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Research and improvement of water metering structures for irrigation systems with non-steady flow conditions in agricultural water use

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Abstract. This article examined the problem of improving the accuracy of water metering at water-metering facilities in irrigation systems operating under variable head conditions and subject to intensive siltation. The relevance of this research stems from the need to ensure accurate water flow measurement under unstable hydraulic conditions and the accumulation of bed sediments, which significantly affect the reliability of the structures and the efficiency of water resource allocation. The accuracy of water metering is of vital importance to agriculture, as it affects compliance with irrigation regimes, the rational use of water and the sustainable water supply to the agricultural sector. Insufficient measurement accuracy can lead to water wastage, disruption to irrigation schedules and reduced crop yields. The aim of this study was to develop and provide a hydraulic justification for an improved diaphragm design that ensures measurement stability and reduces the impact of sediment. The study utilised methods of hydraulic calculation, comparative design analysis and modelling of the structure's operation under various flow regimes and head levels. The influence of the orifice geometry, the position of the bottom opening and the diaphragm configuration on the flow pattern and sediment accumulation processes was assessed. The results showed that, to improve the accuracy of water metering, it is advisable to use two types of diaphragm: a flat plate with an adjustable bottom opening and a design with a fixed opening. It was established that the adjustable opening reduces silting, prevents the cross-section from becoming blocked and stabilises the flow characteristics. The design with a fixed orifice is effective under stable operating conditions. Calculation data confirm a reduction

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in measurement error, an increase in the stability of the flow coefficient and an improvement in the long-term operational reliability of the structure. The practical value of this work lies in the ability to adapt water metering units to various conditions without complicating the design. The proposed solutions contribute to improving water use efficiency and enhancing water distribution management in irrigation systems

Keywords: water metering structure; adjustable diaphragm; bottom outlet; sedimentation; water metering accuracy; Chüy Valley

Introduction

Rational management of water resources is a key factor in the sustainable development of agriculture in Kyrgyzstan, where agricultural production is directly dependent on irrigation systems and limited water resources. The efficiency of water supply affects crop yields, economic stability and food security, and in the context of climate variability, there is a growing need for accurate water metering and rational water distribution. Research by M. Ubaydullaev *et al.* (2024) shows that the main problems relate to the dilapidated state of irrigation networks, insufficient funding and shortcomings in water management, which reduce the efficiency of land use. Consequently, there is a need to modernise existing systems, develop new irrigation networks and improve funding mechanisms. According to FAO (2022), over 90% of agricultural production in Kyrgyzstan depends on irrigated land. The intensification of climate change is leading to water shortages, which have already caused significant crop losses during periods of drought. This is linked to rising temperatures, increased water consumption by crops and a reduction in river flow. Under these conditions, the role of modern monitoring systems, which enable more accurate accounting of water resources, is becoming increasingly important. At the same time, the operation of irrigation canals involves complex hydraulic processes, including fluctuations in water levels, backwater effects and the accumulation of bed sediments. Siltation of the canals alters the flow pattern and reduces flow capacity, which adversely affects the accuracy of water-metering facilities. Additional errors arise due to changes in hydraulic conditions, under which traditional measuring devices do not always function correctly. The operation of irrigation systems is accompanied by complex hydraulic processes, including fluctuations in water levels, non-uniform flow velocities and the influence of head in the lower reach. A significant factor is the transport and accumulation of bed sediments, whilst the silting up of river channels reduces flow capacity and alters the hydraulic characteristics of the flow. Water gauging structures are particularly sensitive to these changes, as the accuracy of water flow measurement depends on their precise operation. In his research, K. Beishekeev (2010) notes the need to develop improved water gauges for channels with extremely turbulent flow and proposes a new design, the effectiveness of which has been confirmed by laboratory studies.

N. Li *et al.* (2026) established that the presence of bed sediments in the vicinity of water-measuring devices leads to a distortion of the flow velocity profile and a redistribution of energy, causing deviations in actual water flow rates from calculated values. Backwater from the downstream reach also has a significant effect, altering the hydraulic flow regime and reducing the reliability of measurements. In this regard, water-metering structures must not only meet accuracy requirements but also ensure strength, stability and durability when subjected to hydraulic loads, filtration processes and possible deformations, which is a prerequisite for their effective and safe operation in irrigation systems. The paper notes that sediment deposition is one of the key factors affecting the accuracy of water metering in irrigation canals. The authors established that sediment concentration determines the thickness of the deposits, whilst the hydraulic parameters of the flow – discharge and bed gradient – regulate the rate at which they accumulate. At the same time, sediment accumulation leads to a rise in the water level and a systematic overestimation of the calculated discharge, with errors potentially reaching significant values under unfavourable hydraulic conditions. The results obtained confirm that channel siltation significantly distorts the relationship between water level and discharge, a factor that must be taken into account in the operation and design of water-measuring structures.

An important avenue for improving the efficiency of water use is the refinement of the designs of water-measuring structures used in irrigation canals, as traditional devices, such as diaphragms and weirs, do not always ensure accuracy under unstable hydraulic conditions, siltation and variable head. W. Liang *et al.* (2026) highlight the need to develop new or upgraded design solutions. As a promising approach, a deformation device has been developed for measuring flow rate in open channels, combining accuracy, portability and low cost. A theoretical model demonstrated a parabolic relationship between velocity and the square root of deformation, whilst the optimal plate parameters ensured an average error of less than 5%, outperforming traditional propeller flowmeters. Such a device is particularly relevant for Kyrgyzstan's irrigation systems, where outdated hydraulic structures lead to water losses, uneven flow and limited controllability, thereby reducing the overall efficiency of water use.

