The Deterioration of Cultural Property by Airborne Pollutants: a Case Study of a Mediterranean Island

INTRODUCTION

The Maltese archipelago is situated in the central Mediterranean, at a distance of 93 km from Sicily, 288 km from North Africa, 1826 km from Gibraltar and 1510 km from Alexandria. It has a total area of ca. 300 sq. km and a coastal length of 50 nautical miles; the length of the largest island (Malta) is 27 km and its width is 14 km. The second largest island of the group is Gozo, which is 14 km long and 7 km wide. Both islands, and especially Malta, are densely populated.

The Maltese islands are characterised as low plateaux, with alluvial valleys and low hills; there are no mountains or rivers. The geology of the entire archipelago is sedimentary in nature, consisting mainly of two types of limestone: Coralline and Globigerina Limestone. The latter type of stone, which outcrops mainly in the south-eastern part of Malta and also in various areas in Gozo, has been used as the main local building material since prehistoric times; it is a very porous, soft, easily worked stone and is still extensively used for building purposes all over the islands. Thus, most constructions, ranging from prehistoric temples to historic buildings, are built of the local Globigerina Limestone.

The population of the Maltese islands currently stands at 350,000 of which approximately 25,000 live on the island of Gozo. The capital city, Valletta, at present has a population of just over 9200, compared with 18,200 inhabitants in 1957 (Annual Abstract of Statistics, 1988). Although this city has, in recent years, lost much of its popularity as a residential area, it remains the commercial capital of the islands, as well as the seat of the Government. It is also an area with a very high concentration of historic monuments; it was founded in 1566 by the Knights of the Order of St. John of Jerusalem, and was largely built by them. It lost many important buildings during the Second World War, and these were subsequently replaced with contemporary constructions. The main town of Gozo (Rabat) has a population of just over 6000 persons, and remains the vital centre of the island.

The majority of the buildings in Malta are concentrated in the south-eastern part of the island. Consequently historic and archaeological sites are found prevalently in this area, though a number of isolated prehistoric and ancient sites are situated in the north-western part as well. The central zone of Gozo also has its fair share of buildings, including old buildings as well as archaeological sites.

Climate

The Mediterranean basin is located in a temperate zone, and lies between 35° and 45° Lat. North. The climate of the area is described as being typically subtropical: dry in summer and wet in winter. However, different areas in this region have their own specific conditions, influenced both by land topographical features and by the sea. Several different sub-climates thus exist, ranging from the wet mountains of Europe, to the desert system of North Africa (Colacino, 1989, 343).

Rain

Precipitation in the Mediterranean basin decreases from north to south and from west to east. The central zone is often characterised by severe aridity. Generally most of the rain in the region falls in the winter months, from November to February, whilst the summer months, from May to September, are generally dry (Colacino, 1989, 346).

The average annual rainfall for the Maltese islands is 60 cm., falling almost exclusively during the winter months; the summers are usually long and dry. Humidity levels throughout the year range from 60-85 % (Meteorological Office Records, Luqa).

Temperature

The Mediterranean region is exemplified by small differences in temperature during the winter and summer seasons, whilst strong variations occur during the transition periods (from cold to warm season and vice versa) (Colacino, 1989, 345).

Temperatures in Malta generally range on average from 11 to 29.5° C; temperatures never fall below 0° C, whilst values as high as 42° C have occasionally been recorded.

