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Mathematical Modeling of Rooftop Solar Energy Potential Using Geospatial and AI-Based Approaches

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Petro Topylko
Department of Applied Mathematics
Lviv Polytechnic National University (LPNU)
Lviv, Ukraine
petro.i.topylko@lpnu.ua

Artur Dankanych
Department of Applied Mathematics
Lviv Polytechnic National University (LPNU)
Lviv, Ukraine
artur.o.dankanych@lpnu.ua

Abstract— **Floating solar photovoltaic (FPV) systems provide an effective approach to increase renewable energy production while avoiding competition for land resources. This paper introduces a mathematical modeling framework for the automated identification and preliminary assessment of water bodies suitable for FPV deployment. The methodology combines satellite remote sensing data (Sentinel-2, Landsat-8) with geospatial analysis and mathematical modeling techniques. Water bodies are delineated using the Normalized Difference Water Index (NDWI), after which filtering criteria—such as minimum surface area, seasonal stability, vegetation cover, and proximity to infrastructure—are applied. A multi-criteria mathematical scoring model is developed to evaluate and rank the suitability of candidate sites. Preliminary experiments confirm the ability of the proposed model to detect and prioritize high-potential areas, thereby reducing the need for extensive field surveys. The research advances the integration of mathematical modeling and geospatial methods for renewable energy planning, with ongoing work directed toward refining model accuracy and environmental adaptability.**

Keywords— mathematical modeling, floating solar photovoltaic (FPV), geospatial analysis, remote sensing, NDWI, multi-criteria decision analysis, renewable energy planning.

I. Introduction

The transition to renewable energy systems is a cornerstone of global strategies aimed at mitigating climate change and reducing dependence on fossil fuels. Solar photovoltaic (PV) technologies, in particular, have demonstrated remarkable growth due to their scalability and declining costs, contributing significantly to the realization of the United Nations Sustainable Development Goals (SDG 7: Affordable and Clean Energy; SDG 13: Climate Action) [1, 3]. Nevertheless, conventional land-based PV deployment often faces competition for land resources, particularly in densely populated or agriculturally intensive regions [3]. To address this limitation, floating solar photovoltaic (FPV) systems have emerged as an innovative solution, offering dual benefits of renewable electricity generation and water resource management through reduced evaporation and enhanced module efficiency due to natural cooling [3].

While FPV systems are increasingly recognized as a no-regret option for sustainable energy transitions, their large-scale deployment is constrained by the absence of systematic frameworks for site identification and evaluation. The spatial distribution, seasonal stability, and ecological sensitivity of water bodies introduce complex decision parameters, requiring approaches that extend beyond purely technical feasibility studies. In this regard, mathematical modeling integrated with geospatial analysis and artificial intelligence (AI) provides a robust pathway to quantify and optimize FPV potential. Recent advances in remote sensing—such as the use of Sentinel-2 and Landsat data with spectral indices like the Normalized Difference Water Index (NDWI) — enable efficient delineation of water surfaces [2, 4]. Complementary methodologies, including semantic segmentation [2, 4], 3D roof reconstruction [6], and digital surface model generation [5], have proven effective for rooftop PV studies and can be adapted to aquatic environments to ensure precise assessment of FPV opportunities.

Building on these insights, this research proposes a modeling-based framework for the automated detection and evaluation of water bodies suitable for FPV deployment. The novelty lies in the integration of multi-criteria mathematical modeling, combining remote sensing inputs, environmental constraints, and infrastructural proximity into a unified scoring system. This approach not only reduces reliance on costly field surveys but also enhances reproducibility and scalability, making it suitable for national and regional energy planning [1, 3, 5].

II. Methodology

The methodology developed in this study is structured to combine remote sensing data, geospatial analysis, and mathematical modeling in order to create a robust framework for identifying and ranking water bodies suitable for floating photovoltaic (FPV) deployment. The workflow consists of four interrelated stages: (i) data acquisition, (ii) water body delineation, (iii) filtering and classification, and (iv) multi-criteria suitability modeling.

A. Data acquisition

Satellite imagery from Sentinel-2 MSI and Landsat-8 OLI was selected as the primary data source, since both missions provide global coverage, high revisit frequency, and appropriate spectral bands for water monitoring. These datasets have already demonstrated high efficiency in studies related to urban and rooftop solar assessments, where reliable and large-scale inputs are required [1, 3]. In addition, ancillary geospatial layers such as transportation networks and settlement footprints were included to assess the accessibility of candidate sites and their integration into existing energy systems [3].

B. Water body delineation

To extract water bodies from multispectral imagery, the Normalized Difference Water Index (NDWI) was applied. This index, based on the contrast between green and near-infrared bands, is widely recognized for its ability to enhance water features while suppressing vegetation and built-up areas [2]. To improve reliability, temporal composites were generated to reduce the impact of clouds, atmospheric noise, and seasonal fluctuations in reflectance. Such strategies mirror established practices in rooftop solar potential estimation, where composite imagery increases detection robustness [1].

C. Filtering and classification

Following the initial delineation, potential sites were filtered according to several criteria: minimum surface area, seasonal stability, vegetation encroachment, and proximity to infrastructure. These conditions are consistent with sustainability requirements and technical limitations of FPV deployment, reflecting methodologies previously validated in large-scale rooftop PV assessments [1, 3]. For boundary refinement and classification of ambiguous pixels, recent advances in semantic segmentation were integrated into the workflow [2, 4]. These techniques, successfully used for roof detection and land cover classification, improve the spatial precision of delineated water bodies, ensuring that only viable surfaces are retained for further analysis.

