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Synthesis Paper

Ukraine's water security under pressure: Climate change and wartime

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ABSTRACT

Ukraine's water resources depend on external water flow and are unevenly distributed across the country. Water security in Ukraine is threatened by climate-related risks, including droughts and floods, resulting in substantial economic losses. But the greatest risks to water security are posed by military operations. Russia's occupation of the southeastern part of the territory of Ukraine and the annexation of Crimea in 2014, along with the start of a full-scale military invasion of Ukraine on February 24, 2022, further worsened the state of Ukraine's water resources. The destruction of the Kakhovka reservoir deprived Ukraine of 10% of its water resources, which were used to support the agricultural and industrial South of Ukraine. It has caused a loss of access to quality drinking water for 6 million people in Ukraine and more that 13 million people have a limited access to water for satisfying sanitary and hygienic needs. The continuation of the war will have multiple negative sustainability implications not only in Ukraine but also on a global scale, hampering the achievement of clean water and sanitation, conservation and sustainable use of water resources and energy, and food security.

1. Introduction

UN-Water [64] defines water security as the ability of the population to guarantee sustainable access to sufficient water of acceptable quality for livelihoods, human well-being and socio-economic development, to ensure protection from water-related pollution and disasters, and to preserve ecosystems in peace and political stability.

Gunda et al. [20] have noted that most water security studies [13,63,66] focus on the quantity of water, without delving into the assessment of water quality and its suitability for meeting the basic needs of society, which are defined by the very concept of water security. Very often the quantity of available water can be of poor quality. Water quality refers to its suitability for various uses and the health of aquatic ecosystems. Water quality has a significant impact on water supply and often determines supply options (WHO, 2017) [72]. The poor quality of water resources, combined with the reduction of water available for consumption due to climate change in many regions of the world, causes water stress and significantly weakens water security.

Water security is threatened by climate-related risks, including droughts and floods, which result in substantial losses to the economy [71,40,42].

Anthropogenic modification of the river ecosystem, such as increased regulation of water flow by numerous dams and the creation of artificial reservoirs, can lead to a change in natural water flow and deterioration of water quality (Ekka et al., 2022; Khvesyk., 2013; McCully et al.,1996) [9,14,24,29,39,43,45].

Another problem related to water security is political instability and wars. Water can be used as a weapon or as a target of armed conflict [15,16]. If water is used as a weapon, it can lead to the complete destruction of water infrastructure and the water security system [17,60,68].

The combination of all the above factors determines Ukraine's water security. Since the beginning of the war, water security in the region has deteriorated dramatically, as Russian troops have repeatedly used water as a weapon by destroying critical water infrastructure.

The internal water resources of Ukraine are quite limited. Only 28.6 % (55.1 km^3) of its water resources originate within its borders; the rest – 120.2 km^3 – comes from neighboring countries. A full 97 % of available water resources are river runoff, while only 3 % constitute groundwater [23]. In addition, water resources are quite unevenly distributed across the territory of Ukraine.

Surface water resources are highly vulnerable to both pollution and climate change. The war in Ukraine started by Russia in 2014 through the annexation of Crimea and the occupation of the southeastern region

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of Ukraine turned into a full-scale invasion by the Russian army into the territory of the sovereign state on February 24, 2023, creating new challenges for Ukraine's water sector. Russia started using water as a weapon, which has had extremely destructive consequences for the country's economy, as well as for the social sphere and the environment. These consequences will soon be felt not only in Ukraine but also in many countries in Africa and Southeast Asia, to which Ukraine exports food.

The objectives of this study are: 1) to show the peculiarities of the structure of Ukraine's water resources, their spatial distribution and use in terms of the country's water security; 2) to characterize the main hydrological objects; 3) to assess the impact of war and climate change on water security; 4) to consider the issue of water security in the South of Ukraine in the future, taking into account climate change, using the example of the Kakhovka reservoir destroyed as a result of military operations.

2. Study area

Ukraine is the second-largest country in Europe and is located in the southwestern part of the East European Plain. The territory of Ukraine is bordered on the south by the waters of the Black Sea and the Azov Sea. More than 95 % of the Ukrainian river basins form part of those two seas' drainage basins. A few rivers belong to the Baltic Sea basin. Ukraine shares borders with the eastern European countries of Belarus, Hungary, Moldova, Poland, Romania, Russia, and Slovakia (Fig. 1a).

The main part of Ukraine is located within the three sub-latitudinal bioclimatic zones: Polissya (zone of mixed forests) in the North, the Forest-Steppe and the Steppe. Only the southern coast of Crimea has a subtropical Mediterranean climate. Ukraine is characterized by notable climate differences across the country. The climate in the territory is generally moderately continental, from moderately cold in the North to moderately warm in the South, with clearly defined seasons. July average temperatures are from −6.5° to −8° C, while July averages + 15.5° to + 20.5° C. Precipitation is characterized by high mean annual values in the Carpathian mountainous region (up to 1600 mm a^{-1}) and Crimea (up to 1150 mm a^{-1}). The mean annual precipitation in other parts of the country varies from 700-750 mm in the Northwest to 300–350 mm in the Southeast (UNFCCC, 2013; Lipinskyi, et al., 2003) [27,65].

3. Methodology

The research methodology is based on:

a) the collection and analysis of information about water resources, climate risks, and the impact of Russia's military aggression from open sources;

b) the collection, processing, and interpretation of information on water resources and their use from Ukrainian and international databases;

c) evaluation of impact of climate change on water resources and assessment of the consequences of the Kakhovka reservoir destruction for the water sector of southern Ukraine.

