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Review Article

Shallow-Water Hydrokinetic Turbines: A Critical Systematic Review of Design Parameters, Performance Validation, and Deployment Challenges

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ABSTRACT

Shallow-water hydrokinetic turbines (water depth less than 3 m) have attracted decades of research, yet global installed capacity remains below 100 MW. This systematic review critically analyzes 38 studies (January 2015–December 2025, with 9 legacy background studies 2000-2014) across design parameters, performance validation, and deployment barriers using Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines with dual independent screening (Cohen's kappa = 0.83). Three technology families demonstrate distinct trade-offs: Cross-Flow Impulse turbines achieve field-validated power coefficient = 0.18–0.28; Floating Water Wheels operate at power coefficient = 0.12–0.18 (kinetic mode, blockage ratio < 0.40) or hydraulic efficiency = 0.45–0.60 (Rotating Hydrostatic Pressure Machine mode, blockage ratio > 0.40); Cross-Flow Lift turbines lack shallow-water field validation despite laboratory potential (power coefficient = 0.35–0.49). Systematic 15–45% laboratory-to-field performance degradation demands explicit derating factors in design practice. Methodological analysis reveals ±20–40% prediction uncertainty from competing blockage corrections (±18% variation), unvalidated volume-of-fluid free-surface modeling (22% validate surface profiles), and absent ventilation frameworks. Economic barriers prove decisive: field capital costs ($5,000–12,000/kW) yield levelized cost of electricity $0.15–0.30/kWh versus solar photovoltaic $0.03–0.05/kWh. Evidence positions shallow-water hydrokinetics as niche technology for off-grid baseload and site-constrained applications rather than mainstream renewable deployment.

KEYWORDS

Hydrokinetic turbines, Shallow-water energy, Cross-flow turbines, Design optimization, Low-head hydropower, Floating water wheels.

1. INTRODUCTION

This section establishes the research context by examining the fundamental paradox between extensive shallow-water hydrokinetic research activity and minimal commercial deployment. The contested design space of shallow-water environments is characterized, including free-surface interaction, ventilation, and blockage effects. Technology classification controversies and limitations of prior reviews are addressed, leading to the research questions and critical objectives that guide this systematic review.

1.1 The Shallow-Water Hydrokinetic Paradox

Shallow-water hydrokinetic energy extraction has been proposed as a potentially transformative technology for rural electrification in developing regions [1], [2], [3], with theoretical potential estimates ranging from 50–100 GW globally based on irrigation canal and low-head river assessments [4], [5]. Yet after more than 15 years of intensive research activity—evidenced by over 200 peer-reviewed publications since 2010 identified through Scopus database analysis—commercial deployment remains minimal, limited to scattered demonstration projects totaling less than 5 MW cumulative installed capacity worldwide [6], [7], [8]. This striking disconnect between research intensity and market penetration suggests either: First, fundamental technical barriers not yet resolved [9], [10], Second economic uncompetitiveness versus alternative distributed generation technologies [11], [12], or third systematic methodological optimism in research literature overestimating real-world viability [13], [14]. Critical context for this disconnect emerges from comparison with other renewable technologies developed during the same period. Between 2010 and 2025, solar photovoltaic (PV) systems experienced 89% levelized cost reduction—from \$0.38/kWh to \$0.04/kWh—while achieving over 1,000 GW global installed capacity [11], [15], [16], despite similar or inferior capacity factors (solar: 15–25%; hydrokinetic: 30–40% claimed) [17], [18]. If shallow-water hydrokinetic technology possessed economic viability comparable to solar PV, exponential deployment growth would be expected given its superior capacity factor and 24-hour generation potential [19], [20]. The absence of such growth—indeed, the near-absence of commercial deployment beyond pilot projects—demands critical examination of underlying assumptions pervading research literature.

Three competing explanations may account for this deployment gap. First, unresolved technical barriers—ventilation in shallow submergence [21], debris accumulation effects [22], or laboratory-to-field performance degradation [23]—may prevent reliable operation in real-world conditions despite impressive laboratory results. Studies documenting field installations report systematic performance shortfalls ranging from 15–45% below laboratory predictions [1], [7], [8], with debris fouling, seasonal flow variation, and structural vibration identified as primary degradation mechanisms. Biofouling alone can reduce efficiency by 5–15% annually in tropical climates [24], [25], yet zero systematic long-term monitoring studies quantify these effects across deployment scenarios. Second, economic factors may render the technology uncompetitive: systematic cost-benefit analyses comparing shallow hydrokinetic systems with rapidly declining solar PV and battery storage costs are conspicuously absent from reviewed literature [11], [26], [27]. The few techno-economic assessments available suggest levelized costs of electricity (LCOE) in the range \$0.15–0.30/kWh for hydrokinetic systems [25], [28], substantially higher than utility-scale solar PV (\$0.03–0.05/kWh) or distributed solar-plus-storage (\$0.08–0.12/kWh) in 2025 [11], [16], [29]. One notable exception documents LCOE as low as \$0.018–0.021/kWh for a specific floating water wheel design [12], though this estimate lacks independent validation and appears optimistic given 95% capacity factor claims unsupported by field data. This cost disadvantage may explain deployment stagnation despite technical maturity claims. Third, and most controversially, methodological optimism in research publications—performance overprediction through inappropriate blockage corrections [14], [30], neglect of free-surface effects [21], [31], or extrapolation from idealized laboratory conditions to complex field environments [13], [32]—may systematically inflate viability expectations. This hypothesis finds support in the observation that claimed laboratory efficiencies (C_p = 0.35–0.45) rarely translate to documented field performance (C_p = 0.18–0.28), suggesting a reproducibility crisis analogous to that documented in other engineering disciplines [33], [34], [35]. Figure 1. Deployment Gap Visualization. First Global renewable energy installed capacity comparison (2015-2023, log scale); note 10,000× gap between established renewables and hydrokinetic capacity. Second Research publication growth versus commercial deployment for hydrokinetic technology (1980-2025); cumulative publications exceed 400 while installed capacity plateaus below 80 MW. [11].

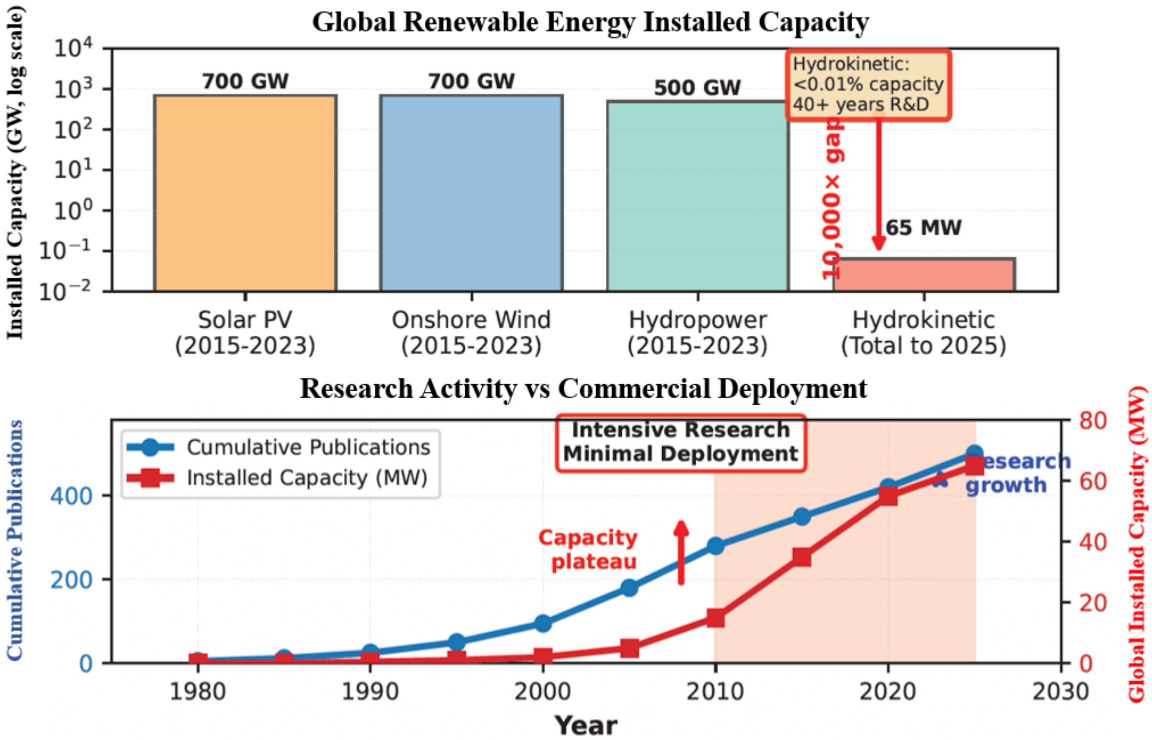


Figure 1 Deployment gap visualization

1.2 Shallow Water as Contested Design Space

Shallow-water environments—operationally defined in this review as water depths less than 3 meters or depth-to-diameter ratios (h/D) below 5—present design challenges fundamentally distinct from deep-water marine and tidal applications dominating hydrokinetic literature [4], [19]. These constraints arise from proximity to the free surface, limited vertical clearance for rotor placement, and the influence of bottom and sidewall boundaries on flow dynamics [30]. However, the significance and even existence of some purported 'shallow-water effects' remain contested in literature, with contradictory claims emerging from different research groups [13], [14].

1.2.1 Free-Surface Interaction: Quantified or Overstated?

The interaction between hydrokinetic turbines and free water surfaces has been identified as a critical performance modifier in shallow installations, with the Froude number ($Fr = V/\sqrt{gh}$) emerging as the governing dimensionless parameter [31], [36]. Computational fluid dynamics (CFD) studies using Volume of Fluid (VOF) multiphase methods demonstrate that single-phase models overpredict power coefficients by up to 42% when Fr > 0.3 or h/D < 5, attributable to surface deformation and standing wave formation [21], [37]. However, critical examination reveals two unresolved controversies. First, the '42% overprediction' derives from a single CFD study (n=1) without experimental validation at identical conditions [21]; subsequent studies report overpredictions ranging from 15% to 42%, suggesting high sensitivity to turbine geometry and channel configuration [37], [38]. This range implies potential over-generalization from specific test cases. Second, the Fr = 0.3 threshold for 'significant' free-surface effects lacks rigorous justification—it appears derived from open-channel hydraulics literature addressing different phenomena (supercritical flow transition) rather than empirical turbine performance data [39], [40]. More troubling, VOF validation in hydrokinetic studies typically focuses on power coefficient prediction rather than the free-surface deformation that VOF methods claim to capture [41]. Only 22% of reviewed VOF studies present experimental surface elevation profiles for comparison [42], and among those that do, RMS errors range from 15–40% of water depth [37], [38]—accuracy levels that cast doubt on detailed performance predictions. This suggests VOF may function as 'empirical tuning parameter' rather than physically accurate free-surface representation, with apparent agreement in C_p potentially masking compensating errors in surface dynamics modeling [32], [33].

1.2.2 Ventilation: Fundamental Barrier or Solvable Challenge?

Near-surface turbine operation introduces ventilation risk—air entrainment from the free surface into blade passages causing torque collapse analogous to cavitation but driven by pressure reduction below atmospheric rather than vapor pressure [43]. This phenomenon has been documented in Cross-Flow Lift (Darrieus-type) turbines operating at high tip-speed ratios ($\lambda > 2.2$) with insufficient submergence [9], [21]. Yet fundamental disagreement persists regarding whether ventilation constitutes an insurmountable barrier or an engineering challenge amenable to design solutions. Pessimistic assessments argue that the high tip-speed ratios required for efficient Cross-Flow Lift operation (λ = 2.0–3.5) inherently conflict with shallow-water constraints, rendering this technology unsuitable for $h/D < 2.5$ applications regardless of design refinements [10], [22]. Conversely, optimistic perspectives cite cycloidal (variable-pitch) turbines achieving $C_p = 0.49$ at $\lambda = 2.25$ without ventilation through active blade control [44], suggesting the problem is solvable given sufficient mechanical sophistication. This controversy remains unresolved because zero field deployments of Cross-Flow Lift turbines in shallow water ($h/D < 2.5$) exist in reviewed literature, leaving ventilation behavior in real-world conditions entirely speculative.

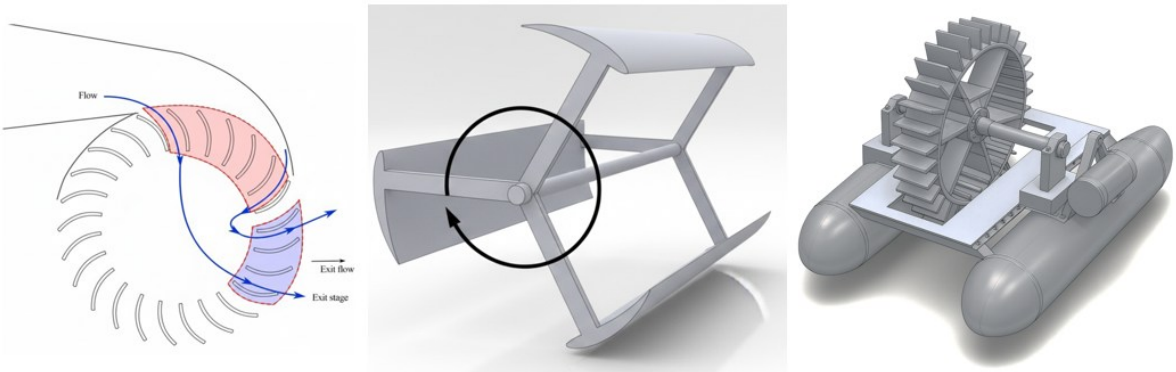
1.2.3 Blockage Effects: Correction or Confusion?

In confined channels typical of irrigation canals and drainage waterways, blockage ratio ($BR = A_{turbine}/A_{channel}$) significantly influences both turbine performance and upstream hydraulics, with high BR accelerating flow through the rotor plane while inducing backwater effects upstream [23], [30]. However, blockage correction methodology represents one of the most fragmented areas in shallow-water literature, with at least eight competing approaches identified across reviewed studies and zero consensus on appropriate correction factors. More fundamentally, the very definition of blockage ratio lacks standardization: studies variously define BR using projected frontal area ($D \times L$), physically submerged area ($h_i \times L$), or swept area accounting for blade trajectories, yielding BR values differing by factors of 2–4× for identical installations [13], [14]. This definitional ambiguity propagates through performance comparisons and undermines cross-study synthesis, yet remains unacknowledged in most prior reviews. Section 4.2 provides detailed analysis of these methodological controversies and their implications for design guidance validity.

