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APPLICATION OF REMOTE SENSING AND GIS ANALYSIS TO DETECT MORPHOLOGICAL CHANGES IN AN ARTIFICIAL LAKE

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Abstract

In this study we have used remote sensing techniques integrated in GIS (Geographical Information System) environment to analyze the rapid morphological changes, spatially significant, occurred in an artificial lake, the San Giuliano Lake located in Basilicata Region (Southern Italy), generated by the damming of the Bradano River, in the period 1984 - 2004. The remote sensing data, derived from Landsat satellite imagery acquired in the same period, were processed using different enhancement techniques and classified with supervised algorithms widely used. The classification accuracy was assessed on the whole study area by estimating the Overall Accuracy (OA), Producer's Accuracy (PA) and User's Accuracy (UA). Data validation were performed with the aid of high resolution orthophoto means of random samples. The innovative approach lies in the way which the use of GIS geoprocessing data analysis and of the Digital Terrain Model (DTM) were integrated. They have allowed the creation of simulated water surfaces, called "false lake surface". A comparison between the false lake surfaces and the true ones, shows that the lacustrine area has experienced a dynamic evolutionary with plani-altimetric changes of water surface and volume stored. These physiographic changes are particularly evident in the subset imagery of years 1984, 1988, 1889, 1993, 1994 and 1995 and consist mainly of a substantial modification of the surface and perimeter of the artificial lake. These changes, related to erosion/sedimentation processes connected to the sedimentary dynamics of the main tributaries of the reservoir (Bradano River and Acquaviva Stream) and slopes overhanging the lacustrine area, are also confirmed by observations in the field. Finally, this study shows that the variations can adversely affect water volume stored with possible impact on the functionality of the reservoir in terms of risk and hazard for the local community.

Introduction

In Italy there are numerous artificial lakes derived from the damming of river networks, especially for the production of electricity. In some areas of the Country they are the only reservoirs of water, both for potable and irrigation use, and play an important role in flood mitigation. Over time, these reservoirs have become wetlands and now they are important habitats for specific flora and fauna or centers of recreational activities [1]: a complex of characteristics that make these areas fundamental for human activities and therefore worthy to be preserved.

However, the continuous sedimentary supply by tributary rivers and that, absolutely minimal, coming from degradation of overhanging slopes on the surface of the lake, modify the floor, the perimeter and shape [2] of the lake in the time, reducing the volume of the water up to the total silting up of the storage basin. This fact implies the possibility that the dam can be overflowed during floods with serious risks of flooding for human communities living downstream [3]. These morphological changes occur rapidly (typically several decades) and are surely predictable if the area is subjected to continuous monitoring of changes [4] in the shape of the lake surface. Thus with suitable and appropriate interventions can be reduced preventively the hazardous situations.

The aerial, topographic and bathymetric surveys are undoubtedly the most useful tools for short-term monitoring of geomorphological changes in these areas of artificial reservoir [5], but are also the most expensive economically and under terms of realization times. However, for the monitoring, it the multitemporal satellite imagery data analysis seems more convenient [6], with results that are perfectly comparable with those resulting from the application of traditional detection methods [7].

In agreement with [8], analysis of satellite data is the most useful tool for environmental monitoring of the wetlands that can be easily joined to traditional surveys with the advantages of being inexpensive and easy and quickly applicable.

The analysis of data from multi-temporal satellite imagery has established itself in Italy in recent years, as an important tool for detection of morphological changes in the short term [9]. Furthermore, the application of this methodology has already been tested by the authors on other similar cases successfully and with reliable results of the monitoring of geomorphological changes.

In this paper we have used the Landsat Thematic Mapper data and Digital Terrain Model (DTM, fig. 2) to detect the space/time and geomorphological changes of the shape and volume of a dammed lake (Lago di San Giuliano) along the Bradano River (Basilicata, Southern Italy), former WWF nature reserve, in the period 1984-2004.

