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Scientific paper

Assessment of water losses in internal water supply networks

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Abstract*. **Relevance.*** The article presents comprehensive studies of water loss assessment in the internal water supply networks. In order to increase the practical value of the studies, in a number of settlements of the Republic of Armenia, systems of internal water supply networks with different technical conditions (number of floors, amount of pressure in the network, year of construction, type of gauging device, etc.) were selected. In terms of these conditions the loss assessment analyses were implemented, taking into account the local conditions. The paper introduces the proposals aimed at reducing the volumes of unaccounted water amounts. ***Aim***. Based on the importance of the issue, we have carried out assessment studies of the loss components of the system, as the correct assessment is important for increasing the efficiency of detection of general leakages of the water supply system. Water balance of the settlements was developed, based on the loss assessment studies carried out in the original conditions and the structure of the housing stock. In the work aimed at increasing the efficiency of water supply system, it became clear that the correct assessment of the components of losses leads to the systematic execution of targeted actions of discovering the loss of the system and their recovery, as well as the development of a road map of reconstruction processes. **Objects.** Water balance supplied for drinking and economic purposes, as well as the components of supplied water. ***Methods.*** Well-known hydraulic principles and laws. Experimental studies were conducted directly on the water supply network while it is operating. ***Results.*** The studies carried out in different settlements show that the unaccounted water amount in the internal water supply network is almost equal to the volume of the sold water amount. In the system which has 71.4% water loss, unaccounted water volume caused by low accuracy of water meters and the emergency condition of internal networks of private houses is over 27.7%.

Keywords: water supply network, water loss, water balance, internal network, efficiency

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Научная статья

Оценка потерь воды во внутренних сетях водоснабжения

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Аннотация. *Актуальность.* Приведены комплексные исследования по оценке потерь воды во внутренних сетях водоснабжения. С целью повышения практической ценности исследований в ряде населенных пунктов Республики Армения были выбраны системы внутренних сетей водоснабжения с различным техническим состоянием (этажностью, величиной давления в сети, годом постройки, типом измерительного устройства и др.), в рамках которых были проведены анализы по оценке потерь с учетом местных условий, а также представлены предложения, направленные на сокращение неучтенных объемов воды. ***Цель.*** Исходя из важности проблемы, нами были проведены оценочные исследования компонентов потерь из системы, так как правильная оценка важна для повышения эффективности обнаружения общих утечек системы водоснабжения. В ходе работы, направленной на повышение эффективности системы водоснабжения, выяснилось, что правильная оценка составляющих потерь приводит к системно-

му выполнению целевых действий по обнаружению утечек из системы и их восстановлению, а также разработке дорожной карты процессов реконструкции. ***Объекты.*** Для оценки потерь в системе был изучен баланс воды, отпускаемой на питьевые и хозяйственные нужды, а также компоненты подаваемой воды. ***Методы.*** Расчеты проводились с использованием известных гидравлических принципов и законов. Экспериментальные исследования проводились непосредственно на сети водоснабжения в процессе эксплуатации. ***Результаты.*** Исследования, проведенные в разных населенных пунктах, показали, что неучтенное количество воды во внутренней сети водопровода практически равно объему проданной воды. Кроме того, по нашим исследованиям, в системе, где потери воды составляют 71,4 %, более 27,7 % – неучтенные объемы воды, что обусловлено низкой точностью показаний счетчиков воды и аварийным состоянием внутренних сетей частных домов.

Ключевые слова: водопроводные сети, потери воды, водный баланс, внутренняя сеть, эффективность

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Introduction

The access to water is crucial for life, prosperity, and all human activities [1]. Water resources must be used effectively to meet the demand of the ever-growing population, considering the limited and dwindling water availability [2]. Water distribution networks face growing pressures from rising population levels, increased urbanisation, more significant uncertainty in supply due to climate change, rising energy prices, volatile global economy, and more complex social and regulatory environment [3].

