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Evaporation Dynamics From Flowing Water Surfaces

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Key Points:

- Combined effects of turbulence and atmospheric forcing on evaporation from flowing surfaces were investigated under controlled laboratory conditions
- Flow-induced turbulence enhances evaporation by a factor of 2–5 relative to placid water surfaces, while its effect may shift between enhancement and suppression depending on the subsurface temperature profile
- Hydrodynamic–atmospheric coupling controls evaporation by exposing warmer or cooler eddies to the evaporating interface

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Abstract In contrast to the wealth of information on evaporation dynamics from placid water surfaces such as lakes and reservoirs, estimating water evaporation from turbulent surfaces of streams remains a challenge. Evidence suggests considerable differences in evaporation rates from flowing water bodies relative to placid surfaces. Here, we experimentally investigate how flow characteristics (velocity and turbulence) and boundary conditions (wind and radiation) regulate evaporation from flowing water surfaces by using a controlled laboratory flume to isolate key hydrodynamic–atmospheric interactions relevant to streams and rivers. We used a closed flume (7.6 m length, 0.31 m width, and 0.5 m depth) imposing different boundary conditions over the test section of 1.5 m in length while other parts of the flume were covered to prevent evaporative losses. Our results demonstrate that the effect of turbulence on evaporation depends on the temperature profile of the water body and redistribution of radiative heat with turbulent mixing highlighting that evaporation emerges from a nonlinear coupling between hydrodynamic mixing and energy availability. Under solar radiation, increased water flow and turbulence can reduce evaporation by suppressing the formation of a warm surface layer and redistributing absorbed heat in depth of the water column. Without shortwave radiation flux, however, enhanced surface velocity and turbulent mixing may cause significant enhancement in evaporation rates up to 2–5 times that of placid water surfaces. Numerical simulations indicate that enhanced surface turbulence and wave activity increase interfacial roughness and shear, regulating the vapor boundary layer and producing spatially heterogeneous and intermittent vapor fluxes. The study offers novel insights into evaporation from wavy and turbulent flowing water surfaces for a better understanding of evaporation from riverine networks across flow regimes and climatic conditions.

1. Introduction

The global fluvial network spans over 80 million kilometers, covering on the order of 800,000 km² of the land surface (Allen & Pavelsky, 2018; Downing et al., 2012; Liu et al., 2022). Evaporation from these dynamic water surfaces influences physical, chemical, and biological processes of river ecosystems (Hebert et al., 2011; Leach et al., 2023; Szeitz & Moore, 2020). It particularly plays a critical role in water-stressed regions, where the efficient use and management of limited water resources are essential for sustaining agricultural, industrial, and ecological demands.

Evaporation from flowing water bodies is affected by numerous thermal and aerodynamic feedbacks (Assouline et al., 2008; Ouellet & Caissie, 2023). The thermal coupling arising from the temperature dependency of vapor concentration not only modifies near-surface air properties and vapor gradients across the viscous boundary layer but also acts to adjust the temperature of water flows influencing stream ecological functions (Lakehal et al., 2008). The onset of turbulence and mixing, coupled with variable radiative regimes of inland flows with distinct characteristics (e.g., depth, flow rate, shade, and topography) add to the complexity of quantifying evaporative losses from water streams. Laboratory experiments and anecdotal reports suggest that surface undulations may enhance evaporative losses by a factor of 2–4, depending on waviness and overlying air flow characteristics (Aldarabseh, 2020; Jodat et al., 2013); in addition, recent numerical simulation studies further demonstrate that water mixing under windless conditions can enhance evaporation rates by more than 2.5 times (Dong et al., 2025).

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While numerous studies on evaporation from wavy surfaces of oceans offer valuable insights, differences in hydrodynamics conditions and heat exchange processes in flowing streams are expected to distinguish evaporation relative to oceans. Evaporation from streams is further complicated by mixing induced energy and momentum transfer within a (shallow) water body that interacts with various radiation regimes (shady sections) and aerodynamic conditions over the surface. Theoretical and experimental studies for quantifying temperature dynamics in flowing water bodies often invoke energy balance closure and flow properties (Buahin et al., 2019; Dugdale et al., 2017; Garner et al., 2014; Gendaszek et al., 2020). Nevertheless, the estimation of evaporation rates and associated heat losses from flowing water surfaces remains largely empirical and dependent on locally calibrated heat and mass transfer models that lack predictability to varying fluvial or climatic conditions (Szeitz & Moore, 2020; Webb & Zhang, 1997).

Current methods for estimating evaporation often rely on eddy covariance (EC) systems for direct flux measurements or on observations of water level changes in floating evaporation pans as a proxy for evaporative flux from flowing water bodies. While EC systems are often constrained by limited fetch (particularly in narrow streams), floating pans remain energetically and hydrodynamically decoupled from turbulent flows (Maheu et al., 2014; Szeitz & Moore, 2020). These measurements are routinely employed to parameterize and calibrate Dalton-type bulk transfer equations (Szeitz & Moore, 2020). However, the underlying mechanisms by which hydrodynamic flow conditions interact with atmospheric boundary layer dynamics to influence evaporation remain inadequately understood, posing a significant challenge for accurate process-based modeling of evaporation in riverine environments.

This study aims to systematically investigate evaporation dynamics from flowing water surfaces. By combining experimental data obtained under well-controlled laboratory conditions with numerical modeling that resolves details of the complex vapor and energy exchanges between flowing water body and overlying air (particularly in turbulent streams), we address a critical gap in our understanding of evaporation from non-placid water surfaces. Specifically, we seek to isolate and quantify the effects of key hydrodynamic and atmospheric factors, examine their interactions and combined impacts on evaporation rates, and develop improved mechanistic insights and parameterizations for integration into hydrological, ecological, and climate models.

2. Methods

2.1. Laboratory Flume Experiments

The experiments were conducted in a laboratory flume with 7.6 m length, 0.31 m width, and 0.5 m depth (Figure 1). Water was circulated in a closed system while a 1.5 m-long test section in the middle of the flume was left open to allow evaporation and the application of controlled boundary conditions. The upstream and downstream sections were covered to minimize unintended evaporative losses.

The system includes two sealed storage tanks (each 1 m³ in volume) that serve as reservoirs for the circulating water. A siphon tube connects the storage tank to an external graduated glass cylinder, enabling accurate monitoring of its water level changes due to evaporative losses from the test section of the flume. Hence, change in water level in the gauge cylinder (marking water level changes in the storage tanks) can be directly translated into evaporation loss from the test section. This setup enabled stable flow conditions while allowing precise quantification of evaporation under controlled experimental scenarios.

The flume was equipped with an integrated measurement and control system. Water flow was regulated via a computer-controlled frequency converter operating within a closed-loop feedback system, ensuring stable and adjustable flow conditions. Transparent glass sidewalls enabled direct visual observation of flow dynamics and surface wave behavior (Figure 1).

To mimic radiative energy input, 20 evenly spaced Osram halogen lamps were mounted above the test section, delivering a uniform and adjustable radiation flux of 0–300 W/m² at the water surface. The irradiance was monitored at the surface using a calibrated pyranometer (ML-02, EKO Instruments, non-stability change: ±2% per year, directional response <10 W/m², Japan). The halogen spectrum closely resembles that of sunlight, peaking at approximately 0.9 μm at a temperature of 3000 K.

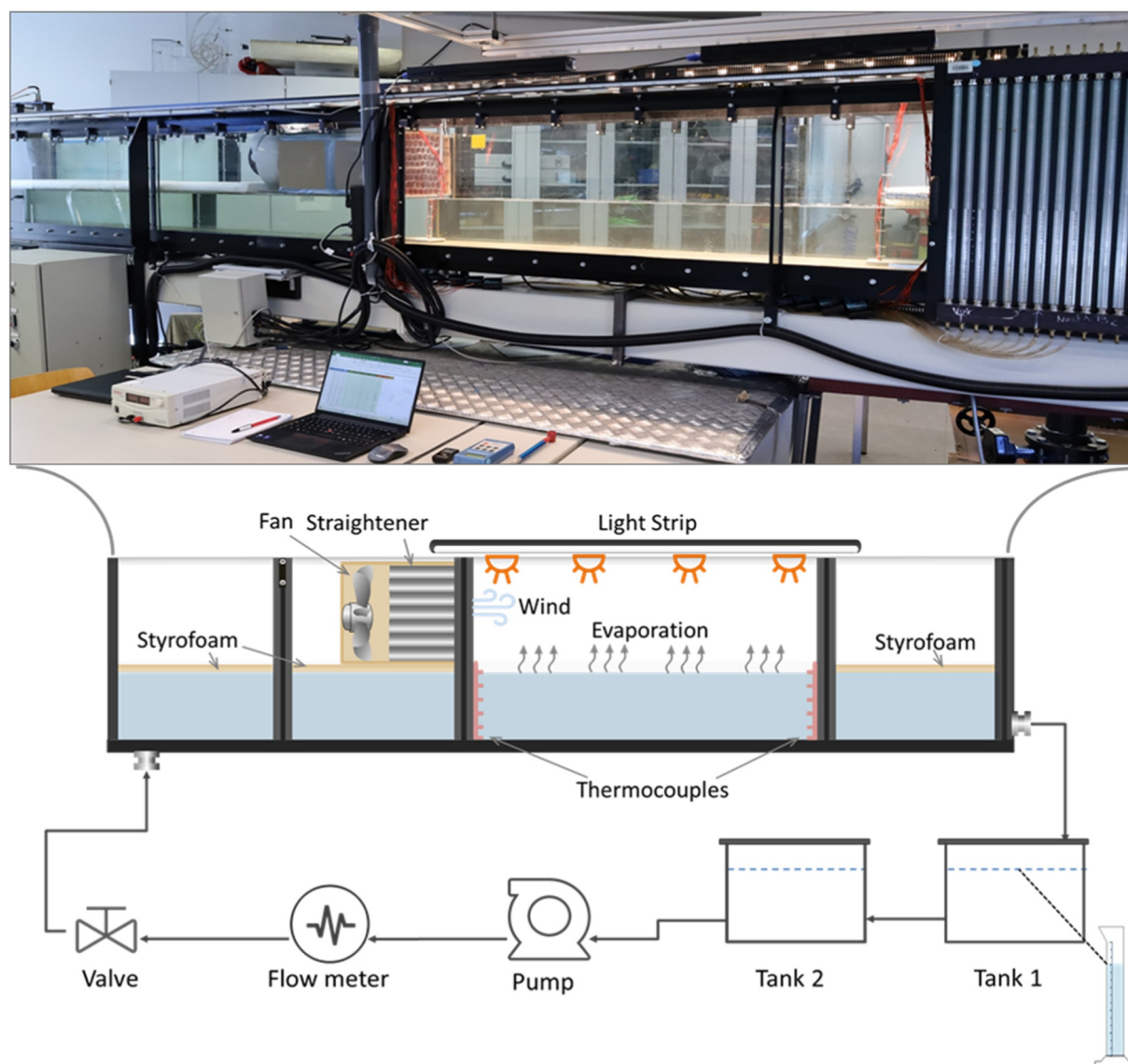


Figure 1. Schematic of the laboratory flume experiment system. The system features a closed-loop adjustable flow circuit that allows precise control of water velocity throughout the flume. A 1.5-m-long exposed test section is equipped with a modular wind supply and radiation unit to simulate controlled surface forcing. Real-time vertical temperature profiles are monitored using multiple thermocouples positioned at various depths below the water surface, enabling detailed analysis of heat transfer dynamics under different flow and atmospheric conditions.

