DOI: 10.31401/WS.2026.proc.35



# Determining the Influence of Solar Radiation on the Dynamics of Lake *Srebarna*'s Water Surface Area through Remote Sensing

*Jelev G.*[1], *Ivanova I.*[1], *Tsvetkova M.*[1], *Zhelezov G.*[2],
*Benderev A.*[2], *Gerginov P.*[2], *Chanev M.*[1]

[1] Space Research and Technology Institute, Bulgarian academy of Sciences,
Acad. G. Bonchev Str., bl. 1, 1113 Sofia, gjelev@space.bas.bg
[2] Geological Institute, Bulgarian Academy of Sciences,
Acad. G. Bonchev Str., bl. 24, 1113 Sofia, p.gerginov@mail.bg

## Abstract

This publication examines the impact of solar radiation on the water surface area of Lake *Srebarna*, the most significant feature of the *Srebarna* wetland system. Data from the Sentinel 2A and Sentinel 2B satellites, along with Normalized Difference Water Index (NDWI) index imagery, were utilized to determine the water surface area for the period from January 1, 2025, to December 31, 2025. Monthly solar radiation totals were calculated for the Natura 2000 protected area. The values were derived using a 30x30 m pixel digital elevation model from the Shuttle Radar Topography Mission (SRTM). The correlation between solar radiation levels and the water surface area of Lake *Srebarna* was investigated, followed by an analysis of the results. The study proves the typical negative correlation between solar radiation intensity and the lake's water surface area within the *Srebarna* Biosphere Reserve.

**Keywords:** solar radiation, *Srebarna* wetland system, digital elevation model, GIS, Remote sensing

## 1. Introduction

Solar radiation is the primary energy source that drives many of the physical and biological processes on Earth. Understanding its importance for the landscape at different scales is key to understanding a wide range of natural processes and human activities [Potužníková et. al. 2023; Choi, et. al. 2019; Hesslerová, et. al. 2019; Dancheva & Asenovski, 2018; Fu, & Rich, 2002]. Wetlands are ubiquitous worldwide, encompassing a vast diversity of ecosystem types and holding significant ecological and social importance. The relationship between wetlands and solar radiation is critical for maintaining ecological balance and regulating climate at regional and local levels. Solar radiation serves as the primary energy source driving wetland processes, and variations in its intensity directly impact their condition. In the context of climate change, wetlands are exceptionally efficient carbon dioxide sinks, thereby helping to mitigate the greenhouse effect. Increased solar activity and warming lead to accelerated water evaporation, which threatens the habitats of numerous bird species, including those of European conservation concern (SPEC) [Fergus, et. al. 2013]. This makes many bird species directly dependent on these zones, such as the *Srebarna* Biosphere Reserve.

Lake *Srebarna* is one of the most significant wetlands in Bulgaria and Europe, characterized by a high degree of biodiversity and complex hydrological processes. It is a shallow Danubian wetland of exceptional importance for European biodiversity. As a site protected under UNESCO and the Ramsar Convention, the lake performs key ecological functions, including maintaining habitats for rare and endangered species [Gerginov, et al., 2026; Ministry of Environment and Water, 2022; Ivanova, 2014; Ramsar Convention Secretariat. 2016; Institute of Biodiversity and Ecosystem Research, 2011].

Solar energy is the primary energy source for wetlands, driving numerous physical and biological processes on Earth. Understanding it is essential for researching natural processes occurring within the landscape at various scales [Potužníková et. al. 2023; Choi, et. al. 2019; Dancheva & Asenovski, 2018; Fu, & Rich, 2002].

Processes within wetlands are governed by the cyclical nature of their primary energy source, directly affecting water and soil temperatures. Consequently, high summer radiation leads to warmer conditions and elevated evapotranspiration. Conversely, winter solar radiation values are much lower, resulting in lower temperatures and reduced evapotranspiration [Mitsch & Gosselink, 2015; Peter, 2008; Kadlec, 1999].

Investigating the impact of solar radiation on wetlands is of great importance both for analyzing process dynamics within these zones and understanding their climatic effects [Potužníková et. al. 2023]. Wetlands and their functions are viewed either as sources or sinks of greenhouse gases, given their capacity to accumulate them. This occurs through the process of evapotranspiration, which exerts a dual cooling and regulating effect on the surrounding landscape due to water phase changes. Evapotranspiration reduces thermal gradients, mitigates temperature extremes, and closes water and mass cycles. Conversely, in areas lacking water and permanent vegetation, the evapotranspiration-condensation cycle slows down. This leads to the transformation of solar radiation into sensible heat, resulting in surface overheating that warms the adjacent air layer. As this warm air rises turbulently, it absorbs larger amounts of water vapor, transporting it to the upper layers of the atmosphere where it condenses. This ultimately leads to the drying of the landscape [Hesslerová et al., 2019].