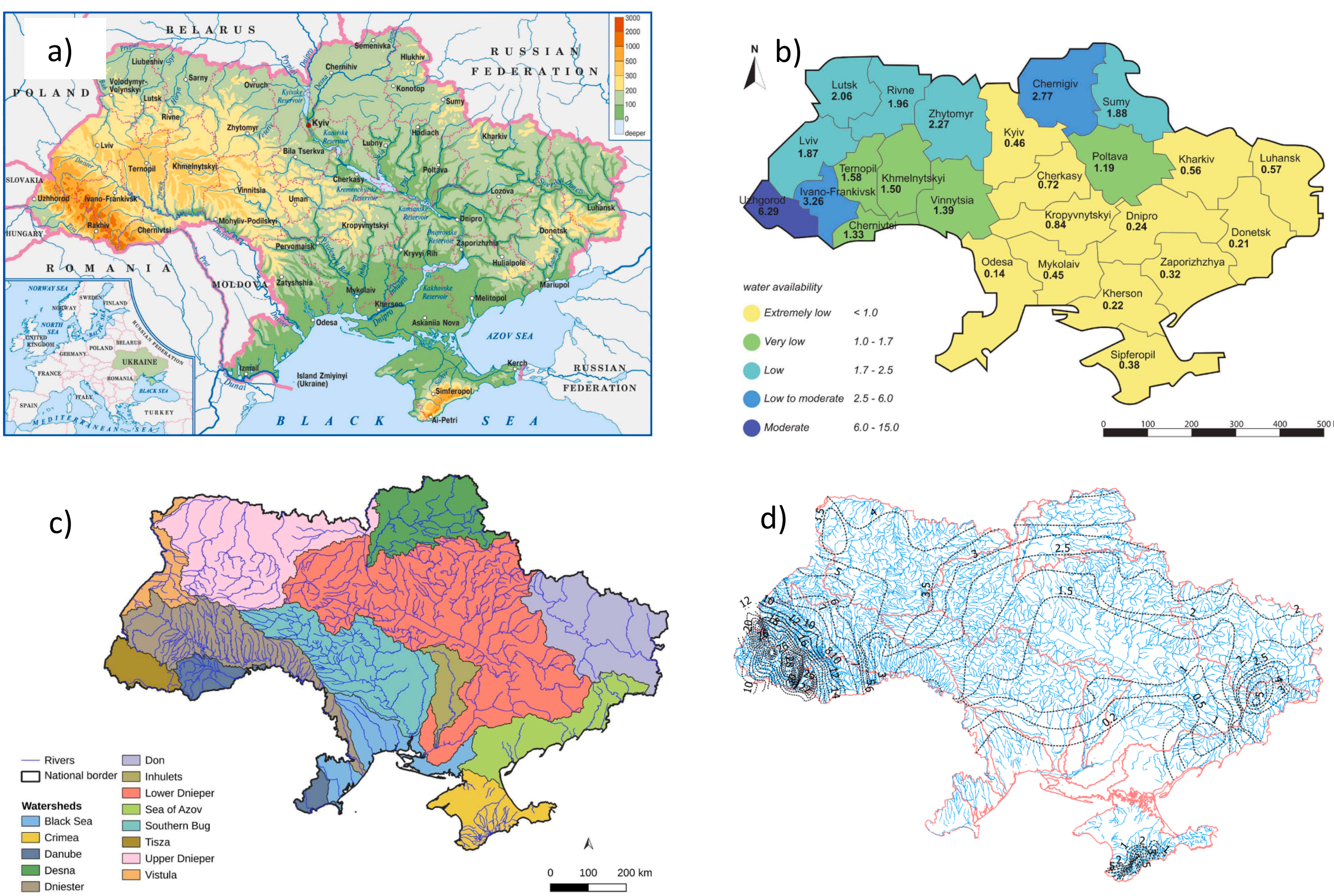

Fig. 1. Water resources of Ukraine: a) Geographical position of Ukraine on the map of Europe. b) Availability of local water resources in the regions of Ukraine, in 1000 s of m^3/per person/year [44]. c) Hydrographic zoning of the territory of Ukraine [19]. d) Spatial distribution of the average annual specific discharge (l/s*km^2*year) of the rivers in Ukraine [33].

3.1. Analyzed data

We used the Global Runoff Data Centre database (GRDC, 2023) [18] and partial runoff data from the Boris Sreznevsky Central Geophysical Observatory in Ukraine, World Bank data on the state of water resources (World Bank, 2020) [70], World Resources Institute data [74], data from the State Cadastre of Ukraine on the use of water resources [34], and informational and analytical data from annual reports by state institutions on the state and use of water resources in Ukraine.

3.2. Climate projections and hydrological models

To assess future changes in the water flow of the largest river basins of Ukraine, we used the regional results of the global hydrological model WaterGAP2 [41] as a reference. In comparison with other applied global water models, this model was the best performing model for this region. It is driven by bias-corrected GCM projections from the ISIMIP project (HadGEM2-ES, MIROC5, IPSL-CM5A-LR, and GFDL-ESM2M) under the RCP 2.6 and RCP 8.5 scenarios [7]. The spatial resolution is 0.5 × 0.5∘, and the time series were divided into two parts: historical simulations (1861–2005) and projections considering greenhouse gas emissions covering the period 2006–2099.

4. The structure, spatial distribution, and use of water resources in Ukraine

Ukraine's total renewable water resources amount to 175.3 km^3 per year, of which 97 % is formed by surface river runoff and only 3 % (5 km^3) through groundwater recharge. According to the index of water resource availability [11], Ukraine has insufficient water resources for development (less than 1700 m^3 per capita). On average, one resident of Ukraine in 2020 had 1,280 m^3 of annual local runoff, while, for example, a resident in Austria had 6,100 m^3 and in Poland 5,500 m^3, with the average for all European countries amounting to 3,040 m^3 [70].

From the data shown in Fig. 1c, it can be seen that the southern, eastern, and central regions of Ukraine are characterized by a critical shortage of water resources. The largest share of the water resources (about 50 %) is concentrated in the Danube basin in the border regions of Ukraine, where the demand for water does not exceed 5 % of its total water resources. Water stress index [12], which is the ratio of withdrawals to average annual resources, according to the World Resources Institute [74] is very high in the South and Southeast of Ukraine (40–80 %), and in places even higher exceeding 80 % (Donetsk-Mariupol industrial region).

In 2021, 9.22 km^3 of water were withdrawn from natural resources (freshwater: 8.86 km^3), of which 1.0 km^3 came from underground water sources, including 0.27 km^3 from mining and quarry water [31].

The largest amount of water was taken in Donetsk (1.54 km^3), Kherson (1.25 km^3), Odessa (1.0 km^3), Zaporizhzhya (0.99 km^3), and Dnipro (0.96 km^3) regions and in the city of Kyiv (0.56 km^3), which accounts for 71 % of the total volume of water withdrawal. The volumes of water withdrawal within river basins and the return of wastewater of various degrees of purification to riverbeds are shown in Table 1.

The distribution of water use by different sectors in Ukraine in 2021 (Fig. 1d) was as follows: 41 % for water supply, 27 % for the energy sector, 17 % for irrigation, 11 % for industry, and 4 % for other uses [31].

Groundwater also has limited use due to its high mineralization, which is formed by sulfates and chlorides. For this reason, 268,000 residents of 9 regions of Ukraine (824 settlements) use drinking water delivered from other regions [61]. The situation is particularly acute in 4 southern regions: Dnipro, Zaporizhia, Mykolaiv, and Odesa.

4.1. Main rivers and water storage

The rivers of Ukraine belong to the basins of three seas. 98 % of the total catchment area belongs to the basins of the Black and Azov Seas, and 2 % to the Baltic Sea [76]. According to the hydrographic zoning of the territory of Ukraine [19], all rivers belong to one of nine basins: the Vistula, the Danube, the Black Sea, the Dniester, the Southern Bug, the Dnipro, the Don, the Azov, and the Crimea (Fig. 1c). The main parameters of the largest river catchments in Ukraine are presented in Table 2. Table 2.

Table 1
Withdrawal of freshwater and the return of non-purified wastewater within river basins of Ukraine in 2022 [34].

River basin	Water withdrawal, km^3	Wastewater discharge to the rivers of the basin, km^3
Dnipro	3.,2	0.,21
Don (Siverskyi Donets)	1.,13	0.,07
Danube	0.,78	0.,033
Rivers of Azov sea	0.,63	0.,029
Dniester	0.,43	0.,011
Southern Bug	0.,25	0.,025
Rivers of the Black Sea	0.,16	0.,003
Visla (West Bug)	0,74	0,11

The spatial distribution of specific discharge in l/(s.km^2) over a long-term period is presented in figure (Fig. 1d), which shows that surface runoff in Ukraine is unevenly distributed across the country. An analysis of the intra-annual flow distribution for Ukrainian rivers shows that for most rivers, the limiting months for water use are August and September. The highest specific discharge rates are observed for the rivers of the Carpathian region and the northern regions of Ukraine in March-April, and of the southern region in February-March (Lukianets. et al., 2020) [27]. Accordingly, for most rivers, autumn is the limiting season and spring is characterized by the highest runoff values.

A network of reservoirs with a total volume of 55.13 km^3 (32 % of Ukraine's water resources) has been created to ensure a stable supply of water during periods of limited flow. Of these, 45.5 % of reservoirs are in the Dnipro River Basin, 17 % in the Southern Bug River Basin, and 13.5 % in the Don River Basin. The Dnipro, from the state border with the Republic of Belarus to Nova Kakhovka, has been transformed into a cascade of reservoirs with a total volume of 43.71 km^3 (Fig. 2, Table 3).

Based on the cascade of Dnipro reservoirs, a powerful water management complex was created, which provides water to almost 30 million people, two-thirds of the territory of Ukraine, 50 large cities, about 10,000 enterprises, 50 large irrigation systems, more than 1,000 service utilities, and 4 nuclear power plants (EUWI, 2019) [10]. Accumulated water resources in the Dnipro reservoirs were used to supply water to the North Crimean Canal with a flow rate of 300 m^3/s, to the Main Kakhovka Canal – 530 m^3/s; to the Dnipro-Donbas Canal – 120 m^3/s, and to the Dnipro-Kryvyi Rih Canal – up to 40 m^3/s. Significant volumes of water are taken from the cascade of Dnipro reservoirs to supply water to large cities and industrial centers: Kyiv, Cherkasy, Kremenchuk, Dniprodzerzhynsk, Dnipro, Zaporizhzhia, Nikopol, Marganets, and Kherson.

Water use is regulated by the Rules for the Operation of the Dnipro Cascade Reservoirs and has a clearly expressed seasonal character (Yatsyk A. et al., 2003) [77]. In the autumn and winter period (October-February), the water use regime is determined primarily by the needs of hydropower. At this time, three large reservoirs (Kyiv, Kremenchuk, and partially Kakhovka) are emptied to pre-flood levels.

