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Experimental Investigation and Mathematical Modeling of Water Flow Velocity and Discharge Measurement using a Current Meter (Propeller-Type)

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Abstract
Accurate measurement of water flow velocity and discharge is a fundamental task in hydrometry, irrigation engineering, and water resources management. Mechanical current meters of the propeller (rotational) type remain widely used in field measurements due to their robustness, simplicity, and suitability for open-channel and river flow conditions. However, the accuracy of such instruments strongly depends on proper calibration, flow conditions, and measurement methodology. This paper presents an experimental investigation and mathematical modeling of water flow velocity and discharge measurements using a propeller-type current meter. The operating principle of the instrument is analyzed, and a linear calibration model relating flow velocity to the rotational frequency of the propeller is formulated. Discharge is determined by integrating point velocity measurements over the cross-sectional area of the flow. Experimental measurements were conducted under controlled hydraulic conditions, and the obtained data were processed using statistical and analytical methods. The results demonstrate a stable linear relationship between the propeller rotational speed and flow velocity within the investigated range, confirming the applicability of the proposed calibration model. Discharge values calculated from measured velocity profiles show good agreement with reference measurements. The presented methodology provides a reliable and practical approach for flow monitoring in hydrometric applications and can be effectively applied in irrigation canals, rivers, and hydraulic engineering practice.

Keywords: water flow measurement; flow velocity; discharge measurement; current meter; propeller-type sensor; hydrometry; experimental modeling.

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Introduction. Accurate measurement of water flow velocity and discharge is a fundamental requirement in hydrometry, irrigation engineering, hydraulic structure design, and water resources management. Reliable flow data are essential for assessing water availability, designing and operating irrigation systems, flood control, and environmental monitoring. In open channels and natural rivers, flow velocity and discharge measurements remain a challenging task due to spatial variability of velocity profiles and changing hydraulic conditions [1,2]. Various methods and

instruments have been developed for measuring flow velocity and discharge, including electromagnetic sensors, acoustic Doppler velocimeters, ultrasonic flow meters, and mechanical current meters. Among these, mechanical propeller-type current meters (often referred to as "current meters" or "rotational meters") continue to be widely used in practical hydrometric applications due to their simplicity, robustness, low cost, and suitability for field conditions [3,4]. International standards and hydrometric guidelines still recognize propeller-type current meters as reference instruments for velocity measurements in open channels and rivers [5].

The operating principle of a propeller-type current meter is based on the relationship between the rotational speed of the propeller and the local flow velocity. Under steady flow conditions, this relationship can be approximated by a linear calibration equation, which must be determined experimentally for each instrument [6]. The accuracy of velocity measurements therefore strongly depends on calibration quality, flow uniformity, and correct positioning of the meter within the flow cross-section. Discharge measurement using current meters is commonly performed by dividing the cross-sectional area into a number of verticals and integrating point velocity measurements over the wetted area. This velocity–area method is recommended by international hydrometric standards and remains one of the most reliable approaches for open-channel discharge measurements [5,7]. However, uncertainties may arise from limited measurement points, non-uniform velocity distribution, and errors in velocity estimation at individual points [8].

Several studies have investigated the performance and accuracy of mechanical current meters under different hydraulic conditions. Rantz [5] and Herschy [6] provided comprehensive methodological frameworks for velocity and discharge measurements using current meters, while more recent works have focused on uncertainty analysis and comparison with modern acoustic techniques [9,10]. Despite the development of advanced electronic and acoustic instruments, propeller-type current meters remain relevant, particularly in regions where simplicity, durability, and low operational costs are critical. Nevertheless, there is a need for renewed experimental investigation and mathematical modeling of propeller-type current meters to quantify their performance under controlled conditions and to improve discharge estimation accuracy. Many existing studies focus primarily on measurement procedures, while fewer works provide a combined experimental and analytical treatment linking rotational speed, flow velocity, and discharge through explicit mathematical models [6,11]. In this context, the present study aims to experimentally investigate water flow velocity and discharge measurements using a propeller-type current meter and to develop a mathematical modeling framework for interpreting the measured data. The study analyzes the calibration relationship between propeller rotational frequency and flow velocity, applies the velocity–area method for discharge computation, and evaluates the consistency of experimental results. The proposed approach contributes to improving the reliability of hydrometric measurements in open-channel and river flow applications.

Materials and Methods

Measurement Instrument and Experimental Setup. The experimental investigation was carried out using a mechanical propeller-type current meter designed for measuring point flow velocity in open channels. The instrument consists of a rotating propeller mounted on a horizontal axis, a shaft, and a mechanical or electronic counting mechanism used to record the number of propeller revolutions over a given time interval.