Study area

The area covered by this study is known as San Giuliano Lake (Fig. 1a) and is located in the Basilicata Region (Southern Italy). It is extended for about 8 km2 and has a storage capacity of about 100 million cubic meters of water. In fact, it is an artificial lake basin made, between 1950 and 1957, by damming a sector of the Bradano River valley following the construction of a large dam built for agricultural and industrial purposes. San Giuliano Lake falls in the south-west of the Province of Matera: in a hilly area with a low population density and strong agricultural, between the points of coordinates: Latitude 40°32'00" and 40°42'00", Longitude 3°52'00" and 4°14'00" (Fig. 1b). It develops between the topographic altitudes of 200 m and 450 m above sea level and lies almost entirely on the Plio-Pleistocene clay sediments, while downstream of the dam the outcropping sediments are only Upper Cretaceous lime stones. Already area of wildlife protection in 1976, accompanied by landscape bond in 1977, San Giuliano Lake became, for about 1300 acres, Oasis WWF in 1989. Moreover, in 2000, the Basilicata Region and the Italian Ministry of Environment have respectively declared this area to be a Nature Reserve and Site of Community Importance (SIC) and then a Special Protection Zone (ZPS). Finally, in May 2003, the area of Lake San Giuliano was inserted, with Ministerial Decree, in the List of Italian Wetlands aimed to the conservation of international areas of interest for the aquatic fauna.

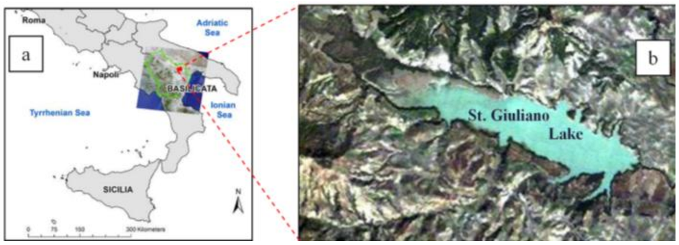


Figure 1. a) Location of the study area; b) San Giuliano Lake.

Materials, methods and techniques

For the mapping of the areas with water bodies or lakes radar and optical satellite data have often been used on which various remote sensing techniques have been applied, such as: classification, visual interpretation, density slicing techniques with multi-band sensors, etc... [10], [11], [12]. [13]; [14]; [15]. These techniques allow the identification of a water body surface (e.g. a lake) and to determine its extent over large areas, also affected by flooding. However, using these techniques there often are obvious limitations due to misclassification of individual pixels, to presences of mixed pixels, to water turbidity, denounced by poor combined response of suspended and bed load sediments, or to visibility problems related to the presence of shadows [16]. The same accuracy of the spatial resolution of the sensor used is a limit, and even the techniques used to obtain a DTM of the area examined are not free of errors. This makes it difficult to obtain an accurate mapping of water surfaces and especially their geomorphological changes unless the latter are not wide enough to exceed significantly the level of accuracy and the sensor resolution.

In this study were used 19 Landsat satellite images acquired, mainly in summer, during the period 1984-2004 (Table 1).

Table 1. Characteristics of satellite images used

N°	Satellite	Sensor	Resampled pixel (m)	Date of acquisition
1	Landsat 5	TM	30 X 30	20 June 1984
2	Landsat 5	TM	30 X 30	13 August 1986
3	Landsat 5	TM	30 X 30	12 April 1988
4	Landsat 5	TM	30 X 30	2 August 1988
5	Landsat 5	TM	30 X 30	9 January 1989
6	Landsat 5	TM	30 X 30	5 August 1989
7	Landsat 5	TM	30 X 30	28 July 1992
8	Landsat 5	TM	30 X 30	31 July 1993
9	Landsat 5	TM	30 X 30	18 July 1994
10	Landsat 5	TM	30 X 30	19 June 1995
11	Landsat 5	TM	30 X 30	7 July 1996
12	Landsat 5	TM	30 X 30	10 July 1997
13	Landsat 5	TM	30 X 30	13 July 1998
14	Landsat 7	ETM +	30 X 30	26 September 1999
15	Landsat 5	TM	30 X 30	7 December 1999
16	Landsat 7	ETM +	30 X 30	21 April 2000
17	Landsat 7	ETM +	30 X 30	13 July 2001
18	Landsat 7	ETM +	30 X 30	14 June 2002
19	Landsat 5	TM	30 X 30	30 August 2004