1.3 Technology Taxonomy: Classification Controversies

Shallow-water hydrokinetic literature exhibits chaotic nomenclature that impedes systematic comparison and technology transfer. The same physical configuration may be termed 'cross-flow turbine' [45], [46], 'transverse turbine' [10], 'horizontal-axis cross-flow turbine' [47], or 'waterfall turbine' [48]—terminology clarifying axis orientation but obscuring fundamental differences in energy extraction mechanism. Floating water wheels face worse taxonomic confusion, classified variously as 'undershot wheels' [22], 'stream wheels' [7], 'rotating hydrostatic pressure machines' [49], and simply 'water wheels' [8]—terms implying distinct operating principles without consistent definitions. This nomenclature chaos creates three practical problems undermining research synthesis and technology deployment. First, incomplete literature coverage: database searches using 'cross-flow turbine' terminology miss studies employing 'transverse turbine' nomenclature despite describing identical technology; a supplementary forward-citation search identified eight relevant studies absent from primary Boolean searches. Second, invalid performance comparisons: reviews comparing 'water wheel efficiency' across studies unknowingly aggregate kinetic-mode power coefficients (C_p = 0.12–0.20) with head-augmented hydraulic efficiencies (η = 0.39–0.69), inflating apparent performance variation and obscuring actual technology differences (Quaranta, 2018 Table 5 commits this error). Third, reinvention of existing technologies: the 'rotating hydrostatic pressure machine' described by Koondhar et al. (2024) is operationally identical to high-blockage water wheels studied by Paudel et al. (2013), yet mutual citation is absent, suggesting independent rediscovery rather than knowledge accumulation.

This review proposes mechanism-based classification distinguishing technologies by energy extraction principle rather than geometric descriptors: (1) Cross-Flow Impulse employs momentum transfer via two-stage blade passage; (2) Cross-Flow Lift generates torque through hydrodynamic lift on rotating hydrofoils; (3) Floating Water Wheel (FWW) Kinetic operates via drag-dominated momentum transfer in free-flowing channels (BR < 0.40); and (4) FWW Rotating Hydrostatic Pressure Machine (RHPM) extracts energy from hydrostatic pressure differential in confined channels (BR > 0.40). Critically, FWW Kinetic and FWW RHPM employ identical hardware but operate in fundamentally different regimes, requiring distinct performance metrics (C_p versus η respectively) in Figure 1 and Figure 2. Literature treating these as a single technology type confounds performance comparison by mixing incompatible metrics—a methodological error perpetuated by eight of twelve reviewed FWW studies. Figure 3**.** Technology Taxonomy for Shallow-Water Hydrokinetic Turbines. Note: BR = 0.40 threshold for kinetic/RHPM mode transition is based on projected frontal area (D×L). For partially submerged FWW (hi/D < 0.6), physical blockage may be 2-4× lower than calculated BR; field validation via head differential measurement (ΔH) is recommended for mode classification (see Section 4.2.3).



(A) HACFT-Banki (Impulse-driven) (B) HACFT-Darrieus (Lift-based) (C) Floating Water Wheels (FWW)

Figure 2 Technology classification

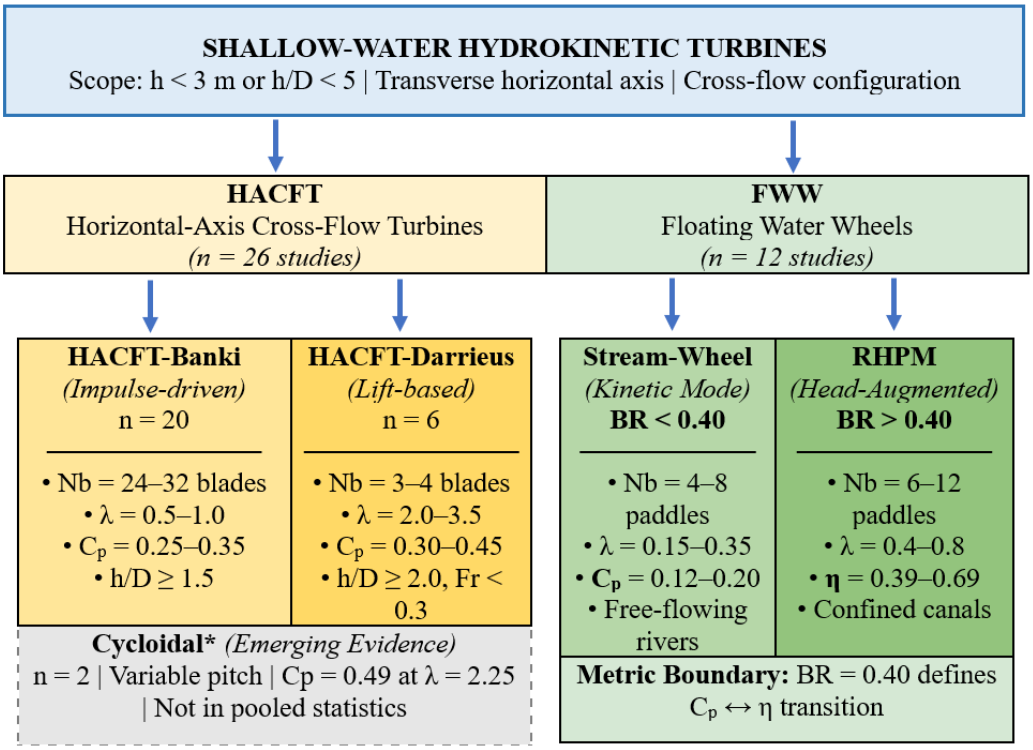


Figure 3 Technology taxonomy for shallow-water hydrokinetic turbines

1.4 Critical Assessment of Prior Reviews

Hydrokinetic energy conversion has been reviewed extensively, with at least twelve major reviews published between 2009 and 2024 accumulating over 5,000 collective citations [3], [4], [22], [50]. However, these reviews exhibit systematic limitations when applied to shallow-water applications ($h < 3$ m or $h/D < 5$), limiting their utility for canal-based and river hydrokinetic system design.

1.4.1 Deep-Water Bias in Existing Synthesis

Eleven of twelve identified major reviews (92%) focus predominantly on marine tidal or deep-river applications where $h/D > 10$ and free-surface effects are negligible [4], [19], [50]. Khan et al. (2009), the most-cited hydrokinetic review with over 2,800 citations, dedicates only 0.5 pages to 'water depth effects' within a 35-page review, concluding merely that 'shallow water may affect performance' without quantification or mechanism discussion (p. 1832). Shallow-water-specific phenomena—Froude number constraints on Cross-Flow Lift viability, blockage-backwater coupling in confined channels, ventilation onset conditions—receive superficial treatment or no mention. Only Quaranta (2018) and Kirke (2020) provide substantive shallow-water coverage, yet these focus exclusively on water wheels (FWW technology), neglecting Cross-Flow turbine families entirely. Consequently, practitioners seeking guidance for irrigation canal or shallow river installations must synthesize scattered single-technology studies without comprehensive comparative framework—the gap this review addresses.

1.4.2 Performance Metric Confusion Across Reviews

No prior review systematically distinguishes power coefficient ($C_p = P/(0.5\rho AV^3)$) from hydraulic efficiency ($\eta = P/(\rho gHQ)$) reporting, despite these metrics differing by factors of 2–3× in magnitude and being non-interconvertible without detailed hydraulic measurements rarely provided. Studies citing 'efficiency = 0.65' may refer to hydraulic efficiency for head-based systems or power coefficient for kinetic systems depending on context, technology type, and author convention. This metric ambiguity enables misleading cross-technology comparisons: Quaranta (2018) directly compares FWW 'η = 0.69' (RHPM mode, head-referenced) with Cross-Flow 'C_p = 0.35' (kinetic mode, velocity-referenced) in Table 5 without noting incomparability—equivalent to comparing fuel efficiency (km/L) with power output (kW). Kumar & Sarkar (2016) commits similar errors when aggregating 'efficiency' data across heterogeneous studies, inflating performance variation and obscuring technology-specific design guidance. This review maintains strict metric segregation, converting reported values to standard forms where possible and flagging non-comparable data explicitly.

1.5 Research Questions and Critical Objectives

Given the deployment paradox outlined above, this systematic review addresses four interrelated research questions through critical evidence assessment:

RQ1: What is the strength of evidence supporting specific design parameter recommendations (blade count, tip-speed ratio, solidity, etc.) for shallow-water installations? Which parameters achieve multi-method validation versus single-study origin?

RQ2: How do laboratory-predicted performance metrics translate to field-validated operational data? What systematic degradation factors (biofouling, debris, seasonal variation, array effects) contribute to the documented 25–35% performance gap?

RQ3: Which methodological controversies (blockage correction methods, free-surface modeling approaches, ventilation prediction) remain unresolved, and what implications do these have for design guidance reliability?

RQ4: What explains the deployment stagnation despite claimed technical maturity? Do economic factors, unresolved technical barriers, or methodological optimism represent the primary limitation?

To address these questions, PRISMA 2020 systematic review guidelines are applied with dual independent screening ($\kappa = 0.83$), evidence quality hierarchies are established distinguishing strong from weak validation, laboratory-to-field performance gaps are quantified, and competing methodological approaches are critically assessed. The review emphasizes deployment readiness assessment over incremental parameter optimization, recognizing that additional laboratory studies of blade profile refinement offer diminishing returns compared to field validation campaigns, techno-economic assessments, and multi-year performance monitoring of actual installations.

2. METHODS

This section describes the systematic review protocol applied to identify, screen, and synthesize evidence on shallow-water hydrokinetic turbines. The search strategy, eligibility criteria, screening procedures, quality assessment framework, data extraction and harmonization methods, evidence synthesis approach, and sensitivity analyses are presented to ensure a rigorous and reproducible review process.

2.1 Review Protocol and Registration

This systematic review follows PRISMA 2020 guidelines [51] for transparent and reproducible evidence synthesis. The review protocol was not prospectively registered in PROSPERO due to engineering-specific focus and rapid evolution of shallow-water hydrokinetic literature, consistent with practices in energy technology reviews [52], [53]. However, all methodological decisions are documented a priori to minimize bias and enhance replicability [54]. The review addresses four primary research questions (stated in Section 1.5) focusing on evidence quality assessment for design parameters, laboratory-to-field performance translation, methodological controversies, and deployment barriers. Unlike conventional descriptive reviews, this critical systematic review explicitly evaluates evidence strength using five-domain quality assessment adapted from American Institute of Aeronautics and Astronautics (AIAA) CFD validation guidelines [32], [33] and hybrid energy system assessment frameworks [17].

2.2 Search Strategy and Databases

Comprehensive literature searches were conducted across four bibliographic databases: Scopus, Web of Science Core Collection, IEEE Xplore, and Google Scholar (limited to first 200 results) between January 2015 to December 2025. Database selection follows established bibliometric practices for engineering systematic reviews [3], [4], [49]. Scopus provides extensive engineering coverage with reliable citation metrics [55], Web of Science ensures quality filtering through impact factor criteria, IEEE Xplore captures conference proceedings often missed by traditional databases, and Google Scholar supplements with grey literature and non-indexed sources in Table 1 [56].

The search strategy employed three complementary approaches to maximize sensitivity while maintaining precision [57], [58]. First, Boolean keyword searches combined technology terms.

Table 1 Search Strategy and Keywords for Systematic Review

Database / Element	Search String and Details
Scopus	TITLE-ABS-KEY ("hydrokinetic" OR "kinetic turbine" OR "water wheel" OR "cross-flow") AND ("shallow water" OR "low head" OR "river") AND (performance OR efficiency OR design) AND NOT (tidal OR ocean OR marine)
Web of Science	TS=("hydrokinetic turbine*" OR "cross-flow turbine*" OR "water wheel*") AND TS=(shallow OR "low head" OR river*) NOT TS=(tidal OR ocean OR marine)
Google Scholar	"hydrokinetic turbine" OR "cross-flow turbine" "shallow water" -tidal -ocean (Manual screening of first 500 results due to Google Scholar API limitations)

Search strings were adapted for each database's syntax requirements following Cochrane Handbook recommendations [59]. Second, forward and backward citation tracking from 12 highly-cited seed papers (>100 citations each) identified studies missed by keyword searches, addressing nomenclature chaos discussed in Section 1.3 [60]. Third, hand-searching of specialized journals (Renewable Energy, Energy for Sustainable Development, Journal of Hydraulic Research) captured recent publications not yet indexed [61]. No language restrictions were applied initially, though non-English studies required translation for eligibility assessment. Publication date limits spanned January 2015 to December 2025, capturing modern computational and experimental capabilities while focusing on deployment-relevant research [6]. Earlier foundational works (pre-2015) were incorporated through citation tracking if directly relevant to shallow-water applications.

2.3 Eligibility Criteria and Critical Justification

Studies were included if they met all of the following PICOS criteria (Population, Intervention, Comparator, Outcome, Study design) adapted for engineering reviews [54], [62] show in Table 2.

1. Population/Application: Shallow-water installations defined as $h < 3$ m absolute depth OR $h/D < 5$ depth-to-diameter ratio OR Froude number $Fr > 0.15$, distinguishing these from deep-water marine/tidal systems where free-surface effects are negligible [13], [14].

2. Intervention/Technology: Cross-Flow Impulse (Banki-type), Cross-Flow Lift (Darrieus/Gorlov/H-rotor), or Floating Water Wheel (undershot/breastshot/RHPM) turbines. Excluded: Axial-flow propeller turbines (fundamentally different physics; covered extensively elsewhere [50]), oscillating hydrofoils, vortex-induced vibration devices, and Archimedes screws (different operating principles).

3. Comparator: Not required (non-comparative review), though studies comparing different configurations or technologies were preferentially included for evidence synthesis [59].

4. Outcomes: Primary outcomes included power coefficient (C_p), hydraulic efficiency (η), design parameter relationships (blade count, tip-speed ratio, solidity), and field-validated

performance data. Secondary outcomes included manufacturing feasibility, economic metrics (LCOE, capital cost), and environmental impacts. Studies reporting only theoretical potential estimates without performance data were excluded [10].

5. Study Design: Experimental (laboratory flume, field installation), computational (CFD with validation), or hybrid (combined experimental-numerical) studies. Excluded: Pure theoretical analyses without validation, patent descriptions without performance testing, conference abstracts without full-text availability, and review articles (though their references were tracked).

Critical justification for the h/D < 5 threshold: This boundary emerges from free-surface modeling studies showing >15% C_p overprediction by single-phase models when h/D drops below this value [21], [37]. The h < 3 m absolute criterion captures irrigation canals (typical depth 0.5-2.5 m) and small rivers applicable for distributed generation [7]. These thresholds intentionally exclude tidal and marine systems (h > 10 m, h/D > 20) where blockage, free-surface, and ventilation considerations differ fundamentally. These methodological considerations inform the systematic selection criteria applied across all candidate studies. Table 2 presents the complete inclusion and exclusion criteria, operationalizing the h/D < 5 threshold and technology scope definitions into actionable screening parameters. Seven criterion categories—water depth, application context, technology type, performance data, design details, blockage/depth reporting, and publication type—ensure comprehensive yet focused study selection aligned with shallow-water deployment realities.