Recent studies, including the work of A. Batykova *et al*. (2024), note that soil cover forms the basis of sustainable agriculture and depends to a large extent on rational water management. Disruptions to irrigation regimes lead to waterlogging or water shortages, causing salinisation, soil degradation and a decline in soil fertility. These problems are particularly acute in irrigation systems with non-steady-state flow regimes, where fluctuations in water levels and flow rates make it difficult to regulate water supply accurately. Inadequate accuracy in water metering under such conditions leads to uneven water distribution and exacerbates negative processes in the soil. In this regard, improving the design of water metering structures that operate effectively under non-steady-state hydraulic conditions is a key area for enhancing the accuracy of water metering, optimising water distribution and ensuring the sustainability of irrigated land. In the work by A. Sabitov & I. Uraiimov (2023), it is noted that the use of accurate and real-time methods for measuring water flow in open channels and pipelines is key to the effective management of water resources. One such method is point-based flow measurement in trapezoidal channels and circular pipes, which enables the collection of real-time data for adjusting water distribution and improving the accuracy of metering under actual operating conditions. Research by A. Batykova *et al*. (2023) notes that organising the efficient use of land and water resources within a system of water users' associations requires a comprehensive approach combining rational land use and sustainable water distribution. In the current context, the development of irrigation systems is focused not only on improving organisational management mechanisms (such as hydro-units and water users' association service zones), but also on the introduction of innovative engineering solutions.

The development of irrigation systems in the Kyrgyz Republic requires the introduction of modern water resource management technologies and the improvement of hydraulic structures. In this regard, the development of innovative engineering solutions aimed at improving water use efficiency and the sustainability of irrigation systems takes on particular significance. Of particular importance in this regard is the development of water-metering devices capable of adapting to changing flow conditions and ensuring the stability of hydraulic characteristics in irrigation networks. Taking into account factors such as variable head, channel siltation and flow irregularities is becoming an important part of both the technical and organisational aspects of water management. Despite the progress made, issues concerning the operational stability of water metering structures when exposed to these factors remain insufficiently studied, which necessitates further research aimed at improving the accuracy of metering and the rational allocation of water resources in irrigated agriculture. A number of studies have examined the use of new types of flow meters. In their paper, Y. Sun *et al*. (2024) note that the vane flowmeter offers an effective method for measuring water flow in small-diameter channels. Thanks to its simple design, resistance to silting and the stable relationship between deflection angle and flow rate, this device demonstrates high potential for improving measurement accuracy.

The aim of this study was to provide a hydraulic justification for improved designs of water meter diaphragms, aimed at enhancing their operational stability and the accuracy of water flow measurement under conditions of variable hydraulic regimes and severe silting.

Materials and Methods

The study was conducted under laboratory and semi-industrial conditions to assess the hydraulic efficiency of improved designs for water-metering structures with diaphragms, intended for measuring water flow in open irrigation canals. The experimental part of the study was carried out on a hydraulic test rig simulating the operating conditions of on-farm irrigation systems in the Kyrgyz Republic, taking into account the characteristic parameters of channel flow, sediment content and water level variability. The experimental setup comprised inlet and outlet channels with rectangular cross-sections, a water-measuring diaphragm with adjustable and fixed water-passage openings, water-level gauges for determining the hydraulic parameters of the flow, and a device to ensure a submerged flow regime. The length of the test section was 6.0 m, the channel width was 0.8 m, and the average flow depth varied between 0.30 and 1.00 m. The water-level gauges were installed in the upper and lower reaches directly adjacent to the diaphragm, and water-level readings were taken after the flow had stabilised, i.e. once a steady-state flow regime had been reached for each specified opening of the outlet. The flow velocity was regulated by varying the head and the water discharge in the system. As part of the study, two modifications of the diaphragms were developed and tested.

An adjustable diaphragm in the form of a flat metal plate 3-5 mm thick, fitted with a rounded lower element of radius R = 0.15 m, designed to reduce turbulence and minimise local hydraulic losses. A non-adjustable diaphragm in the form of a fixed wall, made of metal, reinforced concrete or concrete, with a separately mounted rounded element secured by bolted connections.

The geometric characteristics of the structures were determined taking into account the typical operating conditions of the irrigation canals in the Chüy Valley. The height of the water outlet varied between 0.30 and 0.40 m, whilst the length of the outlet was taken to be equal to the width of the channel at the bottom, which prevented lateral compression of the water jet. The radius of curvature of the lower edge was calculated based on the maximum water depth in the upper reach and determined by the following equation:

$$R \approx 0{,}2H_{Bmax}, \quad (1)$$

where R is the radius of curvature of the lower edge, and H_{Bmax} is the maximum water depth in the upper reach.

The experimental studies were carried out sequentially in several stages. In the first stage, the initial hydraulic parameters of the flow were determined: water discharge, depth, flow velocity and the head difference between the upper and lower reaches. In the second stage, the diaphragm structure under investigation was installed and various flow regimes were modelled, including free-flow and submerged-flow conditions. The submerged flow regime was created and maintained using a weir and a depression in the riverbed in the lower reach; the submerged nature of the flow was monitored visually by checking the water level in the intake section of the structure relative to the weir crest elevation before each series of measurements. During the third stage, multiple measurements of flow parameters were carried out at various values of the orifice opening and head level. The study is based on an analysis of existing water-measuring structures with diaphragms, the hydraulic behaviour of flow through openings under submerged conditions, and calculations of the discharge coefficient using formula (1): The main parameters measured were: water discharge (Q, m^3/s); head (Z, m); height of the water passage opening (h_(op), m); effective cross-sectional area of the flow (ω, m^2); discharge coefficient (μ); stability of the hydraulic regime; and the rate of sediment accumulation upstream of the structure. The water discharge Q at each measurement stage was determined by calculation using Equation (1), based on directly measured values of the head Z and the effective cross-sectional area ω, whilst the obtained values of the discharge coefficient μ were used for the subsequent assessment of the hydraulic efficiency of the diaphragm structures under investigation.

The water flow rate was determined using the following relationship:

$$Q = \mu\omega\sqrt{(2gz)}, \quad (2)$$

where Q is the water flow rate (m^3/s), μ is the discharge coefficient, ω is the effective cross-sectional area of the flow (m^2), g is the acceleration due to gravity (9.81 m/s^2), and z is the difference in water levels between the upper and lower reaches, m.

