ORIGINAL PAPER

GIS MULTITEMPORAL ANALYSIS OF REMOTE SENSING IMAGES TO ASSESS THE SILTING OF ANTHROPOGENIC DAM LAKES IN THE OUTER SUBCARPATHIAN AREA. CASE STUDY: PUCIOASA ACCUMULATION LAKE, ROMANIA

GEORGE MURATOREANU[1], OVIDIU MURARESCU[1*], GICA PEHOIU[1*], MIHAELA SENCOVICI[1], VALENTIN GEORGESCU[2]

Manuscript received: 04.10.2021; Accepted paper: 22.11.2021;
Published online: 30.12.2021.

Abstract. *On Romania's territory, after the major floods that took place during the 70s, the hydrotechnical setup of the large rivers that drain the peri-Carpathian areas was made. The purpose of building these anthropogenic dam lakes is complex, given that extreme hydrological phenomena occurred in late spring and early summer, caused by a significant rainwater supply (about 70%), the difference being made up by the underground supply. Such a hydrotechnical setup was made in the Subcarpathian areas, on large rivers, to mitigate flood waves, but also to create water resources to supply local communities. The main problem facing these lakes is the massive silting due on the one hand to the geological and geomorphological characteristics of the Subcarpathians and, on the other hand, to the high degree of anthropization. The Subcarpathians are, from a geological point of view, made up of friable deposits (marls, clays, marl-clays, gypsums, conglomerates), which trigger a series of geomorphological processes of slope erosion (areal streaming, ravine creation, runoffs, torrential rainfall, and landslides), all of which are involved in the hydrological drainage regime. The Subcarpathians also make up a geographical area with a high density of population and, implicitly, of anthropogenic activities, which under certain conditions favour the erosion and degradation of land. These factors ensure that the solid flow recorded on the Subcarpathian Rivers is between 5-25 million tons/ha per annum. All this leads to the intense silting of anthropogenic lakes, which causes the volume of water stored in the tank to sometimes decrease to 1/3 of its initial volume. Under these conditions, in the extremity of basins, lacustrine plains were formed, and within the dam area, the pelitic sedimentary deposits exceeded 7-10 m in thickness. The aim of this study is to perform a multitemporal analysis of lake silting in the Subcarpathian area by using GIS and integrating the suite of bathymetric elevations and the series of satellite images existing from the time of the lake's construction to present-day.*

Keywords: *anthropogenic basin; silting; pelitic deposits; GIS; water reserve.*

1. INTRODUCTION

Considering that, in Romania, the accumulation lakes were set up in the 19th and 20th centuries in all geographical regions, it was necessary to achieve a regionalization of the

[1] Valahia University of Târgoviște, Faculty of Humanities, Department of Geography, 130004, Târgoviște, România. E-mails: muratoreanug@yahoo.com; ovidiu_murarescu@yahoo.com; gpehoiu@yahoo.com; mihaelasencovici@gmail.com; [*]*Corresponding Authors*: ovidiu_murarescu@yahoo.com; gpehoiu@yahoo.com
[2] Valahia University of Târgoviște, Doctoral School, 130004, Târgoviște, România.
E-mail: georgescuvalentin75@yahoo.com

Romanian territory, from the point of view of the favourable location of these lakes [1, 2]. This was due to the fact that most of them were established in high erosion relief units, which led to a high silting rate. In this case, the following must be taken into account: Ir – geological strength index; Re – erosion rate; Th – hydrochemical type; Gm – degree of mineralization.

The anthropic development of the river basins is based on the need to control the flows with the help of accumulation lakes. Regarding the issue of their location in complex developments within a river basin, all the positive effects that result in the final stage of development are dependent on it [3, 4].

Regarding the mentioned lakes, the control function is provided by the evolution of the accumulated water volume which is returned according to the socio-economic requirements, resulting in a transition rhythm called recovery or replacement index [5]: Ipr = Vi / Vlac, where Vi represents the liquid flow from the respective river basin and the derivatives, and Vlac is the total water volume of the lake. Depending on this index, anthropogenic lakes can be: oligodynamic (<0,5), meso-dynamic (0,5 < Ipr< 5) and poly-dynamic (>5).

In the hilly area, the silting problem is very important, especially for lakes with small volumes, which risk a rapid silting, with negative consequences. In most cases, the number of silted alluvia is much higher (2-4 times higher) than predicted in the design stage [6, 7].

The phenomenon of lake silting is quite complex, starting from the moment it begins operating and ending when it is taken out of commission. When analysing and understanding this process it is necessary to know the sources of the alluvia that form in the respective hydrographic basin and the means of transport in the form of solid flow (dragged and in suspension) [8]. The deposition of the solid flow in a lake basin is influenced by the way it flows through it: density currents, overall composition. In the case of relatively shallow lakes, as in the current example, but also regarding the hydraulic size and elevation at which they are located, the alluvia are deposited along its entire length, from the tail of the lake to the dam [9]. Thus, the deposits start upstream of the lake tail, in the remu area, with those in the lake tail, 0.03-0.05 in diameter, followed by those towards the bottom and the dam area, less than 0.05 in diameter.