The water loss is either leakage or real loss occurring in pipes, storage reservoirs, and customer connections or apparent loss occurring due to customer meter under registration, errors in data handling and billing, or unauthorised use [4]. The non-revenue water includes not only the real losses, but also the apparent losses and the unbilled authorized consumption. Real water losses consist of the physical losses along the system down to the water meters of the clients, which comprise all leakage (from cracks and fractures) and reservoir overflows. The apparent losses cover the non-authorized consumption as well as consumed water that is not metered, data handling and billing errors, underestimation of unmeasured consumption, and client metering inaccuracies [5]. Leakages or unused water amount are useless costs: technical losses from structures, malfunctions of pipelines and equipment and accidents in the form of leakages, as well as illegal connections. Reducing losses will significantly increase the efficiency of the water supply system It is obvious that reducing leakages enables the reduction of water production. In the field of leakage management of water flow distribution networks, leakage detection is a critical research subject [6].

For most developing countries, the apparent water losses can be the major problem due to illegal connections and water theft. Illegal connections are also wasteful expenses, commonly referred to as commercial losses. The responsibility for their registration, detection and bringing them into the legal framework derives from the interests of the water supply organization. Recently, during January 2024, 3048 gauging devices were calibrated in the water supply system of different settlements of the Republic of Armenia (RA). The analysis of the results of the laboratory calibration of the water meters showed that about 41% of the water meters (or 1235 water meters) are malfunctioning or have external interference (the results were taken from monthly Report of the Water Supply Company in RA).

Leakage due to pipe bursts is a major inefficiency in water distribution networks and over 20% of the water entering public supply in England and Wales is lost as leakage, a wastage of over 50 litres per person per day [7]. The annual water loss volume worldwide is substantial; it has been estimated to be 126 billion cubic meters, which costs about USD 39 billion annually [8].

Literature review and problem statement

Traditional leakage identification and analysis methods are unable to offer a rapid response [9]. However, thorough methods for water loss assessment were not available two decades ago [10]. Later, significant advancements were made due to the development of new concepts and methods for water loss management [11]. The components of water loss can be assessed using the common top-down water audit methodology [12] or, alternatively, by establishing a water and wastewater balance [13]. Leakage can also be estimated using Minimum Night Flow analysis [14, 15] or the component analysis of the leakage [16]. Yet, these methods use different approaches (and scales) to estimate the water loss components and thus different corrective measures are prioritized [17] and different economic levels of leakage are planned, contributing to less effective water loss management. Reducing all water losses components to zero is neither technically possible [18] nor economically feasible because the greater the level of the resources employed is, the lower are the additional marginal benefits [19, 20].

Based on the importance of the issue, we have conducted loss assessment studies. In order to increase the practical significance of the work, in a number of settlements of the RA, where water supply services are provided by a private operator, internal water supply

network systems with different technical conditions (number of floors, amount of pressure in the network, year of construction, type of gauging device, etc.) were selected, in terms of which tests and various reconstruction operations were carried out. Operational experience shown that the correct assessment of loss components is important for increasing the efficiency of detection of total leakage from the water supply system [21].

Materials and methods

Al Washali et al reviews some methods to assess water loss [22]. The most accepted indicators of them are as follows [23]:

1. Losses in volume of water:
   a) per length of mains per unit of time;
   b) per length of system per unit of time;
   c) per property per unit of time;
   d) per connection per unit of time;
   e) per connection per unit of time and per unit of system pressure.
2. Non-revenue water as a percentage of system input water volume.
3. Infrastructure leak index, which relates the annual and unavoidable actual losses.

Some authors suggest using hydraulic models to detect leakages in water supply networks [24–26]. Considering the importance of the issue, the International Water Association (IWA) was founded in order to coordinate the working groups on water losses, to improve the water loss index, and to develop management procedures. One of the goals of the association is also to develop a methodology to identify and detect those parts of the water supply network where there are high levels of leakages [27].

Taking into account the provisions of the existing methods, as well as our own studies, we conducted research on the assessment of the components of water losses in the water supply systems of the RA and presented recommendations to reduce the volume of unaccounted water amounts.

In order to assess losses from the system, we have studied the water balance of water supplied for drinking and economic purposes in the RA settlements (Fig. 1), as well as the components of the sold water amount (Fig. 2) for 2022.

