# Anthropogenic Transformation of Hydrological Regime of The Dnieper River

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*Abstract.* Problems of rational water use and water quality assessment are the priorities of many states, especially in the basins of transboundary rivers. Creation and functioning of the cascade of Dnieper reservoirs led to a radical transformation of the hydrological regime of the Dnieper River. As a result, there occurred a significant deterioration of the physical, chemical and biological characteristics of surface water quality, increase of its trophic state, reduction of the efficiency and stability of the aquatic ecosystem of the Dnieper basin, which is largely determined by anthropogenic factors. As a result of interpretation the series of space images (August, 1986-2016) of the satellites Landsat- 5, Landsat- 7 and Landsat-8 with a spatial resolution of 30 meters, the spatio-temporal trend of changes in physical (water transparency), hydrochemical (general phosphorus concentration in water), biological (chlorophyll-a) properties of water areas of reservoirs was determined. In studies trophic state index developed by the Florida Department of Environmental Protection was used to classify all types of water surface, including rivers. It is established that the value of trophic state index in reservoirs is distributed unevenly from 26.5 to 56.5. Continuous water eutrophication processes are intensified by the deterioration of self-purification of the river, lack of effective anti-erosion organization of areas, and climate change. Long strengthening of the eutrophication of the reservoirs of the Dnieper cascade contributes to the increase of the concentration of nutrients, predominance of blue-green algae phytoplankton, reduced transparency, increased content of organic matter, significant deterioration of the aquatic ecosystem and reduced biological productivity of the Dnieper River. The studies of the trophic state of the cascade of the Dnieper reservoirs are of high scientific and practical value for the identification of the consequences of a powerful anthropogenic influence on the hydroelectric system and the identification of problem aspects of their water areas and the further priority development of substantiated spatially adaptive complex and systematic environmental protection measures, enhancement of ecological sustainability, and gradual improvement of ecosystem of the Dnieper River basin.

*Keywords:* Hydrological Regime, Trophic state, Dnieper River, Dnieper reservoirs, Spatio-temporal changes, Remote sensing

The deterioration of the ecological status of water bodies leads not only to their degradation, but also to the problems of their water management. This occurs against the background of reducing the observations network in the state monitoring system and weakening control over the impact of human activity on water objects. Therefore, effective water management is one of the important global challenges facing humanity. Problems of rational water use and water quality assessment are the priorities of many states, especially in the basins of transboundary rivers. Water quality studies are conducted on the basis of regular in-situ measurement, which is a labor-intensive and cost-intensive process that does not cover the entire area of the water object; besides, observations are discrete and, given interpolation of experimental data, the results have low spatial accuracy. System use, along with in-situ measurements of multispectral satellite images is necessary to optimize the researches and expand the data array on the status of water

bodies (Tikhomirov at el 2016). Therefore, in the monitoring of the ecological condition of water objects, the application of data of space remote sensing of the earth (Earth remote sensing) is a promising area, providing a unique opportunity for contactless research and large-scale spatio-temporal assessment of the state of water objects to create an information base for specialized water geoinformation systems. The ecological state of the water body is characterized by a number of features that are easily detected and quantitatively measured with multispectral space images. For most reservoirs, the actual problem of deterioration of water properties as a result of eutrophication is a sharp increase in the biological productivity of green algae (mostly caused by anthropogenic activities), which leads to negative consequences for the entire ecosystem of the reservoir. Selective field researches conducted in the water area, allow proceeding with numerical indicators of the volume of suspended matter in the case of mechanical and

biological contamination. Biological contamination of water bodies is determined by the accumulation in the water mass of so-called biogenic substances - compounds of phosphorus and nitrogen, which cause sharp decrease in oxygen content in water, pH increase, calcium carbonate and magnesium hydroxide precipitation. The content of all these substances is direct or inverse spatial correlation with the amount and degree of biological water contamination across the waters of the reservoir, and can be estimated and recorded using cartographic methods on the basis of selective sampling for chemical analysis (Abrosimov et al 2009).

Scientific papers of many scientists (Zagorodnyaya et al 2010, Silkin et al 2012, Bocharov et al 2015, Pichura et al 2015, Gryshchenko et al 2016) present methodological approaches, algorithms for processing the data of the earth remote sensing, prospects for their use and their practical advantages for assessing changes in the coastal zone of reservoirs, complex study of changes in properties and environmental status of water objects (temperature of warming, turbidity, transparency, concentration of chlorophyll-a, biogenic substances, trophic state, etc.), including individual reservoirs of the Dnieper river.