Several ancillary data and data processing and management software were used in this study. In particular, the software ENVI 4.7 was used for the processing of the satellite data. The ESRI ArcGis 10.1 (with its extensions) was used for spatial analysis of the data.

The topographic data for the construction of the Digital Terrain Model (DTM) were obtained by digitalizing of the Topographic Map of Italy at 1:25000 scale of Italian Military Geographical Institute. Such data have been integrated in GIS environment with the contour lines and the elevation points in scale 1:5.000 of the study area derived by topographic survey made during the construction of the dam. Official data about water levels reached from the lake surface and the effective volume stored were kindly provided by the Consortium of San Giuliano Dam [17] and are reported in Table 2.

Table 2. Hydrometric data of San Giuliano Lake corresponding to the acquisition date of the satellite imagery analyzed. The rows highlighted by bold and asterisk on the number, are referred to the so-called "significant" selected as subset data.

N°	Acquisition date of the satellite imagery	Hydrometric level (m a.s.l.)	Volume of water stored (m^3)
1*	**20 June 1984**	**99,32**	**64.213.480**
2	13 August 1986	98,99	61.262.314
3	12 April 1988	91,68	14.610.690
4*	**2 August 1988**	**93,07**	**20.590.314**
5*	**9 January 1989**	**86,50**	**1.087.887**
6	5 August 1989	88,17	1.949.230
7	28 July 1992	93,86	24.521.123
8*	**31 July 1993**	**91,53**	**14.030.487**
9*	**18 July 1994**	**97,75**	**50.689.706**
10*	**19 June 1995**	**95,07**	**31.243.094**
11	7 July 1996	98,33	55.538.673
12	10 July 1997	97,71	50.360.782
13	13 July 1998	98,94	60.820.872
14	26 September 1999	97,02	44.786.560
15	7 December 1999	96,44	40.335.433
16	21 April 2000	98,35	55.708.679
17	13 July 2001	93,70	23.696.373
18	14 June 2002	92,33	17.261.453
19	30 August 2004	97,60	49.459.251

To obtain a dimensional consistency and the perfect overlapping of the images, the study area was clipped from all original Landsat scenes available (Fig. 1b). The geographical characteristics of these new resized images, containing the study area, are shown in Table 3.

Table 3. Geographical characteristics of resized images.

Size of new images	933 x 642 *pixel*
Top left coordinates	E 611713; N 4507495
Bottom right coordinates	E 639673; N 4488265
Spatial Reference	UTM, zona 33N, datum WGS-84

The interpretation and identification of the objects in these new images was performed with enhancement techniques [18]: contrast stretch, false color composite images, principal component analysis, etc..

The images were classified using the Maximum Likelihood classification algorithm. The results of the classification were verified by the confusion matrix in order to consider the classifications with an accuracy rating for OA, PA and UA over 90% valid only, principally for the "lake water" class. The *polygons* on this latter class were extracted and converted into vector format within the software ENVI 4.7; they were then imported as shape files in ESRI ArcGis, where verified the accuracy by means of overlapping of the vector polygons on the high resolution orthophotos was verified. The correspondence between the data, also checked with random samples methods, was very high (> 90%). So, it was possible to proceed to the next stages of research.

