain the physical health of the wetlands.

4.2 Data uncertainties and study limitations.

This study is not comprehensive and is limited by a variety of different factors, resulting in data uncertainty.

Remote sensing, whilst being an effective and practical tool in monitoring landcover dynamics, can have its reliability affected depending on weather and atmospheric conditions (Jensen, 2009). NDVI derived from optical data can be influenced by cloud cover, which can suppress reflectance from the ground and lead to lower NDVI values. Hence a cloud-free set of images was important to ascertain. However, the employed use of the QA60 cloud mask is not always completely effective in removing all cloud artifacts. A study by Coluzzi et al. (2018) has suggested the product generally underestimated the presence of clouds (with an average omission error of 37.4%), whilst having particular difficulty in detecting cirrus clouds. However, their assessment also concluded that QA60 mostly worked with an overall accuracy of 86.5%. It is therefore possible some clouds may have persisted within the computed images that would have led to reduced NDVI at underlying areas. Due to time restrictions for this study, it was not possible to quantify the extent of cloud misclassifications within the QA60 layers used across each month, if any did occur. Furthermore, generated images may be temporarily inhomogeneous. If no single captured image over the whole spatial area was cloud free for a select month, the affected spatial area may have been replaced by a cloud-free image across a different temporal period and mosaiced together to form a cloud-free result.

There are several other temporal uncertainties. When calculating maximum NDVI, all NDVI images available within a selected month were evaluated and compiled to form a maximum value image. It is not specified in the Earth Engine product description what method was employed for this process. It is possible that the highest NDVI value observed across the different temporal images was selected over a specific pixel space within the duration of the month, with the full image extent being a compilation of pixels from different temporal timestamps to produce the final image. Alternatively, the code selected a single individual image which held the overall highest average NDVI across the temporal selection of other images for the whole spatial extent. Either way, temporal disparities may exist in the pixel space of the computed images. The same would be the case for mean average NDVI, although this does not affect overall results. In respect to other temporal issues, it was originally intended to analyse images as far back as 2017, when the Harmonized Level-2A dataset became available to more confidently establish reference values. However, Earth Engine began encountering errors when attempting to extract data for 2018 and 2017, with no images produced. It was not possible to conduct a reliable statistical analysis to test for significant differences as not enough yearly samples could be ascertained.

As a result of time constraints, it was not possible to conduct a thorough spatial analysis into the distribution of NDVI levels, outside of the visual aids presented in Figures 11 and 13. It should be noted that data losses exist within Figure 13 for the month of July in the form of an incomplete Raster file. When extracting mean NDVI statistics for July 2023, a non-corrupted raster image was utilised. Furthermore, the $dNDVI_t$ displayed within both Figures 11 and 13 have misleading percentage differences over any areas which experienced negative NDVI levels during the reference period. This is because of the mathematical nature of Equation 2, were the division of a positive number by a negative number equals a negative overall change, despite the actual effect being an increase to NDVI.

