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Hydrological regime of Molochnyi Liman under anthropogenic and natural drivers as a basis for management decision-making

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ABSTRACT

Molochnyi Liman is the largest liman (22,000 ha) at the northern coast of the Sea of Azov. Contrary to estuaries, it is an ecotone without typical tides. It is a half-closed water body, with a connection to the Sea of Azov that has periodically renewed or ceased over the course of time. Molochnyi Liman is a wetland of international importance, a hydrological reserve of state significance and is part of the Pryazovskyi National Natural Park. The results of our research have established that termination of the liman/sea connection has led to significant hydrological changes. The most crucial is a reduction in the liman's depth, accompanied with shrinkage in the water surface area, a dramatic increase in salinity to 95 g/l and the loss of several Ramsar criteria. Restoration of the Molochnyi Liman ecosystem requires a positive water balance. There is a need for ensuring the inflow of at least 100 mln m^3 of marine water into the liman through a connecting channel. This will renew normal functioning of the liman and reduce the salinity to an optimal level. The methodical approach used in this work can also be applied to other closed and half-closed water bodies of the Azov-Black Sea Region. The development of a hydrological model can be effectively used as a supportive tool for the management of the Tylihulskyi, Khadzhibeiskyi and Kuyalnytskyi limans in the north-western part of the Black Sea.

1. Introduction

Molochnyi Liman is the largest liman (22,000 ha) at the northern coast of the Sea of Azov. Prior to its complete isolation, it had high productivity typical for ecotones. The liman is a half-closed water body, its connection with the Sea of Azov periodically renewing or ceasing over the course of time. The shallowness and landscape diversity of the coast, the presence of the Molochna River Delta (basin area: 3450 km^2; length of main channel: 197 km) are preconditions for the high biological diversity of the liman's water and terrestrial wildlife. In years with optimal connection to the Sea of Azov, the liman had high bioproductivity capacities,

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especially fish productivity. Acclimatization of the so-iuy mullet (*Liza haematocheilus*) in the water body met the resource requirements of local fishery enterprises.

Molochnyi Liman is a valuable natural area. It has been designated as a wetland of international importance (since 1995), a hydrological reserve of state significance (since 1974) and is part of the Pryazovskyi National Natural Park (since 2010). The warming of water in the early season and the average salinity level has promoted the development of resorts and recreation centres along the coast, especially those catering to children.

Formation of Molochnyi Liman hydrological regime is determined by many natural and anthropogenic drivers, among which the most crucial are:

- runoff from the Molochna River;
- air temperature as a determinant of surface evaporation;
- water exchange with the Sea of Azov.
- Other drivers (water filtration through the spit, wind-driven tides, etc.) are of secondary importance and their impacts on the hydrological regime require additional research.

Since 2000, long periods during which the liman is isolated from the sea and weak renewal by precipitation, along with increased evaporation due to the progressive rise in summer temperatures, have promoted an abrupt increase of evaporation and a reduction in the volume of the water body, which has led to an increase in water salinity. This increase in salinity to the level of hyperhaline water bodies caused fish productivity to drop to zero, which brought losses to fishery enterprises. The drop in water level (from 2.75 m to 1.45 m) resulted in loss of the liman's recreational value and children's recreation centres have to change their management policies and spend additional costs, which has rendered their profit-making abilities doubtful.

Not only has fish productivity been affected by changes in the hydrological regime of the liman, but there have also been essential changes to the structure of breeding, migration and wintering of bird communities, as well as many changes in the abundance of waterbirds, which has international importance to the liman as a Ramsar site.

These ecological and socio-economic effects of changes in the volume, level and chemical composition of the water in Molochnyi Liman required an urgent development of an adequate management strategy for the restoration of fish productivity and recreation value. However, a lack of data on the liman's bottom relief and the surface area dynamics has hampered the development of this management strategy. Without this data, it was impossible to calculate the loss of water volume and its annual dynamics, or to understand the principal changes in water balance. Obtaining such data required implementing new methods, in particular using remote sensing and the deciphering of images of Molochnyi Liman spanning different years.

The development of such a hydrological management strategy for the Azov Sea limans has no direct precedents, even though some recommendations and analytical reviews relevant to the subject had been presented in a number of works on water bodies of the North-Western Black Sea Region (Gopchenko and Tuchkovenko, 2003;Tuchkovenko et al., 2012).

In the meantime, other countries have widely used satellite images for the monitoring of wetlands in their research. The method we have been using is highly effective for analysing changes in the size of water surface area and is actively used by researches in different regions and for various types of water bodies (Alsdorf et al., 2007; Huan Yu and Shu-Qing Zhang, 2008).

We set the goal to not only assess current changes in the liman hydrological regime on the basis of remote sensing and field studies, but to present options for the management and restoration of the former biological productivity and recreational attractiveness of Molochnyi Liman. The development and discussion of these options is the main subject of this paper.

2. Materials and methods

Molochnyi Liman is situated in the North-Western Azov Region, in the south of administrative region of Zaporizhzhia (Fig. 1). The Molochna River enters into the liman's northern part, forming a delta made up of several branches. In the north, a sandy-shell spit separates the liman from the Sea of Azov. The liman coasts are pronouncedly asymmetric. The east coast is higher, while the western one is lower. The connection between the liman and the sea has been artificially supported since 1943.

This liman/sea connection promoted the development of abundant biological diversity of Molochnyi Liman. The connection was maintained for many years by regular dredging of the connecting channel and removal of alluvium. However, in the last 10–12 years the dredging was ceased or made only occasionally. Irregular dredging could not ensure a proper water exchange, which entailed deterioration in some characteristics of Molochnyi Liman. In this research we have analyzed the dynamics of some of the changes that occurred in this water body.

The analysis of the water surface area and adjoining areas of land was conducted using Earth remote sensing data of average and high resolution. We used data from the Pléiades satellite: panchromatic (resolution of 0.5 m) and multispectral (resolution of 2 m), taken in 2013, and data from LandSat 5 (TM sensor) with a 30 m resolution for the years 2003, 2005, 2009, and 2011–2013. The data from the Pléiades satellite were received using the framework of the Pléiades User Group programme (the European space company, Astrium, http://www.astrium-geo.com/). The LandSat data were available under open access from the Glovis website (http://glovis.usgs.gov). All images had <10% cloud cover with no cloud shadow over Molochnyi Liman. Water bodies had low reflectivity, especially in near infrared band (Landsat Handbook, 2013 http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7_Handbook.pdf) and was therefore well identified in the satellite images. For LandSat satellite images, we used a 4–5–3 combination of channels (RS/GIS Quick Start Guides, GIS-Lab, 2005), because a border between water and land was clearly visible with this combination. The Pléiades satellite images were analyzed in a 'natural colours' combination.

