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GIS management of NDT results for the spatial estimation of environmental risks to historic monuments

A. Moropoulou, M. Koui, Ch. Kourteli, N.P. Avdelidis, N. Achilleopoulos
Department of Chemical Engineering, National Technical University of Athens, Greece.

Abstract

Infrared thermographs coordinated with the results of chemical analysis of stone decay products (soluble salts-ion concentrations) and the results of humidity contents permits to evaluate environmental impact assessment on historic masonries. Hence, it provides information in order to assess incompatible environmental management and to valuate new uses of cultural goods. A G.I.S. application on the Medieval Fortification of Rhodes was developed by the NTUA - Materials Science and Engineering Section, using Arc/Info software for the display, query and generally management, of these data. A raster image of the old city serves as the main orientation base map, while measurements of distance and area can be displayed directly on a vector map. These can then be functionally seamlessly integrated in the existing data base with the objective to identify any possible spatial relationships between the various variables (i.e. humidity versus distance from the underground sewage system), as well as to create a structure, which will be capable of accommodating future data and thus develop into a comprehensive and useful tool for data integration and analysis. Devaluating cultural heritage derives form the inevitable marine and urban atmosphere, but as well from the town planning related uses and incompatible environmental management. Environmental loads can be visualized in their spatial distribution in the raster map as salt spray sources, pollution sources and humidity sources.

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1 Introduction

The threat to the heritage and in particular to the building materials (stones, bricks, mortars etc.) is rising due to the intensification of the atmospheric pollution, urbanisation, industry and tourism. Europeans combine their efforts and resources to protect their Cultural Heritage, which, although survived for centuries is now going through nippy deterioration, hardly reversible. The nature of the problems and the past experience establish that in order to attain monument's conservation, studies of their historical and cultural context, diagnostic studies (for the comprehension of causes and decay mechanisms), environmental monitoring and impact assessment, and the selection of the appropriate conservation methods and materials, consist the vital scientific and technical foundation for the proper interventions.
The weathering of monuments could be considered as an interaction between the building materials and the active environmental factors. Interest focuses on the interface between materials and the environment rather than on any intrinsic procedure [1]. The implication of this in diagnostic and conservation research is that, in addition to techniques of direct intervention to the stone itself, the management of environmental factors (natural and man-made environment) that cause stone decay, must also be considered [2].
In this research work, environmental impact assessment is carried out, in co-ordination with analysis of damage, in order to identify the criteria for managing the environmental decay factors [3].

2 Experimental Procedure

In the present work nineteen sampling points were examined, concerning various sites within the Medieval City of Rhodes. Laboratory measurements such as soluble salts-ion concentrations in coordination with ndt in situ investigation (infrared thermography), permit the evaluation of environmental impact assessment on historic monuments. Furthermore, a GIS (Geographical Information System) was developed, in order to display and manage the results obtained from the in situ investigation.

2.1 Laboratory measurements

The samples were crushed in an agate mortar. About 100mg of the resulting powder was dispersed in 100ml of deionized water. The aqueous suspension was filtered through a Millipore 0.2μm pore size filter and the filtrate was analysed. *Ion chromatography (IC)* was performed with a Dionex 4000i instrument, equipped with an AS 11 anion separator column; the fluent was 20 mm NaOH. Ca^{2+} and Mg^{2+} were determined by *atomic absorption spectroscopy (AAS),* whereas Na^{+} and K^{+} were measured by atomic emission spectroscopy (AES),

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(Perkin Elmer 3030 spectrometer). Table 1 shows the concentrations of Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+} in the drilling powder samples that were taken in Rhodes. The concentrations are expressed both in weight percentage of the water-soluble fraction of the stone samples and in meq per 100g stone sample. The former to compare the importance of these anions in the samples taken at different locations in the wall, the latter to enable the comparison between the anionic concentrations and the cationic concentrations in the same stone samples. The average of two measurements was used.

2.2 Non destructive measurements

Infrared Thermography, was used as a measurement technique, in order to provide thermal maps. A thermographic system consists of an IR Detector (TVS - 2000 Mk II LW) and a Processor (AVIO Thermal Video System). The IR Detector uses germanium, is manufactured by mercury-cadmium-telluride (HgCdTe) which gives a spectral response between 8 and 12 μm and requires a stirling cooler system. The IR Detector is connected with a processor that detects the electronic signal, stores it in memory, processes it according to a given software and presents it in an LCD, by the form of a thermograph. The temperature range of the IR Detector spans from -40°C to +300°C.

