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DEVELOPMENT OF AN EFFECTIVE WATER ACCOUNTING METHOD FOR IRRIGATION SYSTEMS FOR AUTOMATED WATER RESOURCE MANAGEMENT SYSTEMS

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Abstract. Currently, due to the increasing trend of water scarcity, it is necessary to use water resources efficiently and to develop and implement effective water accounting methods and automated water resource management systems. This study aims to develop an effective and adequate method, compared to existing ones, for calculating water flow for automated water resource management systems. The presented work examines existing groups of direct and indirect methods of water accounting, identifies their main limitations and characteristic errors that significantly reduce the accuracy of measurements. *Results.* Existing groups of direct and indirect methods and tools for water accounting were analyzed, and their inaccuracies, which lead to reduced precision, along with certain limitations, were identified. For more accurate and adequate water accounting in conditions of uneven, gradually varying water movement in a non-prismatic channel with horizontal and reverse bed slopes, an effective water accounting method is

proposed. *Scientific novelty.* The equations used for a more accurate calculation of water volumes in the channels of irrigation systems in various water flow regimes based on the developed computational scheme for uneven, gradually varying water movement are provided. It is assumed that taking into account the characteristics of real water flow will improve the accuracy of water metering in automatic systems. *Practical value.* The proposed method was tested under the conditions of the K-19 channel in the Turkestan region and demonstrated its efficiency and required level of accuracy. The method can be integrated into intelligent automated water management systems, improving water accounting in irrigation systems.

Keywords: water accounting, irrigation systems, automated water resource management systems (AWMS), direct methods, indirect methods, uneven gradually varying water flow

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СУ РЕСУРСТАРЫНЫҢ АВТОМАТТАНДЫРЫЛҒАН ЖҮЙЕЛЕРІНЕ СУАРУ ЖҮЙЕЛЕРІНДЕГІ СУ ЕСЕПТЕУДІҢ ТИІМДІ ӘДІСІН ӘЗІРЛЕУ

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Аннотация. Қазіргі уақытта су тапшылығының өсу тенденциясына байланысты су ресурстарын тиімді пайдалану, суды есепке алудың тиімді тәсілдерін және су ресурстарын автоматтандырылған басқару жүйелерін әзірлеу және енгізу қажет. Бұл зерттеудің мақсаты қолданыстағы әдістермен салыстырғанда, су ресурстарын автоматтандырылған басқару жүйелері үшін, суды есептеудің тиімді және адекваттығы жоғары тәсілін әзірлеу болып табылады. Ұсынылған жұмыс суды есепке алудың тікелей және жанама әдістерінің қолданыстағы топтарын зерттейді, олардың негізгі шектеулерін және өлшемдердің дәлдігін айтарлықтай төмендететін сипаттамалық қателерді анықтайды. *Нәтижелері.* Суды есептеудің тікелей және жанама әдістері мен құралдарының қолданыстағы топтары талданады, олардың дәлдігінің төмендеуіне әкелетін қателері мен кейбір шектеулері анықталды. Көлденең және кері түбі еңістері бар призматикалық емес арнадағы біркелкі емес, біртіндеп тегіс өзгертін су қозғалысы режимдерінде суды көлемін дәлірек және адекватты есептеудің тиімді әдісі ұсынылған. *Ғылыми жаңалығы.* Су ағынының әртүрлі режимдеріндегі суару жүйелерінің каналдарындағы су көлемін дәлірек есептеу үшін қолданылатын теңдеулер біркелкі емес біртіндеп өзгертін су қозғалысы үшін құрылған есептеу схемасы негізінде ұсынылған және сипатталған. Нақты су ағынының сипаттамаларын есепке алу автоматты жүйелерде суды есепке алудың дәлдігін жақсартады деп болжануда. *Практикалық құндылық.* Ұсынылған су есептеу тәсілі Түркістан облысында К-19 каналы жағдайында сынақтан өтіп, оның тиімділігі мен қажетті дәлдік деңгейін қамтамасыз ететіні анықталды. Бұл әдіс суару жүйелеріндегі суды есепке алуды жетілдіре отырып, суды басқарудың интеллектуалды автоматтандырылған жүйелеріне біріктірілуі мүмкін.

