CONVENTION ON LONG-RANGE TRANSBOUNDARY AIR POLLUTION
UN/ECE INTERNATIONAL CO-OPERATIVE PROGRAMME ON EFFECTS ON MATERIALS, INCLUDING HISTORIC AND CULTURAL MONUMENTS

Report No 60:
Combined stock at risk and mapping for selected urban areas of Italy

July 2009

PREPARED BY THE SUB-CENTRE FOR STOCK OF MATERIALS AT RISK AND CULTURAL HERITAGE

Italian National Agency for New Technologies, Energy and the Environment (ENEA), Rome, Italy
Combined stock at risk and mapping for selected urban areas of Italy

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Summary

The International Co-operative Programme on Effects on Materials, including Historic and Cultural Monuments (ICP Materials) started in 1985. It was initiated in order to provide a scientific basis for new protocols and regulations developed within the Convention on Long-range Transboundary Air Pollution. The main aim is to perform a quantitative evaluation of the effects of multi-pollutants such as S and N compounds, O\(_3\) and particles as well as climate parameters on the atmospheric corrosion of important materials, including materials used in objects of cultural heritage. The primary objective is to collect information on corrosion and environmental data in order to evaluate dose/response functions and trend effects and use the results for mapping areas with increased risk of corrosion, and for calculation of cost of damage caused by deterioration of materials.

This report details a study carried out at city level and focused on two important Italian cities; Rome and Milan. Different distribution maps for the present and possible future scenarios(2020) are shown, such as the inventories of stock of cultural heritage at risk for each selected material (limestone and copper), concentrations of selected pollutants (SO\(_2\)), corrosivity and exceedance of tolerable degradation levels for each material, corrosion-cultural heritage overlapped maps, etc., which could be useful for management strategies for sustainable maintenance and preventive conservation of local Cultural Heritage. A comparison was made of the corrosion effect in both cities. In Milan the dominant pollutant is SO\(_2\) and in Rome ozone. A valuation was carried out of the corrosion effect due to the air pollution measured either on the EMEP scale or on the local urban scale.

The Italian Istituto Superiore per il Restauro e Conservazione valuation scheduled 1194 important monuments in Milan and 3800 in Rome (archeological areas, palaces, churches, monasteries, castles etc.). The eternal city is the richest of Cultural Monuments cities in the world.

According to the maps developed, the risk for the Cultural Heritage in Milan and Rome, from the corrosion point of view due to pollution, is different because of the differences of the pollution type and level. In Rome, due to the low relative humidity, the predicted limestone recession is always lower than the previously established tolerable level. In any case, the methodology proposed is useful and can be if applied to towns, regions or countries in order to quantify the percentage of Cultural Heritage at risk.
1. Introduction

Air pollutants, which together with climatic parameters, are of major importance for the deterioration of many materials used in cultural monuments, are emitted by industrial activities and by the transport sector. These pollutants create a problem on the local scale but they are also transported in the air over long distances. Different international organizations and institutions study these effects. One of them is the UN ECE Convention of Long Range Transboundary Air Pollution (CLRTAP) under which operate the International Cooperative Programme on effects of air pollution on Materials including Cultural Monuments (ICP Materials). This is one of several effect-oriented International Co-operative Programmes (ICPs) dedicated at studying the harmful effect of air pollution on materials.

To reduce the harmful effects of pollutants on human health and the environment, the European Directive 1999/30/EC has been issued relating to limit values for sulphur dioxide, oxides of nitrogen, particulate matter and lead in the ambient air. These limit values have been established with reference to health and ecosystem effects but not to effects on building materials and cultural monuments. The European cultural heritage is very large and cost billions of euro to maintain. It is important to understand the fact that such materials from which the cultural monuments are created are sensitive to pollution at even lower levels than biological systems.