Generally, alluvia are deposited at the entrance and storage of floods into the lake. The silting rate can be estimated using a series of factors: the annual liquid and solid runoff regime, the volume of the lake, the exploitation regime, the physical-mechanical peculiarities of the alluvia, etc. [10, 11].

The silting rate and frequency can be established with the help of the ratio between the volume of accumulation and that of the average annual runoff. In the case of small and medium lakes in the area of the Subcarpathian hills, it shows that the silting time is around several decades, due to the small volumes and the high value of the solid flow. The silting of accumulation lakes can be established based on the correlation r = Wr / V, where Wr is the volume of alluvia silted in the lake over one year (mc), and V represents the initial volume of the lake [5, 6].

The Outer Subcarpathians represent a geographical unit located outside the Eastern and Southern Carpathians, between the valleys of the Moldova and Motru rivers, stretching over an area of 15,100 km^2, that is 6.35% of Romania's territory [12].

A system of well-defined interfluves and allochthonous valleys is developed in this area: Bistriţa, Buzău, Ialomiţa, Argeş, Olt, Jiu etc., to which are added 3-4 generations with shorter autochthonous valleys, with narrow riverbeds, steep, active dynamic slopes, where a recent generation of torrential valleys stands out.

From a climatic point of view, the average annual temperature varies between 6^oC at the contact area with the mountain slopes and 11^oC at the contact area with the Romanian Plain and the Moldavian Plateau, and between 9^oC in the north, at the contact area with the

Suceava Plateau, and 11°C in the south. Precipitation is between 550-600 mm in the south and 800 mm in the north.

Regarding the hydrotechnical set-up, the anthropogenic dam lakes, the area of the External Subcarpathians can be included in the second category of the two areas, according to the degree of favourability.

The Moldavian Subcarpathians are included in the area of a 2nd degree of favourability, due to an allochthonous hydrographic network, with flows of several tens of cubic meters per second, which allow for the establishment of lakes with less than large volumes, but with a high degree of circulation, which resonate with a system of cascading lakes (e.g., Bistriţa river). The silting rate is high, for example the accumulations of Racova and Gârleni on the same river with silting rates in excess of 60%, whereas on the river Tazlău there was Lake Belci, which burst the dam and destroyed it in 1991 due to heavy rainfall.

The Curvature and Getic Subcarpathians fall into the category of restrictive areas for the development of accumulation lakes, due to the fact that the specific runoff is particularly high in this area (over 5 tons/ha/year), which makes their lifespan very short, and the establishment of drainage basins very costly.

Within the Curbură Subcarpathians, Pucioasa Lake was set up on the Ialomiţa River, and in the Getic Subcarpathians there are a series of small accumulation lakes on the Argeş and Olt rivers. On the Argeş there are the Albeşti, Cerbureni, Curtea de Argeş lakes, and on the Olt are the Călimăneşti, Râmnicu Vâlcea, Dăeşti, Râureni and Govora lakes.

Of all the accumulations, the one from Pucioasa, located in the Ialomița Subcarpathians (Fig. 1), on its river counterpart, currently has the highest silting rate. The hydrographic basin of the lake is 428.3 km^2, developed in the mountainous and hilly area [13]. The lake was put into operation in 1975 [10,14], and had an initial area of 90.54 ha at the normal retention level, while the height of the dam enabled the accumulation of an initial water volume of 10.764 million m^3 at a 418 m water level. From the area of this basin, the Ialomiţa river, downstream of Bolboci lake, receives in the mountain area three tributaries with lengths between 11 km (Rătei, Raciu) and 14 km (Brătei). In the Subcarpathians, it has four tributaries: Ialomicioara I (also called Eastern Ialomicioara or Ialomicioara Păduchiosului), which has two tributaries of its own (Cărpiniş, Glod), Ruşeţ, Ţâţa (also called Frumoasa) and Ialomicioara II (also called Western Ialomicioara or Ialomicioara Leaotei), with a single tributary, Frumuşelu or Vaca (Murărescu, 2004). Ialomicioara Leaotei has the highest modulus flow of them all: 0.81 m^3/s.

Under these conditions, the modulus flow of the Ialomiţa River, where it enters the Subcarpathians at Moroeni, is 6.88 m^3/s, and where it enters Pucioasa Lake it reaches 7.69 m^3/s. In the same context, the average solid flow transported by the river increases from 0.5 kg/s to 5.6 kg/s where it enters the lake.

The specific modulus for normal waters varies in the Subcarpathians between 2-5 tons/ha/year, but in the past 20-30 years there has been an increase of up to 10 tons/ha/year, due to massive deforestation and extreme phenomena (precipitation in the form of showers for short periods of time, which generates an intense water flow on the slope). For example, after the historical flood of 2001, at the entrance to Pucioasa Lake, Ialomiţa transported between 11-16 tons of alluvia/ha/year.