A wind supply module, comprising a fan and flow straightener, generated a horizontally uniform overlying airflow in the test section with adjustable wind speeds ranging from 0 to 2 m/s. Wind velocity was measured using a hot-wire anemometer (Testo 425, accuracy: 0.03 m/s + 4.0% of reading, Germany).

Ambient laboratory air temperature and relative humidity were monitored near the flume (Testo 174H, accuracy: $\pm 0.5^{\circ}\text{C}$ and $\pm 3\%$ RH, Germany). Vertical water temperature profiles are obtained via an array of five precision thermocouples (Scantronik NTC, $\pm 0.4^{\circ}\text{C}$ accuracy, Germany) placed at depths of $z_S = 0$ cm, $z_{D1} = 1$ cm, $z_{D2} = 3$ cm, $z_{D3} = 10$ cm, and $z_B = 20$ cm below the water surface. Identical thermocouple arrays were located at both the upstream and downstream ends of the test section to capture vertical thermal gradients and their spatial variability.

During the flume experiments, we adjusted indoor temperature and relative humidity to control the ambient conditions. Although the conditions were relatively stable during each experiment, noticeable fluctuations still

Table 1
Experiment Conditions

Test No.	Water flow condition			Wind speed At the water surface [m/s]	Solar radiation At the water surface [W/m ²]	Water temperature	
	Water depth [m]	Flow rate [m ³ /h]	Water velocity [m/s]			Initial water temperature [°C]	Flume water temperature (time-averaged) [°C]
1	0.2	10.4	0.04	0	0	21.4	21.6
2	0.2	45.0	0.20	0	0	22.6	23.0
3	0.2	91.5	0.40	0	0	22.1	24.1
4	0.2	45.8	0.20	1.3	0	20.5	21.9
5	0.2	46.0	0.20	2.0	0	20.7	21.3
6	0.2	45.0	0.20	0	100	21.6	22.7
7	0.2	45.0	0.20	0	300	21.6	22.8
8	0.2	9.5	0.04	2.0	300	20.9	21.7
9	0.2	45.7	0.20	2.0	300	21.2	21.9
10	0.2	94.5	0.40	2.0	300	23.8	27.3

Note. Experimental test matrix detailing the controlled hydraulic conditions, wind forcing, and solar radiation levels. The experimental design allows isolation of individual and interactive effects of water flow velocity, wind, and radiative heating on evaporation from the flume water surface.

occurred. These variations were taken into account when calculating the evaporation rates. Relevant ambient data are provided in Appendix A.

Additional atmospheric boundary conditions (wind and solar radiation) were imposed in the test section. Controlled evaporation experiments were conducted to examine the effects of water flow, wind, and solar radiation on evaporation, both individually and in combination. Tests included variations in water flow velocity without atmospheric inputs, changes in wind speed and radiation under fixed water flow conditions, and coupled scenarios with all three factors. Specific combinations of water flow velocity, wind speed, and radiation intensity are summarized in Table 1, which outlines the full set of experimental conditions used to isolate and evaluate the influence of each variable and their interactions on evaporation dynamics.

2.2. Numerical Modeling

Numerical simulations were conducted to provide a mechanistic understanding of vapor transport from flowing water surfaces into the overlying air under varying hydrodynamic and ambient conditions. All simulations were performed in two dimensions (2D), using a domain matching the 1.5 m test-section length and 0.2 m water depth of the laboratory flume, with an air-column height of 0.2 m above the mean free surface. The 2D framework captures the streamwise–vertical structure of wave–air coupling and vapor boundary-layer dynamics, which are the primary phenomena of interest here. The numerical simulation cases and their main parameters are summarized in Table 2.

2.2.1. Governing Equations

A compressible, low Mach number, single fluid formulation for two-phase flow is employed, with the phase interface captured using the Volume of Fluid (VOF) method (Brackbill et al., 1992; Hirt & Nichols, 1981). The

Table 2
Summary of Numerical Simulation Scenarios, Flow Conditions, and Reynolds Numbers Considered in the Analysis of Evaporation Mechanisms Under Varying Flow and Wind-Forcing Regimes

Case	Experiment equivalent	Flow conditions	Re	Purpose
C1	Test 1 ($u = 0.04$ m/s, no wind)	0.04 m/s, small ripples ($H = 0.0025$ m)	$\approx 3,700$	Low-Re baseline
C2	Test 3 ($u = 0.40$ m/s, no wind)	0.40 m/s, developed waves ($H = 0.005$ m)	$\approx 35,000$	High-Re, no wind
C3	Test 10 ($u = 0.40$ m/s, 1 m/s tailwind)	0.40 m/s, imposed tailwind, wind-deformed waves	$\approx 35,000$	High-Re, wind forcing

formulation is coupled with transport of water vapor in the gas phase and an enthalpy-based energy equation. Turbulence is modeled using the k - ω SST closure (Menter, 1994). The continuity and momentum equations are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0, \quad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot [\mu_{\text{eff}}(\nabla u + \nabla u^T)] + \rho g + f, \quad (2)$$

where $\mu_{\text{eff}} = \mu + \mu_t$ and f represents surface tension via the CSF method (Brackbill et al., 1992). The energy equation is:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho u h) = \nabla \cdot (k_{\text{eff}} \nabla T) + S_e, \quad (3)$$

with $k_{\text{eff}} = k + \mu_t c_p / Pr_t$. The vapor mass fraction Y_v in the gas satisfies

$$\frac{\partial(\rho Y_v)}{\partial t} + \nabla \cdot (\rho u Y_v) = \nabla \cdot (\rho D_{\text{eff}} \nabla Y_v) + S_m, \quad (4)$$

where $D_{\text{eff}} = D_v + \mu_t / (\rho Sc_t)$.

2.2.2. Interface-Resolved Evaporation Model

A custom evaporation model was implemented via User Defined Functions (UDF) to compute interfacial mass and heat fluxes using a two-resistance framework (Bird et al., 2002; Spalding, 1953):

$$m'' = \rho_g k_{\text{ov}} \ln \left(\frac{1 - Y_{v,\infty}}{1 - Y_{v,i}} \right), \quad \frac{1}{k_{\text{ov}}} = \frac{1}{k_g} + \frac{1}{k_l}, \quad q'' = m'' h_{fg}(T_i), \quad (5)$$

where m'' is the interfacial mass flux, k_g and k_l are the gas and liquid-side mass-transfer coefficients, $Y_{v,i}$ is the saturation mass fraction at the interface, $Y_{v,\infty}$ is the vapor mass fraction in the gas cell adjacent to the interface, and the logarithmic driving force accounts for Stefan flow. The enthalpy of evaporation, h_{fg} , follows the Watson correlation (Poling et al., 2001; Watson, 1943).

The interface is assumed to be at local thermodynamic equilibrium:

$$x_{v,i} = \frac{p_{\text{sat}}(T_i)}{p}, \quad Y_{v,i} = \frac{x_{v,i} M_v}{x_{v,i} M_v + (1 - x_{v,i}) M_a}, \quad (6)$$

where M_v and M_a are molecular weights of water vapor and dry air, respectively, p is the local absolute pressure, and p_{sat} is given by a Magnus-Tetens type correlation valid for 0–50°C (Alduchov & Eskridge, 1996; Sonntag, 1990).

The gas side coefficient k_g uses flat plate Sherwood correlations (Incropera & DeWitt, 2002) with an effective velocity incorporating relative wind and wave motion and wave celerity. A roughness enhancement factor accounts for wave induced transfer augmentation. The liquid side coefficient k_l is the maximum of four mechanisms: molecular diffusion, turbulent surface renewal via the Lamont–Scott closure (Lamont & Scott, 1970), wave induced renewal based on penetration theory (Higbie, 1935), and strain rate surface renewal. The transport limited flux is bounded by the Hertz–Knudsen–Schrage kinetic limit (Marek & Straub, 2001; Schrage, 1953).

Interfacial area density is computed from the VOF field as $a_i = 4\alpha_i(1 - \alpha_i)/L_c$ (Ishii & Hibiki, 2006), where L_c is a characteristic cell length. Volumetric source terms are $S_m = m'' a_i$ and $S_e = -m'' h_{fg} a_i$.

2.2.3. Wave Boundary Conditions

Surface waves are imposed using the Open Channel Wave boundary condition with third-order Stokes wave theory (Fenton, 1985; Dean & Dalrymple, 1991). This nonlinear formulation captures amplitude-dependent dispersion and asymmetric wave profiles (sharper crests, flatter troughs) that affect interfacial geometry and the relative motion between air and water. Third-order theory is appropriate for the intermediate depth conditions considered, where the Ursell number $U_r = H\lambda^2/d^3$ indicates significant nonlinearity (Hedges, 1995; Svendsen, 2006). The domain was initialized from rest with a flat interface at the prescribed free-surface level, after which the waveform, bulk flow velocity, and corresponding hydrostatic pressure profile were applied at the inlet velocity boundary, with phase volume fractions and wave-orbital velocity components updated at each time step consistent with the prescribed wave theory. For Case C3, a uniform streamwise air velocity was additionally imposed in the gas-phase region at the inlet. At the outlet, volume fractions are extrapolated from the interior, preventing spurious drainage or accumulation of either phase at the domain exit. Wave parameters (height, wavelength, free surface level) are specified consistently at inlet and outlet to ensure proper propagation.

2.2.4. Solution Methodology

All simulations were performed in ANSYS Fluent 2025 R1, double precision, parallel. Temporal discretization employed a bounded second order implicit scheme with adaptive time stepping (global Courant number 0.25). Pressure velocity coupling used the coupled scheme. Spatial discretization included second order upwind for momentum, energy, and species; a compressive scheme for VOF; and PRESTO! for pressure. The $k-\omega$ SST model used correlation based near wall treatment. Gas was modeled as an ideal mixture of H_2O , O_2 , and N_2 ; liquid water properties were $\rho_\ell = 998.2 \text{ kg/m}^3$ and $\nu_\ell = 10^{-6} \text{ m}^2/\text{s}$. Turbulent Schmidt and Prandtl numbers were $Sc_t = 0.7$ and $Pr_t = 0.85$ (Kays et al., 2005).