To analyze the data, we used the ArcGIS 10.0 application package (ESRI, Redlands), including the additional modules

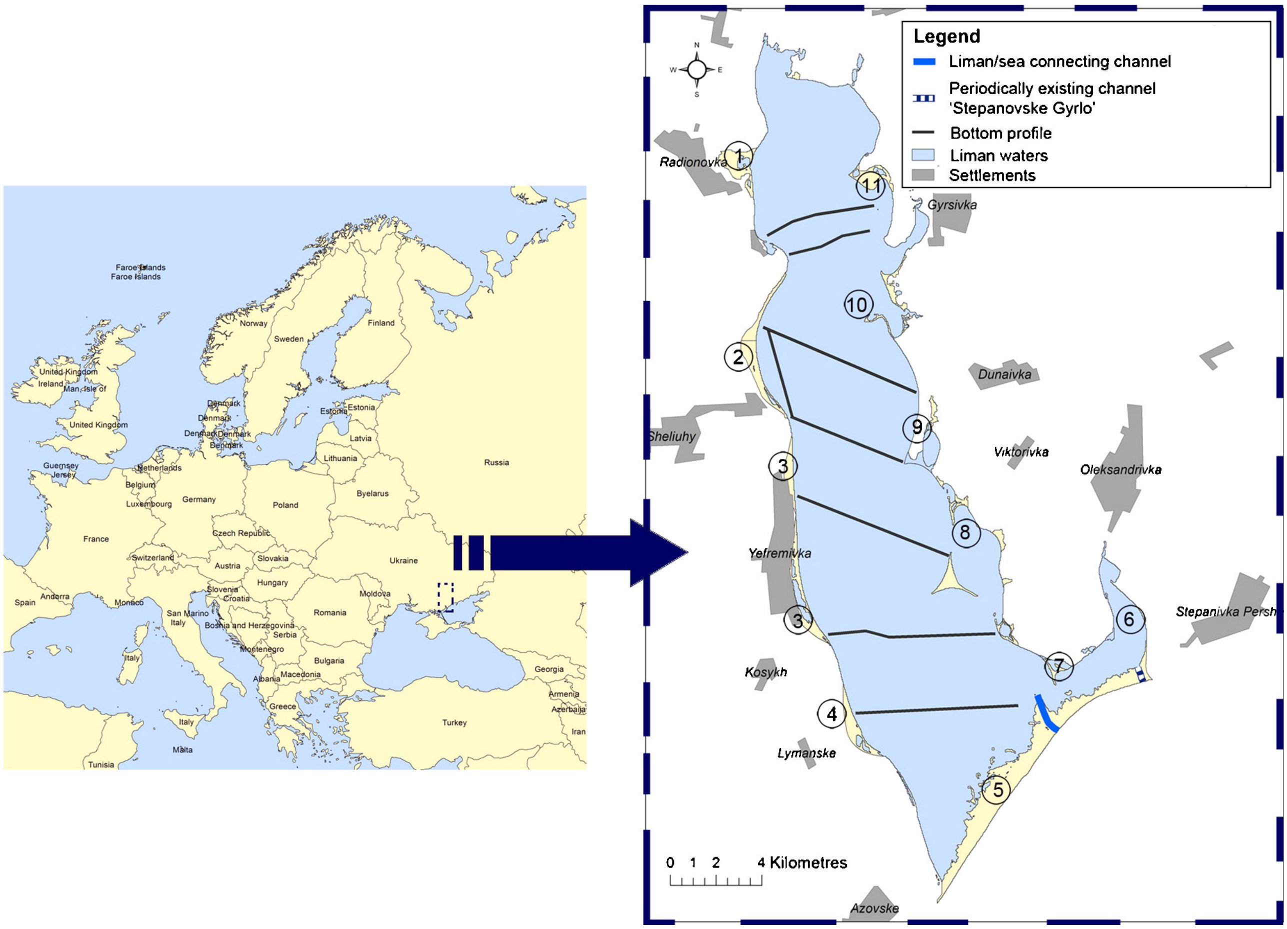

Fig. 1 – Study area. *Molochnyi Liman*: (1) Tashchenak River Floodplain; (2) Sheliuhivskyi Depression; (3) Yefremivskyi Depression; (4) Lymanskyi Depression; (5) Peresyp Spit; (6) Oleksandrivska Bay; (7) Kubek Peninsula; (8) Lake Molochne; (9) Lake Solone, (10) Pidkova Island, (11) Dovgyi Island.
Source: Chernichko et al. (2000).

Spatial Analyst and 3D Analyst that are designed to analyze raster and 3D observation data.

The 4–5–3 channels of LandSat images were combined in one image (using the function 'Composite bands' in ArcGIS 10.0). Using the 'clip' function, we extracted the area of interest (AOI) for all images. The borders of this area of interest corresponded to official borders of Molochnyi Liman as a wetland of international importance (http://wetlands.biomon.org/?p=198), but did not include human settlements.

For the classification of satellite images we used a method called 'Maximum Likelihood Classification' and distinguished three classes: water area, stable areas of land, and exposed areas of the liman's bottom. For each class, approximately 40 signatures were used.

Analysis of the hydrological changes in Molochnyi Liman was based on building a 3D model of the water body using ArcGIS 10.0. Since a map of depths was not available, we created a field mapping of the liman's bottom profile. In 2012, to estimate the water body volume, we measured the liman depth each 200 m along 8 transects (Fig. 1). Measurement points were registered by GPS. These points of measured depths and the 'TopotoRaster' function of the 3D Analyst module (default settings) were used to build a digital relief model (Fig. 2).

The digital relief model allowed for calculating the water volume in the liman (using the 'Surface Volume' function of the 3D Analyst module) based on the data of actual liman depth at control points over different years. To estimate the water inflow in the liman required for the restoration of the liman's ecosystem, we based on the data of the liman/sea water exchange calculated by Oleg Dyakov (Management Plan of Molochnyi Liman, 2005).

