Impact Factor 5.8701 (ICI)

International Journal of Engineering Research-Online
A Peer Reviewed International Journal
ISSN: 2321-7758 http://www.ijoer.in editorijoer@gmail.com

Vol.13., Issue.3, 2025
July-Sept.

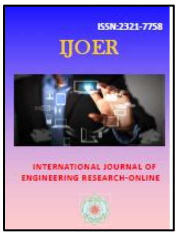
REVIEW ARTICLE

ISSN: 2321-7758

Evolving Paradigms in Hydraulic Structures: From Classical Models to Computational and Sustainable Approaches – A Review

Nabaa Noori Bashboosh[1]*, Rasha A. Aljazaari[2], Alaa Mohsin Dawood[3]
[1]Department of Civil Engineering, University of Kufa, Najaf, Iraq.
*Corresponding author: nabaan.shamsaldeen@uokufa.edu.iq
[2]Department of Civil Engineering, University of Kufa, Najaf, Iraq.
Rashaa.aljazaari@uokufa.edu.iq
[3] Faculty of Technical, University of Alfurat Alawsat Technical, Najaf.
Alaa.dawood@aut.edu.iq

DOI: 10.33329/ijoer.13.3.35



Abstract
Energy dissipation is one of the most important factors to be taken into account during the design and operation of hydraulic structures, mainly for handling supercritical flows downstream from spillways, sluice gates, and chutes. When loose, excessive flow energy can cause scour, cavitation and structural vibration, which in turn threatens operation reliability and life. Over the course of two centuries, research has developed from empirical descriptions of hydraulic jumps to available controlled laboratory experiments and, in recent decades, sophisticated numerical models. Ongoing research is focusing on multiphase flow dynamics, air–water interactions and pressure oscillations in energy dissipators. Notwithstanding these progresses, the reliable forecasting of aeration processes and transformation rates, along with the scaling from lab to prototype applications and considering climate-induced variability in engineering design, are critical challenges. This overview summarizes previous successes and future developments, placing particular emphasis on environmentally acceptable construction materials and energy recovery options. The future hydraulic structures can be more response to the growing requirements of resilience, sustainability and adaptability when incorporating technical efficiency together with environmental responsibility.

Keywords: Hydraulic structures; Energy dissipation; Hydraulic jumps; Computational fluid dynamics (CFD); Sustainability.

1. Introduction

The design and operation of hydraulic structures (e.g., spillways, stilling basins, and energy dissipators) continue to be at the leading edge of hydraulic engineering research because they help guarantee the safety of the structure and high hydraulic performance. Even when there is surplus flow energy, the excess may result in serious erosion and even cavitation and structural instability downstream, especially during large flood events, if not properly dissipated. Hence, the energy dissipation mechanisms have always been a research focus from classical hydraulic jumps to present-day numerical and hybrid modellings [1], [2].

The hydraulic jump has long been one of the most investigated phenomena in open channel hydraulics. From the empirical relations established by Bidone more than two centuries ago, the conjugate depths and energy loss due to confluence form the base for stilling basin layout designs [3]. During the 1950s, behaviors of stilling basins and baffle blocks were investigated in experimental and field studies by various organizations, including the United States Bureau of Reclamation (USBR), which developed a design standard for stilling basins and baffle blocks [4]. These constructions have been replicated all over the world, becoming templates for dissipating the flood downstream of large dams.

With the development of current measuring techniques, laboratory experiments contributed an increased knowledge of the structure of turbulence, the interaction of air with water and pressure fluctuations related to the phenomenon of dissipation of energy [5], [6]. Nevertheless, scale-related phenomena could not be eliminated, and the behavior of the prototype still did not completely agree with laboratory predictions, notably with respect to aeration performance and cavitation resistance.

In recent years, computational fluid dynamics (CFD) techniques have become powerful tools to investigate energy dissipation phenomena at a very fine level of detail. Eulerian methods, including Reynolds-Averaged Navier–Stokes (RANS) models and Volume of Fluid (VOF) tools, have been employed to model free-surface turbulence and hydraulic jumps [7], while Lagrangian techniques, including Smoothed Particle Hydrodynamics (SPH), provide different insights into multiphase flow interactions [8]. Nevertheless, several challenges persist, such as an appropriate modelling of turbulent structures, validation at prototype scale, and sustainability issues in hydraulic structure design [9], [10].

The purpose of this review is to offer a relatively brief (but complete) summary of energy dissipation in hydraulic structures, and document its historical development, common experiments and numerical simulations, and the future research needs for both theory and analysis

2. Review Methodology

A systematic literature review was conducted for the period 1980 -- 2025 based on Scopus, Web of Science, ASCE Library, ScienceDirect, Google Scholar and seminal pre-1980 literature was included for completeness purposes. Database-unique Boolean questions combined search terms for hydraulic system, aeration, cavitation, and numerical simulation methods. After duplicate and multi-stage screening of titles and abstracts, I assessed full text eligible papers and data on geometry, flow conditions, approach and main findings were systematically extracted. Findings were synthesized on the basis of themes: historical context; experiments and field investigations; the framework of numerical models; and newly emerging challenges.