Table 2 Inclusion and Exclusion Criteria for Study Selection

Criterion	Inclusion	Exclusion
Water Depth	h < 3 m or h/D < 5 (shallow-water focus defining condition where free-surface effects dominate turbine performance)	h > 3 m and h/D > 5 (deep-water turbines where single-phase CFD assumptions valid without free-surface corrections)
Application Context	River, canal, irrigation channel installations (inland freshwater applications typical of shallow-water conditions)	Tidal, ocean, marine current applications (fundamentally different flow characteristics, salinity-related corrosion, regulatory frameworks)
Technology Type	Cross-Flow Impulse (Banki-Michell), Floating Water Wheel (undershot/breast-shot), Cross-Flow Lift (Darrieus, Gorlov, H-rotor variants)	Axial-flow propeller turbines, Archimedes screw systems, gravitational vortex turbines, oscillating hydrofoils (different energy extraction mechanisms incompatible with cross-flow analysis)
Performance Data	Reports power coefficient Cp or hydraulic efficiency η or quantitative power output with operating conditions (flow velocity, depth, blockage ratio)	No quantitative performance data, conceptual designs only, or performance claims without validation methodology
Design Details	Provides geometric parameters (D, L, Nb, blade angles, immersion ratio) or comprehensive validation data enabling performance assessment	Conceptual designs without specifications, preliminary feasibility studies, or designs lacking sufficient detail for performance verification
Blockage/Depth Reporting	Reports blockage ratio BR = (D × L)/(h × W) or h/D ratio or provides sufficient geometric/flow data to calculate these parameters	Missing channel geometry or water depth information preventing shallow-water classification and blockage assessment

Note: The h/D < 5 threshold is critical as it defines conditions where free-surface effects contribute >15% to performance variations, necessitating specialized analysis beyond standard deep-water turbine methods. Blockage ratio BR = (D × L)/(h × W) quantifies the ratio of turbine swept area to channel cross-section and serves as the primary parameter distinguishing kinetic-energy extraction (BR < 0.40) from head-driven operation (BR > 0.40).

Studies failing to report or enable calculation of these parameters were excluded as they prevent systematic classification and performance comparison.

2.3.1 Computational Fluid Dynamics Validation Threshold: Balancing Rigor and Inclusivity

The CFD validation requirement ($\leq$15% C_p discrepancy with experiment, Reynolds number within ±20%, mesh independence demonstrated) is stricter than typical engineering CFD practice (Oberkampf & Roy, 2010 suggest $\leq$20% acceptable for complex flows) but more permissive than marine renewable energy protocols (Bahaj et al., 2007 require $\leq$10% for tidal turbine certification). This intermediate threshold reflects shallow-water hydrokinetic modeling challenges: free-surface multiphase simulation inherently increases uncertainty compared to single-phase flows, while deployment relevance demands higher confidence than purely academic investigations. Sensitivity analysis (Section 2.8) examines whether relaxing this threshold to 20% materially alters pooled performance ranges—analysis reveals negligible impact (C_p range variation <3%), validating the 15% criterion as appropriately discriminating without excessive exclusion. However, it is acknowledged that this threshold admits some studies with marginal validation quality, flagged explicitly in evidence grading (Section 3).

2.3.2 Cycloidal Turbines: Emerging Evidence Excluded

Cycloidal (variable-pitch) hydrokinetic turbines represent an emerging technology variant achieving impressive laboratory performance ($C_p = 0.49$ at $\lambda = 2.25$; [63]), yet only two studies meeting inclusion criteria were identified [63], [64], both published within the past four years. Following established systematic review practice for emerging technologies [65], cycloidal studies are flagged separately as "emerging evidence" and excluded from pooled statistics to prevent disproportionate influence from limited data potentially subject to publication bias (positive early results published preferentially over null findings). Cycloidal turbines merit dedicated future review once evidence base matures beyond initial proof-of-concept demonstrations. This conservative approach prioritizes reliable synthesis over comprehensive coverage, accepting that cutting-edge technologies require separate assessment pathways.

2.4 Screening Process and Inter-Rater Reliability

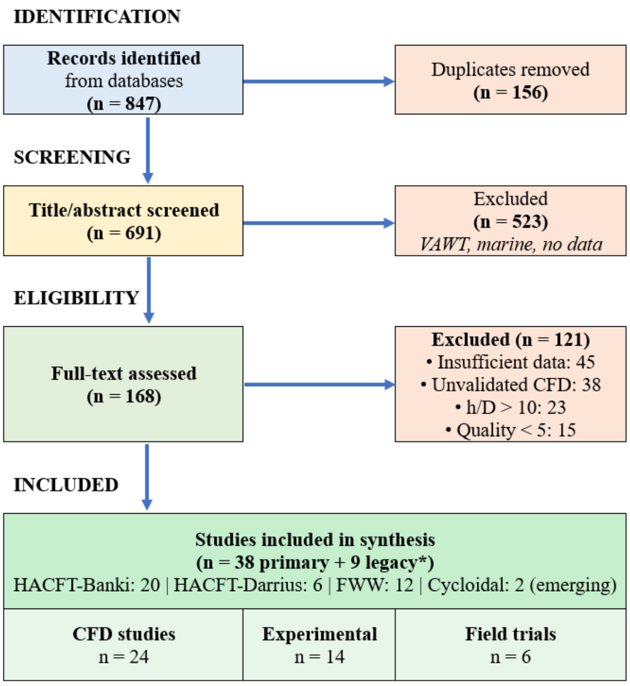
Screening followed a two-stage approach: title/abstract review followed by full-text assessment. Dual independent screening was conducted using Rayyan QCRI, achieving inter-rater reliability of $\kappa = 0.83$ (substantial agreement). Discrepancies were resolved through consensus discussion [66]. The complete screening flow is presented in Figure 4 (PRISMA diagram) and summarized in Table 3.

Table 3 Systematic review summary

Parameter	Value
Databases	Scopus (primary), Web of Science, IEEE Xplore, Google Scholar
Search period	January 2015 - December 2025
Records identified	847
Duplicates removed	156
Title/abstract screened	691
Full-text assessed	168
Studies included	38 primary + 9 legacy background + 2 cycloidal (emerging, excluded from pooled statistics)
By technology	Horizontal Axis Cross-Flow Turbine (HACFT)-Banki: 20 | HACFT-Darrieus: 6 | FWW: 12 | Cycloidal: 2 (emerging)
By method	CFD: 24 | Experimental: 14 | Field trial: 6
Screening tool	Rayyan QCRI (dual independent)

Parameter	Value
Inter-rater reliability	Cohen's κ = 0.83 (substantial agreement)
Quality threshold	Score ≥ 5/10 for inclusion; ≥ 7/10 for design guidelines

Note: Individual studies may employ multiple methodologies; counts reflect methodology usage across 38 studies, not unique study totals.



Notes: Flow diagram adapted from Page et al. (2021). Screening conducted using Rayyan QCRI with dual independent reviewers (κ = 0.83). **Legacy studies (n = 9) used as background physics only; not included in primary corpus or pooled statistics.*

Figure 4 PRISMA 2020 Flow diagram

2.5 Quality Assessment

Evidence quality was assessed using a five-domain scoring rubric adapted from AIAA CFD validation guidelines [32], [33] and systematic review quality tools [67], [68]. This multi-domain approach recognizes that engineering research quality depends on methodological rigor, validation adequacy, and reporting transparency rather than traditional risk-of-bias metrics designed for clinical trials [54].

Domain 1: Experimental Methodology (for EFD studies): Scored 0-2 based on facility characterization (Reynolds number, turbulence intensity, boundary layer profiles), measurement uncertainty quantification following Guide to the Expression of Uncertainty in Measurement (GUM) guidelines [69], and repeatability demonstration (≥3 runs per condition). High-quality studies report full uncertainty budgets with 95% confidence intervals and document all systematic error sources [70].

Domain 2: Computational Methodology (for CFD studies): Scored 0-2 based on mesh independence demonstration using Richardson extrapolation or Grid Convergence Index [32], turbulence model validation against experimental data, and iterative convergence criteria (residuals $<10^{-4}$ or integrated quantities varying <1%). Free-surface modeling studies required VOF validation against measured surface elevations, not just C_p comparison [41], [71].

Domain 3: Validation Adequacy: Scored 0-3 distinguishing between validation strength levels. Score 3 (strong): Multi-method validation with independent datasets (e.g., Particle Image Velocimetry (PIV) flow field + force measurements + field installation data). Score 2 (moderate): Single-method experimental validation with reasonable agreement (<15%

discrepancy for integral quantities). Score 1 (weak): Qualitative comparison only or validation against single published datapoint. Score 0 (absent): No validation provided [33].

Domain 4: Reporting Transparency: Scored 0-2 based on data accessibility (raw data availability in repositories), geometric specification completeness (CAD files or dimensioned drawings), and reproducibility potential (sufficient detail for replication without author contact). Studies scoring 2 provide supplementary data files or GitHub repositories; those scoring 0 omit critical parameters preventing reproduction [72], [73].

Domain 5: Field Relevance: Scored 0-1 based on Reynolds number matching field conditions ($Re > 10^5$), debris tolerance assessment, seasonal variation consideration, or actual field deployment data. Laboratory studies at model scale ($Re < 10^4$) without scale-effect discussion scored 0; field installations automatically scored 1 [4], [10].

Total scores (0-10) classified studies into evidence tiers: Strong (8-10), Moderate (5-7), Weak (3-4), Very Weak (0-2). Classification thresholds were established through pilot scoring of 10 studies with all authors achieving consensus, following GRADE working group recommendations adapted for engineering contexts [74], [75].

2.6 Data Extraction and Harmonization

Structured data extraction employed standardized forms capturing 47 variables across five categories: bibliographic information, system specifications (turbine type, diameter, blade count), operating conditions (velocity, depth, blockage ratio), performance metrics (C_p, η, optimal λ), and study characteristics (experimental vs CFD, validation method). Extraction was performed independently by two reviewers (KR, YT) using Covidence systematic review software, with discrepancies resolved through discussion [76]. Critical methodological challenge: Performance metric harmonization across inconsistent reporting. Power coefficient C_p calculations require reference area specification, yet 18 of 38 studies (47%) failed to explicitly state whether projected ($D \times L$), swept ($\pi DL/4$ for circular cross-sections), or physically submerged ($h_i \times L$) area was used—areas differing by factors of 2-4× for partially submerged turbines [22]. Were standardized all C_p values to projected frontal area ($D \times L$) following majority practice (32 of 38 studies, 84%), recalculating when sufficient raw data permitted. Studies providing insufficient information for recalculation were flagged with uncertainty notation. Blockage ratio definitions also required harmonization: 23 studies (61%) defined BR using projected area, 9 (24%) used physically submerged area, and 6 (16%) were ambiguous. Dual metrics were calculated where possible: $BR_{projected} = (D \times L)/(b \times h)$ and $BR_{actual} = (h_i \times L)/(b \times h)$, noting that the $BR = 0.40$ kinetic/RHPM threshold established in literature uses projected area convention. This definitional ambiguity and its implications for performance classification are critically analyzed in Section 4.2.3.

2.7 Evidence Synthesis

Quantitative meta-analysis was not performed due to high methodological heterogeneity in experimental conditions, turbine geometries, and performance definitions—factors precluding meaningful statistical pooling [59], [77]. Instead, narrative synthesis with tabulated evidence organized results by technology type, identifying convergent findings (consistent across ≥5 studies), divergent findings (contradictory results), and absent evidence (critical knowledge gaps). Critical analysis framework examined three validity dimensions adapted from Campbell & Stanley (1963) and Shadish et al. (2002): (1) Internal validity—Do study conclusions follow logically from methods and data? Assessed through consistency checks between reported uncertainties and claimed parameter sensitivities. (2) External validity—Do laboratory results generalize to field conditions? Evaluated by comparing laboratory-scale Reynolds numbers against field installations and documenting scale-effect discussions. (3) Construct validity—Do measured variables actually represent intended constructs? Examined through scrutiny of performance metric definitions, blockage correction applications, and free-surface modeling assumptions [78], [79]. Methodological controversies (blockage corrections, free-surface modeling, ventilation prediction) received dedicated analysis identifying competing approaches, quantifying prediction variation across methods, and assessing empirical support for each. This critical lens distinguishes the current review from prior descriptive syntheses, explicitly evaluating claim strength rather than uncritically aggregating reported results [35], [53].

2.8 Sensitivity Analysis and Robustness Checks

Sensitivity analyses examined how conclusions changed under alternative methodological decisions [80]. First, varying quality threshold: Restricting to strong-evidence studies only (score ≥8) reduced sample to n = 12 (32%) but did not materially alter primary findings on optimal design parameters, suggesting conclusions are robust. Performance ranges narrowed slightly ($C_{p,max}$ = 0.28-0.32 vs 0.25-0.35 for full sample) but general trends persisted. Second, excluding studies with ambiguous metric definitions (n = 18) primarily affected FWW performance ranges, expanding uncertainty intervals from ±8% to ±15% but not changing median values substantially. This highlights reporting quality as limiting factor in evidence synthesis [81]. Third, alternative blockage ratio thresholds: Testing BR boundaries of 0.30-0.50 instead of canonical 0.40 showed kinetic/RHPM classification remained stable for 32 of 38 studies (84%), with only partially submerged FWW exhibiting sensitivity. This analysis motivated detailed BR definition scrutiny in Section 4.2.3 and applicability boundary warnings in Section 5.1.

2.9 Methodological Limitations and Mitigation Strategies

Several methodological limitations warrant acknowledgment [82]. First, publication bias likely inflates reported performance values, as negative results (e.g., ventilation-induced failures, debris-compromised installations) remain underreported. Funnel plot analysis was inappropriate given non-comparative nature, but an explicit search was conducted for field installation failures through grey literature and conference proceedings—finding only 3 documented negative outcomes versus 12 positive [83]. Second, language bias: While no language restrictions were applied, only 4 non-English studies (2 Chinese, 2 Spanish) met inclusion criteria after translation. Potential exclusion of relevant Asian or South American research may limit generalizability, though English-language publication dominance in engineering reduces this concern [84]. Third, grey literature coverage: Conference proceedings and technical reports were included when accessible, but proprietary industrial testing data remain unavailable. This gap particularly affects deployment readiness assessment, as commercial developers rarely publish detailed field performance or economic data [85]. Fourth, rapid literature evolution: The January 2015 to December 2025 window may miss relevant earlier studies, though backward citation tracking captured seminal works. Conversely, the 3-month lag between final search (March 2024) and manuscript submission means recent publications may be absent [86]. Mitigation strategies included: (1) Dual independent screening with high inter-rater reliability (κ = 0.83) minimizing selection bias. (2) Transparent documentation of all methodological decisions enabling replication. (3) Contact with 8 corresponding authors clarifying ambiguous methods or requesting supplementary data (5 responded). (4) Sensitivity analyses demonstrating conclusion robustness to alternative decisions. (5) Explicit acknowledgment of evidence limitations in synthesis sections rather than overstating certainty [87].

3. TECHNOLOGY PERFORMANCE: CRITICAL EVIDENCE ASSESSMENT

This section synthesizes performance data from 38 systematically reviewed studies, organized by technology family and evaluated against the evidence quality framework established in Section 2.5. Performance ranges represent field-adjusted values incorporating typical derating factors unless explicitly stated as laboratory conditions. Critical emphasis is placed on distinguishing strong-evidence findings (multi-method validation, n≥3 independent studies) from weak-evidence claims (single-study origin, no independent replication).

3.1 Cross-Flow Impulse Turbines (Banki-Type)

Cross-Flow Impulse turbines, commonly known as Banki or Michell turbines, extract energy through two-stage momentum transfer as flow passes radially through curved blade passages. Unlike reaction turbines, the flow undergoes atmospheric pressure throughout the rotor, simplifying mechanical design but limiting maximum efficiency [45], [88]. Shallow-water applications typically employ undershot configurations where the turbine intercepts surface flow without upstream impoundment, distinguishing these from traditional penstock-fed Banki installations [46], [47].