2.3 Methodology

As far as salt decay is concerned, it suffices that the mapping technique renders the distribution of the characteristic decay patterns, i.e. the surface areas undergoing granular disintegration in the form of alveolar disease or hard carbonate crust formation. However, in large heterogeneous systems like masonries, it is the capillary movement and evaporation rate of water, that play the most important role within the processes of leaching out, transport, concentration, and precipitation of soluble salts in the porous building stones. The humidity rises up as far as a steady state is reached, between the water supply and the evaporation. The capillary rise phenomenon proceeds with migration of water or aqueous solutions according to well-defined equilibrium laws [4,5]. The phenomenon is more complex, due to the presence of salts and the deriving physicochemical effects, related with the solubility of salts, in conjunction with the susceptibility of the porous stones, as determined by their micro-structure [6]. From multi-component solutions, the different salt phases precipitate in sequence according to the different solubilities or ion activities. The system fractionates and the salts are being deposited from the moving solution at different places on the wall forming a spatial sequence. It has been proved that humidity and soluble salt distribution within the masonry are correlated among them and in relation to the decay patterns [7]. Hence, the humidity distribution becomes the key element for the environmental impact assessment [8,9].

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3 Results & Discussion

Infrared thermographs co-ordinated with the results of chemical analysis (soluble salts-ion concentrations) and the results of humidity contents permit the evaluation of the environmental impact assessment on the masonry. Hence it provides information in order to assess incompatible environmental management and to evaluate new uses of cultural goods.

Comparison of anionic concentrations along masonry surfaces, shows that Cl^- anions (Table 1) attains maximum values (>10% weight-% soluble fraction) at sampling points facing the sea, as well as at points 12, 17b (in the moat), where masonry surfaces are oriented towards the most frequent and strong north-western winds from the centre of the Aegean sea; especially at the upper parts of the masonry. Also, SO_4^{--} anions attain maximum values at the same points due to the main traffic lines embracing them.