3. Historical Development

The study of energy dissipation in open channel hydraulics has evolved through distinct historical stages, each characterized by different methodological approaches and scientific paradigms.

3.1 Early Observations

Sketches and notes of Leonardo da Vinci from the late 15th century provided the earliest accounts of the turbulent flow phenomena, with qualitative drawings of eddies, vortices and surface instabilities [11]. Although his findings were not rigorously quantitative, they were a first indication of turbulence and energy transfer in rapidly varying flows. These perceptions

International Journal of Engineering Research-Online
A Peer Reviewed International Journal
ISSN: 2321-7758 http://www.ijoer.in editorijoer@gmail.com
Vol.13., Issue.3, 2025
July-Sept.

established a conceptual basis for some experimental studies later on

3.2 Classical Era (19th Century)

The systematic study on the hydraulic jump was first undertaken by Giovanni Battista Bidone (1820) using a flume to measure the relationship between the upstream and downstream depths [12]. Formulation of Bidone for sequent depth and energy dissipation is the first mathematical expression of the hydraulic jump as an empirical formula. This theoretical framework has been later developed, also by Bélanger in 1828 and by Bakhmeteff in the early 20th century, making the hydraulic jump one of the fundamentals of classical hydraulics [13], [14]

3.3 20th Century Advances

In the mid-20th century, as the era of large-scale embankment dam construction unfolded, the demand for standard energy dissipation designs became urgent. The USBR and other research organizations carried out comprehensive experimental campaigns, leading to stilling basin design manuals incorporating baffle blocks, chute blocks and end sills to increase the hydraulic efficiency [15]. The research focused on scour protection, cavitation and safety structure under extreme discharges.

Field-scale studies also found that the Froude-based similarity was successful in predicting conjugate depths; however, prototype-scale degree of aeration, pressure fluctuations and turbulence intensities could not always be matched at a laboratory scale [16], [17]. This discrepancy emphasized the shortcomings of the entirely empirical methods and inspired a combination of physical modelling with numerical simulations.

3.4 Late 20th Century Insights

Subsequent work by Hager and Chanson, supported by advanced laboratory instrumentation such as high-speed cameras and pressure transducers, improved the understanding of turbulence structure, air entrainment, and pressure fluctuations [18], [19]. These developments marked the transition from empirical observations to instrument-assisted experimentation.

3.5 Transition to Modern CFD Era

The foundation laid by these experimental efforts paved the way for the application of Computational Fluid Dynamics (CFD) methods. In particular, the work of Bayon et al. highlighted the potential of modern numerical schemes to replicate hydraulic jump characteristics with high fidelity, albeit at considerable computational cost [20].

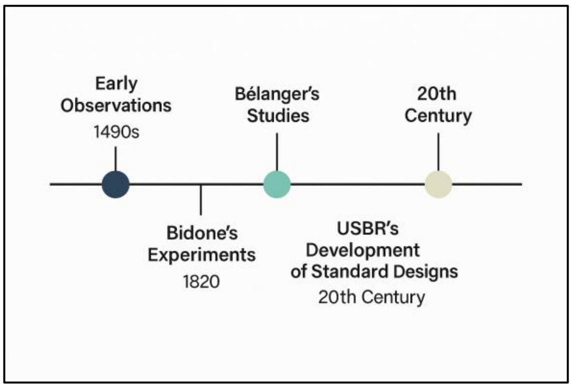


Figure 1. Historical timeline of hydraulic jump research

Table 1. Expanded comparative overview of the historical development of hydraulic jump research

Era	Key Contributors	Methodology	Key Outcomes	Limitations	Impact on Future Research
Early Observations [11]	Leonardo da Vinci (1490s)	Qualitative sketches, observational drawings	First recognition of turbulence, vortices, and eddies in open channel flows	Lack of quantitative data, absence of mathematical formulation	Inspired systematic study of turbulent flows and visualization of complex