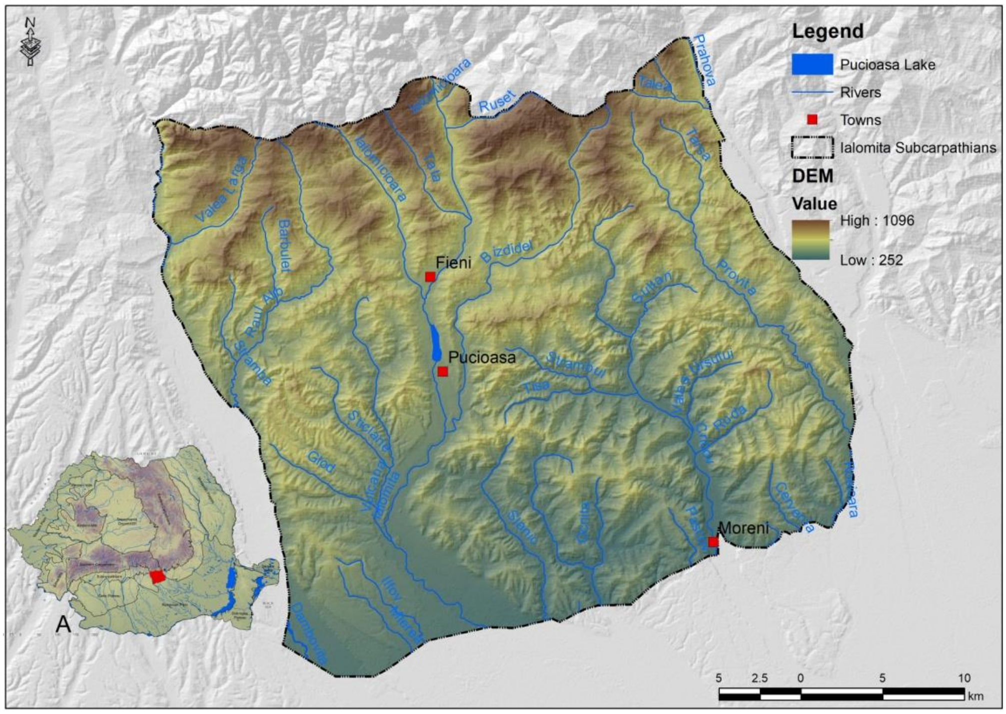

Figure 1. The location of the Pucioasa accumulation lake within the Ialomița Subcarpathians. A – The location of Ialomița Subcarpathians in Romania

2. MATERIALS AND METHODS

In order to establish the degree of silting of Lake Pucioasa, were used the last two bathymetric surveys (1993, 2009) made by the Buzău - Ialomiţa Romanian Water River Basin Administration (ABA), a series of five satellite images, recorded around 10 years apart, and existing classic cartographic documents for this area. Regarding bathymetric rises, it is a method that applies only to small lakes and requires knowing the water level, in our case 418 m. However, it has the disadvantage of entailing difficult working conditions, but also the settlement of wet alluvia during measurements.

Based on the above-mentioned bathymetric surveys, numerical terrain models corresponding to the two years were created, with the help of ArcGis, which were the basis for the initial comparison of the lake surfaces and volumes (Fig. 2). A problem that arose in the process of developing the DEMs was the difference in resolution between the document compiled in 1993 and that of 2009. However, the absolute values of the maximum altitude of the two resulting materials are substantially equal (423 m in 1993, respectively 420.9 m in 2009), which provides us with arguments enabling us to consider the two documents comparable. In the case of the minimum altitude (that at the bed of the lake) it find a level difference of approximately 9 m between the two records, which corresponds to the maximum thickness of the accumulated sediment deposit. Clearly, the 9 m value is an average one and does not precisely reflect the reality for each sector of the lake. For this reason, are resorted to raising bathymetric profiles to complete the image of the lake bed configuration. The DEMs were also the starting point for the construction of transverse profiles located 50 m away from each other, which highlight the raising of the base level in the lake, the direct result of strong silting (Fig. 3).