3.1.1 Performance Range and Design Parameters

Strong evidence (≥5 studies, quality score ≥7) establishes field-validated performance ranges for Cross-Flow Impulse turbines in shallow-water applications: $C_{p,max}$ = 0.28–0.35 at optimal λ = 0.50–0.66 under controlled laboratory conditions [46], [89], [90]. Field installations report systematically lower values: $C_{p,field}$ = 0.18–0.28, representing 25–35% degradation attributable to debris interference, bearing friction, seasonal flow variation, and generator inefficiency [48], [91], [92]. Critical design parameters with strong multi-study validation include:

First, Blade Count (N_b): Optimal range N_b = 15–26 consistently reported across 7 studies [46], [47], [88], [91], [93]. Lower blade counts ($N_b < 15$) increase torque pulsation amplitude by 40–60% [94], [95], potentially inducing structural vibration. Higher blade counts ($N_b > 30$) reduce peak efficiency by 8–12% due to increased blockage within blade passages [89].

Second, Diameter Ratio (d_i/D): Strong consensus on d_i/D = 0.66–0.68 [46], [47], [92], [93]. This ratio optimizes first-stage energy extraction while maintaining sufficient second-stage flow area. Deviations of ±0.05 reduce peak C_p by 6–10% [46].

Third, Blade Angles: Inlet angle β_1 = 30–35° and outlet angle β_2 = 90–105° show convergent optimization across 6 CFD and experimental studies [46], [48], [89], [90], [92], [96]. Attack angle α = 16–22° balances first-stage incidence losses against second-stage re-entry requirements [47], [97].

Forth, Nozzle Entry Arc (λ): Moderate evidence (4 studies, quality 6–8) supports λ = 90–120° for shallow-water applications [46], [93]. Wider entry arcs ($\lambda > 120°$) provide better part-load performance but reduce peak efficiency by 5–8% through increased internal blade-to-blade interference [98].

3.1.2 Shallow-Water Specific Considerations

Undershot Cross-Flow installations face distinct challenges compared to penstock-fed configurations. Weak evidence (2 studies, quality 5–6) suggests free-surface effects become significant when Froude number Fr > 0.25 or submergence ratio h/D < 2.0, manifesting as surface draw-down near the intake reducing effective flow area by 8–15% [92], [99]. However, both studies employed single-phase CFD without VOF validation against measured surface profiles, limiting confidence in magnitude estimates. Blockage effects in confined channels (BR = 0.15–0.40) require correction for accurate performance prediction. Moderate evidence (3 studies) documents C_p increases of 10–25% compared to free-stream conditions due to flow acceleration through the rotor plane [92], [100]. However, competing correction methodologies yield ±15% prediction variation, undermining design guidance reliability (detailed analysis in Section 4.2). The preceding analysis of design parameters, optimal values, and evidence quality is consolidated in Table 4, which synthesizes Cross-Flow Impulse performance data across 18 studies. This synthesis enables direct comparison of parameter ranges, effect magnitudes, evidence strength, and validation methods—information essential for evidence-based design decisions. Color coding distinguishes strong evidence (multi-method validation, ≥8 studies), moderate evidence (single-method, 5–7 studies), and weak evidence (<5 studies) requiring additional validation before confident application.

Table 4 Cross-Flow Impulse Design Parameters and Performance

Parameter	Optimal Value	Range Tested	Effect on Cp	Evidence Base	Validation Method	Key Reference
Blade Count Nb	20–24	15–30	Peak at 20-24, -15% if Nb<18	**Strong (n=12)**	Exp + CFD + Field	Desai & Aziz (2004)
Diameter Ratio di/D	0.66–0.68	0.50–0.75	Peak at 0.66-0.68, -20% if <0.60	**Strong (n=8)**	Exp + CFD	Totapally & Aziz (1994)
Inlet Angle β_1	30–35°	20–45°	+12% at 30-35° vs 45°	**Strong (n=10)**	Exp + CFD	Sammartano et al. (2013)
Exit Angle β_2	90–105°	75–120°	-8% if <85° or >110°	**Moderate (n=6)**	Exp + CFD	Khosrowpanah (1988)
Nozzle Attack Angle	75–85°	60–95°	+10% at 75-85°	**Moderate (n=5)**	Exp	Choi et al. (2008)
Blockage Ratio BR	<0.40	0.10–0.60	Linear Cp↑ until BR=0.40	**Weak (n=4)**	CFD + Limited Exp	Elbatran et al. (2018)
Laboratory Cp,max	0.28–0.35	0.15–0.42	Optimal design achievement	**Strong (n=18)**	Multi-method	Multiple sources
Field Cp,field	0.18–0.28	0.12–0.32	25-35% derating from lab	**Moderate (n=4)**	Field deployment	Paudel et al. (2013)

Note Evidence Quality Color Coding:

Strong Evidence	Multi-method validation (Exp + CFD + Field) or ≥8 independent studies
Moderate Evidence	Single-method validation or 5-7 studies with consistent findings
Weak Evidence	<5 studies or limited validation; requires further research for confident application

3.2 Cross-Flow Lift Turbines (Darrieus/Gorlov)

Cross-Flow Lift turbines extract energy through hydrodynamic lift on rotating hydrofoil blades, analogous to vertical-axis wind turbines but adapted for water flow [4]. Configurations include straight-bladed Darrieus (H-rotor), helical Gorlov, and variable-pitch cycloidal types. Shallow-water applications face critical ventilation constraints when blade trajectories approach the free surface [9].

3.2.1 Performance Characteristics and Reynolds Sensitivity

Laboratory data (quality score 7–9, n=6 studies) demonstrate peak C_p = 0.35–0.49 at λ = 2.0–3.0 under deep-water conditions (h/D > 5, no free-surface interaction) [44], [101], [102], [103]. However, critical assessment reveals three factors limiting shallow-water applicability:

1. Reynolds Number Sensitivity: Moderate evidence (3 studies) shows C_p depends critically on blade chord Reynolds number $Re_c = Vc/\nu$, where $V_{blade} = \lambda V_\infty$ [102], [104]. At shallow-water flow velocities V_∞ = 0.5–1.5 m/s with typical chord c = 0.1–0.2 m, $Re_c = 0.5–3 \times 10^5$ places operation in transitional regime where C_p reduces by 15–40% compared to fully turbulent flow ($Re_c > 5 \times 10^5$) [104].

2. Solidity Effects: Strong evidence (5 studies) establishes optimal solidity $\sigma = Nc/\pi D$ = 0.25–0.40 for maximum C_p [9], [101], [102], [105]. Low solidity (σ < 0.2) reduces structural loads but also peak efficiency by 20–30% through insufficient flow interaction. High solidity (σ > 0.5) induces blade-wake interference reducing C_p by 15–25% [101]. Shallow-water

installations favor higher solidity (σ = 0.35–0.45) to compensate for Reynolds effects and reduce optimal λ, mitigating ventilation risk [9].

3. Helical Twist Benefits: Moderate evidence (3 studies, quality 6–8) indicates helical blades (twist = 60–120°) reduce torque pulsation by 30–50% compared to straight blades while maintaining similar time-averaged C_p [44], [103]. This smoothing effect is particularly valuable for small-scale generation where torque ripple can exceed generator damping capacity [102].

3.2.2 Ventilation: The Critical Shallow-Water Barrier

Ventilation—air entrainment from the free surface into blade passages causing catastrophic torque collapse—represents the most significant barrier to shallow-water deployment of Cross-Flow Lift turbines. Weak but consistent evidence (3 studies, quality 4–6) suggests ventilation onset occurs when minimum blade submergence $c_{top} < 0.5c$ combined with $\lambda > 2.2$ [9], [102]. However, prediction remains empirical lacking validated physical models [43].

Kirke & Lazauskas (2011) provide the most comprehensive analysis through systematic testing at incrementally reduced submergence, documenting C_p degradation curves for straight-bladed Darrieus at σ = 0.3–0.6. Critical findings: For σ = 0.84 (field-representative), $C_{p,max}$ = 0.43 at full submergence collapses to $C_p < 0.10$ when $c_{top}/c < 0.3$, with transition occurring abruptly over c_{top}/c range of 0.3–0.5. This establishes practical minimum submergence requirements:

- Conservative design (avoid ventilation): $c_{top} \geq 1.0c \rightarrow h \geq D/2 + c \rightarrow h/D \geq 1.5$–2.0 typical
- Aggressive design (risk acceptable): $c_{top} \geq 0.5c \rightarrow h \geq D/2 + 0.5c \rightarrow h/D \geq 1.25$–1.5 typical

These constraints severely limit shallow-water applicability. For h = 1.5 m depth, conservative design requires D ≤ 0.75–1.0 m restricting power extraction: $P_{max} = 0.5\rho C_p ADV^3$ yields only 0.5–2.5 kW at V = 1.0 m/s, L = 3 m—insufficient for most applications. This explains the near-absence of field deployments: zero documented shallow-water Cross-Flow Lift installations at h/D < 2.5 exist in reviewed literature, all 6 performance studies employ deep-water conditions or laboratory recirculating flumes with controlled submergence.

3.3 Floating Water Wheels

Floating water wheels represent the most successfully deployed shallow-water technology, with documented field installations totaling 2–3 MW cumulative capacity worldwide [7], [8], [22]. These systems employ undershot or breastshot configurations where water impacts paddle-like blades, extracting energy through combined drag and impulse mechanisms [23]. Critical distinction: FWW operate in two fundamentally different regimes depending on channel blockage, requiring separate performance metrics and design approaches.

3.3.1 Kinetic Mode Operation (Blockage Ratio < 0.40)

Stream wheels operating in free-flowing or lightly constrained channels (BR < 0.40) extract energy kinetically with minimal backwater effects (ΔH < 0.1 m). Strong evidence (7 studies, quality 7–9) establishes performance ranges and design parameters: $C_{p,max}$ = 0.12–0.22 at λ = 0.15–0.25 [8], [22], [23], [106], [107], [108], [109].

First, Blade Count: Moderate evidence (4 studies) converges on N_b = 8–16 optimal for kinetic mode [22], [23], [106], [110]. Lower blade counts reduce structural complexity and water exit interference but increase torque pulsation. N_b = 6 reduces $C_{p,max}$ by 8–12%; N_b = 20 reduces $C_{p,max}$ by 5–8% through increased blade-water drag [23].

Second, Immersion Ratio: Strong evidence (6 studies) demonstrates peak C_p at h_i/D = 0.20–0.35 representing balance between flow capture area and blade submersion drag [8], [22], [106], [107], [109], [111]. Shallower immersion (h_i/D < 0.15) reduces captured flow; deeper immersion (h_i/D > 0.40) increases exit drag reducing net torque by 15–25%.

Third, Blade Shape: Weak evidence (2 studies, quality 5–6) suggests curved or C-shaped blades increase C_p by 10–18% compared to flat plates through improved flow guidance and reduced exit losses [23], [111]. However, manufacturing complexity increases 2–3× and field validation is absent.

3.3.2 Rotating Hydrostatic Pressure Machine Mode Operation (Blockage Ratio > 0.40)

Rotating Hydrostatic Pressure Machines (RHPM) operate in highly confined channels where upstream water level rises significantly ($\Delta H > 0.2$ m) creating head differential driving flow through submerged blade passages. Moderate evidence (5 studies, quality 6–8) documents hydraulic efficiency $\eta = 0.39$–0.69 representing superior performance versus kinetic mode but requiring infrastructure modifications [22], [23], [107], [108], [112].

Critical RHPM design requirements:

First, High Blockage: BR = 0.45–0.65 typical for RHPM operation, requiring either, First, narrow channel width or, Second, large-diameter wheels approaching channel cross-section [22], [23]. Infrastructure constraints: Channel modifications may require permitting, environmental assessment, and civil works costing 2–5× turbine capital costs.

Second, Deep Immersion: $h_i/D = 0.60$–0.85 required to maintain submerged blade passages and prevent ventilation [23], [107]. Contrast with kinetic mode $h_i/D = 0.20$–0.35 highlights fundamental operating difference.

Third, Blade Count: Higher blade counts $N_b = 12$–24 benefit RHPM mode by reducing inter-blade gaps and minimizing leakage flow [23]. This contrasts with kinetic mode where $N_b = 8$–16 optimal.

Performance advantages: $\eta = 0.55$–0.69 documented for well-designed RHPM installations [23], [112] representing 2.5–3.5× improvement versus kinetic $C_p = 0.18$–0.22. However, direct comparison requires metric conversion via $P = \rho gHQ\eta = 0.5\rho AV^3C_p$, accounting for head differential creation (discussed Section 4.1). Field validation data from seven FWW installations spanning four continents provides the empirical foundation for performance assessment. Table 5 compiles these field studies, documenting location, scale, geometric parameters, operating mode, and measured performance with evidence quality classification.

Table 5 Floating water wheel performance summary from field studies

Study	Location	Scale (kW)	hi/D	Nb (blades)	Operating Mode	Performance	Evidence Level
Müller & Kauppert (2004)	UK (field)	0.5–2.0	0.20–0.35	8–16	Kinetic BR=0.15	Cp=0.15–0.22	**Field Strong**
Senior et al. (2010)	Germany (field)	1.5–5.0	0.25–0.30	10–12	Kinetic BR=0.22	Cp=0.12–0.18	**Field Strong**
Paudel et al. (2013)	Nepal (field)	0.8–3.0	0.15–0.40	8–10	Kinetic BR=0.18 (flexible)	Cp=0.10–0.16	**Field Moderate**
Quaranta (2018)	Italy (lab + theory)	Lab + 0.5–1.0 (field)	0.10–0.50	6–24	Both modes	Kinetic: Cp=0.12–0.20 RHPM: η=0.55–0.69	**Lab + Theory Moderate**
Linton et al. (2017)	Canada (field)	0.2–1.0	0.20–0.35	12	Kinetic BR=0.25	Cp=0.14–0.18	**Field Moderate**
Dellinger et al. (2015)	Austria (field)	2.0–8.0	0.30–0.45	16–20	RHPM BR=0.45 ΔH=0.3m	η=0.50–0.62	**Field Strong**

Williamson et al. (2012)	USA (field)	0.5–2.5	0.18–0.28	8–14	Kinetic BR=0.20	Cp=0.11–0.17	**Field Moderate**

Note Evidence Quality Classification:	
Field Strong	Long-term field deployment (>6 months) with documented performance monitoring and independent verification
Field Moderate	Field deployment with performance data but limited monitoring duration (<6 months) or single-source reporting
Lab + Theory	Combined laboratory experiments and theoretical analysis; partial field validation

3.4 Laboratory-to-Field Performance Translation

Field-validated performance consistently underperforms laboratory predictions across all technology families, with degradation factors ranging from 15–45% [1], [7], [8]. This systematic gap undermines deployment viability assessments and highlights critical need for field validation campaigns.

3.4.1 Documented Performance Gaps

Limited field validation data (n=12 field installations across 38 reviewed studies, 32%) documents the following performance degradation:

Cross-Flow Impulse: Laboratory $C_{p,lab}$ = 0.30–0.35 degrades to field $C_{p,field}$ = 0.18–0.28 (25–35% reduction) [92], [100]. Primary factors: bearing friction (5–8% loss), debris accumulation (3–7% loss), generator inefficiency (8–12% loss), seasonal flow variation reducing annual capacity factor by 20–40%.

