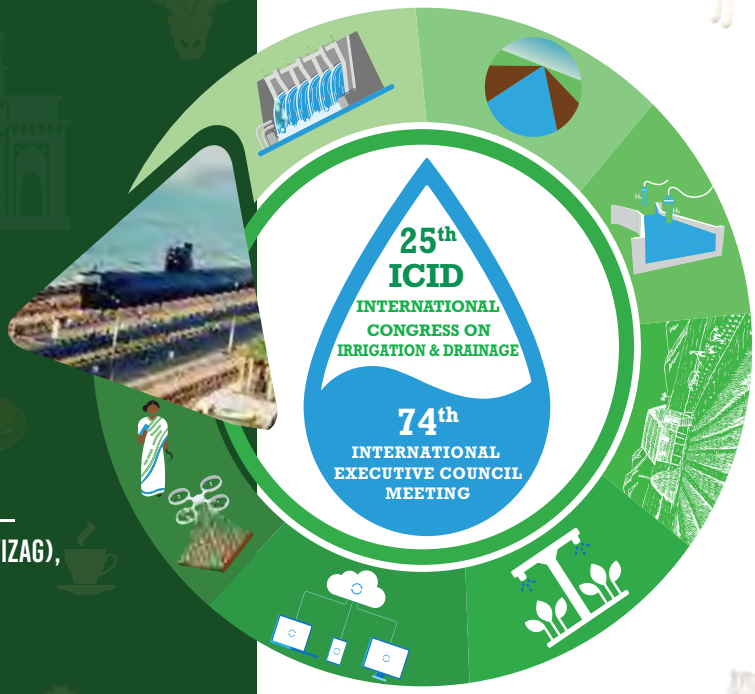
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25TH ICID INTERNATIONAL CONGRESS ON IRRIGATION AND DRAINAGE

1-8 NOVEMBER 2023, VISAKHAPATNAM (VIZAG), ANDHRA PRADESH, INDIA



SIDE EVENT ON

MODERNIZATION OF IRRIGATION SYSTEMS



TACKLING WATER SCARCITY IN AGRICULTURE

LUTTER CONTRE LA PENURIE D'EAU DANS L'AGRICULTURE

INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE

COMMISSION INTERNATIONALE DES IRRIGATIONS ET DU DRAINAGE

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The International Commission on Irrigation and Drainage (ICID), established in 1950 is the leading scientific, technical and not-for-profit Non-Governmental Organization (NGO). The Commission through its network of professionals spread across more than a hundred countries, has facilitated sharing of experiences and transfer of water management technology for over six decades. ICID supports capacity development, stimulates research and innovation and strives to promote policies and programs to enhance sustainable development of irrigated agriculture through a comprehensive water management framework.



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Proceedings

Side Event on

Modernization of Irrigation Systems

Presented at:

25th ICID Congress and 74th IEC Meeting,

1-8 November 2023

Visakhapatnam (Vizag), Andhra Pradesh State, India

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ISBN: 978-81-89610-38-8

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ICT TOOL TO IMPROVE AGRICULTURAL WATER PRODUCTIVITY IN UZBEKISTAN

Sohib Akramov, Rustam Karshiev, Birodar Burhonjonov, Murodjon Ganiyev, Omina Islamova, Sobit Mammatov, Vadim Sokolov, Miloš Ulman[1]

Extended Abstract

In Uzbekistan, 98% of total agricultural production is produced by the irrigated agriculture consuming 85% of water resources, of which only 20% are formed within the country. The increasing deficit of water due to the climate change, trans-boundary problems and population growth is one of the restricting factors for sustainable economic development. Wide use of water-saving irrigation technologies could be one of the ways to combat these challenges, however currently only 10% of the irrigated lands are under such technologies.

To facilitate introduction of irrigation water saving technologies, rational water use and increased water productivity a Mobile Application TOMCHI has been developed within the framework of the National Water Resources Management Project financed by the Swiss Agency for Development and Cooperation and implemented in partnership with the Ministry of Water Resources of Uzbekistan and Agency of IFAS. TOMCHI in Uzbek language is meaning “drop of water”.

The Mobile Application tool designed as a virtual Extension Service for Farmers providing the following tools: (i) access to comprehensive information on applicable in the local context water saving technologies, relevant legislation and best practices; (ii) estimation of respective costs of certain water saving technique implementation; (iii) feedback mechanism and (iv) platform linking water users with local producers and service providers of available water saving technologies.

Mobile application TOMCH – as a consultancy platform for Farmers/Water Users based on web-portal of the Information Analytical and Resource Center of the Ministry of Water Resources of the Republic of Uzbekistan. Regulatory documents

This unique and innovative application is a first step in introduction of ICT tools in daily operations of the Ministry and its subordinated bodies at basin, irrigation system and irrigation district levels, Water Consumer Associations and farmers to promote improved access to knowledge, data collection and real time information exchange. Along the way are water knowledge portal being developed in partnership with the Information Analytical and Resource Center of the Ministry of Water Resources of Uzbekistan, online water resources monitoring tool, unified national agricultural water scheduling software and development of the comprehensive water management database and decision support system of the Ministry.

Keywords: ICT, water saving technologies, agricultural water productivity, rural transformation, digitalization, innovations, mobile application, database, decision support system, water knowledge portal.

Background: Uzbekistan, Water Resources and Irrigation

Along with Liechtenstein, Uzbekistan is one of the only two doubly landlocked countries in the world. Uzbekistan has an area of 448,920 square kilometers. Uzbekistan lies between latitudes 37° and 46° N, and longitudes 56° and 74° E. It stretches 1,425 kilometers from west to east and 930 kilometers from north to south. Bordering Kazakhstan and the Aral Sea to the north and northwest, Turkmenistan to the southwest, Tajikistan to the southeast and Kyrgyzstan to the northeast, Uzbekistan is one of the largest Central Asian states and the only Central Asian state to border all the other four. Uzbekistan also shares a short border (less than 150 km) with Afghanistan to the south.

Uzbekistan is Central Asia's most populous country. Over 33,905 million people live in Uzbekistan (1 January 2020) – about half of total population in Central Asia. Rural population is 49,5% and urban – 50,5%. The most territory of Uzbekistan has a continental, dry (arid) climate, with little precipitation expected annually (100–200 millimeters). The average summer high temperature tends to be 40 °C, while the average winter low temperature is around −23 °C. Less than 10% of its territory is intensively cultivated irrigated land in river valleys and oases. The rest is vast desert (Kyzyl Kum) and mountains.

In Uzbekistan, available water supply is formed by renewable surface and underground waters of natural origin, as well as by return water of anthropogenic origin. Water resources are mainly formed in the transboundary river basins. Only 9.6% of total runoff of transboundary rivers in the Aral Sea basin is formed within Uzbekistan. In

1) All are representing National Water Resources Management (NWRM) Project in Uzbekistan, funded by Swiss SDC, e-mail: info@nwrmp.uz

other words, Uzbekistan is quite dependent from other riparian countries from the point of view of available water resources.



Figure 1. Map of Uzbekistan

The total land area in the Republic of Uzbekistan is 44,892 thousand hectares, which are divided into 8 categories depending on the purpose and procedure for using land, including: agricultural land; lands of settlements; lands for industry, transport, communications, defense and intended for other purposes; lands of environmental protection, health and recreation; lands of historical and cultural significance; lands of the forest fund; lands of water fund; land stock.

Agricultural lands belong to fertile lands, are considered the main means of national wealth, agricultural production and ensuring food security of the country. The total area of agricultural land is 20,236 thousand hectares, of which arable land is 3,988 thousand hectares, perennial plantings - 383.1 thousand hectares, fallow lands - 76 thousand hectares, hayfields and pastures – 11,028 thousand hectares, other lands – 4,760 thousand hectares. Due to the arid climate, agricultural production is almost entirely dependent on irrigation, and only about 752,900 hectares (18%) of arable land are rainfed.

The current annual water demand of all sectors of the economy is about 64.2 km^3 (see table 1 below). In the long run, the demand for drinking water supply from industry, industry and rural areas will increase, while in irrigated agriculture it will decrease due to water-saving technologies and measures to increase fertility.