The computational mesh consisted of approximately 1.2 million fully structured quadrilateral cells. Adaptive interface refinement was applied dynamically as part of the VOF solver, concentrating resolution at the free surface where interfacial mass and momentum exchange are computed. Each simulation was advanced in time until a quasi-periodic stationary state was reached, characterized by wave-driven interfacial dynamics that became repeating and statistically consistent across successive wave cycles, with no secular drift in the time-averaged interfacial mass flux. Flow fields and vapor concentration contours presented in the results correspond to representative instants within this stationary regime, captured at approximately 3 s of simulated physical time. All simulations were performed in parallel on 16 cores of an AMD Ryzen Threadripper PRO 5995WX workstation; each case required approximately 12 hr of wall-clock time.

3. Results and Discussion

3.1. Uncertainty of Measurements

Measurement uncertainty was evaluated from three replicate experiments for each test condition. The uncertainties under four environmental scenarios (no external forcing, wind-only, solar radiation-only, and combined wind-solar radiation conditions) at three flow velocities are presented in the results (details are provided in Appendix B). The maximum uncertainty was approximately 0.877 mm/d, occurring under the combined wind-solar radiation condition at $u = 0.04 \text{ m/s}$, while the mean uncertainty ranged from ± 0.081 to $\pm 0.644 \text{ mm/d}$. These uncertainties primarily arose from unavoidable environmental fluctuations and the finite precision of the measurement instruments.

3.2. Effect of Water Flow Velocity on Evaporation Rates

The experimental results in Figure 2 show the influence of water flow velocity (in the absence of wind and radiation boundary conditions) on evaporation rates. To isolate the influence of water flow characteristics and account for the impact of environmental variability on the measured evaporation results, a correction was applied to the evaporation rate data in Figure 2a. The correction was based on the nonlinear relationship between saturated vapor pressure and temperature, described by the Clausius–Clapeyron equation (Clapeyron, 1834; see Appendix C for details). As seen, there is a strong nonlinear relationship between flow velocity and evaporation rate with an increase in water velocity from 0.04 to 0.4 m/s (Figure 2a), corresponding to Reynolds numbers ranging from 3,700 to 35,000. The Reynolds number was calculated as:

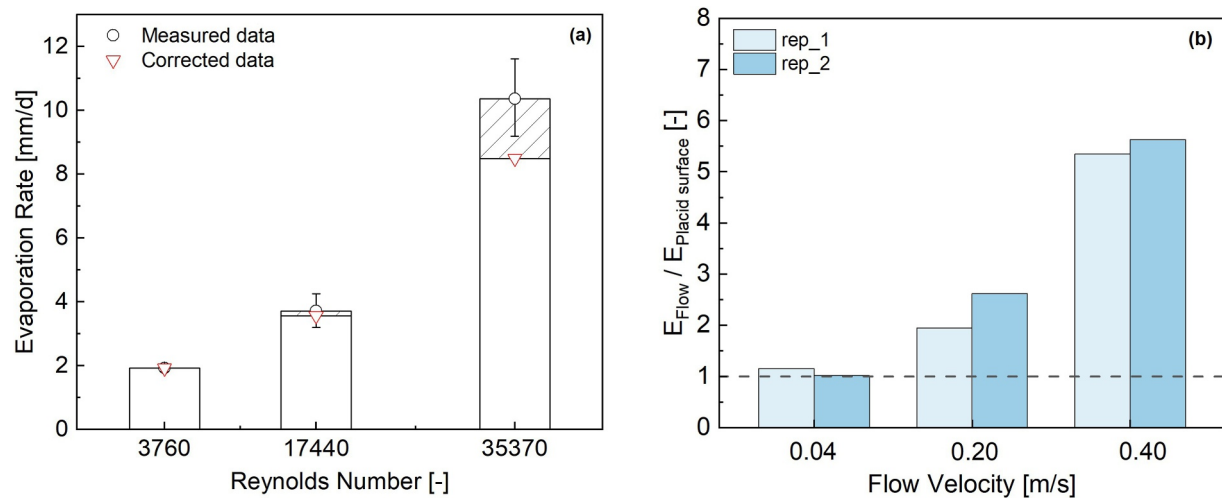


Figure 2. Evaporation rates under various water flow velocities. (a) Variation of evaporation rate with flow velocity under fixed water depth and constant atmospheric conditions, including corrections for temperature and humidity effects on evaporation rate. The triangles (red) denote the corrected values after accounting for variations in temperature and relative humidity. Measured values are shown as circles with error bars (indicate the standard deviation of replicate measurements). The shaded region between the two symbols quantifies the contribution of environmental variability to the observed evaporation rates relative to the base condition with $Re = 3760$. (b) Comparison between evaporation from flowing and placid water surfaces conducted under identical water depth and atmospheric conditions. The vertical axis represents the ratio of the evaporation rate from the flowing surface to that from the placid surface, highlighting the enhancement effect induced by water movement.

$$Re = \frac{uR_h}{\nu_w}, \quad (7)$$

where u is the mean water flow velocity (m/s), R_h is the characteristic length scale, which for open-channel flow was represented by the hydraulic radius (m), and ν_w is the kinematic viscosity of water (m^2/s).

With the increase of flow velocity from 0.04 m/s ($Re \approx 3,700$) to 0.2 m/s ($Re \approx 17,000$), the evaporation rate increased from 1.93 to 3.57 mm/d, representing 85% higher evaporative losses. Further increasing the flow velocity to 0.4 m/s ($Re \approx 35,000$) resulted in a sharp increase in evaporation rate to 8.49 mm/d, a 138% increase relative to the previous step. These results indicate that even moderate increases in flow velocity can lead to disproportionately large increases in evaporation.

Control experiments with placid (non-flowing) water surfaces in a glass column (H: 20 cm–D: 8 cm) under identical environmental conditions confirmed that the presence of flow significantly enhances evaporation. In Figure 2b, evaporation rates at three different water flow velocities are compared to placid water surface reference tests under the same ambient conditions (each repeated twice). The vertical axis shows the ratio of the evaporation from the flowing water to that over the placid surface. The measured evaporation rates for moving water surfaces were found to be 2–5 times higher than those for placid water, depending on flow velocity. This observation aligns with previous studies highlighting the strong coupling between water motion and interfacial heat and mass transfer processes. Turbulent water flow enhances evaporation by continuously disrupting the saturated boundary layer at the water–air interface (Bohren & Albrecht, 2023). Unlike placid water, surface movement over flowing water bodies relative to the stagnant overlying air results in a thinner boundary layer that resembles mass transfer in forced convective streams. The increase in moisture gradient across the air boundary layer significantly enhances vapor transfer at the surface of water flows compared to placid water surfaces (Chuck & Sparrow, 1987; Jodat et al., 2013; Ren et al., 2024). The nonlinear increase in evaporation rate with flow velocity observed in Figure 2a can be partly attributed to the inherent nonlinear relationship between boundary layer thickness and flow velocity (Haghighi & Or, 2013). In addition to altering surface boundary conditions, turbulent flow further enhances vapor transfer at the surface through increased mixing. Karmakar and Acharya (2022) numerically simulated the evaporation process of flowing liquid films and indicated that turbulence led to a local enhancement in evaporation rates of up to 196%.

Turbulence-induced mixing in flowing water bodies plays a crucial role in enhancing heat transfer processes (Aminzadeh et al., 2018; Henderson-Sellers, 1985; Lehmann et al., 2019; Vercauteren et al., 2011). While in placid or weakly mixed water bodies, the lack of vertical heat exchange allows the surface to cool more rapidly due to evaporative latent heat cooling, often forming a pronounced temperature gradient near the interface, turbulent conditions promote the upward transport of warmer water from deeper layers to the surface, which helps to retain surface heat (in the absence of solar irradiance) and supports sustained evaporation. Previous studies on turbulent eddy thermal diffusivity in flowing water have shown that it correlates directly with the turbulent time scale and velocity fluctuations (Eidelman et al., 2013). As the turbulent mixing increases, the vertical velocity variance increases significantly, leading to an enhanced thermal diffusivity.

In addition to improving vertical heat transfer, intermittent eddies also accelerate surface renewal, reducing the residence time of fluid parcels near the interface thereby improving vapor transport efficiency across the air-water interface (Banerjee, 2007; Komori et al., 2010; Law & Khoo, 2002). The surface renewal model links transfer velocity to surface renewal frequency (Lamont & Scott, 1970; Satoru et al., 1982), where increased renewal frequency continuously disrupts the interface and thus facilitates evaporation (Haghighi & Or, 2015; Herlina & Jirka, 2008). The increase in turbulent kinetic energy (TKE) accelerates eddy breakdown, resulting in more frequent renewal of the phase interface (as evidenced by the rise in high-frequency temperature fluctuations) (Jahani et al., 2024). Increased TKE enhances turbulent mixing near the air-water interface, which continuously renews the vapor concentration and temperature fields in the near-surface region and reduces the air-side diffusion resistance. As a result, water vapor is transported more rapidly from the water surface into the air leading to an enhanced evaporation rate.

3.3. Effects of Variable Atmospheric Conditions and Coupled Hydrodynamic Flow on Evaporation Dynamics

Under controlled flow conditions, both wind speed and solar radiation were found to significantly influence evaporation rates from the water surface. Figures 3a and 3b depict the individual and combined effects of wind speed and radiation intensity on evaporation.

It is well established that wind velocity significantly enhances evaporation (Nevermann et al., 2024). The prevailing wind over a water surface continuously removes saturated air, thereby maintaining a vapor pressure gradient between the water surface and the overlying atmosphere (Ojha et al., 2013; Penman, 1956; Shnitnikov, 1974; Wirangga et al., 2023). As wind speed increases, the evaporation rate shows a clear increasing trend. According to our experimental findings, under a fixed water flow velocity of 0.2 m/s, increasing wind speed from 0 to 2 m/s increases the evaporation rate from 3.57 to 6.54 mm/d, representing an increase of 83%. This is primarily attributed to the enhanced vapor pressure gradients between the surface and overlying air, coupled with a reduction in the thickness of the air boundary layer (Haghighi & Or, 2015; Ojha et al., 2013). Laboratory experiments by Assouline and Narkis (2021) demonstrated that reducing wind speed above the free water surface led to a 40%–60% decrease in evaporation, providing strong evidence that wind plays a critical role in changing evaporation rates. This effect becomes especially pronounced when airflow interacts with the rough surface of turbulent water flows in the presence of ripples and surface waves, further enhancing vapor removal.