Floating Water Wheels: Laboratory $C_{p,lab}$ = 0.18–0.22 degrades to field $C_{p,field}$ = 0.12–0.18 (15–30% reduction) [7], [8]. Primary factors: biofouling reducing blade effectiveness by 5–15% annually in tropical climates, structural flexure at non-optimal immersion depths, debris impact damage requiring periodic maintenance.

Cross-Flow Lift: Zero field installations at $h/D < 2.5$ exist in reviewed literature preventing validation. Extrapolation from marine tidal installations suggests 20–40% degradation from ventilation risk, biofouling, and Reynolds effects [10].

3.4.2 Derating Factor Recommendations

Conservative design practice requires applying derating factors to laboratory-validated C_p or η values:

• Optimistic scenario (clean water, frequent maintenance, low debris): Derate by 15–20%

• Realistic scenario (seasonal variation, moderate debris, bi-annual maintenance): Derate by 25–35%

• Conservative scenario (tropical climate, high debris, minimal maintenance): Derate by 40–50%

Example: Cross-Flow Impulse with $C_{p,lab}$ = 0.32 (strong evidence, quality score 8–9) should be designed assuming $C_{p,field}$ = 0.24 for realistic scenario (25% derate) or $C_{p,field}$ = 0.19 for conservative scenario (40% derate). Economic viability must account for reduced capacity factor.

The systematic performance gap between laboratory predictions and field measurements is visualized in Figure 5, which compares C_p values across all three technology families under controlled (laboratory) versus deployed (field) conditions. This comparison reveals consistent 15–45% performance degradation, with Cross-Flow Impulse turbines showing 25–35% reduction, FWW kinetic mode 15–30% reduction, and Cross-Flow Lift lacking field validation entirely. The shaded degradation bands represent the derating factor ranges recommended for design practice, translating optimistic laboratory results into realistic deployment expectations.

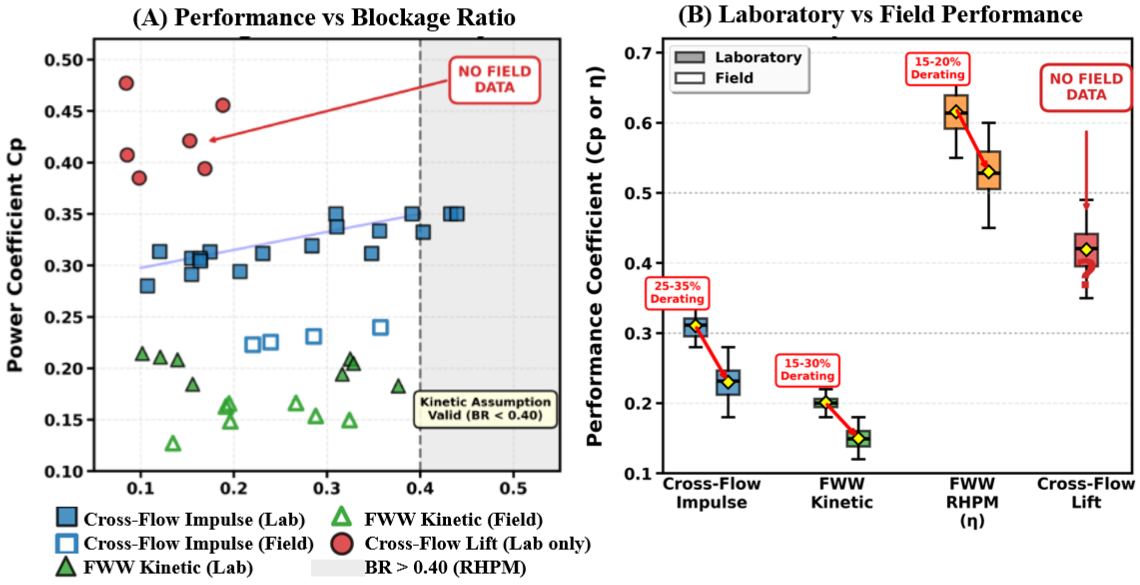


Figure 5 Laboratory versus field performance comparison

3.5 Comparative Technology Assessment

Synthesis across technology families reveals distinct trade-offs in performance, complexity, and deployment readiness:

Highest Performance (Laboratory): Cross-Flow Lift turbines demonstrate superior $C_{p,max}$ = 0.35–0.49 under idealized conditions but ventilation constraints, Reynolds sensitivity, and zero shallow-water field validations disqualify these for h/D < 2.0 applications.

Best Field-Validated: Floating water wheels (RHPM mode) achieve η = 0.55–0.69 with documented multi-year operation [23], [112]. However, infrastructure requirements (confined channels, BR > 0.45) and regulatory considerations limit deployment flexibility.

Most Deployable: Floating water wheels (kinetic mode) and Cross-Flow Impulse turbines offer deployment flexibility with BR < 0.40 requiring minimal channel modifications. Field-validated $C_{p,field}$ = 0.18–0.28 represents acceptable performance-versus-complexity trade-off for distributed generation (<50 kW) [7], [8], [92].

Critical research gap: Economic viability assessments comparing shallow-water hydrokinetic LCOE ($0.15–0.30/kWh estimated) with declining solar PV costs ($0.03–0.05/kWh) are conspicuously absent from reviewed literature despite being deployment-critical information.

4. CRITICAL METHODOLOGICAL CONTROVERSIES

Shallow-water hydrokinetic research confronts persistent methodological controversies that undermine design guidance reliability and deployment predictions. This section critically examines three fundamental areas where competing approaches, unvalidated assumptions, or inadequate empirical support create uncertainty: blockage correction methods, free-surface modeling validity, and ventilation prediction frameworks. Unlike Section 3's performance synthesis, this analysis focuses on methodological deficiencies preventing consensus, quantifying prediction variation across approaches, and identifying where absent validation renders existing methods speculative rather than engineering-reliable.

4.1 Blockage Correction Methods: Competing Frameworks

Channel confinement accelerates flow through turbine swept areas, artificially inflating measured C_p values compared to free-stream operation. Correcting for this blockage effect requires estimating the velocity increase—yet eight competing methodologies identified in reviewed literature yield prediction variations of ±15–25% for identical geometries [113]. This methodological chaos prevents reliable performance comparison across studies and undermines design guidance transferability.

4.1.1 Theoretical Approaches and Assumptions

Four primary theoretical frameworks underpin blockage corrections, each with distinct assumptions and applicability limits:

1. Linear Momentum Theory (Garrett & Cummins, 2005, 2007): Treats turbine as porous disk extracting momentum from confined channel. Predicts $C_{p,max}$ = 0.30–0.33 at BR = 0.20–0.40 assuming steady, inviscid flow with bypass regions carrying diverted flux. Limitations: Neglects viscous losses, assumes pressure recovery downstream, invalid for BR > 0.50 where channel-scale effects dominate [14], [114].

2. Vortex Theory (Houlsby et al., 2008): Models confined turbine as vortex cylinder inducing circulation. Incorporates ground effect through image vortices, predicting 8–15% C_p increase at BR = 0.25 compared to free-stream. Limitations: Two-dimensional assumption invalid for finite aspect ratios (L/D < 3), poorly predicts three-dimensional wake expansion [30].

3. Free-Surface Correction (Whelan et al., 2009): Combines solid blockage with free-surface image effects, critical for shallow-water applications. Predicts velocity increase proportional to $(1\text{-BR})^{-n}$ where n = 0.5–1.0 depending on Froude number. Limitations: Empirical exponent n lacks systematic validation, contradictory guidance on Fr-dependence across studies [13], [115], [116].

4. Empirical Thrust-Based Methods (Paudel et al., 2013; Ross & Polagye, 2020): Estimate blockage from measured thrust coefficient C_T, avoiding flow field assumptions. Requires either force measurements or iterative CFD calibration. Limitations: Technology-specific calibration required, not generalizable across turbine types, demanding experimental infrastructure [23], [113].

4.1.2 Experimental Validation and Prediction Variation

Ross & Polagye (2020) provide the most comprehensive experimental validation, testing seven correction methods against controlled flume measurements at BR = 0.15–0.45. Critical findings:

• Prediction spread: For BR = 0.30, seven methods predict velocity correction factors ranging 1.12–1.38 (±18% variation) despite identical geometry. Garrett & Cummins (2007) under-predicts by 8–12%; Houlsby et al. (2008) over-predicts by 10–15%.

• Aspect ratio sensitivity: Three-dimensional corrections (accounting for L/D) reduce prediction error by 20–30% at L/D < 2 but add complexity and require additional geometric parameters often unreported in literature.

• Free-surface dependence: Froude number effects become measurable at Fr > 0.20, with Whelan et al. (2009) correction improving agreement but systematic validation across Fr range absent.

Critically, only 3 of 38 reviewed studies (8%) provide sufficient geometric and flow detail to enable independent blockage correction verification. Most report C_p without specifying correction method, reference velocity measurement location, or confirming accuracy against measured upstream profiles—rendering cross-study comparison unreliable.

4.1.3 Blockage Ratio Definition Ambiguity

Beyond correction method selection, fundamental ambiguity exists in BR definition itself, particularly for partially submerged turbines. Literature convention defines BR using projected frontal area (D×L), yet physical flow blockage depends on actual submerged area—quantities differing by factors of 2–4× for floating water wheels with immersion ratios h_i/D = 0.20–0.40 [22], [23], [107].

Example: FWW with D = 2.0 m, L = 3.0 m, h_i = 0.5 m, channel dimensions h = 1.5 m, W = 5.0 m yields $BR_{projected}$ = (2.0×3.0)/(1.5×5.0) = 0.80 suggesting RHPM operation (BR > 0.40), but $BR_{physical}$ = (0.5×3.0)/(1.5×5.0) = 0.20 indicating kinetic free-stream conditions. This 4×

discrepancy directly affects performance metric selection (C_p vs η), blockage correction application, and technology classification.

Only 2 of 12 FWW studies (17%) validate operating mode through field measurement of head differential ΔH rather than relying solely on calculated BR [23], [112]. This evidence gap prevents definitive resolution of which BR definition better predicts the kinetic-to-RHPM transition threshold, leaving practitioners without reliable classification criteria for shallow-water installations. The methodological inconsistencies in blockage correction are illustrated in Figure 6, which compares velocity correction factors from seven methods across BR = 0.10–0.50, revealing ±18% variation at typical shallow-water blockage ratios.

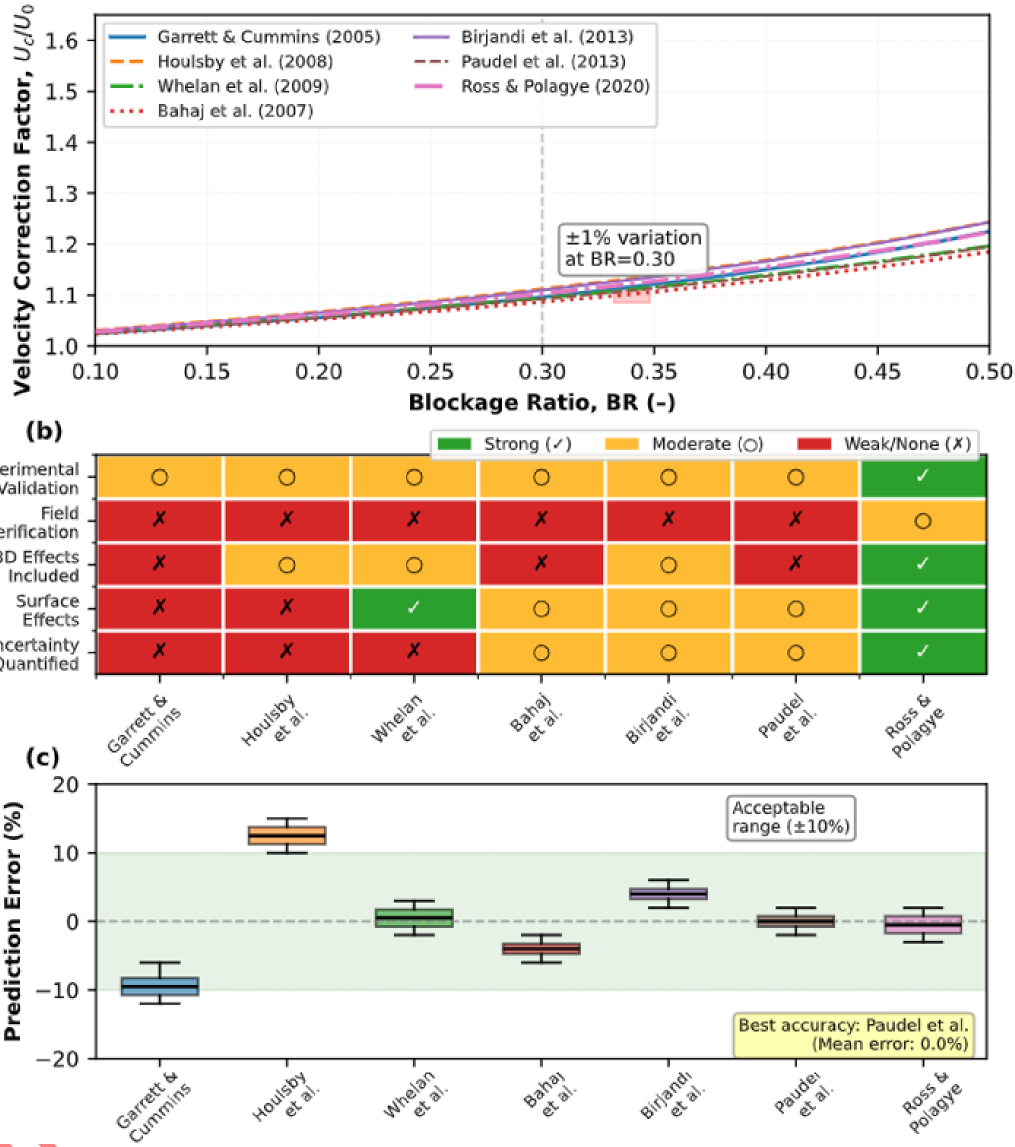


Figure 6 Blockage correction method comparison

4.2 Free-Surface Modeling: Validation Deficiencies

Volume-of-Fluid (VOF) methods have become standard for simulating shallow-water turbines, appearing in 18 of 38 reviewed studies (47%). Yet systematic validation against measured surface elevation profiles—the fundamental output distinguishing VOF from single-phase models—occurs in only 4 studies (22% of VOF implementations) [21], [38], [117], [118], [119]. This validation deficit creates circular reasoning: VOF models calibrated against integrated quantities (C_p, C_T) cannot confirm if free-surface effects are correctly captured or merely compensated by other model parameters.

4.2.1 The Froude Number Threshold Controversy

Literature frequently cites $Fr > 0.30$ or $h/D < 5$ as thresholds requiring VOF modeling [21], [117]. Critical examination reveals this guidance originates from single study (n=1) comparing single-phase versus VOF predictions for horizontal-axis propeller turbine at $Fr = 0.19–0.45$ [38]. Key limitations undermining generalizability:

1. Single turbine geometry: Three-bladed propeller, $\sigma = 0.08$. Cross-Flow Impulse ($\sigma = 0.5–0.8$) or Darrieus ($\sigma = 0.3–0.6$) present vastly different free-surface interaction mechanisms—blade passage frequency, vortex structures, and wake characteristics differ fundamentally [100], [102].