When defining the study area, difficulties were encountered to determine the boundaries of the study polygon. For the most part within Area 1, the boundary between wetland and non-related land classes was simple to identify via visual interpretation – in such cases the boundaries were drawn by eye, traceable using the polygon trace feature in ArcGIS Pro. Issues arose towards the mouth of the delta, where wetland areas towards the south began to be mixed amongst other land classes, resulting in a shattered and pixelated spatial distribution where it was not possible to reliably formulate a boundary. As such, the boundary of the Ramsar protected area for the Dnipro Delta (RSIS, 2022) was used to trace the primary study polygon for Area 1, consequently excluding a small amount of wetland area. Area 2 included large river inlets feeding into the reservoir since they were distinct permanent waterbodies under code 80, which were easy to trace and largely did not encounter any wetlands under code 90. River inlets to the Delta in Area 1 were excluded, as these were relatively small and difficult to determine their end boundaries further up the tributary. This was despite wetland areas were present in most of the tributaries mixed with other land classes. However, a report by the United Nations Environment Programme (2023) suggests that these areas may have been adversely affected and inundated – this would have affected the tributary wetlands but was not considered in this study. Classification uncertainties within the Worldcover dataset may have resulted in the further exclusion wetland areas. According to Zanaga et al. (2022), wetlands with trees or shrubs present may have potentially been misclassified as the "Tree cover" class (code 10), especially if the tree/shrub cover exceeds 10%, as a result of spectral similarities between the two class types. Land class 10 also encompasses tree covering areas which are seasonally or permanently flooded with freshwater (Zanaga et al., 2022). Tree cover made up the bulk of other land classes within Area 1 and was often present amongst the boundaries of both study areas. As such, it is likely that other wetlands exist beyond where the study boundary was drawn, and thus were not considered in this study. However, the quantity of other land classes (1) within both areas was very small and likely did not influence overall results. Determining the boundaries of wetlands is often difficult since they usually involve inconsistent water boundaries such as small tributary streams, marshlands, mangroves, etc. Several different methods have been developed to classify wetlands with some being specific to regions. (Cowardin et al., 1979; Rundquist et al., 2001). For related studies involving wetlands, the methodology used to define their area should be properly motivated to suit the specific geographical conditions at hand.

Wetlands, being complicated ecological systems are sensitive to a variety of different factors. One such factor would be variations in weather patterns on an annual and monthly basis which would result in variations to their observed NDVI. Fluctuations in NDVI levels during different years of the reference period, (such as the reduced NDVI observed in Area 1 for June 2022), may have been because of weather conditions. This has not been analysed as part of this study. It is also important to discuss seasonal effects. The analysis of NDVI during the summer months needs to be recognized in the context that certain vegetation would still have been undergoing growth, consequently resulting in increasing NDVI as the months progressed across all studied years. Entering the autumn season, wetland vegetation would begin to become dormant - resulting in NDVI values to decrease and remain comparatively much lower than that observed during the growing season throughout spring and summer. Because of this, it would be impractical to use this study's methodology for an analysis during the autumn and winter period, whilst the rapid growth in vegetation characteristic of the spring period may result in difficulties to differentiate between 'normal' and unusual NDVI activity. The climatic intensity of a particular season for any given year would affect wetland vegetation in the following season and/or annual period. Furthermore, different species comprising wetlands may be more resilient to changes in hydrological and climatic conditions compared to others, which could lead to the deterioration of specific species, whilst others persevere. The destruction of the dam induced large systematic stress in which several wide-ranging ecological, hydrological, and climatic conditions have been altered in the aftermath of the event. Other researchers have indicated that many of these require further assessment to properly understand their impacts – despite signs of recovery detected in this study, there is a likelihood that the wetlands may face future complications to their wellbeing. As such, it is necessary to continue to monitor these wetlands in the months and years ahead. (Chen et al., 2024; Nepsha et al., 2024; Spears et al., 2024; Wang, 2024).

5 Conclusion

Comparison of NDVI values before and after the destruction of the Kakhovka dam indicate that wetlands have generally seen NDVI levels lower dramatically in the immediate aftermath of the incident across both study areas, in line with expectations. Despite this, there were firm indications that wetlands began to recover in the latter half of the 2023 summer period, with NDVI levels for the month of August returning to levels not so dissimilar to that established during the reference period. The Kakhovka reservoir experienced rapidly increasing NDVI values as summer progressed in 2023. Levels observed greatly surpassed expectation as vegetation quickly began to establish itself across the exposed ground. NDVI is not a comprehensive indicator of wetland health - more comprehensive research will be required by the use of other methods so as to properly ascertain the physical state of the wetlands and their continued recovery in the months and years ahead.

