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Renewed understanding of pond classification systems: A perspective on multifunctional remote sensing classification

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Pond water surfaces (PWS) are independent aquatic ecosystems, artificially excavated or naturally formed, with small area, wide distribution, and pronounced spatial dynamics.[1] However, within aquatic ecosystems, large water bodies such as lakes and rivers attract greater attention, whereas PWS receive considerably less focus—with existing attention largely confined to aquaculture types. In reality, beyond ensuring food production, PWS enhance disaster resilience and regulate regional water quality, serving as vital components of aquatic ecosystems.[2] Despite their importance, current research lacks targeted investigation, functional diversity, and a universal classification system. These gaps obscure the spatial inventory of PWS and their ecological roles across geographical contexts, hindering regional aquatic ecological security and rational water resource use. This paper addresses these challenges and proposes three prospective solutions to promote multifunctional PWS typologies across broader scales and support complex water resource management in aquatic ecosystems.

CURRENT GAPS IN PONDS REMOTE SENSING: EXTRACTION, CLASSIFICATION INTERPRETATION AND ATTRIBUTE ASSOCIATION

Reliance on single data sources and insufficient targeted algorithms hinder large-scale precise extraction

PWS are characterized by small individual sizes and extensive spatial coverage, and their remote sensing extraction currently faces two major bottlenecks.

First, existing data sources often insufficient to balance temporal resolution, spatial resolution, and extraction accuracy. High-frequency medium-resolution imagery (e.g., Sentinel-2) has limited capability in identifying small and micro PWS, making it difficult to capture their rapid changes and thereby constraining the accuracy of large-scale dynamic monitoring.[3]

Second, targeted algorithms remain inadequate. A widely adopted "water index + interference removal" approach relies on the sensitivity of infrared bands to water, but it struggles to efficiently distinguish PWS from other water bodies with similar spectral characteristics and underestimates the spectral complexity of ponds arising from their diverse types.[4] Only by developing a targeted 'spectral + morphological' algorithm can the issues of misclassification and poor generalizability be resolved, thereby enabling large-scale, high-precision automated pond identification and classification.

Insufficiently targeted and scalable functional classification systems

The functional diversity of PWS arises from their varied geographical settings, inherent natural attributes, and differing degrees of human influence.

First, functional characterization is lacking. Existing systems tend to simply classify PWS as 'water bodies' or 'aquaculture ponds,' overlooking the diversity of ecosystem services and biodiversity support PWS provide. Ecological studies have qualitatively shown that PWS in different geographical settings differ fundamentally in dominant ecological functions (e.g., aquaculture, salt production, water supply, and landscaping).[5] Under non-point source pollution, even opposing phenomena may occur: offshore aquaculture acts as source of green tide disasters; salt pans foster halophytic vegetation, and urban landscape ponds become pollutant sinks due to weak self-purification.

Second, geographic generalizability remains insufficient. PWS functional types are closely tied to geographical context; coastal and inland PWS differ in dominant functions, hydrological regimes, and seasonal phenology, leading to interpretation keys. Existing classification studies are largely region-specific or qualitative and fail to quantitatively link PWS types with ecological functions. A framework linking 'geographical features–functional types–interpretation keys' is needed to address functional diversity and geographical heterogeneity and enable precise quantitative identification.

Limited monitoring attributes and spatial gaps in existing data products

Many published datasets remain confined to conventional statistical metrics (e.g., surface area, count, proportion). These one-dimensional conventional metrics cannot support functional analysis and quantitative assessment. In reality, PWS were multidimensional geographical entities, exhibiting differences in water depth, functional type, land use patterns, and landscape configuration. For example, aquaculture ponds and natural ponds differed in depth range, shoreline morphology, and seasonal dynamics, and these differences directly shaped their ecological functions and service values. Existing products generally lacked such functional attributes, are concentrated in East and Southeast Asia, mainly covered aquaculture ponds. Global multi-type products remained scarce, and systematic coverage was virtually absent across Europe, the Americas, and Africa, hindering a comprehensive global inventory of PWS.