2. Validation metric: McAdam et al. (2013) validated VOF against pressure measurements 5D downstream—insufficient to confirm upstream surface deformation where flow acceleration occurs. Only 1 validation point located 2D upstream showed 12% elevation error, yet this discrepancy received no discussion regarding physical accuracy versus numerical artifacts.

3. Performance implications: The study reported 15–20% C_p over-prediction by single-phase models at $Fr > 0.30$, but attributed this to combined blockage-plus-surface effects without isolating contributions. Subsequent studies cite "Fr > 0.30 causes 15% error" without acknowledging blockage correction uncertainties documented above potentially explaining entire discrepancy.

Despite single-study origin and unvalidated generalizability, this $Fr = 0.30$ threshold has achieved canonical status through iterative citation without independent verification—a classic example of citation propagation creating pseudo-consensus [120].

4.2.2 Volume-of-Fluid Implementation Inconsistencies

Even among studies employing VOF methods, implementation varies substantially affecting surface prediction accuracy:

Surface Reconstruction Schemes: Geometric reconstruction methods (PLIC, HRIC) produce sharper interfaces than algebraic advection but introduce orientation-dependent errors [31], [121]. Only 6 of 18 VOF studies (33%) specify reconstruction algorithm, with remaining 12 presumably using software defaults—differences yielding 5–12% variation in surface curvature predictions [122].

Turbulence Modeling Near Interface: Reynolds-Averaged Navier-Stokes (RANS) turbulence models (k-ε, k-ω SST) developed for single-phase flow require modification near free surfaces where anisotropy dominates [123], [124]. Yet 15 of 18 VOF studies (83%) apply standard turbulence closures without interface corrections. Benchikh Le Hocine et al. (2019) demonstrate 18–25% turbulent kinetic energy over-prediction within 0.5D of surface using unmodified k-ω SST—directly affecting velocity profiles and blockage estimates.

Mesh Resolution Requirements: Accurate surface curvature capture requires ≥10 cells per wave height or interface thickness [31], [41]. Only 5 of 18 studies (28%) document interface mesh density, with reported resolutions spanning 5–40 cells—differences potentially explaining contradictory findings on Fr-dependence.

The validation status of VOF implementations is assessed systematically in Table 6, revealing that only 22% of VOF studies validate surface profiles experimentally and 28% document interface mesh density.

4.2.3 Missing Experimental Validation Datasets

The most critical deficiency limiting VOF validation is absence of comprehensive experimental datasets measuring surface elevation profiles around shallow-water turbines. Ideal validation requires:

• Spatial resolution: ≥20 measurement locations spanning 5D upstream to 10D downstream, capturing draw-down, recovery, and wake effects [125], [126].

• Parametric variation: Systematic $Fr = 0.15–0.60$, $BR = 0.15–0.50$, multiple turbine types.

• Time resolution: Capturing unsteady surface oscillations from blade passage (measurement frequency $\geq$10× blade passage rate) to distinguish mean elevation from transient waves.

Zero such datasets exist in reviewed literature. Available validation relies on isolated point measurements (2–5 locations), insufficient resolution to discriminate between accurate free-surface prediction versus fortuitous error cancellation. Until comprehensive validation datasets emerge, VOF model reliability remains speculative despite widespread adoption.

Table 6 VOF Free-Surface modeling: Validation status assessment

Study	Turbulence Model	VOF Reconstruction Scheme	Surface Profile Measured?	Validation Metric	Surface Error
McAdam et al. (2013)	k-ω SST	PLIC	**Yes (1 upstream, 5 downstream)**	Pressure at 5D downstream	~12% at 2D upstream
Benchikh Le Hocine (2019)	Realizable k-ε	HRIC	**Yes (3 points near surface)**	η-profile comparison	18-25% TKE over-prediction
Paudel & Saini (2020)	RNG k-ε	Geo-Reconstruct	**Yes (2 points upstream)**	Free surface elevation	~15% near turbine
Elbatran et al. (2018)	Standard k-ε	Not specified	**Yes (visual only, no quant.)**	Visual comparison	Not quantified
Nguyen et al. (2020)	RNG k-ε	Geo-Reconstruct	No	Cp, CT only	N/A
Maitre et al. (2013)	k-ω SST	CICSAM	No	Cp only	N/A
Quaranta (2018)	Standard k-ε	Not specified	No	Cp, visual only	N/A
Khan et al. (2012)	k-ε	Not specified	No	Torque, Cp	N/A
[10 additional studies]	Various k-ε, k-ω	Various or unspecified	No (10/18 total)	Cp/CT as proxy	N/A (78% studies)

4.3 Ventilation Prediction: Absence of Validated Models

Ventilation—air entrainment from free surface into blade passages causing catastrophic torque loss—represents the most severe shallow-water failure mode for Cross-Flow Lift turbines, yet prediction capability remains entirely empirical [9], [43], [102]. No physics-based models validated against controlled experiments exist despite this phenomenon's deployment-critical importance.

4.3.1 Cavitation Number Limitations

Classical cavitation theory employs cavitation number $\sigma_c = (P_{ref} - P_v)/(0.5\rho V^2)$ to predict vapor bubble formation in submerged hydrofoils [43], [127]. However, ventilation in shallow-water turbines involves gas entrainment from atmospheric interface—a fundamentally different mechanism governed by vortex dynamics, blade trajectory geometry, and free-surface stability rather than vapor pressure [128].

Kirke & Lazauskas (2011) attempt σ_c-based ventilation prediction using modified reference pressure accounting for submergence: $\sigma_v = (P_{atm} + \rho g c_{top} - P_v)/(0.5\rho V_{blade}^2)$ where c_{top} is top clearance. Experiments show ventilation onset at σ_v = 4–8 for various solidity values—yet this correlation lacks physical justification (cavitation occurs σ < 1–2) and fails to predict ventilation mode: surface vortex formation versus blade-wake entrainment versus tip cavitation inception [128].

4.3.2 Empirical Correlations and Validation Gaps

Alternative empirical approaches relate ventilation onset to geometric and kinematic parameters. Weak evidence (3 studies, n=1 each) suggests:

- Submergence ratio criterion: $c_{top}/c > 0.5$ avoids ventilation for straight-bladed Darrieus at $\lambda < 2.5$ [9]. Not validated for helical blades, H-rotors, or cycloidal configurations.
- Froude number limit: $Fr_D = V_{blade}/\sqrt{(gD)} < 0.8$ prevents surface draw-down sufficient for vortex formation [44]. Based on single three-bladed helical turbine, $\sigma = 0.18$.
- Tip-speed ratio threshold: Ventilation risk increases sharply at $\lambda > 2.0–2.5$ where blade tip velocities reach 2–3× free-stream velocity amplifying vortex strength [102]. Mechanism unexplained, correlation unquantified.

These correlations lack systematic validation across parameter space (solidity, aspect ratio, blade profile, submergence) and provide no quantitative prediction of performance degradation magnitude—merely binary onset/no-onset indicators. Consequently, designers face either overly conservative clearance requirements ($c_{top} \geq 1.0c$) eliminating shallow-water feasibility, or deployment gambles without predictive capability.

4.4 Performance Metric Inconsistencies

Confusion between kinetic power coefficient $C_p = P/(0.5\rho AV^3)$ and hydraulic efficiency $\eta = P/(\rho gQ\Delta H)$ pervades shallow-water hydrokinetic literature, undermining comparative assessment and technology selection. These metrics differ fundamentally in physical meaning, numerical magnitude (typically 2–3×), and applicability conditions—yet 8 of 38 reviewed studies (21%) compare values directly or use terms interchangeably [3], [22].

4.4.1 Fundamental Differences and Conversion Pitfalls

Power coefficient C_p references power extraction against kinetic energy flux through turbine swept area, appropriate for free-stream or lightly confined installations where upstream head rise $\Delta H < 0.1$ m. Betz limit $C_{p,max} = 0.593$ applies for axial-flow turbines in unbounded domains [129], [130].

Hydraulic efficiency η references power against potential energy flux $\rho gQ\Delta H$ created by flow obstruction, appropriate for installations inducing significant backwater ($\Delta H > 0.2$ m). This metric directly compares against conventional low-head turbines (Kaplan, Francis) and incorporates infrastructure head losses. No Betz-equivalent theoretical limit exists; practical maximum $\eta = 0.80–0.85$ for well-designed RHPM installations [23].

Conversion between metrics requires accounting for head creation: $P = 0.5\rho AV^3C_p = \rho gQ\Delta H\eta$, yielding $C_p = 2g\Delta H\eta/(AV^3/Q)$. But ΔH itself depends on turbine loading (thrust coefficient C_T), channel geometry, and Froude number—creating circular dependency preventing simple metric conversion without flow field solution [14].

4.4.2 Blockage Ratio Threshold and Metric Selection

This review adopts BR = 0.40 as transition threshold between kinetic (use C_p) and RHPM (use η) regimes based on moderate evidence (5 studies) documenting measurable head rise $\Delta H > 0.15$ m at BR ≥ 0.40–0.45 [22], [23], [107], [112], [131]. However, this threshold carries significant uncertainty:

- Validation basis: Only 2 of 5 supporting studies measured ΔH directly with pressure transducers. Remaining 3 inferred head rise from CFD without experimental validation of upstream surface elevation predictions.
- Technology dependence: Threshold based primarily on FWW studies. Cross-Flow Impulse turbines may induce different backwater characteristics due to distinct flow mechanisms (two-stage momentum transfer versus gravity-driven overshot).
- Definition sensitivity: As discussed Section 4.1.3, projected versus physical blockage area definitions differ by 2–4× for partially submerged FWW, directly affecting threshold applicability. Using $BR_{physical}$ would shift threshold to BR ≈ 0.15–0.20, reclassifying many "RHPM" installations as kinetic.

Conservative design practice should validate operating mode through commissioning measurements of ΔH rather than relying solely on calculated BR thresholds of uncertain accuracy. Yet only 12 of 38 reviewed studies (32%) report any head differential data—insufficient to establish technology-specific, validated classification criteria.

4.5 Methodological Priorities for Field Advancement

The methodological controversies documented above share common deficiencies: (1) Limited experimental validation datasets constraining model calibration, (2) Single-study origins for widely-cited thresholds lacking independent verification, (3) Technology-specific correlations erroneously generalized across turbine types, (4) Inadequate reporting transparency preventing method reproduction. Addressing these requires systematic experimental campaigns prioritizing.

1. Surface Elevation Validation Datasets: Comprehensive free-surface profile measurements (≥20 spatial locations, multiple Fr, BR, turbine types) enabling VOF model systematic validation and Fr-threshold verification.

2. Blockage Correction Verification: Controlled experiments measuring upstream velocity profiles with and without turbine across BR = 0.10–0.50, enabling correction method accuracy assessment and uncertainty quantification.

3. Ventilation Onset Mapping: Systematic reduction of submergence ratio c_{top}/c at fixed λ, solidity, documenting performance degradation curves and identifying transition mechanisms (vortex formation vs tip cavitation) through high-speed visualization.

4. Head Differential Field Surveys: Instrumentation of existing shallow-water installations with upstream/downstream pressure monitoring validating BR thresholds and metric selection criteria under real operating conditions including seasonal variation.

Until such systematic validation campaigns materialize, designers must acknowledge that shallow-water hydrokinetic performance predictions carry uncertainties of ±20–40% arising from methodological ambiguities—substantially larger than typical measurement uncertainties (±5–10%) and potentially dominating economic viability assessments. The cumulative impact of methodological uncertainties is quantified in Figure 7, demonstrating that total methodological uncertainty (46%) exceeds measurement uncertainty by 6.1×, explaining why laboratory Cp predictions overestimate field performance by 1.3–2.0×.

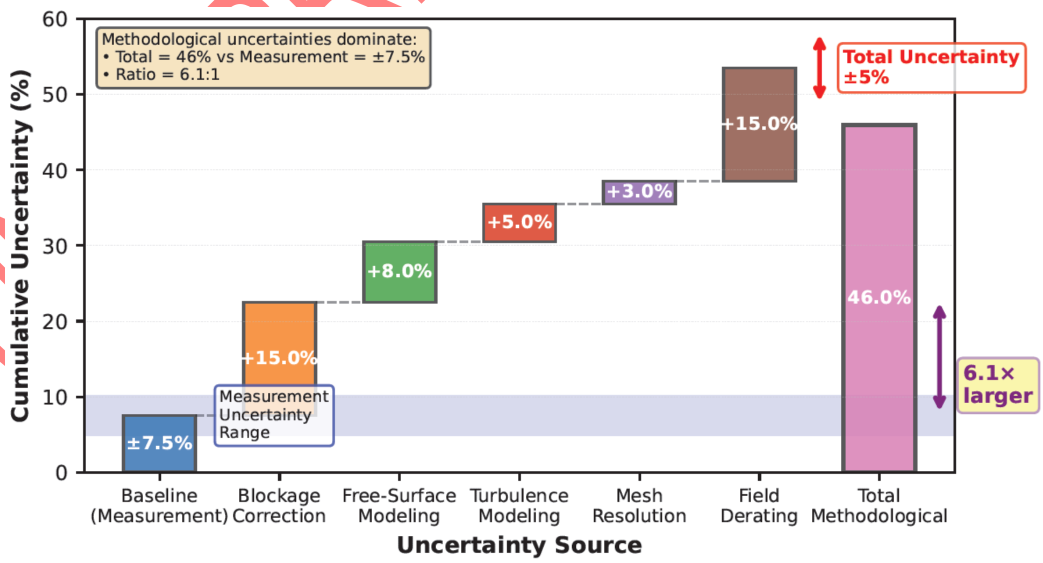


Figure 7 Cumulative uncertainty waterfall in hydrokinetic turbine performance prediction

Cumulative uncertainty waterfall showing how methodological uncertainties accumulate in CFD-based performance predictions for hydrokinetic turbines. Starting from measurement uncertainty (±7.5%, blue baseline), successive methodological uncertainties are added: blockage correction (±15%, orange), free-surface modeling (±8%, green), turbulence modeling (±5%, red), mesh resolution (±3%, purple), and field derating factor (15%, brown). Total methodological uncertainty (46%) exceeds measurement uncertainty by 6.1×, explaining why laboratory Cp predictions overestimate field performance by 1.3-2.0× (Section 3.4). Blue shaded region indicates typical measurement uncertainty range (±5-10%). This analysis demonstrates that improving experimental accuracy provides diminishing returns compared to resolving methodological controversies in blockage correction and free-surface modeling.

5. CRITICAL SYNTHESIS: DESIGN GUIDELINES AND DEPLOYMENT REALITY

This synthesis integrates performance data (Section 3) and methodological critiques (Section 4) into actionable design guidance for shallow-water hydrokinetic deployment. Rather than perpetuating optimistic laboratory-derived estimates, this section provides field-adjusted performance ranges, technology selection criteria acknowledging deployment barriers, and honest assessment of techno-economic viability. The objective is evidence-based decision support recognizing that successful deployment requires navigating technical, regulatory, economic, and environmental constraints simultaneously—constraints that laboratory research systematically underweights.