Measurements were conducted in a straight open-channel section with stable hydraulic conditions to minimize the influence of secondary currents and flow disturbances. The current meter was positioned facing upstream and aligned with the local flow direction to ensure correct interaction between the propeller blades and the flow. Mathematical Model of Flow Velocity Measurement. The operating principle of a propeller-type current meter is based on the proportional relationship between the rotational speed of the propeller and the local flow velocity. The average point velocity vvv is expressed as a function of the propeller rotational frequency n:

$V = an + b$

Where v — local flow velocity (m/s); n — propeller rotational frequency (rev/s); a, b — calibration coefficients determined experimentally.

The rotational frequency is calculated from the measured number of revolutions N during the measurement time t:

$$n = \frac{N}{t}$$

This linear calibration model is widely adopted in hydrometric practice and provides reliable velocity estimation within the calibrated velocity range.

Calibration Procedure

Calibration of the current meter was performed under controlled flow conditions by comparing the measured rotational frequency with reference velocity values obtained from a calibrated flow facility. The calibration coefficients aaa and bbb were determined using linear regression:

$$a = \frac{\sum(n_i - \bar{n})(v_i - \bar{v})}{\sum(n_i - \bar{n})^2}$$

$$b = \bar{v} - a\bar{n}$$

where v_i and n_i are the measured velocity and rotational frequency samples, respectively, and the overbar denotes mean values.

Discharge Measurement Model. Water discharge was determined using the velocity–area method, which is recommended by international hydrometric standards for open-channel flow measurement. The cross-sectional area of the channel was divided into k vertical segments, and point velocity measurements were taken at representative depths within each segment.

The total discharge Q was computed as:

$$Q = \sum_{i=1}^{k} v_i A_i$$

where v_i — mean velocity in the iii-th segment (m/s); A_i — corresponding sub-area (m²).

For sufficiently small segments, the discrete formulation approximates the continuous integral form:

$$Q = \int_A v(x, y)\ dA$$

Velocity Distribution Along the Depth

To account for vertical velocity variation, point velocity measurements were taken at standard relative depths. For shallow flows, a single-point measurement at 0.6 of the total depth was used:

$v_{mean} \approx v_{0.6h}$

For deeper flows, a two-point method was applied:

$$v_{\text{mean}} = \frac{v_{0.2h} + v_{0.8h}}{2}$$

where h is the local flow depth.

Measurement Uncertainty Evaluation

The uncertainty of velocity measurements was evaluated by considering errors associated with rotational counting, timing, and calibration coefficients. The relative uncertainty of velocity measurement was estimated as:

$$\delta v = \sqrt{\left(\frac{\partial v}{\partial n}\,\delta n\right)^2 + (\delta b)^2}$$

The adopted methodology combines experimental calibration of a propeller-type current meter with analytical velocity–discharge modeling. By integrating point velocity measurements across the flow cross-section, the proposed approach enables accurate estimation of water discharge under controlled hydraulic conditions. This methodological framework provides a reproducible basis for evaluating current meter performance and serves as a foundation for the experimental results presented in the next section.

Results

Propeller rotational frequency and flow velocity relationship (v–n)

Current meter calibration experiments were conducted to establish the relationship between propeller rotational frequency and local flow velocity. For each test condition, the number of propeller revolutions was recorded over a fixed time interval, and the rotational frequency was calculated using Eq. (2). The corresponding flow velocity was obtained from reference measurements.

Table 1. Measured rotational frequency and flow velocity

Test No.	Rotational frequency, *n* (rev/s)	Flow velocity, *v* (m/s)
1	0.52	0.38
2	0.74	0.55
3	0.96	0.71
4	1.18	0.88
5	1.41	1.05

Based on the data presented in Table 1, a clear linear dependency between flow velocity and rotational frequency is observed. The corresponding v–n calibration curve is shown in Figure 1, confirming the validity of the linear model introduced in the Methods section.