Table 1. Actual and prospective water consumption (demand) by sectors in Uzbekistan (million m^3 per year)

Water consumers (by priority)	Total water requirement	including by source		
		Surface Water	Underground Water	Return Water
2018				
Domestic utilities	5320	2200	3120	0
Industry	1885	855	1030	0
Rural water supply	485	415	70	0
Fisheries	640	460	0	180
Energy	770	770	0	0
Irrigated Agriculture	55100	50000	1100	4000
Total	64200	54700	5320	4180
2030				
Domestic utilities	6200	2450	3750	0
Industry	3500	1580	1920	0
Rural water supply	950	810	140	0
Fisheries	640	460	0	180
Energy	780	780	0	0
Irrigated Agriculture	48000	46800	700	500
Total	60070	52880	6510	680

Source: Scheme for the Integrated Use of Water Resources of the Republic of Uzbekistan until 2027. Consolidated explanatory note. Association "Vodproekt" under the Ministry of Water resources of the Republic of Uzbekistan. Tashkent. 2018.

At the level of 2030, the total required water volume for Uzbekistan should not exceed 60.1 km^3 per year. According to the Basin Master-Plans (Schemes), the limit (quota) of Uzbekistan as a whole for the basins of the Amudarya and Syrdarya rivers is 63.02 km^3 / year with a 100% availability. In case of less water availability in dry years, water withdrawal limits are reduced.

The country's total annual water withdrawal in the 1980s was about 66.1 km^3. After gaining independence, Uzbekistan clearly shows a tendency to decrease in water consumption and water withdrawal. In particular, during the period 2011-2015, the total water intake amounted to about 53 km^3 per year (Table 2). However, in 2016-19 it was at a level of about 55 km^3 per year. In the dry year 2021, the water intake was only about 45 km^3.

Table 2. Dynamics of actual water withdrawal from rivers (million m^3)

1960		1980		1990		2000			2010	2018		2021	
Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation
30780	27900	64910	55510	56611	58156	53265	35687	56611	44718	54700	50000	45300	39000

It should be noted that the population of the republic from 1980 to the present time has grown from 15 million people to more than 35.2 million people. As a result of population growth, the specific indicator of water consumption per person significantly reduced. An analysis of the use of the water withdrawal limit shows that since 2005 Uzbekistan receives water on average 85.0%, and in dry years, like 2008, 2011 and 2021 about 70-75% of the total annual limit.

Present-day irrigated farming remains one of the most important economic sectors in Uzbekistan, which provides 17% of GDP; but what is the most significant that it is the factor of social stability under ensuring 30% of employment (as of 2021). Thanks to understanding of the social value of irrigation and the wise state policy in the water sector over years of independence, Uzbekistan has managed to maintain its irrigation potential.

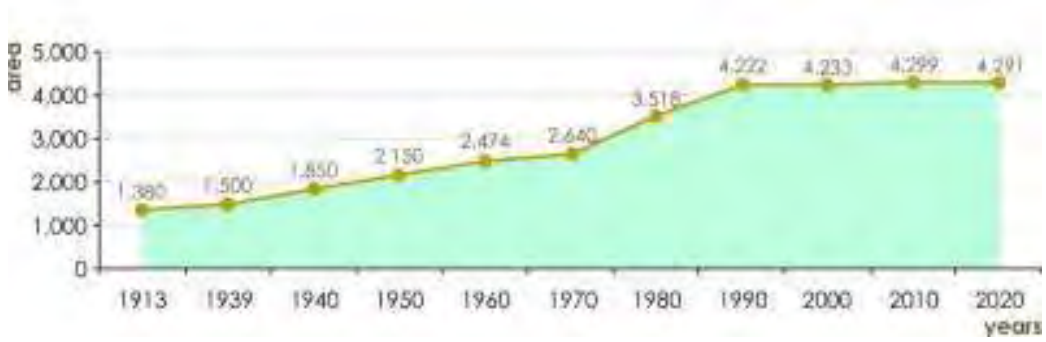


Figure 2. Trends of Irrigation Development in Uzbekistan (area, 000' hectares)

Present-day irrigated farming remains one of the most important economic sectors in Uzbekistan, which provides 17% of GDP; but what is the most significant that it is the factor of social stability under ensuring 30% of employment (as of 2021).

In Uzbekistan, a total length of the inter-farm and on-farm irrigation networks amount to 27,868 km and 154,957 km, respectively. 60 percent of inter-farm canals and 77 percent of on-farm canals have an earth (not lined) channel.

The area of more than 2.2 million hectares is irrigated by pumps that consume electricity of 7,5 billion kWh a year. The following examples show a scale of pumping irrigation: the Karshi Pumping Cascade lifts 200 m^3/sec of water up to 157 m essentially for irrigation of 335,000 hectares in the Karshi Steppe; a cascade of pumping stations along the Amu-Bukhara Canal lift 216.4 m^3/sec of water up to 115 m for irrigation of 315,000 hectares. The Ministry of Water Resources is funding operation and maintenance of 1687 pumping stations where 5284 pump units with total annual capacity of 59.6 billion m^3 of water.

On October 9, 2019 there was released Decree of the President of the Republic of Uzbekistan "On measures to further improve the water management system". By this document priority areas under leadership of the Ministry of Water Resources by the end of 2022 were identified:

- Timely and high-quality development of the Concept for strategic development of water resources in 2020–2030;

- Phased (starting from 2020) implementation of mechanisms for covering a part of the operational costs for the delivery of water by water consumers;
- Bringing the share of land irrigated using water-saving technologies to at least 10 percent of the total area of irrigated land by actively assisting agricultural producers to introduce water-saving irrigation technologies, expanding the production of modern irrigation systems by attracting private investment;
- Institutional, technical and technological development of water management, integration of science with production in this area.

Mobile Application TOMCHI

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Mobile Application TOMCHI is software designed to work using smartphones and other mobile devices. It works in smartphones running on Android and iOS platforms. For smartphones running on the Android platform, the application can be downloaded from the Google Play Market, and for smartphones running on the iOS platform from the Apple Store (Figure32).



Figure 3. Mobile Application TOMCHI (just use the Google Play Market)

Mobile Application (MA) TOMCHI includes information on modern water-saving technologies for irrigation, such as drip, sprinkling and subsoil, also water-saving methods for traditional for Uzbekistan furrow irrigation, such as alternating irrigation and dry inter-row irrigation, short-furrow irrigation and variable-sprinkler irrigation. The MA suggests to use various technical means for furrow irrigation widely used in Uzbekistan, such as the use of flexible irrigation hoses, discrete irrigation, irrigation using furrow-shielded polyethylene film and the use of moisture-retaining hydrogels.

The MA (Interface in Uzbek language) provides information on methods for determining the irrigation time/scheduling for different crops, information on field activities/cultivations that contribute to water conservation. Also, the MA provides information on local manufacturers who produce water-saving irrigation systems, information on service providers for the implementation of water-saving irrigation systems, as well as information on incentives for the implementation of water-saving irrigation systems supported by Government of Uzbekistan.

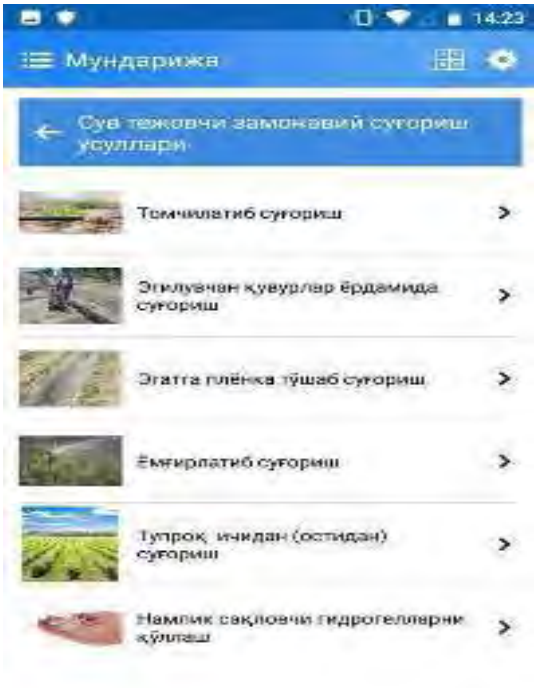


Figure 4. MA “Tomchi”: Section “Modern Water-Saving Irrigation Methods”

The sub-section “Modern Water-Saving Irrigation Methods” provides detailed information on modern advanced water-saving irrigation methods, such as drip irrigation, sprinkler irrigation, subsoil irrigation, the use of flexible polyethylene hoses and films for furrow irrigation, irrigation using water-retaining hydrogels (Figure 4).

Mobile application TOMCHI includes a number of sections. The first one is section “Water-saving irrigation methods”, which consists of two sub-sections:

- “modern water-saving irrigation methods”;

- “water-saving methods of traditional irrigation”.