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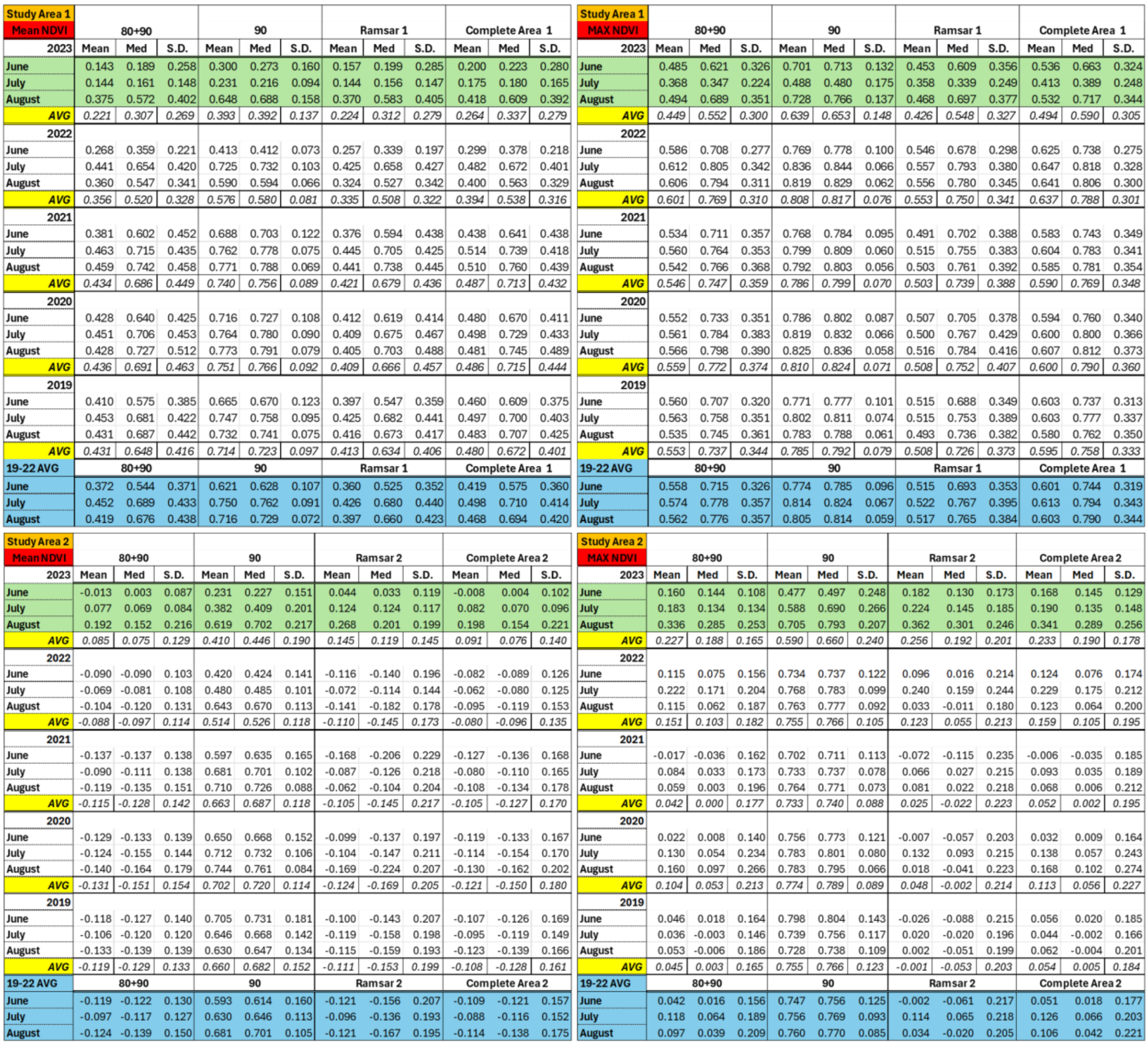
7 Appendices

