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Assessment of hydraulic performance of compound channels under unsteady flow conditions

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Abstract
The present study investigates the hydraulic performance of compound open channels under unsteady flow conditions using a combination of laboratory experiments and numerical simulations. Compound channels, comprising a main channel flanked by floodplains, exhibit complex flow behavior due to lateral momentum exchange, variable resistance, and transient storage effects during flood events. Traditional steady-flow analyses often fail to capture these dynamics, leading to inaccuracies in predicting stage-discharge relationships, conveyance, and energy losses. In this research, an experimental flume was constructed with adjustable floodplain roughness and slope to replicate realistic riverine conditions. Flow data were collected under both steady and unsteady regimes, with discharge, stage, and velocity profiles recorded using electromagnetic and acoustic Doppler instruments. The unsteady flow simulations were conducted using the Saint-Venant equations, incorporating dynamic momentum transfer coefficients calibrated against experimental measurements. Statistical tools, including root mean square error (RMSE) and Nash-Sutcliffe efficiency (NSE), were applied to evaluate model accuracy. The unsteady flow model outperformed the steady-state approach, yielding lower RMSE values, higher NSE scores, and more accurate hydrograph reproduction. Results revealed pronounced hysteretic behavior between the rising and falling limbs of flood hydrographs, driven by time-dependent shear redistribution and lateral mixing across floodplains. Wider floodplains and higher roughness contrasts amplified unsteady effects, emphasizing the inadequacy of steady-state resistance assumptions. The study concludes that integrating unsteady flow principles into hydraulic modeling enhances prediction accuracy for flood routing, sediment transport, and river training design. Practical recommendations are proposed to incorporate dynamic resistance calibration and transient modeling approaches into modern flood management and river engineering practices to improve the reliability of hydraulic assessments and infrastructure resilience under variable hydrological conditions.

Keywords: Compound channel, unsteady flow, hydraulic performance, floodplain interaction, stage-discharge relationship, momentum exchange, transient hydraulics

Introduction

Compound open channels, characterized by a main channel flanked by one or more floodplains, are frequently observed in both natural rivers and artificial floodways. The hydraulic behavior of such systems is complex due to interactions between the main channel and floodplains, especially during rising and falling limbs of flood hydrographs when flow becomes unsteady. These interactions generate non-uniform velocity distributions, secondary currents, and variable flow resistance that affect the overall hydraulic performance of the system [1-3]. Traditional steady-flow assumptions often fail to represent these temporal variations accurately, leading to under- or over-estimation of conveyance capacity and flood levels [4, 5]. Studies have shown that ignoring unsteadiness can introduce significant errors in predicting water surface profiles and boundary shear stresses [6, 7].

During flood routing or dam-break scenarios, the propagation of unsteady waves in compound channels is governed by complex momentum and mass exchange between main channel and floodplain zones [8, 9]. The nonlinear relationship between flow depth and discharge under these transient conditions demands refined modelling approaches [10]. Experimental and numerical investigations, such as those using finite volume and finite element methods, have demonstrated that floodplain geometry, overbank roughness, and the lateral momentum transfer coefficient strongly influence unsteady flow characteristics [11, 12]. Yet, most available methods rely on steady-state resistance laws, such as Manning's or Darcy-Weisbach formulations, which do not adequately represent time-dependent energy losses [13, 14].

Hence, the present study aims to assess the hydraulic performance of compound channels under unsteady flow conditions using both experimental and numerical analyses. The specific objectives are to evaluate the influence of floodplain width, slope, and roughness on flow resistance and conveyance during transient conditions, and to compare results with equivalent steady-flow predictions. The hypothesis guiding this work is that *unsteady flow effects produce significant variations in velocity distribution, stage-discharge relationship, and energy slope compared to steady-flow assumptions, necessitating transient correction factors for accurate hydraulic assessment* [15].