Түйін сөздер: су есептеу, суару жүйелері, су ресурстарын автоматтандырылған басқару жүйелері (СР АБЖ), тікелей тәсілдер, жанама тәсілдер, су ағынының біркелкі емес біртіндеп өзгертін қозғалысы

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РАЗРАБОТКА ЭФФЕКТИВНОГО МЕТОДА ВОДОУЧЕТА НА ОРОСИТЕЛЬНЫХ СИСТЕМАХ ДЛЯ АВТОМАТИЗИРОВАННЫХ СИСТЕМ ВОДНЫМИ РЕСУРСАМИ

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Аннотация. В настоящее время в связи с тенденцией роста дефицита водных ресурсов необходимо эффективно использовать водных ресурсов, разработать и внедрить эффективных методов водоучета и автоматизированных систем управления водными ресурсами. Целью настоящего исследования является разработка эффективного и адекватного, по сравнению существующими способами, метода расчета расхода воды для автоматизированных систем управления водными ресурсами. В представленной работе подвергаются анализу существующие группы прямых и косвенных методов водоучета, выявлены их основные ограничения и характерные погрешности, существенно снижающие точность измерений. Результаты. Проанализированы существующие группы прямых и косвенных методов и средств водоучета, выявлены их погрешности, приводящие к снижению их точности, и некоторые ограничения. Для проведения более точного и адекватного водоучета в режимах неравномерного плавно изменяющегося движения воды в непризматическом русле с горизонтальным и обратным уклонами дна предложен эффективный метод водоучета. Научная новизна. Приведены уравнения, используемые для более точного расчета объема воды в каналах оросительных систем в различных режимах течения воды на основе созданной расчетной схемы движения неравномерного плавно изменяющегося движения. Предполагается, что учёт особенностей реального водного потока позволит повысить точность водоучета в автоматических системах. Практическая ценность. Предложенный метод испытан в условиях канала К-19 Туркестанской области и показал свою эффективность и необходимый уровень точности. Метод может быть интегрирован в интеллектуальные автоматизированные системы управления водными ресурсами, улучшая водоучёт в оросительных системах.

Ключевые слова: водоучет, оросительные системы, автоматизированные системы управления водными ресурсам (АСУ ВР), прямые методы, косвенные методы, неравномерное плавно изменяющееся движение потока воды

Introduction. The water resources of the Republic of Kazakhstan are characterized by their scarcity compared to many other countries. The majority of water resources are supplied by the country's surface waters. Of these, 56% are formed locally, while the remaining 44% come from the runoff of transboundary rivers from Russia, China, Uzbekistan, and Kyrgyzstan. This indicates Kazakhstan's

dependence on transboundary rivers flowing in from neighboring countries (Yespolov et al., 2022). This situation significantly increases the importance of regulating transboundary flows to address the country's existing and potential water-related issues. Additionally, water resources for irrigation in Kazakhstan are distributed unevenly, and some regions experience water shortages for irrigation during summer.

In recent years, the growing trend in water consumption and the declining availability of water resources pose a threat of increasing shortages, especially in the irrigation systems of the southern regions of the country. If the efficiency of water accounting and management systems is not improved, water scarcity will intensify in the coming years, negatively affecting the water supply for the population, irrigation systems, and the state of the environment.

To improve the efficient use of water resources in Kazakhstan, it is necessary to establish reliable accounting for the collection, transportation, and distribution of water at all levels of water management facilities. This should be based on effective water accounting methods and automated water resource management systems (AWMS). However, since issues of uncertainty and fuzziness of some initial data often arise, AWMS needs to be supplemented with elements of intellectualization to ensure their efficiency. In this regard, developing an effective water accounting method for creating AWMS is a relevant scientific and practical challenge for Kazakhstan. This situation motivated this study, dedicated to developing an effective water accounting method, compared to existing methods (Bochkarev, 2012; Masumov, 2015). for use in the creation of intellectualized AWMS.

Materials and methods. The materials for this study include various sources, methods, and approaches to water accounting used in water accounting and water resource management systems within irrigation systems. Since water is one of the most scarce natural resources in the world, including in Kazakhstan, it is essential to manage the distribution and usage of water resources efficiently. In the process of water resource management, water accounting methods and water volume measurements play a critical role.