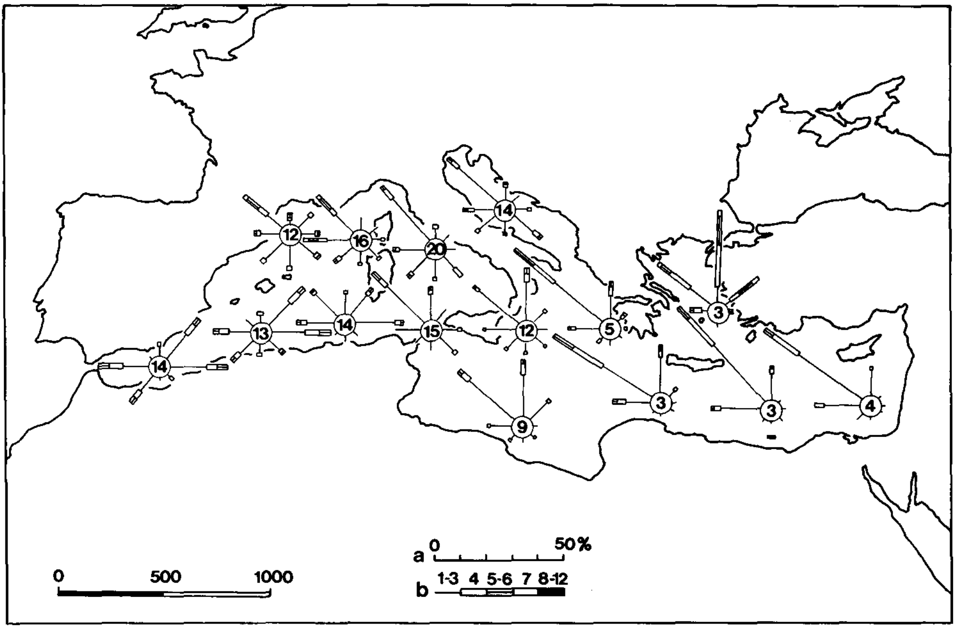

Fig. 1. Wind roses (July) showing the prevalent winds over the central Mediterranean. (After Mediterranean Pilot, 1976).

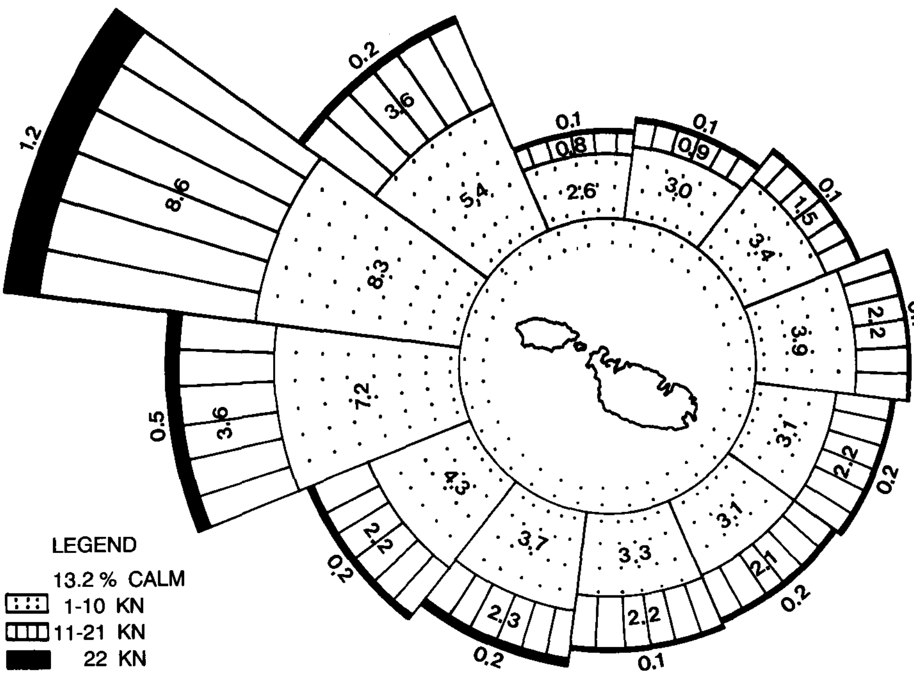

Fig. 2. Wind rose for the Maltese Islands, showing wind direction and speed within specified ranges (1958-1971).

Malta is characterised by a typically Mediterranean marine climate, where the air temperatures from August to December are higher than those recorded from February to June ; this is due to the presence of the sea which exerts a thermoregulatory influence. During the cold season, it acts as a heat source which draws cold air in from the adjacent continental land masses whilst transferring heat and water to the colder land masses. In summer, the sea is cooler than the land resulting in local thermally induced breezes especially along the coasts (Colacino, 1989, 343-354).

Winds

The Mediterranean basin is not dominated by a single wind system ; it is typified by a very high number of local winds. Several regional systems with different patterns occur, and the winds are often strong, particularly during the winter (Colacino, 1989, 346).

The prevalent winds blowing over the central Mediterranean, including the Maltese islands, are shown in Fig. 1. The predominant winds include the *Scirocco*, originating in the hot North African desert regions, which blows towards the southern Mediterranean shores, together with the *Mistral* which originates in southern France, besides those resulting from the cold dry air moving down from the mountains to the sea (e.g. Tramontana). Other main winds include the *Gregale* which blows from the north-east, the *Libeccio* originating from the south-west and the *Levant* from the east.

The predominant winds which affect the Maltese islands are shown in Fig. 2. It is evident that the *Mistral* (north-west) is the wind which mostly prevails over the Maltese islands ; other winds occur with approximately equal frequency, though the *Levant* (east) and *Libeccio* (south-west) tend to show a small prevalence over the other winds.