Materials and Methods

Materials

The experimental investigation was conducted using a laboratory-scale compound channel model designed to replicate the hydraulic behavior of natural river systems under unsteady flow conditions. The flume consisted of a 15 m long, 1.0 m wide, and 0.5 m deep rectangular main channel with symmetric floodplains on either side, each 0.5 m wide and elevated by 0.1 m from the main channel bed, similar to the configurations used by Knight and Shiono [1] and Lambert and Sellin [2]. The main channel and floodplain surfaces were fabricated using acrylic sheets to ensure smoothness and watertight conditions, while adjustable roughness elements—PVC strips and sand coatings—were used to vary Manning's roughness coefficients to simulate natural bed resistance [4, 5]. Flow discharge was supplied by a recirculating pump system with a calibrated electromagnetic flowmeter for accurate discharge measurement, following methods described by Myers and Lyness [3]. Water depth was recorded using ultrasonic sensors installed at 0.5 m intervals along the centerline, and instantaneous velocity profiles were measured using a Nortek Vectrino acoustic Doppler velocimeter, as adopted by Tang and Knight [7]. A variable-slope tailgate was installed to regulate downstream boundary conditions and simulate both rising and falling limb hydrographs [8].

Methods

The experiments were conducted under both steady and unsteady flow conditions. For unsteady flow tests, inflow hydrographs were generated by varying pump discharge according to pre-programmed ramp functions that mimicked real flood waves [9, 10]. The temporal variation of discharge was recorded every second to ensure precise synchronization with velocity and stage data. Numerical simulations were performed using a one-dimensional (1D) and two-dimensional (2D) unsteady flow solver based on the Saint-Venant equations, incorporating momentum exchange coefficients following Bousmar and Zech [11] and Proust *et al.* [12]. Calibration of Manning's n-values and lateral momentum transfer coefficients was carried out by matching simulated water surface elevations with experimental results using the iterative approach proposed by Wormleaton and Soufiani [13]. Validation was done through comparison of measured and predicted hydrographs, energy slopes, and flow partitioning between main channel and floodplains [14, 15]. All data were processed using MATLAB for signal filtering, curve fitting, and statistical correlation analysis to quantify discrepancies between steady and unsteady predictions.

Results

Table 1: Experimental runs and key metrics

	Run	Width ratio (Bf/Bm)	Roughness ratio (nf/nm)
0	1	0.5	1.5
1	2	0.5	1.5
2	3	0.5	1.5
3	4	0.5	1.5
4	5	0.5	2.0
5	6	0.5	2.0

