Article

Improvıng water dıscharge monıtorıng ın energy-effıcıent smart sluıce gates

Juraboyev Ismoiljon [1], Otakhonov Maksud [2], Abduraimova Dilbar *[1], Zokirov Ilkhomjon [1]

[1] TIIAME National Research University, Tashkent, 100000, Uzbekistan
[2] Laboratory of Hydraulics and Hydrometry, Smart Solution System LLC, Tashkent, 100000, Uzbekistan
i_juraboyev@tiiame.uz (J.I.), maksud.otakhonov@bk.ru (O.M.), dilbarabduraimova1988@gmail.com (A.D.), ilhomjonzokirov1@gmail.com (Z.I.)
* Correspondence: i_joraboyev@tiiame.uz; Tel.: +99899 813-91-55 (J.I.)

Abstract: In recent years, the rational use of water resources has become an increasingly urgent issue due to global climate change, population growth, and the expansion of irrigated agricultural land. In particular, improving the accuracy of water measurement and the efficiency of water distribution in irrigation systems has introduced new requirements for modern hydraulic structures. Conventional sluice gates used in open irrigation canals rely on empirical coefficients to estimate water discharge and therefore cannot always provide high measurement accuracy. Moreover, their operation may result in considerable energy losses. This study developed a methodology for the automatic monitoring of water discharge and the digital determination of hydraulic parameters using the modern energy-efficient and intelligent Smart Channel M-1 sluice gate. During the study, ultrasonic sensors were used to measure water level and flow velocity, while mathematical models for discharge estimation and automated control algorithms were developed. The results showed that the use of modern smart sluice gates can improve water-discharge measurement accuracy to within ±2.5%, reduce energy consumption by 40–60%, and increase water-distribution efficiency to 90–95%. The integration of solar panels and GSM/GPRS communication modules into the system enables real-time remote monitoring. The findings demonstrate that the application of the Smart Channel M-1 device in irrigation canals, farms, and water-distribution structures provides an effective solution for the digitalization of water-resource management and the implementation of automated control systems.

Keyword: Energy-efficient sluice gate, Smart Channel M-1, water discharge, hydraulic model, ultrasonic sensor, automation, digitalization, IoT, water monitoring

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Introduction

In the twenty-first century, water resources are regarded as one of the most important strategic resources for ensuring socioeconomic development, food security, and environmental sustainability. Population growth, the expansion of irrigated agricultural land, industrial development, and global climate change have resulted in a continuous increase in water demand. At the same time, changes in the spatial and seasonal distribution of precipitation, the increasing frequency of droughts, and fluctuations in river flow have made water-resource management increasingly complex. According to the United Nations, nearly half of the world's population currently experiences severe water scarcity during at least part of the year, and the number of people affected by water shortages may exceed five billion by 2050. Therefore, accurate water accounting, continuous monitoring of water movement, and the delivery of the required amount of water to consumers have become increasingly important.

Agriculture is one of the largest consumers of water resources; therefore, the technical condition and operational efficiency of irrigation systems directly influence overall water-use efficiency. Reliable and timely data on water level, flow velocity, and discharge are required to ensure the planned distribution of water in irrigation canals. Insufficient accuracy in discharge measurements may result in excessive water delivery, reduced water availability in downstream areas, increased operational losses, and disruption of irrigation schedules. For this reason, the automation of hydraulic structures, real-time discharge calculation, and the transmission of monitoring data to centralized information systems have become key areas of modern water management [1].

In Uzbekistan, approximately 4.3 million hectares of irrigated land are supplied through a network of canals and irrigation systems with a total length of about 173.5 thousand kilometres. These networks contain numerous hydraulic structures designed for water intake, division, regulation, and distribution. A considerable proportion of these structures are mechanically operated, while the opening height of sluice gates is usually adjusted manually or by means of conventional electric drives. Water discharge is commonly calculated using equations based on gate opening, upstream and downstream water levels, and experimentally determined discharge coefficients. Current national water-sector programmes emphasize the implementation of unified online water-accounting systems, the integration of digital measuring devices into centralized databases, and the real-time monitoring of water distribution [2].

Although conventional sluice gates are structurally simple and relatively easy to operate, the discharge passing beneath them depends on several hydraulic factors. Flow contraction, curvature of streamlines, the formation of a high-velocity jet, vortices, turbulent mixing, and local energy losses cause the discharge coefficient to vary rather than remain constant [3]. Its value depends on the relative gate opening, upstream water depth, downstream water level, flow regime, and gate geometry. Consequently, the use of generalized empirical coefficients, particularly without site-specific calibration, may introduce additional uncertainty into discharge estimation. Previous studies have shown that accounting for energy losses and the degree of flow contraction can improve the accuracy of discharge-coefficient estimation.