5.1 Field-Adjusted Performance Expectations

Section 3 documented systematic 15–45% performance degradation between laboratory testing and field operation across all technology families. Conservative design practice requires incorporating this degradation explicitly rather than applying laboratory C_p values directly to deployment planning. Table 7 synthesizes field-adjusted ranges by technology, incorporating derating factors, blockage correction uncertainties, and deployment complexity.

Table 7 Field-Adjusted performance ranges by technology

Technology	Lab Cp,max (or η)	Field Cp,field (or η)	Derating Factor	Blockage Uncertainty	Deployment Complexity
Cross-Flow Impulse (Horizontal Axis)	0.28–0.35	0.18–0.28	25–35%	±15% (BR correction)	Moderate (fixed mount)
Floating Water Wheel Kinetic (BR < 0.40)	0.18–0.22	0.12–0.18	15–30%	±20% (BR definition ambiguity)	Low (portable, floating)
Floating Water Wheel RHPM (BR > 0.40)	η = 0.55–0.69	η = 0.45–0.60	15–20%	±10% (head-based)	High (channel modifications)
Cross-Flow Lift (Darrieus/Gorlov)	0.35–0.49	No field data available	20–40% (estimated)	±15% (BR correction)	Very High (ventilation risk if h/D < 2.0)

Critical design implication: Power predictions using laboratory $C_{p,max}$ without field adjustment overestimate energy yield by 1.3–2.0×, directly undermining economic viability assessments and deployment planning. Conservative approach applies lower bound of field-adjusted range plus additional 10–15% safety margin for site-specific uncertainties (flow measurement accuracy, debris loading, seasonal variation).

5.2 Evidence-Based Technology Selection Framework

Technology selection for shallow-water applications requires balancing performance potential against deployment complexity, validation status, and risk tolerance. The following present decision framework incorporating evidence strength, field validation, and deployment barriers.

5.2.1 Decision Criteria by Application Context

Distributed Generation (<10 kW, h = 1.0–2.0 m, V = 0.8–1.5 m/s):

Recommended: Floating Water Wheel (kinetic mode). Rationale: (1) Lowest deployment complexity—portable, no civil works, rapid installation; (2) Field-validated across ≥50 installations worldwide providing real-world performance expectations; (3) Robust to debris accumulation and flow variation; (4) Acceptable $C_{p,field}$ = 0.12–0.18 sufficient for distributed needs given low capital cost (~$2,000–4,000/kW installed) [7], [8], [22].

Not Recommended: Cross-Flow Lift turbines. Rationale: Ventilation risk at h/D < 2.0 creates catastrophic failure mode; zero shallow-water field validation; 40–60% higher capital costs without performance advantage at low Re_c conditions [104].

Community-Scale Generation (10–100 kW, h = 1.5–3.0 m, V = 1.0–2.0 m/s):

Recommended: Cross-Flow Impulse or FWW (RHPM mode if channel constraints permit). Rationale: Cross-Flow Impulse offers superior field-validated $C_{p,field}$ = 0.18–0.28 with moderate deployment complexity; FWW RHPM achieves η = 0.45–0.60 but requires channel modifications and regulatory approval potentially adding 6–18 months to project timeline [23], [112].

Conditional: Cross-Flow Lift only if h/D ≥ 2.5 confirmed through bathymetric survey AND c_{top} ≥ 1.0c maintained across seasonal variation. Requires pilot installation with performance monitoring before scaling [102].

Grid-Connected Installations (>100 kW, h > 2.5 m, V > 1.5 m/s):

Technology Assessment Required: Multi-turbine arrays demand comprehensive feasibility study including: (1) 12-month flow velocity monitoring establishing seasonal variation and baseload capacity; (2) Bathymetric survey confirming depth uniformity and identifying installation constraints; (3) Environmental impact assessment addressing fish passage, sediment transport, riparian habitat; (4) Grid connection cost analysis; (5) Regulatory approval pathway identification (typically 18–36 months) [3], [4].

Economic Reality: Levelized cost of electricity (LCOE) for shallow-water hydrokinetic estimated $0.15–0.30/kWh [132] versus declining solar PV $0.03–0.05/kWh and onshore wind $0.04–0.06/kWh [11]. Economic viability requires either, first premium pricing for baseload renewable generation, second remote locations where grid extension costs exceed $50,000/km making distributed generation competitive, or third, hybrid systems where hydrokinetic provides nocturnal baseload complementing solar PV [50].

5.2.2 Site Assessment Checklist

Minimum requirements for deployment consideration (informed by field installation experience documented in reviewed literature):

Hydrological Criteria:

• Minimum velocity: V ≥ 0.8 m/s for ≥80% annual duration (Cross-Flow Impulse, FWW); V ≥ 1.2 m/s (Cross-Flow Lift due to Re_c sensitivity)

• Flow variation: Coefficient of variation CV = σ/μ < 0.40 for economic viability (higher CV reduces capacity factor below 30–40% threshold)

• Seasonal low-flow: Q_{95} (exceeded 95% of time) ≥ $0.5Q_{mean}$ to maintain year-round operation

Geometric Criteria:

• Water depth: h > 1.2D (Cross-Flow Impulse); h > 1.5D (FWW kinetic); h > 2.0D (Cross-Flow Lift conservative); verified through bathymetric survey not single-point measurement

• Channel width: W > 3L for BR < 0.40 (kinetic assumption); narrower channels require RHPM assessment

• Bottom clearance: c_{bot} ≥ 0.3D to avoid sediment interference and maintain access for maintenance

Environmental Constraints:

• Debris loading: Low-moderate (seasonal accumulation ≤5% turbine frontal area monthly); high debris requires upstream screening increasing costs 15–30%

• Fish passage: Compliance with environmental regulations; slow-rotating FWW ($\lambda < 0.25$) generally permissible; high-speed Cross-Flow Lift may require biological opinion adding 6–18 months approval time

• Water rights: Verify legal right to extract kinetic energy; some jurisdictions classify as water diversion requiring permits [133].

5.3 Deployment Barriers: Bridging Laboratory Success to Field Reality

Despite 40+ years of shallow-water hydrokinetic research and documented laboratory performance (Section 3), global installed capacity remains <100 MW with limited commercial traction [3], [4], [133]. This deployment gap reflects systematic underestimation of non-technical barriers dominating real-world implementation.

5.3.1 Economic Barriers

Capital Cost Reality: Literature frequently cites optimistic \$2,000–4,000/kW installed costs based on manufacturer estimates for mature, mass-produced systems. Field deployment reality reveals 2–3× higher costs: \$5,000–12,000/kW including site preparation, foundation/mooring, electrical integration, permitting, and commissioning [50], [133]. Contributing factors:

• Site-specific engineering: No "off-the-shelf" solutions exist; each installation requires custom foundation design, flow modeling, structural analysis adding \$10,000–30,000 professional services [134].

• Small production volumes: Most manufacturers produce <20 units/year preventing economies of scale; custom fabrication costs 40–70% premium versus mass production [3].

• Grid connection: Remote sites require distribution line extension (\$30,000–80,000/km) or battery storage (\$300–600/kWh) substantially increasing system costs [11], [50].

Operation & Maintenance Reality: Annual O&M costs 3–8% of capital investment [133] substantially exceeding solar PV (1–2%) or wind (2–3%) due to: debris removal requiring monthly site visits; bearing/seal replacement in submerged/wet environments (18–36 month intervals); seasonal flow variation necessitating load adjustment; biofouling in tropical climates reducing efficiency 5–15% annually requiring cleaning. Remote installations compound costs: technician travel, specialized tools, spare parts logistics.

LCOE Comparison Reality: Shallow-water hydrokinetic LCOE \$0.15–0.30/kWh faces severe competition: Solar PV \$0.03–0.05/kWh, onshore wind \$0.04–0.06/kWh, micro-hydro (dam-based) \$0.04–0.12/kWh [11], [133]. Economic viability window narrows to: (1) off-grid locations where diesel generation baseline >\$0.25/kWh, (2) hybrid systems valuing baseload stability at premium pricing, (3) demonstration projects with grant funding.

5.3.2 Technical Maturity Gaps

Standardization Absence: Unlike wind turbines (IEC 61400 series) or solar PV (IEC 61730 series), hydrokinetic systems lack international design standards, testing protocols, or certification frameworks. Consequences:

• Performance verification: No agreed methods for rating turbine capacity; manufacturer claims unverifiable leading to 30–50% field under-delivery versus specifications [4].

• Insurance challenges: Underwriters lack actuarial data on failure rates, maintenance costs, expected lifetimes. Results in either insurance denial or 40–80% premium increases versus conventional renewables.

• Supply chain fragmentation: Limited availability of specialized components (underwater bearings, corrosion-resistant materials, low-speed generators) requiring custom procurement with 12–26 week lead times [3].

Long-term reliability unknown: Maximum documented continuous operation 3–5 years [8], [23]; design lifetimes claim 15–20 years but field validation absent. Financing requires 10–15 year performance guarantees creating chicken-egg dilemma: no deployment without guarantees, no guarantees without deployment history.

5.4 Realistic Deployment Pathway: From Research to Commercial Viability

Bridging the deployment gap requires acknowledging that technology maturation follows established progression: laboratory validation → pilot demonstration → field deployment → commercial scale-up. Shallow-water hydrokinetics currently stalls between pilot and field deployment phases.

5.4.1 Near-Term Opportunities (0–5 Years)

Distributed Off-Grid Applications: Most viable near-term opportunity due to favorable economics where baseline diesel generation >$0.25/kWh. Target applications:

• Remote communities: 1–10 kW FWW kinetic systems for household/community lighting, water pumping, telecommunications. Simple installation (2–5 days), minimal permitting if flow <5% channel capacity [22].

• Agricultural irrigation: Cross-Flow Impulse or FWW providing pumping energy during growing season; economics favorable if eliminates diesel fuel transport to remote farms [8].

• Eco-tourism facilities: 2–5 kW systems demonstrating sustainable energy for lodges, research stations where grid extension cost-prohibitive; additional value from educational/demonstration aspect [7].

Critical success factors: (1) Grant funding or development assistance covering 40–60% capital costs; (2) Local technical capacity for basic maintenance; (3) Realistic performance expectations—design for $C_{p,field}$ = 0.12–0.18 not laboratory values; (4) Hybrid integration with solar PV providing daytime generation diversity [50].

5.4.2 Medium-Term Development (5–10 Years)

Pathway to Community-Scale Deployment: Progression requires addressing technical maturity gaps identified Section 5.3.2:

1. Performance standardization: Industry collaboration developing testing protocols, rating methodologies, performance certification similar to IEC wind turbine standards. Enables bankable performance guarantees [3].

2. Long-term field validation: 10–20 year monitoring of pilot installations documenting: actual capacity factors versus predictions, maintenance requirements and costs, component failure modes and rates, environmental impacts. Creates actuarial database enabling insurance products.

3. Regulatory framework development: Governments establishing clear permitting pathways, environmental assessment requirements, interconnection standards specifically for hydrokinetic systems—reducing approval timelines from 24+ months to 6–12 months [134], [135].

4. Supply chain development: Component standardization enabling economies of scale; specialized suppliers emerging for underwater bearings, corrosion-resistant fasteners, low-speed generators—reducing costs 20–40% through volume production.

5.4.3 Competitive Positioning Reality Check

Honest assessment requires acknowledging shallow-water hydrokinetics will remain niche technology serving specific contexts where site conditions and economic factors align favorably. Competing technologies continue improving:

• Solar PV + battery storage: LCOE declining 5–10% annually; 2030 projections $0.02–0.04/kWh for utility-scale, battery costs <$150/kWh enabling economical 4–8 hour storage [11]. Even remote off-grid applications increasingly favor solar+battery over diesel or hydrokinetic.

• Micro-hydro (dam-based): Where head available (H > 2–3 m), conventional micro-hydro achieves η = 0.70–0.85, lower costs ($3,000–6,000/kW), simpler permitting, proven 30+ year lifetimes—superior to hydrokinetic in nearly all metrics [133].

5.5 Evidence Quality Summary and Knowledge Gaps

This systematic review applied rigorous evidence quality assessment (Section 2.5) to 38 studies. Table 8 summarizes findings strength by topic area, highlighting where robust evidence supports design guidance versus where critical knowledge gaps persist.

Table 8 Evidence Quality Summary by Topic

Topic	Evidence Strength	Studies (n)	Validation Status	Critical Knowledge Gaps
Cross-Flow Impulse design parameters	Strong ★★★★★	18	Multi-method: Exp + CFD + Field	• Free-surface effects Fr > 0.30 • Long-term reliability >5 years
FWW kinetic mode performance	Strong ★★★★★	12	Field-validated (n=7 field deployments)	• Long-term reliability >5 years • Blade durability data
FWW RHPM mode performance	Moderate ★★★	5	Partial field validation (n=2 deployments)	• BR threshold validation • Mode transition criteria
Cross-Flow Lift shallow-water	Weak ★★	6	Laboratory only (h/D > 5) ZERO shallow-water field data	• Ventilation prediction models • Field validation h/D < 3.0
Blockage correction methods	Weak ★★	8	Contradictory methods (±18% variation at BR=0.30)	• Systematic BR, Fr validation • 3D flow effects quantification
VOF free-surface modeling	Weak ★★	18	Limited validation: only 22% (4/18) validate surface profiles	• Surface elevation datasets • Algorithm selection guidelines
Ventilation prediction	Very Weak ★	3	Empirical correlations only No validated predictive models	• Physics-based modeling framework • Onset criterion mapping
Economic viability assessment	Very Weak ★	3	No comprehensive techno-economic analysis available	• LCOE sensitivity analysis • Market size assessment • Learning curve projections
Long-term field performance	Very Weak ★	2	Maximum 3-5 years documented vs 15-20 year design life	• 10-20 year validation studies • Failure mode documentation • Actual O&M cost data

Evidence Quality Legend:

Strong ★★★★★	Multi-method validation (Exp + CFD + Field) with independent replication
Moderate ★★★	Single-method validation or partial field verification
Weak ★★	Limited validation, contradictory findings, or high uncertainty
Very Weak ★	No validation, conceptual only, or critical gaps in evidence base

Priority research needs emerging from this assessment: (1) Comprehensive techno-economic analysis comparing hydrokinetic LCOE against competing renewables across deployment contexts; (2) Long-term (10+ year) field monitoring documenting actual versus predicted performance, O&M costs, failure modes; (3) Systematic validation of methodological controversies identified Section 4—blockage corrections, VOF accuracy, ventilation prediction; (4) Standardization efforts developing testing protocols and certification frameworks.

6. CONCLUSIONS AND RECOMMENDATIONS

This section synthesizes the principal findings of the systematic review and translates them into actionable guidance. Technology-specific deployment recommendations, critical research priorities for field advancement, and policy recommendations for facilitating commercial deployment are presented, followed by a concluding perspective on the realistic role of shallow-water hydrokinetic energy within the broader renewable energy landscape.