7.1 Earth Engine Code:

```
// Earth Engine Code for mean NDVI over Ukraine study area for June 2019
// Import the Sentinel-2 dataset
var s2 = ee.ImageCollection('COPERNICUS/S2_SR_HARMONIZED');

// Filter the collection to the area of interest (Ukraine)
var ukraine = /* color: #d63000 */ee.Geometry.Polygon  ([
  [[22.0, 52.3], [40.0, 52.3], [40.0, 44.3], [22.0, 44.3]]
]);

var start_date = '2019-06-01';
var end_date = '2019-06-30';
var s2_ukraine = s2.filterBounds(ukraine)
                .filterDate(start_date, end_date);

// Filter out cloudy pixels using quality flags
var cloudMask = s2_ukraine.map(function(image) {
  var qa = image.select('QA60');
  // Bits 10 and 11 are cloud shadow and cloud, respectively.
  var cloudShadowBit = 1 << 10;
  var cloudBit = 1 << 11;
  var mask = qa.bitwiseAnd(cloudShadowBit).eq(0)
            .and(qa.bitwiseAnd(cloudBit).eq(0));
  return image.updateMask(mask);
});

// Calculate NDVI on the cloud-free images
var ndvi = cloudMask.map(function(image) {
  var nir = image.select('B8');
  var red = image.select('B4');
  return image.addBands(nir.subtract(red).divide(nir.add(red)).rename('NDVI'));
});

// Compute mean average NDVI
var avg_ndvi = ndvi.mean();

// Display the average NDVI image
var avg_ndvi_single = avg_ndvi.select('NDVI');
Map.addLayer(avg_ndvi_single, {
  min: -1,
  max: 1,
  palette: ['red', 'white', 'green']
}, 'Mean NDVI');

print(avg_ndvi);

// Export the average NDVI image to Google Drive
Export.image.toDrive({
  image: avg_ndvi_single,
  description: 'Avg_NDVI_SRH_June2019',
  scale: 10,
  region: ukraine,
  maxPixels: 1e9
});
```

7.2 Results Spreadsheet Extract:



Study Area 1 Mean NDVI	80+90			90			Ramsar 1			Complete Area 1		
2023	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.
June	0.143	0.189	0.258	0.300	0.273	0.160	0.157	0.199	0.285	0.200	0.223	0.280
July	0.144	0.161	0.148	0.231	0.216	0.094	0.144	0.156	0.147	0.175	0.180	0.165
August	0.375	0.572	0.402	0.648	0.688	0.158	0.370	0.583	0.405	0.418	0.609	0.392
AVG	*0.221*	*0.307*	*0.269*	*0.393*	*0.392*	*0.137*	*0.224*	*0.312*	*0.279*	*0.264*	*0.337*	*0.279*
2022												
June	0.268	0.359	0.221	0.413	0.412	0.073	0.257	0.339	0.197	0.299	0.378	0.218
July	0.441	0.654	0.420	0.725	0.732	0.103	0.425	0.658	0.427	0.482	0.672	0.401
August	0.360	0.547	0.341	0.590	0.594	0.066	0.324	0.527	0.342	0.400	0.563	0.329
AVG	*0.356*	*0.520*	*0.328*	*0.576*	*0.580*	*0.081*	*0.335*	*0.508*	*0.322*	*0.394*	*0.538*	*0.316*
2021												
June	0.381	0.602	0.452	0.688	0.703	0.122	0.376	0.594	0.438	0.438	0.641	0.438
July	0.463	0.715	0.435	0.762	0.778	0.075	0.445	0.705	0.425	0.514	0.739	0.418
August	0.459	0.742	0.458	0.771	0.788	0.069	0.441	0.738	0.445	0.510	0.760	0.439
AVG	*0.434*	*0.686*	*0.449*	*0.740*	*0.756*	*0.089*	*0.421*	*0.679*	*0.436*	*0.487*	*0.713*	*0.432*
2020												
June	0.428	0.640	0.425	0.716	0.727	0.108	0.412	0.619	0.414	0.480	0.670	0.411
July	0.451	0.706	0.453	0.764	0.780	0.090	0.409	0.675	0.467	0.498	0.729	0.433
August	0.428	0.727	0.512	0.773	0.791	0.079	0.405	0.703	0.488	0.481	0.745	0.489
AVG	*0.436*	*0.691*	*0.463*	*0.751*	*0.766*	*0.092*	*0.409*	*0.666*	*0.457*	*0.486*	*0.715*	*0.444*
2019												
June	0.410	0.575	0.385	0.665	0.670	0.123	0.397	0.547	0.359	0.460	0.609	0.375
July	0.453	0.681	0.422	0.747	0.758	0.095	0.425	0.682	0.441	0.497	0.700	0.403
August	0.431	0.687	0.442	0.732	0.741	0.075	0.416	0.673	0.417	0.483	0.707	0.425
AVG	*0.431*	*0.648*	*0.416*	*0.714*	*0.723*	*0.097*	*0.413*	*0.634*	*0.406*	*0.480*	*0.672*	*0.401*
19-22 AVG	80+90			90			Ramsar 1			Complete Area 1		
June	0.372	0.544	0.371	0.621	0.628	0.107	0.360	0.525	0.352	0.419	0.575	0.360
July	0.452	0.689	0.433	0.750	0.762	0.091	0.426	0.680	0.440	0.498	0.710	0.414
August	0.419	0.676	0.438	0.716	0.729	0.072	0.397	0.660	0.423	0.468	0.694	0.420