Smaller reservoirs (Kaniv, Dniprodzerzhynske and Dniprovske) are kept at levels close to the lower design reservoir level (LDR). All reservoirs are filled in the spring. If necessary, measures are taken to reduce the maximum flow rates to avoid downstream flooding.

In the summer, reservoirs are intensively used to draw water into the largest canals that provide water supply to cities and are used for irrigation. The use of water for various economic purposes involves taking

Table 2
Main characteristics of the largest river catchments in Ukraine [67].

River/Gauge	Catchment area, km^2	Observation period, years	Mean annual discharge, m^3/s	Q max annual, m^3/s	Qmin annual, m^3/s
Western Bug,Litovezh	6,740	1979–2020	32.3	285	3.50
Danube,Reni	811,000	1921–2020	6,510	16,000	1,280
Danube,Kiliy estuary	813,000	1959–2020	3,770	8,960	1,100
Tysa,Vylok	9,140	1954–2020	201	3,650	10.4
Latoritsa,Chop	2,870	1956–2020	34.8	653	2.66
Uzh,Uzhgorod	1,970	1946–2020	28.8	1,680	0.46
Siret,Storozhynets	672	1953–2020	6.49	898	0.10
Prut,Chernivtsi	6,890	1895–1911, 1919–1924, 1926–1935, 1945–2020	71.7	5,200	1.90
Dniester,Sambir	850	1946–2020	11.0	1,040	0.05
Dniester,Mohyliv Podilskyi	43,000	1983–2020	250	4,510	48.6
Southern Bug,Olexandrivka	46,200	1914–2020	84.6	5,320	2.60
Ingul,Novogorozhene	6,670	1931–1941, 1943–2020	7.48	850	no data
Dnipro,Nedanchychi	103,000	1972–2020	557	4,150	93.1
Dnipro,Kakhovka HPP	482,000	1956–2020	1,290	9,740	11.8
Pripyat,Lyubyaz	6,100	1963–2020	12.3	331	no data
Desna,Chernihiv	81,400	1884–2020	321	8,090	29.4
Seim,Mutin	25,600	1925–2020	92.7	3,580	8.,00
Ros,Korsun-Shevchenkivsky	10,300	1928–2020	21.1	1,240	0.03
Sula,Lubny	14,200	1936–2020	27.,4	1,140	0.38
Psel,Zapsilya	21,800	1927–1940, 1950–2020	48.7	1,100	0.80
Vorskla,Kobelyaky	13,500	1965–2020	31.9	580	1.61
Samara,Kocherezhki	19,800	1938–1941, 1952–2020	13.9	867	0.02
Ingulets,Kryvyi Rih	8,600	1936–2020	7.50	1,110	0.17
Siverskyi Donets,Lysychansk	52,400	1892–1910, 1925–2014, 2017–2020	98.0	3,310	3.90
Kalmius,Rozdolne	1,690	1956–2012	11.1	378	0.14
Salgyr,Listyane	3,540	1977–2012	2.72	40.2	0.05

into account the interests of the fishery and ensuring environmental flow. Particular attention was paid to releases from the Kakhovka Reservoir, as the Dnipro estuary region is characterized by significant fish productivity. A rapid and significant decrease in water levels during the ice-free period − more than 10 cm per day − is undesirable for the fishery [69].

A significant decrease in water levels in the reservoirs is possible only in cases of anticipation of a major flood and the threat of flooding the coastal area and economic facilities located there. The mode of operation of reservoirs also depends on the technical features of the hydroelectric power plants (HPP). For example, the small capacity of the former Kakhovka HPP makes it difficult for other HPPs in the Dnipro cascade to operate. Therefore, in order to increase electricity production at these HPPs, they simply have to discharge water through the spillway channel in the Kakhovka HPP dam ("idle" discharges). After the construction of the cascade of reservoirs, the Dnipro River has turned from a fast-flowing river into a series of stagnant reservoirs of polluted water. The Dnipro's water exchange slowed down 30 times (Khvesyk, 2011) [24]. The influx of a significant amount of nutrients from point and diffuse sources has contributed to the development of anthropogenic eutrophication processes [56], which significantly degrades water quality and directly affects water security. Changes in the hydrological regime, rising water temperatures, and increasing concentrations of nitrogen and phosphorus in water have led to the disappearance of rheophilic species characteristic of running waters and the rapid reproduction of stagnophiles adapted to conditions of reduced water exchange. The proliferation of stagnophiles (blue-green algae) has led to eutrophication and the associated deterioration in water quality. After all, the decomposition of phytoplankton biomass (15,000 mg/m^3) consumes from 4400 to 5400 mg of oxygen (1.5–1.8 g of oxygen per 1 g of phytoplankton dry weight). This often leads to dramatic consequences for the oxygen regime of eutrophic water bodies. In low-water years and when the water level is significantly drawn down due to water abstraction and use for electricity generation in the summer, the oxygen concentration decreases to 2–4 mg/dm^3 (25–27 % saturation), and the carbon dioxide content increases to 25 mg/dm^3. During this period, suffocation in the water of reservoirs is often observed, and many fish die [4]. The destruction of dead biomass of blue-green algae causes about 17.1 thousand tons of mineral nitrogen and 0.6 thousand tons of mineral phosphorus to enter the bottom layer of water. Shallow water areas with eutrophic status are formed in areas of stagnant water with elevated temperatures and occupy up to 40 % of the area of the Dnipro reservoir cascade − about 2.8 thousand km^2 (Pichura, 2021) [37].

5. Results and discussion

5.1. Water security of Ukraine under climate change

The results of the study of Ukraine's climate (Pillai et.al, 2022) show that starting from the end of the 1990 s, the average annual air temperature was consistently higher than in the period from 1961 to 1990. Since 2007, it has exceeded the average value for the period 1961–1990 by 1.5 °C. The last decade was the warmest on record in Ukraine. In some years, the average annual temperature increase exceeded 2.0 °C (2.3 °C in 2015 and 2.7 °C in 2019). The daily minimum temperature rise is the largest in the cold seasons, while the daily maximum temperature increases the most in summer. This factor influences changes in the hydrological regime, seasonality, and the magnitude of floods [58,59], as the timing of floods changes under the influence of rising air temperatures (floods occur earlier than in the past) and their magnitude decreases.

In recent decades, there has been an increase in the magnitude of floods along the mountain rivers of the Carpathians and the Crimea. The recurrence and magnitude of high floods in the Transcarpathian region are projected to increase by the end of this century [6]. The area exposed to the risk of river flooding in Ukraine is about 165,000 km^2, which is almost 30 % of the country's surface area.