The long-term salinity dynamics of Molochnyi Liman was estimated using literature data (Pavlov, 1961; Yankovsky, 1965; Demchenko, 2004) and since 2009, it has been measured using a portable conductivity metre (model sensION+EC5 of Hach Company).

Samples were taken seasonally at monitoring stations located in upper, middle and lower parts of the liman. Changes in the structure of fish and bird fauna (the main components of the Molochnyi Liman ecosystem) were registered by the authors during field studies. Species composition of fish was studied using a fry dragnet (6.5 mm mesh size) and fishnets (20–50 mm mesh size). Seasonal catches were done in 10 study

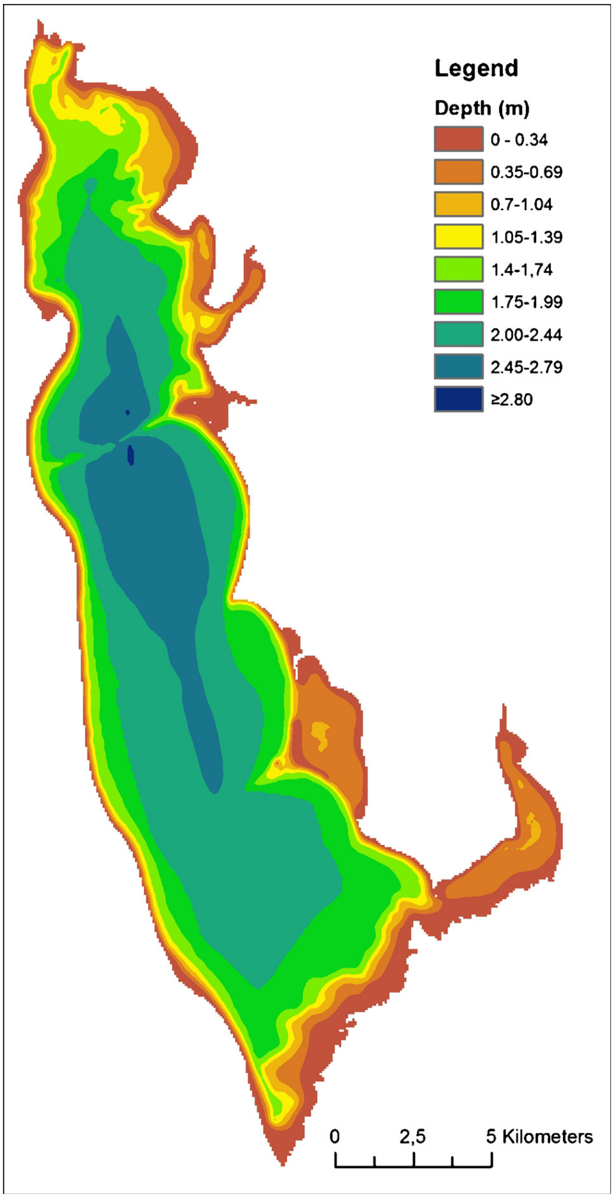

Fig. 2 – The digital relief model of Molochnyi Liman.

areas in different parts of the liman (Demchenko, 2004). Long-term monitoring of the liman avifauna, mostly waterbirds, has been taking place since 1990. For birds, a method of absolute census in count sites was used (Chernichko et al., 1992, 1998). Details of this method are presented in a publication of the Wetlands International Programme 'Guidance on waterbird monitoring methodology: Field protocol for waterbird counting' (Delany, 2011). To track historical changes in the liman, the available literature data were also used (Demchenko et al., 2012; Chernichko et al., 2000).

To evaluate the long-term temperature dynamics, data from the Henichesk Meteostation were used, since it was the closest meteostation to the study area with weather conditions the most similar to Molochnyi Liman. The temperature data were obtained from the website of the National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/). There are several commonly used variants for establishing the thermal characteristics of summer season (Blutgen, 1972) and for making assessments of temperature dynamics and revealing trends; of these variants, we used a sum of positive temperatures above 15 °C. The mean of this daily measured temperature indicates the beginning of the climatic summer (Khromov and Mamontova, 1974). Additionally, during summer months, when daily temperatures were high and latitudinal winds were active at the Azov-Black Sea coast, evaporation from the liman's water surface grew sharply (almost twice as much for each additional 10 °C), which promoted a decrease in water level.

Depth measurements in 2012 and partial ichthyological and ornithological studies in 2009–2012 were carried out as described in Chernichko et al. (2013).

3. Results and discussion

3.1. *Natural drivers of liman hydrological characteristics*

Changes in the regime and biological productivity of the Sea of Azov are significantly depended on periodical fluctuations in climate-forming processes and river runoff. A determining role of these processes had been indicated by Knipovich (1938) and Izhevsky (1961). Fluctuations in the river runoff and water exchange with the Black Sea during interaction with wind, as well as air temperature, are the main factors that form a structure of time-space changes in the oceanological fields and bioproductivity of the Sea of Azov (Gargopa, 2003).

Hydrological characteristics of the Sea of Azov and climate-forming processes in the region have a considerable impact on the conditions of Molochnyi Liman and we need to take into account the dynamics and possible trends of these processes. Thus, the main characteristics of the hydrometeorological regime of the Sea of Azov in modern conditions (mainly during the past 10–15 years) are positive trends in precipitation amounts and temperature, as well as changes in atmospheric circulation (Hydrometeorological Conditions of the Seas of Ukraine, 2009).

To analyze temperature trends in the region, we used a sum of positive temperatures (see Section 2), which would provide the most significant effect in terms of evaporation in the case of Molochnyi Liman. Analysing the trend line it is important to note a gradual long-term increase of the sum of positive temperatures, and especially high growth of them in the period 2008–2012 (Fig. 3).