Table 1: Concentrations of samples

	Weight - % soluble fraction							meq / 100g sample						
	Anions			Cations				Anions			Cations			
sample	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{++}	Mg^{++}
5,1,1	9.700	3,200	1,800					14,987	2,778	1,000				
5,1,2	12.800	4,000	0.700					15,418	2,787	0,318				
5,1,3	12,800	3,700	1.100					18,040	3,018	0,575				
5,2,1	13,200	1,400	6,500					21,211	1,319	3,844				
5,2,2	4,600	0,600	0,800					16,659	1,197	0,935				
5,2,3	14.200	3,300	2,400	0.1253	0.0427	0.7743	0.0285	17,375	2.295	1,080	5.4532	1,0938	36.8395	2,1839
5,3,1	12.400	2.400	6,000					12,757	1,433	2,278				
5,3,2	12,500	2.200	1.500					12,553	1,270	0,555				
5,3,3	13.100	1,800	2,000					15,094	1.187	0,862				
5,4,1	8.100	1,000	18,000					7,925	0,733	7,690				
5,4,2	6,000	7,800	3,200					5,852	4,218	1,118				
5,4,3	7.000	4,300	3,000	0,1039	0,0228	0.434	0.024	6.792	2,377	1,075	4,5225	0,5769	21,8584	19769
9b,1	1.500	10.700	2,000					1.102	4,673	0,570				
9b,2	0,600	3,800	0.700					0,323	1.205	0,136				
9b,3	1.300	4.500	3,000					0,985	1,891	0,821				
9b,4	0,400	0,400	0,600					0,336	0,204	0,161				
9"b,1	0.700	0,900	0,800					0,525	0,356	0.217				
9"b,2	1,400	1,400	1,400					1,533	0.909	0.550				
9"b,3	3,900	2,800	2,400					4,017	1.548	0,906				
9"b,4	0,900	0.700	0.500					0,542	0.284	0,119				
9b1,1	1,000	0,800	0,400	0.055	0.052	0.4684	0,0218	1,534	0,742	0,249	2.3931	1,3309	23.3733	1.7737
9b1,2	1,800	1,400	0,500	0.0277	0.0207	0.698	0,0272	2,213	0.948	0.104	1,2058	0,5317	34.8313	2,8398
9b1,3	3.000	1,900	2.100	0,012	0,011	0,5117	0.0208	2.299	0.881	0.808	0.5225	0.2826	25,5375	1.6998
9b2,1	1.000	0,900	0.700					0,602	0.302	0,160				
9b2,2	0,800	0,800	0,600	0.011	0.0129	0.3755	0.0086	0,298	0.174	0,002	0.4816	0.3324	18.7386	0.7129
9b2,3	0.200	0,200	0.200	0.0433	0.0184	0.8456	0.0249	0.318	0.144	0.098	1,0296	0.4727	42.198	2.0527
9b3,1	0.800	0.600	0.800	0.0228	0.0203	0.5221	0.0218	0.649	0.299	0.241	0.9949	0.5214	26.0543	1.799
9b3,2	0.700	1.000	0.800	0.0136	0,012	0.5149	0,0149	0.308	0.269	0.132	0.5889	0.3091	25.8961	1.2331
9b3,3				0.0171	0,0215	0,6473	0,0127				0,7468	0.5518	32.3041	1.0489
9b4,1	0.400	0.300	0.500	0,0247	0,0219	0.3503	0,0065	0,841	0,397	0.464	1.0781	0,5807	17,4817	0,7057
9b4,2	0.800	0,700	0.600	0.0123	0,0133	0,3326	0.0078	0,359	0.196	0.097	0.5359	0.3403	16.6006	0.6487
9b4,3	0,400	0.500	0.400					0,233	0.174	0.094				
9"b1,1				0,0334	0,031	0.5083	0,0267				1.4833	0.7934	25,3669	2.1204
9"b1,2				0.0283	0,0331	0.5043	0.018				1,022	0.8474	25.1689	1.3229
9"b1,3				0.0472	0,0316	0,5689	0.0172				2.057	0,8062	28.3914	1,4183
9"b2,1				0.0157	0,0157	0,3206	0,0185				0.6872	0.404	15,0095	1.529
9"b2,2														
9"b2,3														
9"b3,1				0.067	0,0354	0.5539	0.0179				2.6419	0.9071	27.6415	1,4769
9"b3,2				0.0498	0.0319	0.5947	0.0174				2.1864	0.8161	29.6795	1.432
9"b3,3				0.0148	0.0297	0.5482	0.0156				0.6359	0.7602	27.3575	1.2828
9"b4,1				0.0314	0,0214	0,3298	0,0099				1.3694	0.6495	16.4588	0.8222
9"b4,2				0.0382	0.03	0,4726	0,0179				1.6656	0.7685	23.5634	1.4754
9"b4,3				0,0253	0,0283	0,4853	0.0199				1.1042	0.8746	24.2173	1.6379