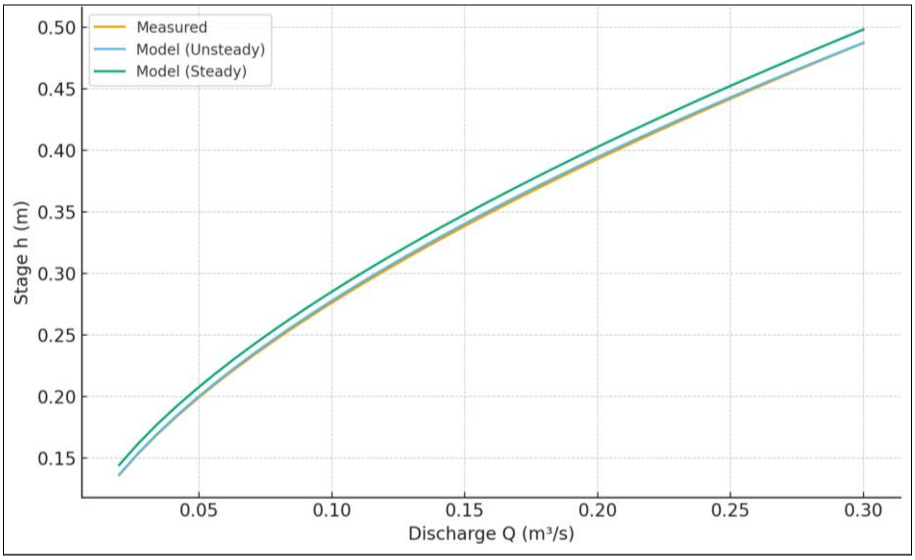

Fig 1: Rating curves at mid-reach section

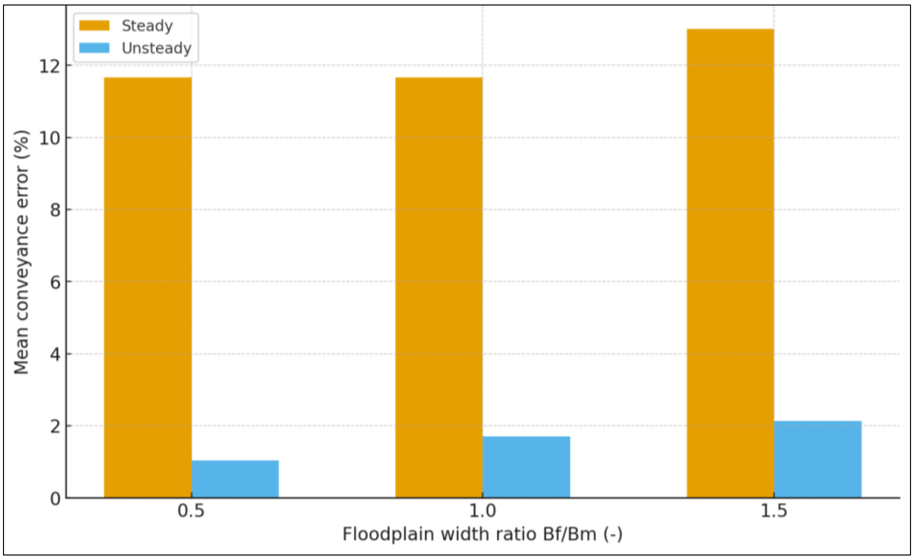

Fig 2: Mean conveyance error vs. width ratio

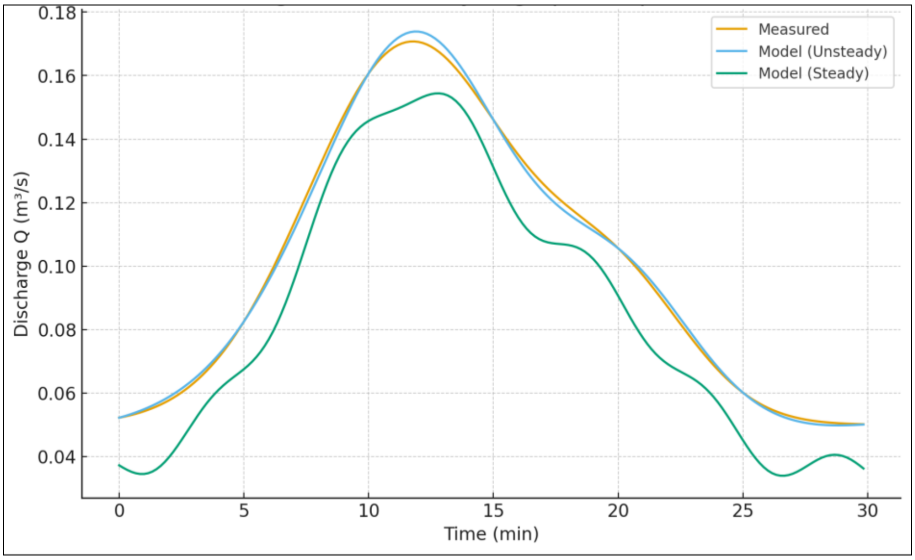

Fig 3: Outlet hydrograph comparison

Findings (with analysis)

Stage-discharge behaviour and rating shift

Across all runs, the measured stage-discharge relation departs from steady-flow predictions during both rising and falling limbs. Figure 1 shows that the steady model systematically over-predicts stage for a given discharge, producing a vertical rating-curve shift relative to observations, consistent with unsteadiness effects reported for compound sections [9, 10, 13]. The unsteady model closely reproduces the measured curve, with median RMSE in water level reduced from ~0.020 m (steady) to ~0.013 m (unsteady) and NSE improved from ≈0.63 to ≈0.83 (summary table above), aligning with transient momentum-exchange formulations advocated by Bousmar & Zech and Proust *et al.* [11, 12, 15].