AIR POLLUTION IN THE MALTESE ISLANDS

External sources, neighbouring countries

The prevailing and often quite strong winds of the Mediterranean region have always shifted vast quantities of natural pollutants around the area, including desert sand from N. Africa, volcanic ash and gases from active cones, and marine aerosol from the sea. Today these same winds are, in addition, circulating large quantities of man made pollutants around the basin.

The principal activities in the region by which man causes pollution are the heavy industries, including the power stations, together with oil production, transport and refining (Fig. 3).

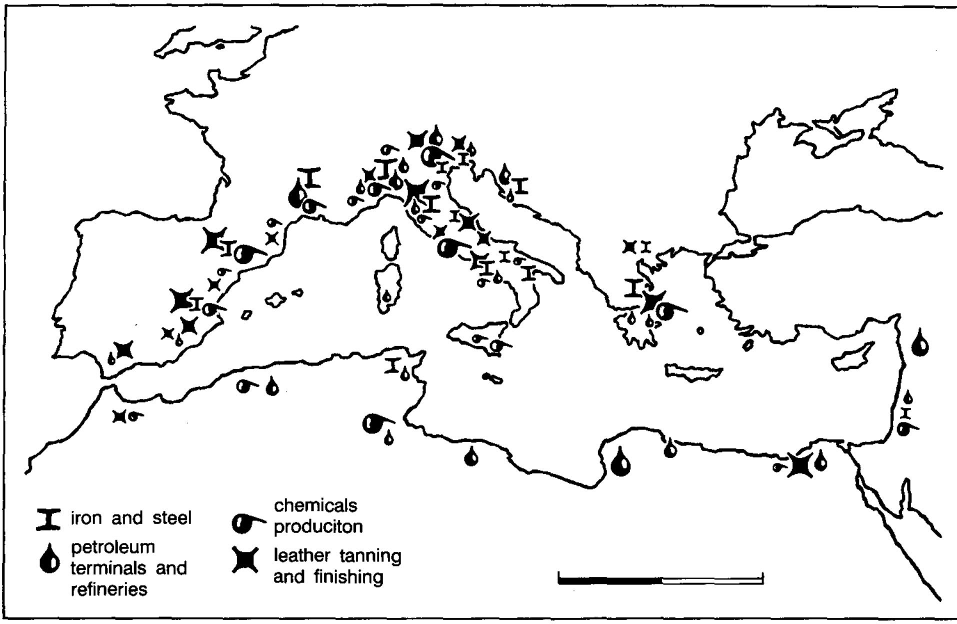

Fig. 3. Location of major industrial areas along the Mediterranean Basin (After Helmer, 1977).

A. Oil Pollution

The oil producing countries of the region are located primarily in North Africa (in particular Libya, Algeria and Egypt). Pollutants emanate primarily from oil spills and leakage from loading points – this is problematic because the lighter molecular weight hydrocarbons (as much as 25 % of the oil) evaporate from an oil slick, thus entering the atmosphere. Accidents at extraction points or during transport, may thus not only bring about combustion of the oil, but also transfer large amounts of pollutants to the air. Such accidents, though occurring rarely, greatly disrupt the environment when they do happen. In addition, a great number of oil refineries are located on the shores of the Mediterranean ; these include those of Sicily, S. Italy, Sardinia, Algeria, Libya and Egypt, as well as others in the Middle East and in Southern Europe. The breaking down of crude oil into its various products releases a large number of pollutants into the surrounding air, including the usual emissions of combustion, as well as losses of hydrocarbons, especially lower molecular weight paraffins (Hodges, 1977, 108).

B. Heavy industries

Many of the countries bordering the Mediterranean Sea, and especially those of Southern Europe, possess major industrial complexes on their Mediterranean shores (Fig. 3). Many iron and steel, chemical and leather