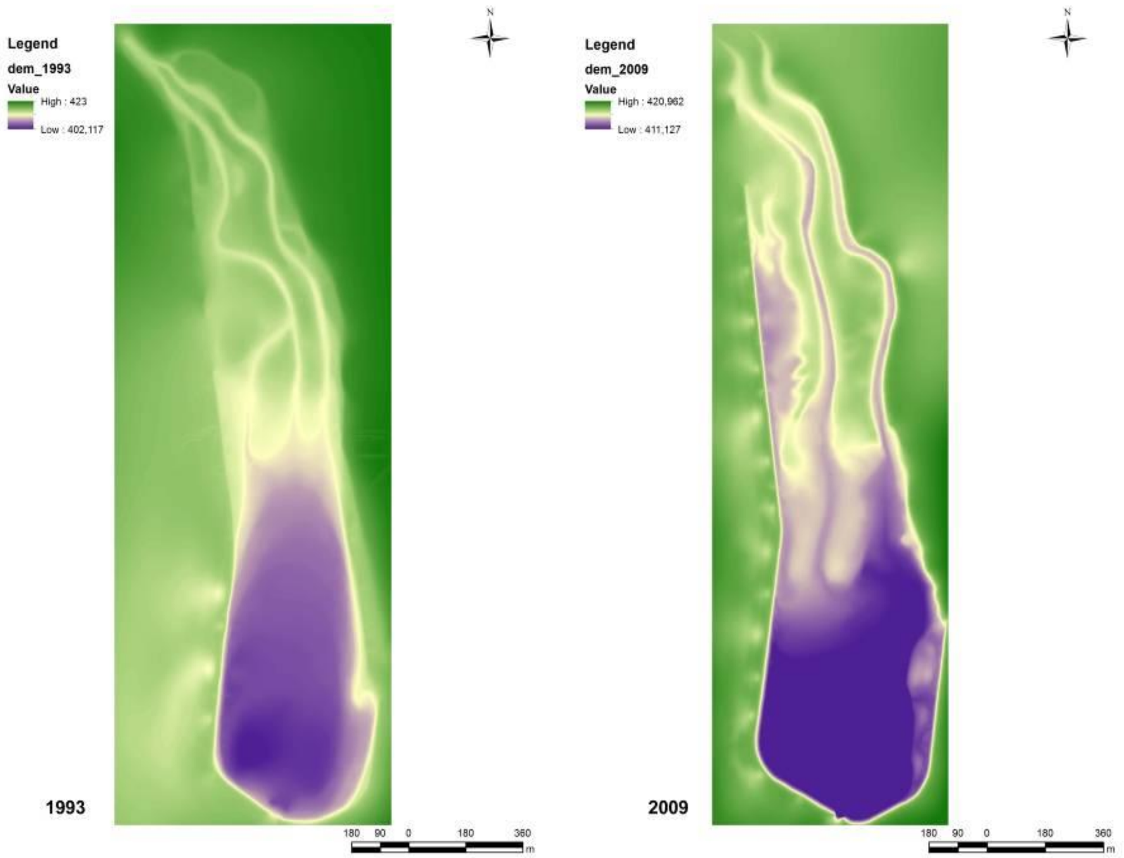

Figure 2. Numerical terrain models of the Pucioasa lake basin, compiled on the basis of the bathymetric rises (1993, 2009) performed by the Buzău - Ialomița Romanian Water River Basin Administration.

The lake was des-silted three times before 2009 by using the method of washing the alluvia with the aid of flood waves. This method increases the transport energy in the tail area of the lake, where the sediments are gathered. The containment - evacuation operations at the flood dam are pursued until the dislocated and transported sediment reaches the valves in the main dam, which are opened by regulating the flood flow.

Until 1988 (after 13 years of use), the degree of silting was 33.5% [5], while in 1993 it reached 47%, which reduced the volume of water stored at approx. 5.9 million m^3. Bed clearings in 1993 and 2009 were necessary due to the fact that in 1991, 1997, 2001, 2005 and 2007 there were large amounts of precipitation which generated an intense slope washing process, resulting in large amounts of solid sediment in the Subcarpathian area. In 2006, the volume of water in the lake was 5.47 million m^3, and in 2009, 3.59 million m^3 (a silting of 63%), while the useful volume of water is 2.93 million m^3 during the present day.

The silting of Pucioasa Lake is also reflected in the decrease of its actual surface area, in the appearance in the upstream sector of a real fluvial delta, formed by arms, sand banks and lakes and which has already developed its own flora and fauna. The monitoring of the decrease of the lake surface area was performed with the aid of the comparative analysis of the Landsat and Sentinel 2A satellite images obtained through USGS via the www.earthexplorer.gov portal. Taking into account the time-spanning extension over almost 50 years (1975 - 2019), the quality and characteristics of the images used varied, and were constantly improving.