Many studies have examined water accounting and water accounting methods (Pacheco et al., 2020; Albaina et al., 2023; Arregui et al., 2010). For instance, Pacheco et al. conducted a techno-economic analysis of water accounting devices (Pacheco et al., 2020) while Albaina et al. explored the effects of various accessories installed upstream of large water meters (Albaina et al., 2023). These studies proposed approaches that combine technical and economic research, enabling more accurate assessments of measurement errors and the influence of various factors on measurement quality. The technical research includes methodologies for measuring errors that occur at different flow rates and analyzing the resulting measurements, while economic studies use various methods to determine when to replace water meters based on management needs.

Arregui et al. developed a graphical method for calculating the optimal

replacement period for water meters and proposed tools that integrate observation data with global databases to enhance data collection for water resource accounting (Arregui et al., 2010) The authors of other studies (Kamienski et al., 2019; Manimegalai et al., 2020) introduced an IoT-based platform for intelligent water resource management and a smart irrigation system with monitoring. Madias et al. demonstrated the effectiveness of smart water meters for consumers (Madias et al., 2023) However, these and other studies do not explore methods and tools for water accounting that can effectively distribute water resources across irrigation systems under various water flow conditions (e.g., with straight, horizontal, or reverse bed slopes).

The tools and methods for water accounting that can be used in irrigation systems are considered in the study (Bochkarev et al., 2013). According to modern legal and regulatory documents, direct and indirect methods are used in practice as standardized measurement methods.

Direct methods of water flow measurement are used for metrological testing, calibration, and certification of flow meters and other specialized equipment. Direct methods include volumetric, gravimetric, and volumetric-hydraulic approaches, which rely on various calculation dependencies. Because volumetric and volumetric-hydraulic methods require significant financial resources, they are primarily used for calibration of working measurement tools as per metrological standards. The volumetric method involves measuring volume and height, but its accuracy heavily depends on the devices, tools, and the operator's skill, making it less precise.

The gravimetric method offers higher accuracy compared to other water accounting methods, with errors mainly arising from determining the weight of the water, which is measured more accurately.

The **channel method** involves determining water flow and runoff by observing water levels at a control section where the relationship between the flow rate (Q) passing through the section and the corresponding water levels (H) is pre-established: $Q=f(H)$. The channel method does not require the construction of special facilities. However, it is not operationally efficient, cannot be automated, and measurement errors can occur due to channel deformation caused by erosion or silting. On fixed channels, where there are no backwater or recession effects and stable sections exist, the channel method ensures an acceptable level of accuracy for water accounting. However, there are specific conditions for applying this method: during water flow measurements, the bed and banks of the natural or artificial watercourse must be sufficiently stable. Currently, the channel method remains the primary approach for water accounting at key irrigation sources, headworks, and accounting points of main and large canals.

The hydraulic method is applied when water flow through a structure depends on the fixed dimensions of some of its elements. This method is based on the installation of hydrometric facilities or devices at specific points in irrigation systems. These facilities or devices allow the measurement of water flow passing through them.

Tracer methods involve introducing markers into the water flow, such as floats, salt solutions, or other materials. In practice, the channel and hydraulic methods are the most widely used for water accounting. In the next section, the authors of this study propose and describe a more efficient water accounting method for irrigation systems designed for automated water resource management systems.

Results and discussion. The following efficient water accounting method is proposed, which utilizes modern tools to ensure a high level of accuracy and operational efficiency in measuring water flow within automated systems. This method involves the use of water level sensors and controller equipment integrated into an automated water accounting system. For this study, the K-19 canal located in the Turkestan region, designed for irrigation systems in the area, was selected. An automated water accounting system was installed at the canal, incorporating water level sensors and controller equipment for real-time water accounting.

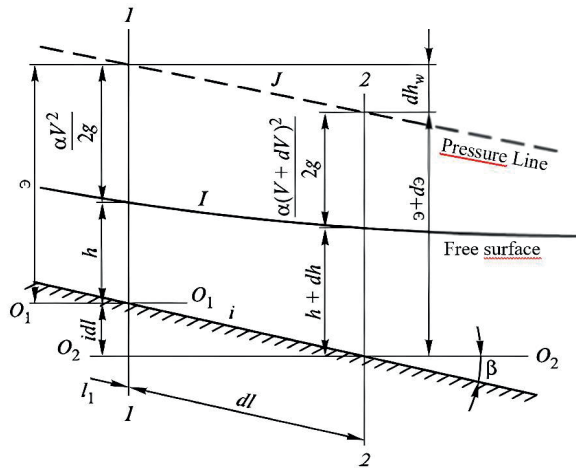
Based on the analysis and verification conducted, the proposed water accounting method demonstrated its efficiency, considering the existing backwater conditions in the K-19 canal. Graduated tables showing the relationship between flow rates and water levels were developed, and the consistency of the water accounting process with the automation requirements for this canal was evaluated. The method was validated for canals like K-19 that operate under backwater conditions.