Thus, the sub-section focuses on the most popular technologies of advanced irrigation which in recent years have been actively stimulated by the government for agricultural irrigated lands in Uzbekistan. It also provides information on the use of moisture-retaining hydrogels for the efficient use of water (soil moisture conservation) when growing crops.

Each part of the sub-section describes in detail the presented irrigation method, its advantages, the conditions for their applicability, the constituent elements of the irrigation method, the rules for the design, specifics of construction and operation of certain irrigation system. The sub-section “Water-Saving Methods of Traditional Irrigation” provides information on water-saving methods of traditional surface furrow irrigation (gravity irrigation), in particular, water-saving methods (irrigation by alternating water and dry rows, irrigation using short furrows and irrigation with a variable stream).

Section "Enterprises". This section provides information on the main local manufacturers who produce elements of water-saving irrigation systems. The section includes detailed information and contacts of the main manufacturers / factories, design organizations and service providers. The section also provides examples of the most successfully implemented in local conditions technologies and results and lessons from functioning water-saving irrigation systems.

Section “Governmental Incentives to Support Water Conservation”. The section highlights governmental efforts to stimulate wide practical introduction of water-saving irrigation systems, in particular drip irrigation systems. In Uzbekistan, farmers (agricultural producers) using traditional irrigation methods to grow crops usually do not pay for water, but pay a Unified Land Tax. For farmers using water-saving irrigation technologies, in particular, introducing a drip irrigation system, a privilege has been established by Government for exemption from the payment of a Unified Land Tax for a period of 5 years.

The section also provides information on the provision of soft loans and subsidies (in the amount of 50% of the installation cost) to farmers who are going to install drip or other water-saving irrigation methods. At the same time, the information in this section is constantly updated in the light of new decisions by the government to promote water conservation.

Section “Setting Schedule of Irrigation”. This provides information for certain farmer on determining the timing of irrigation for crops based on a visual assessment of changes in soil conditions and crops grown at the particular field. That is done on the basis of instrumental measurements of changes in soil moisture, which farmer should put into MA. The section also provides recommendations on methods for assessing changes in soil moisture using various laboratory devices, such as thermostats, remote sensors and cameras to determine the suction pressure in plant leaves.

Section “Promotion of Measures for Water Conservation”. This provides information and recommendations on measures that effectively contribute to water conservation. The section provides information on soil cultivation measures both before sowing and during the vegetation of plants, which contribute to reducing water infiltration into the deep layers of the soil.

Information is also provided on measures that contribute to reducing the evaporation of moisture from the soil surface. As such, measures are presented for tillage (inter-row cultivation of the soil) and the use of various materials to cover the soil surface (mulch) and measures to reduce the wind force over the surface of the irrigated field (use of forest strips). Section “Calculator”. In this section, users who want to install water-saving irrigation technologies at their irrigated fields, in particular, a drip irrigation system, can determine the approximate cost of purchasing and installation of drip irrigation system.

The calculator takes into account various types of crops and various options for planting schemes. At the same time, in drip irrigation systems for orchards and gardens, irrigation hoses with special drippers are suggested, for field drip irrigation systems that are designed to irrigate field crops with a wide-row planting pattern, irrigation hoses with ordinar droppers are used.

Knowledge about the price of drip irrigation systems allows farmers to make decisions on attracting investments for introducing drip irrigation systems and successfully conclude contracts for the installation of drip irrigation systems. The section of the mobile application “Useful Links” provides information about the legal framework (legislative acts) useful for farmers' water management. This section also presents various newsletters, recommendations and guidelines promoting the rational use of water resources.

The latest version of the mobile application also presents the “News” section, which publishes various interesting information and stories about effective methods of using water resources. This section is updated daily with new information from around the world.

Thus, the use of various information and communication technologies in the field of water use such as the Tomchi mobile application improved the awareness of water consumers about water-saving irrigation methods and, along with government measures to stimulate the use of water-saving technologies, contributed to an increase in the efficiency of water use in agriculture. At the same time, the area of irrigated land in Uzbekistan, where water-saving irrigation technologies are used, has increased about 5 times over the past 3 years, and the volume of water resources used has been reduced by 20% throughout the country.

Telegram group is one of the main channels for direct communication with the large audience of farmers and WST producers. The number of subscribers of the "Tomchi” channel coupled with the group “Tomchi experts" is steadily growing, though the audience, as well as the thematic area, is very specific 7 to 10 posts are published daily totaling to around 3000 per year. Most of the articles are prepared as a response to the requested questions asked in the group. Having understood that TOMCHI expert group is the place for getting answer to any urgent question, the number of subscribers radically increase from 2170 at the end of 2020 approaching to 4500 in December of 2021.

The number of videos in TOMCHI YouTube channel is steadily growing due to project's own videos created and videos related to the topic collected by the project staff. The number of videos has grown significantly after collaboration with the water saving technology producers was established. The country's largest producers contact the project requesting to place the videos with their projects on installing WST in various regions for various crops, making the channel one of the main video platforms for knowledge sharing and promotion of WST. The videos are also uploaded on national video Streaming platform mover.uz, which is free of change.

CREATION CONDITIONS FOR INNOVATIONS IN THE ZONE OF THE ARAL SEA CRISIS

Vadim Sokolov[1]

Extended Abstract

On May 18, 2021, the UN General Assembly adopted a special Resolution 75/278 “Declaring the Aral Sea region a zone of environmental innovations and technologies”. The concept of such zone is effective mechanism for implementation of the principal post-2015 intergovernmental agreements which Uzbekistan signed with responsibility – namely: 2030 Agenda and Sustainable Development Goals, Paris Agreement on Climate Change, and Sendai Framework on Disaster Risk Reduction 2015-2030 - for the Aral Sea Basin.

We are fundamentally changing the ideology of solving the Aral catastrophe: we do not just draw attention to the ecological crisis in order to reduce its negative consequences, but create a mechanism to eliminate it. The Concept coverage area is the whole Central Asia, taking into account common regional approach to implementing measures in the Aral Sea basin, with priority results aimed to improving socio-economic and environmental situation in the Priaralye. There is need for fundamental change in practice and scope, which can lead to restoration and functional integrity of ecosystems which are the basis for socio-economic development in the Aral Sea region. Strategic priorities for development of innovations in the Aral Sea region:

- creation of legal and regulatory framework
- creation of financial system for attraction innovations
- creation of scientific platform for the Aral Sea region
- growing qualified personnel and support networking among research institutions and universities, stimulation of creativity

The regulatory framework should provide mechanisms and instruments for regulating relations at the regional level, taking into account the rules and norms of international law, aimed at improving effectiveness of the water resources management system in the Amudarya and Syrdarya river basins, including incentives and responsibility mechanisms, as well as water resources management rules, guaranteeing conservation of water resources and electricity, ensuring a guaranteed water supply for the Aral Sea it-self.

Keywords: Aral Sea, Ecological innovations, Ecosystems restoration, Socio-economic developments, Environmental crisis stabilization

Crisis of the Aral Sea

The Aral Sea, which was unique, beautiful and one of the largest inland water bodies in the world, almost ended up on the verge of a complete extinction, spelling unprecedented disaster and irreparable damage to the life of the more than 60 million people living here, to the ecosystem and biodiversity of the Aral Sea and adjacent territories. The Aral Sea with its significant water surface (over 69.790 km^2) and water volume about 1080 km^3, served until the mid-1960s as a climate control reservoir and mitigated sharp weather fluctuations in the Central Asian region. Coming to the region, mainly from the west, the air masses warmed up in the winter, and cooled in the summer over the water area of the Aral Sea. Due to this temperature regime, the moisture, carried by air currents, fell out as precipitation over the mountains of Tien Shan and Pamir in the autumn-winter period, replenishing snow cover and volume of the glaciers.

Since 1960, in connection with the intensive irrigation and hydropower development in the Aral Sea basin, the total water consumption in the Amudarya and Syrdarya basins began to increase rapidly due to regulation and irretrievable withdrawal of surface runoff: 7.7 km^3 / year in 1961-1965; 17km^3 / year in 1966-1970; 30km^3 / year in 1971-1975 and up to 50 km^3 / year or more at the end of the 80s. Thus, since 1960, the negative water balance of the sea has become the norm and, from 1970 to 1990, the annual balance deficit exceeded 30 km^3.

The formation of such big deficit in the sea balance is also largely due to climatological factors - in the seventies the water formation in the Amudarya and Syrdarya rivers was 20-25% lower than normal and the total renewable water resources of the Aral Sea were 20-25 km^3 / year less than before.