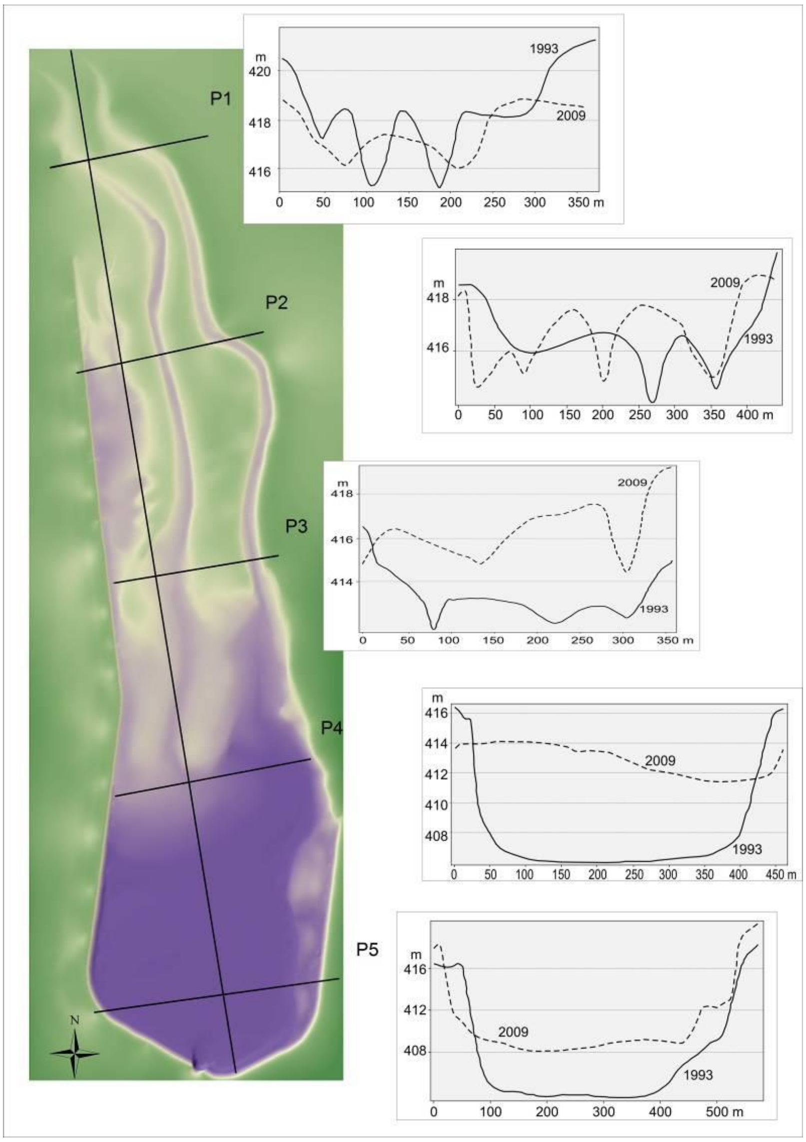

Figure 3. Cross-sectional profiles based on numerical terrain models for 1993 and 2009.

The satellite images used were chosen so as to cover the analysed time interval with a gap of about 10 years between them. The characteristics of the images used, which allowed us to perform the comparative analysis, are fully described on the official websites of the Landsat (https://landsat.gsfc.nasa.gov/) and Sentinel (https://sentinels.copernicus.eu/), satellites, as well as compared on the https://www.usgs.gov/ website, a synthesis of which can be seen in Table 1.

Table 1. A comparison between the spectral band characteristics of the satellite images used (https://landsat.gsfc.nasa.gov/; https://www.usgs.gov/; https://sentinels.copernicus.eu/)

Item No.	ID	Date recorded	Satellite	Spectral Band
1	EMP197R29_3M19790802	August 2, 1979	Landsat 3	Band 4 – Green (0.5-0.6 µm) Band 5 – Red (0.6-0.7 µm) Band 6 – close infrared (0.7-0.8 µm) Band 7 – close infrared (0.8-1.1 µm)
2	P183R029_5X19900821	August 21, 1990	Landsat 5	Band 1 – Blue (0.45 -0.52 µm) Band 2 – Green (0.52 – 0.60 µm) Band 3 – Red (0.63 – 0.69 µm) Band 4 – NIR (0.77 – 0.90 µm)

Item No.	ID	Date recorded	Satellite	Spectral Band
				Band 5 – SWIR (1.55 – 1.75 µm) Band 6 – Thermal Infrared (10.40 – 12.50 µm) Band 7 – SWIR 2.09 – 2.35 µm)
3	P183R029_7X20000605	June 5, 2000	Landsat 7	Band 1 – Blue (0.45 -0.52 µm) Band 2 – Green (0.52 – 0.60 µm) Band 3 – Red (0.63 – 0.69 µm) Band 4 – NIR (0.77 – 0.90 µm) Band 5 – SWIR (1.55 – 1.75 µm) Band 6 – Thermal Infrared (10.40 – 12.50 µm) Band 7 – SWIR 2.09 – 2.35 µm) Band 8 – Panchromatic (0.52 – 0.90 µm)
4	LT05_L1TP_183029_ 20090724_20161023_01_ T1	July 24, 2009	Landsat 5	Band 1 – Blue (0.45 -0.52 µm) Band 2 – Green (0.52 – 0.60 µm) Band 3 – Red (0.63 – 0.69 µm) Band 4 – NIR (0.77 – 0.90 µm) Band 5 – SWIR (1.55 – 1.75 µm) Band 6 – Thermal Infrared (10.40 – 12.50 µm) Band 7 – SWIR 2.09 – 2.35 µm)
5	L1C_T35TLK_A021540_ 20190807T092032	August 7, 2019	Sentinel 2A	Band 1 – Coastal aerosols (central wavelength - 0.443 µm) Band 2 – Blue (central wavelength - 0.490 µm) Band 3 – Green (central wavelength - 0.56 µm) Band 4 – Red (central wavelength - 0.665 µm) Band 5 – NIR (central wavelength - 0.705 µm) Band 6 – NIR (central wavelength - 0.74 µm) Band 7 – NIR (central wavelength - 0.783 µm) Band 8 – NIR (central wavelength - 0.842 µm) Band 8a – NIR (central wavelength - 0.865 µm) Band 11 – SWIR (central wavelength - 1.61 µm) Band 12 – SWIR (central wavelength - 2.19 nm)

August 2, 1979 – is used a Landsat 3 document, whose Multispectral Scanner (MSS) sensor generates images with a spatial resolution of 57-60 m, throughout four spectral bands corresponding to the close visible and infrared field.