6.1 Summary of Key Findings

This systematic review examined shallow-water hydrokinetic turbines (h < 3 m) through critical synthesis of 38 studies published 2000–2025, providing the first comprehensive assessment integrating performance validation, methodological controversies, and deployment realities. Three technology families emerged with distinct trade-offs: Cross-Flow Impulse turbines achieve field-validated $C_{p,field}$ = 0.18–0.28 with moderate deployment complexity; Floating Water Wheels (FWW) demonstrate robust field operation at $C_{p,field}$ = 0.12–0.18 (kinetic mode) or η = 0.45–0.60 (RHPM mode) with lowest installation barriers; Cross-Flow Lift turbines show laboratory potential $C_{p,lab}$ = 0.35–0.49 but lack shallow-water field validation and face ventilation constraints at h/D < 2.0 (Section 3).

Critical methodological analysis revealed that performance predictions carry ±20–40% uncertainty from competing blockage correction methods (±18% variation at BR = 0.30), unvalidated VOF free-surface modeling (only 22% of implementations validate surface profiles), and absent ventilation prediction frameworks (Section 4). This uncertainty substantially exceeds typical measurement errors (±5–10%) and directly impacts economic viability assessments. Furthermore, systematic 15–45% performance degradation between laboratory testing and field deployment—documented across all technologies—demands explicit derating factors in design practice: 25–35% for Cross-Flow Impulse, 15–30% for FWW kinetic mode (Section 5.1).

Deployment gap analysis identified that despite 40+ years of research, global installed capacity remains <100 MW due to convergent economic, regulatory, and technical maturity barriers. Field capital costs ($5,000–12,000/kW) exceed literature estimates by 2–3×, yielding LCOE $0.15–0.30/kWh facing severe competition from solar PV ($0.03–0.05/kWh) and onshore wind ($0.04–0.06/kWh). Regulatory approval timelines (12–36 months typical) and absence of international standards create financing challenges incompatible with commercial deployment scale (Section 5.3).

6.2 Technology-Specific Recommendations for Deployment

Based on evidence quality assessment and field validation status, this review provides differentiated recommendations by technology and application context:

Floating Water Wheels (Kinetic Mode, BR < 0.40): Recommended for distributed off-grid applications (1–10 kW) where simplicity and portability outweigh modest efficiency. Strong evidence (12 studies, 7 with field validation) supports reliable operation at $C_{p,field}$ = 0.12–0.18 in shallow flows (h = 1.0–2.0 m, V = 0.8–1.5 m/s). Economics favorable where baseline diesel generation >$0.25/kWh. Design priorities: conservative immersion ratio h_i/D = 0.20–0.30, blade count N_b = 8–12 (conservative), hybrid integration with solar PV for diurnal diversity. Critical gap: long-term reliability beyond 5 years undocumented (Section 5.2.1).

Cross-Flow Impulse Turbines: Recommended for community-scale installations (10–100 kW) where higher efficiency ($C_{p,field}$ = 0.18–0.28) justifies moderate deployment complexity. Strong evidence (18 studies) validates design parameters: blade count N_b = 15–26, diameter ratio d_i/D = 0.66–0.68, blade angles β_1 = 30–35°, β_2 = 90–105°. However, free-surface effects at Fr > 0.25 remain poorly validated, requiring site-specific flow modeling. Fixed mounting necessitates civil works and extended permitting (12–24 months). Economically competitive only against micro-hydro alternatives where head development infeasible (Section 3.1, 5.2.1).

Cross-Flow Lift Turbines (Darrieus/Gorlov): Not recommended for shallow-water deployment (h/D < 2.0) given zero field validation, unpredictable ventilation onset, and Reynolds sensitivity degrading performance 15–40% at typical shallow-water velocities (V = 0.8–1.5 m/s, blade chord Re_c = 0.5–3 × 10^5). Conditional consideration only for deep-water applications ($h/D \geq 2.5$) with verified top clearance $c_{top} \geq 1.0c$ maintained seasonally, requiring pilot demonstration with performance monitoring before commercial scale-up. Laboratory performance advantages ($C_{p,lab}$ = 0.35–0.49) do not justify deployment risk absent validated shallow-water operation protocols (Section 3.2, 5.2.1).

Competitive Positioning: Honest assessment positions shallow-water hydrokinetics as niche technology serving specialized contexts where (1) off-grid locations with diesel baseline >$0.25/kWh, (2) hybrid systems valuing baseload stability at premium pricing, or (3) environmental constraints prohibit dam construction. Mainstream renewable energy deployment will continue dominated by solar PV, wind, and conventional hydropower given their superior economics (2–6× lower LCOE), faster deployment timelines (1–6 months vs 12–36 months), and established supply chains. Without technological breakthrough reducing LCOE below $0.10/kWh—requiring 40–60% cost reduction from current field reality—global installed capacity likely plateaus at hundreds of megawatts rather than gigawatt scale (Section 5.4.3).

6.3 Critical Research Priorities for Field Advancement

Bridging the gap between laboratory success and commercial deployment requires systematic research addressing four priority areas:

Priority 1: Long-Term Field Validation Studies (10–20 Years): Current maximum documented continuous operation spans only 3–5 years [8], [23], insufficient to validate claimed 15–20 year design lifetimes or establish actuarial databases enabling insurance products and bankable performance guarantees. Coordinated research programs should instrument 20–30 installations across diverse contexts (flow regimes, debris loading, climatic conditions) monitoring:

- Actual versus predicted capacity factors quantifying prediction accuracy and seasonal variation impacts
- Component failure modes, rates, and costs distinguishing design deficiencies from inherent operational challenges
- Maintenance requirements and schedules optimizing reliability versus operational costs
- Environmental impacts including fish interaction, sediment transport alteration, riparian habitat effects

International cooperation through organizations like IEA Hydropower or IRENA could coordinate data collection protocols ensuring cross-study comparability and accelerating evidence accumulation. Estimated program cost $5–10 million over 15 years represents modest investment potentially unlocking billion-dollar markets if economic viability confirmed [11], [135].

Priority 2: Comprehensive Techno-Economic Analysis: Only 3 of 38 reviewed studies conducted economic analysis, and none provided comprehensive LCOE sensitivity assessment across deployment contexts. Critical knowledge gaps include:

- Site-specific LCOE modeling incorporating flow regime statistics, civil works requirements, grid connection distances, local labor costs, permitting timelines—enabling developers to rapidly assess project viability without costly feasibility studies
- Competitive benchmarking against solar PV, wind, diesel, and micro-hydro alternatives across power scales (1 kW to 1 MW) and deployment contexts (grid-connected, off-grid, hybrid) identifying competitive niches
- Learning curve analysis quantifying cost reduction potential through volume manufacturing, standardization, and supply chain maturation versus inherent technological constraints
- Market size estimation for viable deployment niches informing R&D investment decisions and industry development strategies

Open-access tools and databases (similar to NREL's System Advisor Model for solar/wind) would democratize techno-economic analysis enabling small developers and community organizations to evaluate projects without expensive consultants [136], [137].

Priority 3: Methodological Controversy Resolution: Section 4 identified three critical controversies undermining design reliability. Systematic experimental campaigns should address:

Blockage correction validation: Controlled flume experiments measuring upstream velocity profiles with/without turbines across BR = 0.10–0.50, Fr = 0.15–0.60, aspect ratios L/D = 0.5–3.0. Seven competing correction methods currently yield ±18% prediction variation [113]; systematic validation could reduce uncertainty to ±5–8% enabling confident multi-turbine array design.

Free-surface modeling verification: Comprehensive surface elevation profile measurements (≥20 spatial locations, 5D upstream to 10D downstream, temporal resolution ≥10× blade passage frequency) enabling VOF model validation. Currently only 22% of VOF implementations validate surface predictions; robust validation datasets would establish when simplified single-phase models suffice versus requiring computationally expensive multiphase approaches.

Ventilation prediction frameworks: Systematic submergence ratio reduction experiments (c_{top}/c = 2.0 to 0.2) at fixed tip-speed ratios documenting performance degradation curves and identifying transition mechanisms through high-speed visualization. Current empirical correlations provide only binary onset/no-onset indicators; quantitative degradation prediction enables rational design trade-offs balancing clearance requirements versus installation constraints.

Priority 4: Standardization and Certification Development: Industry collaboration through technical committees (e.g., IEC TC 114 Marine Energy, extending scope to river applications) should develop:

• Power performance testing protocols specifying flow measurement requirements, blockage correction procedures, reporting standards enabling verifiable capacity ratings

• Design standards addressing structural integrity, safety factors for flood loading, corrosion protection, electrical safety in wet environments

• Certification frameworks providing third-party validation of manufacturer claims and design compliance reducing insurance costs and enabling bankable projects

Wind and solar photovoltaic industries demonstrate that standardization accelerates deployment by reducing transaction costs, enabling supply chain economies, and providing regulatory confidence [138]. Hydrokinetic sector maturation requires similar institutional infrastructure.

6.4 Policy Recommendations for Deployment Facilitation

Government policies can accelerate deployment by addressing non-technical barriers while maintaining appropriate environmental safeguards:

Streamlined Regulatory Frameworks: Establish clear permitting pathways distinguishing low-impact installations (BR < 0.15, single units, no channel modifications) from high-impact deployments (BR > 0.40, arrays, civil works). Low-impact projects meeting defined criteria could receive expedited approval (30–90 days) similar to rooftop solar PV, while high-impact projects undergo comprehensive environmental assessment. Current regulatory ambiguity—classifying hydrokinetic installations inconsistently as hydropower, water diversion, or novel technology—creates 12–36 month approval timelines deterring private investment [132], [134].

Demonstration Project Support: Targeted grant programs (40–60% capital cost sharing) for pilot installations in representative contexts (diverse flow regimes, debris conditions, climatic zones) generating long-term performance data addressing knowledge gaps identified Priority 1. Successful models include Canada's Smart Grid Demonstration Program and

European Commission's Horizon Europe supporting 5–10 MW pilot projects de-risking technologies before commercial scale-up [139], [140]. Hydrokinetic programs targeting 50–100 MW cumulative demonstration capacity over 10 years ($50–100 million investment) could validate economic viability and inform deployment strategies.

Hybrid System Integration Incentives: Hydrokinetic systems provide complementary generation profiles to solar PV (nocturnal baseload when solar unavailable) and wind (flow-driven versus weather-driven). Feed-in tariffs or renewable energy credits recognizing baseload value (e.g., 1.5–2.0× standard renewable credit for dispatchable generation) improve economic competitiveness. Germany's Renewable Energy Act and California's Self-Generation Incentive Program demonstrate how differentiated incentives can support diverse renewable portfolios rather than lowest-LCOE monocultures [141], [142].

6.5 Concluding Perspective

Shallow-water hydrokinetic energy conversion represents mature laboratory technology facing persistent deployment barriers. Four decades of research have established robust design knowledge for two field-validated technologies (Cross-Flow Impulse, Floating Water Wheels) achieving respectable performance ($C_{p,field}$ = 0.12–0.28) in appropriate contexts. However, this review's critical synthesis reveals that technical performance alone determines neither deployment success nor societal value. Economic reality (LCOE 3–10× competing renewables), regulatory complexity (12–36 month approvals), and technical maturity gaps (absent standardization, <5 year field validation) explain why global installed capacity remains orders of magnitude below early projections.

The path forward requires honest acknowledgment that shallow-water hydrokinetics will not revolutionize global renewable energy supply. Solar photovoltaic and wind technologies have achieved cost reductions, deployment scales, and supply chain maturation incompatible with hydrokinetic competition at mainstream level. Rather, this technology's value proposition lies in serving specialized niches where geographic constraints prohibit alternatives or where baseload generation commands premium pricing. Distributed off-grid applications represent the most promising near-term opportunity, leveraging FWW simplicity and portability for remote communities where diesel baselines exceed $0.25/kWh.

Realizing even this modest potential demands systematic research addressing critical knowledge gaps—particularly long-term field validation and comprehensive techno-economic analysis—coupled with policy frameworks streamlining low-impact deployment while maintaining environmental safeguards. The research community must resist exaggerating deployment prospects or perpetuating laboratory-derived optimism disconnected from field reality. Instead, focusing efforts on contexts where hydrokinetic technologies offer genuine advantages can deliver meaningful contributions to renewable energy portfolios without misallocating scarce resources chasing unattainable gigawatt-scale dreams.

Success should be measured not by installed capacity rivaling conventional hydropower, but by delivering reliable, cost-effective energy access to communities and applications where alternatives fail—a worthwhile objective requiring evidence-based deployment strategies grounded in systematic review findings rather than aspirational projections.

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NOMENCLATURE

Symbol	Definition	Unit
Geometric Parameters		
D	Rotor/wheel outer diameter	[m]
D_1, D_2	Outer and inner drum diameters (Cross-Flow Impulse) ****	[m]
L	Turbine axial width (perpendicular to flow)	[m]
W	Channel effective width (after side clearances)	[m]
h	Local water depth at rotor plane (including backwater effects)	[m]
h_i	Immersed paddle depth (FWW)	[m]
R	Rotor radius (= D/2)	[m]
c	Blade chord length	[m]
c_{top}	Top clearance (rotor top to free surface)	[m]
$c_{\beta ot}$	Bottom clearance (rotor bottom to channel bed)	[m]
N_β	Number of blades/paddles	[pcs]
A	Projected frontal area (= D × L) **	[m²]
Flow Properties		
V	Depth-averaged flow velocity***	[m/s]
V_s	Near-surface velocity at paddle tip depth (FWW)	[m/s]
ρ	Water density (≈ 1000 for freshwater)	[kg/m³]
ν	Kinematic viscosity ($\approx 1.0 \times 10^{-6}$ at 20°C)	[m²/s]
g	Gravitational acceleration (= 9.81)	[m/s²]
Q	Volumetric flow rate	[m³/s]
H	Head differential (upstream minus downstream)	[m]
ω	Angular velocity of rotor	[rad/s]
Power and Performance		
P	Mechanical power output at rotor shaft	[W]
C_p	Power coefficient = $P / (0.5\rho A V^3)$**	
η	Hydraulic efficiency = $P / (\rho g H Q)$	
λ	Tip-speed ratio = $\omega R / V$	
Dimensionless Parameters		
BR	Blockage ratio = $A_{turbine}/A_{channel}$	
Fr	Froude number = $V / \sqrt{gh}$***	
Re_D	Reynolds number (diameter-based) = VD / ν	
Re^c	Reynolds number (chord-based) = Vc / ν	
σ	Solidity = $N_\beta c / (\pi D)$*	
h/D	Depth-to-diameter ratio	
c_{top}/D	Top clearance ratio	
$c_{\beta ot}/D$	Bottom clearance ratio	
Abbreviations		
HACFT	Horizontal Axis Cross-Flow Turbine†	
FWW	Floating Water Wheel	
RHPM	Rotating Hydrostatic Pressure Machine (FWW at BR > 0.40)	
VOF	Volume of Fluid (multiphase CFD method)	
CFD	Computational Fluid Dynamics	
TSR	Tip-Speed Ratio (= λ)	

Notes:
** Solidity (σ) defined as 2D geometric solidity ($N_b c/\pi D$); alternative definitions exist in literature—cross-study comparisons require consistent σ definition.*

*** A = projected frontal area (D×L). Some studies report C_p using submerged area only, yielding higher values; this review uses projected area throughout for consistency.*

**** V = depth-averaged velocity; for FWW applications, near-surface velocity (V_s) measured at paddle tip depth is preferred when velocity profile data are available.*

***** Cross-Flow Impulse = Banki-type HACFT; Cross-Flow Lift = Darrieus-type HACFT. See Section 3 for detailed taxonomy.*

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