Water Amount Entering the System (thousand m³)	541469.9
Uncollected Water Amount (thousand m³)	386404.4
Collected Water Amount (%)	71.4
Sold Water Amount (thousand m³)	155065.0

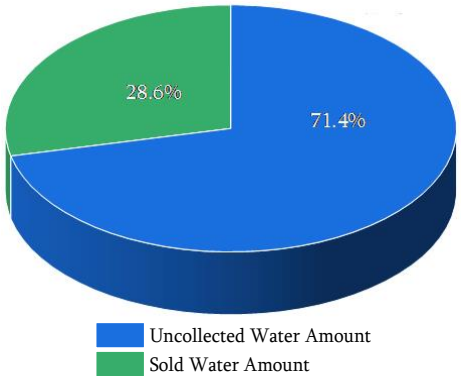

Fig. 1. *Water balance of 2022*
Рис. 1. *Водный баланс 2022 г.*

According to the conducted research, the loss in the studied system is 71.4%, and the main part of the sold water amount is utilized in the sector of residential customers, but it is only 18.4% of the produced water (Fig. 2). Based on the aforementioned, we believe that the indicated index is not satisfactory, and there is a need to carry out original studies in order to assess the losses in the indicated area.

In order to fully calculate the water losses (losses) from the water supply system of the RA settlements, we separately assessed the following two components:

- • losses from internal networks of housing blocks,
- • losses from internal networks of private households.

In order to solve the posed issue, the structure of the RA housing stock was also studied, which is presented in Table 1.

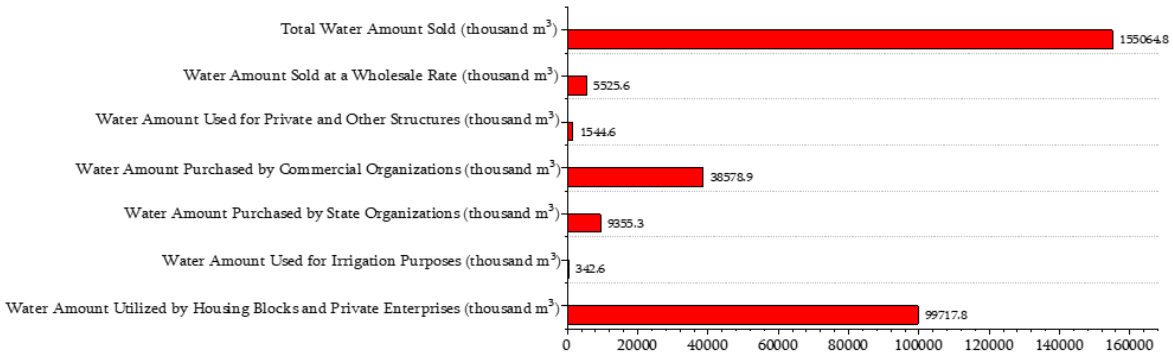

Fig. 2. *Components of water amount sold during 2022*
Рис. 2. *Компоненты объема проданной воды в 2022 г.*

Table 1. *Number of apartments of housing blocks and private houses per the RA Marzes, 2022*

Таблица 1. *Количество квартир в многоквартирных домах и частных домах по марзам Республики Армения (РА), 2022 г.*

RA Settlements Населенные пункты РА	Apartments in housing blocks, units Квартиры в жилых домах, кол-во	Private houses, units Частные дома, кол-во
Yerevan/Ереван	250872	64843
Other settlements Другие населенные пункты	209931	362620
Total/Всего	460803	427463

According to the presented data, the RA housing stock consists of 461000 (52%) apartments and 427000 (48%) private houses, and the majority of housing blocks are located in Yerevan City, and private houses are located in the rest of the settlements. Based on the aforementioned, in order to increase the degree of accuracy of the results of the research, the assessment works of losses in housing blocks were carried out in the water supply network of Yerevan City, while that of the private sector – in other settlements.

In order to have the fundamental answer to the mentioned issues, the article presents our studies of 2022. Based on them, all the provisions given in the article were tested during the operation of the existing water supply systems and received a positive result.