The purpose of the research is to determine the spatio-temporal tendency of the change in the trophic state of the Dnieper reservoirs over the past 30 years on the basis of the data of the earth remote sensing satellite images.

### MATERIAL AND METHODS

The study used the Trophic State Index (TSI), which was developed by the Florida Department of Environmental Protection and is used to classify all types of water surfaces, including rivers. The scale of this index is a numerical one (Table 1) and each major area of the trophic division represents a doubling of the concentration of the surface biomass of phytoplankton, which makes the classification of the trophic state more acceptable. Quantitative description of the status of a reservoir is extremely important when choosing a strategy for protecting its ecosystem. Most lake ecosystems divide the continuum of the trophic state of reservoirs into five classes: ultra-oligotrophic, oligotrophic, mesotrophic, eutrophic, and hypertrophic [Henderson-Sellers et al 1987].

TSI value can be calculated by three parameters: physical (water transparency, which is determined by the Secchi index-TSD), hydro-chemical (concentration of total phosphorus in water-P), biological and biochemical (chlorophyll-a-Chla, biomass of phytoplankton-B $_P$) [Carlson 1977].

The value of total phosphorus content makes it possible to determine and assess the impact of different anthropogenic sources on biogenic contamination and eutrophication process in all types of water objects. This makes it possible to predict the potential biomass of primary production in reservoirs as a result of anthropogenic eutrophication with the use of earth remote sensing. The decoding of space images is based on the study of light absorbing and light dispersive properties of natural waters; the degree of transparency of water provides an opportunity to determine the trophic state of reservoirs' cascade.

**Table 1.** Trophic state index (TSI) and correlation of the trophic state indicators of water objects

| Type of trophic state | TSI | Transparency of water determined by Secchi disc (TSD), m | Phosphorus (P), µg/dm$^3$ | Chlorophyll-a (Chla), µg/dm$^3$ |
|---|---|---|---|---|
| Ultra-oligotrophic, very pure | 0 | 64 | 0.75 | 0.04 |
| | 10 | 32 | 1.5 | 0.12 |
| | 20 | 16 | 3 | 0.34 |
| | 30 | 8 | 6 | 0.94 |
| Mesotrophic, slightly contaminated | 40 | 4 | 12 | 2.6 |
| | 50 | 2 | 24 | 6.4 |
| Eutrophic, moderately contaminated | 60 | 1 | 48 | 20 |
| | 70 | 0.5 | 96 | 56 |
| Hypertrophic, dirty | 80 | 0.25 | 192 | 154 |
| | 90 | 0.12 | 384 | 427 |
| | 100 | 0.062 | 786 | 1183 |

| Calculation of TSI on the basis of separate indicators | Calculation of trophic state indicators of water objects on the basis of TSI |
|---|---|
| TSI=60-14.41 Ln (TSD) <br> TSI=4.15+14.42 Ln (P) <br> TSI=30.6+9.81 Ln (Chla) | TSD=64.31 exp (-0.0695 TSI) <br> P=0.748 exp (0.0694 TSI) <br> Chla=0.042 exp (0.1025 TSI) |

Antropogenic eutrophication of reservoirs is manifested in spatial heterogeneity of planktonic algae, leading to a significant reduction in water clarity, which is mainly caused by the content of different colored dissolved and suspended substances. Variation in the concentration of chlorophyll-*a* changes the reflection capacity of water – increase in its concentration lowers the reflection capacity of water in blue wavelengths and increases in green wavelengths. The trophic state index of the cascade of the Dnieper reservoirs is calculated by F.T. Shumakov's formula [Shumakov 2011]:

$TSI = 82.02 – 31.88 TM1/TM2 + 1.13 TM4; r=0.85, r^2=0.73$

where TM1 and TM2, TM4 mean the value of the brightness of the reflecting channel.

The spatio-temporal estimation of the trophic state is based on interpretation of a series of space images (August, 1986-2016) of Landsat-5, Landsat-7 and Landsat-8 satellites with a spatial resolution of 30 meters. Licensed software products ENVI + IDL 4.4 and ArcGIS 10.1 have been used to interpret and create thematic maps.