After verification of the accuracy, the data were displayed simultaneously (overlay) to allow a quick visual comparison analysis. Although all the polygons exhibit perimeter changes, this analysis has highlighted that only some of these changes are of a value such to be appreciated at the geometric resolution (30 m per pixel) of the Landsat images used. This has allowed to take a deeper consideration of those images (called "significant"), relative to the years of acquisition 1984, 1988, 1989, 1993, 1994 and 1995 (Table 2) and discard the others in which the variations in the height of the lake level are less than the resolution limit of the input data.

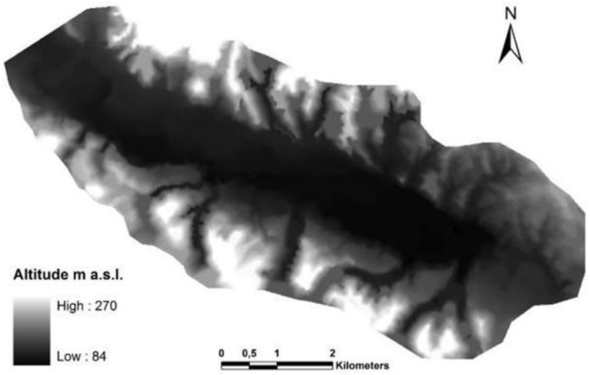


Figure 2. Digital Terrain Model (DTM) of the study area from pre-lake topography.

In order to distinguish the variations of the lake shoreline due to the simple lowering/raising of the lake-level from those related to the morphological changes of the shape of the lake caused by erosion/progradation phenomena induced by the tributaries of the lake (Bradano River and others minor), it was necessary to derive from a pre-lake's DTM (Fig. 2) of the false or simulated surfaces [19] representing the shapes that the real lacustrine surfaces would assume in the absence of topographic changes.

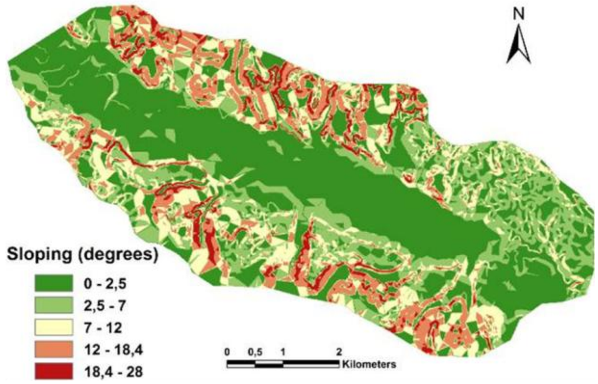
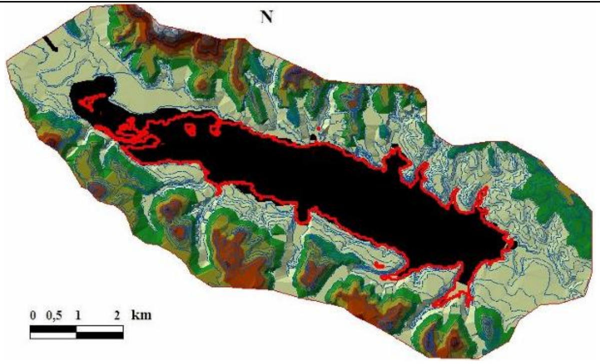
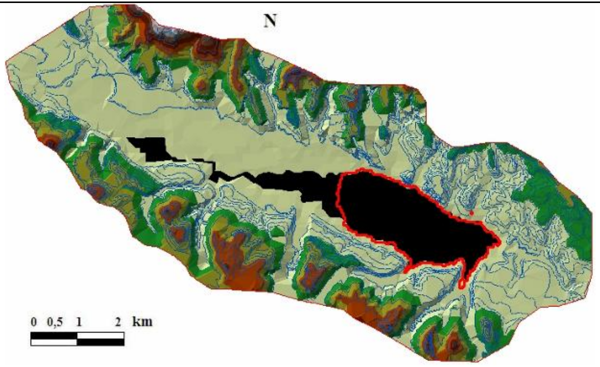