The research utilized high-precision, calibrated instruments, including the Nikon XF laser total station, the dual-frequency GPS GS-1200 navigation device, and the GR-21M hydrometric propeller.

For calculating water flow, sensors and a tabular flow meter were used to measure water level and compute flow rates based on predefined relationships between level and flow.

The velocity regime across the K-19 canal's cross-section was studied using hydrometric techniques, with measurements of water slope and channel bed slope conducted using the laser total station and dual-frequency navigation device. The results showed that factors such as channel bed silting, overgrowth, and obstructing structures creating backwater conditions significantly influence the canal's average velocity and throughput capacity. These factors result in a dynamic regime known as "established uneven gradually varying water flow."

Established uneven gradually varying water flow is characterized by changes in flow properties along its length. If these changes (e.g., velocity and flow rate) occur gradually over the flow's length, the flow is described as gradually varying. The primary task in studying such uneven flow in an open channel is to determine the variation in depth along the flow, i.e., to construct the curve of the free surface of the water flow. The computational scheme for uneven gradually varying water flow is presented in Figure 1.



J – Pressure line; I – Free surface; α – Kinetic energy coefficient; V – Flow velocity;
 g – Acceleration due to gravity; h – Height from the channel bed to the free surface of the water;
 i – Variable bed slope; l – Length from the horizontal line $O_2 - O_2$ to the horizontal line $O_1 - O_1$ from the beginning of the slope to the intersection with vertical line $1 - 1$; β – Angle between the end of the slope and the horizontal line $O_2 - O_2$; ϵ – Distance between the free surface and the pressure line; h_w – Distance from the pressure line to the intersection with the horizontal line from the start of the pressure line.

Figure 1. Computational scheme for uneven gradually varying water flow

The equation for uneven gradually varying flow in a non-prismatic channel with a straight sloped bed can be written as:

$$\frac{dh}{dl} = \frac{i^0 - \frac{Q^2}{\omega^3 C^2 R} + \frac{\alpha Q^2 d}{g \omega^3}}{1 - \frac{\alpha Q^2 B}{g \omega^3}} \quad (1)$$

where dh/dl – change in flow depth along the channel length; i_0 – bed slope of the channel; Q – water discharge in the channel; α – kinetic energy coefficient; ω – flow cross-sectional area; C – chezy coefficient (hydraulic coefficient); R – hydraulic radius, defined as the ratio of the flow cross-sectional area to the wetted perimeter; B – width of the channel; g – acceleration due to gravity.

Similar expressions, considering the slope's sign, can be derived for prismatic channels with horizontal and reverse bottom slopes. In prismatic channels, the live cross-sectional area of the flow can only vary due to changes in depth. By substituting $d\omega/dl=0$ into Equation (1), we obtain the differential equation for uneven, gradually varying flow in prismatic channels with a positive bottom slope:

$$\frac{dh}{dl} = \frac{i_0 - \frac{Q^2}{\sim^2 C^2 R}}{1 - \frac{aQ^2 B}{g^3}} \quad (2)$$

Introducing the (2) kinetic parameter and using the concept of the flow characteristic $K = \sim C\sqrt{R}$ for an arbitrary depth h of uneven flow, we derive:

$$\frac{dh}{dl} = \frac{i_0 - \frac{Q^2}{K^2}}{1 - P_K} \quad (3)$$

where K – flow characteristic; Π_K – kinetic parameter. Other parameters are as described above.

Expressing the flow rate Q using Chezy’s formula via the flow characteristic K_0 , which corresponds to the normal depth h_0 in the channel for a given slope i_0 , we can write:

$$\frac{dh}{dl} = i_0 \frac{1 - (K_0/K)^2}{1 - P_K},$$

where K_0 – is the flow characteristic corresponding to the normal depth.