The costs for deterioration and soiling of different materials due to air pollution are huge and the damage to culture targets endangers seriously the cultural heritage. Effective policy making requires environmental impact assessment, cost benefit analysis and risk management. All these techniques need a serious scientific basis to support the assessment and the calculation of the effects of pollution.

The policy makers and local heritage owners or managers as end users need reliable, up-to-date data on air quality and its effects on heritage. The information that they require, though arising from the same sources (pollution monitoring, damage estimation and impact modeling), need interpretation at different scales. The work presented here is focused on the establishment of a scientific reference in order to help to the decision makers and heritage managers for strategic decisions at a local or city level. It has been done through a choice of material indicators and corrosion/recession threshold levels based on best available scientific data including deterioration models, spatial distribution and mapping of pollutants and of stock of materials at risk, cost estimates and comparison studies of different conservation approaches.

This report presents the study on assessment of stock at risk and mapping areas of increased corrosion risk in the downtowns of Milan and Rome, Italy. It covers a detailed inventory of cultural heritage and different distribution maps for the present and possible future scenarios (2020): inventories of stock of cultural heritage at risk for each selected material (limestone and copper), concentrations of selected pollutants (SO₂, NO₂, O₃ and PM₁₀), corrosion and exceedance of tolerable degradation levels for each material, and corrosion-cultural heritage overlapped maps. These could be useful for management strategies for sustainable maintenance and preventive conservation of local cultural heritage.

The models, that were validated and further developed, take into account the present multi-pollutant situation, where apart of SO₂ also NOx, ozone and particulate matter are considered.
The dose-response functions, which describe the deterioration of the individual materials, are used for assessment of threshold levels of corrosion/recession.

An evaluation and comparison were done of the corrosion effect of cultural monuments exposed in Milan and Rome. The differences of the degradation effects on materials in the two cities are important.

A valuation of corrosion effect due to the air pollution measured on EMEP and local urban level scale was carried out. As expected the urban air pollution produce heavier corrosion effect on monuments exposed in large cities like Rome and Milan than in the rural areas (EMEP scale).

2. Inventory of Cultural Heritage

We developed the inventory of cultural heritage (CH), including all monuments, palaces, churches, archeological areas, buildings and sculptures included in the official last census of the Istituto Superiore per la Conservazione e Restauro of Rome (ICR). All monuments in the list are exposed in open air.

Microsoft Excel was used, recording as main information the following fields:

1. Inventory Number.
2. Denomination (name of the object).
3. Category (church, museum, sculpture, memorial stone, monolith, etc.).
4. Address.
5. X and Y UTM coordinates.
6. Materials used in the construction of the building in order of presence.
7. Construction period.

In most cases, the materials were very roughly described. In the case of objects without any description of materials, in-situ inspection is also very useful.

Most of the cultural monuments in Rome and Milan - very representative cities for the Italian CH - are created using stone and copper or bronze. In this study as indicative material we selected limestone and copper.

A) For Milan the ICR list includes 1194 sites. In our study we selected 134 sites which are important palaces, archeological areas, churches, convents and statues. They are all situated in the central part of the city within a 6 km diameter. The old ordinary buildings situated in this area were not taken in consideration, not because they are not considered as CH but from a practical point of view in order to better represent special CH on the maps.

B) For Rome the ICR list includes 3799 sites, this is the city with the riches CH in the world. In our study we selected 969 sites which are important palaces, archeological areas, churches, convents and statues. All they are situated in the central part of the city within a 6 km diameter. Similar to Milan the old ordinary buildings situated in this area were not taken in consideration.
3. Pollution Database

The environmental data used are as follows:

A) For Milan air pollution data for the year 2000 were used. (Figure 1). In the central part of the city 5 stations were situated measuring daily and monthly average environmental data of air pollutants (SO$_2$, O$_3$, NO$_2$, NOx, PM$_{10}$), temperature, rain precipitation, relative humidity, etc.