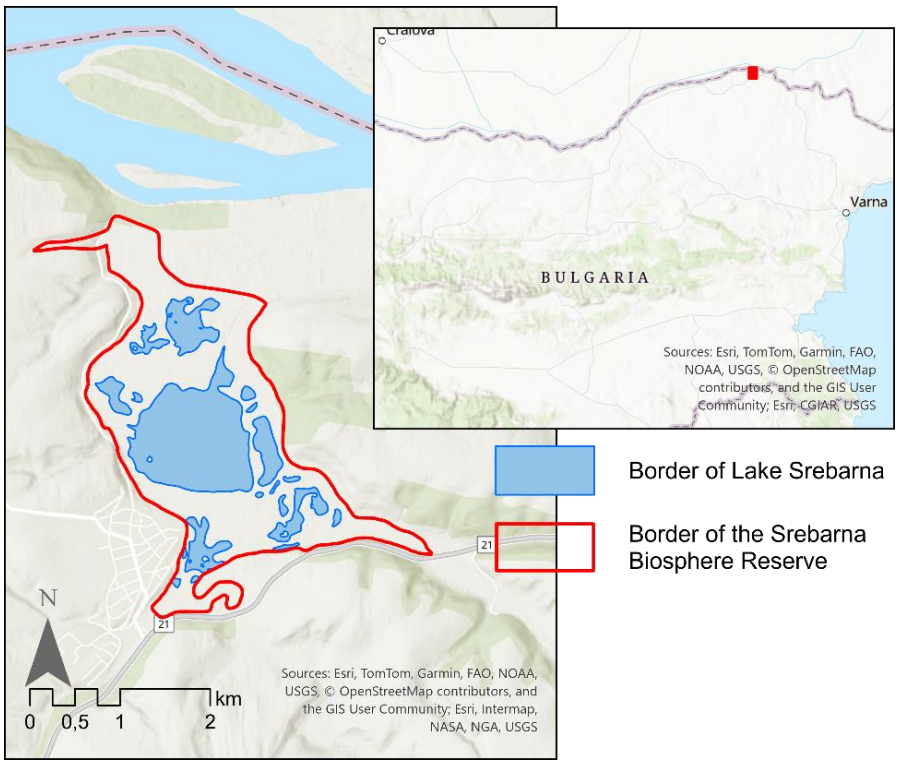



***Figure 1.*** *Study area: Borders of the Srebarna Biosphere Reserve and Lake Srebarna, Source: [NATURA natura2000, https://natura2000.egov.bg/]*

Consequently, wetlands and solar radiation exist in a continuous, dynamic interaction that determines both ecosystem health and local climate.

Geographically, *Srebarna* is located in the northeastern part of Bulgaria, in close proximity to the Danube River (Figure 1), with which it is linked through complex hydrological

interactions. The lake's hydrological regime is determined by a dynamic water balance shaped by the joint action of surface inflow, groundwater, precipitation, and evaporation [Gerginov et al., 2026].

A particularly significant factor in this process is solar radiation, which influences the intensity of evaporation processes and the seasonal variability of water volumes. Due to its shallow nature and limited water exchange with the river, Lake *Srebarna* is highly sensitive to climate variations and anthropogenic impacts [Ivanova, 2014; Michev, & Stoyneva, 2007].

In 1948, *Srebarna* was declared a managed reserve. In 1975, the *Srebarna* Managed Reserve was designated under the Ramsar Convention on Wetlands of International Importance. It was declared a UNESCO Biosphere Reserve in 1977 and was inscribed on the UNESCO World Cultural and Natural Heritage List in 1983. The Ramsar Convention obliges member states to protect the ecological character of their sites to ensure the maintenance of habitats for rare and endangered species [Gardner et al. 2023; Michev, & Stoyneva, 2007]. Currently, the *Srebarna* Managed Reserve is part of the NATURA 2000 network under site code BG0000241.