**RESULTS AND DISCUSSION**

Prior to the reservoirs cascade creation, the change in water level in the Dnieper River was characterized by a pronounced high spring flood, low stand of level in summer and winter limits, and low autumn floods, but the creation of a cascade in reservoirs with a total water-surface area of 6981 km² fundamentally changed the hydrological regime of the Dnieper River, which gained lake properties. The water reservoirs are indicated in the direction of the Dnieper River flow: Kyiv (filled in 1964-1966, area 922 km²) → Kaniv (filled in 1974-1976, area 675 km²) → Kremenchuk (filled in 1959-1961, area - 2252 km²) → Dniprodzerzhynsk (built in 1964, area - 567 km²) → Dnipro (built in 1932, restored after the Second World War in 1948, area - 410 km²) → Kakhovka (filled in 1955-1958, area - 2155 km²). In the reservoirs, the current speed dropped sharply - from 0.6-0.8 m/s to 0.3-0.02 m/s. Depending on the morphometric features, the location in the cascade of the reservoir, and the season, water exchange and flowage decreased up to 24 times, which caused the formation of static zones.

The increase in water temperature occurs from the upper Kyiv reservoir to the part of the lower Kakhovka reservoir near the dam. This increase in different months ranges from 0.2 to 7.4°C. The corresponding hydrological and temperature changes in the regime result in spatio-temporal intensification of the antropogenic impact on the eutrophication state of the reservoirs, which causes the development of planktonic algae, significant decrease in the transparency of water and the deterioration of the trophic state of reservoirs. The fundamental point in assessing the eutrophication process is to determine the trophic state of the reservoirs, which actually reflects the metabolism of the ecosystem (inflow, accumulation and energy consumption),
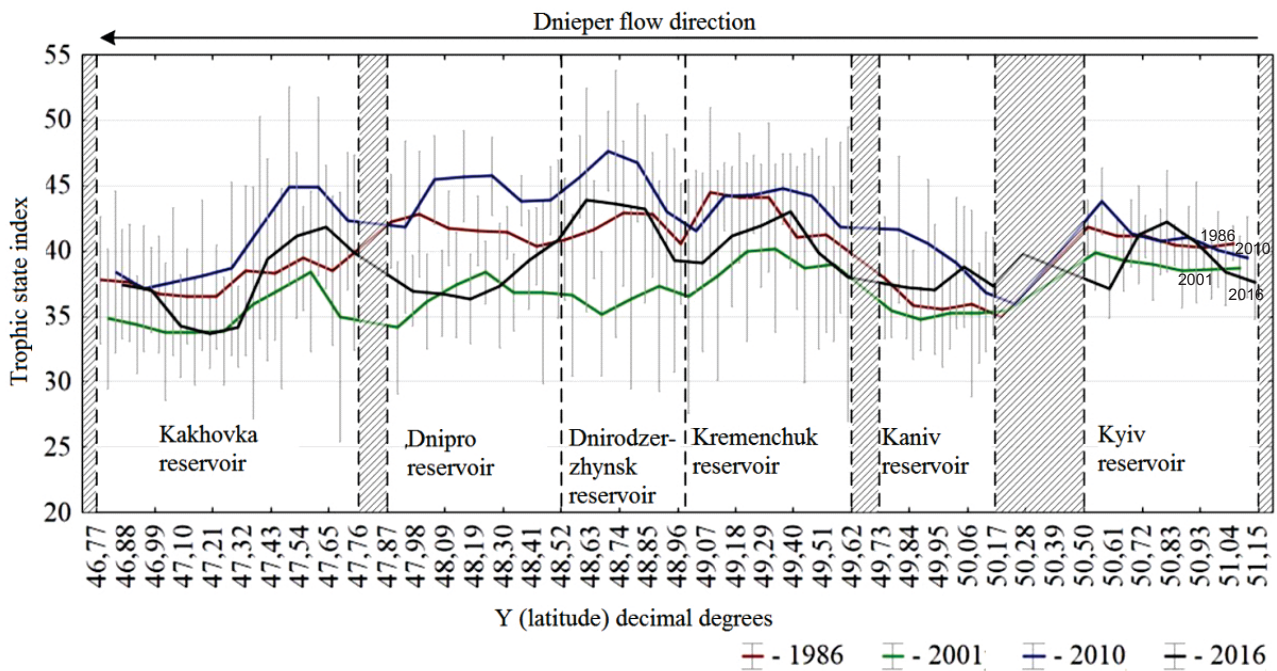


**Fig. 1.** Zonal distribution of trophic state index in cascades of Dnieper reservoirs for August 1986-2016 years

and shows its ecological state. The inflow of excessive amounts of nutrients as a result of anthropogenic contamination leads to significant changes in the ecosystems of reservoirs and acceleration of successive processes. Eutrophication of reservoirs depends not only on the load of biogenic substances on the water bodies, but also on the conditions of development of autotrophic hydrobionts, i.e., from climatic, hydrodynamic and morphological features of reservoirs. Low temperature, insufficient solar radiation, high flow velocities, high depth, turbidity of water and other environmental factors can limit blooms given sufficient concentration of nutrients. The most intensive eutrophication occurs in well-heated and lighted shoal areas, which occupy up to 40 per cent of the area of the cascade of the Dnieper reservoirs. The process of eutrophication is considered as a consequence of the violation of the stability of aquatic ecosystems, which fundamentally distinguishes it from the notion of pollution.