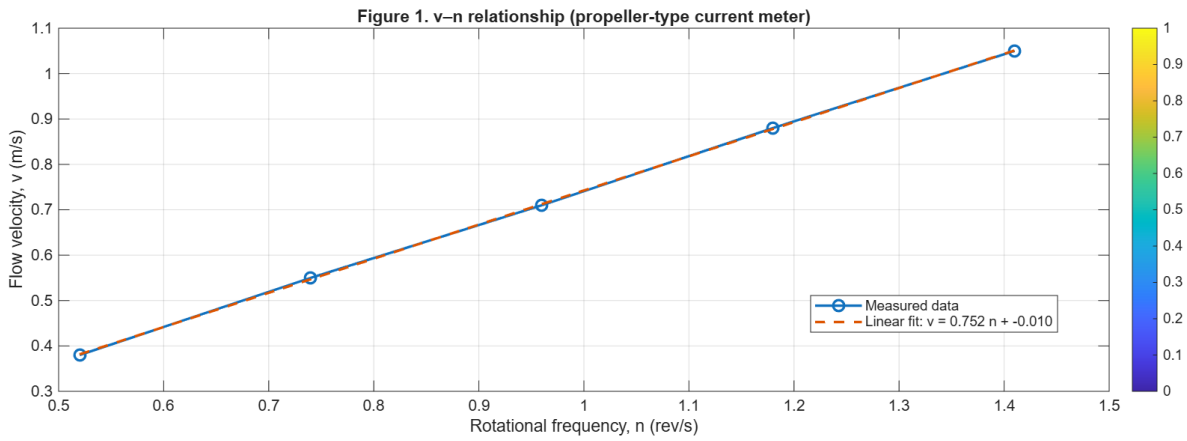

Figure 1. Relationship between flow velocity and propeller rotational frequency (v–n)

Vertical velocity distribution and depth-averaged velocity (Q–depth)

Velocity measurements were performed at different relative depths within the flow to evaluate the vertical velocity distribution. Measurements were taken at 0.2*h*, 0.6*h*, and 0.8*h*, where *h* denotes the local flow depth.

Relative depth	Velocity, *v* (m/s)
0.2*h*	0.92
0.6*h*	0.81
0.8*h*	0.74

The results indicate a typical vertical velocity profile, with maximum velocity occurring near the upper part of the flow and decreasing toward the channel bed due to frictional effects. The velocity–depth profile derived from Table 2 is illustrated in Figure 2.

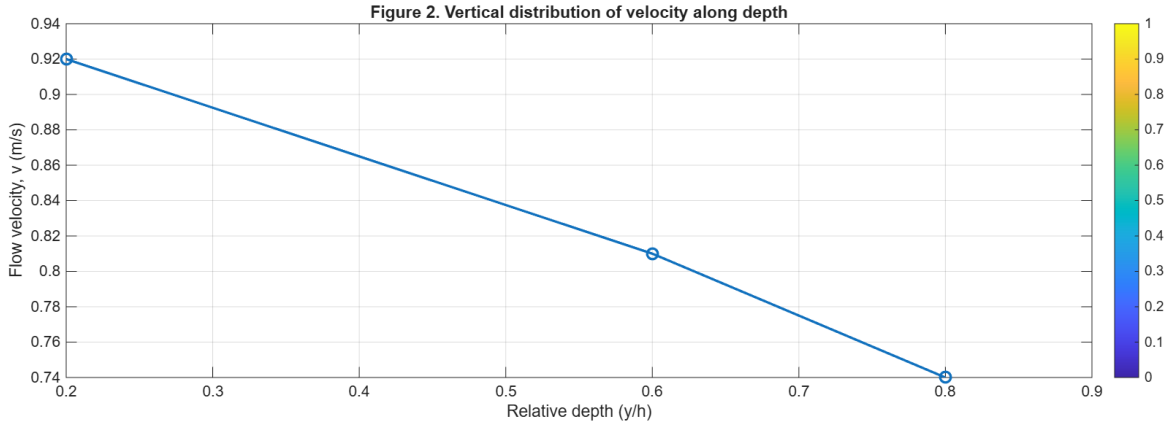

Figure 2. Vertical distribution of flow velocity along the water depth

Discharge estimation using the velocity–area method

Discharge was computed by dividing the channel cross-section into vertical segments and applying the velocity–area method described in Section 2. The depth-averaged velocity for each segment was determined using the one-point or two-point method, depending on flow depth.

Table 3. Discharge calculation results

Segment No.	Depth, *h* (m)	Mean velocity, *v* (m/s)	Area, *A* (m²)	Partial discharge, Q_i (m³/s)
1	0.42	0.76	0.21	0.160
2	0.48	0.81	0.24	0.194
3	0.46	0.79	0.23	0.182
Total	—	—	—	**0.536**

The dependence of discharge on flow depth derived from Table 3 is presented in Figure 3, illustrating the sensitivity of total discharge to changes in water depth.

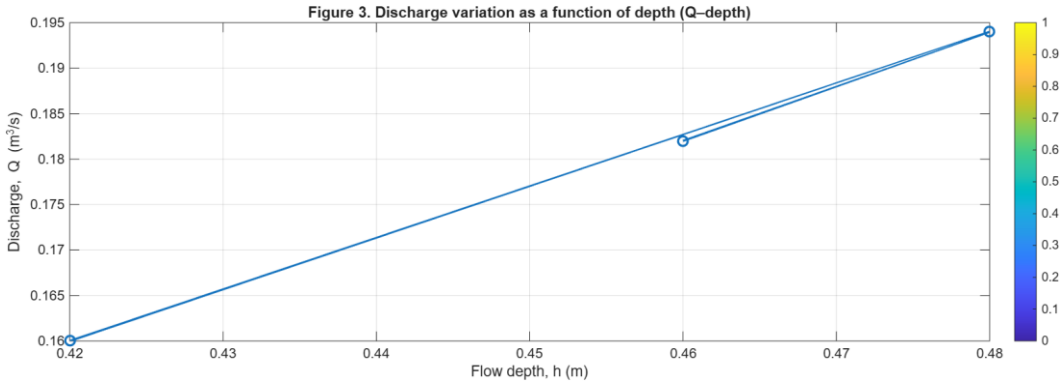

Figure 3. Discharge variation as a function of flow depth (Q–depth)