Discussion and results

Assessment of losses in internal networks of housing block

According to the data of Statistical Committee of Armenian Republic out of the 888266 apartments of the RA housing stock, 460803 are apartments in housing blocks. Taking into account that the density of housing blocks in Yerevan exceeds the same indicator of other settlements several times, therefore, in order to increase the accuracy of the calculations, further studies were carried out in the water supply network of Yerevan itself. The conducted studies shown that the internal water supply and drainage networks of the housing blocks that are the subject of the research are in a technically poor condition. If some repairing works were carried out by the residents in the area of the basement floors, then no investments were made on the water supply and especially the drainage pipelines in the area from the building water meter assembly to the external network in the last 20–30 years, except for the partial repairing works conducted by the local self-government bodies in the internal water supply network of the buildings.

It is also necessary to mention that currently there are privatized facilities of various purposes in the internal networks, which in their turn not only do not try to maintain the systems located in these areas, but by performing certain reconstructions of the basements, they make it more difficult to maintain the systems.

There are about five thousand 4 to 16-storey housing blocks in Yerevan. The studies were implemented in all districts of Yerevan city using water meters of various degrees of accuracy, as well as selecting buildings of different floors which were built in different years and have one or more water supply points. In order to clearly assess the volume of unaccounted water amount caused by gauging devices installed in the building, targeted and original experimental studies requiring large investments were carried out. Their purpose was to replace the water meters installed in all apartments of the buildings separated by the selective principle with water meters of class B and C with acceptable accuracy. As well as to identify the volumes of losses caused by inaccuracies and various manipulations of gauging devices.

11 housing blocks with a total of 668 apartments were selected in Yerevan, on the entry lines of which high-accuracy class C gauging devices of the "SENSU" brand were installed. Gauging devices in all apartments were replaced with highly accurate B and C class "Actaris" water meters. Fig. 3 shows the results recorded in one of the buildings, where before replacing the water meters, the amount of water entering the building was 6072 m^3/month, and the amount of water forming revenue was 2607 m^3/month, therefore the loss in the internal network was 43%. Three months after replacing the water meters, the amount of water entering the building was 4400 m^3/month (decreased by 1672 m^3), and the revenue was 3630 m^3/month (increased by 1023 m^3), therefore, the loss decreased and amounted to 17.5% (Fig. 3).

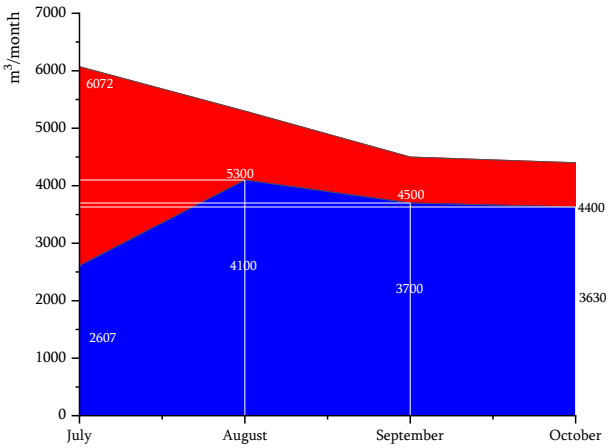

Fig. 3. *Results of replacing water meters in a housing block*

Рис. 3. *Результаты замены счетчиков воды в многоквартирном доме*

Analyzing the results of the loss assessment of the internal networks of the selected buildings, it can be stated that the unaccounted water amount generated from the gauging devices installed in the apartments of housing blocks and the internal networks of the build-

ings (from the general gauging device of the building to the customer's apartment) is about 57% of the water supplied to the building (in the calculations 55% is considered). By the way, after installing class B or C water meters with different degrees of accuracy, the amount of loss in the internal networks of buildings ranged from 14 to 18 percent. And since the cost of a high class C water meter is 3–4 times higher than the cost of a class B water meter, it was economically impractical to acquire class C water meters.

Based on the results of the studies, the efficiency of the internal networks of housing blocks can be assessed with the following expression:

$$W_{unac.w.}=(W_1-W_2)-(W_3-W_4), \quad (1)$$

where W_1 and W_3 are the water amounts supplied to the building before and after the replacement of the water meters (m^3/month), while W_2 and W_4 are the monthly utilized water amounts before and after the replacement of the water meters (m^3/month).