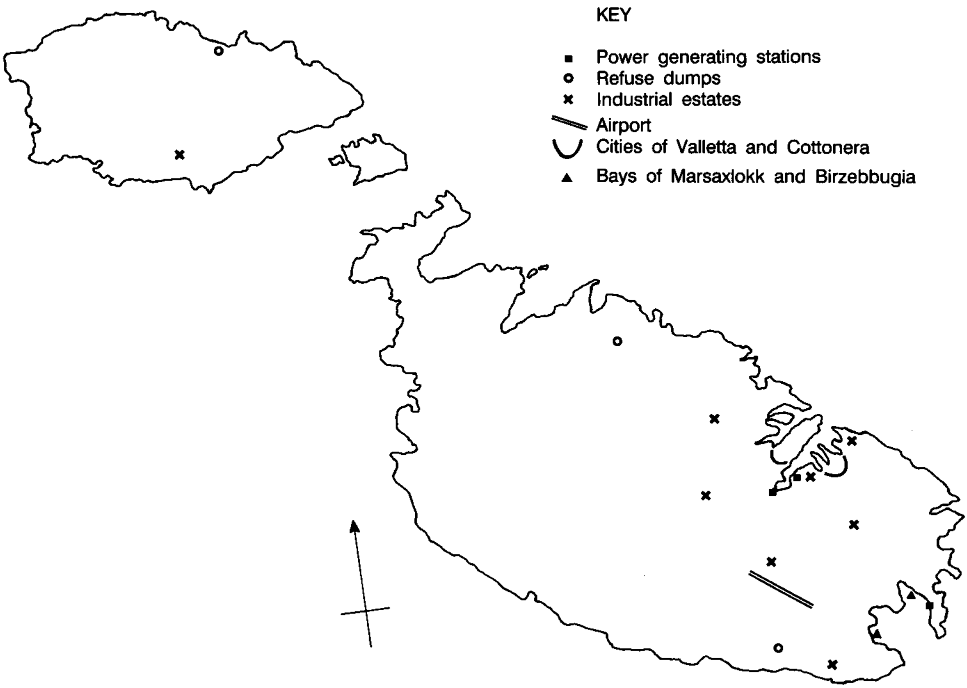

Fig. 4. Map of the Maltese Islands, showing the location of major towns, power generating plants, industrial estates and refuse dumps.

tanning and finishing industries, as well as numerous pulpmills and paper-making industries, are located in the northwest Mediterranean, the Adriatic and west Aegean littorals. These release numerous airborne pollutants into circulation over the Mediterranean basin.

Local sources

A. Energy generation

The largest local emitter of pollutants in the Maltese islands is the electricity generating Power Station, which is located on the east coast of Malta (Fig. 4). Electricity is the main source of energy in the islands, supplying industry, the commercial sector as well as domestic households. With a continually expanding population and rapid growth of the national economy (mainly involving the industrial and tourism sectors), demands on the supply of electrical energy are continually increasing (Annual Abstract of Statistics, 1988) (Table 1).

The current escalation in the demand for energy can be partly accounted for by the increase in water consumption. Malta has no rivers or lakes, and very few natural springs. Potable water is either obtained by extraction from the Mean Sea Level Aquifer, or else recovered from sea water. Until

TABLE 1. — POWER GENERATED AND CONSUMPTION FOR THE MALTESE ISLANDS, 1981-1988 (ANNUAL ABSTRACT OF STATISTICS, 42 (1988), 201)

Year	Total Generated	Used in Station	Consumed										Lost in distribution & unaccounted for (Malta and Gozo)
			Industrial		Commercial		Domestic		Street Lighting		Sundries		
			Malta	Gozo	Malta	Gozo	Malta	Gozo	Malta	Gozo	Malta	Gozo	
1981/82	588559	35314	130730	5905	123785	5970	128319	7328	9961	1290	1030	–	138927
1982/83	652168	42740	171851	4952	130092	6499	155768	7885	9983	1296	432	–	120670
1983/84	715471	40638	182932	4191	144541	9167	188952	9317	10025	1302	666	–	123740
1984/85	767283	48574	194876	3026	156118	10860	189861	10399	10520	1367	977	–	140795
1985/86	826233	52048	202569	3050	174128	10602	192557	10256	11083	1411	1247	–	167282
1986/87	933409	67544	288547	3000	174129	10909	199866	10209	13724	1520	1428	–	212533
1987/88	992497	82568	273012	4289	194562	11960	229401	12632	14580	1600	2094	–	174799

a few years ago, distillation was the only means employed to convert sea water into potable water; now four reverse osmosis plants are in operation for this purpose. In 1988 the production of water by these plants accounted for 40 % of the total consumption of water for that year (Annual Abstract of Statistics, 1988). Distillation plants are still being used in conjunction with the power station; this water is partially used for station feedwater make-up and the rest goes to supplement the potable water supply (Enemalta Report 1989, 13). The reverse osmosis plants consume a large amount of electrical energy, and hence contribute substantially to the present increase in energy production.

The power station generates electricity exclusively by burning fossil fuels. Until 1982, only oil was burnt. However, coal was introduced in 1983, and since then both coal and oil have been burnt. Initially, coal accounted for just under 25 % of the country's energy production; it now accounts for approximately 50 % of the total fuel burnt yearly.