Furthermore, the climate has shown changes in the number of hot

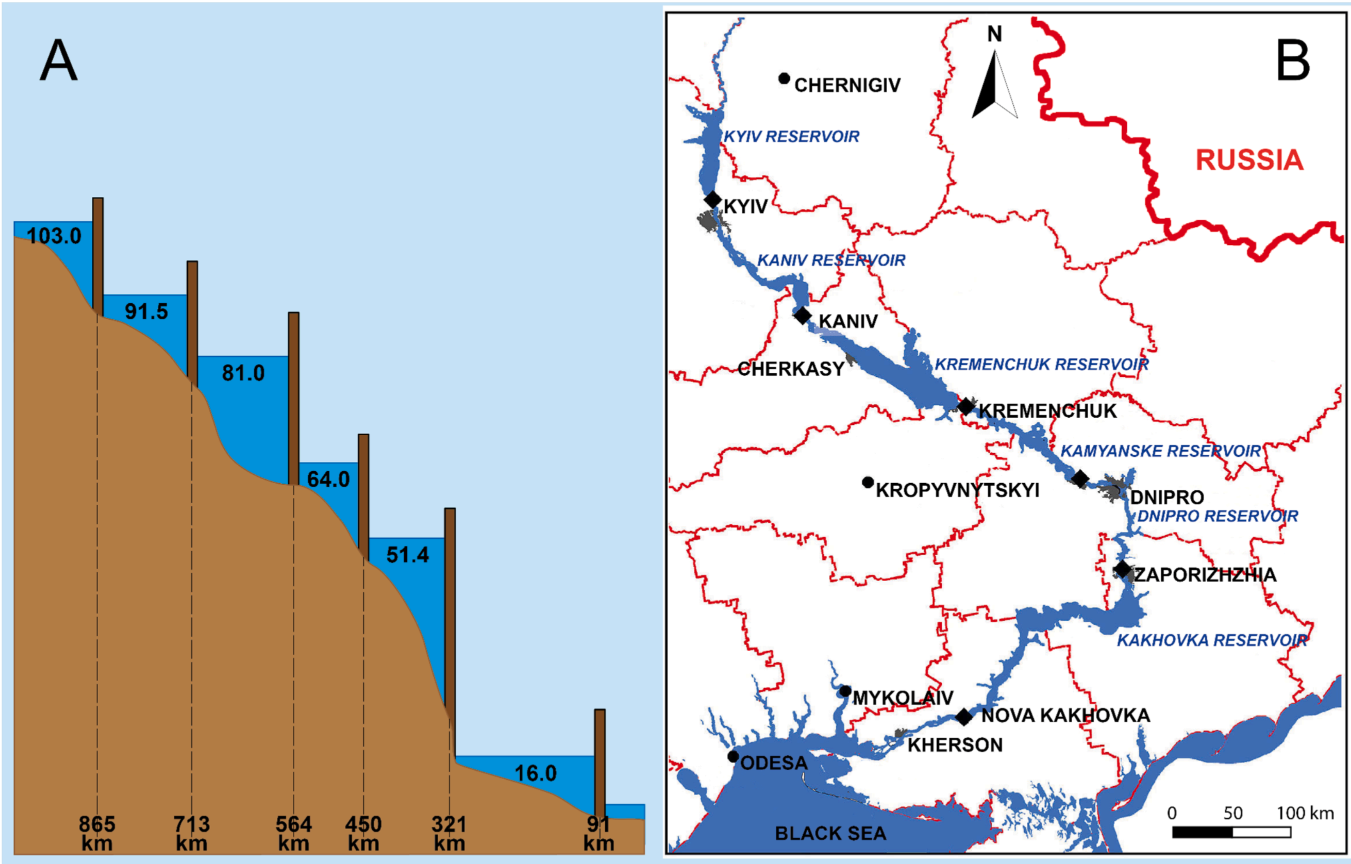

Fig. 2. Dnipro reservoir cascade: a) sketch of reservoir water levels (m a.s.l) and locations of the dams (distance from the sea); b) overview map of artificial lakes and dam locations.

Table 3
Main parameters of reservoirs of Dnipro HPP cascade [4].

Characteristics	Reservoir Kyiv	Kaniv	Kremenchuk	Kamyanske	Dnipro	Kakhovka
Year of reservoir filling	1966	1976	1961	1964	1932	1956
The Dnipro catchment area in the HPP cross –section (thousand km km^2)	239	336	383	424	463	482
Average volume of runoff on HPP cross-section (km^3)	33.1	43.9	47.8	52.0	52.2	52.2
The total volume of the reservoir (km^3)	3.73	2.50	13.52	2.46	3.32	18.18
Useful storage of regulation (km^3)	1.17	0.30	8.97	0.53	0.85	6.78
Water table area (km^2)	922	582	2252	567	410	2155
Average depth (m)	4.0	3.9	6.0	4.3	8.0	8.4
Shallow water area (%)	34	26	18	32	39	5
Average water mineralization (mg/dm-3)	285	297	305	282	330	332
Type of runoff regulation	seasonal	daily	annual	weekly, daily	weekly, daily	annual

Water security in Ukraine is threatened by climate risks, incl. droughts and floods, resulting in substantial economic losses. Since the Russian war against Ukraine, the water resources are seriously at risk due to the attacks on water infrastructure.

days, the duration of heat waves, and the heat load [52,53]. An increase in air temperature and uneven distribution of precipitation, along with abundant local precipitation in the warm season, which does not ensure effective accumulation of moisture in soil, can cause an increase in the frequency and intensity of droughts [49]; Semenova and Vicente-Serrano, 2024) [51]. The recurrence of drought is increasing even in the Polissya eco-region (Northern Ukraine), which used to be sufficiently wet, as well as in the northern areas of the Forest Steppe. [1,57]. Prolonged droughts lead to the formation of seasonal water stress along the rivers of Ukraine and greatly reduce the level of water security in the region [50]. According to their data, since 1991, the area of the dry and very dry zones has increased by 7 % and covers almost one-third of the territory, including 11.6 million hectares of arable land.

Our simulation of the water flow in Ukraine's main river catchments [5,7] shows that even under the "moderate" RCP 2.6 scenario river discharge is expected to decrease in the majority of Ukrainian river basins toward the middle and end of the 21st century. Under the "business as usual" projections (RCP 8.5), river discharge is projected to decrease more strongly at the end of the century, and in combination with the rising temperature and declining precipitation this may lead to notably lower water availability in the southern part of Ukraine. Rising temperature provokes changes in the hydrological regimes of the rivers. The peak of spring runoff will shift to earlier months, and in summer the runoff will decrease for most basins (Fig. 3). Such a change could create an additional challenge for agriculture, which is entirely dependent on the availability of water for irrigation.

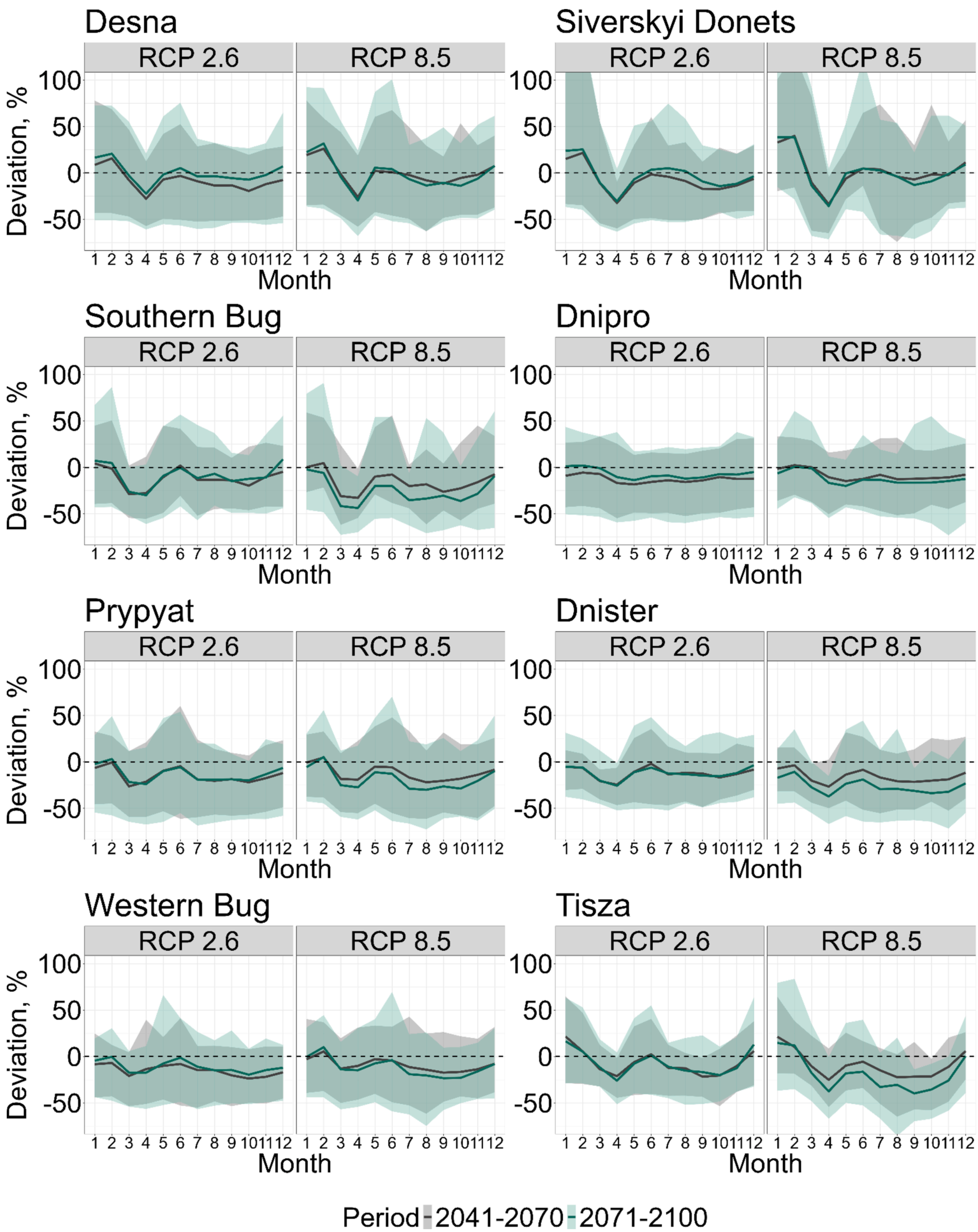

Fig. 3. Projected changes in the long-term mean monthly river discharge for two future periods (2041–2070 and 2071–2099) under RCP 2.6 and RCP 8.5. Colored ranges show a range of global hydrological model WaterGAP2 results based on the four bias-corrected GCM projections from the ISIMIP project and solid lines show multi-model means. [7].