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12,1	10.400	10.300	7.500					28.185	15.980	7.526				
12,2	13.800	15.800	2.300					19.772	13.041	1.258				
12,3	14.000	11.400	11.400					17.393	8.398	5.420				
12,4	10.400	10.800	9.900					13.260	7.730	4.653				
12,1,1	14.800	4.100	2.800	0.1626	0.0822	0.4336	0.0261	18.470	2.920	1.185	7.0727	2.1023	21.6369	2.1561
12,1,2	18.400	5.900	4.500	0.182	0.0705	0.5024	0.0174	16.016	2.928	1.450	7.9182	1.7752	25.0712	0.14378
12,1,3	17.900	5.200	5.400	0.1754	0.0746	0.6505	0.0204	13.959	2.300	1.549	7.6311	1.9068	32.4643	1.6837
12,2,1	7.700	1.600	6.800					18.363	1.972	5.350				
12,2,2	18.400	3.200	3.400	0.2163	0.0706	0.358	0.0094	15.869	1.594	1.082	9.4089	1.6058	17.6658	0.7772
12,2,3	12.600	2.400	2.300					10.002	1.104	0.679				
12,3,1	10.900	3.800	8.900	0.1033	0.0499	0.4019	0.0177	9.706	1.984	2.947	4.4954	1.1502	20.0555	1.4563
12,3,2	6.300	2.000	17.500	0.0593	0.0539	0.3165	0.0187	4.000	0.863	4.857	2.8814	1.3766	15.7943	1.5461
12,3,3	6.300	2.000	17.500					4.890	0.863	4.857				
17*a1,1	0.300	13.100	0.300					0.256	6.600	0.085				
17*a1,2	0.400	31.400	0.000					0.315	15.872	0.000				
17*a1,3	0.300	0.700	0.000					0.156	0.202	0.000				
17*a2,1	0.300	0.200	0.400					0.441	0.162	0.199				
17*a2,2	0.300	1.000	0.000					0.178	0.324	0.000				
17*a2,3	0.200	0.700	0.000					0.152	0.333	0.000				
17*a3,1	0.100	0.300	0.000					0.169	0.238	0.000				
17*a3,2	0.300	32.900	0.200					0.334	19.213	0.060				
17*a3,3	0.200	29.900	0.000					0.260	18.498	0.000				
17*a4,1	3.400	26.000	1.700					3.833	17.029	0.729				
17*a4,2	8.700	2.500	1.300					5.299	0.863	0.292				
17*a4,3	4.300	18.100	0.800					4.559	11.022	0.313				
17b1,1	10.000	18.500	0.000	0.1418	0.0925	0.4106	0.0134	11.340	12.041	0.236	8.1706	2.3677	20.4916	0.1055
17b1,2	8.300	17.000	0.300					17.488	20.350	0.217				
17b1,3	19.200	22.600	0.600	0.3562	0.141	0.475	0.0183	19.621	13.226	0.219	15.4964	3.8064	23.7032	1.506
17b2,1	7.800	4.700	8.400	0.1462	0.1004	0.7762	0.016	7.982	2.840	3.237	8.3623	2.5686	38.6842	1.3726
17b2,2	7.200	3.800	1.200	0.0947	0.622	0.3573	0.0082	4.806	1.486	0.314	4.1234	1.8913	17.8301	0.6796
17b2,3	3.500	4.500	0.000	0.0598	0.0509	0.4485	0.0122	2.266	1.674	0.000	2.6013	1.3037	22.5309	1.0061
17b3,1	0.400	0.900	0.000	0.0175	0.0189	0.789	0.0121	0.417	0.502	0.000	0.7627	0.4658	39.3767	1.0017
17b3,2	0.300	3.900	0.000	0.0078	0.011	0.4824	0.0076	0.340	2.687	0.000	0.3341	0.2823	24.0757	0.6316
17b3,3	0.300	5.000	0.000	0.0159	0.0154	0.3953	0.0119	0.212	2.437	0.000	0.6921	0.3942	19.7268	0.9817
17a,1,1				0.0066	0.0076	0.322	0.0076				0.2905	0.1952	16.0699	0.6279
17a,1,2				0.0468	0.0121	0.4536	0.0117				2.0369	0.3118	22.6376	0.963
17a,1,3				0.0205	0.0161	0.3625	0.0142				0.8959	0.4139	19.0688	1.17
17a,2,1				0.0131	0.0182	0.3509	0.0131				0.5699	0.4667	17.5129	1.0776
17a,2,2				0.0084	0.0089	0.3861	0.0103				0.366	0.2278	19.2683	0.6552
17a,2,3				0.1341	0.0146	0.351	0.0102				0.6996	0.374	17.5173	0.6422
17a,3,1				0.0068	0.0167	0.4583	0.033				0.3001	0.4769	22.6719	2.7164
17a,3,2				0.0124	0.224	0.3821	0.0339				0.5431	0.5748	19.0677	2.7841
17a,3,3				0.0098	0.0167	0.4983	0.0291				0.43	0.4282	24.4197	2.3991
17a,4,1				0.08	0.0258	0.5926	0.0229				3.4798	0.861	29.5749	1.886
17a,4,2				0.0829	0.0218	0.4294	0.0164				3.6089	0.5583	21.4273	1.357
17a,4,3				0.085	0.026	0.615	0.0185				3.6972	0.6649	30.6866	1.5218

By the means of GIS, thermal images permit a better strategic planning intervention. The user can select to view the base-maps, along with the test points-locations, information on available data for each test point or finally the full data for a specific test point. Figure 1, visualizes the results of the infrared thermographic investigation, presenting five of the nineteen sampling points examined.