B) For Rome air pollution data for the year 2005 were used. (Figure 2). In the central part of the city 11 stations were situated measuring daily and monthly average environmental data of air pollutants (SO$_2$, O$_3$, NO$_2$, NOx, PM$_{10}$), temperature, rain precipitation, relative humidity, etc.

4. Dose-Response Functions

The most recent dose response functions for corrosion in the new pollution situation in Europe have been developed in a joint effort between the EU project MULTI-ASSESS and the ICP Materials multi-pollutant exposure program, (see Table 1). The corrosion of metals is expressed as mass loss (ML, g m$^{-2}$) and the degradation of limestone is expressed as surface recession (R, μm). These functions include a range of pollution and climate parameters. The pollution parameters are the gases SO$_2$, HNO$_3$, O$_3$ and particulates as PM$_{10}$, expressed in μg m$^{-3}$. The climatic parameters are temperature (T, °C), quantity wet precipitation (Rain, mm), relative humidity (RH, %) and acidity in wet precipitation (H$^+$, mg L$^{-1}$). For some materials (carbon steel, copper, cast bronze and limestone) the effect of relative humidity is introduced through the parameter RH60, which is equal to (RH-60) when RH>60, otherwise 0.

In this study, the dose response functions for limestone and Cu were considered and the spatial corrosion distribution maps of both materials in the Milan for 2000 and Rome for 2005 were obtained.

5. Stock at Risk

We need of a uniform approach for policy makers to may indicate them a target levels of corrosion.

When the UN/ECE Mapping Manual is applied to tolerable levels, the tolerable corrosion rate, first year exposure (K$_{tol}$) can be calculated as:

$$K_{tol} = n \times K_b$$

(1)

here n is a factor and K$_b$ is the background corrosion rate, first year exposure for Europe. In the MULTI-ASSESS project was established that, with n=2.5 and taking into account the background corrosion rates during the first year of exposure, taken from the UN/ECE Mapping Manual, the estimated tolerable corrosion rates calculated from Equation 1 are almost identical to the tolerable levels established from maintenance intervals (corrosion depth before action/tolerable
In Table 2 the tolerable corrosion rate for the first year of exposure for the common materials are indicated for \( n=2.5 \). The tolerable corrosion rates given in Table 2 are those used for further assessment of target levels and is thus considered a conservative lower estimate of the tolerable level.

We may calculate the corresponding acceptable pollution concentrations from the tolerable corrosion rate using the dose-response functions. From the tolerable corrosion rates indicated in Table 2 and the real measured or estimated corrosion rates we may establish if a specific site may be classified as tolerable or exceeding (risk) site.

6. Mapping

GIS (Geographic Information System) applications are tools that allow users to create interactive queries (user created searches), analyze the spatial information, edit data, maps, and present the results of all these operations. A GIS is any system for capturing, storing, analyzing, managing and presenting data and associated attributes that are spatially referenced to Earth. In the strictest sense, it is any information system capable of integrating, storing, editing, analyzing, sharing, and displaying geographically referenced information.

In this study GIS maps at different scenarios were developed: pollutants (SO\(_2\), O\(_3\), NO\(_2\), NOx, Particulate Matter, etc.), Cultural Heritage (limestone and Cu), corrosion (limestone and Cu) and overlapped corrosion-Cultural Heritage.

Here we used, the ArcGis 8.1 software with the Spatial Analyst Extension for the preparation of the maps. The Kriging Interpolation method for representing data (environmental, corrosion, loss mass, etc.) in the map was employed, with varying grid cell size up to 200 by 200 meters.

A) Milan

6.A.1 Cultural Heritage maps

The spatial distribution maps of selected Immoveble Cultural Heritage of Milan are represented on Figure 3. The concentration of important CH is higher in the central part of the city. On the figure the most important Cultural Monuments are separated in 3 different categories: castles and palaces, archeological areas and churches and convents, indicated in different way.