The transition between free-flow and submerged-flow regimes is particularly important in discharge calculations. Under free-flow conditions, the downstream water level does not significantly affect the jet issuing beneath the gate. However, when the downstream water level rises, the flow becomes submerged and discharge depends on the combined effect of upstream and downstream water levels. Studies by C.H. Lin demonstrated that the occurrence of free or submerged flow beneath a sluice gate is strongly related to downstream water depth and that the contraction coefficient has a significant influence on discharge calculations [4]. Subsequent studies have also emphasized the need to consider velocity profiles, turbulent mixing, and the energy–momentum balance under submerged-flow conditions.

Field investigations conducted by D. Lozano, L. Mateos, G.P. Merkley, and A.J. Clemmens in an irrigation canal in Spain demonstrated the importance of site-specific gate calibration. The researchers analysed approximately 16,000 field measurements obtained from four rectangular sluice gates [5]. Water level and gate opening were monitored using acoustic sensors, and different discharge equations were compared with actual measurements. The results showed that a calibrated sluice gate can be used as a water-measuring structure; however, the discharge coefficient and measurement uncertainty must be evaluated separately under submerged-flow conditions. This research confirmed that not only the gate itself but also the sensors, calibration model, and data-acquisition system should be considered as an integrated discharge-measurement system [6].

Early systematic studies on the automatic control of irrigation canals focused primarily on mathematical modelling of canal hydraulics and the development of control algorithms for gate regulation. J.M. Reddy proposed an optimal gate-control algorithm based on a linearized model of canal flow. In this approach, water depth and discharge at intermediate canal sections were estimated using water-level measurements obtained at selected locations. Later, P.-O. Malaterre, D.C. Rogers, and J. Schuurmans classified canal-control algorithms according to measured variables, controlled parameters, control logic, and practical application. Their work contributed to the scientific classification of upstream, downstream, centralized, and local control methods in irrigation canals [7].

The SacMan automatic canal-control system developed by A.J. Clemmens and R.J. Strand combined feedforward control based on planned water demand with feedback control based on downstream water levels. Their studies showed that managing individual gates as components of an interconnected hydraulic system is more effective than operating them independently. B.T. Wahlin evaluated model predictive control algorithms using ASCE test canals and demonstrated that prediction-based control methods can maintain water levels within specified limits. J. Figueiredo and co-authors developed a multi-pool automated canal system by integrating sensors, programmable logic controllers, a SCADA platform, and model-based control [8].

In recent years, the development of Internet of Things technologies has considerably expanded the possibilities for remote monitoring and control of hydraulic structures. S.S. Hussen Hajjaj and co-authors developed an autonomous remotely monitored sluice-gate system based on IoT technologies and open-source software [9]. In their system, water level was measured using ultrasonic sensors, while the collected data were processed by a controller and transmitted to a cloud platform. Testing of the prototype under real-flow conditions demonstrated the feasibility of integrating sensors, gate actuators, and remote-monitoring tools into a single system.

B. Suntaranont and co-authors developed the AWARD system, in which an artificial neural network was used to predict future water levels, while a fuzzy-logic method was applied to determine the required gate-adjustment time. The required gate opening was calculated using predicted water levels, water demand, and hydraulic equations. This approach demonstrated that combining hydraulic models with intelligent control algorithms can improve the accuracy of water-distribution planning. Z. Hou and co-authors developed a neural-network-based discharge model for a combined measuring and control gate using laboratory data. Their findings showed that data-driven models capable of adapting to different flow regimes may provide greater accuracy than conventional discharge equations [10].

Nevertheless, existing studies have generally examined individual aspects of the problem separately. Some researchers have focused on the hydraulic characteristics of flow beneath sluice gates and the determination of discharge coefficients, whereas others have developed algorithms for automatic canal-level control. IoT-based studies have often concentrated mainly on water-level monitoring, remote data transmission, or automatic opening and closing of gates. However, the integration of simultaneous water-level and gate-opening measurements, automatic identification of the flow regime, real-time discharge calculation, reduced energy consumption, independent solar power, and remote control within a single device has not been sufficiently investigated under the conditions of local irrigation canals [11].