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Figure 1. The Aral Sea Basin - relevant territories of Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan

Table 1. Water Balance of the Aral Sea, km^3/year

Time period	Water income		Losses for Evaporation	Balance
	Rivers flow	Precipitation		
1911-1960	56,0	9,1	66,1	-1,0
1961-1970	43,3	8,0	65,4	-14,1
1970-1980	16,7	6,3	55,2	-32,2
1981-1990	3,9	6,2	43,7	-33,6
1991-1994	21,0	4,6	33,6	-8,0
1995-2002	4,81	3,5	28,6	-20,29

The Aral Sea was divided into the North and South in 1989 as a result of lowering the water level and drying out of the Berg Strait. By the end of the 1990s, the Great (Southern) Aral Sea turned into a hyperhaline (salt) reservoir. Salinity in 1997 was 57‰ (ppm). In 1997, Barsakelmes island was connected to land, in 2001 - Vozrojdenie island.

In 2003, the South Aral Sea was divided into eastern and western parts, which were connected by a narrow strait Uzun-Aral, located at an altitude of 29 m. This location does not allow the mixing of water from two reservoirs. In 2004, the small lake Tuschibas, which was previously the eponymous Gulf of the Aral Sea, was separated from the Eastern part. In 2005, the Small Aral Sea was cut off from the Great Sea by the Kokaral dam - in Kazakhstan. Both water bodies were finally disconnected.

The Kokaral dam, which blocks the Berg Strait in between the North Aral Sea (Small Sea) and the South Aral Sea (Big Sea), was designed to regulate the water level in the Small Sea. The length of the dam is 13,034 m, the width is up to 100-150 m. The height of the dam crest is 6 m (45.5 m abs), the filling of the Small Sea is supposed to reach 42.2 m abs. A structure with nine spillways to discharge of 600 m^3 / s was built on the dam to release excess water.

Today, the surface area of the remaining parts of the Aral Sea is less than 10% of the area in 1960. It is distributed between three reservoirs - the Western Sea with an area of 3.12 thousand km^2, the Eastern Sea with an area of 0.50 thousand km^2, and the Small (Northern) Aral - with an area of 2.35 thousand km^2. Accordingly, the volume of water decreased by almost 15 times.

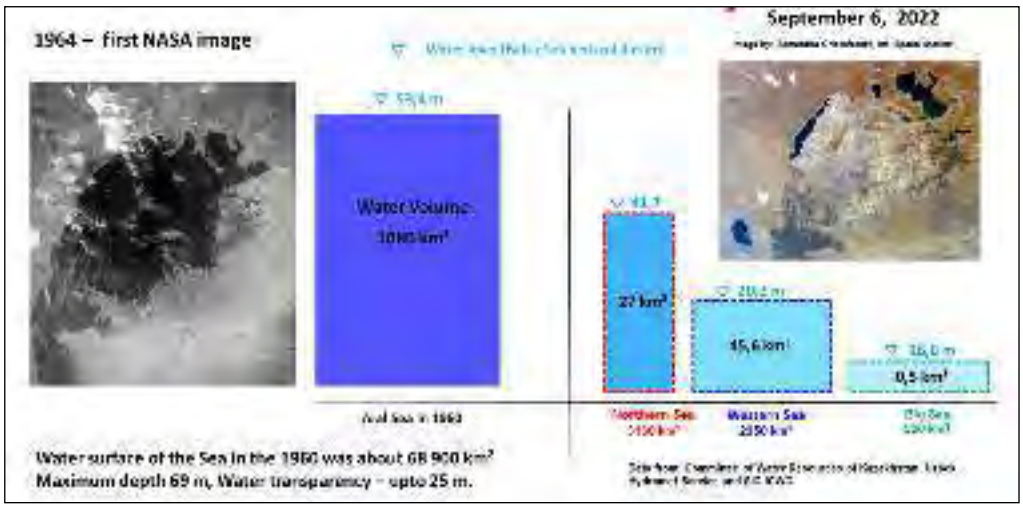


Figure 2. The Aral Sea in the Past and Today

For the full restoration of the Aral Sea, 1080 km^3 of water (sea volume at the level of 1950s) plus about 50 km^3 annually will be required to compensate evaporation losses. The total annual runoff of the Amudarya and Syrdarya rivers is about 120 km^3. Thus, in order to fill the sea in the same volume, it will be necessary to completely stop all economic activity in the basin for at least 30-40 years - that is mostly unrealistic!

Summit of Heads of States of IFAS founders

Due to active work of the International Fund for Saving the Aral Sea, in 2018, two meetings of the Fund's Board were held and in August the IFAS Summit of the Heads of the Founding States of IFAS was held in Turkmenistan, which gave new impulses to solving the problems of the Aral Sea.

The President of the Republic of Uzbekistan, Shavkat Mirziyoyev suggested a number of important initiatives that, if they are implemented, will be able to: - "dramatically improve the unfavorable environmental situation in our region." For this “decisive and non-standard measures are needed”.

The main initiative of the President of Uzbekistan - to declare “Priaralye - the Zone of Environmental Innovations and Technology”. The Objectives of this initiative is - to create conditions for common actions taken by the countries in the Aral Sea basin aiming to transform zone of ecological crisis associated with drying of the Aral Sea into a zone of socio-economic developments through introduction of environmental innovations and technologies.

Unfortunately, until today there is no in-depth analysis of the results of the three programs (ASBP) within the framework of IFAS. However, we can prove that over the past 25 years, the provisions of the Concept to solve the problems of the Aral Sea, which was adopted by IFAS in 1993, have practically become obsolete. Much has been done by the countries to mitigate the consequences of the Aral Sea disaster, the socio-economic conditions in the regional countries have changed, the water situation in the region has changed dramatically. In the Aral Basin, as elsewhere in the world, the impacts of climate change are really observed. Many other factors also indicate that it is time to change practices regarding the creation of ecosystem resilience with economic growth.

Concept “Aral Sea Area Zone of Environmental Innovations and Technologies”

On May 18, 2021, the UN General Assembly adopted a special Resolution 75/278 “Declaring the Aral Sea region a zone of environmental innovations and technologies”.
Following this support from the UN there was adopted Resolution of the Cabinet of Ministers No. 41 of January 25, 2022 "On additional measures to turn the Aral Sea region into a zone of environmental innovations and technologies **“.** This document was developed as part of the implementation of Presidential Decree No. PP-5202 of July 29, 2021 “On measures to implement the special resolution of the United Nations General Assembly of May 18, 2021 “On declaring the Aral Sea region a zone of environmental innovation and technology.” Document approved:

- The concept of transformation of the Aral Sea region into a zone of ecological innovations and technologies;
- Multilateral "Roadmap" on the priorities of attracting foreign investment in the Aral Sea region for 2022-2026.

The concept includes the following areas:

- Creation of "driver" clusters for technological innovations, including introduction of effective methods of ecosystem management, in particular, new technologies that save natural resources;
- Development and implementation of economic and financial innovations, formation of market and price mechanisms necessary to stimulate technological innovation and create "green" jobs;
- Implementation of innovative policies and legal innovations, including reducing risks associated with climate change, implementing agricultural and green economic strategies, and implementing land reforms that stimulate investment by landowners.

The multilateral "road map" for attracting foreign investment in the Aral Sea region for 2022-2026 includes:

- Priorities for implementation of measures for integrated development of the Aral Sea region in 2022-2026;
- Measures to expand international cooperation for sustainable development of the Aral Sea region and monitoring of programs and projects implementation;
- List of projects aimed at sustainable development of the Aral Sea region.

Coverage area for activities is the whole Central Asia (five countries – Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan plus Afghanistan in coming future), taking into account common regional approach to implementing measures in the Aral Sea basin, with priority results aimed to improving socio-economic and environmental situation in the Aral Sea zone. We are suggesting fundamental change in practice and scope of policy developments and implementing actions, which can lead to restoration and functional integrity of the ecosystems which are the basis for socio-economic development.

The concept “Aral Sea Area Zone of Environmental Innovations and Technologies” is effective mechanism for implementation of the principal post-2015 intergovernmental agreements which Uzbekistan signed with responsibility – namely: 2030 Agenda and Sustainable Development Goals, Paris Agreement on Climate Change, and Sendai Framework on Disaster Risk Reduction 2015-2030 - for the Aral Sea Basin. Common actions will be identified that simultaneously support achievement of the goals and targets of above-listed agreements. This creates opportunity to build regional and national policy coherence and foster risk-informed policy and decision-making.