					hydraulic behavior
Classical Era [12], [13]	Bidone (1820); Bélanger (1828)	Flume experiments, empirical formulations	Definition of hydraulic jump, sequent depth equations, energy dissipation relations	Restricted to small-scale laboratory conditions; neglect of scale effects	Established theoretical framework for later design standards; introduced energy dissipation as a hydraulic priority
Early 20th Century [14]	Bakhmeteff (1932); Bazin; others	Open-channel hydraulics theory, systematic experiments	Broader hydraulic principles; classification of jumps; conceptual link to turbulence	Limited instrumentation to capture turbulence and aeration accurately	Motivated refinement of turbulence models and practical guidelines for dam engineering
Mid-20th Century [15], [16]	USBR (1950s–1980s); Rajaratnam (1960s–70s)	Large-scale flume tests, prototype studies, design manuals	Development of stilling basin types (I–IV), baffle blocks, end sills; standardized scour protection	Strong reliance on empirical scaling; prototype vs. model discrepancies	Provided global benchmark manuals; influenced dam safety codes and basin retrofitting practices
Late 20th Century [17], [18], [19]	Hager (1992); Chanson (1990s)	Advanced lab instrumentation, high-speed cameras	Improved understanding of turbulence structure, aeration, and pressure fluctuations	Limited computational capacity for CFD validation	Paved the way for integrating turbulence models, multiphase flow studies, and eco-hydraulics
21st Century [20]	Bayon et al. (2020); Wu, CFD community	Computational Fluid Dynamics (CFD), RANS, VOF, SPH	Numerical replication of hydraulic jumps, hybrid modelling, and enhanced visualization	High computational cost; model validation challenges; limited prototype data	Opened directions for eco-friendly dissipators, resilience against climate-induced extreme floods, and sustainability-based hydraulic design

4. Experimental and Field Studies

Experimental research was the cornerstone of hydraulic engineering in the mid-20th century, particularly experiments with lab flumes used to investigate spilling basins and hydraulic jumps under controlled conditions. Such models enabled researchers to systematically investigate flow conditions, conjugate depths and the influence of appurtenances such as weir blocks and baffle piers [21]. Laboratory experiments offered an initial opportunity to simulate extreme discharges at a manageable scale, and particularly to generate useful design charts and empirical correlations [22].

Visualization techniques were some of the techniques used to elucidate some of the characteristics of roller, the recirculating region and its other structure, such as dye injection, high-speed photography and later PIV [23], [24]. Concurrently, velocity probes together with pressure transducers have made it possible to measure fluctuating pressures and shear stresses on basin floors, which leads to a better understanding of the process of air entrainment and cavitation inception [25].

However, it was soon found that F = 1 laboratory Froude scaling by itself was insufficient to model full-scale events, particularly in flows that contained significant air–water interaction. On-site experiments demonstrated the difference in aeration, bubble size distribution, as well as wave-wave and wave–pressure fluctuation when the tests were scaled up on big dams [26]. From prototype field tests, although the trends of conjugate depth and energy dissipation were correctly shown in the laboratory results, the turbulence intensity and aeration efficiency substantially differed from those of the prototype [27].

The above limitations clearly point to a requirement for field monitoring in combination with laboratory studies. Similar long-scale prototype measurements, for example, at the Hoover Dam and other large hydraulic projects, have also indicated that aeration devices and graded surfaces are necessary to minimize the risk of cavitation [28, 29]. As such, the laboratory flume studies and prototype investigations formed the backbone of design guidance offered by national and international authorities and continue to do so today [30]

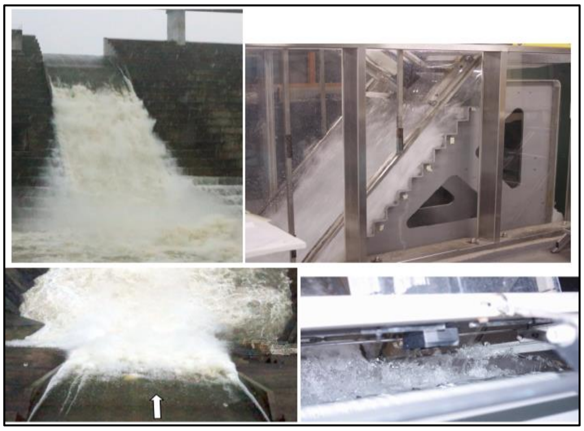


Figure 2. Prototype vs. laboratory stepped spillways (1V:0.8H): side-by-side comparison of aeration and energy dissipation [28].

Table 2. Comparative strengths and limitations of laboratory and field studies

Study Type	Strengths	Limitations
Laboratory Flumes [21], [22], [23], [24], [25]	- Controlled boundary conditions allow systematic parameter variation (e.g., slope, discharge, basin geometry). - High repeatability of experiments. - Cost-effective for preliminary design testing. - Enabled visualization of turbulence, roller formation, and bubble dynamics using dyes, high-speed cameras, and PIV. - Provided empirical correlations for	- Pronounced scale effects limit aeration accuracy and cavitation inception prediction. - Limited ability to reproduce prototype turbulence intensities and air–water distributions. - Restricted to relatively low Reynolds numbers compared to full-scale flows.

	sequent depth, energy loss, and flow regime classification.	- May underpredict pressure fluctuations and cavitation damage.
Field Studies [26], [27], [28], [29], [30]	- Capture full-scale flow conditions, including aeration, cavitation, and turbulence at prototype Reynolds numbers. - Provide long-term performance data of energy dissipators (e.g., Hoover Dam, Tarbela Dam). - Essential for validating laboratory models and CFD simulations. - Identify operational issues such as sediment deposition, basin scour, and cavitation erosion. - Allow optimization of retrofitting designs under real discharges.	- Very high cost and logistical complexity. - Limited repeatability due to variable discharge and environmental conditions. - Safety challenges during extreme flood events. - Instrumentation often constrained by harsh flow conditions (submergence, debris, aeration). - Data availability is scarce compared to laboratory datasets.