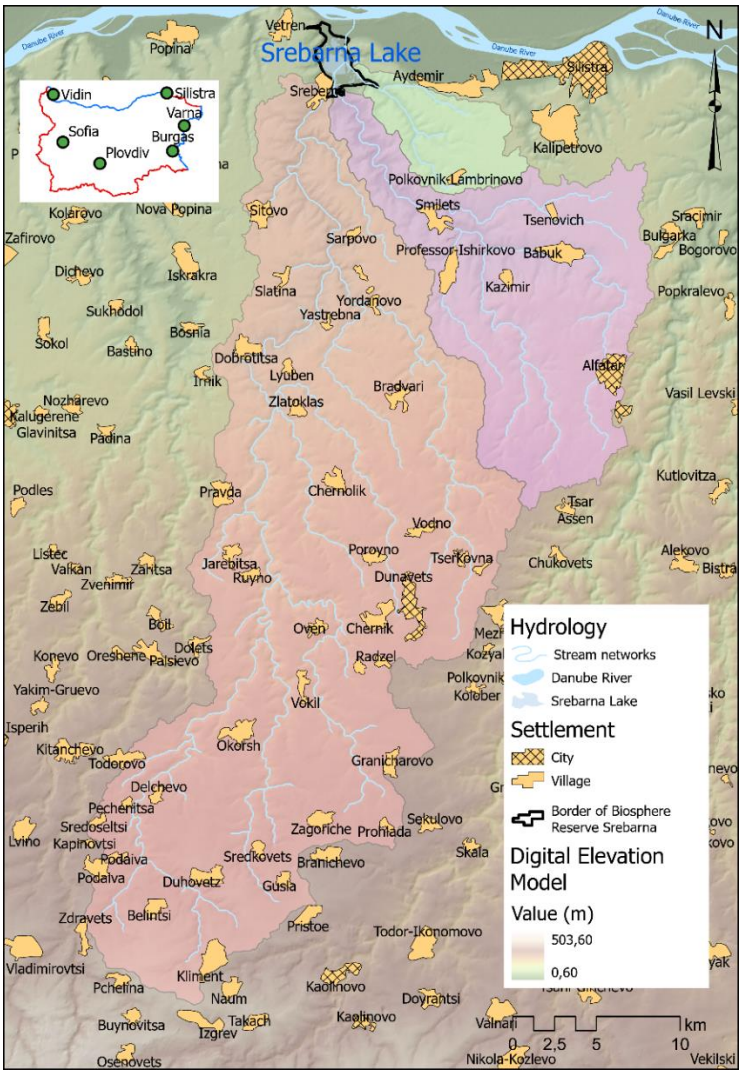



***Figure 2.*** *The watershed of the study area generated by the DEM*

The lake's catchment area (959.68 km²) is drained by the Srebrenska and Kalnezha rivers, which exhibit a highly variable hydrological regime and nearly dry up during the summer-autumn period (Figure 2). Based on its hydro-morphometric parameters, the lake is classified as a small water body, with a surface area of up to 10 km².

## 2. Purpose and objectives

The objective of this study is to determine the impact of total solar radiation on the variations of the water surface area of Lake *Srebarna* within the *Srebarna* wetland system, utilizing remote sensing and Geographic Information Systems (GIS) for the period from January 1, 2025, to December 31, 2025.

To achieve this, the following primary tasks were established:

- Determining the monthly surface area and variations of the water body of Lake *Srebarna* for the period from January 1, 2025, to December 31, 2025, using the NDWI index;
- Generating maps that display the total solar radiation within the *Srebarna* Biosphere Reserve using GIS software (ArcGIS Pro);
- Analyzing the resulting tabular and graphical data.

## 3. Materials and Methods

Data from SentinelHub [Kovács et al., 2026] were utilized, specifically Sentinel-2 satellite imagery focusing on bands B03 (Green) and B08 (NIR). One cloud-free image (0% cloud cover over the study area) was selected for each month of the year. Within the specialized software ArcGIS Pro, these two bands were used to calculate Normalized Difference Water Index (NDWI) imagery based on the following formula:

$$NDWI = (Green - NIR) / (Green + NIR), \text{ reference by [McFeeters, 1996].} \quad (1)$$

The resulting index images were reclassified, and NDWI values greater than 0.3 were delineated as the water surface area of Lake *Srebarna* [Ahmed & Ahmed, 2026; Du et al., 2016; McFeeters, 2013], after which the water surface area was calculated.

To compute the amount of area-wide solar radiation, a Digital Elevation Model (DEM) with a pixel size of 30x30 m, derived from the Shuttle Radar Topography Mission (SRTM) [USGS, EarthExplorer, 2026], was employed. Using the built-in tool in ArcGIS Pro, the total area solar radiation was calculated for each month of 2025 [Raster Solar Radiation, 2026]. The lake's water surface area values were then correlated with the mean solar radiation values calculated for the study area. The results were processed and visualized as a chart using MS Excel. A flowchart of the research methodology is presented in Figure 3.

## 4. Results and Discussion

The results of the statistical analysis regarding the relationship between area-wide solar radiation (kWh/m²) and the water surface area ($km^2$) are graphically presented in Figure 4. The graph illustrates a typical negative correlation between the intensity of area-wide solar radiation and the water surface area of the lake within the *Srebarna* Reserve. For better visualization, Table 1 displays the monthly data and the resulting values for the Average of Area Solar Radiation (kWh/m²) and NDWI for the *Srebarna* Biosphere Reserve. The changes in the state of Lake *Srebarna* and the spatial distribution of the monthly area-wide solar radiation are clearly visible.

Analysis of Correlation Points

*Radiation Peak (July – August):* Solar irradiance reaches its maximum during this period, driving peak evaporation rates. This directly corresponds to the lowest water levels and the maximum contraction of the open water surface area (Figure 4).