Study Area 1 MAX NDVI	80+90			90			Ramsar 1			Complete Area 1		
2023	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.
June	0.485	0.621	0.326	0.701	0.713	0.132	0.453	0.609	0.356	0.536	0.663	0.324
July	0.368	0.347	0.224	0.488	0.480	0.175	0.358	0.339	0.249	0.413	0.389	0.248
August	0.494	0.689	0.351	0.728	0.766	0.137	0.468	0.697	0.377	0.532	0.717	0.344
AVG	*0.449*	*0.552*	*0.300*	*0.639*	*0.653*	*0.148*	*0.426*	*0.548*	*0.327*	*0.494*	*0.590*	*0.305*
2022												
June	0.586	0.708	0.277	0.769	0.778	0.100	0.546	0.678	0.298	0.625	0.738	0.275
July	0.612	0.805	0.342	0.836	0.844	0.066	0.557	0.793	0.380	0.647	0.818	0.328
August	0.606	0.794	0.311	0.819	0.829	0.062	0.556	0.780	0.345	0.641	0.806	0.300
AVG	*0.601*	*0.769*	*0.310*	*0.808*	*0.817*	*0.076*	*0.553*	*0.750*	*0.341*	*0.637*	*0.788*	*0.301*
2021												
June	0.534	0.711	0.357	0.768	0.784	0.095	0.491	0.702	0.388	0.583	0.743	0.349
July	0.560	0.764	0.353	0.799	0.809	0.060	0.515	0.755	0.383	0.604	0.783	0.341
August	0.542	0.766	0.368	0.792	0.803	0.056	0.503	0.761	0.392	0.585	0.781	0.354
AVG	*0.546*	*0.747*	*0.359*	*0.786*	*0.799*	*0.070*	*0.503*	*0.739*	*0.388*	*0.590*	*0.769*	*0.348*
2020												
June	0.552	0.733	0.351	0.786	0.802	0.087	0.507	0.705	0.378	0.594	0.760	0.340
July	0.561	0.784	0.383	0.819	0.832	0.066	0.500	0.767	0.429	0.600	0.800	0.366
August	0.566	0.798	0.390	0.825	0.836	0.058	0.516	0.784	0.416	0.607	0.812	0.373
AVG	*0.559*	*0.772*	*0.374*	*0.810*	*0.824*	*0.071*	*0.508*	*0.752*	*0.407*	*0.600*	*0.790*	*0.360*
2019												
June	0.560	0.707	0.320	0.771	0.777	0.101	0.515	0.688	0.349	0.603	0.737	0.313
July	0.563	0.758	0.351	0.802	0.811	0.074	0.515	0.753	0.389	0.603	0.777	0.337
August	0.535	0.745	0.361	0.783	0.788	0.061	0.493	0.736	0.382	0.580	0.762	0.350
AVG	*0.553*	*0.737*	*0.344*	*0.785*	*0.792*	*0.079*	*0.508*	*0.726*	*0.373*	*0.595*	*0.758*	*0.333*
19-22 AVG	80+90			90			Ramsar 1			Complete Area 1		
June	0.558	0.715	0.326	0.774	0.785	0.096	0.515	0.693	0.353	0.601	0.744	0.319
July	0.574	0.778	0.357	0.814	0.824	0.067	0.522	0.767	0.395	0.613	0.794	0.343
August	0.562	0.776	0.357	0.805	0.814	0.059	0.517	0.765	0.384	0.603	0.790	0.344