5. Numerical and Computational Advances

The ability of computational fluid dynamics (CFD) has revolutionized the characterization of energy dissipation phenomena in hydraulic structures. Computational methods also offer dual opportunities with laboratory experiments and enable the resolution of flow dynamics that may be impossible to measure, including turbulent structures, air–water interactions, and multiphase interfaces. Computational paradigms. A number of computational paradigms have been developed with different methods of modelling and levels of precision.

5.1 Eulerian Approaches

Eulerian formulation is still the most popular approach for hydraulic engineering, because they are efficient and robust. The Reynolds-Averaged Navier–Stokes (RANS) models, such as k-ε and k-ω SST, have been applied to describe turbulence in hydraulic jumps and stilling basins [31]. The models offer time-averaged solutions which capture global flow behaviours; however, they are unable to resolve instantaneous turbulent fluctuations. Although expensive in computation, LES has a higher accuracy in predicting turbulent energy spectra and vortices [32].

5.2 Volume of Fluid (VOF) Methods

The VOF (Volume of Fluid) method has been widely accepted to represent free surfaces, and to simulate air–water interactions in multiphase flows. It has been widely used in the modelling of hydraulic jumps, stepped spillways and aeration phenomena, and numerical predictions of the void fraction distributions and surface oscillation have been reported as in good agreement with experimental results [33], [34]. However, VOF is intrinsically subject to numerical diffusion and hence a sufficiently fine grid is necessary to obtain numerical accuracy in aerated regions.

5.3 Lagrangian Approaches

On the other hand, the Lagrangian approach, represented by SPH [35] and the DEM, is a meshless formulation that is well-suited for modelling highly violent free-surface deformations and particle-added flows. These methods represent multiphase flow interactions in a more natural way, and have been used to model hydraulic jumps, granular scour processes and sediment–flow interactions [36]. Nevertheless, the high cost of computation and difficulties in turbulence modelling are drawbacks that cannot be ignored.

5.4 Hybrid Approaches

Given the restricted nature of those paradigms, recent literature suggests moving from the paradigms to hybrid modelling. CFD coupled with physical experiments showed potential for the validation of prototype-scale energy dissipation mechanisms [37]. Moreover, the combination of Eulerian–Lagrangian schemes both exploits the strength of continuum solvers, while maintaining particle representation, which enables further accurate modelling of air entrainment and turbulence-driven mixing [38], [39]. It is progress such as these that send a clear message that the future hydraulic structure design and analysis will be multiscale and Multiphysics coupled [40].

Table 3. Comparative overview of numerical approaches for hydraulic energy dissipation modelling

Approach	Advantages	Limitations	Typical Applications
Eulerian (RANS/LES)	• Well-established in engineering practice, robust solvers available in commercial CFD codes. • Efficient for time-averaged turbulence predictions (RANS). • LES resolves large-scale turbulent eddies, improving accuracy for highly unsteady flows. • Suitable for large Reynolds number flows with strong turbulence [31], [32].	• RANS underestimates instantaneous turbulence structures and air entrainment. • LES requires very fine meshes and a high computational cost. • Sensitive to boundary conditions and near-wall treatment [31], [32].	• Hydraulic jumps in stilling basins. • Energy dissipation studies in dam outlets. • Flow aeration and pressure fluctuation analysis.
VOF (Volume of Fluid)	• Accurately captures free-surface evolution and multiphase interfaces. • Predicts void fraction distribution and aeration efficiency. • Suitable for violent free-surface oscillations and flow breakup phenomena. • Integrated in most CFD packages [33], [34].	• Smeared interfaces due to numerical diffusion. • Requires fine mesh and small-time steps to resolve air–water interactions. • Limited in turbulence–bubble coupling without additional sub-models [34].	• Stepped spillways with high aeration. • Air–water interface tracking in hydraulic jumps. • Flow in plunge pools and jet impingement.
Lagrangian (SPH/DEM)	• Mesh-free, ideal for large deformation, breaking waves, and violent splashing. • Captures particle-scale multiphase phenomena naturally. • Handles complex boundaries and moving objects efficiently. • SPH well-suited for incompressible free-surface flows, DEM for granular–fluid coupling [35], [36].	• Computationally intensive for large domains. • Difficult calibration of kernel functions and smoothing lengths (SPH). • Limited turbulence modelling and validation at prototype scales. • DEM is expensive when particle numbers are high [35], [36].	• Hydraulic jumps with strong splashing and spray. • Scour processes around hydraulic structures. • Sediment entrainment and transport dynamics.