August 21, 1990 – a Landsat 5 image, a satellite launched in 1984, using the Multispectral Scanner System (MSS) sensor and the Thematic Mapper instrument, provided images with a resolution of 60 m throughout 7 spectral bands.

June 5, 2000 – a Landsat 7 image that generates 8 spectral bands in the visible - infrared range, at a resolution of 30 m via the Enhanced Thematic Mapper Plus (ETM +) sensor.

July 24, 2009 – a Landsat 5 image

August 7, 2019 – a Sentinel 2 image, made by the MultiSpectral Instrument (MSI) sensor with a resolution of 10 m in the green spectral band and 20 m in the infrared.

In order to make a comparison between the satellite images recorded in this range, were used the Normalized Differentiation Water Index (NDWI) [15], using the Green and Near Infrared spectral bands. Choosing this method, to the detriment of other options used [16, 17] was dictated by the differences in resolution and by the existence of the two spectral bands in all five images, including in the Landsat 3 image. The used algorithm is frequently adopted, and is expressed by the ratio between the values of the spectral response of the yellow and near-infrared bands.

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

The bands corresponding to the algorithm are used, according to the technical specifications (Table 1). Thus, resulted in five documents distributed over the mentioned time interval with resolutions between 60 m (Landsat 3 and 5) and 10 m (Sentinel 2). After reclassifying the pixels, the contours and dimensions of the water body were extracted, as corresponding to the five years (Fig. 4).

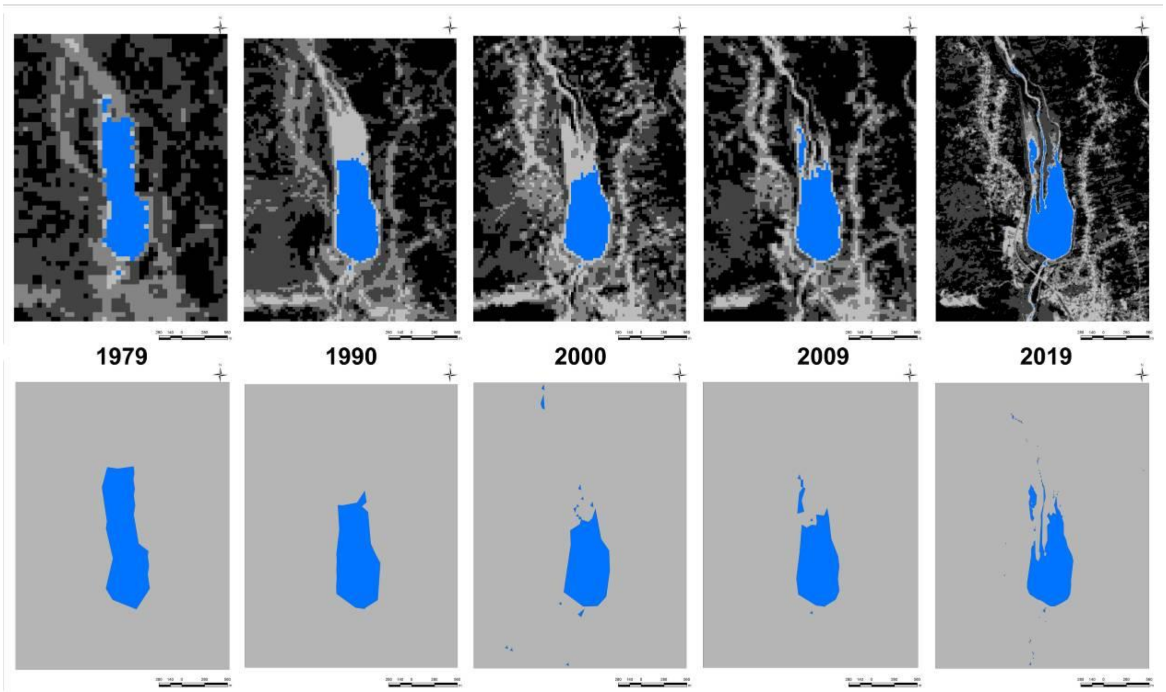

Figure 4. The evolution of the water body between 1979 and 2019, based on the differentiated water index

3. RESULTS AND DISCUSSION

The analysis of the resulting maps allows us to follow the over-arching evolution of the Pucioasa lake basin's surface, an evolution that highlights its rapid decrease due to the accelerated dynamics of the relief and the high degree of denudation in the Subcarpathian area.