Both key areas of the Aral Sea (the Small Sea in the North – in territory of Kazakhstan, and the South Aral Sea with adjacent dried bottom and remnants of the Aral Sea in Uzbekistan) lack the necessary volume of water resources due to both water balance issues (e.g. inefficient use of water and unproductive water loss) as well as the current level of water demand, which could be more efficiently managed. Uncertain (not stable in time and volume) water supply creates significant challenges to fully implement all necessary measures for ecosystem restoration and socio-economic development of the entire Aral Sea region. In principle, both the demand and supply side of water resources balance need to be supported by robust and timely data and analytics, climate risk analysis, and holistically and efficiently managed. By implementing proposed Concept - on income side of water balance - water management system (such as unproductive water loss reduction) will be improved, ensuring a predictable and stable flow of water to the Amudarya and Syrdarya river deltas, based on regional cooperation of all countries of the Aral Sea basin in water conservation, management and optimal use of transboundary water resources. On out-come side of water balance, agreed measures will be implemented to reduce the consumption and ensure proper balance between supply and demand.

Along with the Road-mapt, a multi-stakeholder (private-public/governmental) partnership will be nurtured through establishment of an Aral Sea Region Innovation Platform, to roll out a deep demonstration of rapid, systemic change, building on key processes and policies already underway, but without mistakes from the past. Proposed innovation approach is that in complex and uncertain contexts answers are not possible through analysis alone, the situation can be changed by experimentation.

Our innovation approach has emerged from recognition that complexity of environmental, social and economic problems as faced in Karakalpakstan (Uzbekistan) and Kyzylorda (Kazakhstan) cannot be addressed using a traditional, linear, planning and implementation approach – the sequence of analysing-planning-implementing-evaluating does not work in complex systems contexts with existing challenges. It is the relationships and interdependencies between complex programmes, rather than implementation of individual as before. It is the coherence and scalability of systemic portfolio approach to innovation that offers a new proposition for donors, governments and private investors – an opportunity to invest in joined up, accelerated learning (in an innovation portfolio) about the optimized combination of projects that will create fastest pathway from the Aral Sea as region of crisis to region of opportunity and risk-informed sustainable development.

The overall goal of Government’s initiative is to position Uzbekistan and the Aral Sea region as a global pioneer in harnessing systems innovation to finance the transformation of the economy and society within the zone of ecological crisis, creating new and better opportunities for its people, while helping revive a declining ecosystem that should be improved and sustained over time. As a result, the well-being and prosperity of all Aral Sea region

communities will be advanced and climate and ecological crisis impacts significantly reduced to support the achievement of the 2030 agenda targets.

The Program for Rational Use of Water Resources

How much water is needed to sustain remains of the Aral and water bodies and wetlands in the South Aral Sea region (including the Amudarya delta)? Those water bodies can be divided into 3 zones according to their water sources regime (Figure 3, Table 2):

1. Left-bank zone (West) - the territory under the command of the Raushan canal system, drainage collectors of KKS and GK. The main water bodies are the Sudoche wetland lakes - Akushpa, Tayly, Bolshoy Sudoche and Begdulla-Aydin, Lake Karateren and the lakes of the Karadzhar system - Mashankol, Khojakol, Ilmenkol

2. The central zone - the territory under command of the main channel of the Amudarya, canals Taldyk (Kungrad-Moynaq), Moynaq (Glavmyaso) and Marinkinuzyak. The main water bodies are the Mezhdurechinsk reservoir (including Maypost and Domalak lakes), Rybachie and Moynaq lakes, Zakirkol lake and Makpalkol lake.

3. Right-bank zone (East) - the territory under the command area by channel of Kazakhdarya, drainage collectors KS-1, KS-3. The main water body is Zholdyrbas. Also, the territory supplied by the drainage collector KS-4 to small lakes of the Akpetki gorge.

To solve problems of water supply to this zone, Uzbekistan Government initiated in 2002 project «Creation of Small Local Water Bodies in the Amudarya Delta». In result of the project by 2025, the necessary engineering infrastructure will be created, which will be able to provide the optimal water horizon for the stability of ecosystems and economic activity in the reservoirs of the southern Aral Sea region.

Table 2. Water bodies and wetlands in the Southern Aral Sea landscape

Name of water body	Water level (Baltic system), m	Area, km2	Water volume, million.m3
Dried Aral Sea area and surrounding Ustyurt Plateau			
Sarykamysh Lake and surrounding Ustyurt Plateau (shared with Turkmenistan)	8,0	959,7	70000
West Aral and surrounding Ustyurt Plateau (shared with Kazakhstan)	24,6	5110 (including water surface 3175)	43600
Left-bank (Eastern) zone of the Prearalie			
Wetland of the Sudoche lake	52,5	464,7	884
Mashankul and Khojakul Lake complex	53,0	50,7	440
Central zone (Amudarya delta)			
Mezhdurechensk water reservoir	57,0	320	420
Rybachie reservoir	51,0	64,0	136
Moynaq reservoir	51,6	97,4	163
Makpalkol lake	53,0	12,0	63,0
Maypost lake	55,0	27,1	30,0
Zakirkol lake	56,5	15,8	17,8
Right-bank (Western) zone of the Prearalie			
Zholdyrbas Lake	52,0	297,2	477
Akpetki Lakes and surrounding	53,0	391,5	100
Sub-total in Prearalie		**1740,4**	**2730,8**

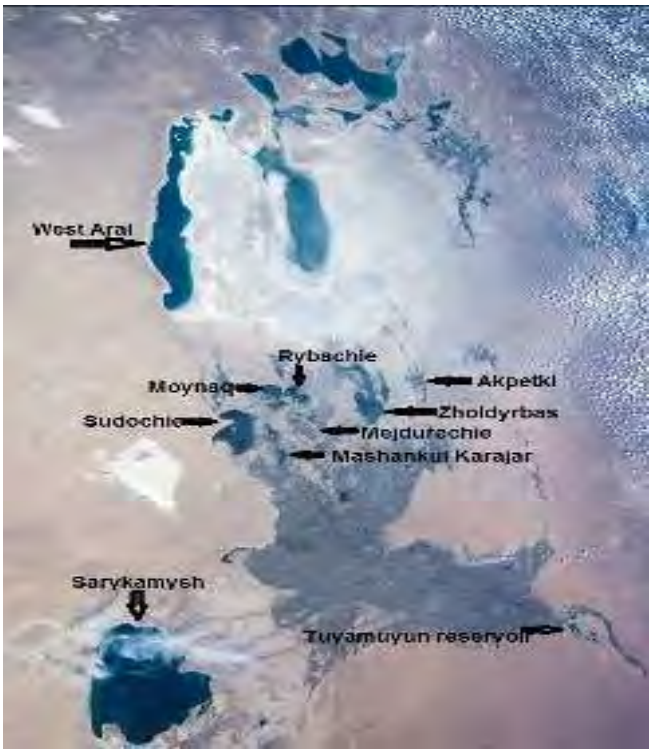


Figure 3. The water bodies and wetlands in the South Aral Sea region

Important to note, that in 1995 Uzbekistan joined the United Nations Convention to Combat Desertification (UNCCD), which put certain obligations in 2016 to provide Neutral Land Degradation (NLD) - or "a condition in which the volume and quality of land resources necessary to maintain ecosystem functions and services and enhance food security remain stable or increase within a given time and space framework."

However, the above-mentioned water stability and Neutral Land Degradation can be provided only under the condition of stable water supply to this zone through the Amudarya river and collectors. The average volume of required water supply is estimated not less than 6,0 km^3 per year. The following actions are undertaken by Uzbekistan to achieve this goal:

- Establishing coordinated with other countries water limits in the middle- and upper-stream of the Amudarya and Syrdarya basins with the determination of the degree of water availability in comparison with the actual water demand;

- Preservation of and sustainable management of wetland ecosystems and coastal corridors of the Aral Sea basin to support sustainable livelihoods, including protection of existing water bodies and improving their connectedness to increase functional integrity and a gradual ecosystem regeneration;

- Provide reduced water consumption rates in the upper- and lower-reaches, by increasing their uniform water supply during the growing season and reducing all types of losses (increasing system efficiency and irrigation equipment efficiency), as well as releasing 3-4 km^3 of water along main channel of the Amudarya river for the delta;

- Transfer of part of waste (collector-drainage) waters from the Khorezm and Bukhara oasises to the lower reaches of the Amudarya - 3 km^3.

During the already mentioned Summit of the Heads of the Founding States of International Fund for the Aral Sea Saving (IFAS), which was held in August 2018, President of Uzbekistan suggested one more special initiative - "It is necessary to drastically increase the level of regional cooperation in water conservation, management and rational use of transboundary water resources".