International Journal of Engineering Research-Online
A Peer Reviewed International Journal
ISSN: 2321-7758 http://www.ijoer.in editorijoer@gmail.com
Vol.13., Issue.3, 2025
July-Sept.

Hybrid	• Combines the advantages of Eulerian continuum solvers and Lagrangian particle methods. • Allows multiscale representation: large-scale flow by Eulerian CFD, fine-scale entrainment by SPH/DEM. • Enables integration of CFD with physical model experiments for validation. • Provides best compromise between accuracy and computational feasibility [37],[40].	• Methodologically complex; requires coupling algorithms. • High demand for computational resources when coupling multiple solvers. • Limited availability of validated hybrid codes for hydraulic applications [38], [39].	• Multiphase flows with aeration and cavitation. • Prototype-scale dissipation structures (spillways, stilling basins). • Complex free-surface interactions (air entrainment, jet plunging, energy recovery).

6. Emerging Challenges

Notwithstanding great progress in computation and experiment, there are still difficulties in simulating and designing hydraulic energy dissipation systems exactly. These factors are due to the complexity of multiphase turbulent flows, environmental fluctuation, and sustainability interests. They are essential for the safe and optimal functioning of spillways, stilling basins, and other hydraulic structures.

6.1 Air–Water Interaction

Estimation of aeration processes in hydraulic jumps and stepped spillways is also an important unanswered question. Air entrainment contributes significantly to energy dissipation, pressure fluctuations, and cavitation control; however, most of the turbulence and multiphase models do not accurately predict bubble transport and void fraction distribution [41], [42]. Recent developments in experimental visualization methods, such as high-speed visualization and phase-detection probes, have helped to better understand this process, but scaling of prototype aeration is still challenging to model numerically [43].

6.2 Scale Effects

Physical models commonly have the limitation of scale and time, which is often restricted when applied to prototype conditions (e.g. laboratory scale). Similarity is also good for predicting conjugate depths, but scaling laws of air entrainment, turbulence intensity, and energy dissipation are not directly extendable [44], [45]. The difference between the behaviour of the model and of the prototype is still an important limitation that must be overcome by integrating hybrid modelling with large-scale experimentation [46].

6.3 Climate Change Impacts

The impact of climate change on extreme flood events is a challenging issue faced by hydraulic infrastructures. The conventional design criteria possibly do not provide sufficient safety factors with the hydrologically variable conditions [47]. Energy dissipation methods need to be more flexible, robust, and able to tolerate larger discharges without large extents of scour or cavitation [48]. Recent research highlights that there is a requirement for scenario-based design frameworks that explicitly account for hydrological uncertainty to enable consideration of energy dissipation, decisions to plan or not plan events [49].

6.4 Sustainability Considerations

Nowadays, sustainability is becoming a key issue in hydraulic works design. The review of the literature indicates that eco-friendly building materials, low-carbon and minimal green design are gradually being encouraged [50]. Furthermore, there are increasing efforts to make use of dissipated energy, e.g. in micro-hydropower recovery systems that are included in a stilling basin or downstream channel. Such new ideas are in line with global sustainability objectives but have to be validated intensively before implementation on a larger scale.

Table 4. Comparative overview of emerging challenges in hydraulic energy dissipation

Challenge	Impact on Design	Key Limitations	Research Needs / Future Directions
Air–Water Interaction	It directly influences energy dissipation efficiency, the relative jump length (Lj/y_1), depth ratios (y_2/y_1), the cavitation index (σ), and the root-mean-square (rms) pressure fluctuations; it also defines the placement and dimensions of aerators in stepped spillways, while controlling air concentration distributions α(z), vertical concentration gradients, and associated structural vibration and noise.	Bubble transport (break-up/coalescence) and size distribution remain poorly represented; phase-detection probes are intrusive with biases; weak turbulence–air coupling in RANS/VOF; strong sensitivity to grid resolution and timestep in highly aerated zones.	Population Balance Equations (PBE) coupled with the Volume of Fluid (VOF) method for predicting bubble size distributions; hybrid Eulerian–Lagrangian strategies combining VOF with discrete bubble tracking, alongside LES–VOF frameworks; prototype-scale aeration experiments for model validation; deployment of advanced optical diagnostics (including HSI, PIV/PLIF, and refractive-index matching); and rigorous Uncertainty Quantification (UQ) supported by Bayesian model calibration. [41],[43]
Scale Effects	The transferability of laboratory findings is limited, as preserving the Froude number alone does not guarantee similarity in Reynolds and Weber numbers; this leads to discrepancies in aeration patterns, relative energy losses (ΔE/E),	Impossibility of simultaneously preserving Fr, Re, and We; air entrainment and turbulence scaling unreliable; cavitation and trapped air effects distorted at model scale; small flume size limits	"Large-scale, pressurized laboratory modeling that preserves the coupled effects of Froude and Weber similarity; hybrid approaches integrating physical experiments with computational fluid dynamics (CFD)