As stated above, the power station is located inside the Grand Harbour on the east coast of the main island of the archipelago and in close proximity (within ca. 2 km) to the capital city Valletta, as well as to the three old cities (Cottonera). This is one of the most densely built-up areas of the island. Therefore, the effects of the fuel effluents are for the most part felt in this highly sensitive region. There is also another much smaller Power Station in the near vicinity (Corradino); this was used by the British military who was based in Malta up until 1979; it is a diesel burning plant, and is now used only as a back-up system. A new power station is at present under construction which will take over the energy supply to the islands, as the present plant has now reached its maximum generating capacity and has outlived its normal life span. The new power station is to be located on the south-east coast of the island of Malta, at Delimara (Fig. 4). This is further to the south than the cities of Valletta and Cottonera and will therefore decrease the direct influence of airborne pollutants on these cities. Strong winds, especially those blowing from the south-east will continue to affect these areas, though to a lesser degree, whilst simultaneously creating a whole new set of adverse conditions for other areas situated in proximity to this zone. The new power station, like the old one, will be functioning exclusively on the burning of fossil fuels. The installation of a means of eliminating both particulate matter and sulphur dioxide gas are being considered; the present plant possesses dust arrestors to remove some of the fly ash.

The disposal of fuel ash from the burning of coal poses a major problem (Enemalta Report, 1989). Currently, the fuel ash is being collected in hoppers and eventually disposed of by dumping at il-Mara, near Hal-Far, which is an open dump. Dust clouds are generated during transport of the fuel ash, from spills and from the dump itself. So far alternative uses of this waste material have not been actively sought. In addition, the storage of coal (kept in open stock yards close to the present power station) and its transport and handling also generate dust that can be transported by wind.

B. Industry

The industrial sector accounts for 28 % of the total energy consumed (Annual Abstract of Statistics, 1988) (Table 1). Besides the large consumption of electrical energy, there is also the utilisation of great quantities of water; and as water production locally depends, to a large extent, on the utilisation of energy, these two factors call for the burning of ever increasing amounts of fossil fuels, with the resulting escalating emission of polluting effluents.

There are no heavy industries on the islands. The local industry is mainly manufacturing, producing for the most part clothing, food and beverages, electronic parts, machinery and transport equipment, as well as chemicals (including petroleum, coal, rubber and plastic products). In addition, the ship-building and ship-repairing industry is the largest private enterprise on the islands. Quarrying and construction are also an important part of the local economy, together with lime-making, though to a lesser extent (Census of Production, 1986).

The main industries are grouped together in eight industrial estates, of which five are located in the south-east of Malta, and a further two are to be found in the central part of the island; there is one industrial estate on the island of Gozo (Fig. 4).

C. Traffic

Land traffic

The traffic situation in the Maltese islands is serious. In 1988 there were about 127,000 registered vehicles, of which 77 % were private and hire cars, and 15 % buses and commercial vehicles. Given that the total area of the Maltese islands is 300 sq. km., this gives a density of over 400 cars per sq. km. (Annual Abstract of Statistics, 1988) (Table 2).

For traffic to enter Valletta, a special licence is required by non-residents; this is obtainable on demand by paying an additional fee, and tends to limit to a small extent the amount of traffic which plies through the streets of the capital city. In addition, passage through the main street is limited to certain hours in the early morning and afternoon – the street is otherwise a closed pedestrian area.

In 1989, the total amount of gasoline consumed in the Maltese islands was 57,000 metric tons, in addition to 74,000 metric tons of gasoil for the same period. Diesel fuel is used mainly in vehicular transport, machinery

TABLE 2. — MOTOR VEHICLES IN THE MALTESE ISLANDS, 1985-1988
(ANNUAL ABSTRACT OF STATISTICS 42 (1988), 182)

	1985	1986	1987	198
TOTAL	111210	114197	117150	126828
of which :				
Private Cars	79712	82580	86298	94095
Cars for Hire	2547	3018	3206	3542
Omnibuses	645	646	636	697
Commercial Vehicles	17524	17178	16579	18597
Motor Cycles	9587	9405	9146	8406
Other	1195	1370	1285	1491

and furnace heating ; it is also supplied to seacraft and vessels (Enemalta Report 1989, 18-20). Gasoline is primarily used for land vehicles ; lead-free petrol was introduced in 1990, the consumption of which currently forms only a very small fraction (1 %) of the total.