One of the quality of the use of GIS tools is the possibility of presenting data and associated attributes in a dynamic mode, i.e. it is possible to zoom a specific area, present only data that match certain criteria in the database, etc.

6.A.2 Pollutants maps

In this study we used the air pollution data for Milan for 2000. The developed maps with the database of pollution (the local network of environmental stations shown in Figure 1), the distribution map of SO\(_2\) in year 2000 is shown in Figures 5. From the figure is evident that in the north-east part of the city the concentration of SO\(_2\) is higher than in the rest of the city centre. The concentration of SO\(_2\) was chosen because it is the most active pollutant producing degradation of both limestone and Cu.
6.A.3 Recession maps

Using the Multi-Assess dose-response functions to each cell of the varying grid up to (200 x 200 m), once the environmental parameters needed were obtained from the network of test sites (Figure 1), and with the help of the Kriging Interpolation method, the recession maps for Cu and limestone for 2000 were elaborated.

6.A.4 Overlapped Recession/Cultural Heritage maps

Overlapping the recession maps for limestone end Cu with the Cultural Heritage database, where information concerning the location and materials used for each object is included, permit us to elaborate the recession rate maps. Here we reported the annual recession of Portland limestone cultural heritage and of Cu cultural heritage made of this materials Figures 8 and Figure 9 respectively.

6.A.5 Stock at risk

In the case of limestone (Figure 8), where recession levels in the city are in the range 7.2-9.2 µm/year, in a very large part of the studied area it is higher than the tolerable level (8.0 µm). In this case the interested area cover more than 30% of whole studied surface. Again it is situated in the north-east part of the city where different important monuments are situated.

In the case of cooper in Milan, (Figure 9), the predicted recession rate in 2000 from the dose-response function are in the range 0.64 – 0.82 µm , in large part of the studied area it is higher then the tolerable level (0.79µm) The area interested is situated in the north-east part of the city where different important monuments are situated.

These results show that the risk for the Cultural Heritage in Milan, from the corrosion point of view due to pollution, in important part of the studied area is high and it is case that the policy makers and owners of the CH start to search adequate solutions.

The comparison of the predicted corrosion levels from the dose-response function in 2000 (0.64 – 0.82 µm and 7.2-9.2 µm for copper and Portland limestone respectively) and the actual measured values in the ICP-Materials test site Nº 15 (Milan) in 2000 (0.81µm and 8.8 µm for copper and Portland limestone respectively) confirms the validity of the function for this region.

6.A.6 Exceeding maps

In Milan a exceeding maps due to the air pollution for 2000 for limestone and Cu was elaborated (Figure 10). This maps was elaborated representing the areas in which the recession levels exceeds the maximum tolerable ($K_{tol} = 2.5 \times K_b$), i.e. 8.0 µm in the case of limestone and 0.79µm for Cu. From it is evident that for both materials the north-east part of the studied area of Milan is at risk of recession which rate is higher then the tolerable rate. This phenomenon is much more large and acute for limestone which is very widespread material used in this area in the construction of the CH. In around 30% of the studied area the recession of limestone exceed the maximum tolerable ($K_{tol}=2.5 \times K_b$), i.e. 8.00 µm/year.
6.A.7 Future scenarios

In this case we elaborate a two different future scenarios consisted in the estimation of the levels of recession of Portland limestone and Cu in 2020:

1. An optimistic trend during the period 2000-2020 (with a reduction of less then 10% of the mass lost and recession during this period)

2. A pessimistic trend during the period 2000-2020 (following a 10% higher reduction of mass loss and recession during this period).

In Figures 11 and 12 the maps for Portland limestone and cooper respectively are shown. As can be observed the annul recession could be for both materials and scenarios with north-east part of the studied area in which in 2020 it will superate the maximum tolerable level significantly (9.3 µm and 0.85µm).