	void fraction (α), and peak pressure, which in turn affect stilling basin geometry, block elevations, and potential scour hazards.	observation of nonlinear instabilities.	supported by cross-scale calibration; establishment of systematic protocols for documenting prototype–model discrepancies; and development of design charts derived from extended dimensionless groups (Fr, We, Re, σ, ks/y1) [44],[46]
Climate Change Impact	Alters non-stationary hydrological regimes: increases PMF, shifts in IDF curves, more frequent extreme events → demands higher discharge capacities, stronger scour protection, and resilient energy dissipators.	Deep uncertainty in climate projections; limited long-term monitoring records; poor linkage between climate–hydrology–hydraulic models; difficulty translating scenarios into design parameters.	Adaptive Pathways and Robust Decision-Making (RDM) frameworks; probabilistic multi-scenario flood risk analyses; multi-objective optimization of stilling basins with environmental constraints; retrofittable energy dissipation elements (labyrinth weirs, fusegates). [47],[49]
Sustainability	Integration of Life-Cycle Assessment (LCA), reduced CO_2 footprint in concrete/steel; minimized excavation and protection works; improved water quality and aeration; potential for energy recovery (micro-hydropower) from dissipated flows.	Lack of long-term durability datasets for low-carbon materials under turbulence/cavitation; immaturity of design standards for integrated micro-hydro units; higher complexity in operation and maintenance.	Implementation of low-clinker binders and recycled aggregates, application of cavitation-resistant surface treatments validated under prototype conditions, integration of modular micro-turbines within stilling basins, adoption of design-for-disassembly and proactive maintenance strategies, and utilization of standardized sustainability indicators (energy recovered per kWh relative to tons of

			CO_2-equivalent avoided). [50]

• *Key nondimensional similarity parameters for scaling and comparative analyses include the Froude number (Fr), Reynolds number (Re), Weber number (We), cavitation index (σ), void fraction (α), hydraulic jump length (Lj), and the relative energy dissipation ratio (ΔE/E).*

• *Validation framework: (i) systematically controlled laboratory experiments, (ii) in situ prototype field measurements, (iii) computational fluid dynamics simulations (RANS/LES with VOF treatment), and (iv) advanced hybrid Eulerian–Lagrangian approaches, all underpinned by rigorous uncertainty quantification and Bayesian-based model calibration.*

7. Conclusions

The study of the energy dissipation in hydraulic structures has evolved significantly, starting from empirical relations of hydraulic jumps up to sophisticated experimental investigations, numerical solutions or hybrid methods, which mix experimental and numerical approaches. This shift is due to both progress in hydraulic science and a demand for more efficient and safer hydraulic systems capable of solving advanced environmental problems.

Later studies have very incrementally moved on from channel depth–discharge relations and responses to detailed problems of turbulence structure, multiphase interactions or air entrainment at high spatial and temporal resolution. Recent numerical simulations have enabled detailed observations of the free surface phenomena and the vortex dynamics, and the air entrainment processes, and experimental studies at large scales have validated the findings and unveiled issues relative to the scaling of these small-scale models. Yet open questions remain in the upscaling from laboratory scale and prototype-like conditions on the aeration efficiency, scour protection, cavitation control and turbulence scaling. These problems are further complicated by the increase in variability of the hydrological regimes in the context of climate change and the need for robust and flexible energy dissipator structures.

And after that, a second theme, which will take on a defining role in the future of hydraulic engineering, is sustainability. Implementation of green building materials, reducing the carbon footprint of construction and the possibility of recovering energy from waste flow are some examples of the shift toward 'green' and 'responsible' engineering. These hydraulic structures, designed with sustainability goals, also give the possibility for engineering to fit with safety and functionality, not only now but with long-lasting value in ecology and society.

The way forward in the future of energy dissipation research is towards greater integration of the experimental, computational and field scale studies. Combining and hybrid strategies, which would get the best from both, appear to be the most appealing way to overcome the current limitations. Parallel to this, resilience will also need to be embedded within the design paradigms more holistically, rather than simply embodying sustainability in terms of material selection and operation mode. Ultimately, hydraulic energy dissipation systems should evolve towards integrated designs as multifunctional infrastructures that offer security, efficiency and added value as sustainability and society of concern.

References

[1] R. H. French, Open-Channel Hydraulics. New York, NY, USA: McGraw-Hill, 1985.

[2] V. T. Chow, Open-Channel Hydraulics. New York, NY, USA: McGraw-Hill, 1959.

[3] G. Bidone, "Experiments on hydraulic jumps," Memorie della Reale Accademia delle Scienze di Torino, vol. 25, pp. 21–39, 1820.

[4] USBR, Hydraulic Design of Stilling Basins and Energy Dissipators. Denver, CO,

USA: U.S. Bureau of Reclamation, Engineering Monograph No. 25, 1987.