In response to this, Ministry of Water Resources of Uzbekistan prepared "The Water Sector Development Concept of Uzbekistan for the period of 2020-2030". This document is recently under public discussion via Governmental web-portal and expected in August 2020 there will be released a special Presidential decree on its official adoption and implementation.

The goal of water sector development in Uzbekistan is to create conditions for meeting the ever-growing needs of people, economy and environment for water, ensure efficient water resources management and use, ameliorative

condition of irrigated lands, and achieve water and food security in the context of the growing water scarcity and global climate change.

To improve efficiency of the water sector and to introduce market principles and commercial practices, proper improvements in water management system are envisaged. First, is partial transfer of water management functions to water consumers (farmer associations, WCAs, clusters, etc.) according to well-defined criteria and guidelines encompassing clear split of responsibilities, economic efficiency, social equity and environmental sustainability. Second, wider introduction of public-private partnership (PPP) and other outsourcing principles into water management system. The PPP principles suppose long-term contractual partnerships between public water utilities and private sector aimed at implementation and financing of water infrastructure projects that are currently managed by public sector and financed by the state budget. It is planned to transfer to outsourcing (with a possibility of transferring the existing utilities to trust and other forms of property management):

- Operation and maintenance of water assets;
- Rehabilitation, construction and modernization of water assets;
- Other water sector related services.

The transfer of assets and services to public and private partnership should be carried out exclusively on a competitive basis under transparent procedures. Decentralization of water system management, including outsourcing and PPP mechanisms, has the potential to increase water efficiency through water delivery cost reduction, increased water productivity and use, which will be achieved through optimization of production processes, implementation of modern technologies and creating incentives for efficient water use.

An important tool for water policy implementation is the water tax for efficient water use and penalties for water pollution and overuse. Improvement of taxation and penalty system will contribute to more efficient water use and improved water quality. In this regard, it is planned to improve a methodology for calculating tax and fine rates for different categories of water consumers taking into account their industry and technological specifics and the quality of return flow, including water salinity and other contaminants. For further wide application of water-saving technologies and increased water productivity and water use efficiency in agriculture, the following measures are expected:

- Further development of state support system for agricultural producers, who apply water-saving methods and technologies;
- Widespread implementation of water-saving technologies with water delivery using pumping stations and pumping units, including in the cultivated areas irrigated with irrigation wells and vertical drainage wells;
- Improvement of incentive mechanisms for research and development on using water-saving methods and technologies, taking into account soil, climatic and other regional characteristics of the country and incorporating lessons from past, including developing highly efficient systems that require lower maintenance costs;
- Improvement of cooperation between industrial sectors in manufacture of components and spare parts for water-saving irrigation systems, including drip and sprinkler irrigation technologies;
- Awareness raising about water saving technologies including highly efficient surface irrigation methods;
- Development of guidelines for the design, implementation and application of water-saving technologies, as well as criteria for evaluating their performance based on specifics of irrigated areas, crops and varieties;
- Organization of training, retraining and advanced training of experts on implementation and use of water-saving irrigation practices and technologies;
- Expanding the technology for crop pattern development using automated laser planners, as well as an underground closed irrigation system using modern flexible pipes;
- Development and implementation of evidence-based water rotation standards in industry and municipal services;
- Use of remote sensing systems for monitoring and targeted water productivity improvement;
- Implementation of water rotation and other arrangements, as well as technologies to control field level water losses and non-revenue water.

The main targets and indicators expected in result implementation of the Concept are as following (Table 3).

Table 3. The main targets and indicators of the Concept of water sector development in the Republic of Uzbekistan for 2020-2030

Indicator	Unit	Actual (2019)	Indicators to be achieved by years			
			2020	2021	2025	2030
Rational Use of Water Resources						
Improving efficiency rate of irrigation networks	%	0,63	0,64	0,65	0,68	0,73
Reduced proportion of irrigated areas with limited water availability	Thousand hectares	560	526	492	356	190
	%	13	12	11	8	4
Modernization of primary and inter-farm canals and increased share of canals with lining	km	9 675,7	9 960,3	10 529,4	11 425,7	13 175,7
	%	34	35	36	40	46
Replacement of existing pumping station units with energy-saving pumping units	units	732	163	163	653	1 750
Replacement of obsolete electric motors of pumping stations with new electric motors	units	1 627	214	219	903	2 100
Energy savings at pumping stations	Billion kWh	8,0	7,6	7,3	7,0	6,0
Scaling up Utilization of Water-Efficient Technologies						
Implementation of water-saving irrigation technologies	Thousand hectares	127,5	250	350	1 000	2 000
	%	3	5	8	23	47
Increased share of areas with drip irrigation technologies implemented	Thousand hectares	77,4	125	200	250	500
Improvement of Ameliorative Condition of Irrigated Lands						
Reduced proportion of salinized irrigated areas	Thousand hectares	1 935	1 926	1 906	1 852	1 722
	%	45,7	45	44,6	43	40
Reduced proportion of areas with critical level of subsurface water (0-2 m)	Thousand hectares	1 051,1	988,1	945,2	859,2	773,36
	%	24	23	22	20	18
Reduced proportion of areas with strong and medium salinity in relation to total irrigated areas	Thousand hectares	607	581	559	516	430
	%	14	13,5	13	12	10
Reclamation of land plots where cultivation was stopped	Thousand hectares	48	58,2	41,5	150,8	

Concluding remarks

The operationalization of the Concept will lead to transformational and sustained improvement in quality of lives and livelihoods of people in the Aral Sea region and restoration of a vibrant ecosystem and increased biodiversity of the Aral Sea basin.

Theory of change of the Concept is to develop a coherent, flexible Aral Sea Region Innovation Platform, adopting innovation approach to empower diverse groups of people to change practice, through exploration, experimentation and deep demonstrations. Initially in Karakalpakstan and then engaging the wider Aral Sea region, building on the Human Security Principles.

Our collective efforts in the Aral Sea region can be an inspiration for transformative, systems innovation approaches in other complex crisis regions across the world.

DECISION SUPPORT IN SUBSURFACE DRIP IRRIGATION SYSTEMS DESIGN IN THE CONTEXT OF IRRIGATION RESTORATION IN UKRAINE

Prof. Romashchenko Mykhailo[1], Dr. Bohaienko Vsevolod[2], Mrs. Sardak Anastasiia[3]

ABSTRACT

"Irrigation and Drainage Strategy of Ukraine up to 2030" provides for irrigated area increase by 1.0-1.2 mln ha. Irrigation potential raise is possible ensuring efficient water usage given strong manifestation of climate change in Ukraine and infrastructure destruction due to Russian aggression. Efficiency is achieved applying water-saving irrigation methods and decision support systems during their design and operation.Among such methods, subsurface drip irrigation systems requires significant costs for construction and operation. We propose a technique for the determination of its design parameters (installation depth and distance between pipelines) based on the modelling of moisture transport.

We use two-dimensional Richards equation in terms of pressure with parameters – water retention curves and hydraulic conductivity - determined processing laboratory analysis results.Irrigation is simulated maintaining average moisture content in the root zone in a narrow range of high values (>80% of field capacity (FC)). Another considered option is pulse irrigation with maintainable range of 90-95% - 100% FC in the root zone's part located close to emitters. Determining the irrigation regime that ensures optimal water consumption with minimal infiltration water losses is performed using mathematical modelling.

System's resilience to weather extremes and climate change is assessed simulating meteorological scenarios series generated by a stochastic weather generator. The objective function is the costs for system creation and operation averaged over all meteorological scenarios. Its minimization is performed by a genetic algorithm.Since modelling the entire growing season is a computationally complex problem, we consider only the period of maximum water consumption.

Computational experiments' results demonstrates compliance with the practice of designing subsurface drip irrigation in southern Ukraine. Further technique's development is possible applying it for the generation of practical recommendations for various crops and climatic zones.

Keywords: subsurface drip irrigation; moisture transport; modelling; optimization

1. Introduction

One of the most important problems of humanity, namely the food problem, is not solved with the passage of time but, on the contrary, worsens. Climate change and population growth are the main drivers of this aggravation. One of the ways to solve this problem is the development of irrigation as a tool to ensure sustainability and higher productivity of agriculture in the conditions of progressive climate change. Ukraine belongs to the number of countries that, according to the definition of FAO, have a leading role in solving the world food problem. Its agricultural resource potential, provided that modern farming technologies are used, is sufficient for food production in volumes sufficient to feed at least 500 million people.