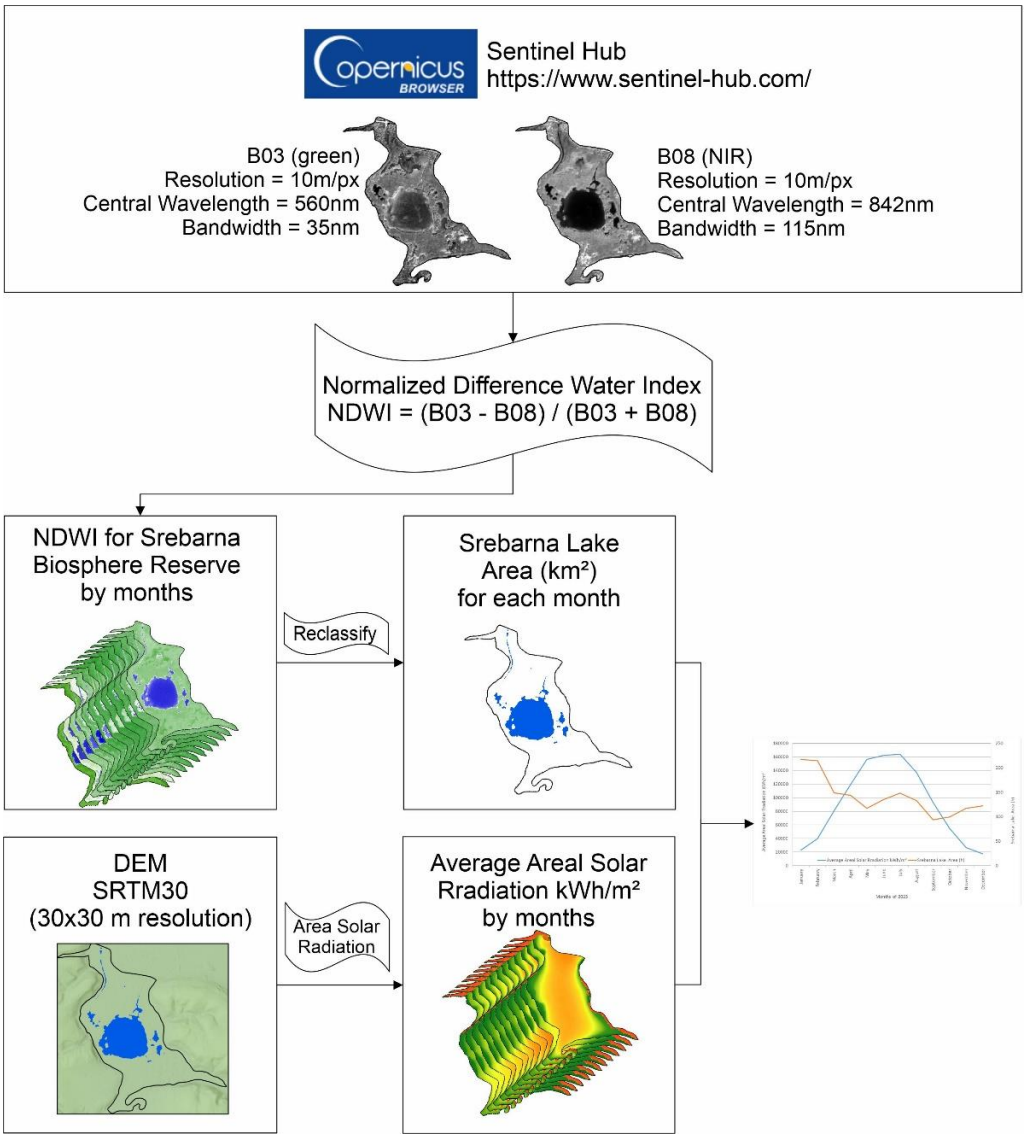



***Figure 3.*** *Scheme of research methods*

*Maximum Water Surface Area (March – April):* Solar radiation remains moderate during these months, while the lake is replenished by the spring high-water stage of the Danube River combined with snowmelt.

*Critical Transition Zone (May – June):* A sharp decline in the water surface area occurs concurrently with rising solar radiation levels, marking the most ecologically dynamic period for the ecosystem (Figure 4).

This observed model underscores the critical importance of sluice gate management (anthropogenic intervention) in mitigating extreme solar anomalies to sustain regional biodiversity.

Zonal Heterogeneity of the Correlation

The correlation between solar radiation and the water surface area within the *Srebarna* Biosphere Reserve is non-homogeneous (the overall linear correlation for the entire year is slightly negative – **r** is approximately equal to **-0.26**). Due to the lake's specific morphometry, this relationship exhibits distinct spatial variations across different zones:

*Central Water Body (Zone of Strong Negative Correlation):* The correlation is most pronounced across open water areas. The absence of macrophyte vegetation allows solar radiation to heat the water column directly, leading to maximized evaporation and rapid surface area contraction during periods of intense sunlight.