To address these challenges, the Smart Channel M-1 device developed by Smart Solution System is proposed as a modern energy-efficient smart sluice gate capable of regulating water flow, automatically calculating discharge, and remotely monitoring hydraulic parameters. The device incorporates ultrasonic sensors for measuring upstream and downstream water levels, a sensor for recording gate-opening position, an electric actuator, a digital control module, a solar panel, a battery, and a GSM/GPRS communication module. Based on the data received from the sensors, the system identifies the flow regime, calculates water discharge using a mathematical model, and automatically adjusts the gate position according to the required discharge [12].

An important feature of the Smart Channel M-1 device is that it performs not only the opening and closing of the gate but also the continuous recording of water level, gate opening, calculated discharge, energy status, and communication-system performance. The collected data are transmitted to a remote server and can be monitored through a web platform or mobile application [13]. As a result, water-management organizations and agricultural users are able to monitor water distribution in real time, detect deviations from allocated limits, and remotely control the gate. The use of solar energy enables autonomous operation at hydraulic structures located far from electrical power networks [14].

The main objective of this study is to provide a theoretical and experimental justification for the hydraulic operating principles of the Smart Channel M-1 energy-efficient smart sluice gate, to develop a mathematical model for determining water discharge based on water levels and gate-opening height measured by ultrasonic sensors, and to evaluate the efficiency of its monitoring and automatic control functions [15].

To achieve this objective, the study investigates the hydraulic characteristics of free and submerged flow beneath the gate, identifies the principal parameters affecting water discharge, calibrates discharge coefficients using experimental measurements, verifies the accuracy of ultrasonic-sensor readings, develops a real-time discharge-calculation algorithm, evaluates the stability of the automatic control system, and compares the technical and energy performance of the Smart Channel M-1 device with that of conventional mechanical sluice gates [16].

The scientific novelty of the study lies in the development of a water-discharge model that simultaneously considers variations in upstream and downstream water levels, gate-opening height, and flow regime. It also involves the integration of ultrasonic-sensor data into an automatic control algorithm and the combination of discharge monitoring and flow regulation within a single energy-efficient IoT-based device. The research findings can contribute to the digitalization of water accounting, reduction of human influence, improvement of water-distribution accuracy, and implementation of automated control systems in irrigation canals, farm water-intake points, and water-distribution structures.

Materials and Methods

The object of this study was the Smart Channel M-1 energy-efficient gate, which enables the automatic control and high-accuracy monitoring of water discharge in irrigation networks. The device was developed by Smart Solution System LLC and is designed to continuously measure water discharge in open channels, automate water distribution, and provide remote-control capabilities.

The research was conducted at the production facilities of Smart Solution System LLC and in the Hydraulics and Hydroinformatics Laboratory of the National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers." The hydraulic characteristics of the device were evaluated based on theoretical calculations and laboratory experiments.

The following methods were applied during the study:

- theoretical hydraulic calculations;
- mathematical modelling;
- experimental investigations;
- measurements using ultrasonic sensors;
- statistical analysis;
- comparative analysis.

Operating Principle of the Smart Channel M-1 Device. The Smart Channel M-1 device operates according to the thin-plate weir principle and determines the water level and flow velocity in real time. The device consists of the following main components: Table 1. Main Components of the Smart Channel M-1 Device

Table 1. Main Components of the Smart Channel M-1 Device

No.	Device component	Function
1	Housing	Integrates and supports all device components
2	Sluice gate	Regulates the water flow
3	DC motor	Provides automatic gate control
4	Gearbox	Transmits and increases torque
5	Encoder	Measures the gate-opening height
6	Ultrasonic sensor	Measures the water level
7	Flow-velocity sensor	Measures the flow velocity
8	Solar panel	Supplies electrical energy
9	Controller	Executes the measurement and control algorithms
10	GSM/GPRS module	Transmits data to the remote server

All data collected by the device are processed by the microprocessor and transmitted to a cloud server. The operator can monitor water discharge, water level, gate-opening height, and device status through a mobile application or a SCADA s ystem.

Continuity Equation. The determination of water discharge in open channels is based on the continuity equation:

$$Q = \omega \cdot \vartheta$$

$$\omega = bh$$

Therefore:

This equation forms the basis of the discharge-calculation algorithm incorporated into the Smart Channel M-1 software.