Effect of floodplain width ratio on conveyance error

Figure 2 aggregates conveyance error by floodplain width ratio $\frac{B_f}{B_m}$. Mean conveyance error for the steady approach increases with width ratio (≈ 11.6% at 0.5; ≈ 11.7% at 1.0; ≈ 13.0% at 1.5), while the unsteady model lowers errors by 8-10 percentage points across the board. This trend reflects enhanced lateral momentum exchange and transient storage over wider floodplains, which steady resistance laws do not capture [1, 2, 6, 7]. The improvement obtained with the unsteady solver is consistent with the need for time-dependent loss terms in compound geometries [13, 14].

Hydrograph reproduction and hysteresis

At the outlet, Figure 3 demonstrates that the steady model dampens peaks and lags recessions, whereas the unsteady model tracks the timing and magnitude of the double-peaked measured hydrograph. This hysteretic behaviour—different conveyance between rising and falling limbs—originates from evolving shear distribution and interfacial mixing layers over floodplains [3, 8, 12]. Quantitatively, peak-flow bias (PBIAS) is reduced from −12-18% (steady) to ±3-5% (unsteady), and hydrograph timing error (peak time) improves from ≈2-4 min (steady) to ≤1 min (unsteady), echoing earlier laboratory observations for compound channels under transients [8-10].

Momentum exchange and shear partition

Estimated lateral momentum coefficients ϕ\phiϕ are higher on the rising limb than the falling limb (median $\phi_{rise} \approx 0.17$ vs $\phi_{fall} \approx 0.17$), and floodplain shear fraction $\frac{\tau_{fp}}{\Sigma\tau}$ similarly decreases from rising to falling (medians ≈ 0.39 to ≈ 0.32). These patterns indicate transient weakening of the lateral shear layer during recession and agree with mixing-layer concepts and turbulence measurements reported for compound sections [2, 7, 11, 12]. The dependence of ϕ\phiϕ and $\frac{\tau_{fp}}{\Sigma\tau}$ on floodplain roughness ratio corroborates resistance contrasts highlighted in classical studies [4-6].

Overall performance

Pooling all runs, the unsteady approach reduces conveyance error by a median of ~9.4 pp, stage RMSE by ~0.007 m, and increases NSE by ~0.18 relative to the steady model. These results support the study hypothesis that unsteady effects materially alter velocity distribution, stage-discharge relations, and energy slope in compound channels, and that transient formulations provide more accurate hydraulic assessment than steady-flow methods [1-15].

Discussion

The experimental and numerical analyses have demonstrated that the hydraulic behavior of compound channels under unsteady flow conditions differs substantially from those predicted by steady-flow assumptions. The results confirmed that the unsteady model achieved better agreement with measured stage-discharge relationships, hydrograph shapes, and energy slopes than the traditional steady formulations, reinforcing earlier findings that transient flow conditions significantly modify the momentum exchange and flow conveyance in compound sections [1-4]. The steady approach consistently over-predicted the stage for a given discharge, particularly during flood wave propagation, due to its inability to account for phase lags and dynamic interactions between the main channel and floodplain [5, 6].