For the walls facing the sea, the nearby-located port activities pollute the atmosphere in the area, whereas for the walls in the moat (point 12 and 17b), city centre pollutants are transferred by the north-western winds. The evidence of gypsum crystals in the relevant points is to be underlined. Concerning humidity contents (in the dry period) a general trend presents an average level between 1-2% in the sea-facing surfaces, suffering from alveolar disease under rapid evaporation while an average between 2-6 % is presented in the case on the surface in the moat suffering more or less by crust formation under mild evaporation conditions. However in positions such as the theatre of the moat (9b, 9*b), where recent interventions lead to landfilling of the lower parts of the walls along with plantation and watering, humidity contents present over-doubled levels (3-12% for the old stones).

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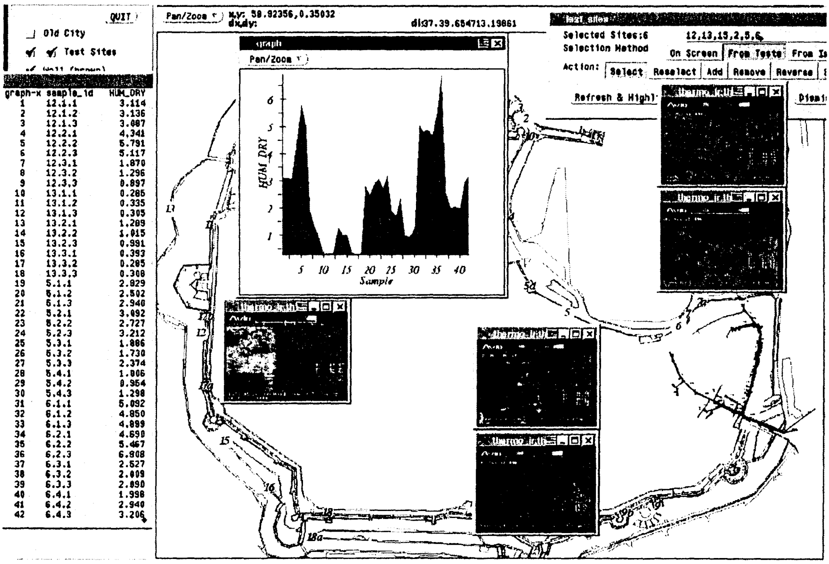

Figure 1: Infra Red Thermographs managed by GIS for the medieval fortifications of Rhodes.

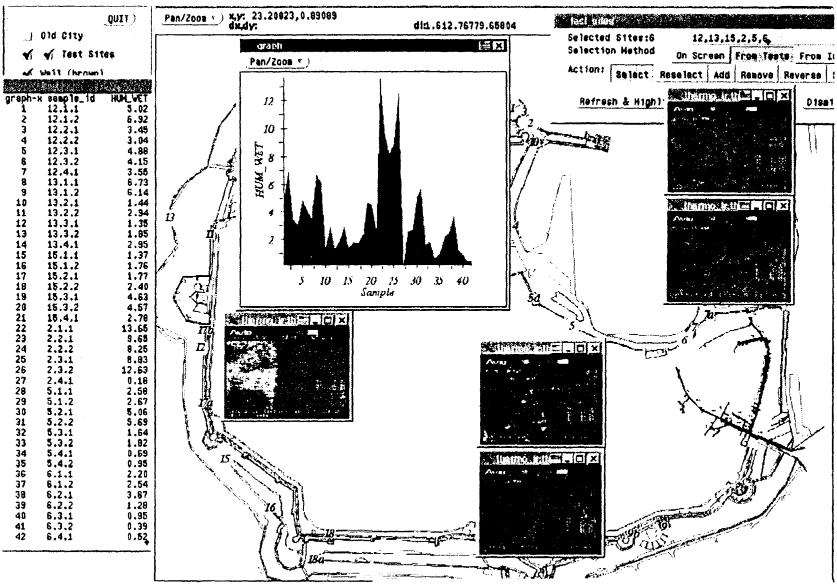

Figure 2: Infra Red Thermographs managed by GIS for the medieval fortifications of Rhodes for the Environmental Impact Assessment and related management regarding the planning of underground networks.