5.2. Impact of war on water resources and water infrastructure: Water as a weapon

Russia's occupation of the southeastern part of the territory of Ukraine and the annexation of Crimea in 2014, along with the start of a full-scale military invasion of Ukraine on February 24, 2022, have further worsened the state of Ukraine's water resources. It is already known [48]; Gleick P., 1993; [36] that during active hostilities, water infrastructure is damaged and destroyed, water quality deteriorates, and water often becomes unavailable. The Russian-Ukrainian war is accompanied by significant environmental degradation, which can be called an environmental catastrophe. It is projected that the environmental impacts of this war will last a long time [78].

During this war, a significant number of water infrastructure facilities were destroyed, including more than 1,947 linear kilometers of water supply networks, 25 treatment facilities, 182 water pumping stations. Most of them are in Kharkiv, Luhansk and Donetsk regions. In addition, 159 wells have been destroyed or damaged, most of them in the Kharkiv region. Laboratories that analyzed the state of water supply in the region were also destroyed or damaged. According to preliminary estimates, more than 582 km of sewerage networks were damaged, and 183 sewage pumping stations were partially damaged or completely destroyed, most of which are located in the Kharkiv region. A total of 51 sewage treatment plants are also believed to be destroyed or damaged [25].

According to the study of Hapich et al. [21] the following – complete of partial – destructions resulted from the hostilities: the Kakhovka, Oskil, Pechenizka, Karachunivka and Karlivka reservoirs; the municipal water supply and sewerage in Mykolaiv, Kharkiv, Mariupol, Chernihiv, Bakhmut, Sievierodonetsk, Vuhledar, Lysychansk and Avdiivka, as well as the termination or partial termination of the main water supply channels to the Kakhovka and North-Rohachytsia irrigation systems, Dniprovska and North-Kryvorizka irrigation systems, Dniprovska and North-Kryvorizka irrigation systems; the main canals for water supply to the Kakhovka and Pivnichno-Rohachytsia irrigation systems, as well as the Dnipro-Donbas, Dnipro-Kryvyi Rih, and Pivnichno-Krymsky canals. Thus, it becomes clear that the military aggression from Russia threatens Ukraine's water security, creates new global risks, and violates basic human rights [32].

The continuation of the war will have multiple negative implications for sustainability not only in Ukraine but also at the global scale, hampering the achievement of clean water and sanitation, conservation and sustainable use of water resources, and energy and food security [54].

As a result of Russia's invasion of Ukraine, as of August 1, 2022 the territory that is temporarily controlled by Russian troops completely encompasses two river basin regions: those of the Crimea (since 2014) and Azov regions. As well as parts of four other river basin areas: approx. 69 % is made up of the Don River Basin, 22 % the Black Sea River Basin, and 6 % the Dnipro River Basin (Khilchevskyi and Grebin, 2022) [22]. Russia's military action has not only led to the destruction of civilian infrastructure, but also destroyed natural ecosystems and polluted the environment [3].

A very dangerous situation has developed with the water infrastructure of Donbas (an industrial region in Easth Ukraine in the plain of the Rivers Donets and lower Dnieper) following its occupation by Russia, including breakdowns in the water pumping system and the flooding of many mines that store toxic and nuclear waste. [79] reported on chlorine leaks at water filtration plants during the attacks on water treatment facilities in Avdiyivka and the danger of polychlorinated biphenyls entering the water environment from destroyed power plants. Military actions and the destruction of water infrastructure led to artificial water stress. Thus, in Russian-occupied Mariupol, about 350,000 residents were left without access to water, and 470,000 residents in Mykolaiv [8,60]. As a consequence of the war, according to the World Wildlife Fund [75] more than 6 million Ukrainians have limited or no access to clean water, and more than 280,000 ha of forests have been destroyed or felled. Significant damage was caused to water infrastructure, including pumping stations, treatment plants, and sewage facilities [55].

5.3. Destruction of the Kakhovka dam as a result of military operations and artificial water shortage in southern Ukraine

On June 6, 2023, the Russian occupying forces blew up the dam of the Kakhovka reservoir with 18.2 km^3 of water and destroyed it [21,17]. Due to the dam breach, the water level in the reservoir began to decrease at a rate of 15 cm per hour (Fig. 4a, brownish line). Already on June 7, 2023, at the Nikopol gauge (upstream the destroyed dam) the water level dropped to 2.2 m. On the same day, the water level below the destroyed dam at the Kherson gauge rose to 5 m above the "0″ level of the gauge (Fig. 4a, blue line).

The maximum water loss from the reservoir occurred during June 6 and the first half of the day of June 7. On June 11, all gauges at the Kakhovka reservoir stopped measuring due to a sharp drop in water levels. The volume of the Kakhovka reservoir on June 11 decreased by 72 %. Water losses reached 14.395 km^3 of water, and the water level in the reservoir in the Nikopol area dropped to 9.04 m.

On June 8, the water level of the Kakhovka reservoir (gauge Nikopol) decreased by 4.18 m down to 12.59 m BS (Baltic Sea height altitude system) compared to the level of June 5, and the volume of the reservoir during this period decreased by almost a factor of 2 (by 8.5 km^3). The water level has fallen below the critical levels of water intake (12.7 m) for water supply to the cities of Zaporizhzhya in the Zaporizhzhya region, Energodar (at the site of the Nuclear Power Plant, (NPP) Zaporishya), Nikopol, Marganets, Kryvorizky in the Dnipro region, Berislavsky, Kakhovsky in the Kherson region, and Melitopol. On June 8, at the Kherson gauge (below the dam) the water level reached its maximum level at 3:00 am at the 5.68-m mark, after which the water level began to slowly decrease. There was flooding of coastal areas and residential, industrial, and economic facilities in the city of Kherson and the surrounding region (Fig. 4b). According to the calculations of the Ukrainian Hydrometeorological Institute based on satellite images, as of June 11,309 km^2 were flooded (Fig. 4c).

The flooded zone covered 80 settlements in the Kherson and Mykolaiv regions(Fig. 4c), and at that time the Kakhovka reservoir was almost completely emptied (Fig. 4d, 4e).

The destruction of the reservoir led to the loss of 18.2 km^3 of water (10.4 % of Ukraine's water resources) and significant losses for the country's entire water sector. As a result of the Russian armed aggression, Ukraine has lost almost a third of its accumulated fresh water reserves worth more than USD 18 billion. It has caused a loss of access to quality drinking water for 6 million people in Ukraine and more that 13 million people have a limited access to water for satisfying sanitary and hygienic needs (Pichura V. et al., 2024)[38]. As a result, 31 irrigation systems were stopped in the Dnipro, Kherson, and Zaporizhzhia regions with a total area of 584,000 ha (Fig. 4f), from which about 4 million tons of grain and oilseed crops worth USD 1.5 billion were harvested every year [30]. According to evaluation of the World Mission [73], the resulting loss of agricultural land could cause "the biggest global food crisis since World War II".

Preliminary assessments suggest that, in peacetime, complete restoration of water infrastructure will cost more than USD 5 billion. Reconstruction of the Kakhovka Reservoir, alone, will cost USD 1–1.5 billion and take ten years [21].

The operation of the Dnipro-Kryvyi Rih canal has stopped, which may lead to the shutdown of the Kryvyi Rih thermal power plant (TPP). Significant risks arise for the operation of Zaporizhzhia TPP and for Zaporizhzhya nuclear power plant (NPP), which is the most powerful nuclear power plant in Europe. The filling level of the NPP cooling ponds, which is necessary for the plant to receive water for its turbine capacitors and safety systems, depends on the water level in the Kakhovka reservoir. A sudden loss of water needed for the reactor's active cooling system can lead to a scenario analogous to the accident at the Fukushima Daiichi NPP in Japan in 2011 [2].