Today, the ecosystem of the Dnieper River is considerably damaged. High agricultural development, sewage treatment, intensive development of coastal strips and so leads to intensification of anthropogenic eutrophication in waters of Dnieper reservoirs cascade. If the necessary environmental protection measures are not taken, there will come a time when these processes will become irreversible. In reservoirs, processes of anthropogenic eutrophication reach limits that exceed the possibility of self-purification of natural waters in the process of natural biotic circulation.

One of the most informative indicators of evaluation and establishment of trophic state of water bodies is chlorophyll-a content. The most statistical codependence with remote sensing records was shown by chlorophyll-a - the main pigment in green plants, including single-celled algae (phytoplankton). Chlorophyll-a is assigned the most important role in photosynthesis among few tens of pigments contained in the photosynthetic apparatus of algae. Information about chlorophyll-a concentration and its changes in water bodies is a criterion for evaluation of production and phytoplankton biomass, as well as an indicator of water pollution. During the years of research, chlorophyll-a concentration (Chla) in August in the waters of the Dnieper reservoirs cascade ranged between 0.2-31.7 mg/dm$^3$ follwed by  Kyiv (→ Kaniv) → Kremenchuk → Dniprodzerzhynsk → Dnipro → Kakhovka . Seasonal course of phytoplankton dynamics is an important characteristic that is used when assessing the trophic state of the reservoir. Thus, oligotrophic reservoirs are characterized by one small peak of biomass in the spring, mesotrophic – by a presence of depression at the beginning of the summer against the background of moderate algae development, and a significant biomass of phytoplankton can be observed throughout eutrophic waters throughout the season .

The content of the main pigment of green plants of chlorophyll-a is considered to be *a* general environmental and physiological characteristic of algae development and photosynthetic activity, allowing representing biomass in terms of the essential component of plant cell. Previously defined (Mineeva 2012) recommended calculation values of chlorophyll-a content per unit of phytoplankton biomass (Chl/B) for reservoirs of various trophies: for oligotrophic waters - 0.18; mesotrophic and eutrophic waters - 0.40; high-eutrophic or hypertrotrophic waters – 1.03.

Municipal and agricultural waste waters entering the reservoir contain significant concentrations of nitrogen and phosphorus, resulting in a significant amount of pollutants in the Dnieper reservoirs, which contributes to the "blooming" of water. Estimation of the trophic state of the reservoir, as a rule, is based on the quantitative dependencies of indicators of biological productivity of water on the content of mineral nutrition elements (nitrogen and phosphorus), the presence of which has a significant impact on the development and photosynthesis of phytoplankton (Naumenko 2007). The results of numerous studies on the eutrophication of natural waters show that priority is given to phosphorus in reservoirs – according to current estimates, primary production is limited by this element in more than 80 per cent of investigated reservoirs; besides, the decrease in the concentration of phosphorus in water bodies is not accompanied by a rapid fall in their biological productivity and intensity of exposure to the development of phytoplankton. According to the interpreted space photographs, during the research period, the concentration of phosphorus (P) in August in the waters of the cascade of the Dnieper reservoirs varied within the range of 2.5-66.4 µg/dm$^3$: Kyiv (P - 6.5-40.2 µg/dm$^3$) → Kaniv (P - 2,5-44,8 µg/dm$^3$) → Kremenchuk (P - 4,1-66,4 µg/dm$^3$) → Dniprodzerzhynsk (P - 4,1-4,4,4 µg/dm$^3$) → Dnipro (P - 3.8-45.7 µg/dm$^3$) → Kakhovka (P - 3.6-44.3 µg/dm$^3$). The total phosphorus intake in the Black Sea coastal waters from the Dnieper River inflow over the past 60 years has increased by 6.7 times (from 1.7 to 11.4 thousand tons/year) (Kresin et al 1987, Hydrometeorology and hydrochemistry of the seas of the USSR, 1992, The state of the environment of the Black Sea 2002), which is the result of enhanced eutrophication of Dnieper cascade reservoirs and maintaining of the necessary level of mineral nutrition of excessive phytoplankton.