To improve the reliability of the measurements, each experiment was repeated at least five times, after which the mean values of the measured parameters were calculated. The reproducibility of the results was verified by comparing the experimental data from repeated tests and analysing measurement deviations. The permissible error in determining water flow did not exceed ±3-5%, which meets the requirements for hydrometric studies of open irrigation channels. A comparative assessment of the effectiveness of the proposed designs was carried out according to the following criteria: the value of the discharge coefficient (μ); stability of the hydraulic regime; the extent of local energy losses; resistance to silting; accuracy of water flow measurement; and operational reliability of the structure. Methods of hydraulic analysis, comparative modelling and statistical processing of experimental data were used to analyse the results. Calculations and the processing of measurement data were carried out in Microsoft Excel, which made it possible to identify patterns in the variation of the discharge coefficient under different operating conditions of the structure and to verify the results obtained by comparing them with existing hydraulic models and data from recent studies.

Bernoulli's equation was formulated for cross-sections 1-1 and 2-2, which pass through the free surface of the flow in the upper and lower reaches, respectively. The reference plane 0-0 was taken at the level of the excavation (sump) of the water-measuring structure. To analyse the hydraulic conditions, a free-flow scheme is considered, reflecting the main characteristics of flow motion in the absence of head. Figure 1 shows the free-flow scheme.

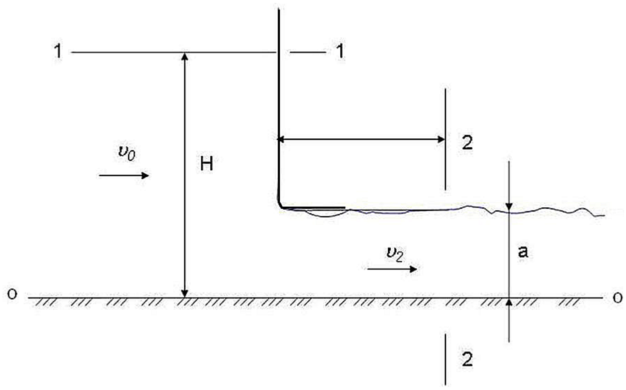

Figure 1. Free-flow diagram
Source: compiled by the authors

The flow rate of the submerged flow through the water meter:

$$Q = \mu\omega_2\sqrt{2gz}, \quad (3)$$

where Q – water flow rate through the water metering structure, m^3/s; μ – discharge coefficient; ω_2 – area of the outlet orifice, m^2; z – effective head, m; g – acceleration due to gravity, 9.81 m/s^2.

Results and Discussion

Traditional diaphragm designs used in open-channel water metering structures are characterised by a number of design features that limit their hydraulic efficiency. These features include the presence of a sill beneath the flow opening, jet constriction around the perimeter of the opening, and a relatively short length of the opening relative to the channel width. Taken together, these factors lead to a reduction in the structure's flow capacity and a decrease in the accuracy of water flow measurement. Hydraulic studies of water-metering structures have noted that the presence of a sill and sharp edges causes additional local energy losses, as well as contributing to an uneven distribution of velocities within the flow. Recent laboratory studies by Z. Wenzheng *et al.* (2024) also confirm that the geometry of the restricting elements and the nature of the inlet weirs significantly influence velocity distribution, turbulence and the actual flow rate in critical sections of the channels, leading to flow rates lower than theoretical values, all other things being equal.

A schematic diagram of an improved water-measuring structure with a diaphragm, comprising inlet and outlet channels, a depression in the riverbed, a diaphragm with a water-passage opening, and level gauges installed in the upper and lower reaches. Figure 2 illustrates the structural features of the structure and the relative positions of its main components.

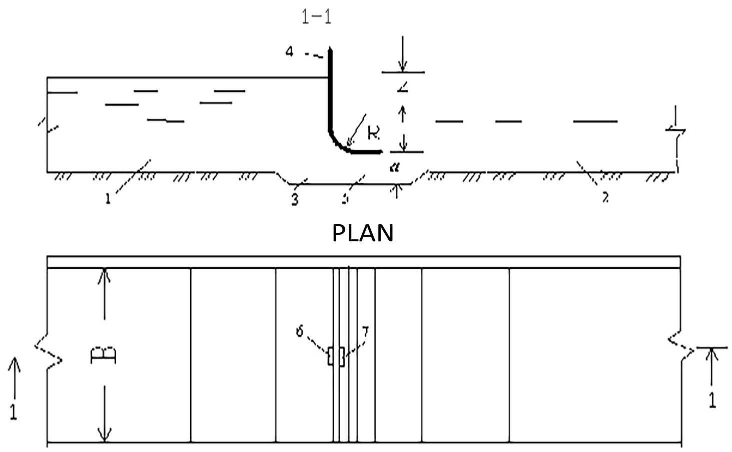

Figure 2. Schematic diagram of an improved water-measuring structure with a diaphragm
Note: 1 – inlet channel; 2 – outlet channel; 3 – recess in the channel bed; 4 – diaphragm; 5 – water passage; 6 – water level gauge in the upper reach; 7 – water level gauge in the lower reach
Source: developed by the authors

The design features of the improved formwork developed by M.V. Butyrin, as well as its spatial configuration and main elements, are shown in Figure 3, which illustrates front and side views of the structure.

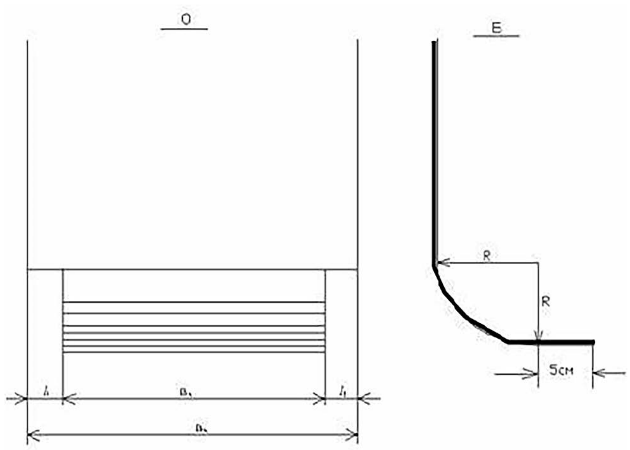

Figure 3. Improved shield designed by M.V. Butyrin
Note: a – front view; b – side view
Source: prepared by the authors

To ensure a submerged flow regime, special design solutions are employed to regulate flow conditions and enhance the stability of the hydraulic regime. Figure 4 shows diagrams of the device for ensuring a submerged flow regime, including a sluice gate and a depression in the riverbed.