According to preliminary estimates (August 2023), the environmental damage caused by the destruction of the reservoir reached more

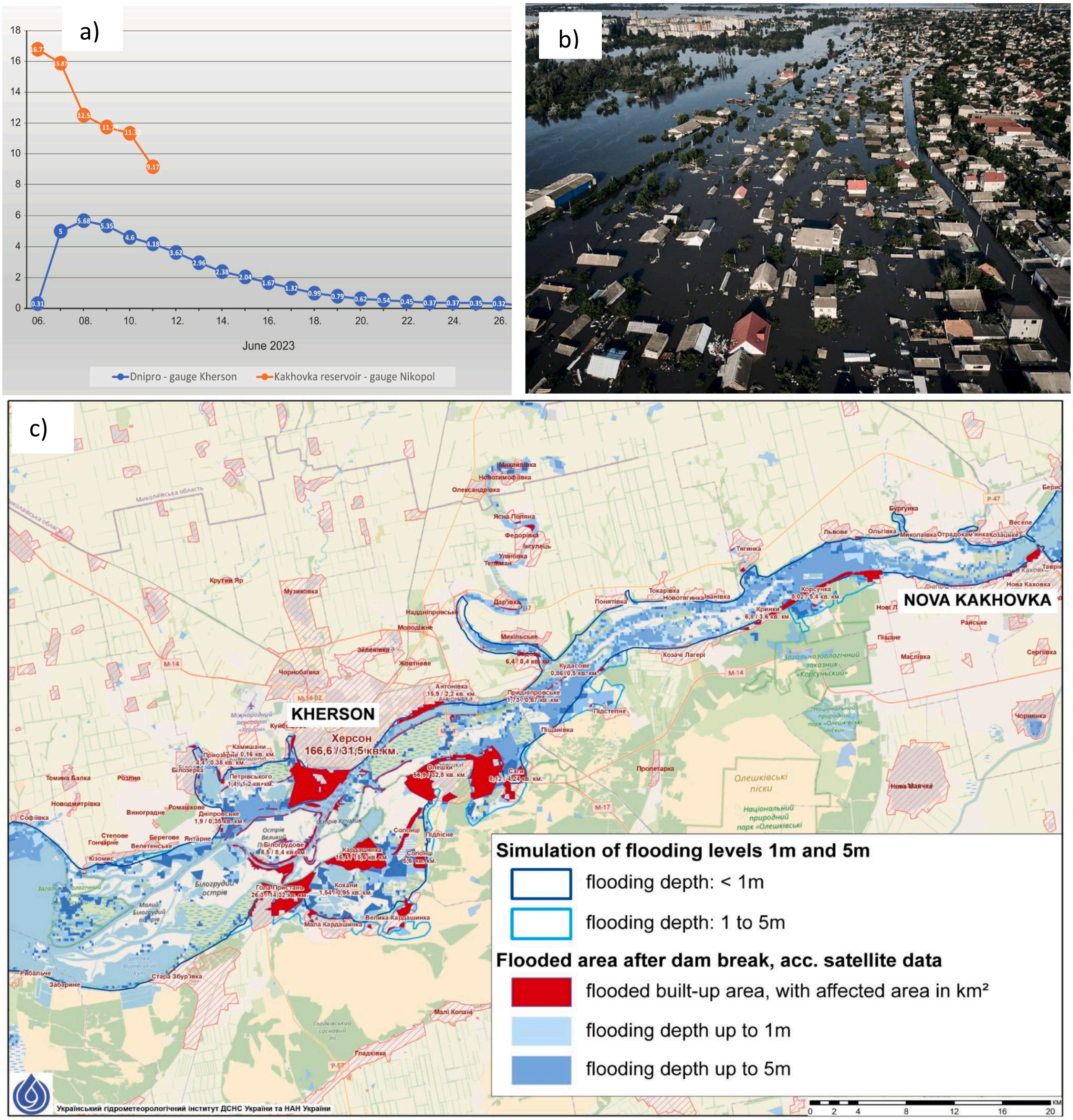

Fig. 4. Development of the hydrological situation after the destruction of the Kakhovka reservoir dam: a) The drop in the water level in the Kakhovka reservoir (Nikopol gauge) and the formation of the severe flood wave below the dam of the Kakhovka HPP (Dnipro-gauge Kherson) after the dam destruction at 2:50 am local time (23:50 GMT) on June 6, 2023 (according to the operative information from Ukrhydroenergo and the Ukrainian Hydrometeorological Center). The water level is shown in meters above the gauge's zero line. b) View of flooded areas downstream of Kakhovka dam on June 9, 2023 (photo: Associated Press). c)Wide-spread inundation as a consequence of flooding after the Kakhovka dam breach, on June 7–8, 2023 (Oreshchenko A., 2024) [35]. d) Upstream Kakhovka dam view on June 17, 2023, after the dam was blown up, Dnipro Oblast (photo: Ukrhidroenergo). e) Kakhovka reservoir emptying from the moment of the dam collapse until June 20, 2023 (Oreshchenko A., 2024) [35]. f) Water infrastructure (canals and water pipes) of southern Ukraine.

than USD 3.7 billion (Ministry of Environmental Protection and Natural Resources of Ukraine, 2023a). However, losses due to the entry of pollutants into the Black Sea have not yet been taken into account. There is also a risk of transfer of radionuclides from the bottom sediments of the Kakhovka reservoir, which accumulated there over several decades after the explosion at the Chornobyl NPP and their migration through the cascade of Dnipro reservoirs [46,28,47].