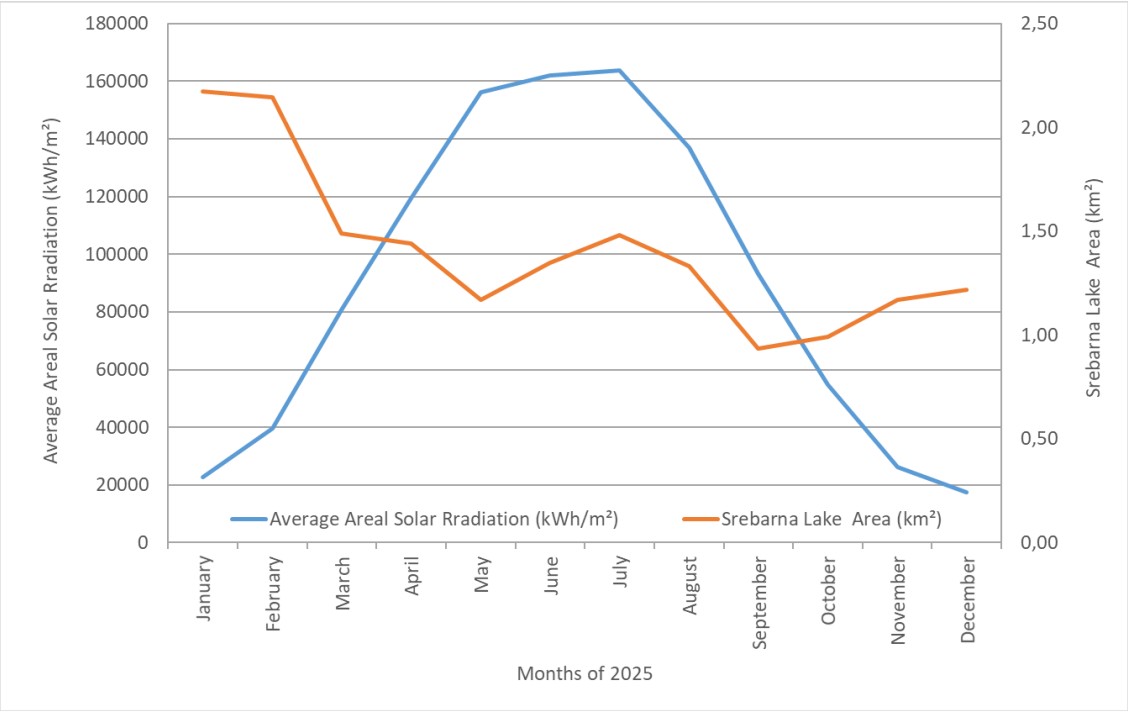



***Figure 4.*** *Relationship between Average Areal Solar Rradiation kWh/m² and Srebarna Lake Area (km²)*

*Peripheral Shallow Zones (Zone of Leading Correlation):* In the shallowest parts of the lake, even minor increases in solar radiation lead to complete water recession. The spatial distribution in these sectors shows the highest sensitivity, with the water surface disappearing here first.

*Floating Reed Island Zones (Zone of Weak/Buffered Correlation):* In areas dominated by dense vegetation and floating reed beds (tuprak), area-wide solar radiation is primarily absorbed by biomass. The canopy shades the underlying water and reduces direct evaporation from the water surface, stabilizing water levels against solar influence.

*Northern Sector (Feeding Channel Interface):* In the zone adjacent to the sluice gates connecting the lake with the Danube River, the natural correlation is frequently altered by anthropogenic intervention. When water levels drop critically due to high solar radiation, water is artificially transferred from the Danube, expanding the water surface area despite elevated radiation levels.

The quantitative data presented in Table 1 yields crucial insights into the seasonal dynamics and the complex interaction between solar radiation levels and the water surface area of Lake *Srebarna* during 2025.

*Winter Maximum and Minimum Irradiance (January – February):* During the first two months of the year, the average area solar radiation is at its lowest annual levels, shifting from 22770 kWh/m² in January to 39,749 kWh/m² in February. Concurrently, the lake reaches its maximum recorded water surface area for the year (2.17 km² and 2.15 km², respectively). This

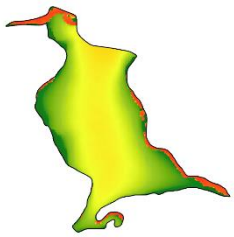
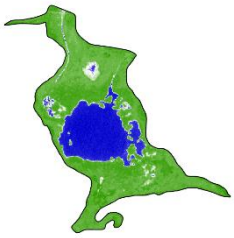
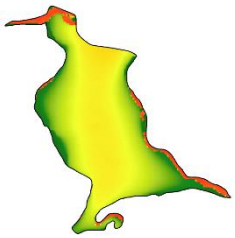
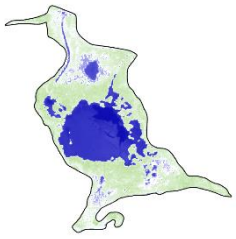
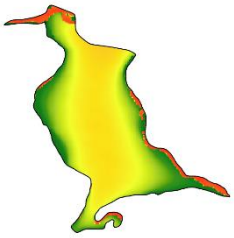
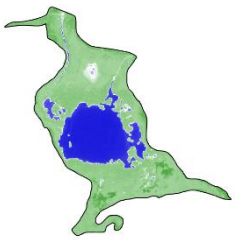
phase is characterized by low thermal energy, minimum evaporation rates, and accumulated winter precipitation.