[5] H. Chanson, Hydraulics of Open Channel Flow: An Introduction. Oxford, U.K.: Butterworth-Heinemann, 2004.

[6] H. Chanson, "Air–water flow measurements with intrusive phase-detection probes: Can we improve their interpretation?" Journal of Hydraulic Engineering, vol. 138, no. 4, pp. 343–349, 2012.

[7] Y. Wu and J. Rajaratnam, "Characteristics of hydraulic jumps," Journal of Hydraulic Engineering, vol. 122, no. 9, pp. 546–554, 1996.

[8] A. H. Shakibaeinia and A. Yeganeh-Bakhtiary, "Smoothed particle hydrodynamics for simulation of hydraulic jumps," Applied Ocean Research, vol. 31, no. 4, pp. 251–254, 2009.

[9] L. Hager, Energy Dissipators and Hydraulic Jump. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1992.

[10] A. Bayon, V. López-Jiménez, R. Maza, and J. Garcia, "Numerical modeling of hydraulic jumps with CFD tools: Recent advances and future perspectives," Water, vol. 12, no. 1, pp. 1–21, 2020.

[11] K. R. Langley, Leonardo da Vinci's Studies of Turbulence and Fluid Motion. Cambridge, U.K.: Cambridge Univ. Press, 1995.

[12] G. B. Bidone, "Expériences sur le remou hydraulique," Mem. Acad. Sci. Turin, vol. 25, pp. 21–39, 1820.

[13] J. Bélanger, Essai sur la Solution Numérique de Quelques Problèmes Relatifs au Mouvement Permanent des Eaux Courantes. Paris, France: Carilian-Goeury, 1828.

[14] B. A. Bakhmeteff, Hydraulics of Open Channels. New York, NY, USA: McGraw-Hill, 1932.

[15] USBR, Hydraulic Design of Stilling Basins and Energy Dissipators. Denver, CO, USA: U.S. Bureau of Reclamation, Engineering Monograph No. 25, 1987.

[16] A. Rajaratnam, "Hydraulic jumps," Advances in Hydroscience, vol. 4, pp. 197–280, 1967.

[17] H. Chanson, The Hydraulics of Open Channel Flow. Oxford, U.K.: Elsevier, 2004.

[18] L. Hager, Energy Dissipators and Hydraulic Jump. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1992.

[19] R. M. Khan and P. M. Steffler, "Model–prototype scale effects in hydraulic jumps," Canadian Journal of Civil Engineering, vol. 15, no. 6, pp. 1037–1046, 1988.

[20] P. Julien, River Mechanics. Cambridge, U.K.: Cambridge Univ. Press, 2002.

[21] B. E. Launder and D. B. Spalding, The Numerical Computation of Turbulent Flows. London, U.K.: Academic Press, 1974.

[22] U. Piomelli, "Large-eddy simulation: Achievements and challenges," Progress in Aerospace Sciences, vol. 35, no. 4, pp. 335–362, 1999.

[23] C. W. Hirt and B. D. Nichols, "Volume of fluid (VOF) method for the dynamics of free boundaries," Journal of Computational Physics, vol. 39, no. 1, pp. 201–225, 1981.

[24] A. Bayon, R. Maza, and V. López-Jiménez, "Numerical modeling of hydraulic jumps using CFD tools," Water, vol. 12, no. 1, pp. 1–15, 2020.

[25] J. J. Monaghan, "Smoothed particle hydrodynamics," Reports on Progress in Physics, vol. 68, no. 8, pp. 1703–1759, 2005.

[26] A. H. Shakibaeinia and A. Yeganeh-Bakhtiary, "SPH modeling of hydraulic jumps," Applied Ocean Research, vol. 31, no. 4, pp. 251–254, 2009.

[27] P. H. Sellin, H. Chanson, and J. Scruton, "Physical modeling and CFD coupling in hydraulic structures," Journal of Hydraulic Research, vol. 49, no. 6, pp. 673–685, 2011.

[28] J. Hu and H. Chanson, "Hydraulics and energy dissipation on a steep stepped

spillway: physical modelling in a large-size facility," Fig. 2, 2023/2024..

[29] G. Oger, M. Doring, and D. Le Touzé, "Hybrid Eulerian–Lagrangian methods for multiphase flows," Computers & Fluids, vol. 112, pp. 1–15, 2015.

[30] H. Chanson, Advances in Hydraulics and Water Engineering. Singapore: Springer, 2021.

[31] H. Chanson, "Air–water flow measurements with intrusive phase-detection probes," Journal of Hydraulic Engineering, vol. 138, no. 4, pp. 343–349, 2012.

[32] A. Bayon, R. Maza, and V. López-Jiménez, "Numerical modeling of aeration in hydraulic jumps," Water, vol. 12, no. 1, pp. 1–20, 2020.

[33] F. Felder and H. Chanson, "Air–water flow properties in stepped spillways," Environmental Fluid Mechanics, vol. 14, no. 6, pp. 1273–1293, 2014.