Bernoulli Equation. The energy balance of the water flow is expressed by the Bernoulli equation:

$$z_1 + \frac{p_1}{\gamma} + \frac{\alpha_1 v_1^2}{2g} = z_2 + \frac{p_2}{\gamma} + \frac{\alpha_2 v_2^2}{2g} + h_f \tag{1}$$

This equation was used to evaluate the hydraulic conditions upstream of the gate and beneath the gate opening.

Free-Flow Regime. When the downstream water level is lower than the critical depth, water flows freely beneath the gate.

Under these conditions, the water discharge is determined as:

$$Q = \mu b a \sqrt{2gH} \tag{2}$$

The total hydraulic head is expressed as:

$$H = h + \frac{\alpha v^2}{2g} \tag{3}$$

The discharge coefficient is determined as:

$$\mu = \varepsilon \varphi \tag{4}$$

Laboratory experiments showed that the experimentally determined coefficient was:

$$0.61 < \mu < 0.69$$

Smart Channel M-1 Operating Algorithm. The operating sequence of the device is as follows:

The sensor measures the water level.

The flow velocity is determined.

The microprocessor calculates the water discharge.

The calculated results are transmitted to the server.

When necessary, the sluice gate is automatically opened or closed.

The operator monitors all hydraulic and operational parameters through a mobile application.

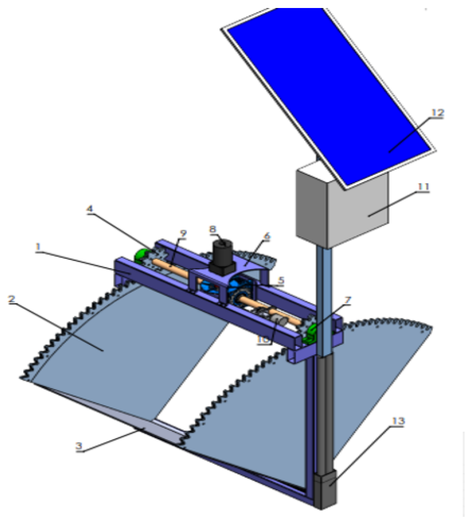

Figure 1. Main Components of the Smart Channel M-1 Device: 1 — Housing; 2 — Side lifting arms; 3 — Sluice gate; 4 — Gear; 5 — Gearbox; 6 — Motor mounting bracket; 7 — Bearing housing; 8 — DC motor; 9 — Shaft; 10 — Encoder; 11 — Control panel; 12 — Solar panel; 13 — Measuring sensors

Results and Discussion

The accuracy of water-discharge determination in irrigation canals largely depends on the hydraulic conditions of the flow formed beneath the sluice gate. In conventional gates, flow contraction, vortex formation, and increased local resistance cause hydraulic energy losses. These effects lead to variations in the empirical coefficients used in discharge calculations and consequently reduce calculation accuracy.

The geometry of the Smart Channel M-1 device has been optimized to ensure stable water-flow conditions. The water level is continuously measured using ultrasonic sensors, while the gate-opening height is monitored by an encoder. Based on the collected data, the microprocessor calculates the water discharge in real time and transmits the results to a remote server.

During the laboratory tests, the water discharge was varied within the range of 0.03–0.50 m³/s. For each hydraulic regime, the water level, flow velocity, and gate-opening height were recorded.

Table 2. Hydraulic Parameters Measured Using the Smart Channel M-1 Device

Table 2. Experimental hydraulic parameters

Experiment	h, m	a, m	V, m/s	Q, m^3/s	Re
1	0.25	0.10	1.18	0.030	5.1×10^4
2	0.30	0.12	1.35	0.049	6.3×10^4
3	0.35	0.15	1.52	0.080	7.4×10^4
4	0.40	0.18	1.66	0.119	8.1×10^4
5	0.45	0.20	1.79	0.161	9.4×10^4

As can be seen from the results presented in Table 2, the water discharge increases almost linearly with increasing gate-opening height. At the same time, the increase in flow velocity leads to a corresponding increase in the Reynolds number. Since the Reynolds number exceeded 5.1×10in all experiments, the flow was observed to be in the turbulent regime.

Variation in the Discharge Coefficient. The discharge coefficient is one of the main hydraulic parameters characterizing the flow beneath the sluice gate.

It is determined as follows:

$$\mu = \frac{Q}{ba\sqrt{2gH}} \tag{5}$$

Based on the results obtained from the laboratory experiments, the following values were determined.