A FRESH APPROACH: COMPREHENSIVE DATASET INCORPORATING SPECIALIZED ALGORITHMS, CLASSIFICATION SIGNS, AND QUANTITATIVE ATTRIBUTES

Targeted extraction model: Multi-factor Integrated Pond Index (MIPI)

PWS types vary in spectral signatures and exhibit strong spatiotemporal heterogeneity and dynamic complexity driven by multiple factors, including water quality, and land-use interactions. Intra- and inter-annual dynamics further challenge traditional methods relying on single spectral indices or fixed thresholds. This paper proposes shifting from a single-source, single-feature approach to multi-source fusion and multi-dimensional synergy, integrating satellite data, targeted indices, and machine learning.

First, multi-feature fusion enhanced feature discriminability. Optical and synthetic aperture radar data provided complementary spectral, geometric, and backscattering information. A ±2-day matching strategy aligned the two data sources. The fused dataset improved the identification of rapid phenological changes and morphological adjustments in PWS resulting from practices such as draining. Second, multi-feature interpretation signs were constructed to establish a multifunctional PWS index. This index integrated spectral, spatial, geometric, contextual, and phenological information.

Spectral features comprised satellite bands, with high-contribution bands (e.g., water vapor bands) identified from known sample sets, and widely applied spectral indices integrated to derive specific features and enhance multi-type PWS interpretation. Spatial and geometric features, including shape regularity, and spatial arrangement (e.g., the grid-like distribution of aquaculture ponds), were quantified using high-resolution imagery; Contextual features captured the topological relationships between PWS and surrounding environment. Phenological features were quantified using multi-temporal imagery. Among PWS types, aquaculture ponds showed the strongest seasonal variation, contracting in winter and remaining stable from March to October; image acquisitions were limited to this window. Other types showed weak seasonality and had limited effect on feature extraction.

A machine learning framework integrated these features for classification and extraction. Object-based image analysis aggregated features into

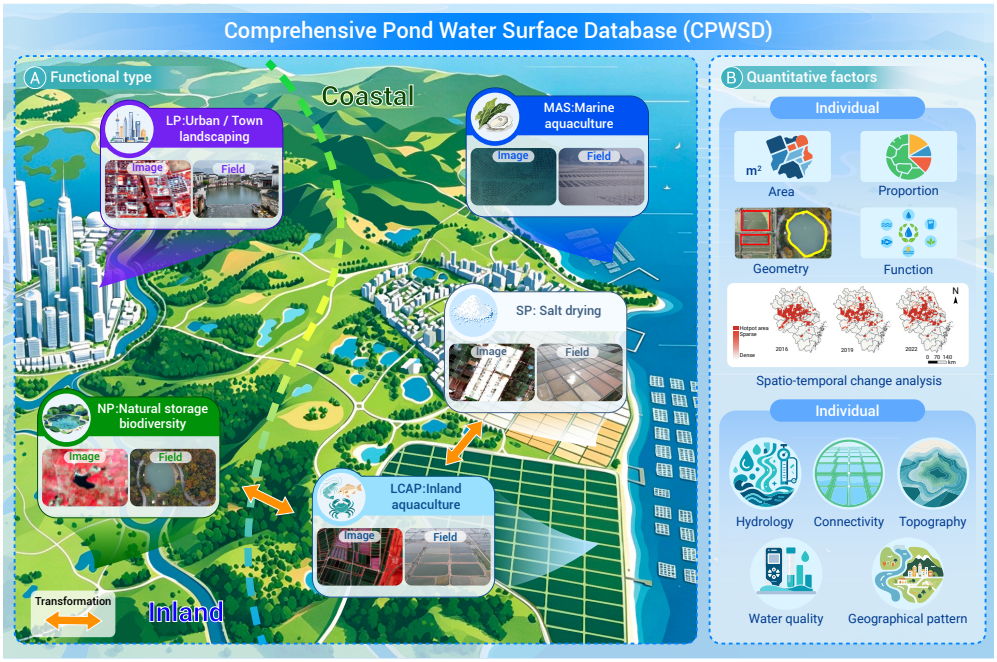


Figure 1. A vision for comprehensive pond water surface database (CPWSD) (A) Five major functional PWS types across coastal and inland areas—urban/town landscaping, marine aquaculture, natural storage/biodiversity, salt drying and inland aquaculture—based on which the classification system is constructed. Under certain geographical conditions and anthropogenic influences, transformations occur among LCAP, NP, and SP. (B) Quantified comprehensive elements, including both intrinsic attributes and environmental attributes.