Among the physical indicators, only the transparency of water is taken into account for assessing the trophic state of aquatic ecosystems, which is determined by the depth of
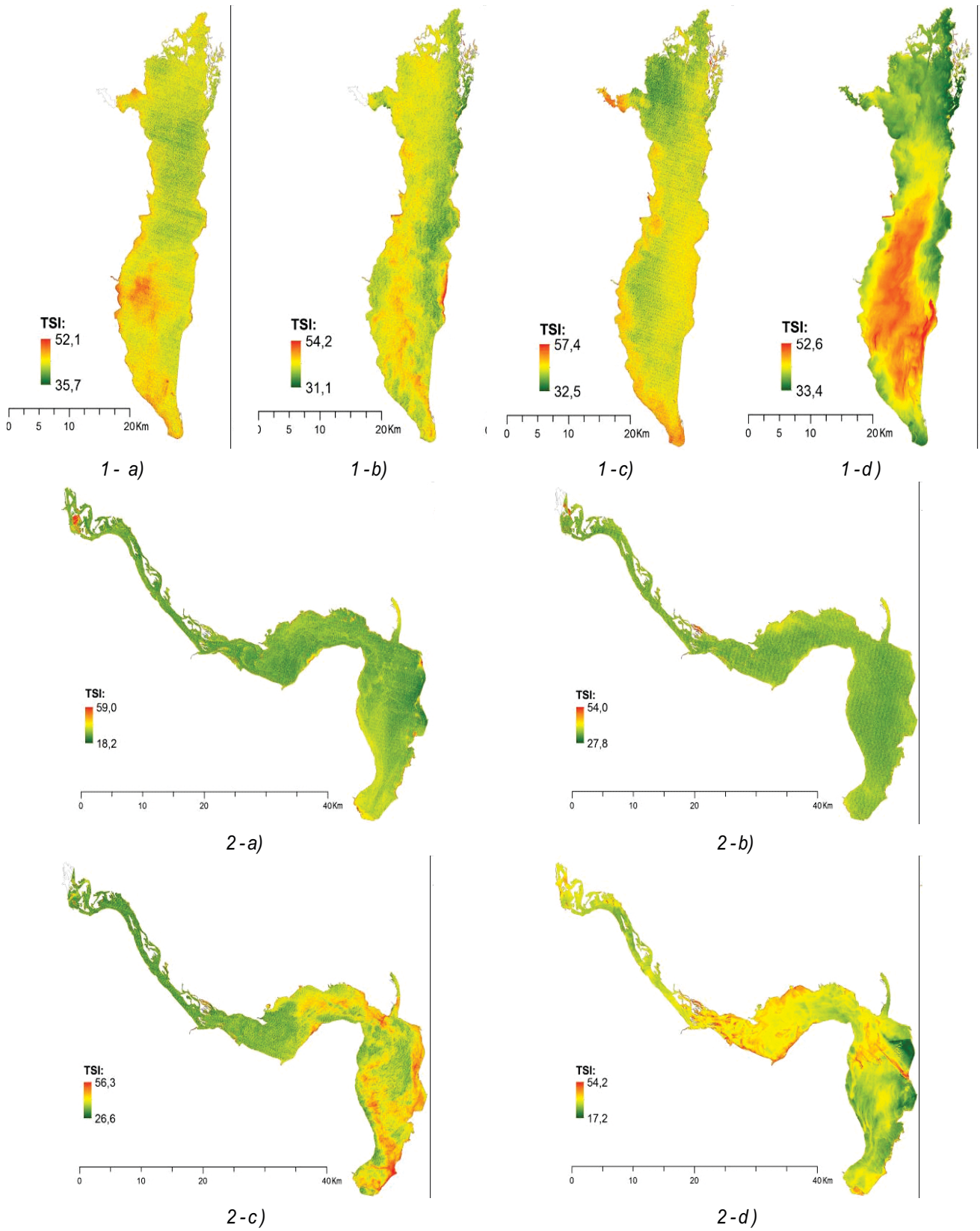
**Fig. 2.** The regularities of the spatio-temporal change in the trophic state index (TSI) in August in Kyiv (**1**) and Kaniv (**2**) reservoirs for 1986-2016 on the basis of remote sensing data: a) 1986, b) 2001, c) 2010, d) 2016, e) spatial distribution of TSI by the years of research
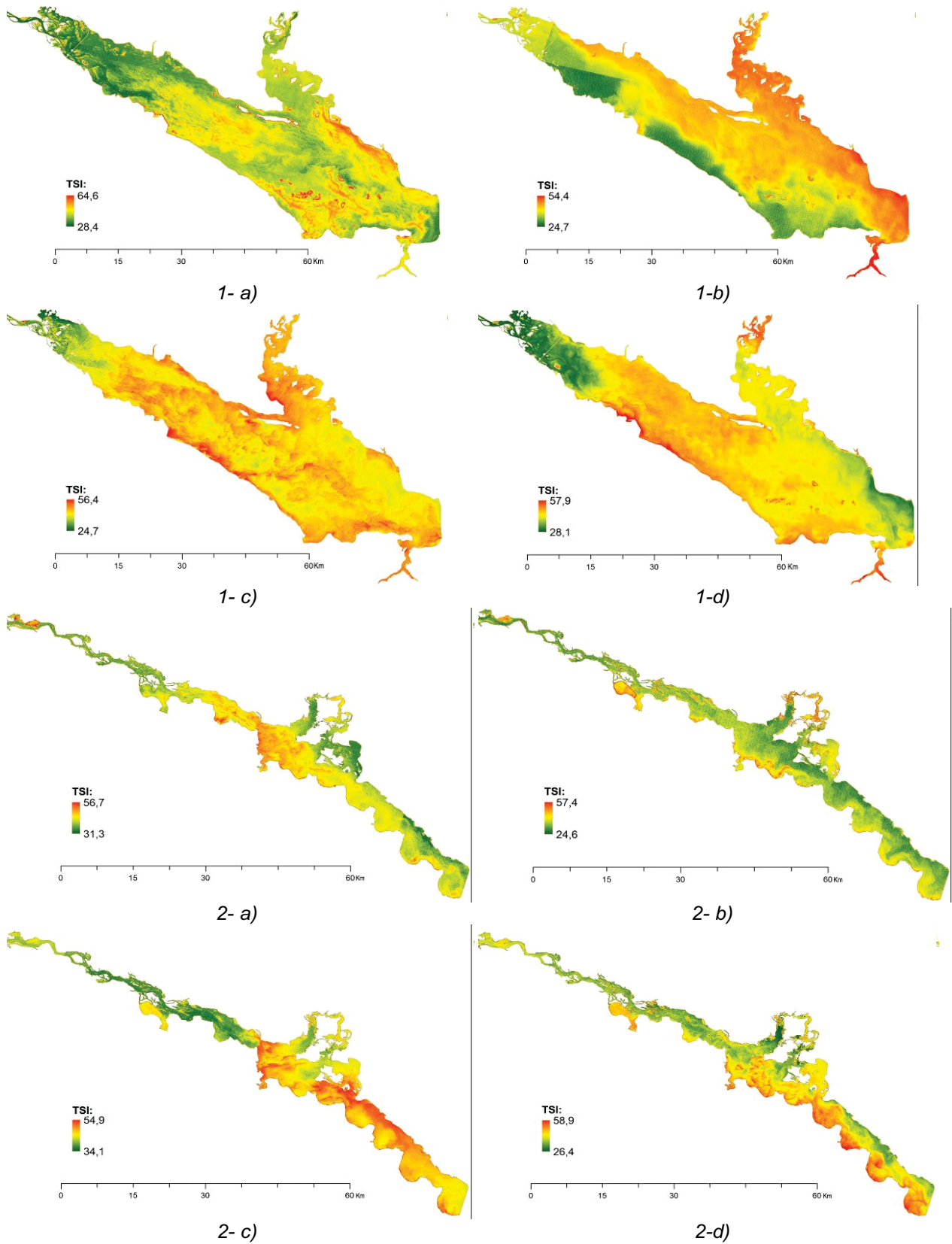