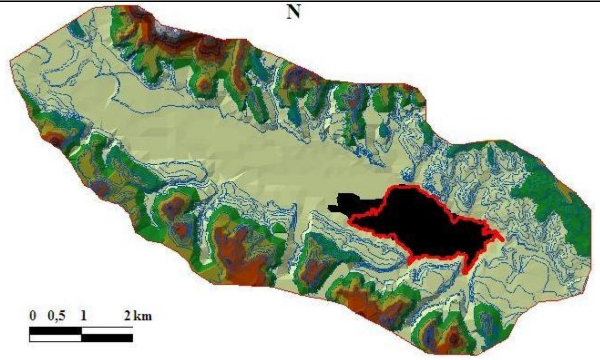
Figure 3. Slope map derived from DTM.



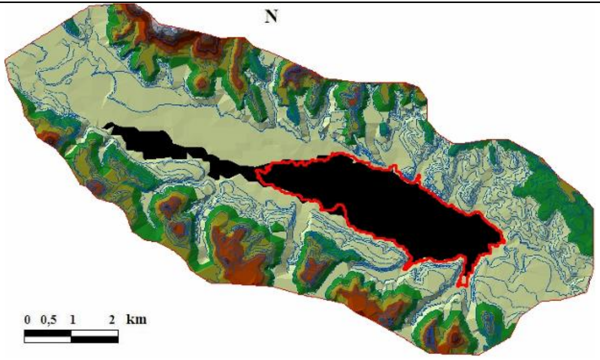
Year: 1984, lake level: 99,32 m a.s.l.



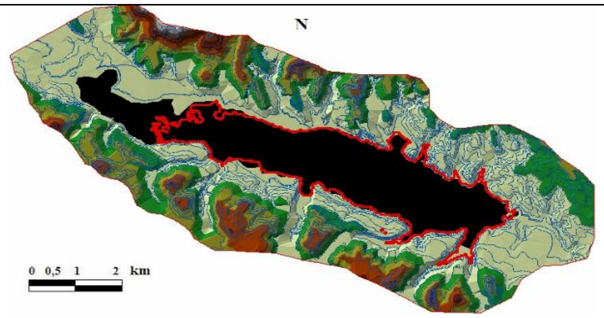
Year: 1988, lake level: 93,07 m a.s.l.



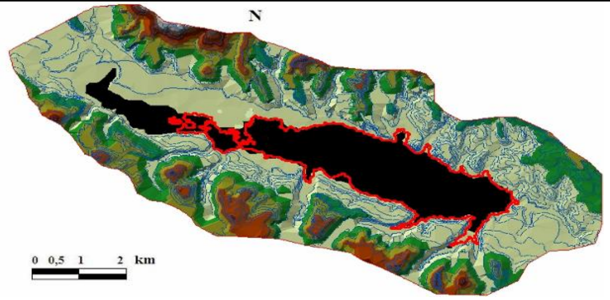
Year: 1989, lake level: 86, 50 m a.s.l.



Year: 1993, lake level: 91,53 m a.s.l.



Year: 1994, lake level: 97,75 m a.s.l.



Year: 1995, lake level: 95,07 m a.s.l.

Figure 4. Series of representations and comparison by overlay between the real lake surfaces (red line) and false lake surface (black shape) for each significant image (year 1984 to 1995).

This operation was carried out for all significant images reported in tab. 2 in order to obtain a series of representations (Fig. 4) of the false lake surfaces (black colored) related to the real lake level for each year considered. These false surfaces are obtained by intersecting the DTM on the same real lake levels with a black plane surface.

The spatial resolution (30 m per pixel) of the Landsat dataset used represents a limitation for the small changes recording, but it can be considered negligible for greater changes aimed for this study.