In addition to temperature, the Molochna River runoff has a large impact on the liman hydrology and this runoff is highly affected by hydrotechnical constructions. Molochna River Basin (3450 km^2) includes 99 bodies of water (total volume 29.17 mio. m^3); of these, seven are reservoirs (total volume: 16.47 mio. m^3) and 92 are ponds (total volume: 12.7 mio. m^3). Such a large number of hydroconstructions pronouncedly influence the river runoff, which ranges from 13.87 to 154.96 mio. m^3 between years and on average amounts to 53.46 $\pm$ 5.45 mio. m^3 (Programme on ecological rehabilitation of the Molochna River Basin, restoration of hydrological regime, welfare and biodiversity conservation, 2013). During the past years (2008–2012) the runoff did not exceed 20 mio. m^3, which negatively affected the hydrological regime and salinity of Molochnyi Liman.

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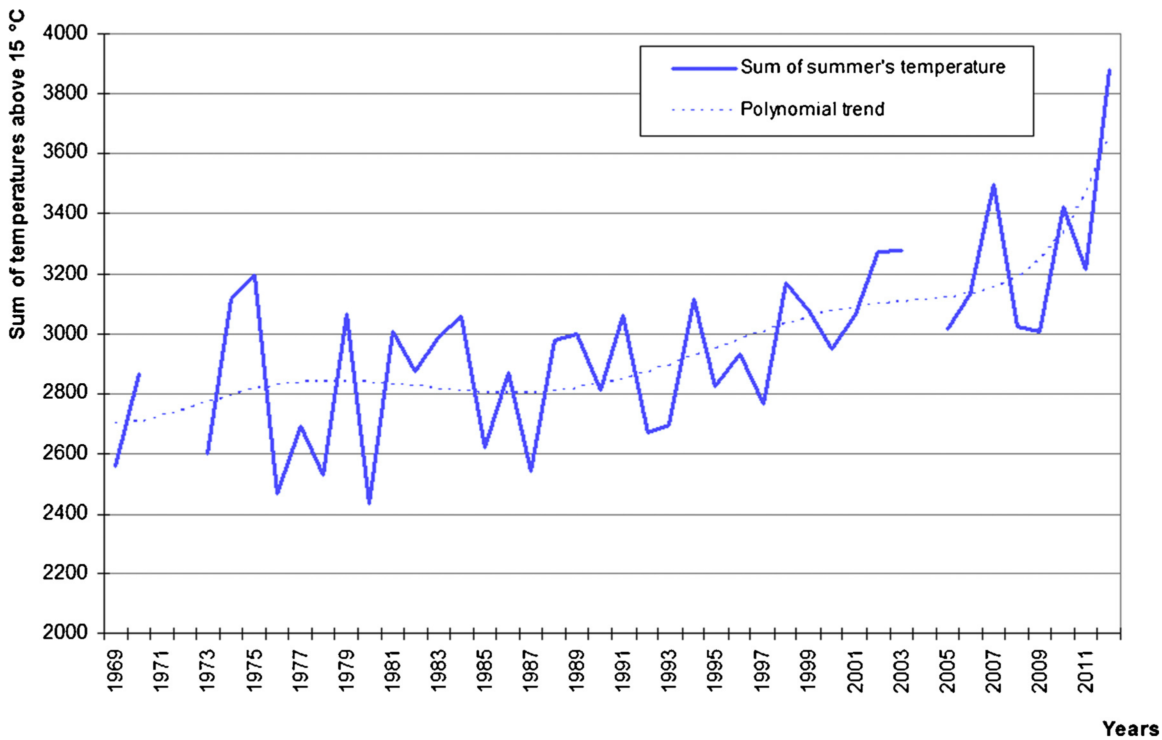

Fig. 3 – Sum of daily summer temperatures above +15 °C. Several years have no data available. Source: data from the Henichesk Meteostation.

As a result, an increase in air temperature (the consequence of increasing evaporation) and a decrease in river runoff are crucial natural drivers for the hydrological conditions in Molochnyi Liman.

3.2. *Anthropogenic drivers of liman hydrological characteristics*

Effective functioning of the liman ecosystem has always depended on the liman/sea water exchange, which is facilitated via a man-made channel. Previously, Molochnyi Liman had been a closed ultrahaline water body. Only in some years (1909, 1929, 1931–1932 and in 1940) had the sandy-shell spit been washed out, while fresher seawater penetrated into the liman (Yankovsky, 1965). However, each following year, the channel was again silted with sand and the liman renewed its closed state.

In 1943, a series of targeted explosions during World War II military operations created a deep breach in the spit. The strait, developed as the result of this activity, was afterwards heavily washed out by autumn storms and acquired more resistance to muddying. After formation of this channel, the liman came into a new phase of its existence and was transformed into a half-closed water body. This newly formed channel provided a good liman/sea connection with sufficient water exchange.

Thus, following the artificial breakthrough of the spit, the sea became a main ecosystem driver. Other drivers (fresh river waters, in particular that of Molochna River, surface storm runoff, evaporation and wind-driven tides) play only a secondary role.

Constant penetration of the sea water through the channel, which sometimes widened to 400 m, and the appearance of a new channel (the so-called 'Stepanovske Gyrlo') considerably intensified hydrological processes. New currents forming in the liman involved all the water masses in a circular movement.

Since 1965, the hydrological and hydrochemical situation has deteriorated. Instead of dredging the new channel, a new sluiced channel project was initiated. In 1972, during the course of the project's construction work, the liman was isolated from the sea, which led to significant changes in its hydrological conditions (Alekseev 1979).

In 2003, technical, economical and juridical conflicts resulted in the ceasing of regular dredging works, which over the next few years greatly transformed the liman's hydro-ecosystem. This led to the shallowing of the liman, along with shrinkage of the water surface area and an intensive rise in salinity.

3.3. *Dynamics of Molochnyi Liman hydrological parameters*

Natural and anthropogenic drivers (Sections 3.1 and 3.2) changed the dynamics of many hydrological parameters in the liman, in particular the water surface area, depth and salinity.

In the period when the hydrological connection between Molochnyi Liman and the Sea of Azov had been consistently supported and up to 2005, the water surface area had remained relatively stable (within 22,000 ha).

Analysis of satellite images for the 2003–2013 period showed that the water surface area was pronouncedly

Table 1 – The dynamics of the main hydrological characteristics of Molochnyi Liman in 2003–2013.