B) Rome

6.B.1 Cultural Heritage maps

The spatial distribution maps of selected Immovable Cultural Heritage of Rome are represented on Figure 4. The concentration of important CH is higher in the central part of the city. On the figure the most important Cultural Monuments are separated in 3 different categories: castles, archeological areas and churches and convents, indicated in different way.

6.B.2 Pollutants maps

In this study we used the air pollution data for Rome for 2005. The developed maps with the database of pollution (the local network of environmental stations shown in Figure 2) the distribution map of SO$_2$ in year 2005 is shown in Figure 6. The concentration of SO$_2$ was chosen because it is the most active pollutants producing degradation of both limestone and Cu.

From the figure is evident that in the south west part of the city the concentration of SO$_2$ is higher than in the rest of the city centre. This is most populated and with higher traffic area of Rome. Close to it is situated the second airport of the city – Ciampino.

One of difficulties which we find in this elaboration was that in Rome not all quality air pollution stations measures all parameters which we need to may calculate the corrosion/recession applying the dose/response functions. So we utilise the data from all available monitoring stations in Rome, including those which are outside the studied area, applying the spatialisation techniques for each pollutant and meteo-climatic parameter. (Figure 7). The calculated recession rate is a result of elaboration of dose/response function using the calculated previously grid values instead of only individual point values. In Rome we used the most environmental data from 8 monitoring stations.
6.B.3 Recession maps

Using the Multi-Assess dose-response functions to each cell of the varying grid up to (200 x 200 m), once the environmental parameters needed were obtained from the network of test sites (Figure 2), and with the help of the Kriging Interpolation method, the surface recession for Cu and for limestone for 2005 was elaborated.

6.B.4 Overlapped Recession/Cultural Heritage maps

Overlapping the recession maps for limestone and Cu with the Cultural Heritage database, where information concerning the location and materials used for each object is included, permit us to elaborate the recession rate maps. Here we reported the annual recession of Portland limestone and of Cu cultural heritage made of this materials for 2005 Figures 13 and Figure 14 respectively.

6.B.5 Stock at risk

In the case of limestone (Figure 13), where recession rate in the city are in the range 6.4-7.4 µm/year, which is lower than the tolerable level (8.0 µm). Even if the maximum value of the recession is visible in the south east part of the city, the values are lower of the tolerable level.

In the case of cooper, (Figure 14), the predicted recession levels in 2005 from the dose-response function are in the range 0.43 – 0.49,µm in the studied area it is lower then the tolerable level (0.79 ,µm).

These results show that the risk for the Cultural Heritage in Rome, from the corrosion point of view due to air pollution, indicate that all Cultural Heritage objects are located in areas where recession rates are lower than the maximum tolerable.

One explanation of these low corrosion levels in Rome, as well as the absence of significant differences among areas inside the city, could be due to consider zero the function RH60 in the dose-response function for limestone (see function 3) when relative humidity (RH) is lower than 60%. When RH<60% (as in this case) RH60= 0, and the influence of SO2 is not considered in the dose-response function:

Copper \[ ML = 0.0027[SO_2]^{0.32}[O_3]^{0.79}Rh\cdot\exp{f(T)}t^{0.78} + 0.050Rain[H^+]t^{0.89} \tag{2} \]

Where \( f(T) = 0.083(T-10) \) when \( T\leq10°C \), otherwise \(-0.032(T-10)\)

Limestone I = 4.0 + 0.0059[SO_2]RH_{60} + 0.054Rain[H^+] + 0.078[HNO_3]RH_{60} + 0.0258PM_{10} \tag{3} 

The comparison of the predicted recession levels from the dose-response function in 2005 (0.43 – 0.49,µm and 6.4-7.4 µm for copper and Portland limestone respectively) and the actual measured values in the ICP-Materials test site N° 13 (Rome) in 2005 (0.50 µm and 8.1 µm for copper and Portland limestone respectively) confirms the validity of the function for this area.
6.B.6 Exceeding maps

In Rome exceeding maps due to the air pollution for 2005 for limestone and Cu was elaborated (Figure 15). From it is evident that for both materials the predicted levels are lower then the maximum tolerable \((K_{tol}=2.5 \times K_b)\), i.e. 8.0 \(\mu\)m in the case of limestone and 0.79 \(\mu\)m in the case of copper. In 2005 the predicted recession of limestone from the dose-response function is in the range 2-2.5 times the background level and of Cu it is in the range 1.5 times the background level.