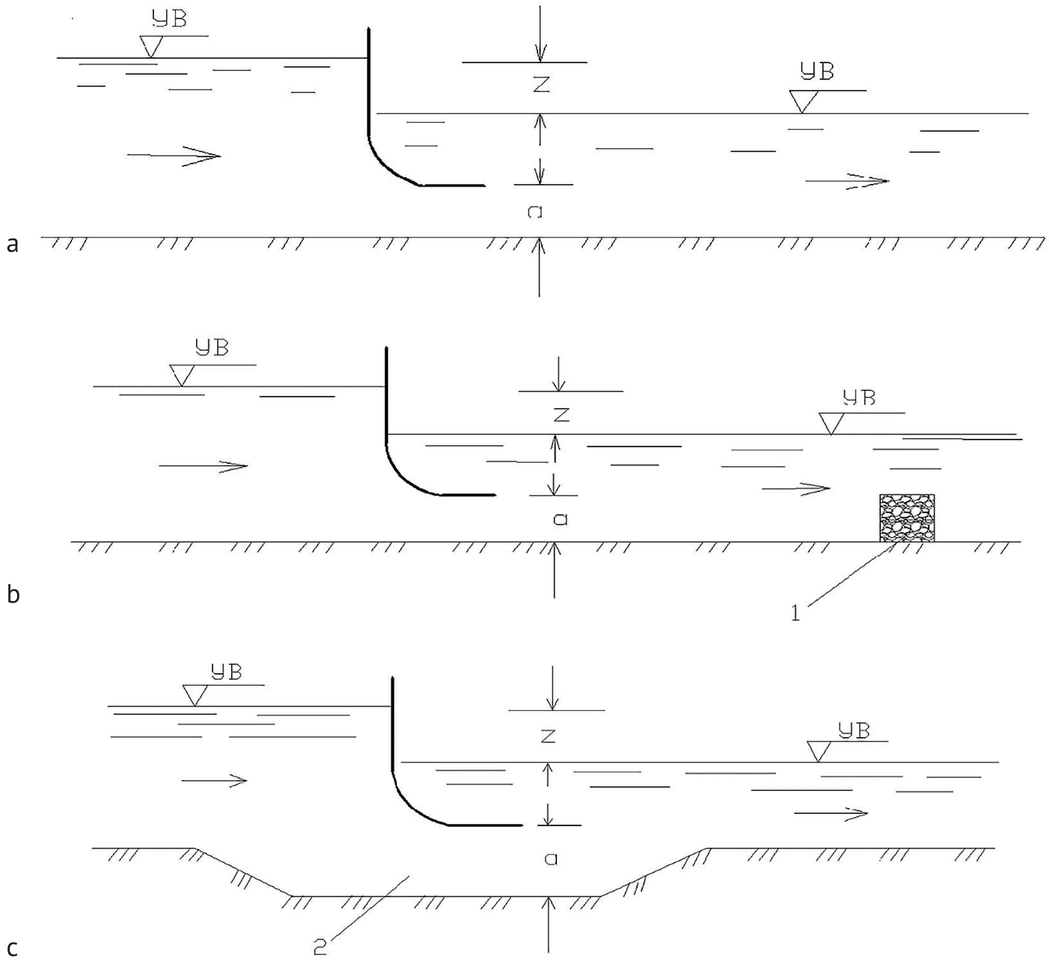

Figure 4. Schematic diagrams of devices for ensuring a submerged flow regime

Note: 1 – sluice weir; 2 – depression in the riverbed

Source: compiled by the authors

The paper by A. Nicosia *et al.* (2023) demonstrates that the outflow process from a linear constriction under free-flow conditions can be modelled using dimensional analysis and conditions of incomplete self-similarity. The proposed equation relating flow rate to the stage is characterised by an exponent close to 2 and a coefficient dependent on the angle of inclination of the device's side walls relative to the channel bank, which provides an accurate estimate of the flow rate with an error of less than ±3% in 93.7% of cases. In conventional water-meter diaphragm designs, the water flow passing through the orifice experiences jet compression along the vertical and horizontal boundaries, which leads to a reduction in the effective flow area. The presence of sharp edges and weirs increases flow turbulence and energy losses. This is particularly noticeable in irrigation canals with high levels of bed sediment: sediment deposition upstream of the weir gradually alters the geometry of the structure and impairs flow conditions. The proposed linear constriction device is characterised by its simple design, ease of installation, low cost and high measurement accuracy, making it an effective solution for practical water metering.

In later designs of water-measuring diaphragms, improvements were proposed aimed at eliminating these shortcomings. In the improved designs (Fig. 3), the sill beneath the orifice was completely removed, and the lower edge of the orifice was formed as a smooth radial curve. The radius of curvature is taken to be approximately $R \approx 0.2H_{Bmax}$, where H_{Bmax} is the maximum water depth in the upper reach. Furthermore, the length of the opening was increased to match the width of the channel at the bottom, which made it possible to virtually eliminate lateral compression of the jet. These design modifications significantly improved the hydraulic performance of the structure.

Furthermore, box-type spillway stabilisers are widely used in the irrigation systems of the Kyrgyz Republic; these stabilise the water flow and reduce local hydraulic losses. The use of such devices ensures a uniform distribution of flow even when the water level in the canal fluctuates. Mathematical modelling of the proposed spillway stabiliser has made it possible to determine a pressure range of $H_{max}/H_{min} = 3.0$ and a hydraulic coefficient of c = 2 m/s. The results of the study confirm the high efficiency of the stabilisers in reducing turbulence and maintaining a steady water flow rate, complementing the effects achieved by improved water meter diaphragm designs. Based on experimental measurements of flow rates and water levels, flow coefficient values were obtained for various operating modes of the structure. The results of the calculations are presented in Table 1.