discrete objects, and ensemble algorithms such as Random Forest performed classification. Training samples came from field surveys and visual interpretation of high-resolution imagery, covering multiple PWS types and non-PWS surfaces across different geographical settings. Adaptive dynamic thresholding generated segmentation thresholds and assessed feature importance, improving automation and robustness for large-scale extraction. MIPI and multiple features enabled high-precision, transferable classification and overcame fixed-threshold limitations. Validation used a confusion matrix with random points, supported by field surveys, published datasets, and statistical yearbooks.

Functional classification system for PWS: Types and interpreting signs

According to the current land use classification and field survey, the PWS are reconstructed as: artificially excavated or naturally formed water surfaces with a storage capacity below 100,000 m^3 at normal water level, an area exceeding 1,000 m^2, and multiple utilization functions.

To address the lack of a functional classification system, this paper proposes a global-scale, land–sea integrated standardized PWS classification system based on existing research, distinguishing terrestrial and marine, including landside clustering aquaculture ponds (LCAP), marine aquaculture ponds (MAS), salt pans (SP), landscape ponds (LP), and natural ponds (NP) (Figure 1A). Although all PWS types belong to the same aquatic ecosystem, different types exhibit distinct remote sensing signatures. LCAP typically appear as regular geometric shapes along coastlines or around lakes, whereas SP are concentrated in coastal mudflat with checkerboard or grid-like texture patterns. Shape feature analysis (e.g., shape index and aspect ratio) can effectively separate artificial ponds (e.g., SP and LCAP) from NP. Topological relationships further characterize the surrounding environment and spatial connections among PWS types.

Comprehensive PWS database integrating intrinsic and contextual attributes

Given the dual limitations of existing PWS data in attributes and spatiotemporal coverage, this paper constructs an integrated global-scale PWS database with comprehensive 'Intrinsic + Contextual' attributes at two-year intervals for refined pond management. The database extends beyond area statistics and incorporates multidimensional information on PWS and their surroundings (Figure 1B):

Intrinsic attributes, as the first-level attributes, refer to the PWS themselves: (1) geometric and morphological attributes: surface area, water depth, and water storage volume at normal water level; (2) spectral and physicochemical attributes: key water quality indicators such as chlorophyll-a and water transparency, which can assess eutrophication status and primary productivity; (3) functional classification attributes.

Contextual attributes extend to the surrounding geographical pattern: (1) watershed and hydrological attributes; (2) topographic and spatial location attributes, such as elevation, slope, and spatial distribution characteristics; (3) landscape and connectivity metrics, such as PWS density and connectivity with ditches and rivers; (4) geographic pattern and global dynamic characteristics, derived from coupled multi-source data such as land use; (5) driving factor analysis (e.g., policy, population, and extreme climate). The policy scoring index draws on an international policy assessment framework and comprises three dimensions: policy instruments (e.g., subsidies, environmental regulation), policy support intensity (three-level scoring), and policy coverage (e.g., aquaculture planning).

Taken together, three solutions are proposed. First, the MIPI index bridges algorithmic gaps in multi-type PWS detection and enables accurate large-scale extraction. Second, a coastal–inland multifunctional classification system fills the gap in operational functional typology with interpretation keys. Third, the CPWSD overcomes limited attribute scope and spatial coverage in existing products. These components form an integrated, standardized, multi-layered PWS dataset that locates and quantifies PWS, reveals their state, changes, and drivers, and supports multi-scale research from global hydrology to regional sustainability.

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AUTHOR CONTRIBUTIONS

Yijun Tong: Methodology, Investigation, Validation, Software, Formal analysis, Writing-Original Draft; Chen Lin: Conceptualization, Supervision, Project administration, Funding acquisition, Resources, Writing-Review& Editing; Wenlan Feng: Writing-Review& Editing, Validation; Junfeng Xiong: Writing-Review& Editing; Zhiyu Kang: Visualization. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.