6.B.7 Future scenarios

In this case we elaborate a two different future scenarios consisted in the estimation of the levels of recession Portland limestone and Cu in 2020:

3. An optimistic trend during the period 2005-2020 (with a reduction of less than 10% of the mass lost and recession during this period)

4. A pessimistic trend during the period 2005-2020 (following a 10% higher reduction of mass loss and recession during this period).

In Figures 16 and 17 the maps for Portland limestone and copper respectively are shown. As can be observed the annual recession could only for limestone in the pessimistic scenario in the south east part of the studied area in 2020 will arrive close to the maximum tolerable level (8.0 \(\mu\)m).

7. Rome and Milan – differences

In Rome and Milan we have different air pollution situation, with higher concentration of \(\text{SO}_2\) and RH in Milan. This determine a higher recession of limestone and corrosion of copper in Milan than in Rome. As we may see from Figure 18 the areas with higher recession of limestone are with a definite location and are different for the two cities. For Milan it is situated in the north-east part of the city, while in Rome it is concentrated in the south-west from the city centre. This area of Rome is with very high population density, with heavy traffic and close to it is situated a part of the industrial zone and the second airport (Ciampino) of the capital. The result is different when we see the corrosion for copper Figure 19. While for Milan the area with higher corrosion value is the same as for limestone – north-east, for Rome the situation is different, here we have not a definite area with high corrosion, but the corrosion gradually became higher in the west part of the studied area.

8. Corrosion in EMEP and urban pollution situation

It is known that the air pollution in the urban areas generally is higher than in remote areas. The main reason for this is that in the towns the concentration of the population is high and the antropic activity determinate the air pollution there. First of this activities is the traffic and the heating systems. In the Convention of Long Range Transboundary Air Pollution the most of valuations of the effects of air pollution on the different ecosystems and materials are based on the EMEP model, which calculate the different air pollution concentrations over Europe on the basis of a grid system 50 x 50 km. The model did not
consider the urban pollution, because it is considered local pollution, not transboundary. As expected the urban air pollution is higher and as underlined before is heavily influenced from local sources (traffic, heating systems, manufacture and other activities).

In this study we confront the recession and corrosion rate for limestone and copper calculated on the basis of pollution data measuring in the urban monitoring stations in Milan and the data calculated from EMEP model in the respective cell of the city.

For copper (Figure 20), the recession rate in Milan is 0.65 – 1.1µm/year, from urban stations data and 0.54 µm/year from EMEP grid. In this case the calculated corrosion rate with the urban data is around 30 % higher then in the EMEP grid.

For limestone (Figure 21), the recession in Milan is 7.2 – 9.2 µm, from urban stations data and 5.2 µm from EMEP grid. In this case the calculated recession rate with the urban data is around 40 % higher then in the EMEP grid.

9. Conclusions

- An inventory of Cultural Heritage exposed to the atmosphere in Milan and Rome has been carried out, including descriptions of materials. The inventory contents 1194 for Milan and 3799 for Rome immovable Cultural Heritage objects. A selection of the main CH objects in a limited (6 km. diameter) very central area of the two cities was done. A division in 3 different categories of CH was applied: castle and public palaces, archaeological areas and churches and convents.

- Different distribution maps have been developed: inventory of stock of cultural heritage at risk for each selected material (cooper and limestone), selected pollutants (SO2, NO2, O3 and PM10), corrosivity for each material (by the application of dose-response functions), corrosion-Cultural Heritage overlapped maps, exceeding maps etc. To save space in this report only a part of the maps was published.