Characteristic	Years				
	2003	2005	2009	2012	2013
Water surface area (ha)	21269	21945	16442	16723	14229
Surface area of accumulative formations and dried-up bottom parts (ha)	2859	2183	7686	7405	9899
Maximal liman depth (m)	2.8	2.8	1.78	1.8	1.22
Water volume (mln m^3)	369.62	370.00	180.46	180.92	86.75
Average water salinity (g/l)	30.0	23.4	51.0	54.0	82.5

shrinking (Table 1, Fig. 4). The main causes for this are the absence of a steady connection with the sea, the insufficient volume of river runoff and too little precipitation amounts.

In 2013, the intensity of shrinkage again intensified due to the specific relief of the liman bottom, which was almost flat with a smooth decrease in depth from the centre to the coasts and with relatively sharp depth changes in a coastal zone induced by the trough-shaped form of the bottom. If the connection between the liman and the sea remains as it was in 2013, further shrinkage is predicted. According to our predictions, already in 2014, it could be 9500–12,000 ha (in case of continued decrease of water level by 30–50 cm, as was the case in 2013).

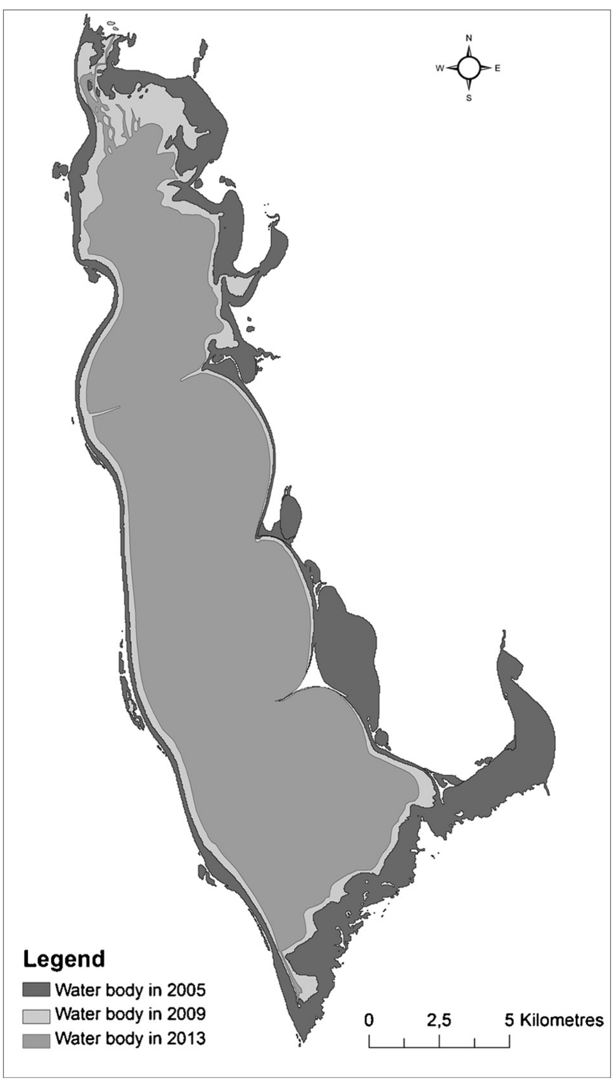

Fig. 4 – Dynamics of Molochnyi Liman's water surface area during 2005–2013.

Water volume in Molochny Liman is important for the estimation of water and salt balance. The water volume for the past 10 years is shown in Table 1 and Fig. 5. Analysis of the recent dynamics showed that the terminated liman/sea connection has led to a loss of over 282 mio. m^3 of the liman's water, i.e., approximately ¾ of its maximal possible volume.

A decrease in the liman's water level naturally entails an increase in the surface area of accumulative formations. The gradual nature of the transition of accumulative formations to the bottom of the liman complicates the analysis of their surface area dynamics; as a result, we have considered them together as dried-up (dry) areas of the liman.

The largest dried-up areas were observed along the low eastern coast and in the upper and lower reaches of the liman (1100–1300 m from the border of maximum water's edge), and along Peresyp Spit (800–2100 m). This is explained by the higher hypsometrical location of the liman bottom.

A decrease in water level, which exposed areas of the liman bottom, also connected some islands and peninsulas (Pidkova Island, Dovgyi Island) with the coast and added them to the overall area of the liman coastline.

As was mentioned previously (Sections 3.1 and 3.2), the main salinity drivers for Molochnyi Liman are inflow of fresher waters from the Azov Sea and freshwater river runoff from the Molochna and Tashchenak. The maximum activity of the channel and the Molochna River reduce the salinity indices of the liman, which was especially noticeable in the period of 1943–2003, when the liman/sea connection through the channel had been active (Fig. 6).

In recent years, due to the deteriorated liman/sea water exchange, there has been no observation of pronounced stratification in the different areas of the liman. A decrease in salinity (by 2–5 g/l) was recorded only in the liman's upper reaches, due to the influence of the Molochna River. Generally, the closed liman is characterized by a considerable rise in salinity, up to 104 g/l in some areas. During the past few years, the average liman salinity ranged from 35 to 95 g/l.

3.4. *Ecological and socio-economic changes*

Molochnyi Liman is an important link in the large Azov-Black Sea Ecological Corridor, which is targeted at the conservation of landscape and biological diversity in terms of three important conservation statuses: it is designated as a wetland of international importance (Ramsar site), a national nature park and a hydrological reserve of state importance.