[34] R. M. Khan and P. Steffler, "Model–prototype scale effects in hydraulic jumps," Canadian Journal of Civil Engineering, vol. 15, no. 6, pp. 1037–1046, 1988.

[35] L. Hager, Energy Dissipators and Hydraulic Jump. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1992.

[36] H. Chanson, The Hydraulics of Open Channel Flow. Oxford, U.K.: Elsevier, 2004.

[37] IPCC, Climate Change 2021: The Physical Science Basis. Geneva, Switzerland: Cambridge Univ. Press, 2021.

[38] A. Schleiss and M. Franca, "Impact of climate change on hydraulic structures," Hydropower & Dams, vol. 24, no. 3, pp. 52–60, 2017.

[39] A. G. S. Barrera and J. P. Matos, "Adaptive design of spillways under climate uncertainty," Water Resources Management, vol. 33, no. 12, pp. 4015–4030, 2019.

[40] A. Rossi, P. Gaudio, and F. Marra, "Sustainable hydraulic structures: Eco-friendly design and energy recovery," Renewable Energy, vol. 152, pp. 1230–1241, 2020.

[41] H. Chanson, Hydraulic Jumps: Turbulence, Air Entrainment and Energy Dissipation. London, U.K.: CRC Press, 2015.

[42] A. Bayon, R. Maza, and V. López-Jiménez, "Numerical modeling of hydraulic jumps using CFD tools," Water, vol. 12, no. 1, pp. 1–20, 2020.

[43] P. H. Sellin, H. Chanson, and J. Scruton, "Physical modeling and CFD coupling in hydraulic structures," Journal of Hydraulic Research, vol. 49, no. 6, pp. 673–685, 2011.

[44] R. M. Khan and P. M. Steffler, "Model–prototype scale effects in hydraulic jumps," Canadian Journal of Civil Engineering, vol. 15, no. 6, pp. 1037–1046, 1988.

[45] J. J. Monaghan, "Smoothed particle hydrodynamics," Reports on Progress in Physics, vol. 68, no. 8, pp. 1703–1759, 2005.

[46] IPCC, Climate Change 2021: The Physical Science Basis. Geneva, Switzerland: Cambridge Univ. Press, 2021.

[47] A. Rossi, P. Gaudio, and F. Marra, "Sustainable hydraulic structures: Eco-friendly design and energy recovery," Renewable Energy, vol. 152, pp. 1230–1241, 2020.

[48] A. Schleiss and M. Franca, "Impact of climate change on hydraulic structures," Hydropower & Dams, vol. 24, no. 3, pp. 52–60, 2017.

[49] A. G. S. Barrera and J. P. Matos, "Adaptive design of spillways under climate uncertainty," Water Resources Management, vol. 33, no. 12, pp. 4015–4030, 2019.

[50] G. Oger, D. Le Touzé, and M. Doring, "Hybrid Eulerian–Lagrangian methods for multiphase flows," Computers & Fluids, vol. 112, pp. 1–15, 2015.

[51] H. Chanson, Hydraulic Jumps: Turbulence, Air Entrainment and Energy

Dissipation. London, U.K.: CRC Press, 2015.

[52] A. Bayon, R. Maza, and V. López-Jiménez, "Numerical modeling of hydraulic jumps using CFD tools," Water, vol. 12, no. 1, pp. 1–20, 2020.

[53] P. H. Sellin, H. Chanson, and J. Scruton, "Physical modeling and CFD coupling in hydraulic structures," Journal of Hydraulic Research, vol. 49, no. 6, pp. 673–685, 2011.

[54] R. M. Khan and P. M. Steffler, "Model–prototype scale effects in hydraulic jumps," Canadian Journal of Civil Engineering, vol. 15, no. 6, pp. 1037–1046, 1988.

[55] J. J. Monaghan, "Smoothed particle hydrodynamics," Reports on Progress in Physics, vol. 68, no. 8, pp. 1703–1759, 2005.

[56] IPCC, Climate Change 2021: The Physical Science Basis. Geneva, Switzerland: Cambridge Univ. Press, 2021.

[57] A. Rossi, P. Gaudio, and F. Marra, "Sustainable hydraulic structures: Eco-friendly design and energy recovery," Renewable Energy, vol. 152, pp. 1230–1241, 2020.

[58] A. Schleiss and M. Franca, "Impact of climate change on hydraulic structures," Hydropower & Dams, vol. 24, no. 3, pp. 52–60, 2017.

[59] A. G. S. Barrera and J. P. Matos, "Adaptive design of spillways under climate uncertainty," Water Resources Management, vol. 33, no. 12, pp. 4015–4030, 2019.

[60] G. Oger, D. Le Touzé, and M. Doring, "Hybrid Eulerian–Lagrangian methods for multiphase flows," Computers & Fluids, vol. 112, pp. 1–15, 2015.