Additionally, evaporation rates increase with increasing solar radiation, reflecting the critical role of radiative energy input (Raupach, 2001; Rodrigues et al., 2020; Yihdego & Webb, 2018). We observed that the evaporation rate increased from 3.57 mm/d (no shortwave radiation) to 3.65 mm/d (100 W/m²) and 4.51 mm/d (300 W/m²), indicating more than 26% increase across the full radiation range tested. The increase in radiation raises the water surface temperature that enhances the surface vapor pressure and increases the evaporation potential (Raupach, 2001). This result is supported by independent observational and experimental studies (e.g., eddy covariance and stable isotope-based methods), which have consistently demonstrated a positive sensitivity of evaporation to variations in incoming shortwave radiation (Heck et al., 2020; Jansen et al., 2022; Roderick et al., 2009; Vystavna et al., 2021). Research on lake systems has shown that evaporation is highly sensitive to variations in radiative flux, especially in warmer climates (Cui et al., 2021; Hu et al., 2017). However, note that the response of evaporation to increasing shortwave radiation under flowing-water conditions differ from that typically expected for placid water surfaces. In the present experiments, evaporation did not increase substantially during the initial increase in radiation intensity, whereas a pronounced enhancement occurred only after the

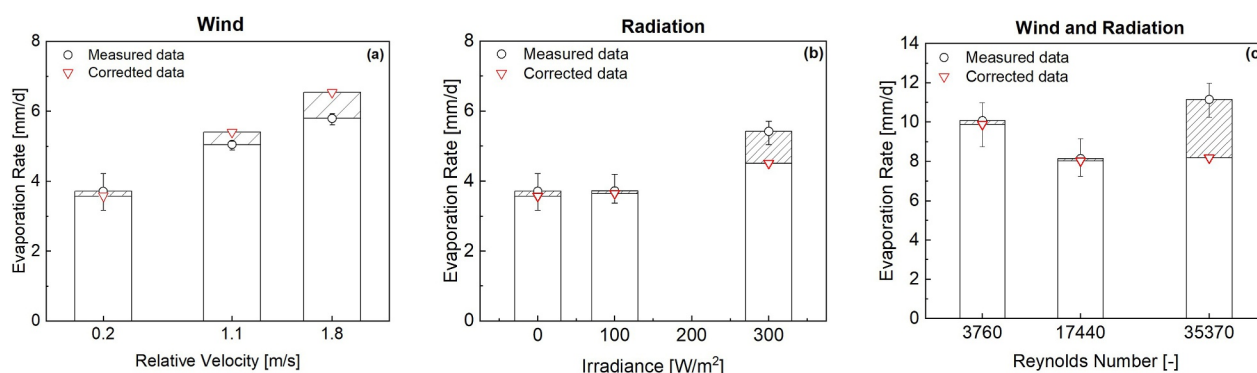


Figure 3. Evaporation enhancement under various atmospheric and hydrodynamic conditions. The results demonstrate the distinct effects of wind-induced turbulence, radiative energy input, and advective flow on surface evaporation dynamics. (a) Influence of wind speed (0–2 m/s) on evaporation rate under constant water flow velocity (0.2 m/s). (b) Influence of incoming shortwave radiation (0–300 W/m²) on evaporation rate with fixed water flow velocity (0.2 m/s). (c) Influence of water flow velocity (0.04–0.4 m/s) on evaporation rate under fixed wind speed (2 m/s) and radiation (300 W/m²). Circles with error bars represent measured values; red triangles and shaded areas indicate corrected values and the contribution of environmental variability, respectively.

radiative forcing exceeded a certain threshold. This behavior suggests that flow-induced mixing and internal heat redistribution influence the contribution of radiative energy in driving evaporation.

The influence of water flow velocity on evaporation rates was further investigated under constant atmospheric boundary conditions (fixed wind speed and solar radiation). The experimental results revealed a non-monotonic response where evaporation rates initially decreased slightly at low water flow velocities before increasing at higher velocities (Figure 3c). Our findings, consistent with earlier studies (Carlier & Papalexandris, 2024; Rezazadeh et al., 2020), suggest that evaporation does not necessarily increase continuously with intensified water surface flows; it may even be lower than the evaporation rate measured over a calm water surface under comparable atmospheric conditions (Easterbrook, 1969; Schluskel et al., 1990). Similar phenomena have been reported in Rezazadeh et al. (2020), investigating evaporation from water reservoirs in the presence of surface flows. They observed that increasing the water surface velocity initially reduces the evaporation rate up to a certain flow rate, after which the evaporation rate gradually increases.

Without surface flows and associated mixing, absorption of longwave radiation at the surface and gradual decay of shortwave radiation with depth of the water body lead to strong thermal stratification, with warm water accumulating at the surface and cooler water remaining below. This stratification hampers vertical mixing, allowing surface temperatures to rise and sustain a high vapor pressure gradient that promotes evaporation (Fernandez et al., 2012; Fischer, 1979; Imberger & Patterson, 1989). With increasing flow velocity, vertical mixing disrupts this stratification and brings cooler water from below to the surface. This, in turn, lowers the surface temperature and consequently decreases the evaporation rate (Helfer et al., 2011, 2018; Rachid et al., 2022; Rezazadeh et al., 2025). The gradual increase in evaporation rate with increasing water flow velocity to 0.4 m/s, as observed in the experimental results, was traced back to heat input from the circulation pump. This artificial effect was corrected by accounting for the influence of increased water temperature on the saturated vapor pressure at the surface, ensuring that the measured evaporation enhancement reflects only the hydrodynamic effects of flow.

Due to the presence of tailwind over the test section of the flume (direction of the flow), increasing the water flow velocity to 0.4 m/s further reduces the relative velocity between the water surface and the overlying air mass. This primarily leads to a decrease in the vapor pressure gradient, which would typically reduce evaporation. However, the stronger turbulence associated with higher water flow velocity enhances exchange processes at the air–water interface, partially compensating for the reduced vapor pressure gradient. As a result, the corrected evaporation rate remains nearly unchanged despite the increase in water flow velocity from 0.2 to 0.4 m/s.

Our results suggest that under constant radiative forcing, the evaporation response reflects a competition between two opposing effects: (a) vertical mixing of warm surface with cold layers beneath reduces surface temperature and thus vapor pressure gradient at the surface, and (b) turbulence-enhanced interfacial exchange, which tends to increase evaporation by facilitating heat and vapor transport across the air–water interface. At sufficiently high

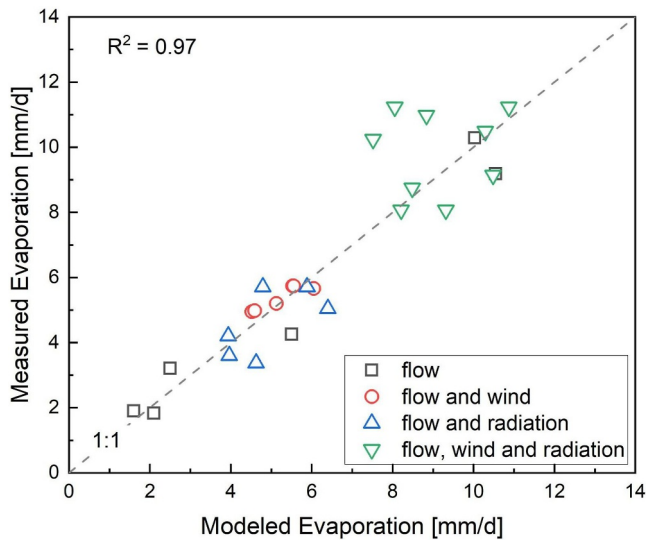


Figure 4. A comparison of evaporation rates from laboratory measurements with energy balance modeling results (see Appendix D).

water flow velocities, the latter effect can partially or fully offset the former, leading to increases in evaporation despite the continued redistribution of absorbed energy within the water body due to the mixing. This interplay provides a mechanistic explanation for the contrasting evaporation–flow velocity relationships observed under radiative and non-radiative conditions.

These results indicate that, for flowing water bodies, evaporation is governed not only by the efficiency of turbulent transport but also by the competing effects of near-surface energy accumulation and turbulent heat redistribution.

Additionally, the simplified energy balance established for the experimental system shows that, under different flow velocity conditions, the total energy input to the system and individual heat flux components are generally balanced (see Figure 4). This closure indicates that the measured evaporation flux is physically reasonable, and suggests that the dominant energy fluxes are largely accounted for within the experimental uncertainty. Detailed descriptions of the components contributing to the system's energy closure are provided in Appendix D.

3.4. Mechanistic Analysis of Evaporation Under Combined Atmospheric and Hydrodynamic Conditions

To investigate the mechanisms by which water flow velocity and wind influence surface evaporation, numerical simulations were conducted for three representative cases spanning Reynolds numbers from approximately 3.8×10^3 to 3.5×10^4 . These cases included low- and high-flow conditions, as well as a wind-forcing scenario with a 1.0 m/s tailwind. The computational domain was identical to the experimental test section (1.5×0.31 m).

Under low water velocity and no-wind conditions with fine surface ripples, a relatively thick and stable vapor boundary layer forms above the water surface (see Figure 5a). Within this (stable) layer, weak vapor

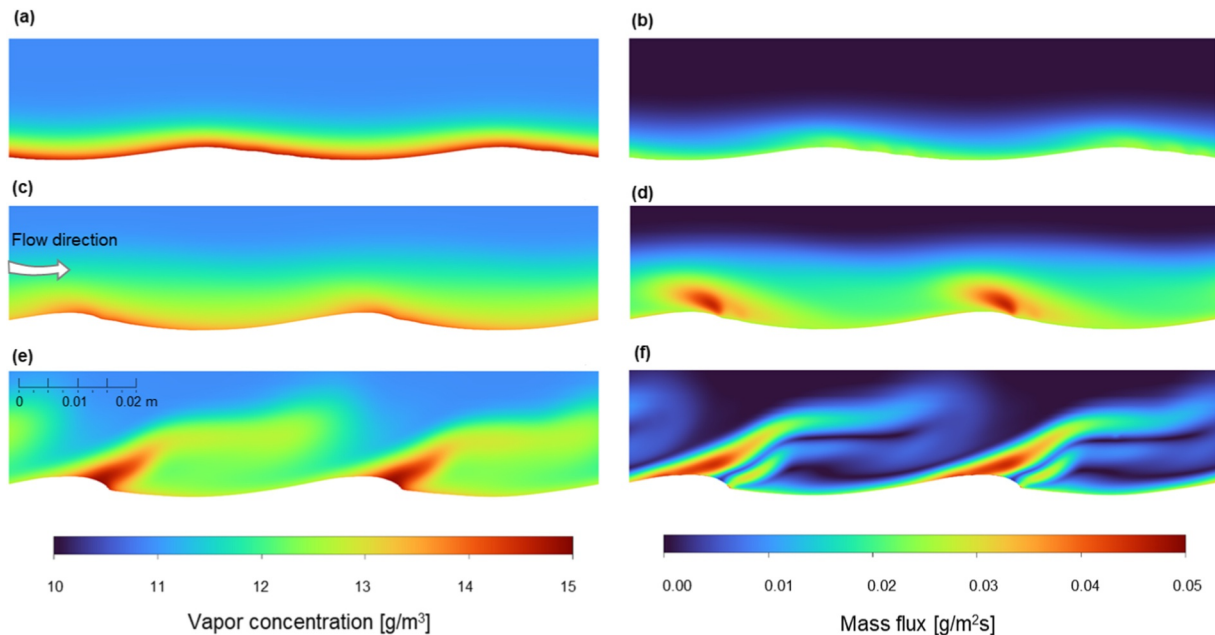


Figure 5. Numerical simulation contour maps of vapor concentration and mass flux. The results demonstrate the distinct effects of water-induced turbulence and wind on surface evaporation dynamics. In all panels, the flow direction is from left to right. The left column shows the vapor concentration fields, while the right column presents the corresponding evaporation mass flux. (a, b) Low-velocity, no wind condition ($u = 0.04$ m/s; wave height = 0.0025 m): (a) vapor concentration and (b) mass flux; (c, d) high-velocity, no wind condition ($u = 0.40$ m/s; wave height = 0.005 m): (c) vapor concentration and (d) mass flux; (e, f) high-velocity condition with wind forcing, identical to case (c, d) but with an imposed tailwind of 1 m/s. Color contours indicate vapor concentration and flux intensity, illustrating the effects of interfacial waves and air–water coupling on surface evaporation.