Sea Traffic

Malta is largely dependent on external trade for almost all essential commodities. The majority of trade is loaded and unloaded at the Grand Harbour. Unloading of dangerous petroleum products takes place at Marsaxlokk Bay, whilst the neighbouring bay of Birzebbugia is currently being developed into a freeport (Fig. 4) ; this, together with the imminent location of the new power station in this area, will soon make the south-east tip of the island the leading locality for the supply of pollutants to the rest of the islands.

The number of vessels which entered the harbour in 1988 was just over 3,400, including both cargo and passenger vessels (Annual Abstract of Statistics, 1988) ; the total number of vessels which entered the harbour between 1979 and 1988 was 29,800 (Clews, 1990). Prior to 1979, when Malta was still being used as a military base by the British, the number of vessels using the Grand Harbour was significantly greater and included, in particular, a large number of military vessels — nowadays only a small number of such ships occasionally pay courtesy visits.

Air Traffic

There is only one airport on the islands, also located to the south of Malta, at Luqa (Fig. 4). This caters for all passenger as well as commercial flights. There has been a steady increase in the number of flights in recent years, both due to the expanding tourist sector as well as to an increase in commerce. There were 9500 registered flights in 1988 (an increase of almost 11 % over the previous year) (Annual Abstract of Statistics, 1988). Between 1979 and 1988, 75,800 aircraft used the Luqa airport (Clews, 1990).

D. Domestic energy production

Kerosene is widely consumed by domestic households, generally for heating purposes. The sharp increase in the sale of this product in recent years has reinforced a longstanding suspicion that it is being utilised for other purposes ; especially its abusive utilisation as fuel for heavy vehicles. The exhaust emitted by some of these vehicles would appear to confirm this suspicion.

Liquid petroleum gas (LPG) is also widely used in households for cooking and heating purposes. 15,400 metric tons of LPG were consumed in 1988/89, a 7.8 % increase over the previous year (Enemalta Report 1989, 18-19).

E. Other sources

Particular localised sources of air pollution include refuse dumps (two on Malta and one on Gozo) (Fig. 4) which are open dumps and which release pollutants into the air when combustion, whether spontaneous or otherwise, occurs. Another specific source includes the ship repair yards, where grit blasting occurs periodically – this releases quantities of sand and grit into the air sufficient to give rise to complaints by residents in the nearby Cottonera area.

Discussion

The principal atmospheric pollutants produced in the Mediterranean region are sulphur oxides from the burning of oil and coal, nitrogen oxides from internal combustion engines and other high temperature combustion, including fuel burning for energy generation, and particulate matter, another by-product of combustion. Carbon monoxide and low molecular weight hydrocarbons are, in addition, also released from gasoline powered vehicles and industrial processes. Ozone is produced as a secondary pollutant where heavy traffic occurs and strong sunlight is present.

In addition, particular industries are also emitters of specific pollutants, including sulphur dioxide (SO_2) and hydrogen sulphide (H_2S), ammonia (NH_3) and acid fumes, particularly hydrochloric (HCl) and hydrofluoric (HF) acids, and chemical dust (the inorganic chemical industry). Mercaptans and organic sulphur compounds are also released by some industries (Hodges, 1977, 108-109).

The emissions of the local electric power plant, which burns both oil and coal, constitute the major source of sulphur dioxide gas and particulate matter on the islands. Nitrogen oxides, carbon monoxide and carbon dioxide are also released into the atmosphere, as well as smaller quantities of halogens, heavy metals, unburnt hydrocarbons and trace elements. Besides, transport, especially land traffic, is also a significant contributor of pollutants, especially nitrogen oxides. Other combustion sources, such as residential heating units, are not in widespread use, and can therefore be ignored.

Three separate studies of the amount of pollutants expected from the new power station currently being built were carried out in 1988 : two as part of an official environmental impact assessment (Micallef, 1988, 91-107 ; Schembri, 1988, 51-68) and one as part of an independently commissioned report (Vella, 1988, A15-A26). It appears that a similar study was never carried out in connection with the present plant. However, as the fuels to be utilised in the running of the new plant are identical to those currently being burnt, and as the strength and direction of the winds in both localities can be assumed to be similar (both localities are situated on the south-east coast of the island, within approximately 8 km of each other) (Fig. 4), the above-mentioned studies can be employed to assess the current levels of pollutants emitted by the present power station. The significant difference lies in the fact that whereas the present plant is located literally on the door-step of the sensitive areas of Valletta and Cottonera, the new plant will be situated further to the south.