Taking into account the fact that before the replacement of water meters, the water amount provided to any building under study is about 2.2 times higher than the sold water amount, and after the replacement of water meters – only 1.18 times, the following expression can be written:

$$W_{unac.w}=(2{,}2W_2-W_2)-(1{,}18W_4-W_4)=1{,}2W_2-0{,}18W_4. \quad (2)$$

Based on the results of the tests, if we accept that the water amount sold before the studies was almost 30% less than the water amount sold after the replacement of water meters, the following can be written: $W_4/W_2=1.3$. In this case, expression (2) will take the following form:

$$Q_{unac.w.}=1{,}2W_2-0{,}18\times1{,}3W_2\approx W_2. \quad (3)$$

Therefore, the unaccounted water amount in the internal networks can be assessed by expression (3).

During 2022, the water amount sold in housing blocks was 49.9 million m^3, applying the above expression; it can be stated that there is about 50 million m^3/year of water loss in the internal networks of housing blocks, which is almost 9.0% of the amount of water produced. Summarizing, it can be said that large water loss in the internal networks of housing blocks is caused by the inaccuracy of the gauging devices installed in the apartments and the commercial losses caused by affecting them in various ways.

Assessment of leakages from the internal network of private households

In Armenia 362620 of the 427463 units of private houses available in the housing stock are located in 10 marzes, so in order to increase the degree of accuracy of the research, the studies were carried out in the marz settlements. During the conducted studies, the rate of water losses in private households was assessed. The losses are mainly caused by hidden accidents on the entry lines, inaccuracies of gauging devices, as well as illegal connections.

Through the analysis of the results of studies carried out on Hatis street of Abovyan City and 5 streets of other settlements in the RA, the work was carried out aimed at assessing the volume of unaccounted water amount.

The following activities were carried out during the studies on Hatis street:

- the entry lines of all 115 private houses were reconstructed, up to the boundary separating the customer's area from the street (enclosure, fence, etc.), where water meter wells were installed;
- water meters calibrated in the hydrometric laboratory were installed on the entry lines feeding the private houses. The water meter assemblies were taken out of the territory owned by the customer and installed in the wells on the sidewalk;
- using special tools (flow meter, leak noise correlator, aquaphone) and gradual testing at night, all hidden accidents were identified and eliminated;
- registration of water meter readings was carried out twice a month before the start of construction works and after the completion of the works.

The changes in the outputs recorded after the listed works are shown in Fig. 4.

The d=160 mm diameter steel pipeline located in the studied section of Hatis street was built in the late 1970s. It passes along the sidewalk and is affected by small dynamic forces as a result of the non-intensive traffic of the street. The pipeline is fed from the Abovyan daily regulation reservoir and provides 24-hour water supply to 115 customers. The pressure in the water line ranges from 2.8 to 3.2 atm and is mostly stable because it is within the service range of the pressure regulator.

In order to present the picture more clearly, the volumes of water supply and consumption recorded during the test are shown in Table 2. It is important to note that the pressure in the street water supply system remained almost constant during the test.

As it can be seen from the presented results, the water amount consumed on Hatis street decreased from 7100 to 2820 m^3 and amounted to 4280 m^3, while the utilized water amount increased by 1077 m^3 and amounted to 3295 m^3. In this case, expression (1) can also be used, where W_1 and W_3 are the water amounts entering the district before reconstruction and after reconstruction (m^3/month), and W_2 and W_4 are the water amounts sold before reconstruction and after reconstruction (m^3/month). Taking into account that before the implementation of the works, the volume of water amount entering the district was 3.2 times more than the sold water amount, and after the works it was 1.3 times, so in this case the expressions (4) and (5) can be written:

$$W_{unac.w}=(3{,}2W_2-W_2)-(1{,}3W_4-W_4)=2{,}2W_2-0{,}3W_4. \quad (4)$$

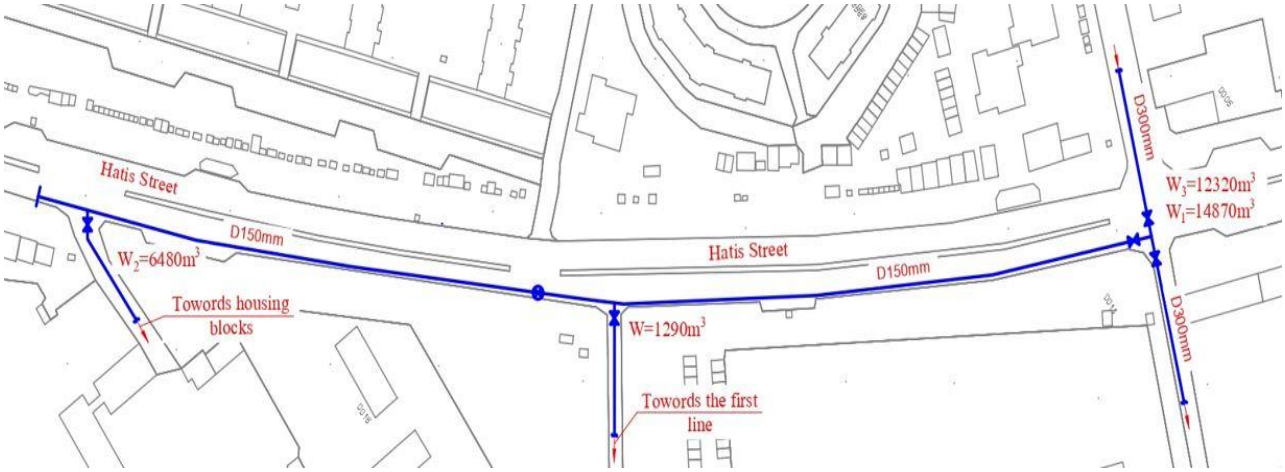

Fig. 4. *Hatis street water supply scheme*
Рис. 4. *Схема водоснабжения улицы Атис*

Table 2. *Results of research conducted in the section of private households*
Таблица 2. *Результаты исследования, проведенного в секции частных домохозяйств*

Water amounts of network sections Объёмы воды на участках сети	Water amount, m³/month Объем воды, м³/мес.		Test results Результаты испытаний	
	before the work was done до проведения работ	after the work was done после окончания работ	m³	%
Entering Hatis street/Въезд на улицу Атис	14870	12320	–2550	–17,15
Towards housing blocks На пути к многоквартирным домам	6480	6490	10	0,15
Towards the first lane/К первой полосе	1290	1550	260	20,16
Water amount consumed in the studied section of Hatis street (households) Количество потребляемой воды на исследуемом участке улицы Атис (домохозяйства)	7100	4280	–2820	–39,72
Water amount sold in the studied section of Hatis street (households) Количество воды, реализуемой на исследуемом участке улицы Атис (домохозяйства)	2218	3295	1077	48,56

Based on the test results, if we accept that the water amount sold before the studies was almost 1.5 times less than the water amount sold after the works, then it will be $W_4=W_2/1.5$, so we will have the following:

$$W_{unac.w.}=2{,}2W_2-0{,}2W_2=2{,}0W_2. \quad (5)$$

In other words, it can be stated that the specific weight of the unaccounted water amount in the private sector, compared to the sold water amount, almost doubles the same indicator of housing blocks.

Under original conditions, similar tests were carried out on Nairyan and Yeritasardakan streets of Abovyan City, as well as on Teryan, Rustaveli and Lazo streets of Gyumri City, and almost the same results were obtained in all cases (Table 3).

During 2022, the water amount sold in the private sector was 49.9 million m^3. Applying the above expression, it can be concluded that there was almost 100 million m^3 of unaccounted water amount in the internal network of the private sector per year, which was 18.5% of water production.