Study Area 2 Mean NDVI	80+90			90			Ramsar 2			Complete Area 2		
2023	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.
June	-0.013	0.003	0.087	0.231	0.227	0.151	0.044	0.033	0.119	-0.008	0.004	0.102
July	0.077	0.069	0.084	0.382	0.409	0.201	0.124	0.124	0.117	0.082	0.070	0.096
August	0.192	0.152	0.216	0.619	0.702	0.217	0.268	0.201	0.199	0.198	0.154	0.221
AVG	*0.085*	*0.075*	*0.129*	*0.410*	*0.446*	*0.190*	*0.145*	*0.119*	*0.145*	*0.091*	*0.076*	*0.140*
2022												
June	-0.090	-0.090	0.103	0.420	0.424	0.141	-0.116	-0.140	0.196	-0.082	-0.089	0.126
July	-0.069	-0.081	0.108	0.480	0.485	0.101	-0.072	-0.114	0.144	-0.062	-0.080	0.125
August	-0.104	-0.120	0.131	0.643	0.670	0.113	-0.141	-0.182	0.178	-0.095	-0.119	0.153
AVG	*-0.088*	*-0.097*	*0.114*	*0.514*	*0.526*	*0.118*	*-0.110*	*-0.145*	*0.173*	*-0.080*	*-0.096*	*0.135*
2021												
June	-0.137	-0.137	0.138	0.597	0.635	0.165	-0.168	-0.206	0.229	-0.127	-0.136	0.168
July	-0.090	-0.111	0.138	0.681	0.701	0.102	-0.087	-0.126	0.218	-0.080	-0.110	0.165
August	-0.119	-0.135	0.151	0.710	0.726	0.088	-0.062	-0.104	0.204	-0.108	-0.134	0.178
AVG	*-0.115*	*-0.128*	*0.142*	*0.663*	*0.687*	*0.118*	*-0.105*	*-0.145*	*0.217*	*-0.105*	*-0.127*	*0.170*
2020												
June	-0.129	-0.133	0.139	0.650	0.668	0.152	-0.099	-0.137	0.197	-0.119	-0.133	0.167
July	-0.124	-0.155	0.144	0.712	0.732	0.106	-0.104	-0.147	0.211	-0.114	-0.154	0.170
August	-0.140	-0.164	0.179	0.744	0.761	0.084	-0.169	-0.224	0.207	-0.130	-0.162	0.202
AVG	*-0.131*	*-0.151*	*0.154*	*0.702*	*0.720*	*0.114*	*-0.124*	*-0.169*	*0.205*	*-0.121*	*-0.150*	*0.180*
2019												
June	-0.118	-0.127	0.140	0.705	0.731	0.181	-0.100	-0.143	0.207	-0.107	-0.126	0.169
July	-0.106	-0.120	0.120	0.646	0.668	0.142	-0.119	-0.158	0.198	-0.095	-0.119	0.149
August	-0.133	-0.139	0.139	0.630	0.647	0.134	-0.115	-0.159	0.193	-0.123	-0.139	0.166
AVG	*-0.119*	*-0.129*	*0.133*	*0.660*	*0.682*	*0.152*	*-0.111*	*-0.153*	*0.199*	*-0.108*	*-0.128*	*0.161*
19-22 AVG	80+90			90			Ramsar 2			Complete Area 2		
June	-0.119	-0.122	0.130	0.593	0.614	0.160	-0.121	-0.156	0.207	-0.109	-0.121	0.157
July	-0.097	-0.117	0.127	0.630	0.646	0.113	-0.096	-0.136	0.193	-0.088	-0.116	0.152
August	-0.124	-0.139	0.150	0.681	0.701	0.105	-0.121	-0.167	0.195	-0.114	-0.138	0.175