- Future scenarios of the recession/corrosion for both materials in optimistic and pessimistic air pollution situation for Milan and Rome was elaborated.

- A valuation of the different recession rate effects due to the different air pollution situation between Rome and Milan was elaborated.

- A confront between the corrosion/recession effects of the both materials due to the different air pollution data bases used (EMEP and urban monitoring stations) indicate that in most of the cases the degradation effect produced from the air pollution is higher and more correct monitoring directly in the city.

- The risk for the CH made from limestone and cooper in Rome, from the corrosion point of view due to air pollution, is lower than in Milan, being the prediction of cooper and limestone recession always lower than the previously established tolerable levels for those materials due, maybe to the low relative humidity (<60%) in Rome.
10. Acknowledgements

The authors of this paper would like to thank:

1. The Istituto Centrale per la Conservazione e Restauro of Rome, specially Dr. G. Accardo and Dr. R. Rinaldi from the laboratory of Physics for the data and the help offered during the inventory of Cultural Heritage.

2. The Regional Agency of Air Pollution of Milan and specially Dr. G. Tebaldi (†) and his colleagues from U.O.ARIA – Rete e Modellistica, for urban environmental data.

3. The Istituto Superiore di Sanità, specially Dr. G. Viviano and Dr. M. Ferdinandi from the Unit Igiene dell’aria, for urban environmental data.

11. References


TABLE 1. List of dose-response functions for the multi-pollutant situation, including temperature function, for unsheltered materials exposed for one year. Units and abbreviations are described in the text.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dose-response function</th>
<th>Temperature function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>$ML = 51 + 1.39[SO_2]^{0.6}Rh_{60}e^{0.15(T-10)} + 1.29Rain[H^+] + 0.593PM_{10}$</td>
<td>$f(T) = 0.15(T-10)$ when $T&lt;10^\circ C$, $-0.054(T-10)$ otherwise</td>
</tr>
<tr>
<td>Zinc</td>
<td>$ML = 3.5 + 0.471[SO_2]^{0.22}e^{0.018Rh_{60}} + 0.041Rain[H^+] + 1.37[HNO_3]$</td>
<td>$f(T) = 0.062(T-10)$ when $T&lt;10^\circ C$, $-0.021(T-10)$ otherwise</td>
</tr>
<tr>
<td>Copper</td>
<td>$ML = 0.0027[SO_2]^{0.32}[O_3]^{0.79}Rh\cdot\exp{f(T)}t^{0.78} + 0.050Rain[H^+]t^{0.89}$</td>
<td>$f(T) = 0.083(T-10)$ when $T\leq10^\circ C$, otherwise $-0.032(T-10)$</td>
</tr>
<tr>
<td>Cast Bronze</td>
<td>$ML = 1.33 + 0.00876[SO_2]Rh_{60}e^{0.060(T-11)} + 0.0409Rain[H^+] + 0.0380PM_{10}$</td>
<td></td>
</tr>
<tr>
<td>Portland limestone</td>
<td>$R = 4.0 + 0.0059[SO_2]Rh_{60} + 0.054Rain[H^+] + 0.078[HNO_3]Rh_{60} + 0.0258PM_{10}$</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 2. Tolerable corrosion rate based on background corrosion rates and $n=2.5$