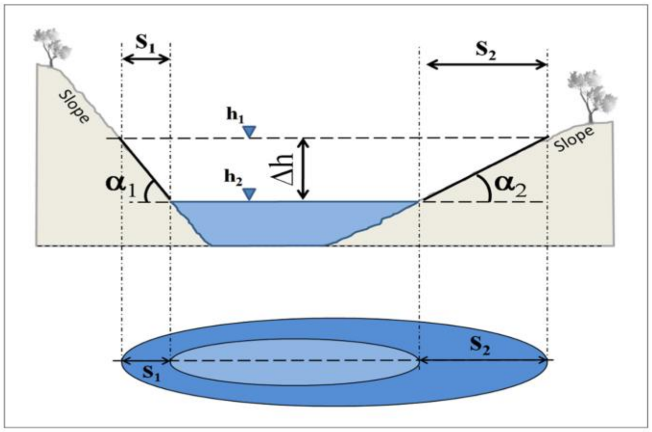


Figure 5. Scheme showing the effect of variations in height of the lake level ($\Delta h = h_1 - h_2$) on the planimetric changes ($s_1, s_2, \ldots s_i$) of the lake surface as a function of slope ($\alpha_1, \alpha_2, \ldots \alpha_i$).

In addition, from the scheme of Fig. 5 emerges that the variations in the shape of lake surface, in general, are quantitatively expressed with the s_i segment, which is a function of altitude difference (*Δh*) and the angle (*α*) of slope along the line of maximum slope, according to the relation (1).

$$s_i = \Delta h \cdot ctg(\alpha_i) \qquad (1)$$

From this relation it is clear that the planimetric variation s_i is detectable, with the same **Δ*h***, only when the **α** slope angle do not exceeds a given value (threshold value) imposed from the geometric resolution of the images. This threshold value is obtained from the relation (2).

$$\alpha = arctg\left(\frac{Eq}{px/2}\right) \qquad (2)$$

In (2) ***Eq*** is the equidistance of contour lines used for the construction of the DTM in this study, it is 5 m which is the minimum altimetric value possible in our analysis. The denominator (px/2) represents also the minimum value (15 m in our case) below which the planimetric change, documented by the pixel, is not recognized, so that from the (2) we have a angle threshold value (α) equal to 18,4°. Applying (1) to our data, plani-altimetric displacements recorded from the "significant" images become appreciable only for α values less than 18,4° (threshold value), provided that **Δ*h*** is equal to or greater than ***Eq*** value.

From DTM (fig. 2) was derived a Slope map (Fig. 3) in which the threshold value (18.4°) allows to distinguish the areas where the plani-altimetric changes are detectable from those where that's not possible.

Results and discussion

The result of the topologic overlay of all the polygons of the lake surfaces extracted from the whole dataset available is shown in Fig. 6.

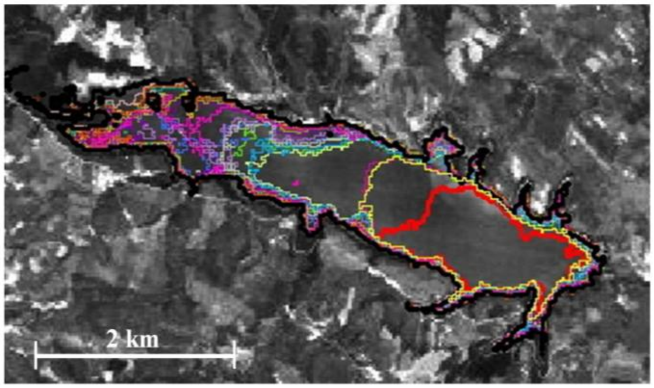


Figure 6. Representation of lake surface polygons relative to the whole dataset of images available for the period 1984 to 2004.

The shape and size variations of these polygons are mainly due to the different hydrometric heights reached by the level of the lake in all acquisition years of imagery (Fig. 7).