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Devaluating cultural heritage derives from the inevitable marine atmosphere, but as well from town planning related uses and incompatible environmental management. Environmental loads can be visualised in their spatial distribution in the raster map (Figure 3), classified as follows:

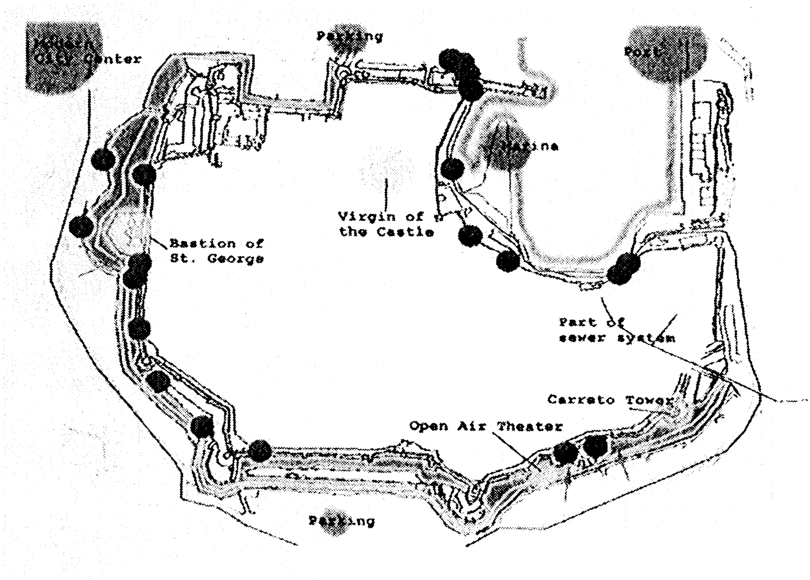

Figure 3: Raster Map showing environmental loads & uses. Brown colour shows the moat. Yellow colour shows cultural uses, Red colour shows pollution sources, Green colour (arrows) show plantings, Dark grey line shows part of the sewer system.

Environmental loads:
Salt spray sources (blue) - sea borders, wind directions and frequency.
Pollution sources (red) - main traffic lines, commercial port, city centre marina and parking.
Humidity sources - Negative management i.e. land filling, plantation and watering (green arrows), Positive management (like by drainage and cleaning of plantation etc. (brown) and by introduction of new uses, as cultural uses etc. (yellow)), Infrastructure system (like sewage system etc. (dark grey lines)). Their design has to manage humidity positively.

Environmental Management interventions
In order to tackle environmental loads, the following management interventions are suggested, concerning:

Active management (directly to environmental sources)

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Pollution sources:

* allocation of the pollutants sources through comparative examination of the accumulations on the monumental surfaces employing isotope analysis
* monitoring of the pollutants and aggregation emitted from every possible source
* elimination of the pollutants by proper urban planning, measures and regulations concerning the responsible sources (port, traffic, parking, central heating, tourism activities etc.).

Humidity sources:

* Estimation of critical humidity contents and localisation of sources
* Evaluation of environmental works (infrastructures, landfillings, planting, watering, etc.) as negative or positive management of humidity sources.
* Elimination of humidity sources under critical humidity contents (drainage, cleaning of plants, maintenance, etc.)

Preservation of the integral cultural and natural Environment

* Active : Environmental management
* Introduction of new uses (rehabilitation) supporting, sustaining and maintaining environmental management. Suggested uses are recreational and cultural uses, controlled tourism activities, etc. Elimination improper uses like the ones assessed as having negative impact to the monumental structure and surface.
* Proper urban planning and plan of land uses.

Passive Management (indirectly - Preservation of materials and structures)

* Diagnosis weathering (decay) mapping and environmental impact assessment
* Conservation planning and implementation

Monitoring, control and maintenance interventions regarding materials, structures and ongoing environmental management.

4 Conclusions

Integrated environmental management should be attempted according to environmental, functional, material, structural and social criteria with the objective of rejecting the negative impact on the monuments and the historical complexes as a whole. This could prevent supplementary damage and maintain the necessary conservation level, while the historic site, city or complex would be revitalised through new uses and its role would be strengthened.
The development of the database, managed by a GIS is used to create alternative recommendations truly relevant to conservation and planning strategies. The results give feedback for decision support regarding historical preservation planning policies. This expert system could be used as a pilot one for "Historic Complexes', Cities' or Sites' Environmental Management towards

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Conservation". Possible comparisons among historical complexes might assess and upgrade the validity of the pilot plan.

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