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**Fig. 3**. The regularities of the spatio-temporal change in the trophic state index (TSI) in August in Kremenchuk (**1**) and Dniprodzerzhynsk (2) reservoirs as for 1986-2016 on the basis of remote sensing data: a) 1986, b) 2001, c) 2010, d) 2016, e) spatial distribution of TSI by the years of research
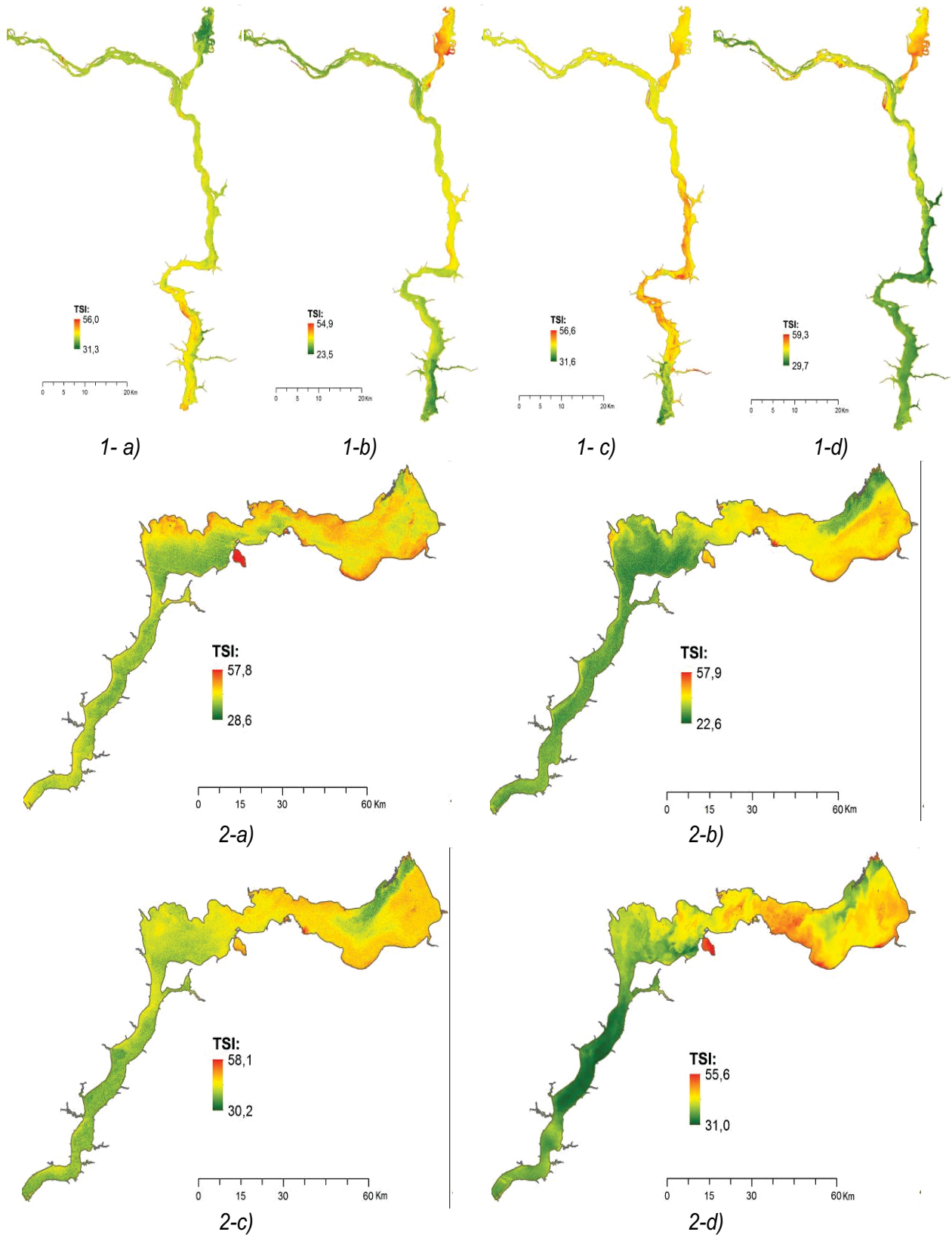
**Fig. 4.** The regularities of the spatio-temporal change in the of trophic state index (TSI) in August in Dnipro (1) and Kakhovka (2) reservoirs for 1986-2016 on the basis of remote sensing data: a) 1986, b) 2001, c) 2010, d) 2016, e) spatial distribution of TSI over the years of research