Table 1. Results of determining the discharge coefficient μ

Experiment No.	Head difference Z, m	Opening height h_(op), m	Flow rate Q, m^3/s	Area ω, m_2	Discharge coefficient μ
1	0.20	0.30	0.125	0.090	0.95
2	0.25	0.30	0.145	0.090	0.96
3	0.30	0.35	0.180	0.105	0.97
4	0.35	0.35	0.205	0.105	0.98
5	0.40	0.40	0.240	0.120	0.99

Source: developed by the authors based on the results of experimental studies

As can be seen from Table 1, the obtained values of the discharge coefficient lie within the range μ ≈ 0.95-0.99, which confirms the high hydraulic efficiency of the proposed designs. There is a consistent trend towards an increase in μ as the head difference increases and the orifice parameters are optimised. The calculations presented directly confirm the experimental and theoretical principles of the research methodology and demonstrate its applicability for evaluating the performance of water-measuring structures with a rounded lower edge and box-type structures.

When analysing water flow through a diaphragm, Bernoulli's equation, expressed for the cross-sections upstream and downstream of the nozzle, is taken as the basis. Since the pressure in both cross-sections is the same (atmospheric), and given that, with a submerged outlet, the water depths in the upper and lower reaches are similar and the channel width remains constant, the velocity head at the inlet can be disregarded. As a result, the equation is significantly simplified. Under these conditions, the difference in water levels between the upper and lower reaches is effectively equal to the head loss. In other words, the entire difference in water levels is expended on overcoming local resistance as the flow passes through the nozzle. Energy losses are determined by the total coefficient of local resistance, which is the sum of the resistance at the inlet to the nozzle and at its outlet. For the design under consideration, this coefficient is small (approximately 0.13), indicating relatively favourable hydraulic flow conditions. By equating the difference in levels to the head loss, an expression for the average flow velocity within the nozzle is obtained. Analysis shows that the velocity is slightly less than the theoretical (ideal) velocity of free flow. This reduction is accounted for by the velocity coefficient, which in this case is approximately 0.94. Since there is no jet compression (the compression coefficient is taken to be equal to one), the discharge coefficient coincides with the velocity coefficient. Consequently, the actual flow rate through the nozzles is approximately 94% of the theoretical value, which indicates a sufficiently high hydraulic efficiency of the design under consideration. Consequently, when determining the flow rate of submerged flow, there is no need to take into account the approach velocity υ_0. Knowing the flow equations for free and submerged flow, it is possible to determine the head H_1 in the upper reach of the weir, since under actual operating conditions it is precisely through this value that the construction height of the hydraulic structure with the weir can be determined. The head (or water depth) upstream of the diaphragm is determined at the maximum flow rate of the hydraulic structure as the sum of the difference in water levels between the upper and lower reaches and the water depth downstream of the nozzles (in the intake section of the structure). Thus, the water level upstream of the diaphragm depends on both the hydraulic head and the conditions in the lower reach. The head difference, in turn, is related to the water flow rate through the opening (nozzles), with the flow rate being determined taking into account the discharge coefficient, which reflects the effects of jet compression and hydraulic losses. The geometric characteristics of the opening, in particular its area, also have a direct influence on the structure's flow capacity.

The opening in question is rectangular in shape, with its width taken to be equal to the width of the channel, which ensures a uniform flow and simplifies the hydraulic calculations. The water depth in the lower reach (intake) is determined as the sum of the so-called service depth in the discharge channel and the additional depth resulting from the operating conditions of the intake section of the structure. The design depth is determined using established hydraulic equations for uniform water flow, in particular using equations of the Chazé type, which take into account the effective cross-sectional area, the hydraulic radius and the channel gradient. The depth of the receiving section, given a fixed outlet height, must ensure that the intake is submerged from the downstream side even at minimum flow rates. This condition is important for the stable operation of the structure and accurate water metering. O. Baev (2023) notes that, when designing and operating irrigation canals and water-metering structures, it is necessary to take into account the interrelationship between the hydraulic parameters of the flow and the structural characteristics of the structures, drawing on classical methods of hydraulic calculation. In particular, research into the hydraulics of irrigation canals has demonstrated the applicability of various types of design problems, enabling the determination of flow capacity, gradient, roughness coefficient, flow depth and the dimensions of the canal's cross-section, which together provide a reliable description of the hydraulic regime. Under steady-state flow conditions in the inlet, the intake depth must be determined taking into account the geometric parameters of the structure, the normal water depth in the channel and an additional depth margin, as specified by regulatory guidelines. This margin is necessary to ensure that the inlet is fully submerged and to prevent disruption of the hydraulic regime. Overall, the analysis carried out shows that the flow parameters, including water depth, discharge and channel characteristics (including the roughness coefficient), are interrelated and must be considered holistically – taking into account both the hydraulic behaviour of the flow and the structural features of the water-measuring structure, which is in line with modern approaches to the calculation and design of irrigation systems. The energy state of the water flow in the nozzle can be determined by comparing the height of the orifice (nozzle)α with the critical depth, which is determined using the following formula:

$$h_{np} = \sqrt[3]{\frac{\alpha \cdot q^2}{g}}, \tag{4}$$

where h_{np} is the critical flow depth; α is the Coriolis coefficient, $\alpha = 1.08/52/$; q is the specific water flow rate, $g = \frac{Q}{b}$; g is the acceleration due to gravity, $g = 9.81$ m/s^2.

If the orifice height $a > h_{np}$, the flow condition in the nozzle is laminar; if $a < h_{np}$, it is turbulent. The energy state of the flow in the nozzle can also be determined by the Froude number – *Fr.* In the case of turbulent flow in the nozzle below the diaphragm, the task of measuring flow rate becomes more complicated, as a hydraulic jump occurs in the lower run-out section of the water meter. When the surface roller of the hydraulic jump is positioned above the orifices of the proposed water meter, a flow regime known as "submerged flow" arises, which is intermediate between free and submerged flow. In this regime, the flow rate for submerged flow is determined by the formula:

$$Q = \mu \cdot a \cdot b\sqrt{2g \cdot (H_0 - h_z)}, \tag{5}$$

where Q is the volumetric flow rate of the fluid; μ is the discharge coefficient; a is the orifice height; b is the orifice width; g is the acceleration due to gravity; H_0 is the head taking into account the approach velocity in the upper stilling basin; h_z is the depth at the outlet of the nozzle.