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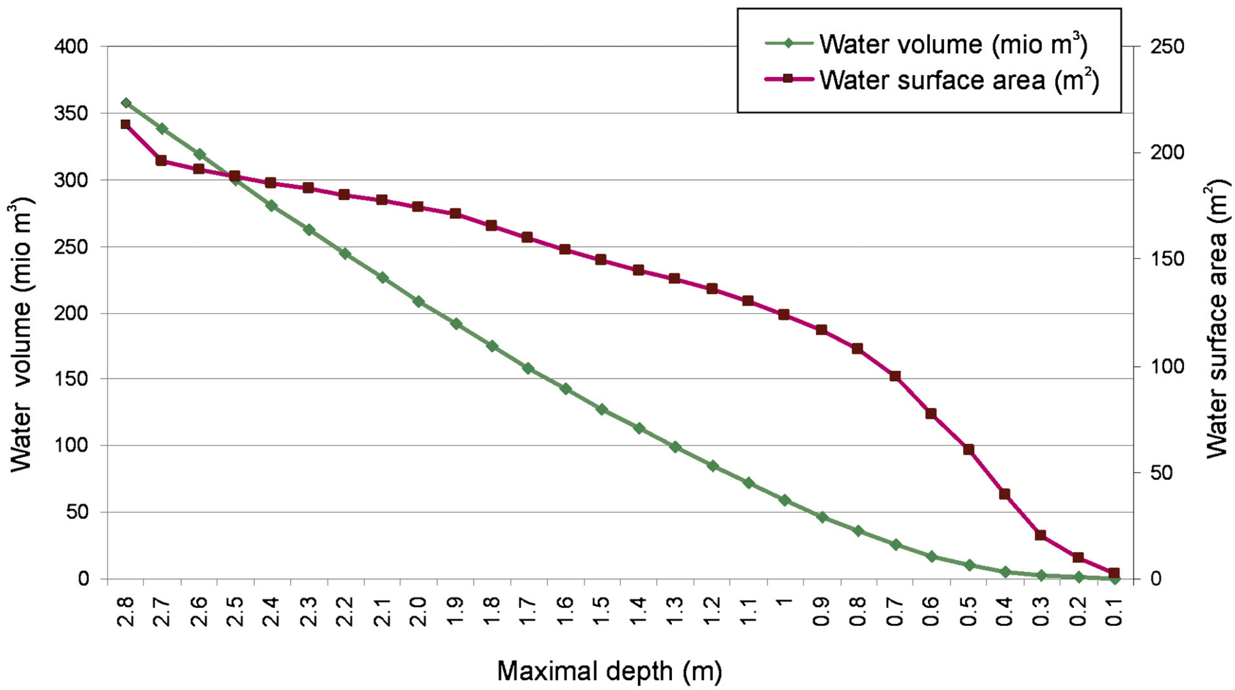

Fig. 5 – The dependence of the water volume and water surface area of Molochnyi Liman on the liman's depth.

According to Ramsar criteria (Directory of Ukraine's Wetlands, 2006), Molochnyi Liman is valuable for the conservation of bird species richness as follows:

149 bird species (49% of the total number of bird species observed in the liman) relate to different SPEC categories (Species of European Conservation Concern); 15 species (5.4%) are included in the IUCN Red List of Threatened Species; 259 species are protected under the Bern Convention and 147 under the Bonn Convention; 96 (35%) are protected by the African-Eurasian Waterbird Agreement (AEWA); 41 (15%) are under the scope of the CITES

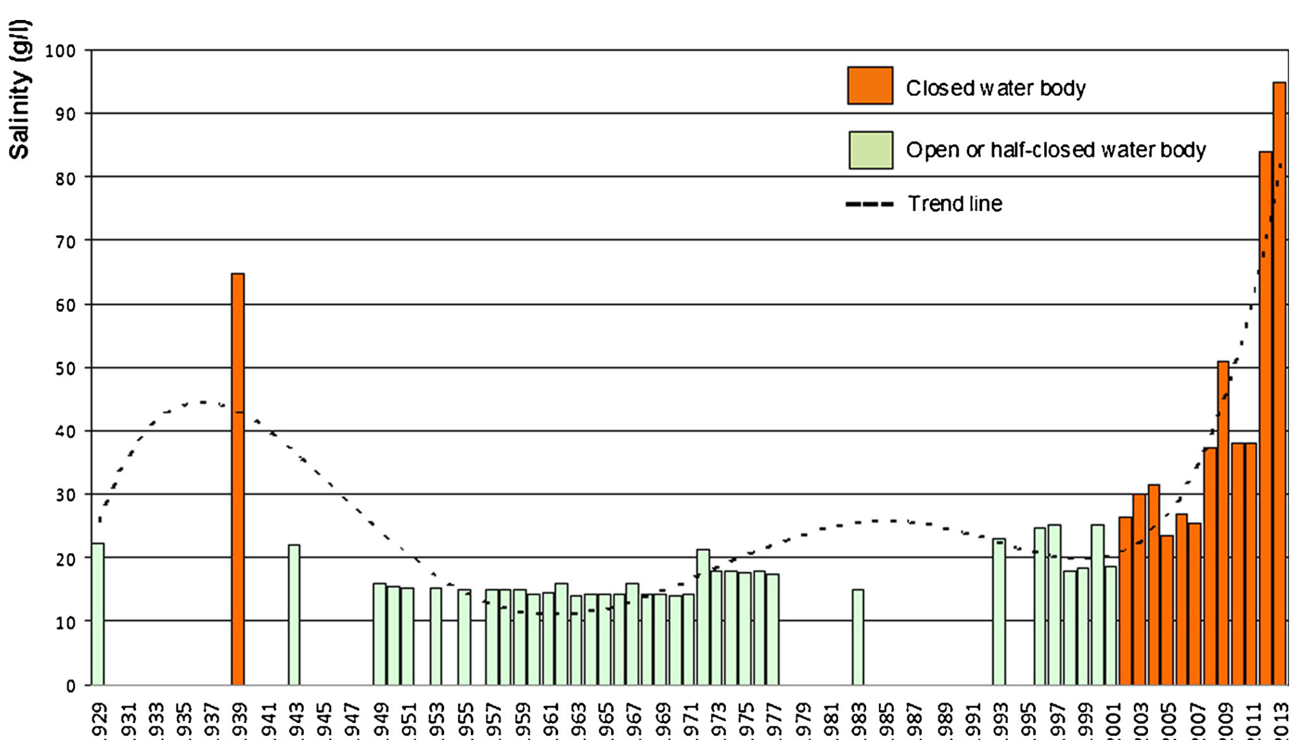

Fig. 6 – The long-term salinity dynamics of Molochnyi Liman.

Convention; 44 species of birds (16%) are listed in the Red Data Book of Ukraine (2009).

Supports the breeding of several thousand pairs of waterbirds; some of these periodically constitute 1% of the European population of the species.

Regularly holds more than 20,000 individual waterbirds of one or several species in migration and winter seasons in the liman.

Plays a significant role in the reproduction of the so-iuy mullet population (*L. haematocheilus*) and the European flounder (*Platichthys luscus*) in the Azov Basin.

The liman had these properties until the end of the 20th century, in the period of optimal salinity and high water level. Since the early 21st century, however, significant hydrological changes have led to a decrease in the liman's productivity, changes in bird species composition, the disappearance of fish and a considerable reduction in the species composition of invertebrates.