<table>
<thead>
<tr>
<th>Material</th>
<th>Background corrosion</th>
<th>Background corrosion depth</th>
<th>Factor for acceptable corrosion</th>
<th>Tolerable corrosion rate per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2.8 µm</td>
<td>2.5</td>
<td>7.0 µm year⁻¹</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>3.1 g/m²</td>
<td>0.46 µm</td>
<td>2.5</td>
<td>7.8 g/m² 1.1 µm year⁻¹</td>
</tr>
<tr>
<td>Copper</td>
<td>2.8 g/m²</td>
<td>0.34 µm</td>
<td>2.5</td>
<td>7.1 g/m² 0.8 µm year⁻¹</td>
</tr>
<tr>
<td>Bronze</td>
<td>2.1 g/m²</td>
<td>0.25 µm</td>
<td>2.5</td>
<td>5.25 g/m² 0.6 µm year⁻¹</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.2 µm</td>
<td>2.5</td>
<td>8.0 µm year⁻¹</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1 - Network of urban environmental monitoring stations in Milan.
**Fig. 2** - Network of urban environmental monitoring stations in Rome.
**Fig. 3** - Map of spatial distribution/location of the most important Immovable Cultural Heritage objects in the centre of Milan.
Fig. 4 - Map of spatial distribution/location of the most important Immovable Cultural Heritage sites in the centre of Rome.
**Fig. 5** - The concentration of SO$_2$ (µg S/m$^3$) in Milan city centre with the most important Cultural Heritage objects in 2000.
Fig. 6 - The concentration of SO$_2$ (µg S/m$^3$) in Rome city centre with the most important Cultural Heritage sites in 2005.
In Rome city centre, not all the Air quality Station measure the parameters needed to calculate corrosions.

So we chose to determinate by spatialisation techniques each pollutant and each meteo climatic parameter using all the Air Quality Station of the Municipality.

Final corrosion rate was the result of the application of the dose/response function using all the grid previously obtained instead of individual point values.

Fig. 7 - The enlarged number of environmental monitoring stations used for calculate the corrosion/recession effect on limestone and copper in Rome.
Map of Milan city centre

with location of the most important CH sites and
Recession rate for Limestone
in the year 2000.
Unit is: μm/year

\[ R = 4.0 + 0.0059[SO_2] + 0.054\text{Rain}[H^+] + 0.078[HNO_3] + 0.0256\text{PM}_{10} \]

**Fig. 8** - Limestone recession map of most important CH objects for 2000 in Milan city centre.
Fig. 9 - Copper recession map of most important CH objects for 2000 in Milan city centre.
Fig. 10 - Milan exceeding map for limestone (left) and copper (right) recession with the CH sites for 2000.
**Fig. 11** - Milan exceeding map for limestone recession: optimistic scenario - 10% (left) and pessimistic scenario + 10% (right).
Fig. 12 - Milan exceeding map for copper recession: optimistic scenario - 10% (left) and pessimistic scenario + 10% (right).
Fig. 13 - Limestone recession map with the most important CH sites for 2005 in Rome city centre.
Map of Rome city centre
with location of the most important CH sites and Recession rate for Copper in the year 2005.
Unit is: μm/year

ML=0.0027[SO2]^{0.32}[O3]^{0.79}
Rhe^{-0.78}+0.050Rain[H+]^{0.89}
R=ML/8.93 g cm^{-3}

Fig. 14 - Copper recession map with the most important CH sites for 2005 in Rome city centre.
Fig.15 - Rome exceeding map for limestone (left) and copper (right) recession with the CH sites for 2005.
Fig. 16 - Rome exceeding map for limestone recession: optimistic scenario - 10% (left) and pessimistic scenario + 10% (right).
Fig. 17 - Rome exceeding map for copper recession: optimistic scenario - 10% (left) and pessimistic scenario + 10% (right).
Fig. 18 - Limestone recession map for Milan for 2000 (left) and Rome for 2005 (right) with the most important CH sites in the respective city centres.
Fig. 19 - Copper recession map for Milan for 2000 (left) and Rome for 2005 (right) with the most important CH sites in the respective city centres.
Fig. 20 - Comparison between copper recession map for Milan elaborated on the basis of urban monitoring data and EMEP models data, included the CH sites in the city centre.
Fig. 21 - Comparison between limestone recession map for Milan elaborated on the basis of urban monitoring data and EMEP models data, included the CH sites in the city centre.