The realization of these opportunities is limited by insufficient level of natural moisture supply on the one hand and the military aggression of Russian Federation on the other. Regarding the latter it is possible to suggest that this action is temporary and with the joint efforts of the people of Ukraine and international community, the aggression of Russian Federation against Ukraine will be stopped and Ukraine will be able to take measures to restore full-fledged economic activity throughout its territory within the internationally recognized borders, including the agricultural sector of economy, the role of which, as already noted, is extremely important for solving the world food problem. The only factor, which will affect sustainability and efficiency of agriculture, will remain insufficient level of natural moisture supply that will continue to deteriorate due to climate change. Indeed, according to forecast data (Romashchenko et al., 2020) from 65% (in 2050) to 80% (in 2100) of the territory of Ukraine will be characterized by a significant (over 150 mm) deficit of climatic water balance (Fig. 1).

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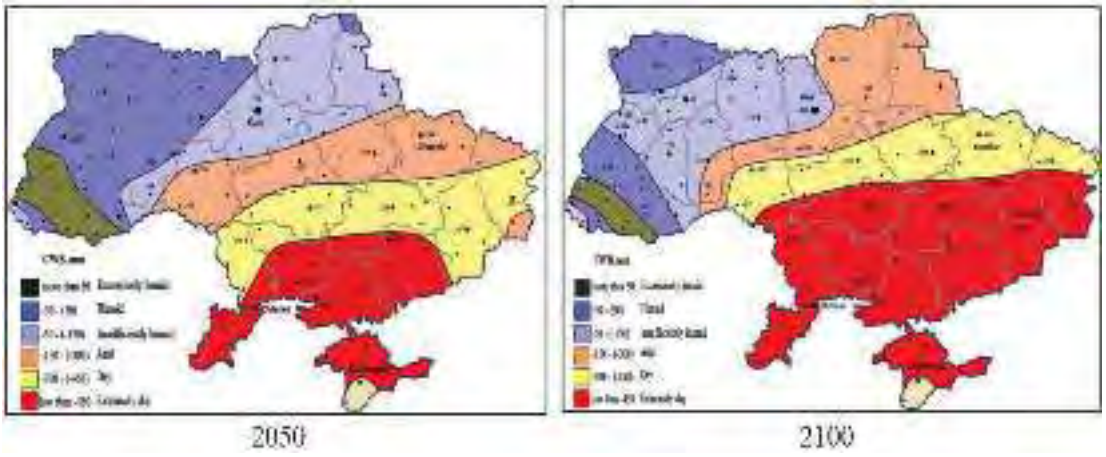


Figure 1. Forecast of moisture supply conditions in Ukraine according to annual climatic water balance
*source: Romashchenko et al. (2020)

Under these conditions, sustainable agriculture without irrigation will be impossible. That is why the Cabinet of Ministers of Ukraine approved the "Irrigation and Drainage Strategy in Ukraine for the period until 2030" and the Action Plan for its implementation developed with the participation of experts from the World Bank and FAO. These government program documents provide for an increase in irrigated areas by 1.0-1.2 million hectares, as well as water regulation using drainage systems on ~1.0 million hectares. Therefore, taking into account the significant increase in the water demand of agricultural crops to cover the deficit of natural water supply, the main methods of irrigation that will be used are low-pressure and low-intensity sprinkling irrigation along with drip irrigation. Moreover, the volumes of drip irrigation's application due to significant, compared to sprinkling irrigation, saving of water, fertilizers, and electricity will constantly grow. But the process of the extension of drip irrigation's application, especially the most prospective of its varieties — the subsurface drip irrigation — needs the solution of several technical and technological problems. These problems are related to the substantiation of the parameters of subsurface drip irrigation systems (SDIS) with respect to the conditions of their application and water supply regimes, the usage of which allows obtaining maximal economic effect with minimal capital expenses on their construction and the expenses of irrigation water on the unit of crop yield.

The design parameters of SDIS, which need to be determined, include the depth of installation and the distance between irrigation pipelines. The importance of the correct definition of these parameters is due to their decisive influence both on the amount of capital expenses for the construction of SDIS and on the possibility of forming a favourable soil water regime for the development of irrigated crops with minimal water consumption.

According to the data of experimental studies, the consumption of irrigation water depends not only on the structural parameters of SDIS, but also on the water supply regime. Therefore, in addition to the determination of installation depth and the distance between irrigation pipelines, the research problem also includes the substantiation of water supply regime for subsurface drip irrigation.

Determining the design values of SDIS parameters can be carried out using expert assessments or mathematical modelling tools. The basis of such modelling is, on the one hand, a description of moisture transport processes in soils, and on the other hand, a technological approach to the determination of irrigation schedules and rates on the base of plant development models. The main approach to the scheduling of irrigation is based on monitoring moisture supply to the root layer of soil (Campbell et al., 1982; Sharma et al., 2021).

Models of moisture transport under drip irrigation (Arbat et al., 2008; Romashchenko et al., 2016) are based mainly on Richards differential equation (Richards, 1931) in two-dimensional setting or are constructed from experimentally determined contours of moistening (Holzapfel et al., 1990). Algorithms for automating the selection of parameters of subsurface drip irrigation systems can be considered as an optimization procedures superposed on moisture transport models with objective functions based mainly on the economic evaluation of efficiency and limitations arising from the biological need to provide plants with moisture.

Among the works studying algorithms of this class, we can highlight Kandelous et al. (2012), Seidel et al. (2015), and abd el Baki et al. (2017).

The pulse regime of water supply for drip irrigation (Rank and Vishnu, 2021; Karmeli and Peri, 1974) provides, in contrast to constant irrigation, the supply of water to the zones of maximum concentration of plants' root systems in the shortest possible cycles of fixed or variable duration in accordance with the actual water demand. The use

of the pulse irrigation regime makes it possible to create moisture levels higher than field capacity (FC) in certain zones of the moistened volume. In this way, moisture and nutrients become more available to plants in the respective zones than in the cases when other irrigation regimes are used. This, in turn, leads to more intensive growth of plants' root systems in the moistened zones (Segal et al., 2006; Shani, 1991), which is one of the main features of the pulse regime of drip irrigation.

Differential models of moisture transport allow without significant corrections to carry out predictive modelling when irrigation regimes, soil, or crop parameters are changing. At the same time, from the best of our knowledge, most of the studies on such modelling and its use in decision support in irrigation (see, e.g. Friedman et al. (2016), Gonzalez Perea et al. (2020), Phogat et al. (2012)) consider fixed root systems of plants without taking into account the hypothesis regarding their dependency on the moistened zone during the pulse drip irrigation.

2. Modelling tools

Richards equation (Richards, 1931) stated in terms of water head in two-dimensional setting has the form (Romashchenko et al., 2021)

$$C(h)\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}(k(H)\frac{\partial H}{\partial x}) + \frac{\partial}{\partial z}(k(H)\frac{\partial H}{\partial z}) - S, 0 \le x \le L_x, 0 \le z \le L_z, t \ge 0 \quad (1)$$

where $h(x,z,t) = \frac{P(x,z,t)}{\rho g}$ is the water head, *m*, $H(x,z,t) = \frac{P(x,z,t)}{\rho g} + z$ is the full moisture potential, *m*, $P(x,z,t)$ is the suction pressure, *Pa*, ρ is the density of water, *kg/m³*, g is the acceleration of gravity, *m/s²*, $C(h) = \frac{\partial \theta}{\partial h}$ is the differential soil moisture content, *%/m*, $\theta(x,z,t)$ is the volumetric soil moisture content, *%*, $k(H)$ is the hydraulic conductivity, *m/s*, $S(x,z,t)$ is the source function, *%/s*, that simulates the extraction of moisture by plants' roots and its supply by subsurface drip irrigation.

The model based on equation (1) in two-dimensional setting assumes that the distance between emitters is sufficient for the formation of a uniform moistened zone along irrigation pipelines.

Boundary and initial conditions subject to Equation (1) as well as the form of source function are given in Romashchenko et al. (2021). We assume that a fixed number of plants and a given number of irrigation pipelines are placed at a given depth in the solution domain.

Water retention curves of soils are described by van Genuchten's model (van Genuchten, 1980) in the form $\theta(h) = \theta_0 + \frac{\theta_1 - \theta_0}{\left[1 + \left(10\alpha|h|\right)^n\right]^{1-1/n}}$ with coefficient values that vary from layer to layer and can be obtained fitting the model to laboratory studies' results. The dependency between hydraulic conductivity and pressure is represented according to Averyanov's model (Averyanov, 1982) in the form $k(H) = k_f\left(\frac{\theta(H-z)-\theta_0}{\theta_1-\theta_0}\right)^\beta$ where k_f is the saturated hydraulic conductivity, β is the fixed exponent, the values of which are taken from experimentally obtained dependencies $k(H)$.