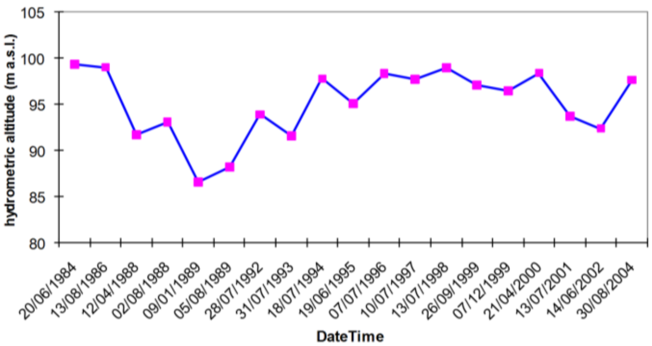


Figure 7. Variations of the hydrometric level of the lake during the period 1984 -2004.

The various overlaps between polygons shown in Fig. 6 does not always allow a visible distinction of planimetric changes experienced by the lake surface, because in the analyzed period there are many hydrometric levels which are very similar (Fig. 7). This is also evident from histogram shown in Fig. 8.

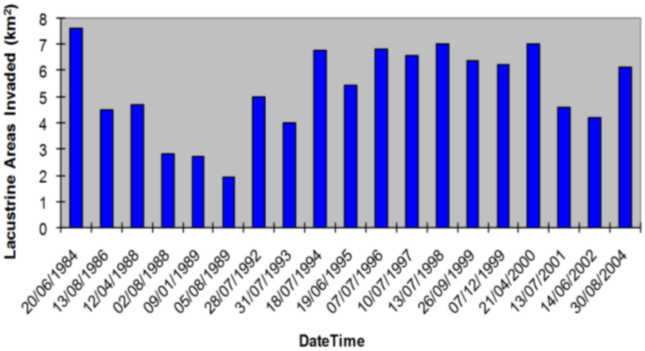


Fig. 8. Histogram of the extension of the lake surface areas in the period 1984 – 2004

This becomes an important limitation especially when the limit of geometric resolution of imagery in the data analysis is not exceeded. As already stated above, to overcome this limitation we have carried out the analysis of data of only the significant images. In fact, the overlay of these images (Fig. 4) shows that the perimeters and the forms described by different polygons to respective topographic heights are clearly distinguished and therefore are not affected by this limitation.

The 1989's image shows the minimum extension of the lake surface, found in the series of data examined, corresponding to the minimum of 86.65 m a.s.l. In comparison, on the other hand, the 1984's image shows the maximum extension of lake surface corresponding to the maximum lake level reached of 99.32 m a.s.l. The morpho-topographic intermediate situations show the geomorphological evolution of the lake surface in terms of hydrometric dynamics.

In order to determine the plani-altimetric [20] in terms purely geomorphologic, a comparison by overlay between the real lake surfaces detected from significant images and those false (Fig. 4) derived from DTM, both corresponding to the same hydrometric heights achieved during the same years, was made.

Looking the Fig. 4, it evident that the shape variation is higher in the apex of the lake, and this would mean that the contribution of the supply of sediments from the main river, Bradano River, is the principal responsible of the different between the true (red line) and false lake shape (in black).

Obvious differences emerge from this comparison between the two situations represented: the false lake surface always appears bigger than the real one in each image, that is also quantitatively reported in the Fig. 9.

The false water volume (F.l.v in Table 4) represents the value of water stored in the reservoir under the assumption of no loading of sediments occurred during time, in a morphology derived from the DTM at the time before of dam construction. The processed volume is limited from a plan represented to the false water surface at a determinate level and the surface or terrain derived from DTM.

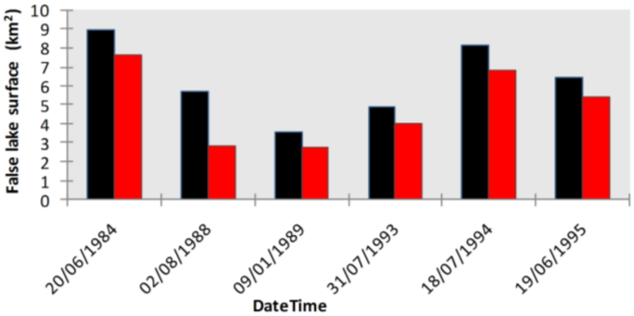


Figure 9. Histogram of the extensions of the real (red) and false (black) lake surface areas compared

In agreement with literature data ([21]; [22]; [23]) these differences mean, in general, that there are obvious topographical changes in the physiography of the reservoir, whose values are such as to condition also the volumes of water stored that result to be reduced, as shown from the differences between the false water volume stored and the real one (Table 4).