Thus, the gradual decrease in water level and the rise in salinity has led to negative changes in forage capacity, reduced the water content in the river delta and brought about the loss of nesting sites on islands. Consequently, the abundance of breeding waterbirds have noticeably reduced and by the late 1990s/early 2000s amounted to about 10,000 pairs of 40 species (Demchenko et al., 2012). Shallowing of the liman redistributed birds within its borders: former islands disappeared but several new islands formed where nesting of a high number of species was recorded, though with noticeably lower abundance. A number of rare species included in the Red Data Book of Ukraine also declined from 13 to six (Demchenko et al., 2012).

A further decrease in water level excluded available nesting areas for waterbirds and in 2013, their summarized number only just exceeded 70 pairs. In future, nesting can be expected on several new islets in the upper liman reaches. These islets, when exposed, will provide nesting grounds for some species.

Another situation was traced for the distribution of migratory birds. The availability of shallows (up to 20–25 cm deep) in the upper and lower liman reaches had determined forage capacity for herons, ducks, gulls and waders, the maximal numbers of which in autumn had reached 4000–8000 individuals in the upper reaches and 6000–12,000 in the lower reaches. The surface area of shallows had been small and greatly dependent on wind-driven changes of water level.

After shallowing of the liman, the situation changed radically. On the one hand, the area of shallows considerably increased. On the other hand, increased salinity sharply reduced the forage capacity for fish-eating, mollusc-eating and phytophagous birds. Changes in macrozoobenthos communities induced by increased salinity led to an abundance of several hyperhaline species. This abundance promoted the increase of food resources and correspondingly, the abundance of waterbirds that included benthos organisms in their diet. Due to this fact, in 2013 autumn concentrations of waders and gulls in the upper liman reaches reached a record number of 25,000–30,000 individuals and in the liman lower reaches, the number of these species ranged from 20,000 to 25,000. However, the abundance of ducks, coots and herons noticeably reduced due to a lack of forage resources in the waters of Molochnyi Liman. The abundance of some ecological groups of birds on stopovers noticeably changed, but at the same time, there was insignificant change in general species diversity.

A similar depletion of species abundance and negative changes were also recorded in fish communities. Fish studies from 1996 to 2000 found that Molochnyi Liman held 33 species and subspecies of fish relating to 14 families (Demchenko, 2004).

Since 2002, drastic changes have been induced by the liman's almost complete isolation from the sea. In fact, the channel is only occasionally dredged in spring to provide entry to the so-iuy mullet (*L. haematocheilus*) for spawning and for allowing in autumn the coming out of its juvenile fish. Under these conditions, a sharp decrease in water level in the liman was registered. The liman water salinity increased to 30–40 g/l in 2010–2011 and in 2013 reached a concentration over 90 g/l (Fig. 6).

This situation resulted in several reductions of fish species diversity. Indeed, field studies conducted in 2012 recorded only four species of fish: the so-iuy mullet (*L. haematocheilus*), the big-scale sand smelt (*Atherina pontica*), the European flounder (*P. luscus*) and the grass goby (*Zosterisessor ophiocephalus*). It should be noted that these fish species were recorded only in the upper and lower parts of the liman, where the water salinity is several times lower due to the entrance of water from the Molochna River and the Sea of Azov during sea storms. All these fish are euryhaline and can endure salinity up to 50 g/l. For this reason, these species were no longer recorded following an increase in salinity during the summer–autumn period of 2013.

Thus, as a result of the dramatic increase in salinity and changed hydrological conditions, the liman completely lost several Ramsar criteria in terms of the abundance of breeding birds and fish, and partially lost other criteria on bird abundance. These changes may create a negative image for the Ukraine in respect of the Ramsar Convention's international obligations.

In addition to ecological value, Molochnyi Liman is also a source of many natural resources; it is used for recreation, fishing and hunting, has vegetation and land resources and has hydrological, mineralogical, climatic and aesthetic value (Management Plan 2005). The most important among these aspects are fish and recreational resources.

When analysing the fishery value of Molochnyi Liman, it should be noted that historically, it has had high fish productivity. Thus, from the 1950s to 1960s, annual catches constituted 290 tonnes and fish productivity was 54 kg/ha. Over the period 1993–2000, annual fish catches amounted to 12 tonnes and fish productivity decreased by a factor greater than 20. Since the 2000s, commercial fishery on the liman was ceased due to the declined numbers of its main commercial fish species.

The primary commercial species of the liman have always been gobies, flounders and Black Sea mullets (Chesalin et al., 2002). Since the late 20th century, the so-iuy mullet (*L. haematocheilus*) had been successfully acclimatized in the Azov-Black Sea Basin. There are high concentrations of this fish on annual spawning migrations in the mouth of Molochnyi Liman from the side of the Sea of Azov, and in

1998, this resulted in its record catch of 1000 tonnes. In the rest of the liman, catches of this fish constituted 34.9 tonnes.

Thus, in the 1990s, Molochnyi Liman turned into one of the main spawning areas for the so-iuy mullet. This fact raises the status of this water body as a valuable spawning area in the Azov-Black Sea Basin, supporting an abundance of this important commercial fish species. Unfortunately, isolating the liman from the sea during the past decade negatively affected the spawning of the so-iuy mullet and the replenishment of commercial stock with young fish. This led to sharp decrease in catches of the so-iuy mullet in the Sea of Azov, which saw annual catches from 2000 to 2009 in the Ukraine and the Russian Federation exceeded 6000 tonnes. This was due to the highly productive spawning of the so-iuy mullet in Molochnyi Liman at the end of the previous and the beginning of the current millennia. Since 2010, annual catches of the so-iuy mullet in the Sea of Azov have continued to decrease and in 2013 constituted only 751 tonnes. This decline was caused by inefficient spawning of the species from 2006 to 2010, provoked by negative hydrological changes in Molochnyi Liman. As a result, in 2013 the catches of the so-iuy mullet in the Sea of Azov dropped by more than 5000 tonnes, and according to our estimations it led to a direct loss of circa USD 3–5 million.