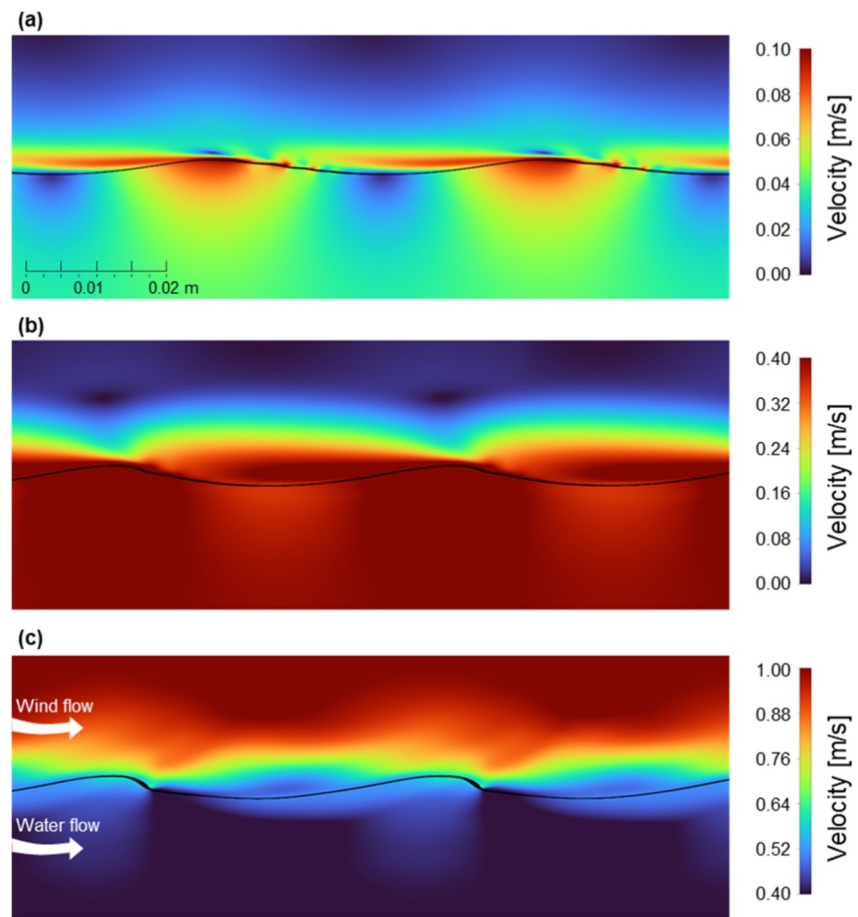


Figure 6. Numerical simulation contour maps of velocity. The results illustrate the velocity distribution under identical flow conditions, illustrating the development of the velocity field across the air–water interface and the momentum transfer. (a) Low-velocity, no wind condition ($u = 0.04$ m/s; wave height = 0.0025 m); (b) high-velocity, no wind condition ($u = 0.40$ m/s; wave height = 0.005 m); (c) high-velocity condition with wind forcing, identical to case (b) but with an imposed tailwind of 1 m/s. In all panels, the flow direction is from left to right. The black curves represent the shape and position of the air–water interface under the current flow conditions. Color contours represent the velocity magnitude, illustrating the influence of flow velocity, interfacial waves, and air–water coupling on the flow field.

concentration gradients near the air–water interface shapes where vapor transport to the overlying air mass is dominated by molecular diffusion resulting in weak interfacial mass fluxes (Figure 5b). Compared with a completely placid water body, water motion may increase evaporation. This enhancement occurs because flowing water induces relative motion at the air–water interface, producing tangential velocity and interfacial shear that can exceed the bulk-averaged water velocity (as shown in Figure 6a). Momentum transfer across the interface induces airflow in the air and modifies the near-interface velocity field. The resulting air-side motion may reduce the resistance associated with the near-surface concentration boundary layer, enhance air renewal, and thereby promoting vapor diffusion into the overlying air.

As the water flow velocity increases and larger waves develop at the surface, numerical simulations show a reduction in the thickness of the high-vapor-concentration layer near the water surface (Figure 5c). Concurrently, the tangential velocity and shear stress at the surface rise which consequently enhance momentum exchanges between flowing water surface and initially stagnant overlying air (Figure 6b). Hence, the vapor boundary layer is continuously disturbed, resulting in larger local concentration gradients as shown in Figure 5c. Intermittent flushing of water vapor by (dynamic) surface waves reduces vapor accumulation near the interface. Under this condition, the evaporative mass flux is characterized by localized enhanced fluxes (Figure 5d). As the water flow velocity increases, both the frequency and intensity of these intermittent events increase, resulting in a pronounced increase in the mean evaporation rates.

Comparative simulations with and without wind conditions indicate that differences in evaporation dynamics are primarily driven by the coupling between air–water relative velocity and dynamic evolution of the water surface waves. Without airflow, the wavy water surface remains relatively stable (Figure 5c). The presence of wind significantly increases the interfacial relative velocity, particularly at windward wave crests (Figure 6c). Under wind-induced shear, the velocity near the air–water interface is significantly higher than the bulk water velocity, enhancing shear-driven vapor transport (see Figure 5e). The airflow disrupts the stable wave structure, inducing dynamically evolving surface morphology. At wave crests, direct exposure to the high-speed airflow significantly enhances the air–water relative velocity and interfacial shear stress, thereby promoting shear-driven vapor transport and resulting in a pronounced increase in local mass flux (Figure 5f). In contrast, wave troughs are characterized by a relatively sheltered, low-velocity flow environment, where the interfacial airflow decelerates and may even undergo local flow separation due to wave-induced geometric effects. This leads to a substantial reduction in interfacial shear stress and turbulent fluctuations. Moreover, under wind conditions, the airflow primarily skims tangentially over the wave crests, while low-speed recirculation or weak retention zones develop within the troughs, limiting vertical vapor transport and producing a comparatively lower mass flux in the trough regions. Consequently, evaporative mass transfer under wind conditions exhibits pronounced spatial heterogeneity across the wavy water surface. These contrasts intensify the spatial heterogeneity of interfacial mass transfer. Relative to no-wind conditions, tailwind increases the mean evaporation flux, while local fluxes exhibit strong variability linked to wave evolution. High-flux regions migrate with the wave field, indicating an evaporation process dominated by intermittent, spatially localized transport events.

4. Conclusion

This study systematically examined the influence of water flow characteristics and atmospheric boundary conditions on evaporation rates from flowing water surfaces. We observed that increasing water flow velocity from 0.04 to 0.20 m/s increases evaporation by approximately 85%, while further increasing to 0.40 m/s almost doubles the rate. Control experiments under placid conditions confirmed that the presence of water flow greatly amplifies evaporation, with rates from flowing water surfaces being 2–5 times higher than those from placid water, depending on flow intensity.

Atmospheric boundary conditions including wind speed and solar radiation further showed strong control over evaporation rates. Increasing wind speed from 0 to 2 m/s raised the evaporation rate from 3.57 to 6.54 mm/d, representing an increase of approximately 83%. Solar radiation elevated surface temperature and vapor pressure, intensifying the phase change process and further increasing evaporation.

More importantly, the results reveal that evaporation from flowing water bodies emerges from the coupled effects of flow dynamics and energy partitioning. By simultaneously controlling air–water exchange and the redistribution of absorbed radiative energy, flow turbulence fundamentally regulates the evaporation dynamics. This explains the contrasting evaporation responses observed under radiative and non-radiative conditions in flowing water bodies and highlights the importance of hydrodynamic controls in evaporation processes.

Numerical simulations revealed that surface roughness and wind–surface interactions enhance vapor fluxes. While at low flow velocities, a thick vapor boundary layer limits mass transfer, surface waves enhance interfacial roughness as flow increases, thereby thinning the boundary layer and generating strong spatial variability in local fluxes. Our findings demonstrated that tailwinds accelerate vapor removal at wave crests, while troughs remain partially sheltered, explaining the observed enhancement of evaporation under wind forcing. High-flux regions migrating with the wave field indicate that evaporation is jointly regulated by the relative shear velocity at the air–water interface and surface waves generated by turbulent water flow, with intermittent, spatially localized transport events dominating the overall vapor flux.

Under constant atmospheric boundary conditions (i.e., fixed wind speed and solar radiation), the influence of water flow velocity on evaporation rates demonstrated a complex, non-monotonic behavior. This reflects the intricate coupling between hydrodynamic flow characteristics and atmospheric forcing. At low water flow velocities, weak vertical mixing brings cooler water upward, partially disrupting the thermal stratification and leading to a reduction in surface temperature. Turbulent mixing in the water column is limited, and evaporation is primarily controlled by the shear velocity near the air–water interface. However, as flow velocity increases further, turbulence intensifies, and surface waves contribute to regulating the thickness of the vapor boundary layer. Enhanced turbulent mixing also promotes a more uniform distribution of absorbed solar energy throughout

the upper water column, modifying the thermal structure of both the bulk water and the near-surface layer. The enhanced turbulent mixing interacts synergistically with atmospheric factors, improving heat and mass transfer at the air–water interface and thereby significantly accelerating evaporation. This nonlinear interplay highlights the necessity of considering both flow and atmospheric conditions jointly to fully understand and predict the evaporation process over flowing water bodies. Work is underway to frame the turbulent interactions at the air–water interface via turbulent surface renewal theory in which renewal at the water and air sides of the interface govern the resulting instantaneous thermal regime and the evaporative flux.

Appendix A: Laboratory Ambient Condition

In Table A1, we list the ambient conditions (air temperature and relative humidity) to illustrate how conditions vary during an experiment and between experiments. During the experiments, ambient conditions were maintained relatively stable, with fluctuations in air temperature generally within $\pm 1.5^\circ\text{C}$ and relative humidity within $\pm 10\%$. However, due to external influences such as weather variability and incidental air heating caused by inefficient pump work at high flow rates, it was not possible to maintain perfectly constant conditions throughout all tests. These deviations in ambient parameters introduced minor variability in evaporation rates. Nevertheless, the influence of such variations was carefully accounted for and statistically separated during the data analysis to ensure the reliability of the reported results.