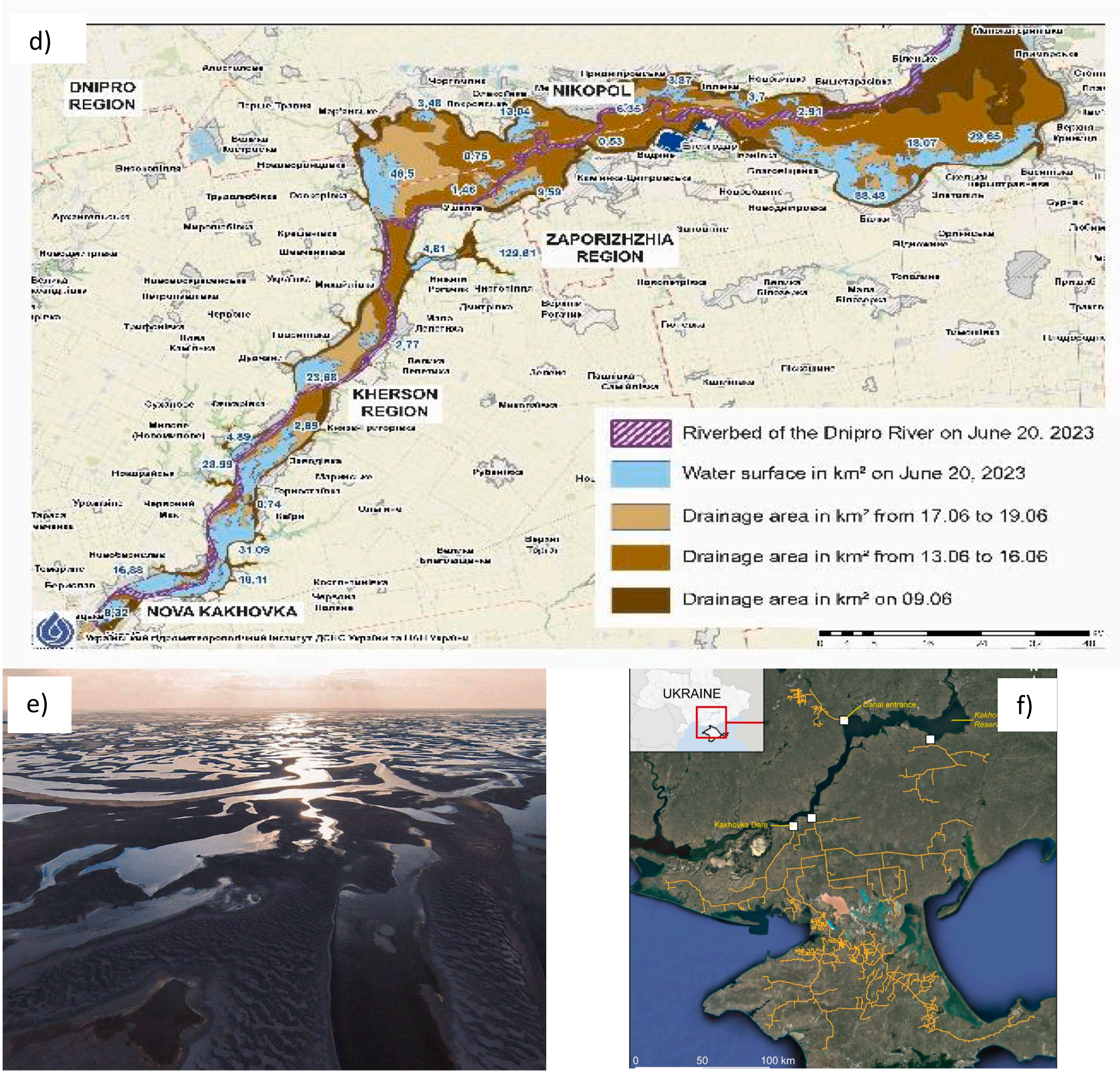

Fig. 4. (*continued*).

5.4. Analysis of water balance of the Kakhovka reservoir and availability of water resources in the future

To estimate the deterioration of water security in the South of Ukraine after the reservoir's destruction, two types of water balanceof the Kakhovka reservoir have been explored: 1) the estimated water balance developed by the State Agency of Water Resources of Ukraine [62] for years with different water availability – medium (50 % runoff availability) and low water levels (75 % and 95 % availability) and 2) the real water balance, based on measured hydrological flow parameters and indicators of water use [67].

The consumption part of the real water balance from the inflow value is composed as follows: 84 % discharges through the turbines of the power plant (including the environmental flow), about 6 % evaporation from the surface of the reservoir, 5.5 % irrigation, 2.3 % water supply for cities and the Zaporizhzhia NPP and TPP, and 2.2 % infiltration water loss. It is clear that after the loss from the reservoir the amount of inflow, which is regulated by water discharges through the dam of the Dnipro reservoir, will not change (Fig. 5a). However, the amount of water that was previously lost through evaporation and infiltration (about 10 % of the inflow every year) will be available in the future after the inundations will have recededng and river a course will have formed downstream. This is 4.2 km^3 of water for a normal water year (50 % reliability), 3.4 km^3 for a dry water year with 75 % reliability, and 2.8 km^3 for a very dry water year with 95 % reliability.

If we compare calculated monthly volumes of water inflow [62] into the reservoir in years of differing water flow reliability (50 %, 75 %, and 95 %) with its consumption for various needs but without including environmental flow to the lower Dnipro, then it turns out that the greatest water management load on the reservoir should come during the growing season (from May to October). The maximum water abstraction is reached in August-September and is 7.74 % in an average water year (50 % reliability), 9.64 % in a dry water year (75 % reliability), and 11.46 % in a dry water year (95 % reliability) (Fig. 5b).

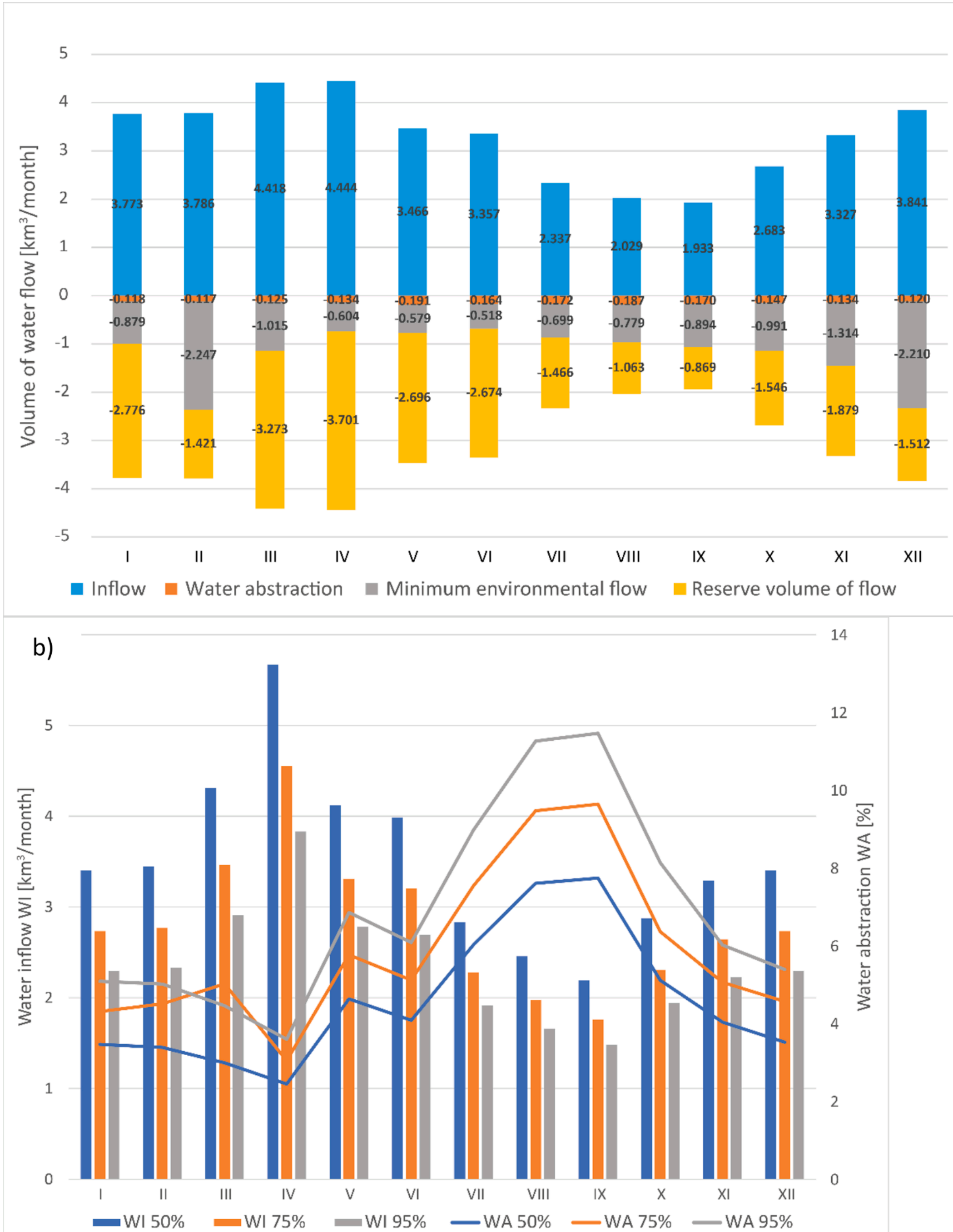

Fig. 5. Water balance of the Kakhovka reservoir a) before dam breach (6.06.2023) for a hydrological year with a 50% reliability of water flow. b) Comparison of the volumes of water abstraction (WA50%, WA75%, WA95%) of the Kakhovka reservoir with the water inflow (WI 50%, WI75%, WI95%) in hydrological years with different reliability of water flow. c) Deviation (%) of projected values of long-term mean monthly discharge of the river Dnipro at the gauge Kakhovka HPP in the two future periods (2041–2070 and 2071–2099) under RCP2.6 and RCP 8.5 scenarios from long-term mean monthly river discharge calculated for a normal water year (50% reliability). d) Quantification of projected losses of monthly water flow of the river Dnipro (PL, km^3) due to climate change at the gauge Kakhovka HPP by comparing projected flow values (PF, km^3) with the average monthly runoff calculated from observation data over a multi-year period.

Taking into account the possible increase in the inflow part of the water balance of the Dnipro River at the gauge of the Kakhovskaya Hydro Power Plant (HPP) due to the cessation of evaporation and infiltration losses of approximately 10 %, the amount of water will be sufficient to meet existing needs.