Table 4. Quantitative data revealed by the overlay comparison between real and false lake surface in significant images; H.l. = Hydrometric level (m a.s.l.); F.l.s.= False lake surface (km^2); R.l. = Real lake surface (km^2); S.d. = Surfaces difference (km^2); F.l.v. = False lake volume (m^3); R.l.v. = Real lake volume (m^3); V.d. = Volume difference (m^3)

Image date time	H.l.	F.l.s.	R.l.	S.d.	F.l.v.	R.l.v.	V.d.
20/06/1984	99,32	8,98	7,61	1,37	73.863.187	64.213.480	9.649.707
02/08/1988	93,07	5,68	2,80	2,88	28.550.372	20.590.314	7.960.058
09/01/1989	86,50	3,53	2,73	0,80	1.242.891	1.087.887	155.004
31/07/1993	91,53	4,88	4,01	0,87	20.389.432	14.030.487	6.358.945
18/07/1994	97,75	8,11	6,78	1,33	60.372.427	50.689.706	9.682.721
19/06/1995	95,07	6,45	5,44	1,01	40.663.006	31.243.094	9.419.912

The value of these differences demonstrates the existence of an important sedimentary dynamics, made by the main tributaries of the artificial lake (especially Bradano River and Acquaviva Stream), and an active, but less intensive, morpho-evolutive dynamics of the slopes of the lake area [24]. These statements are confirmed by morphological observations conducted in the field on the studied area.

Conclusions

From data image processing of Landsat satellite and their GIS modeling the lake surfaces and the associated perimeters for each year of the period 1984 – 2004 were extracted. They were subjected to comparison by topological overlay and shown as a series of polygons of shape, size and altitude hydrometric different in order to evidence the geomorphological changes.

This result appears, however, strongly influenced by the limit of geometric resolution of the images (30 m), especially when the spatial variations among all polygons are less than 15 m. To obviate this drawback a selection of images were performed, like a data-subset called significant, in which the spatial relationships among the polygons are more pronounced and then the geomorphological changes are more evident.

Through the use of a detailed pre-lake DTM it has been possible to reconstruct, for each year of acquisition and at the same real hydrometric height, a series of false or simulated lake surfaces that should represent the same lake surfaces but without morphological changes.

The comparison between two polygons representing false and true lake surfaces reveals obvious quantitatively evaluated differences. They demonstrate the entity of the plani-altimetric modifications suffered from the reservoir during the examined period. Such entities of modifications are surely to be attributed, as found also in the field, to the sedimentary dynamics of the river mouth and slope degradation processes.

From all data analyzed, the results obtained reveal that the study area is characterized by a appreciable progressive narrowing and secure silting of the reservoir, which is documented by the difference between the simulated or expected volume and the real one of water stored. This latter consideration, from the point of view of the hazard, could have serious consequences in terms of risk both for humans with their heritage and the whole natural environment surrounding the reservoir. In fact, are several cases known in Italy where have already occurred similar disasters caused to dam overtopping. This kind of risk is not only in terms of loss of the resources but also for the functionality of the dam itself whose services are important for the local already weak economy. Moreover, the wetland protected area, generated by Bradano River damming, could also be seriously damaged or destroyed. Finally, the data and results obtained demonstrate the goodness of the methodology applied. That is a valid and inexpensive tool for environmental monitoring in this kind of situation and where there are minimum and rapid changes of the topographic surface.

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