As can be seen from the equation, determining the flow rate under this flow regime becomes ambiguous. In addition to the dimensions of the orifices *a* and *b,* the flow coefficient of the nozzle and the geometric head in the upper reach *H*, it is also necessary to know the approach velocity υ_0 (which, in the case of a submerged flow, has practically no effect on the determination of the flow rate) and the depth at the centreline of the hydraulic channel h_z. When considering the hydraulic scheme of a submerged outflow through the proposed water-measuring device with a diaphragm and bottom nozzles, the elimination of the trapezoidal channel cross-section presents certain specific challenges. In particular, the bottom nozzle is limited by the width of the channel at the bottom, i.e. it has a cross-sectional dimension of $a \cdot b$, whilst the side sections on the channel slopes are covered by an impermeable diaphragm. When analysing the flow scheme, these additional side walls must be taken into account, as they may lead to a slight reduction in the flow meter's discharge coefficient. Parabolic flume channels and the structures installed within them possess specific hydraulic characteristics, and their actual flow capacity depends on the roughness coefficient of the watercourses, as well as the design features of the bottom inserts and diaphragms. The authors emphasise that, when designing and operating water-metering, water-release and network structures, it is necessary to take into account the influence of lateral constraints on the accuracy of water flow measurements, which is particularly important for the sustainable operation of irrigation systems in the Kyrgyz Republic (Mambetov *et al.*, 2022). If the bottom orifice of the nozzle extends across the entire lower part of the channel cross-section, i.e. has a trapezoidal shape, then the theory presented here also requires refinement, as the flow rate through a narrow orifice cannot be determined using the small-orifice model when $a < 0.1$H. In this case, the flow rate through a large trapezoidal orifice can be determined using:

$$Q = \mu \cdot \sqrt{2g} \int_{H_1}^{H_2} b_2 \cdot \sqrt{2 \cdot d_z}, \tag{6}$$

where Q is the fluid flow rate (volumetric flow rate, m^3/s); μ is the discharge coefficient; g is the acceleration due to gravity (≈9.81 m/s^2); H_1 and H_2 – integration limits corresponding to the head at the upper and lower edges of the orifice (nozzle); b_2 – variable width of the trapezoidal orifice; z – current depth.

The results of hydraulic studies show that the use of rounded lower edges on water-measuring diaphragms and the use of box-type spillway stabilisers make it possible to reduce local energy losses and increase the discharge coefficient. Most experimental studies note that the discharge coefficient in designs with a rounded edge can increase by 5-10% compared with designs with sharp edges. Calculations carried out as part of this study confirm these findings: the obtained values of the discharge coefficient lie within the range $\mu \approx 0.95$-0.99. This indicates the high hydraulic efficiency of the proposed solutions and their stability under various flow conditions, whilst the combined use of a box-type stabiliser provides additional flow stabilisation and reduces pressure fluctuations.

A diagram of the improved water-measuring structure with a diaphragm is shown in Figure 2. The design comprises inlet and outlet channels, a recess in the channel bed, a diaphragm and a water passage. Water levels are monitored using level measuring rods in the upper and lower reaches. The depression in the channel bed ensures a submerged flow regime. The submerged regime is considered one of the most stable operating regimes for water gauging structures, as the influence of external factors on the flow rate is reduced by the head, which stabilises the flow. Under these conditions, the discharge coefficient becomes more constant and is less dependent on fluctuations in water levels, whilst the error in discharge measurement is reduced by 10-15% compared with free flow. This is particularly important for water metering in irrigation systems. For instance, in their paper, P. Sultanbekova *et al.* (2025) note that, in conditions of freshwater scarcity, there is a growing need for the rational use of collector-drainage water, significant volumes of which, if managed inefficiently, can deteriorate the ecological and land-improvement conditions of the areas concerned. Similar patterns are observed in closed irrigation systems. For instance, J. Ishanov (2025) notes in his work that the uniformity of water distribution in pipelines is determined by their diameter, length, flow rate, pressure and the gradient of the terrain. The proposed mathematical model, based on the 10% criterion, enables the optimisation of water distribution and an increase in the efficiency of irrigation systems. Despite the improvements made, issues relating to the detailed design of the diaphragm remain insufficiently studied. In existing solutions, the main focus is on the geometry of the orifice, whilst the design and methods of fixing the diaphragm are considered only to a limited extent. As part of this study, two modifications of the diaphragms have been developed, differing in design and operational characteristics.

The first variant consists of an adjustable diaphragm in the form of a flat plate (Fig. 4). The design comprises an upper flat metal plate 3-5 mm thick and a lower rounded element with a radius of $R = 0.15$ m. This radius has been chosen on the basis of the average hydraulic conditions in mountainous and foothill watercourses, where the water depth is typically between 0.6 and 1.0 m. The rounded element consists of two short sections: a vertical section and a horizontal section. The vertical section is used to bolt the element to the shield, whilst the horizontal section ensures that the flow is directed in a parallel jet pattern. A sealing gasket is used to ensure a watertight connection between the structural elements. The main advantage of the adjustable orifice is the ability to vary the height of the water passage. This allows the structure to be used not only for measuring water flow rate but also for regulating water distribution within the channel. Water flow is determined by the relationship Q (Z, h_(open)), where Z is the difference in water levels between the upper and lower reaches, and h_(open) is the height of the opening. This approach allows for changes in hydraulic conditions to be taken into account and enables the water supply to be adjusted promptly.