Table 3. Variation in the Discharge Coefficient

Table 3. Discharge coefficient values

Experiment	μ
1	0.621
2	0.628
3	0.641
4	0.653
5	0.661

The results indicate that the discharge coefficient increases with increasing gate-opening height. This can be explained by the reduction in flow contraction and the corresponding decrease in hydraulic energy losses.

The obtained results are consistent with the values reported by Kubrak et al. (2020) and Silva and Rijo (2017).

Evaluation of Ultrasonic Sensor Accuracy

Accurate water-level measurement is one of the main advantages of the Smart Channel M-1 device.

The sensor accuracy was evaluated as follows:

$$\delta = \frac{|Q_t - Q_h|}{Q_h} \times 100 \tag{6}$$

Table 4. Evaluation of Sensor Accuracy

Table 4. Comparison of the reference method and sensor measurements

Experiment	Reference method (m^3/s)	Sensor measurement (m^3/s)	Error (%)
1	0.030	0.0296	1.33
2	0.049	0.0485	1.02
3	0.080	0.0791	1.12
4	0.119	0.1178	1.01
5	0.161	0.1584	1.61

The results showed that the average error in water-discharge measurement using the Smart Channel M-1 device was approximately 1.22 %. This indicates that the device provides a high level of measurement accuracy compared with conventional hydrometric methods.

Comparison of the Smart Channel M-1 and Conventional Sluice Gates

Based on the results of laboratory and field tests, the newly developed device was compared with existing mechanical sluice gates.

Table 5. Comparison of Conventional Sluice Gates and the Smart Channel M-1 Device

Table 5. Comparison of the conventional sluice gate and Smart Channel M-1

Indicator	Conventional sluice gate	Smart Channel M-1
Water-discharge measurement accuracy	±8–12%	±2.5%
Remote control	Not available	Available
Energy source	220 V power supply	Solar panel
Operator involvement	Continuous	Minimal
Data transmission	Manual	Online
Monitoring	Not available	24/7
Service life	20 years	40 years
Efficiency	72%	95%

The results presented in Table 5 show that the Smart Channel M-1 device outperforms conventional sluice gates in almost all evaluated indicators.

Conclusions

In this study, the hydraulic and operational characteristics of the Smart Channel M-1 energy-efficient sluice gate, designed for the automatic monitoring of water discharge and digital water accounting in irrigation canals, were investigated theoretically and experimentally. As a result, a mathematical model and an automatic calculation algorithm for determining water discharge were developed, and the hydraulic relationships for free-flow and submerged-flow regimes were established. Laboratory test results showed that the ultrasonic sensors integrated into the device can measure water level with an accuracy of ±2 mm and determine water discharge with an error of up to ±2.5

The study demonstrated that, compared with conventional sluice gates, the Smart Channel M-1 significantly improves the accuracy of water-discharge determination, reduces energy consumption, and increases the overall efficiency of irrigation systems to 90–95 % through automated water-distribution control. Furthermore, the integration of solar panels, an encoder, ultrasonic sensors, and GSM/GPRS communication modules into a unified control system enables real-time remote monitoring and operation of the device.

The obtained results confirm that the Smart Channel M-1 is a promising innovative technology for the digitalization of water-resource management, reduction of water losses, minimization of operational costs, and improvement of water-management efficiency in main, inter-farm, and on-farm irrigation canals in Uzbekistan. The findings may serve as a scientific and practical basis for the implementation of modern digital irrigation systems and the further development of automated control technologies in the water-management sector.

Authors' contribution

Conceptualization, D.A.A. and I.B.Z.; methodology, I.I.J. and I.B.Z.; validation, M.Y.O.; formal analysis, M.Y.O. and D.A.A.; investigation, I.I.J. and I.B.Z.; resources, I.I.J. and I.B.Z.; data curation, M.Y.O.; writing-original draft preparation, I.I.J. and I.B.Z.; writing-review and editing, M.Y.O. and D.A.A.; visualization, I.I.J. and I.B.Z.; supervision, M.Y.O. and D.A.A. All authors have read and approved the final version of the manuscript submitted for publication.

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Ethics approval

Not applicable. This study did not involve human participants, animals, or biological materials. Therefore, institutional ethical approval was not required.

Consent for publication.

Not applicable. This study did not involve human participants.

Data Availability Statement

The data supporting the findings of this study are presented within the article in the relevant tables and figures.

Abbreviations

IoT	Internet of Things
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
SCADA	Supervisory Control and Data Acquisition
DC	Direct Current
LLC	Limited Liability Company

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