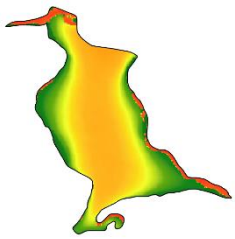
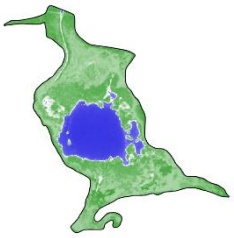
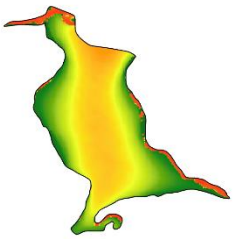
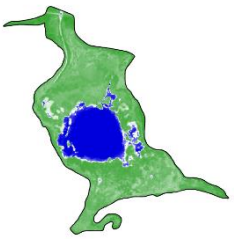
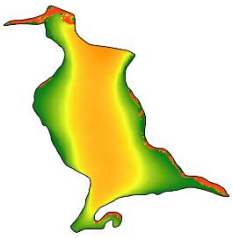
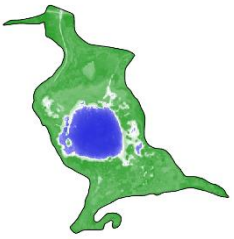
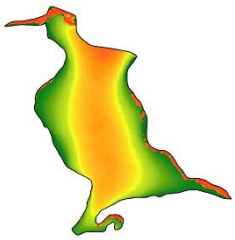
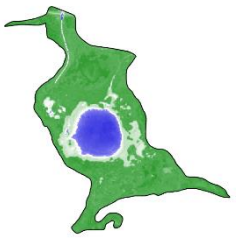
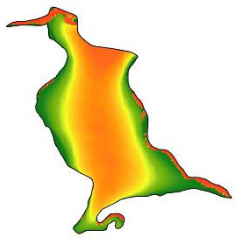
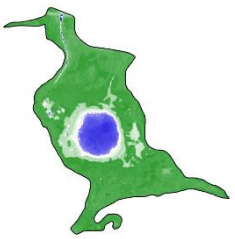
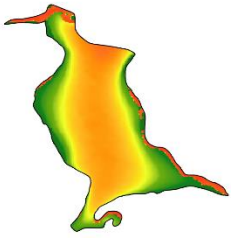
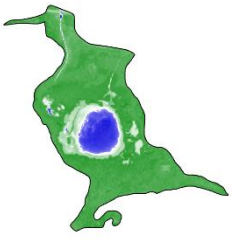
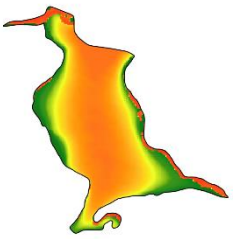
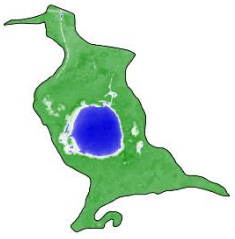
*The Spring Inflow Paradox (March – April):* As spring progresses, a sharp increase in solar radiation is observed, rising to 80680 kWh/m² in March and 119407 kWh/m² in April. Under purely climatic conditions, this energy influx would trigger early evaporation; however, the lake area remains relatively stable, dropping only slightly to 1.49 km² and 1.44 km². This stability highlights the buffering effect of the spring high-water stage of the Danube River and regional snowmelt, which temporarily counteracts the rising solar input.

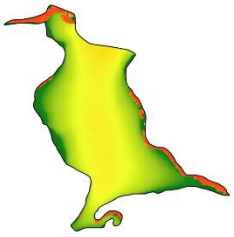
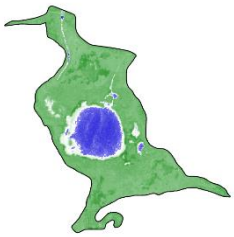
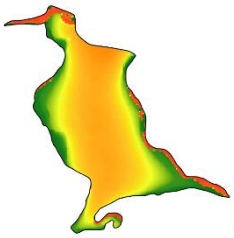
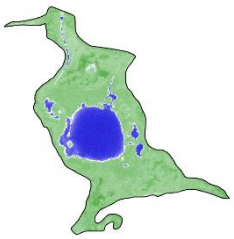
*Summer Evaporation and the June–July Artificial Expansion:* A critical hydrological shift occurs in May, where the area contracts to 1.17 km² as radiation climbs to 156143 kWh/m². Interestingly, during peak radiation months – June (162048 kWh/m²) and July (163806 kWh/m²) – the water surface area exhibits an anomaly, expanding to 1.35 km² and 1.48 km², respectively. This clear disruption of the negative correlation serves as mathematical proof of anthropogenic intervention, confirming that the sluice gates were opened to safeguard the wetland's ecosystem from critical drying.