When comparing the pollutants released by both oil and coal, oil is found to be by far the greater culprit as regards emission of SO_2, having, on average, a total S content of 3.5 %, whereas the imported coal contains 0.5 % S (Vella, 1988, A15). However, whereas oil can be considered to produce virtually no ash, coal has a 10-15 % ash content. It has been estimated that if 4800 tonnes of coal are burnt per day, this will release 2800 tonnes of fly ash per year into the atmosphere (as well as 227760 tonnes of coarser particulate matter which will have to be dumped) (Vella, 1988, A15-A18). These values have been calculated for a peak power output of 360 MW. In the present plant, the maximum demand recorded so far is 215 MW (Enemalta Report, 1989, 9). If, as is the case, the same type of fuels are burnt, the current plant releases 836 tonnes of fly ash into the atmosphere per year at peak production, given that currently coal is used for the generation of 50 % of the energy consumed locally (oil makes up the other 50 %).

In the case of power stations located near the coast, as is the local plant, the effluents will tend to drift over the land during the day. On winter nights, however, a layer tends to be formed where the temperature increases with height, a condition known as a thermal inversion. In such a situation, air circulation is slow and pollutants are not dispersed; they tend to remain at a constant height, or may be brought to the ground by local turbulence caused by warm surfaces (Torraca, 1982, 43-44; Amoroso and Fassina, 1983, 167-169).

Other meteorological factors influencing the dispersion of air pollutants include temperature gradients, atmospheric reactions and rain. However, dispersion of gases depends primarily on wind speed and turbulence. The latter is greatly affected by topography, buildings and other obstructions, which change the local wind speed and direction as well as creating turbulence (Amoroso and Fassina, 1983, 164-167). A city, due to the individual disposition of its buildings and streets, can profoundly modify all meteorological parameters, creating local microclimates in the area, with each street experiencing its own wind field (Colacino, 1989, 347).

In the case of the new power station, calculations of maximum ground level concentrations of pollutant gases (S and N oxides), as well as aerosol, gave as a worst possible case that of a near calm, clear day; on such an occasion, the concentration of pollutants was found to be at a maximum at 1 km from source; on a clear day with a wind speed of 5 knots, maximum values are expected to be reached at 1.8 km from the site, depending on the direction of the wind (Vella, 1988, A21).

These calculations can be extrapolated to explain the present situation, as it affects the cities of Valletta and Cottonera. Thus, on a calm day, the pollutants from the present power station are capable of reaching the suburbs of Valletta, and also spread towards Senglea (one of the three cities of Cottonera). There are on average 48 days in the year with no wind (Fig. 2).

Besides, winds blowing from the south and south-west, at a speed of 5 knots (9.25 km), blow stack effluents straight into the heart of the cities of Valletta and Cottonera; this situation occurs for approximately 1 month in the year. Stronger winds will of course cause effluents to travel further, though at the same time diluting them. Winds coming from other directions will, for the most part, blow gas flues landwards, towards the heavily urbanised areas of the south of Malta.

Another significant factor affecting the levels of pollutants on the islands is the heavy traffic, which circulates particularly in the urbanised south of Malta, and the high average age of the locally circulating cars. The average annual emission by a petrol-burning car with no emission controls has been calculated as 770 kg of carbon monoxide (CO), 240 kg of hydrocarbons and 40 kg of N oxides (Hodges, 1977, 127). In Malta, with 97,600 registered cars (in 1988), this would give a total of 75,000,000 kg of CO, 23,400,000 kg of hydrocarbons and 3,900,000 kg of N oxides per year, if all registered cars were petrol driven. Commercial vehicles and buses tend, for the most part, to be diesel powered; this fuel is heavier and less volatile than gasoline, and although its exhaust emits 1/10 as much CO as gasoline for comparable amounts of fuel consumed, it releases roughly the same amounts of hydrocarbons and nitrogen oxides (NO_x) into the air (Hodges, 1977, 127-128). Very little particulate matter or S oxides are emitted by petrol driven vehicles; diesel engines, particularly if a diesel/kerosene mix is used, can however produce a considerable amount of particulate matter. Under particular climatological conditions (especially in the presence of strong sunlight), photochemical smog is generated by the reaction of unburnt hydrocarbons in automobile exhaust gases, with N oxides acting as catalysts; this results primarily in the production of ozone. Although in itself this gas is not directly harmful to many materials, except organic ones, it enhances the oxidation of SO_2, leading to the accelerated formation of sulphates (Amoroso and Fassina, 1983, 103-104).

Emissions from aircraft make up a small but noticeable component of the airborne pollutants, and occur significantly in the vicinity of the airports. Hydrocarbons, CO, N oxides and particulate matter are released into the air. The latter is composed largely of fine carbon particles (approximately 5 microns in diameter), which are not burned completely, although modern engines do tend to reduce carbon formation a great deal (Hodges, 1977, 135, 140 and 141).