Table A1
Ambient Conditions (Air Temperature T_{air} and Relative Humidity RH) Under Different Experimental Conditions

Water flow velocity [m/s]	No wind, no radiation [T_{air}/RH]	Only wind [T_{air}/RH]	Only radiation [T_{air}/RH]	Wind and radiation [T_{air}/RH]
0.04	$21.2 \pm 0.6^\circ\text{C}/54 \pm 6\%$	—	—	$21.6 \pm 0.8^\circ\text{C}/50 \pm 3\%$
0.20	$21.6 \pm 0.9^\circ\text{C}/57 \pm 5\%$	$20.3 \pm 0.6^\circ\text{C}/59 \pm 4\%$	$21.5 \pm 0.9^\circ\text{C}/50 \pm 8\%$	$22.0 \pm 0.9^\circ\text{C}/52 \pm 5\%$
0.40	$22.4 \pm 1.3^\circ\text{C}/59 \pm 4\%$	—	—	$23.5 \pm 1.4^\circ\text{C}/54 \pm 4\%$

Appendix B: Measurement Uncertainties

The measurement uncertainties were estimated from the variability among three replicate experiments for the different flow and environmental forcing conditions, as summarized in Table B1.

Table B1
Measurement Uncertainties (mm/d) Under Different Environmental Forcing Conditions and Water Velocities

Water velocity [m/s]	No external forcing	Wind		Solar radiation		Combined forcing Wind 2 m/s + Solar 300 W/m ²
		1.3 m/s	2 m/s	100 W/m ²	300 W/m ²	
0.04	± 0.070					± 0.877
0.2	± 0.305	± 0.081	± 0.098	± 0.246	± 0.199	± 0.550
0.4	± 0.702					± 0.506

Appendix C: Correction of Evaporation Flux for Temperature and Humidity Effects

The evaporation rates obtained in our measurements are sensitive to the variation of vapor concentration gradient at the surface, which varies nonlinearly with temperature as described by Clausius-Clapeyron equation.

We account for the effects of variations in air temperature and humidity, and pump heating on the alternation of evaporation rates and water temperature in the experimental data. To quantify these, we invoked a simplified mass transfer framework which expresses the evaporation flux as:

$$E = \frac{\Delta C}{R} \quad (\text{C1})$$

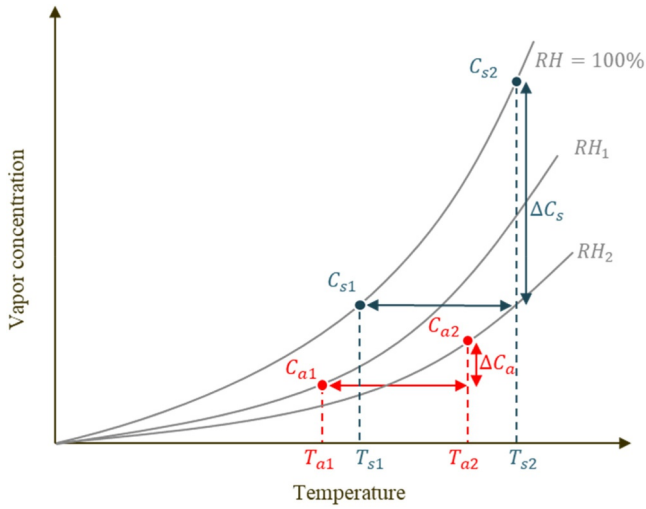


Figure C1. Relationship between temperature and saturation vapor concentration.

Where $\Delta C = C_s - C_a$ presents the vapor concentration difference between the water surface and the overlying air, and R denotes the moisture transfer resistance. This formulation is analogous to Fick's law of diffusion, where the flux is proportional to the concentration gradient and inversely proportional to the diffusive resistance.

The vapor concentrations on the water surface (C_s) and in the air (C_a) are derived from the ideal gas law

$$C_s = \frac{e_{\text{sat}}(T_{\text{surf}})}{R_G/M \cdot T_{\text{surf}}} \quad (\text{C2})$$

$$C_a = \frac{\text{RH} \cdot e_{\text{sat}}(T_{\text{air}})}{R_G/M \cdot T_{\text{air}}}, \quad (\text{C3})$$

where e_{sat} is the saturation vapor pressure at temperature T , RH is the relative humidity, T_{surf} and T_{air} are the temperatures of the water surface and air, respectively, R_G is the ideal gas constant, M is the molar mass of water vapor.

Based on the measured temperature difference (ΔT), the corresponding change in saturated vapor concentration (ΔC_s) was estimated using the

Clausius-Clapeyron relation. This adjustment allows the evaporation flux to be corrected, effectively isolating the influence of water flow velocity from atmospheric effects (Brutsaert, 2013).

For each flow condition, the vapor concentration gradient ($C_s - C_a$) was calculated from the measured environmental variables. The corresponding moisture-transfer resistance was then determined from the measured evaporation rate:

$$R = \frac{(C_s - C_a)}{E}. \quad (\text{C4})$$

Accordingly, R was evaluated independently for each flow condition and was not assumed constant. The lowest-flow case ($u = 0.04$ m/s) was selected as the reference condition, assuming negligible thermal influence from the circulation system.

As illustrated in Figure C1, an incremental temperature increase from T_1 to T_2 leads to a nonlinear increase in the saturation vapor concentration from C_{s1} to C_{s2} , resulting in a concentration difference ΔC_s . Here T_2 represents the measured water surface temperature for each experimental run, whereas T_1 is the temperature corresponding to the reference condition. Similarly, a change in air humidity or temperature leads to a variation ΔC_a in air-side vapor concentration. This change illustrates the temperature sensitivity of evaporation, which is particularly relevant in coupled atmospheric-hydrodynamic conditions.

This can be expressed as:

$$C_{s2} = C_{s1} + \Delta C_s \quad (\text{C5})$$

$$C_{a2} = C_{a1} + \Delta C_a. \quad (\text{C6})$$

Accordingly, the modified evaporation flux under the perturbed environmental conditions becomes:

$$E_2 = \frac{C_{s2} - C_{a2}}{R_2} = \frac{1}{R_2} [(C_{s1} + \Delta C_s) - (C_{a1} + \Delta C_a)]. \quad (\text{C7})$$

The equation can be decomposed into two physically meaningful terms:

$$E_2 = \frac{C_{s1} - C_{a1}}{R_2} + \frac{\Delta C_s - \Delta C_a}{R_2} \quad (\text{C8})$$

The first term reflects the base-level evaporation under steady-state conditions with constant temperature and humidity. The second term represents the contribution of changing environmental variables, such as increased water temperature (with pump action) or altered atmospheric temperature and humidity, which modify the local vapor pressure gradient and thus enhance or suppress evaporation.

Appendix D: Energy Balance Closure

The model considers the energy balance based on a simplified representation of flowing water surfaces and lateral heat fluxes, providing a theoretical foundation for the interpretation of experimental results. The energy balance model accounts for conductive heat exchange through the flume walls, flow friction, and heat input from the pump, all influencing the energy storage of the water body. The surface boundary condition considers radiative, latent, and sensible heat fluxes (Cooley, 1970; Rezazadeh et al., 2020):

$$\Delta Q = (R_n - H - LE)A_s + Q_V + Q_{\text{cond}} + Q_{\text{mech}} \quad (\text{D1})$$

Where ΔQ is the change in energy stored in water (W), R_n is the net radiation flux (W/m^2), H is the sensible heat exchange between water surface and air (W/m^2), LE is latent heat flux (W/m^2). A_s is the surface area of the test section (m^2). Q_{mech} is the heat generated by mechanical equipment (W) (the pump in our experiments). In the presence of water inflows and outflows, the net advective heat input to a water body is determined from the volume-weighted heat content of the flowing water, denoted as Q_V (W). Note that in the present experiments, water is circulated by a pump within a closed system; consequently, the temperature difference between inlet and outlet flows quickly approaches zero at the start of each experiment so that Q_V approaches zero. Q_{cond} is the conductive heat transfer with the surrounding environment via the tank walls and connection tubes (W).

ΔQ , the change in energy stored in water, is shown in Equation D2, which was calculated from the measured temporal changes in water temperature:

$$\Delta Q = \rho_w C_w V (\Delta T_w / t), \quad (\text{D2})$$

where C_w is the heat capacity of water ($C_w = 4,180 \text{ J/kg K}$), V is the total volume of water in the tank (m^3), ΔT_w is the changes in water temperature during the experiment (K), and t is the experiment period (s). R_n is the net radiation flux (Rezazadeh et al., 2020):

$$R_n = (1 - \alpha_w) R_s + \sigma \epsilon_w (\epsilon_a T_a^4 - T_w^4), \quad (\text{D3})$$

where α_w is the water albedo (0.05), R_s is the shortwave radiation (W/m^2), σ is the Stefan–Boltzmann constant ($\text{W/m}^2 \text{ K}^4$), ϵ_w and ϵ_a are the emissivity of water (0.95) and air (0.90), respectively, and T_a and T_w are the corresponding mean air and water temperatures (K). Equation D4 represents the sensible heat flux between the water surface and the atmosphere (Rezazadeh et al., 2020).

$$H = (K_a / \delta) (T_w - T_a) \quad (\text{D4})$$

where K_a is the thermal conductivity of air (W/m K), and δ is the thickness of the air boundary layer above the water surface (m). The value of δ is obtained from the Equation D5 (Aminzadeh & Or, 2014):

$$\delta = \frac{22\nu}{0.1U}, \quad (\text{D5})$$

where ν is the kinematic viscosity of air (m^2/s), and U is the relative velocity of wind flow to water flow (m/s).

The conductive heat exchange through the tank walls, connection tubes, flume walls and bottom and was estimated as:

$$Q_{\text{cond}} = \sum_i K_i A_i \left(\frac{\Delta T_i}{\Delta x_i} \right), \quad (\text{D6})$$

where K_i is the thermal conductivity of the material (W/m K), A_i is the heat transfer area (m^2), ΔT_i is the temperature difference across the wall (K), and Δx_i is the wall thickness (m). The subscript i refers to the tank walls, connecting pipes, flume walls, and flume bottom.

Q_{mech} is the heat that is mainly generated due to the water pump during the experiment. This heat is transferred to the water and causes the water to heat up. The amount of this released heat depends on the power and efficiency of the pump.

See Rezazadeh et al. (2020) for additional details regarding the parameterization of individual surface energy balance components.

The evaporation rate for all experiments was estimated using the energy balance equation. A comparison between the laboratory results and the analytical findings derived from the energy balance equation demonstrated an acceptable level of agreement between the laboratory observations and the results derived from the energy balance equation.