The destruction of the Kakhovka HPP and the impact of the war on water infrastructure may introduce some uncertainty into the calculations of Dnipro's projected water flow in the future. The consumptive part of the reservoir balance will definitely change. However, the inflow of the former reservoir balance will remain, as there is a scheme for water flow regulating according Rules for the Operation of the Dnipro Cascade Reservoirs (Yatsyk A. et al., 2003). Calculations of the water inflow to the Lower Dnipro after the destruction of the Kakhovka HPP were performed on the basis of flow simulations for two periods 2041–2070 and 2071–2099 for for RCP 2.6 and RCP 8.5 [7]. The results show a significant intra-annual redistribution of water flow (Fig. 5c) due

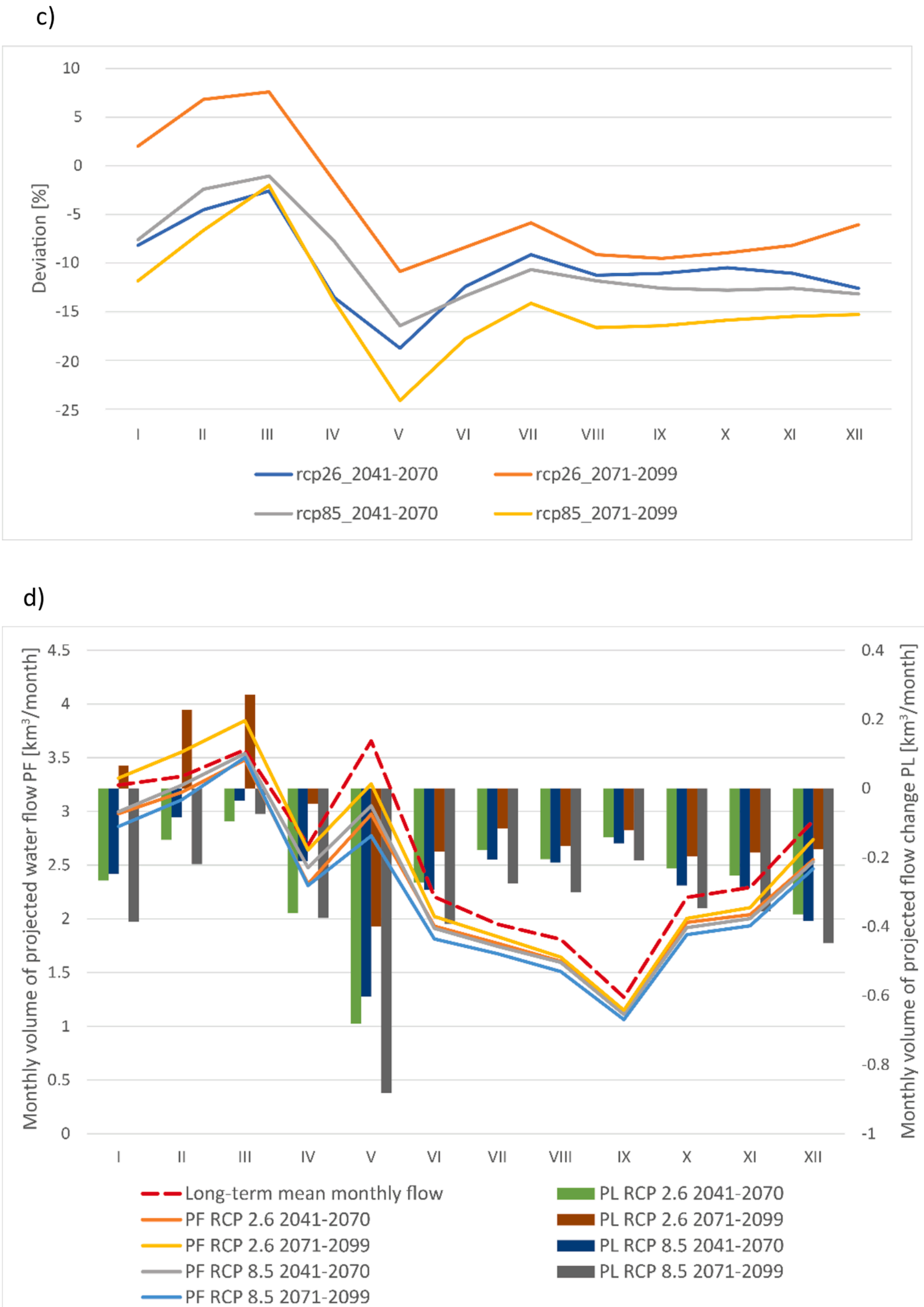

Fig. 5. (*continued*).

to climate change.

In most months of the year, under both scenarios there will be a decrease in flow. The runoff will decrease the least in winter and spring – from 1 to 12 %. And, according to RCP 2.6, at the end of the century it may even slightly increase. The largest decrease in flow is expected under all scenarios and in all estimated periods in May – from 10 to 24 %, because snow melt season is projected to occur earlier in the year.

To estimate the possible loss of monthly flow volumes from the Dnipro River under the influence of the climate in the future, we compared the results obtained for the projected monthly flow with the average value of the monthly flow over a long-term period (Fig. 5d). Based on these calculations, it can be stated that a critical decrease in flow, which would exceed 10–15 % of the average long-term norm for most months of the year, is not expected under most scenarios. Only in the month of May the flow could be reduced by 16–24 % (Fig. 5 c, d). It should be noted that the month of May is the beginning of the growing season in the agricultural sector and the need for water for irrigation in this month is usually higher than in previous months.

However, a comparison of possible water losses due to climate change with the flow reserve that will remain after water withdrawal and discharge of the necessary minimum environmental flow in the lower Dnipro proves that in the month of May there will be a fairly large flow reserve in the Dnipro River, which will probably be able to mitigate the possible concequences of the climatic impcats on the water flow.

In addition, given that the flow of the lower Dnipro will now be regulated by a cascade of reservoirs located above the Dnipro HPP, a possible shortage of water resources in the month of May can be prevented in advance by artificially regulating the flow through the dam of the Dnipro HPP.

6. Conclusion

Ukraine's water resources are quite limited and unevenly distributed over the territory, which creates potential obstacles to full access to water and reduces water security in certain regions of the country. Most water resources are concentrated in the northern and western regions of Ukraine, where the rate of water use per capita is the lowest in the country. However, in central Ukraine, and especially in the South, the availability of water resources is extremely low (140–720 m^3 per person per year), and the level of consumption due to the development of industry and agriculture is the highest. Therefore, the water resources in most parts of Ukraine are particular vulnerable to military actions, if water is used as a weapon.

For the continuous supply of water to all water users, 55.1 km^3 of water (32 % of Ukraine's water resources) is accumulated in reservoirs. Of special importance for Ukraine are six large reservoirs on the Dnipro River, which provide water to the central and southern regions of Ukraine (two-thirds of the country's territory). The largest (18.2 km^3 of water) and the most important of them is the Kakhovka reservoir, which supplies water to the southern regions of Ukraine, including the Crimean peninsula.

The destruction of the Kakhovka Reservoir by Russian troops resulted in the loss of almost 10.4 % of Ukraine's water resources and posed a real threat to water security in the industrial and agricultural South. The destruction of the region's water infrastructure led to the shutdown of hundreds of small and large enterprises; dozens of large cities were left without water supply; and a powerful flood wave destroyed settlements, worsened the sanitary and hygienic living conditions of the population, and caused significant flows of refugees. The Russian army uses water as a weapon to destroy the basis for life in Ukraine. This situation can be considered as an attempt of ecological genocide of the population of Ukraine.

Our calculations, which also take into account the impact of climate, confirm the flow of a sufficient amount of water through the Dnipro River to the South of Ukraine even after the removal of the Kakhovka reservoir. Restoration of water supply in the region is only a technical problem, which can be solved in a short but peaceful time by attracting investments into the reconstruction of water infrastructure based on modern technologies. However, all other consequences caused by the destruction of the reservoir are long-term in their impact on the environment and the social sphere and require several decades for recovery. The consequences of Russia's use of water as a weapon will soon be felt not only in Ukraine but also in many countries in Africa and Southeast Asia, which receive Ukrainian food exports worth billions of dollars.

Credit authorship contribution statement

S. Snizhko: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **I. Didovets:** . **A. Bronstert:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data sharing is not applicable to this article as no new data were created. River discharge date are available from the source institutions on request. Used remote sensing data are publicly available.

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