*Late Summer Drop and Autumn Stabilization (August – December):* Following the closure or cessation of water transfers, August and September experience a rapid contraction of the lake area, reaching the absolute annual minimum of 0.94 km² in September, driven by the cumulative thermal stress of the preceding months. In the autumn (October – December), solar radiation drops sharply back to its minimum of 17518 kWh/m², allowing the water basin to steadily recover to 1.22 km² by December.

***Table 1.*** *Monthly maps and extracted values of area solar radiation (kWh/m²), NDWI, and lake surface area for the Srebarna Biosphere Reserve during 2025*

| Data, month of 2025 | Maps and Average of Area Solar Radiation (kWh/m$^2$) for *Srebarna* Biosphere Reserve | | NDWI for *Srebarna* Biosphere Reserve | *Srebarna* Lake Area (km$^2$) |
|---|---|---|---|---|
| January |  | 22770 |  | 2,17 |
| February |  | 39749 |  | 2,15 |
| March |  | 80680 |  | 1,49 |

| | | | | |
|---|---|---|---|---|
| April |  | 119407 |  | 1,44 |
| May |  | 156143 |  | 1,17 |
| June |  | 162048 |  | 1,35 |
| July |  | 163806 |  | 1,48 |
| August |  | 137077 |  | 1,33 |
| September |  | 93166 |  | 0,94 |
| October |  | 54650 |  | 0,99 |

| | | | | |
|---|---|---|---|---|
| November |  | 26331 |  | 1,17 |
| December |  | 17518 |  | 1,22 |

## 5. Conclusion

This study demonstrates the high efficacy of integrating Sentinel-2 satellite data and Geographic Information Systems (GIS) for the environmental monitoring of sensitive wetland ecosystems. By leveraging high spatio-temporal resolution imagery, the research successfully established a clear correlative link between solar radiation and the hydrological dynamics of the *Srebarna* Biosphere Reserve. The identified spatio-temporal heterogeneity and the negative correlation between solar radiation intensity and the lake's open water surface area highlight the profound impact of climate drivers on water volume fluctuations.

The pronounced climate pressure observed during the peak summer months (July–August) underscores the vulnerability of the reserve to seasonal temperature and radiation increases. These findings emphasize that modern remote sensing tools are indispensable for capturing rapid environmental changes that traditional ground-based monitoring might miss. Consequently, the methodology presented herein provides a reliable framework for park managers and policymakers to implement timely, data-driven conservation strategies.

Ultimately, while multispectral data offer valuable insights, comprehensive wetland management requires a multi-sensor approach. Future research must expand upon these findings by integrating Synthetic Aperture Radar (SAR) data to overcome cloud-cover limitations, utilizing advanced satellite products, and employing unmanned aerial vehicles (UAVs) for ultra-high-resolution localized assessments. Such advancements will significantly enhance the predictive modeling and long-term preservation of critical protected areas like Lake *Srebarna*.

## Acknowledgments

The research carried out within the project "Hydrogeological Mechanisms of Sustainable Recharge and Conservation of Karst Wetlands: A Study of the '*Srebarna*' System" is funded by the Bulgarian National Science Fund at the Ministry of Education and Science of Bulgaria under Contract No. KP-06-N94/7/10.12.2025 for the funding of fundamental scientific research.

## References

Ahmed, E. A. I., Ahmed, M. M. M. (2026). Temporal dynamics of Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) in semi-arid Gadarif Region, Sudan (1985–2024). *International Journal of Sustainable and Green Energy*, Vol. 15, No. 3, pp. 93–103. DOI: 10.11648/j.ijsge.20261503.11.

Choi, Y., Suh, J., Kim, S.-M. (2019). GIS-based solar radiation mapping, site evaluation, and potential assessment: A review. *Applied Sciences*, Vol. 9, No. 9, 1960. DOI: 10.3390/app9091960.

Dancheva, A., Asenovski, S. (2018). Study of waste disposal thermal radiation using satellite data and considering solar influence. *Aerospace Research in Bulgaria*, Vol. 30, pp. 16–25. DOI: 10.3897/arb.v30.e02.

Kovács, D. D., Musial, J., Bojanowski, J., Clarijs, D., de la Mar, J., Zlinszky, A. (2026). Copernicus Data Space Ecosystem establishes public cloud processing for Earth observation data. *Scientific Data*, Vol. 13, 537. DOI: 10.1038/s41597-026-06765-8.