Nomenclatures

ρ	mixture density
RH	relative humidity
T_{air}	air temperature
E	evaporation flux
C	vapor concentration
R_G	ideal gas constant
M	molar mass of water vapor
u	water velocity
R_h	hydraulic radius
ν_w	kinematic viscosity of water
p	local absolute pressure
f	external force
t	time
h	enthalpy
g	gravity
a_i	interfacial area density
L_c	characteristic cell length
S_m	mass source term
S_e	energy source term
μ_{eff}	effective viscosity
μ_t	turbulent viscosity
k_{eff}	effective thermal conductivity
D_{eff}	effective diffusivity
D_o	molecular diffusivity
Y_o	mass fraction

m''	interfacial mass flux
q''	latent heat flux
k_g	gas-side mass transfer coefficient
k_l	liquid-side mass transfer coefficient
k_{ov}	overall transfer coefficient
h_{fg}	enthalpy of evaporation
T_i	interface temperature
M_v	molecular weights of water vapor
M_a	molecular weights of dry air
p_{sat}	saturation vapor pressure
$x_{v,i}$	interfacial vapor mole fraction
$Y_{v,i}$	interfacial vapor mass fraction
$Y_{v,\infty}$	bulk-gas vapor mass fraction
Re	Reynolds number
Pr_t	Prandtl number
Sc_t	Schmidt number
C_o	Courant number

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The laboratory experimental data of this study was archived via Zenodo at <https://doi.org/10.5281/zenodo.20644725> (Hou, 2026).

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References

- Aldarabseh, S. M. (2020). *Evaporation rate from free water surface*. Western Michigan University.
- Alduchov, O. A., & Eskridge, R. E. (1996). Improved Magnus form approximation of saturation vapor pressure. *Journal of Applied Meteorology*, 1988–2005(4), 601–609. [https://doi.org/10.1175/1520-0450\(1996\)035<0601:imfaos>2.0.co;2](https://doi.org/10.1175/1520-0450(1996)035<0601:imfaos>2.0.co;2)
- Allen, G. H., & Pavelsky, T. M. (2018). Global extent of rivers and streams. *Science*, 361(6402), 585–588. <https://doi.org/10.1126/science.aat0636>
- Aminzadeh, M., Lehmann, P., & Or, D. (2018). Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements. *Hydrology and Earth System Sciences*, 22(7), 4015–4032. <https://doi.org/10.5194/hess-22-4015-2018>
- Aminzadeh, M., & Or, D. (2014). Energy partitioning dynamics of drying terrestrial surfaces. *Journal of Hydrology*, 519, 1257–1270. <https://doi.org/10.1016/j.jhydrol.2014.08.037>
- Assouline, S., & Narkis, K. (2021). Reducing evaporation from water reservoirs using floating lattice structures. *Water Resources Research*, 57(6), e2021WR029670. <https://doi.org/10.1029/2021wr029670>
- Assouline, S., Tyler, S. W., Tanny, J., Cohen, S., Bou-Zeid, E., Parlange, M. B., & Katul, G. G. (2008). Evaporation from three water bodies of different sizes and climates: Measurements and scaling analysis. *Advances in Water Resources*, 31(1), 160–172. <https://doi.org/10.1016/j.advwatres.2007.07.003>
- Banerjee, S. (2007). The air-water interface: Turbulence and scalar exchange. In *Transport at the air-sea interface: Measurements, models and parametrizations* (pp. 87–101). Springer Berlin Heidelberg.
- Bird, R. B., Stewart, W. E., & Lightfoot, E. N. (2002). *Transport phenomena* (2nd ed.). Wiley.
- Bohren, C., & Albrecht, B. (2023). *Atmospheric thermodynamics*. Oxford University Press.
- Brackbill, J. U., Kothe, D. B., & Zemach, C. (1992). A continuum method for modeling surface tension. *Journal of Computational Physics*, 100(2), 335–354. [https://doi.org/10.1016/0021-9991\(92\)90240-y](https://doi.org/10.1016/0021-9991(92)90240-y)
- Brutsaert, W. (2013). *Evaporation into the atmosphere: Theory, history and applications* (Vol. 1). Springer Science & Business Media.
- Buahin, C. A., Horsburgh, J. S., & Neilson, B. T. (2019). Parallel multi-objective calibration of a component-based river temperature model. *Environmental Modelling & Software*, 116, 57–71. <https://doi.org/10.1016/j.envsoft.2019.02.012>

- Carrier, J., & Papalexandris, M. V. (2024). Turbulent natural convection in an air–water system with evaporation across the free surface. *International Journal of Multiphase Flow*, 177, 104873. <https://doi.org/10.1016/j.ijmultiphaseflow.2024.104873>
- Chuck, W., & Sparrow, E. M. (1987). Evaporative mass transfer in turbulent forced convection duct flows. *International Journal of Heat and Mass Transfer*, 30(2), 215–222. [https://doi.org/10.1016/0017-9310\(87\)90109-8](https://doi.org/10.1016/0017-9310(87)90109-8)
- Clapeyron, B. P. E. (1834). Memoir sur la puissance motrice de la chaleur. *Journal de l'École royale polytechnique*, 153–190.
- Cooley, K. R. (1970). Energy relationships in the design of floating covers for evaporation reduction. *Water Resources Research*, 6(3), 717–727. <https://doi.org/10.1029/wr006i003p00717>
- Cui, Y., Zhang, X., & Liu, Y. (2021). Radiative and aerodynamic contribution to evaporation: Eddy-covariance comparison between a plain and a plateau lake. *Earth and Space Science*, 8(10), e2021EA001913. <https://doi.org/10.1029/2021ea001913>
- Dean, R. G., & Dalrymple, R. A. (1991). Water wave mechanics for engineers and scientists. *World Scientific*.
- Dong, P., Chang, H., Deng, N., Guo, S., & Li, M. (2025). Multiphysics modeling of open-water evaporation: Quantifying the natural convection effects of water. *Applied Thermal Engineering*, 278, 126964. <https://doi.org/10.1016/j.applthermaleng.2025.126964>
- Downing, J. A., Cole, J. J., Duarte, C. M., Middelburg, J. J., Melack, J. M., Prairie, Y. T., & Tranvik, L. J. (2012). Global abundance and size distribution of streams and rivers. *Inland Waters*, 2(4), 229–236.
- Dugdale, S. J., Hannah, D. M., & Malcolm, I. A. (2017). River temperature modelling: A review of process-based approaches and future directions. *Earth-Science Reviews*, 175, 97–113. <https://doi.org/10.1016/j.earscirev.2017.10.009>
- Easterbrook, C. C. (1969). A study of the effects of waves on evaporation from free water surfaces (18). US Bureau of Reclamation.
- Eidelman, A., Elperin, T., Gluzman, I., Kleorin, N., & Rogachevskii, I. (2013). Experimental study of temperature fluctuations in forced stably stratified turbulent flows. *Physics of Fluids*, 25(1), 015111. <https://doi.org/10.1063/1.4775380>
- Fenton, J. D. (1985). A fifth-order Stokes theory for steady waves. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 111(2), 216–234. [https://doi.org/10.1061/\(asce\)0733-950x\(1985\)111:2\(216\)](https://doi.org/10.1061/(asce)0733-950x(1985)111:2(216))
- Fernandez, R. L., Bonansea, M., Cosavella, A., Monarde, F., Ferreyra, M., & Bresciano, J. (2012). Effects of bubbling operations on a thermally stratified reservoir: Implications for water quality amelioration. *Water Science and Technology*, 66(12), 2722–2730. <https://doi.org/10.2166/wst.2012.507>
- Fischer, H. B. (1979). *Mixing in inland and coastal waters*. Academic Press.
- Garner, G., Malcolm, I. A., Sadler, J. P., & Hannah, D. M. (2014). What causes cooling water temperature gradients in a forested stream reach? *Hydrology and Earth System Sciences*, 18(12), 5361–5376. <https://doi.org/10.5194/hess-18-5361-2014>
- Gendaszek, A. S., Dunham, J. B., Torgersen, C. E., Hockman-Wert, D. P., Heck, M. P., Thorson, J., et al. (2020). Land-cover and climatic controls on water temperature, flow permanence, and fragmentation of Great Basin stream networks. *Water*, 12(7), 1962. <https://doi.org/10.3390/w12071962>
- Haghighi, E., & Or, D. (2013). Evaporation from porous surfaces into turbulent airflows: Coupling eddy characteristics with pore scale vapor diffusion. *Water Resources Research*, 49(12), 8432–8442. <https://doi.org/10.1002/2012wr013324>
- Haghighi, E., & Or, D. (2015). Evaporation from wavy porous surfaces into turbulent airflows. *Transport in Porous Media*, 110(2), 225–250. <https://doi.org/10.1007/s11242-015-0512-y>
- Hebert, C., Caissie, D., Satish, M. G., & El-Jabi, N. (2011). Study of stream temperature dynamics and corresponding heat fluxes within Miramichi River catchments (New Brunswick, Canada). *Hydrological Processes*, 25(15), 2439–2455. <https://doi.org/10.1002/hyp.8021>
- Heck, K., Coltman, E., Schneider, J., & Helmig, R. (2020). Influence of radiation on evaporation rates: A numerical analysis. *Water Resources Research*, 56(10), e2020WR027332. <https://doi.org/10.1029/2020wr027332>
- Hedges, T. S. (1995). Regions of validity of analytical wave theories. *Proceedings of the Institution of Civil Engineers: Water Maritime and Energy*, 112(2), 111–114. <https://doi.org/10.1680/iwtme.1995.27656>
- Helfer, F., Andutta, F. P., Louzada, J. A., Zhang, H., & Lemckert, C. (2018). Artificial destratification for reducing reservoir water evaporation: Is it effective? *Lakes & Reservoirs: Research & Management*, 23(4), 333–350. <https://doi.org/10.1111/lre.12241>
- Helfer, F., Zhang, H., & Lemckert, C. (2011). Modelling of lake mixing induced by air-bubble plumes and the effects on evaporation. *Journal of Hydrology*, 406(3–4), 182–198. <https://doi.org/10.1016/j.jhydrol.2011.06.020>
- Henderson-Sellers, B. (1985). New formulation of eddy diffusion thermocline models. *Applied Mathematical Modelling*, 9(6), 441–446. [https://doi.org/10.1016/0307-904x\(85\)90110-6](https://doi.org/10.1016/0307-904x(85)90110-6)
- Herlina, & Jirka, G. H. (2008). Experiments on gas transfer at the air–water interface induced by oscillating grid turbulence. *Journal of Fluid Mechanics*, 594, 183–208. <https://doi.org/10.1017/s0022112007008968>
- Hou, L. (2026). Evaporation rate from flowing water surfaces_experimental data [Dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.20644725>
- Higbie, R. (1935). The rate of absorption of a pure gas into a still liquid during short periods of exposure. *Transactions of the American Institute of Chemical Engineers*, 31, 365–389.
- Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics*, 39(1), 201–225. [https://doi.org/10.1016/0021-9991\(81\)90145-5](https://doi.org/10.1016/0021-9991(81)90145-5)
- Hu, C., Wang, Y., Wang, W., Liu, S., Piao, M., Xiao, W., & Lee, X. (2017). Trends in evaporation of a large subtropical lake. *Theoretical and Applied Climatology*, 129(1–2), 159–170. <https://doi.org/10.1007/s00704-016-1768-z>
- Imberger, J., & Patterson, J. C. (1989). Physical limnology. *Advances in Applied Mechanics*, 27, 303–475.
- Incropera, F. P., & DeWitt, D. P. (2002). *Fundamentals of heat and mass transfer* (5th ed.). Wiley.
- Ishii, M., & Hibiki, T. (2006). *Thermo-fluid dynamics of two-phase flow*. Springer.
- Jahani, B., MacDonald, M., & Norris, S. E. (2024). Turbulent stratified open channel flow with solar heating up to Pr = 7 using direct numerical simulation. *International Journal of Heat and Fluid Flow*, 110, 109620. <https://doi.org/10.1016/j.ijheatfluidflow.2024.109620>
- Jansen, F. A., Uijlenhoet, R., Jacobs, C. M., & Teuling, A. J. (2022). Evaporation from a large lowland reservoir—observed dynamics and drivers during a warm summer. *Hydrology and Earth System Sciences*, 26(11), 2875–2898. <https://doi.org/10.5194/hess-26-2875-2022>
- Jodat, A., Moghiman, M., & Shirkhani, G. (2013). An experimental investigation on the effects of surface gravity waves on the water evaporation rate in different air flow regimes. *Heat and Mass Transfer*, 49(12), 1823–1830. <https://doi.org/10.1007/s00231-013-1211-2>
- Karmakar, A., & Acharya, S. (2022). Numerical simulation of evaporating wavy falling liquid films in laminar gas streams. *International Journal of Heat and Mass Transfer*, 198, 123426. <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123426>
- Kays, W. M., Crawford, M. E., & Weigand, B. (2005). *Convective heat and mass transfer* (4th ed.). McGraw-Hill.
- Komori, S., Kurose, R., Takagaki, N., Ohtsubo, S., Iwano, K., Handa, K., & Kurose, K. (2010). Sensible and latent heat transfer across the air–water interface in wind-driven turbulence. In *In Proceedings of the symposium on gas transfer at water surfaces* (pp. 78–89). Kyoto.
- Lakehal, D., Fulgosi, M., Banerjee, S., & Yadigaroglu, G. (2008). Turbulence and heat exchange in condensing vapor–liquid flow. *Physics of Fluids*, 20(6), 065101. <https://doi.org/10.1063/1.2919803>