Compared to the initial area of 90.54 ha, taken as a point of reference in its year of establishment (1975), we find a decrease of the registered area by 13% in just four years (1979) (Table 2, Fig. 5). Since 1979, there has been a slow but steady decline in the surface area of the water basin, which reached just 46 ha in 2019, about half of the initial area.

Where the surface area was reduced by half, the water volume has significantly dropped due to both the decrease in the surface area and the drastic reduction of the water depth in the terminal sector of the lake. The latter phenomenon is easily identified based on bathymetric, as well as ground profiles where the appearance of a true fluvio-lacustrine delta is noted, having an area of about 44 ha where the accumulated sediments had already been fixed by permanent vegetation (the marsh, grass and arboreal kind), and where even microecosystems formed (Fig. 6).

There is also an uplift of the drainage channel of the Ialomița Valley, which has created a bed bordered by longitudinal sand banks visible half-way through the lake. There sand banks are partially fixed by vegetation, whose evolution is very fast. In 2019, the sand bank sectors fixed by vegetation were 563 m away from the canopy of the dam while the newer sediments, still not fixed, were only 389 m away from the Pucioasa dam.

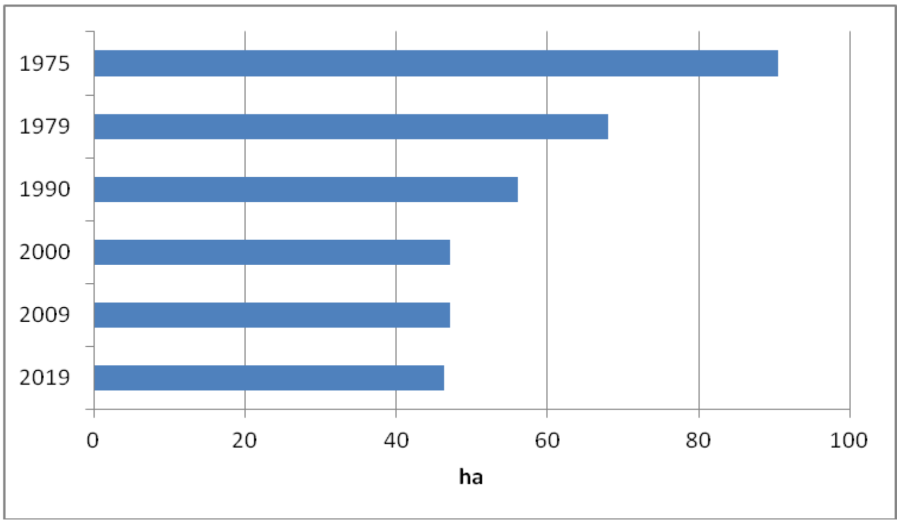

Figure 5. The evolution of the aquatic surface of Pucioasa Lake from its establishment - until 2019

Table 2. The evolution of the water surface area between 1975 - 2019

Year	1975	1979	1990	2000	2009	2019
Surface area (ha)	90.54	68.0363	56.0572	47.2072	47.0888	46.3345