The second variant consists of a non-adjustable diaphragm in the form of a wall (Fig. 4). The design comprises a main wall made of metal, concrete or reinforced concrete, as well as a separately manufactured rounded element which is attached to the wall by bolted connections. Various design options are possible, including rigid or removable fastening of the element, as well as its installation on the front or rear side of the wall. A. Churaev & L. Yuchenko (2022) note that, in the context of open irrigation networks, the main problems remain the poor technical condition of water metering points, a lack of measuring instruments and limited financial resources, which hinder the implementation of complex and costly water flow measurement systems. In this regard, it is advisable to use simple, reliable and affordable hydrometric structures, in particular the "fixed channel" type, which have proven their effectiveness. The main advantage of the design in question is its ease of operation: unlike adjustable orifices, it contains no moving parts, which increases the structure's reliability and reduces the need for maintenance. Determining the water flow rate in this case is reduced to measuring only the difference in water levels Z, which significantly simplifies operation, particularly in remote and hard-to-reach sections of irrigation systems, where the use of complex equipment is difficult or economically unfeasible. A comparison of the results obtained with data from other studies shows that the proposed designs offer a number of advantages. In most previously developed water-metering structures, the discharge coefficient varies widely depending on flow conditions and the degree of silting in the channel. In some cases, its value may fall to $\mu \approx 0.80$-0.85. In the proposed designs, the absence of a weir, the increased length of the orifice and the rounded lower edge ensure a more stable value for the discharge coefficient.

Of particular importance is the structure's resistance to silting and sediment accumulation. In traditional water-measuring structures, the presence of a sill in front of the orifice promotes sediment accumulation and the formation of deposits, which over time leads to a reduction in the effective cross-sectional area of the orifice. In the proposed designs, this drawback is eliminated by the absence of a sill and the use of a rounded edge. The water flow passes freely through the orifice without creating conditions for sediment accumulation

(Vatankhah & Ghaderinia, 2018). Practical calculations and analysis of the hydraulic characteristics show that the proposed designs maintain a high stability of the discharge coefficient even under variable inundation conditions and partial silting of the channel. The discharge coefficient values range from $\mu \approx 0.95$-0.99, which corresponds to the best performance figures reported in contemporary hydraulic studies.

The proposed design solutions are particularly promising for on-farm irrigation channels in the Chüy Valley. These channels are characterised by unsteady hydraulic conditions, significant fluctuations in water levels and an intense inflow of sediment. Under such conditions, the use of traditional water-metering structures is often accompanied by a reduction in the accuracy of water flow measurements and the need for regular canal cleaning. As noted in the research by B. Kurumshiev *et al*. (2021), the water supply system for the irrigation networks of the Kyrgyz Republic comprises a complex network of hydraulic structures that ensure the supply of water from mountain rivers to main and distribution canals. The authors emphasise that the parameters of hydraulic structures and water supply schemes are shaped by natural conditions, topography and the characteristics of mountain rivers, which determine the specific nature of irrigation systems' operation and necessitate the refinement of engineering solutions during the operation of water management facilities. The paper by R. Aliev & A. Djalilov (2024) examines two methods for determining water flow in open irrigation systems: the "velocity-area" and "gradient-area" methods, as well as issues relating to the modernisation of the "gradient-area" method with a view to the remote transmission of parameters and the improvement of their processing. Based on experimental studies, the authors demonstrated that the maximum error of the "gradient-area" method compared with the "velocity-area" method is 0.7%, which confirms its high accuracy and importance for modern water metering systems. The use of improved diaphragms in water metering installations makes it possible to further enhance the reliability of the systems and reduce operating costs.

Improvements to the diaphragm design, achieved by eliminating the threshold, increasing the length of the orifice and using a rounded lower edge, ensure a significant increase in the hydraulic efficiency of the water metering structure. The proposed adjustable and non-adjustable diaphragm designs ensure stable operation of the structure under various hydraulic conditions and can be recommended for use in irrigation systems with high silt content.

Conclusions

As a result of the research carried out, two modifications of water-measuring diaphragms for open irrigation channels were developed and analysed: an adjustable diaphragm in the form of a flat shield and a non-adjustable diaphragm in the form of a wall with a rounded bottom element. The proposed design solutions are aimed at increasing the hydraulic efficiency of water-measuring structures, improving flow conditions and enhancing the accuracy of water flow measurement in irrigation systems. Calculation of the discharge coefficient for vertical sluice gates with a wide weir crest in freely submerged flows using the best-subset regression method. An accurate determination of the discharge coefficient is possible by taking into account both free-flow and submerged-flow conditions, which is important for irrigation, water supply and the safety of structures. The hydraulic analysis carried out confirmed that the main factors in improving the gate's efficiency are the removal of the sill in front of the water passage, increasing the length of the passage to the width of the channel at the bottom, and the use of a rounded lower edge to the passage. Calculations showed that with these design solutions, the discharge coefficient μ reaches 0.95-0.99, which is 5-10% higher than that of traditional diaphragms with sharp edges and a sill, whilst the reduction in hydraulic losses contributes to an increase in flow capacity and greater stability of the flow characteristic as water levels change. The method proposed by the authors ensures a high level of calculation accuracy (coefficient of determination 0.993, root mean square error 5.04%), which confirms its practical applicability for the design of water metering structures.

An analysis of flow regimes has shown that ensuring the orifice operates in a submerged mode stabilises the hydraulic parameters of the flow and reduces the impact of water level fluctuations on the accuracy of flow measurement. Under conditions of variable head, the calculated error in flow rate determination can be reduced by approximately 10-15% compared with traditional water meter designs. The proposed adjustable diaphragm allows the height of the water passage to be varied within a range of 3-5 cm or more, enabling simultaneous regulation and measurement of water flow according to the relationship $Q(Z, h_{(op)})$. The non-adjustable diaphragm design is characterised by ease of operation and enhanced reliability, as determining the flow rate requires only the measurement of the water level difference Z. The absence of a threshold and the presence of a rounded bottom edge also help to reduce sediment accumulation and minimise the likelihood of the water meter structure becoming silted up.

The proposed designs are particularly effective for on-farm canals in irrigation systems, where unsteady hydraulic conditions and significant sediment inflow are typical. Under such conditions, the use of the developed diaphragms can improve the stability of the structure's hydraulic characteristics and reduce operational maintenance costs. The results of this study support the recommendation to implement the developed designs in the design and reconstruction of water gauging stations for irrigation systems in the Kyrgyz Republic.