- Lamont, J. C., & Scott, D. S. (1970). An eddy cell model of mass transfer into the surface of a turbulent liquid. *AIChE Journal*, 16(4), 513–519. <https://doi.org/10.1002/aic.690160403>
- Law, C. N. S., & Khoo, B. C. (2002). Transport across a turbulent air-water interface. *AIChE Journal*, 48(9), 1856–1868. <https://doi.org/10.1002/aic.690480904>
- Leach, J. A., Kelleher, C., Kurylyk, B. L., Moore, R. D., & Neilson, B. T. (2023). A primer on stream temperature processes. *Wiley Interdisciplinary Reviews: Water*, 10(4), e1643. <https://doi.org/10.1002/wat2.1643>
- Lehmann, P., Aminzadeh, M., & Or, D. (2019). Evaporation suppression from water bodies using floating covers: Laboratory studies of cover type, wind, and radiation effects. *Water Resources Research*, 55(6), 4839–4853. <https://doi.org/10.1029/2018wr024489>
- Liu, S., Kuhn, C., Amatulli, G., Aho, K., Butman, D., Allen, G. H., et al. (2022). The importance of hydrology in routing terrestrial carbon to the atmosphere via global streams and rivers. *Proceedings of the National Academy of Sciences of the United States of America*, 119(12), e2114114119.
- Maheu, A., Caissie, D., St-Hilaire, A., & El-Jabi, N. (2014). River evaporation and corresponding heat fluxes in forested catchments. *Hydrological Processes*, 28(23), 5725–5738. <https://doi.org/10.1002/hyp.10071>
- Marek, R., & Straub, J. (2001). Analysis of the evaporation coefficient and the condensation coefficient of water. *International Journal of Heat and Mass Transfer*, 44(1), 39–53. [https://doi.org/10.1016/s0017-9310\(00\)00086-7](https://doi.org/10.1016/s0017-9310(00)00086-7)
- Menter, F. R. (1994). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, 32(8), 1598–1605. <https://doi.org/10.2514/3.12149>
- Nevermann, H., Aminzadeh, M., Madani, K., & Shokri, N. (2024). Quantifying water evaporation from large reservoirs: Implications for water management in water-stressed regions. *Environmental Research*, 262, 119860. <https://doi.org/10.1016/j.envres.2024.119860>
- Ojha, C. S. P., Kumar, M., & Saini, J. S. (2013). Analysis of evaporation data under roughness-induced wind flow. *Journal of Hydrologic Engineering*, 18(6), 665–674. [https://doi.org/10.1061/\(asce\)he.1943-5584.0000658](https://doi.org/10.1061/(asce)he.1943-5584.0000658)
- Ouellet, V., & Caissie, D. (2023). Towards a better understanding of the evaporative cooling of rivers: Case study for the Little Southwest Miramichi River (New Brunswick, Canada). *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques*, 48(2), 189–205. <https://doi.org/10.1080/07011784.2023.2177196>
- Penman, H. L. (1956). Estimating evaporation. *EOS Transactions of the American Geophysical Union*, 37(1), 43–50.
- Poling, B. E., Prausnitz, J. M., & O'Connell, J. P. (2001). *The properties of gases and liquids* (5th ed.). McGraw-Hill.
- Rachid, N., Issam, N., Abdelkrim, B., Abdelhamid, A., & Amina, H. (2022). Pond energy dynamics, evaporation rate and ensemble deep learning evaporation prediction: Case Study of the Thomas Pond—Brenne natural regional Park (France). *Water*, 14(6), 923. <https://doi.org/10.3390/w14060923>
- Raupach, M. R. (2001). Combination theory and equilibrium evaporation. *Quarterly Journal of the Royal Meteorological Society*, 127(574), 1149–1181. <https://doi.org/10.1002/qj.49712757402>
- Ren, J., Xu, J., Tian, S., Shi, K., Gu, T., Zhao, J., et al. (2024). Hydrodynamic solar-driven interfacial evaporation-gone with the flow. *Water Research*, 266, 122432. <https://doi.org/10.1016/j.watres.2024.122432>
- Rezaadeh, A., Akbarzadeh, P., & Aminzadeh, M. (2020). The effect of floating balls density on evaporation suppression of water reservoirs in the presence of surface flows. *Journal of Hydrology*, 591, 125323. <https://doi.org/10.1016/j.jhydrol.2020.125323>
- Rezaadeh, A., Akbarzadeh, P., ShahMardan, M. M., & Aminzadeh, M. (2025). A novel method for assessing evaporation in small water bodies: Considering floating covers, water surface flows, and wind speeds. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 49(6), 1–22. <https://doi.org/10.1007/s40996-025-01783-9>
- Roderick, M. L., Hobbins, M. T., & Farquhar, G. D. (2009). Pan evaporation trends and the terrestrial water balance. II. Energy balance and interpretation. *Geography Compass*, 3(2), 761–780. <https://doi.org/10.1111/j.1749-8198.2008.00214.x>
- Rodrigues, C. M., Moreira, M., Guimarães, R. C., & Potes, M. (2020). Reservoir evaporation in a Mediterranean climate: Comparing direct methods in Alqueva Reservoir, Portugal. *Hydrology and Earth System Sciences*, 24(12), 5973–5984. <https://doi.org/10.5194/hess-24-5973-2020>
- Satoru, K., Hiromasa, U., Fumimaru, O., & Tokuro, M. (1982). Turbulence structure and transport mechanism at the free surface in an open channel flow. *International Journal of Heat and Mass Transfer*, 25(4), 513–521. [https://doi.org/10.1016/0017-9310\(82\)90054-0](https://doi.org/10.1016/0017-9310(82)90054-0)
- Schlüssel, P., Emery, W. J., Grassl, H., & Mammen, T. (1990). On the bulk-skin temperature difference and its impact on satellite remote sensing of sea surface temperature. *Journal of Geophysical Research*, 95(C8), 13341–13356. <https://doi.org/10.1029/jc095ic08p13341>
- Schrag, R. W. (1953). *A theoretical study of interphase mass transfer*. Columbia University Press.
- Shnitnikov, A. V. (1974). Current methods for the study of evaporation from water surfaces and evapotranspiration. *Hydrology Science Bulletin*, 19(1), 85–97. <https://doi.org/10.1080/02626667409493873>
- Sonntag, D. (1990). Important new values of the physical constants of 1986, vapor pressure formulations based on the ITS-90, and psychrometer formulae. *Zeitschrift für Meteorologie*, 70, 340–344.
- Spalding, D. B. (1953). The combustion of liquid fuels. *Symposium (International) on Combustion*, 4(1), 847–864. [https://doi.org/10.1016/s0082-0784\(53\)80110-4](https://doi.org/10.1016/s0082-0784(53)80110-4)
- Svendsen, I. A. (2006). Introduction to nearshore hydrodynamics. *World Scientific*.
- Szeitz, A. J., & Moore, R. D. (2020). Predicting evaporation from mountain streams. *Hydrological Processes*, 34(22), 4262–4279. <https://doi.org/10.1002/hyp.13875>
- Vercauteren, N., Huwald, H., Bou-Zeid, E., Selker, J. S., Lemmin, U., Parlange, M. B., & Lunati, I. (2011). Evolution of superficial lake water temperature profile under diurnal radiative forcing. *Water Resources Research*, 47(9). <https://doi.org/10.1029/2011wr010529>
- Vystavna, Y., Harjung, A., Monteiro, L. R., Matiatos, I., & Wassenaar, L. I. (2021). Stable isotopes in global lakes integrate catchment and climatic controls on evaporation. *Nature Communications*, 12(1), 7224. <https://doi.org/10.1038/s41467-021-27569-x>
- Watson, K. M. (1943). Thermodynamics of the liquid state. *Industrial & Engineering Chemistry*, 35(4), 398–406. <https://doi.org/10.1021/ie50400a004>
- Webb, B. W., & Zhang, Y. (1997). Spatial and seasonal variability in the components of the river heat budget. *Hydrological Processes*, 11(1), 79–101. [https://doi.org/10.1002/\(sici\)1099-1085\(199701\)11:1<79::aid-hyp404>3.0.co;2-n](https://doi.org/10.1002/(sici)1099-1085(199701)11:1<79::aid-hyp404>3.0.co;2-n)
- Wirangga, R., Mugisidi, D., Sayuti, A. T., & Heriyani, O. (2023). The impact of wind speed on the rate of water evaporation in a desalination chamber. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 106(1), 39–50. <https://doi.org/10.37934/arfmts.106.1.3950>
- Yihdego, Y., & Webb, J. A. (2018). Comparison of evaporation rate on open water bodies: Energy balance estimate versus measured pan. *Journal of Water and Climate Change*, 9(1), 101–111. <https://doi.org/10.2166/wcc.2017.139>