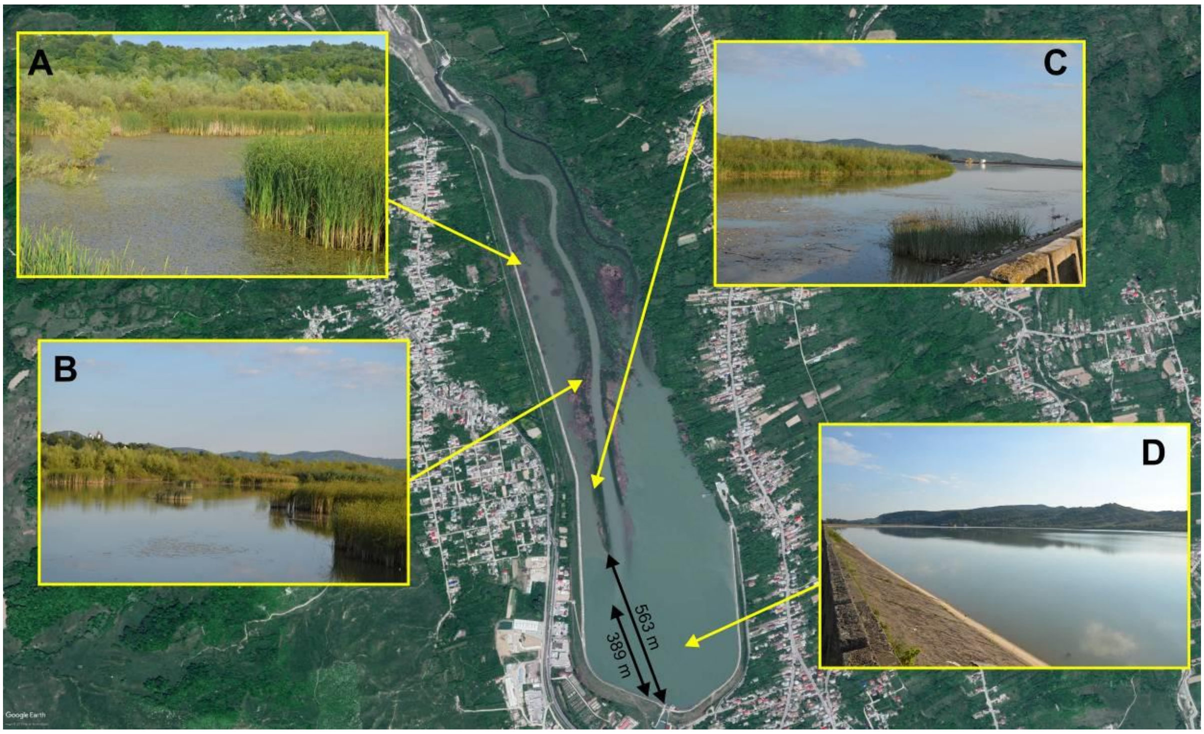

Figure 6. The evolution of the fluvio-lacustrine delta in the terminal sector of Lake Pucioasa

4. CONCLUSIONS

The dynamics of the silting of Pucioasa Lake reflects the high intensity of upstream erosion in the Ialomița Subcarpathian basin, as reflected in the volume of solid flow. While the monitoring of the volume of water in the lake can be done mainly on the basis of raising bathymetric profiles, the surface evolution is studied through the use of satellite images and the application of standardized indices of water differentiation, which can all be a precise and easy to tool to apply. The choice of the index used must be made taking into account the inspected time gap and the characteristics of the satellite images, so that they may be compared. Following the progressive silting process, the thickness of the pelitic sediments is approx. 6 m in the dam area, and towards the terminal sector of the lake these sediments reach 18-20 m in thicknesses, which triggered the creation of a fluvio-lacustrine plain. Unless, intervene quickly with specific clearing measures, the subsequent evolution of Pucioasa Lake tends lead to a fluvio-lacustrine plain in the centre of the Ialomiţa Subcarpathians. Whereas for the downstream sector, near the lake dam, de-silting is still a valid possibility, the terminal sector is very likely beyond that, given the stabilization and consolidation of sediments and their conversion into stable land.

Acknowledgements: *The authors would like to thank Mr. Răzvan Zarea with the Buzău - Ialomiţa Romanian Water River Basin Administration for his support in providing the bathymetric profiles of Pucioasa Lake.*

REFERENCES

[1] Gâştescu, P., *Lakes, reservoirs, and ponds*, **4**(1), 15, 2010.
[2] Romanescu, G. et al., *History of Building the Main Dams and Reservoirs*, Proceedings of 2nd International Conference on Water Resources and Wetlands, Tulcea, Romania, 485, 2014.
[3] Singh, V.P., *Dam Breach Modeling Technology*, Springer, Amsterdam, 1996.
[4] Zhong, Q.M. et al., *J. Geotech. Geoenviron. Eng*., **145**(5), 1, 2019.
[5] Gâştescu, P. et al., Lacurile de baraj antropic, între necesitate şi modificări ale mediului. In Sorocovschi, V. (Ed.), *Riscuri şi catastrofe*, Casa Cărţii de Ştiinţe, Cluj-Napoca, 2003.
[6] Giurma, I., *Colmatarea lacurilor de acumulare*, Editura HGA, Bucureşti, 1997.
[7] Radoane, M., Radoane, N., *Geomorphology*, **71**(1-2), 112, 2005.
[8] Albu, L.M., Enea, A., Iosub, M., Breaban, I.G., *Water*, **12**(4), 090, 2020.
[9] Hedvig, S., Szabolcs, K., Róbert-Csaba, B., *J. Environ. Radioact*., **173**, 11, 2017.
[10] Murarescu, O., *Resursele de apă din spaţiul carpatic dintre Dâmboviţa şi Prahova şi valorificarea lor*, Editura Transversal, Târgovişte, 2004.
[11] Romanescu, G. et al., *Rev. Chim. (Bucharest)*, **65**(3), 344, 2014.
[12] ***** *Geografia României*, vol I., Editura Academiei Române, Bucureşti, 1983.
[13] Murarescu, O., et al., Aspects concerning the cloging of Pucioasa Lake, *Proceedings of Water resources and wetlands*, Romanian Limnogeographical Association, Targoviste, pp. 130-135, 2012.
[14] Loghin, V., *Annals of Valahia University of Targoviste - Geographical Series*, **I**, 77, 1999.
[15] McFeeters, S.K., *Int. J. Remote Sens.*, **17**(7), 1425, 1996.
[16] Gao, B., *Remote Sensing of Environment*, **58**(3), 257, 1996.
[17] Rogers, A.S., Kearney, M.S., *Int. J. Remote Sens.*, **25**(12), 2317, 2004.
[18] https://landsat.gsfc.nasa.gov/
[19] https://www.usgs.gov
[20] https://sentinels.copernicus.eu/
[21] www.earthexplorer.gov