visibility of Secchi disc. Because of its simplicity, this method is widely used to approximately evaluate the status of reservoirs. The correlation of transparency, biological and hydrochemical indicators of the trophic state of water objects are comprehensively presented in the works of A.P. Musatov [Musatov 2001]. The statistical dependencies proposed by worker allow to describe the development of separate trophic chains of aquatic ecosystems based on various indicators of trophic state, energy flows through ecosystems, and the interconnections of individual parameters. According to interpreted aerospace photographs, it is determined that for 30 years in August transparency according to Secchi disc (TSD) of water in Dnieper reservoirs cascade ranged within 1.1 – 19.4 meters: Kyiv (TSD – 1.2-7.4 m.) → Kaniv (TSD – 1.1- 19.4 m.) → Kremenchuk (TSD – 0.7-11.6 m.) → Dniprodzerzhynsk (TSD – 1.1-11.6 m.) → Dnipro (TSD – 1.0-12.6 m.) → Kakhovka (TSD – 1.1 – 13.0 m.).

A series of thematic raster models and statistical characteristics of spatio-temporal nonuniformity of distribution of index and rate of trophic state of Dnieper reservoirs cascade in August are shown in Fig. 1-7. The use of cartographic material allowed tracking the process of spatio-temporal changes in the impact of anthropogenic activities on the trophic state of water in six reservoirs for 1986-2016. The zonal trend cyclical increase in trophic state index (Fig. 1) from the upper Kyiv reservoir to the part of the lower Kakhovka reservoir near the dam.