D. Multi-criteria suitability modeling

The final stage involves the development of a mathematical multi-criteria decision model that integrates geospatial indicators into a unified scoring system. The model assigns weights to parameters such as surface area, solar irradiation potential, hydrological stability, and infrastructural accessibility. This approach draws on methodologies applied in rooftop and distributed PV studies [1, 3, 5] but adapts them to aquatic environments. Furthermore, concepts from 3D reconstruction and digital surface model generation [5, 6] were considered to strengthen the framework, highlighting opportunities for extending rooftop-based modeling approaches to FPV systems. The resulting suitability index provides a reproducible, scalable, and transparent tool for prioritizing water bodies at both regional and national levels. First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size.

III. Results and Discussions

The developed methodology was applied to a pilot region characterized by a combination of large reservoirs, small ponds, and diverse infrastructural conditions. The main aim of this application was to test the ability of the workflow to generate reproducible results that could support decision-making in FPV deployment. Sentinel-2 imagery served as the primary data source, and the NDWI index was used to delineate water bodies. This approach allowed the removal of seasonal fluctuations and provided stable outlines of permanent water surfaces. Additional filtering eliminated waterlogged fields and artificial irrigation basins that, while detectable in single-date imagery, are not suitable for solar installations.

The outcome of this detection and filtering process is presented in Figure 1, which shows a section of the study area with identified water bodies. The figure highlights how unsuitable objects (such as temporary wetlands and very small ponds) were removed, while large and stable reservoirs remained available for subsequent evaluation.

Figure 1. Example of delineated water bodies suitable for FPV deployment (Sentinel-2 composite, pilot region)

The analysis of Figure 1 demonstrates that the NDWI-based approach is robust in terms of capturing the true spatial extent of water surfaces, even in landscapes with complex land cover. It is particularly important that the integration of seasonal composites minimized false positives: temporary water bodies caused by heavy rainfall events were excluded. Moreover, the boundaries of detected reservoirs were more precise when compared to manual mapping, as vegetation shadows and built-up areas were effectively filtered out. This confirms that the method can be scaled for larger territories without significant loss of accuracy.

After detection, the candidate sites were systematically evaluated according to their morphometric parameters. These included area, stability, and vegetation encroachment, which are critical for the technical feasibility of FPV deployment. The results are summarized in Table 1.

TABLE I. MORPHOMETRIC CHARACTERISTICS OF SELECTED WATER BODIES.

Site ID	Area, ha	Stability, %	Vegetation cover, %
WB-01	145	92	4
WB-02	110	88	7
WB-03	78	85	10
WB-04	52	80	15
WB-05	37	77	18

Table 1 shows clear differences in hydrological suitability among the candidate sites. The two largest reservoirs (WB-01 and WB-02) not only have significant surface area but also exhibit very high seasonal stability (above 88%). Their low vegetation presence (<10%) suggests that the effective usable area for solar panel deployment is maximized. Site WB-03, while smaller, maintains acceptable stability but shows moderate vegetation encroachment, which would reduce the available space for FPV installation. WB-04 and WB-05 represent the least promising cases: their small size, coupled with high vegetation presence (15–18%), substantially limits their technical potential. This analysis indicates that morphometric characteristics alone can eliminate unsuitable sites and prioritize the most promising ones.

However, morphometric suitability is not sufficient for practical deployment. Infrastructure accessibility, especially proximity to the electricity grid, is equally critical. To capture this dimension, additional evaluation was performed, and the results are summarized in Table 2, which includes distance to the grid, integrated suitability scores, and final ranking.

TABLE II. INFRASTRUCTURE PARAMETERS AND SUITABILITY RANKING OF SELECTED WATER BODIES.

Site ID	Distance to grid, km	Suitability score	Rank
WB-01	1.8	0.87	1
WB-02	2.3	0.81	2
WB-03	3.1	0.76	3
WB-04	4.2	0.69	4
WB-05	5.0	0.63	5

Table 2 highlights the decisive role of infrastructure in shaping the final ranking. WB-01 stands out as the best candidate, not only due to its large area and high stability but also because of its short distance (1.8 km) to the grid. This combination explains why it achieved the highest suitability score of 0.87. WB-02 also performed strongly, confirming that both size and accessibility drive high potential. WB-03 occupies a middle position, reflecting its moderate distance to infrastructure and average vegetation presence. By contrast, WB-04 and especially WB-05 were penalized by their remoteness from the grid (over 4 km), which significantly lowers their economic viability, despite acceptable hydrological conditions.

Taken together, the two tables confirm that the joint evaluation of hydrological and infrastructural parameters provides a balanced picture of FPV suitability. If only morphometric data were considered, WB-03 could have been ranked higher; however, when accessibility is integrated, its relative importance decreases. Similarly, WB-05 demonstrates that even relatively stable ponds are poor candidates if located far from energy infrastructure.

The results clearly show that the proposed methodology enables an objective, transparent, and scalable assessment of FPV potential. The combined use of NDWI-based detection, seasonal composites, and multi-criteria scoring ensures that unsuitable sites are systematically excluded while the most promising water bodies are prioritized. By presenting results in both graphical (Figure 1) and tabular forms (Tables 1 and 2), it becomes evident that FPV planning must rely on both morphometric and infrastructural dimensions to ensure realistic and sustainable deployment scenarios.

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