Study Area 2 MAX NDVI	80+90			90			Ramsar 2			Complete Area 2		
2023	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.
June	0.160	0.144	0.108	0.477	0.497	0.248	0.182	0.130	0.173	0.168	0.145	0.129
July	0.183	0.134	0.134	0.588	0.690	0.266	0.224	0.145	0.185	0.190	0.135	0.148
August	0.336	0.285	0.253	0.705	0.793	0.207	0.362	0.301	0.246	0.341	0.289	0.256
AVG	*0.227*	*0.188*	*0.165*	*0.590*	*0.660*	*0.240*	*0.256*	*0.192*	*0.201*	*0.233*	*0.190*	*0.178*
2022												
June	0.115	0.075	0.156	0.734	0.737	0.122	0.096	0.016	0.214	0.124	0.076	0.174
July	0.222	0.171	0.204	0.768	0.783	0.099	0.240	0.159	0.244	0.229	0.175	0.212
August	0.115	0.062	0.187	0.763	0.777	0.092	0.033	-0.011	0.180	0.123	0.064	0.200
AVG	*0.151*	*0.103*	*0.182*	*0.755*	*0.766*	*0.105*	*0.123*	*0.055*	*0.213*	*0.159*	*0.105*	*0.195*
2021												
June	-0.017	-0.036	0.162	0.702	0.711	0.113	-0.072	-0.115	0.235	-0.006	-0.035	0.185
July	0.084	0.033	0.173	0.733	0.737	0.078	0.066	0.027	0.215	0.093	0.035	0.189
August	0.059	0.003	0.196	0.764	0.771	0.073	0.081	0.022	0.218	0.068	0.006	0.212
AVG	*0.042*	*0.000*	*0.177*	*0.733*	*0.740*	*0.088*	*0.025*	*-0.022*	*0.223*	*0.052*	*0.002*	*0.195*
2020												
June	0.022	0.008	0.140	0.756	0.773	0.121	-0.007	-0.057	0.203	0.032	0.009	0.164
July	0.130	0.054	0.234	0.783	0.801	0.080	0.132	0.093	0.215	0.138	0.057	0.243
August	0.160	0.097	0.266	0.783	0.795	0.066	0.018	-0.041	0.223	0.168	0.102	0.274
AVG	*0.104*	*0.053*	*0.213*	*0.774*	*0.789*	*0.089*	*0.048*	*-0.002*	*0.214*	*0.113*	*0.056*	*0.227*
2019												
June	0.046	0.018	0.164	0.798	0.804	0.143	-0.026	-0.088	0.215	0.056	0.020	0.185
July	0.036	-0.003	0.146	0.739	0.756	0.117	0.020	-0.020	0.196	0.044	-0.002	0.166
August	0.053	-0.006	0.186	0.728	0.738	0.109	0.002	-0.051	0.199	0.062	-0.004	0.201
AVG	*0.045*	*0.003*	*0.165*	*0.755*	*0.766*	*0.123*	*-0.001*	*-0.053*	*0.203*	*0.054*	*0.005*	*0.184*
19-22 AVG	80+90			90			Ramsar 2			Complete Area 2		
June	0.042	0.016	0.156	0.747	0.756	0.125	-0.002	-0.061	0.217	0.051	0.018	0.177
July	0.118	0.064	0.189	0.756	0.769	0.093	0.114	0.065	0.218	0.126	0.066	0.203
August	0.097	0.039	0.209	0.760	0.770	0.085	0.034	-0.020	0.205	0.106	0.042	0.221