Table 3. *Results of studies carried out in the private sector*
Таблица 3. *Результаты исследований, проведенных в частном секторе*

Street Names Названия улиц	Объем воды, м³/мес./Water amount, m³/month			
	supplied/подаваемой		sold/реализуемой	
	before the work was done до проведения работ	after the work was done после окончания работ	before the work was done до проведения работ	after the work was done после окончания работ
Nairyan/Наирян	77760	81300	22062	33131
Yeritasardakan Еритасардакан	129600	70570	39312	56531
Teryan/Терян	25920	20800	7812	12790
Lazo/Лазо	36288	15230	12230	14676
Rustaveli Руставели	46656	27550	14251	23035

Analyzing the results of the study, it can be concluded that the inputs to private households were once carried out with gross violations of technical norms, which leads to the occurrence of hidden accidents, in particular:

- the necessary burial depths of the pipes were not observed;
- built with poor quality pipes;
- construction and installation works were carried out by people without professional qualifications;
- in many cases, after reconstruction of the entry line of the house by the resident, the previous water line was not dismantled, which caused both commercial and hidden leakage;
- due to the location of the water meter assembly on the owner's territory, it was possible to make illegal connections to the gauging device for irrigation and water intake for other purposes;
- after the replacement of the water lines implemented in the streets during the Soviet years, the old water lines were not decommissioned and therefore many private houses have two water connections, from the old and new water lines, one of which is illegal.

Assessment of components of losses in Yerevan water supply systems

The results of the comprehensive research on unaccounted water amounts in the internal water supply network are summarized in Table 4.

Table 4. *Water balance of Yerevan water supply systems*

Таблица 4. *Водный баланс систем водоснабжения города Еревана*

Components of unaccounted water amount Составляющие неучтенного количества воды	Unaccounted water amount Неучтенный объём воды	
	million m^3/year млн $м^3$/год	in % to produced water в % к добываемой воде
Housing blocks/Жилые блоки	50,0	9,2
Private households Частные домохозяйства	100,0	18,5
Total losses from internal networks Общие потери от внутренних сетей	150,0	27,7
Sold water amount Количество проданной воды	155,1	28,6
Total (produced water amount) Итого (объем добываемой воды)	541,5	100,0

The studies carried out in different settlements show that the unaccounted water amount in the internal water supply network is almost equal to the volume of the sold water amount. In the system which has 71.4% water loss, over 27.7% of it is unaccounted water volume caused by low accuracy of water meters and the emergency condition of internal networks of private houses, and 43.7% is the water loss in the external water supply system (Fig. 5).

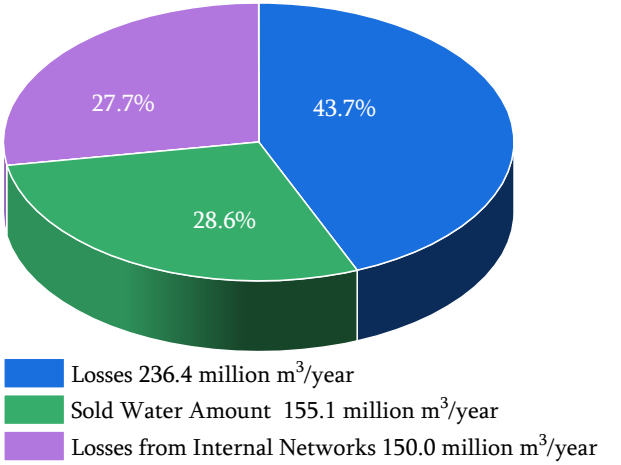

Fig. 5. *Balance scheme of annually produced water amount*

Рис. 5. *Схема баланса годового количества добываемой воды*

Conclusions

1. Research conducted under real conditions showed that internal water supply systems are in poor condition. Technical losses and unaccounted consumption of water in the water supply system of housing blocks and private houses make up 27.7% of the produced water.
2. In order to improve the operation of the internal water supply and drainage system of housing blocks and inventory water losses reaching up to 60% and then to eliminate them, it is recommended to carry out urgent investments.
3. According to the technical-economic calculations, the investments made in order to eliminate the above-mentioned loss are perhaps the most effective means for reducing the amount of unaccounted water, because according to the provisions of the article, in order to eliminate the uninventoried water amount that constitutes huge volumes in internal networks, it is enough to replace the gauging devices with the ones having the highest accuracy, and in the case of private houses, the entry lines of the latter as well.
4. It is necessary to define the priority of the distribution network zoning, to detect and eliminate losses at the current stage, considering the technical condition of the system.

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