Du, Y., Zhang, Y., Ling, F., Wang, Q., Li, W., Li, X. (2016). Water bodies' mapping from Sentinel-2 imagery with Modified Normalized Difference Water Index at 10-m spatial resolution produced by sharpening the SWIR band. *Remote Sensing*, Vol. 8, No. 4, 354. DOI: 10.3390/rs8040354.

Fergus, R., Louwe Kooijmans, J., Kwak, R. (2013). *BirdLife International Global Survey on the Status of Urban Bird Conservation*. BirdLife International, Cambridge.

Fu, P., Rich, P. M. (2002). A geometric solar radiation model with applications in agriculture and forestry. *Computers and Electronics in Agriculture*, Vol. 37, pp. 25–35.

Gardner, R. C., Okuno, E., Pritchard, D. (2023). Ramsar Convention governance and processes at the international level. In: *Ramsar Wetlands*, pp. 37–67. Elsevier. DOI: 10.1016/B978-0-12-817803-4.00003-6.

Gerginov, P., Totev, Y., Zhelezov, G., Zhelev, G. (2026). Hydrogeological mechanisms of sustainable recharge and preservation of karst wetlands: The "Srebarna" system study. In: *19th Congress of Geologists of Serbia "Geology for Sustainable Solutions": Book of Abstracts*. Bor Lake, Serbia, Serbian Geological Society, p. 209. ISBN: 978-86-86053-27-5.

Hesslerová, P., Pokorný, J., Huryna, H., Harper, D. (2019). Wetlands and forests regulate climate via evapotranspiration. In: An, S., Verhoeven, J. (Eds.), *Wetlands: Ecosystem Services, Restoration and Wise Use*. Ecological Studies, Vol. 238. Springer, Cham. DOI: 10.1007/978-3-030-14861-4_4.

Information System for Protected Areas from the Ecological Network NATURA 2000 (2026). Protected site BG0000241. Available at: https://natura2000.egov.bg/EsriBg.Natura.Public.Web.App/Home/ProtectedSite?code=BG0000241&siteType=BirdsDirective.

Institute of Biodiversity and Ecosystem Research, Bulgarian Academy of Sciences (2011). Ecological Station at Srebarna Biosphere Reserve. Available at: http://www.iber.bas.bg/?q=bg/node/103.

Ivanova, I. (2014). *Study on the Dynamics of Floating Reed Islands in the "Srebarna" Managed Nature Reserve and Lumina Lake from the Roșu–Puiu–Lumina Lake Complex in the "Danube Delta" Biosphere Reserve, Based on Satellite, Ground, and GPS Data*. Academic Publishing House "Prof. Marin Drinov", Sofia, 120 pp. ISBN: 978-954-322-762-4. (In Bulgarian).

Kadlec, R. H. (1999). Chemical, physical and biological cycles in treatment wetlands. *Water Science and Technology*, Vol. 40, No. 3, pp. 37–44. DOI: 10.1016/S0273-1223(99)00417-5.

McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, Vol. 17, No. 7, pp. 1425–1432. DOI: 10.1080/01431169608948714.

McFeeters, S. K. (2013). Using the Normalized Difference Water Index (NDWI) within a Geographic Information System to detect swimming pools for mosquito abatement: A practical approach. *Remote Sensing*, Vol. 5, No. 7, pp. 3544–3561. DOI: 10.3390/rs5073544.

Michev, T., Stoyneva, M. P. (Eds.). (2007). *Inventory of Bulgarian Wetlands and Their Biodiversity. Part 1: Non-Lotic Wetlands*. Elsi-M. ISBN: 978-954-9441-09-3.

Ministry of Environment and Water (2022). *Management Plan for the "Srebarna" Nature Reserve*. Sofia. (In Bulgarian).

Mitsch, W. J., Gosselink, J. G. (2015). *Wetlands*. 5th ed. John Wiley & Sons, 752 pp. ISBN: 978-1-119-01978-7.

Lafleur, P. M. (2008). Connecting atmosphere and wetland: Energy and water vapour exchange. *Geography Compass*, Vol. 2, No. 4, pp. 1027–1057. DOI: 10.1111/j.1749-8198.2007.00132.x.

Potužníková, K., Koucká Knížová, P., Chum, J., Podolská, K., Kouba, D., Mošna, Z., Georgieva, K., Bojilova, R., Kirov, B., Asenovski, S. (2023). Summer tropospheric mesoscale situations with impact on the ionospheric plasma. *Proceedings of the Fifteenth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"*, pp. 89–97. ISSN: 2367-7570. DOI: 10.31401/WS.2023.proc.

Ramsar Convention Secretariat (2016). *An Introduction to the Ramsar Convention on Wetlands*. 7th ed.

Esri (2026). Raster Solar Radiation. *ArcGIS Pro Documentation*. Available at: https://doc.esri.com/en/arcgis-pro/latest/tool-reference/spatial-analyst/raster-solar-radiation.html.

USGS (2026). *EarthExplorer*. Available at: https://earthexplorer.usgs.gov/.