The appointment of watering is modelled at the time when average moisture content in the root layer of soil becomes less than a specified value. Watering continues until the value of this indicator reaches 100% of FC.

Numerical solution of the initial-boundary value problem for the model based on Equation (1) is performed according to the implicit finite-difference Crank-Nicolson scheme (Samarskii, 2001) on a uniform grid. Systems of linear algebraic equations are solved by the TFQMR algorithm (Freund, 1993). The starting time step was taken equal to 1 s with its further change during the calculations in order to achieve optimal balance of accuracy and speed.

Meteorological scenarios are generated by a stochastic weather generator (*weathergen* software was used - https://github.com/ARVE-Research/gwgen). The Hargreaves-Samani formula (Hargreaves and Samani, 1985) is used to obtain estimates of potential evapotranspiration. This approach allows, in particular, to carry out simulations taking into account climate change adjusting the input climatic data based on the scenarios of predicted changes.

The depth of root system together with the values of Leaf Area Index (LAI) and crop coefficient in the proposed simulation technique are determined based on the model of changes in crop's development stages with the accumulation of a certain amount of average daily temperatures (Rithchie and Nesmith, 1991). It is assumed that the corresponding parameters vary linearly from stage to stage. The date of crop sawing is set as an input parameter of the model, after which the duration of the growing season and the dynamics of LAI, root system's depth, and crop coefficient are determined based on the generated meteorological scenario.

The proposed algorithm for optimizing structural parameters of subsurface drip irrigation systems has the following peculiarities:

1) A given number of randomly generated meteorological scenarios is considered;

2) The objective function to be minimized is the sum of the expenses for the creation of the system and for the supply of water during a given period under unchanged crop and its growing conditions averaged over all weather scenarios.

3) Minimization of the objective function is performed by a genetic algorithm (Mitchell, 1996).

Since modelling the entire growing season under several weather scenarios is a computationally complex task, a simplified model is proposed based on the assumption that subsurface drip irrigation systems are able to provide adequate moisture throughout the season if they are able to do so during the period of maximum water consumption.

When modelling the pulse regime of subsurface drip irrigation we proceed from the hypothesis that root system is developing in the zones moistened by emitters and its size depends on the size of these zones (Segal et al., 2006; Shani, 1991). The size of the root-containing zone is determined by the method of successive approximations depending on the moistened zone created by the watering at a given rate.

The duration of watering when simulating the pulse regime is considered fixed with the schedule adapted the to changes in soil moisture, which is typical for automatic management of drip irrigation (Obaideen et al., 2022). At the same time, due to the adaptation of the root system to the irrigation regime, maintenance of a given narrow range of moisture content in the root zone is achieved.

3. Testing of modelling tools

Testing of the proposed methodology was carried out on the basis of monitoring data obtained in 2020 during the cultivation of corn in the State Enterprise "Experimental Farm "Veliki Klyny" (Kherson region, Ukraine).The procedure for optimizing the parameters of the subsurface drip irrigation system was performed for the case of modelling a range of 10 days at the highest level of water consumption (5.1 mm/day) while maintaining moisture content in the ranges of 80-95% of FC and 90-95% of FC.

In the case of a pre-irrigation threshold at the level of 80% of FC, the best option according to the simulation results was to install drip pipelines at the distance of 66 cm from each other at the depth of 21.8 cm. The calculated distance between the pipelines and the depth of their installation were close to the distances used in the experiment. The average seasonal volume of water supply among 10 random weather scenarios was equal to 701 mm (27 irrigations with a rate of 22-29 mm) with a coefficient of variation equal to 3%, seasonal evapotranspiration equal to 465 mm, and total precipitation equal to 168 mm. It can be stated that at a given level of hydraulic conductivity, the range of maintained moisture content, and the dynamics of root-containing layer's depth, significant water losses are possible due to infiltration into the layers below the root zone.

In the case of a pre-irrigation threshold equal to 90% of FC, the determined optimal values of system's parameters did not significantly differ from the case of 80% of FC: the distance between the pipelines was 62 cm with the installation depth equal to 21.5 cm. The seasonal volume of water supply was 1063 mm (124 irrigations with a rate of 13 mm). Thus, according to the simulation results, with soil's saturated hydraulic conductivity equal to 15 cm/day, an increase in the pre-irrigation threshold leads to a significant increase in water losses.

Mathematical modelling of the pulse regime was carried out using the hydro-physical characteristics of 20 types of soils of Ukraine obtained on the base of the data on their granulometric composition using *Rosetta* software. Soils were considered homogeneous, data on their upper layer (up to 20/30 cm) were used throughout the simulation

domain depth. The value of the parameter β in Averyanov model was assumed to be equal to 3.5 for all 20 soils. Based on the simulation results, it can be concluded that the infiltration below the 1 m layer, which are the main cause of irrigation water losses in all simulated scenarios, are primarily correlated with the filtration coefficient (R^2=0.6) as well as with the volumetric moisture content value for field capacity (R^2=0.7).

At the same time, the modelled residual of water balance, which is defined as the accumulation or use of moisture reserves in 1 m soil layer, significantly correlates with water head value at the level of field capacity (R^2=0.86).

The total volume of irrigation shows the strongest correlation with the parameter *n* of van Genuchten model (R^2=0.63). However, this level of correlation is first provided by soils for which *n<1.2*. Such values in the studied dataset correspond to absolute values of water heads at the level of field capacity more than 30 kPa and the situations when higher irrigation rates than the specified basic rate of 3 m^3/ha are required to maintain moisture content in the range of 95-100% of field capacity. If we consider soils with *n>=1.2*, the total volume of irrigation has high correlation level with the same initial parameters as infiltration below 1 m layer: the filtration coefficient (R^2=0.65) and the volumetric moisture content value for field capacity (R^2=0.75).

Considering the connection of the modelling results with hydro-physical properties of soils, particularly their filtration and water-holding capacity, we can state that on soils of heavy mechanical composition (heavy loams, clays) with low filtration and high water-holding capacity the pulse regime of water supply to the moistened zones should maintain moisture level as close as possible to field capacity with relatively large irrigation rate per pulse and low frequency of pulses. On soils of light mechanical composition (sandy soils, sandy loams) with high filtration and low water-holding capacity in moistened zones it is necessary to maintain a lower level of moisture supply, but in the narrowest possible range (90-95% of field capacity) that requires conducting irrigation at lower rates with higher frequency of pulses.

4. Conclusions

The determination of cost-effective design parameters of subsurface drip irrigation systems requires combined consideration in the optimization problem of such factors as soil moisture transport, crop development, and variability of weather conditions. The proposed approach of solving this problem uses a genetic algorithm to find such a depth of irrigation pipelines installation and a distance between them that would ensure maintaining a given range of root zone moisture content with minimal expenses for system construction and operation within a given period. Consideration of a series of randomly generated weather scenarios allows assessing the impact of possible extremes in weather conditions on the ability of the system to maintain the required level of moisture content and allows taking climate change into account.

The conducted computational experiments demonstrated the correspondence of the modelling results to the observation of the dynamics of moistened zones and the general practice of designing subsurface drip irrigation systems in the conditions of southern Ukraine.

The developed technique of modelling moisture transport in the conditions of the pulse regime of water supply under drip irrigation is based on the hypothesis that in this case root systems of plants develop first in the zones of active moistening. For a given duration of watering, the technique allows evaluating irrigation water losses, the use of moisture reserves, and system's resistance to changes in water demand, providing information about the efficiency of irrigation water usage to decision-makers.

The results of the simulation of the pulse regime according to the developed technique strongly suggest that on soils with heavy mechanical composition the pulse regime should maintain a high level of moisture supply with a relatively large irrigation rate per pulse and low frequency of pulses. On soils with light mechanical composition, irrigation regime should have the opposite character — lower rates with higher frequency of pulses.

Further development of the technique is possible in the direction of its application for the generation of practical recommendations for growing different crops in different climatic zones and for the substantiation of projected water supply regimes to achieve the maximum level of economic efficiency of irrigation.

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Question 64: What alternative water resources could be tapped for irrigated agriculture?

Quelles ressources alternatives en eau pourraient être exploitées pour l'agriculture irriguée?

Question 65: Which on-farm techniques can increase water productivity?

Quelles techniques agricoles peuvent augmenter la productivité de l'eau?

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