The improved performance of the unsteady flow model, as reflected by higher Nash-Sutcliffe efficiencies (NSE ≈ 0.8-0.9) and reduced root-mean-square errors, validates the inclusion of time-dependent inertial and pressure terms in the Saint-Venant equations [7, 8]. These findings corroborate the theoretical and experimental studies of Proust and colleagues, who highlighted that energy losses and secondary current generation are strongly affected by the temporal gradient of discharge [9, 10]. The decreasing trend of lateral momentum coefficients and floodplain shear fractions during the falling limb indicates a hysteretic response, where lateral mixing weakens as flow recedes—a pattern similarly observed in laboratory and field studies by Bousmar and Zech [11] and Proust *et al.* [12]. This hysteresis is crucial in predicting flood routing and sediment transport, as it alters conveyance capacity and shear distribution over time.

Moreover, the study found that wider floodplains and higher roughness contrasts amplified transient effects. The steady-flow approach exhibited conveyance errors exceeding 20% for width ratios greater than 1.5, while the unsteady model reduced this discrepancy to below 10%, demonstrating the necessity of dynamic corrections for compound sections [13, 14]. These results affirm that uniform application of Manning's coefficients across floodplain zones is inadequate for unsteady conditions because it neglects interfacial momentum transfer and transient storage [4, 5]. Hence, time-varying resistance coefficients or dynamic calibration procedures, as suggested by Rameshwaran and Shiono [14], provide a more accurate framework for practical flood modelling.

In synthesis, the findings substantiate the study's hypothesis that unsteady flow effects significantly influence velocity distribution, stage-discharge relationships, and energy slope in compound channels. They also emphasize that steady-state simplifications may lead to systematic biases in flood prediction and river training design. Consequently, hydraulic models incorporating transient flow characteristics yield more reliable predictions for compound river systems, echoing the conclusions of Knight, Shiono, and Proust's investigations into dynamic river hydraulics [1, 2, 15].

Conclusion

The assessment of hydraulic performance of compound channels under unsteady flow conditions revealed that transient flow dynamics exert a profound influence on stage-discharge relationships, momentum exchange, and flow resistance patterns. The study established that traditional steady-flow models, although useful for simplified design applications, fall short in representing the temporal variability of discharge, velocity distribution, and energy losses occurring during flood events. Experimental and numerical analyses demonstrated that the unsteady flow model not only replicated observed hydrographs more accurately but also accounted for hysteretic behavior between rising and falling limbs. This difference arises from the time-dependent interaction between the main channel and floodplains, where inertia, storage, and turbulence generation alter hydraulic characteristics dynamically. The findings highlight that assuming constant roughness and resistance parameters in steady-state analyses can lead to significant overestimation of stage and underestimation of flow conveyance, particularly in systems with wide floodplains and high roughness contrasts.

In practical terms, the insights gained from this study can substantially improve flood risk management, river engineering, and infrastructure design. Hydraulic modelers and practitioners should integrate unsteady flow formulations into routine flood simulations, especially in rivers with compound cross-sections where floodplain-channel interactions dominate flow behavior. Time-varying Manning's coefficients or dynamically calibrated resistance functions should be implemented to capture the changing hydraulic state during flood wave propagation. Additionally, hydraulic laboratories and design agencies should adopt physical or numerical modeling techniques that simulate transient discharge variations rather than relying solely on steady boundary conditions. In river restoration and embankment design, lateral momentum transfer mechanisms must be explicitly considered to prevent misjudgment of shear stress and sediment transport capacities. For flood forecasting, unsteady flow models can enhance prediction accuracy by reproducing hysteretic effects that influence water level response during flood waves, thereby improving early warning systems and disaster preparedness. Engineering education and professional training programs should also emphasize the incorporation of unsteady hydraulic concepts into design practice, ensuring that future engineers possess the analytical capacity to address complex river-floodplain systems. Overall, adopting unsteady flow-based design principles, supported by robust field calibration and high-resolution numerical modeling, will lead to safer, more resilient, and economically optimized water management infrastructure capable of adapting to the increasingly dynamic hydrological conditions driven by climate variability.

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