In addition to fishery resources, Molochnyi Liman has significant recreational potential. Recreational development is divided into two directions: the use of recreational centres and spontaneous recreation. There are 36 recreational centres located within the liman coast and a flow of organized recreation shows 50–70,000 seasonal visitors. Spontaneous unorganized recreation was estimated as 3000–5000 persons per season (Management Plan, 2005).

However, these figures of recreational use relate to the period of high water level and low salinity in the liman. With the worsening of hydrological parameters, recreation in the area has also suffered. Current estimations show that the number of seasonal visitors does not exceed 5000 persons. Such a reduction in visitors has critically affected the profitability of recreational centres and children's camps, causing a number of them to be suspended.

When summarizing hydrological changes, we should note that the liman is characterized by two different ecological states. The first state is characterized by the liman/sea connection through an active channel. In this case, the liman has high productivity, optimal salinity of 20–25 g/l, high biological diversity and socio-economic potential. This state had been recorded until the end of the 20th century. The second ecological state is determined by the liman's isolation from the sea. In this case, the salinity rose to 70–90 g/l, biodiversity was impoverished, commercial fish catches decreased and the water level dropped, among other negative effects. The second state has been recorded since 2002.

3.5. *Analysis of the liman hydrological regime as a tool for management policy- and decision-making*

Section 3.4 showed that high salinity has led to a dramatic reduction in hydrobiont species diversity. In its current state, the liman has lost some species of fish, molluscs and large crustaceans, which undermines its value for fisheries. Low water level and high salinity has caused the collapse of the recreational infrastructure along the liman's coast. Most resorts and children's recreational centres have as a result terminated their activities.

In the past 10–15 years, the negative changes in the hydroecosystem of Molochnyi Liman have raised discussions on the urgent need for effective decision-making concerning the restoration of liman/sea water exchange. A current approach, based on a simple liman/sea connection through an artificial channel without precisely determining the depth and width of the channel was not accepted as a solution to the problem.

The hydrological model we have designed allows for calculating the necessary parameters for the construction of a new channel. The most important hydrological parameter is the intensity of the liman/sea water exchange, whereas other positive components (river runoff and precipitation) play only a secondary role. According to our calculations, the positive water balance requires an inflow of at least 100 mio. m^3 of marine water. This amount of water will reinstitute the former salinity level of the liman, which is optimal for high fishing productivity and will restore the area's recreational capacities.

The obtained results can be applied for improving the scientific-and-practical level of ecosystem restoration works at Molochnyi Liman. We hold the view that, to decide on the ecological and socio-economic problems of Molochnyi Liman, the following set of management activities should be implemented:

1. *Restoration of an optimal hydrological regime*. Decision-making regarding this problem is a priority. The building of a new hydrotechnical construction with breakwaters requires justification regarding the choice for optimal location. To date, there are several projects that propose to build a connecting channel using different construction techniques and in different places. However, an important fault in all of them is that they lack estimations concerning the water and, correspondingly, the salt balance of Molochnyi Liman. Without data on these factors, it is impossible to determine the main parameters of depth and width for the designed channel. If the characteristics of the channel are not mathematically justified it can lead to insufficient liman/sea water exchange, which will provoke a rise in salinity or excessive water exchange and will reduce salinity to a lower level rather than an optimal one.
2. *Development and further implementation of an integrated programme for restoration of the natural ecosystems of Molochnyi Liman*. This programme will allow for efficient future policy- and decision-making concerning problems of Molochnyi Liman. An important element in this context is the implementation of integrated measures to support the hydrological regime and fish-breeding, and the development of recreation and implementation of effective management of the liman's resources. This management should be ensured by the administration of the Pryazovskyi National Nature Park (NNP), based on an existing management-plan and a project of the NNP territorial organization. Correspondingly, the programme designers should take into account the project in terms of territorial organization as well as the functional zoning of the NNP.

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3. *Legislative regulation of ecological issues*. Implementation of environmental measures on Molochnyi Liman requires the rigorous application of current international and national legislation as follows:
   - a channel should be built on the lands of the Pryazovskyi National Nature Park and provided for permanent use.
   - development of the natural ecosystem restoration programme of Molochnyi Liman should take into account the functional zoning of the Pryazovskyi National Nature Park, the management regime and other legislative documents.
   - according to one of the proposals, the building of a new connecting channel is planned on land belonging to the local reserve 'Stepanovska Kosa' (Stepanovska Spit). This fact contradicts legislation and needs to be legally settled.
   - Ukraine should inform the International Union for Conservation of Nature (IUCN) about negative changes in Molochnyi Liman in accordance with the Ramsar Convention.
4. *Enforcement of scientific studies*. In many aspects, Molochnyi Liman is an object of long-term study. Along with this study, there is a need for organizing integrated hydrological and hydrochemical research. This research will allow for monitoring negative changes and clearly determine the main trends in the ecological status of the liman.

We should note that the methodical approach applied in this work can be applied to other closed and half-closed water bodies of the Azov-Black Sea Region. The development of a hydrological model can be effectively used as a supportive tool for the management of the Tylihulskyi, Khadzhibeiskyi and Kuyalnytskyi limans in the north-western part of the Black Sea.

4. Conclusions

A no-longer functioning liman/sea connection has led to significant hydroecological changes of the Molochnyi Liman. The most crucial of these changes is a reduction in liman depth, accompanied by shrinkage of the water surface area. This led to a dramatic increase in salinity to 95 g/l, conditions in which most hydrobionts cannot survive. As a result, the water body lost several Ramsar criteria: Criterion 4 on breeding birds and Criterion 8 on the spawning of fish. In addition, Criteria 2 and 5 only partially match the current ornithological situation at the liman. These changes may create a negative image of Ukraine in respect of the Ramsar Convention's international obligations.

We showed that using Remote sensing data is effective for the ecological assessment of the dynamics of water surface area and adjoining coastal areas for the liman. According to these data, Molochnyi Liman has shrunk from 21,945 ha to 14,229 ha during the period 2005–2013, which reduced the liman water volume to less than a quarter of its maximum value. The restoration of the Molochnyi Liman ecosystem is therefore urgent and requires a positive water balance. In its current state, it is necessary to ensure the inflow of at least 100 mln m^3 of marine water into the liman through a connecting channel. This will reinstate normal functioning of the liman and reduce salinity to an optimal level, which will favour the numerous ecological and socio-economic benefits that this important natural area is bringing to Ukraine and the region at large.

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