Using the hydraulic index of the channel:

$$\frac{S_{K_1}}{K^2} = \frac{S_{h_1}}{h^2} \quad (4)$$

We obtain the equation for uneven flow in prismatic channels of regular shape:

$$\frac{dh}{dl} = i_0 \frac{1 - (h_0/h)^x}{1 - P_K} \quad (5)$$

For prismatic channels with a horizontal bottom $i_0=0$:

$$\frac{dh}{dl} = - \frac{\frac{Q^2}{K^2}}{1 - P_K}$$

For channels with a reverse slope ($i_0 < 0$)

$$\frac{dh}{dl} = - \frac{i_0 + \frac{Q^2}{K^2}}{1 - P_K}$$

When considering differential equations (3) and (4), the flow rate Q should be taken as constant. The variables are the flow characteristic K and the kinetic parameter Π_K , as they depend on the cross-sectional characteristics of the flow ω ,

x , B , R , C , which vary along the length of the prismatic channel due to changes in depth h during uneven flow. It is evident that at certain depth values h the flow characteristic K and the kinetic parameter Π_k may take such values that the term in parentheses in the denominator of the right-hand side of these equations approaches zero.

For channels with a slope $i_0 > 0$ when the numerator of equation (3) equals zero, we obtain:

$$i_0 - Q^2 = 0. \quad (6)$$

From this, $dh/dl=0$, which corresponds to the constancy of flow depth along the channel, i.e., uniform flow ($h=h_0$). This is also directly derived from expression (6), which represents Chezy's formula $Q=K\sqrt{J_0}$ for uniform flow. Thus, it is confirmed that uniform flow is possible in a prismatic channel with a positive bottom slope $i_0 > 0$. The derivative $dh/dl=tg\theta$, where θ – is the angle between the tangent to the curve of the free water surface and the line $N-N$ of normal depth or the line $K-K$ of critical depth. Consequently, if the depth of uneven flow in a channel with a slope $i_0 > 0$ approaches the normal depth $h \rightarrow h_0$, then $dh/dl=tg\theta \rightarrow 0$, meaning the free surface asymptotically approaches the $N-N$ line.

Based on the theoretical description of established uneven gradually varying water flow in the K-19 channel, it was determined that to obtain accurate discharge data while simultaneously considering various factors affecting the hydraulic flow regime (artificial backwater, backwater in branch channels, siltation, and vegetation growth), the water flow chart must be frequently adjusted. Thus, the results of the velocity study along the length of the K-19 channel indicate that the average velocity and discharge are influenced by the backwater regime created by obstructive structures along the channel, siltation of the channel bed, and vegetation growth. Collectively, these factors create a dynamic regime referred to as "established uneven gradually varying water flow." This type of flow impacts the velocity regime of water in the channel and leads to changes in discharge at the same water level. Therefore, it is necessary to continuously adjust the water flow chart for a backwater-type channel like K-19.

During the research, the installed equipment (a table-based flow meter) in the pilot project on the K-19 channel functioned properly. Water flow rate calculations were performed using the provided graduated level/discharge tables. However, discrepancies in water discharge measurements between the hydrometric propeller and the installed devices at the head section of K-19 were due to the absence of corrections in the water flow chart. The graduated dependencies (charts) provided by the RGP "Su-Metrology" branch did not account for the backwater regime, indicating that the methodology for constructing these charts should consider established uneven gradually varying water flow.

Conclusions: The proposed and described method for measuring water flow in open channels transitions traditional accounting methods into a digital format.

However, it is essential to calculate and implement adjustments in the water accounting sensors' programs based on the operational regimes of the channel (e.g., backwater, siltation, vegetation growth). The program must automatically adjust water accounting when backwater conditions arise. This is the primary reason for inaccuracies in sensor readings. This observation applies to all sensors using ultrasonic methods to measure water flow levels, regardless of the manufacturer or brand. These sensors operate based on the following principle: the sensor emits ultrasonic pulses, the product surface reflects these pulses, and the sensor registers them again. The time taken for the reflected ultrasonic signal to return is directly proportional to the distance traveled.

Based on the conducted research, it can be concluded that despite operational difficulties when using modern water accounting devices in channels with slight slopes operating in automatic mode, automating the water accounting process is considered feasible. However, it requires continuous adjustment of the water flow chart, depending on the flow type and the operational state of the channel. Regarding the accuracy and reliability of the data provided by the water accounting sensors studied in the K-19 channel case, it can be affirmed that sensors of this class and type operate correctly within the specified technical accuracy limits.

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