This is largely caused by the transfer of biogenic substances and their additional inflow from the Dnieper River as a result of economic activity. The largest values of TSI (from 39.57 to 45.25) throughout the cascade of reservoirs were observed in 2010, the smallest (from 35.12 to 39.42) - in 2001.

The hydrological regime of the Dnieper River in modern conditions has acquired lake properties as a result of artificial regulation. Moreover, constant processes of eutrophication of reservoirs are aggravated by the deterioration of the river self-cleaning process, lack of effective anti-erosion organization of the territories, and climate change [Lisetskiia et al 2016]. The colder water temperature and low TSI values indicate the presence of a current, while the water stagnation zones have an elevated temperature regime that stimulates the accumulation of nutrients, the active development of planktonic algae and the increase of TSI in water bodies. On the example of Kakhovka reservoir a strong power correlation dependence of the influence of air temperature (T) on the formation of trophic state (TSI) of reservoirs is observed, which has the form: $TSI = 7.95.10^{-15} \cdot T^{10,56} + 36,0$; $r^2 = 0.71$.

It has been established that the trophic state level within individual reservoirs is distributed unevenly: the TSI value varies from 26.5 to 56.5, this corresponds to oligotrophic (TSI ≤30), mesotrophic (30 < TSI ≤ 50) and eutrophic (50 < TSI ≤ 70) status of water objects. The average value ($\bar{X}$ (min-max)) and the level of variation (V,%) of the TSI in the cascade of Dnieper reservoirs during the years of research were: in Kyiv $\bar{X}$ - 38.8-40.7 (31.1-57.4), V -2, 12-6.34%; Kaniv $\bar{X}$ - 35.1-38.0 (17.2-59.0), V – 3.88-7.03%; Kremenchug X - 39.4-44.3 (24.7-64.6), V - 3.94-9.60%; Dniprodzerzhynsk $\bar{X}$ - 36.3-45.3 (24.6-58.9), V - 6.08-11.08%; Dnipro $\bar{X}$ - 36.8-44.3 (23.5-59.3), V – 4.97-8.10%; Kakhovka reservoir $\bar{X}$ - 36.8-43.3 (22.6-58.8), V – 6.58-10.45%. Changes in the trophic state of reservoirs are determined by the presence of currents, their speed and temperature regime. The lower reaches of the Dnieper River has a high degree of regulation. In some parts of the water area the index of trophic state exceeds the value of 70, which corresponds to hypertrophic state.

## CONCLUSIONS

Continued intensification of eutrophication of water bodies of Dnieper cascade increases the concentration of biogenic substances, dominance of blue-green algae in phytoplankton, reduction of transparency, increase of soil organic matter, significant deterioration in the status of aquatic ecosystems and reduction of the biological productivity of the Dnieper River, making it impossible to provide favorable conditions by using water for drinking, household, recreational and fishery purposes. In order to protect the water objects of the Dnieper basin from contamination with biogenic substances in the conditions of agricultural activity, we suggest a complex of organizational and economic, agricultural and special measures. Organizational and economic measures - the establishment of an optimal ratio of agricultural land, rational use and protection of arable land against erosion by introducing field crop rotation; increase of productivity, rational use and protection of natural forage lands against erosion by introduction of haymaking turns, sowing of perennial grasses and others; regulation of drainage of thaw and storm water. Agro-technical measures – introduction of soil protecting crop rotation; using scientifically grounded systems of soil fertilization. Hydrotechnical and hydro-ameliorative measures – creation of anti-erosion hydraulic structures at the water-intake area, as well as in the upper and lower parts of the ravines; creation of storage ponds drainage; construction of bioengineering structures, use of drainage and wastewater for re-irrigation. Forest and ameliorative measures – creation of forest shelter belts, afforestation for

water protection in ravine systems, irrigated lands, on the banks of rivers and canals, near reservoirs, ponds, on drained lands and pastures; preservation and restoration of thickets of cane, typha, sedges and other plants on the banks of rivers and lakes, near water intake structures in the form of filtration belts, as well as the creation of such belts on the way of sewage and drainage water dumping.

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