The use of these improved water gauging devices may contribute to a more rational distribution of water resources and an increase in the efficiency of agricultural production. Further research should focus on conducting field experiments under real-world operating conditions in irrigation canals, as well as on refining the flow characteristics of the structure under various flooding regimes and degrees of siltation.

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Айыл чарба сууну пайдалануу шарттарындагы агымдын стационардык эмес режиминде иштеген сугат системалары үчүн суу эсептөөчү конструкцияларды изилдөө жана өркүндөтүү

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Аннотация. Макалада өзгөрмө подпордук режимдерде жана интенсивдүү ылай басуу шарттарында иштеген ирригациялык системалардын суу өлчөөчү курулмаларында суу эсебинин тактыгын жогорулатуу маселеси каралат. Изилдөөнүн актуалдуулугу туруксуз гидравликалык шарттарда жана түпкү чөкмөлөрдүн топтолушу учурунда суунун чыгымын ишенимдүү эсепке алууну камсыз кылуу зарылдыгы менен негизделет, анткени бул факторлор курулмалардын ишенимдүүлүгүнө жана суу ресурстарын бөлүштүрүүнүн натыйжалуулугуна олуттуу таасир этет. Суу эсебинин тактыгы айыл чарбасы үчүн өзгөчө мааниге ээ, себеби ал сугаруу режимдеринин сакталышына, сууну сарамжалдуу пайдаланууга жана агрардык секторду туруктуу суу менен камсыздоого түздөн-түз таасир этет. Өлчөөлөрдүн жетишсиз тактыгы суунун ашыкча сарпталышына, сугаруу графиктеринин бузулушуна жана түшүмдүүлүктүн төмөндөшүнө алып келиши мүмкүн. Изилдөөнүн максаты өлчөөлөрдүн туруктуулугун камсыз кылган жана чөкмөлөрдүн таасирин азайткан өркүндөтүлгөн диафрагма конструкциясын иштеп чыгуу жана анын гидравликалык негиздемесин берүү болгон. Изилдөөдө гидравликалык эсептөө, конструкцияларды салыштырмалуу талдоо жана курулманын ар кандай агым режимдеринде жана подпор деңгээлдеринде иштөөсүн моделдөө ыкмалары колдонулган. Тешиктин геометриясынын, түпкү өтмөктүн жайгашуусунун жана диафрагманын конфигурациясынын агым түзүмүнө жана чөкмөлөрдүн топтолуу процесстерине тийгизген таасири бааланган. Изилдөөнүн жыйынтыктары суу эсебинин тактыгын жогорулатуу үчүн диафрагмалардын эки түрүн колдонуу максатка ылайыктуу экенин көрсөттү: жөнгө салынуучу түпкү тешиги бар жалпак калкан жана туруктуу тешиги бар конструкция. Жөнгө салынуучу тешик ылай басууну азайтып, өтмөктүн жабылып калышын алдын алып, суу чыгымынын мүнөздөмөлөрүнүн туруктуулугун камсыздай турганы аныкталды. Туруктуу тешиги бар конструкция эксплуатациянын туруктуу шарттарында натыйжалуу болуп саналат. Эсептик маалыматтар өлчөө каталарынын азайышын, чыгым коэффициентинин туруктуулугунун жогорулашын жана курулманын узак мөөнөттүү ишенимдүүлүгүнүн өсүшүн тастыктады. Иштин практикалык мааниси суу өлчөө түйүндөрүн конструкцияны татаалдаштырбастан ар кандай шарттарга ылайыкташтыруу мүмкүнчүлүгүндө турат. Сунушталган чечимдер сууну пайдалануунун натыйжалуулугун жогорулатууга жана ирригациялык системаларда суу бөлүштүрүүнү башкарууну жакшыртууга көмөктөшөт

Негизги сөздөр: суу өлчөөчү курулма; жөнгө салынуучу диафрагма; түпкү тешик; чөкмөлөр; суу эсебинин тактыгы; Чүй өрөөнү

Исследование и совершенствование конструкций водоучета для ирригационных систем с нестационарным режимом течения в условиях сельскохозяйственного водопользования

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Аннотация. В статье рассматривается проблема повышения точности водоучета на водомерных сооружениях ирригационных систем, функционирующих в условиях переменных подпорных режимов и интенсивного заиления. Актуальность исследования обусловлена необходимостью обеспечения достоверного учета расхода воды при нестабильных гидравлических условиях и накоплении донных наносов, что существенно влияет на надежность сооружений и эффективность распределения водных ресурсов. Точность водоучета имеет важное значение для сельского хозяйства, так как влияет на соблюдение режимов орошения, рациональное использование воды и устойчивое водообеспечение аграрного сектора. Недостаточная точность измерений может приводить к перерасходу воды, нарушению графиков полива и снижению урожайности. Целью работы были разработка и гидравлическое обоснование усовершенствованной конструкции диафрагмы, обеспечивающей стабильность измерений и снижение влияния наносов. В исследовании использованы методы гидравлического расчета, сравнительного анализа конструкций и моделирования работы сооружения при различных режимах течения и уровнях подпора. Оценено влияние геометрии отверстия, положения донного проема и конфигурации диафрагмы на структуру потока и процессы накопления наносов. Результаты показали, что для повышения точности водоучета целесообразно применение двух типов диафрагм: плоского щита с регулируемым донным отверстием и конструкции с фиксированным отверстием. Установлено, что регулируемое отверстие снижает заиление, предотвращает перекрытие сечения и стабилизирует расходные характеристики. Конструкция с фиксированным отверстием эффективна при стабильных условиях эксплуатации. Расчетные данные подтверждают снижение погрешности измерений, повышение стабильности коэффициента расхода и увеличение надежности функционирования сооружения в долгосрочной перспективе. Практическая ценность работы заключается в возможности адаптации водомерных узлов к различным условиям без усложнения конструкции. Предложенные решения способствуют повышению эффективности использования воды и улучшению управления водораспределением в ирригационных системах

Ключевые слова: водомерное сооружение; регулируемая диафрагма; донное отверстие; наносы; точность водоучета; Чуйская долина