Temporal variation of discharge (Q–time)

To analyze temporal stability, discharge measurements were repeated at regular time intervals under steady inflow conditions.

Table 4. Discharge variation over time

Time (min)	Discharge, Q (m^3/s)
0	0.532
10	0.538
20	0.535
30	0.541
40	0.536

The time-dependent discharge variation is shown in Figure 4. The results demonstrate minor fluctuations around the mean discharge value, indicating stable hydraulic conditions and consistent performance of the current meter during the measurement period.

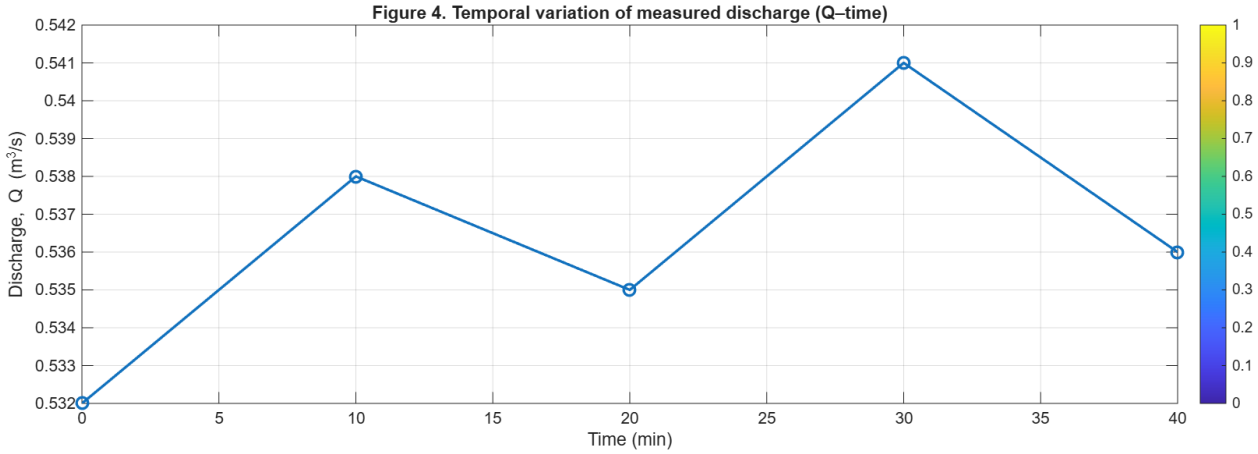

Figure 4. Temporal variation of measured discharge (Q–time)

The experimental results confirm a stable linear relationship between propeller rotational frequency and flow velocity, a characteristic vertical velocity distribution across the flow depth, and consistent discharge estimates obtained using the velocity–area method. These results provide a quantitative basis for evaluating the performance of the propeller-type current meter and serve as the foundation for further analysis in the Discussion section.

Conclusion. This study presented an experimental investigation and mathematical modeling of water flow velocity and discharge measurement using a propeller-type current meter. The applied methodology combined controlled laboratory measurements with analytical calibration and velocity–area integration, providing a systematic framework for evaluating the performance of mechanical current meters in open-channel flow conditions. The experimental results confirmed a stable linear relationship between propeller rotational frequency and local flow velocity within the investigated measurement range, validating the use of a linear calibration model for practical hydrometric applications. The observed vertical velocity distribution followed typical open-channel flow behavior, supporting the applicability of standard one-point and two-point measurement methods for estimating depth-averaged velocity. Discharge values calculated using the velocity–area method demonstrated consistent behavior with respect to both flow depth and time, indicating reliable measurement performance and stable hydraulic conditions during the experiments. Minor temporal variations in discharge were attributed to natural flow fluctuations rather than instrument-related errors, further confirming the robustness of the measurement approach. Overall, the findings highlight that propeller-type current meters remain effective and reliable instruments for measuring flow velocity and discharge in open channels when proper

calibration and measurement procedures are applied. The proposed experimental and analytical framework can be readily implemented in irrigation canals, rivers, and hydraulic engineering practice. Future work will focus on extending the analysis to unsteady flow conditions and comparing mechanical current meter performance with modern acoustic and electromagnetic measurement techniques.

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