However, in addition to local sources, it is obvious that pollutants also reach Malta from its neighbouring countries. When the Scirocco wind blows, visible quantities of desert dust are deposited on any exposed surface. Hence, it can safely be assumed that at least some of the pollutants emitted from heavy industries and oil refineries on the N. African coast (those which have a long residence time in the atmosphere) also travel northwards towards Malta with the same winds. Similarly, winds blowing from the north also carry pollutants, both natural and artificial, from Sicily (only 93 km away), as well as from the Italian mainland, to Malta.

These pollutants include mainly SO_2, H_2S and ash from active volcanoes (Etna and Stromboli both being quite close), besides Sand N oxides, CO, hydrocarbons and particulate matter from petroleum refineries, energy generating plants and heavy industries. The other pollutants, already mentioned, would also be in general circulation in the area.

Local and regional circulations in the area move these airborne pollutants away from their source, over and around the basin. Depending on the particular area under consideration, however, either natural or artificial pollutants, or both, may dominate. In Southern Italy, for example, natural sources predominate due to the presence of several active volcanoes; during its active phase, Etna is in fact capable of releasing a quantity of SO_2 which is comparable to the emission of between 10 and 20 large power plants burning oil with a 3 % S content ! However, there are also a large number of industries in the area, capable of producing large quantities of additional sulphur oxides, as well as nitrogen oxides and particulate matter. In addition, sea salt deposition occurs all over the Mediterranean basin, predominantly in coastal areas (Bacci et al., 1990, 365-368).

Particulate matter (or aerosol) includes all solid or liquid substances suspended in the atmosphere, and includes sea spray, smoke, dust and mists. It can be divided into coarse matter (dustfall) and finer particles ; the coarser matter (larger than 15 or 20 microns) is short-lived and generally settles near the source, whereas the finer matter (suspended particulate matter) remains aloft for a long time and travels over long distances with air currents ; descent time depends on the nature of wind and precipitation (Thomson, 1986, 131-132).

As regards the gaseous pollutants, different gases have different lifespans in the atmosphere. For example, the residence time of SO_2 in the air is normally 4 days, a value which is, however, largely influenced by removal mechanisms such as rain or direct deposition, or the SO_2 is converted into sulphuric acid in the presence of N oxides and hydrocarbons, or in the presence of trace metals (Amoroso and Fassina, 1983, 93-94). Hence, it is quite likely that this pollutant reaches Malta from neighbouring countries.

The lifespan of nitrogen oxides in the atmosphere is of about 5 days. They are removed by being oxidised to nitrate following adsorption by aerosols ; they are also involved in photochemical reactions and can be removed by rain (Amoroso and Fassina, 1983, 62-63). It is, therefore, extremely likely that, as in the case of SO_2, this pollutant reaches the Maltese islands from the surrounding countries. Both S and N oxides contribute significantly to the acidity of rain in polluted areas.

Other gases have very long residence times in the atmosphere, such as CO, (about 3 years), and hydrocarbons (4 years). Hence, any emission of these pollutants, whatever the location of their source around the Mediterranean basin, has a great probability of reaching Malta, though often in a greatly diluted form.

Pollutants released into the atmosphere in the industrialised countries of N. Europe, however, have little chance of reaching the region. The mountains of the northern Mediterranean countries act as barriers, blocking the air masses and allowing them to reach the basin only through very narrow channels between a series of mountain chains.

Dry and wet deposition

Small particles and gases can be removed from the air by either dry or wet deposition. Large particles, on the other hand, are mainly removed by dry deposition due to sedimentation. Dry deposition consists in the accumulation on a surface of airborne pollutants transported by winds and turbulence. Wet deposition comprises the incorporation of pollutants in cloud droplets (rain out) and removal by falling rain (washout) ; this type of deposition leads to the formation of acid rain (Amoroso and Fassina, 1983, 135-138).

Dry deposition is a slower but more continuous process than wet deposition ; the latter imposes sudden but infrequent doses of pollutants, mostly in dilute solution. Both dry and wet fluxes will be greatest when air concentrations of pollutants are high. Rates of deposition by dry mechanisms are intimately related to air quality in the immediate vicinity of the receptor surfaces ; for dry deposition, particle and gas fluxes will be increased when condensation is taking place (and decreased when evaporation occurs), and will occur preferentially on the coolest parts of exposed surfaces. Condensation, which occurs when warm, humid air impinges on a cool surface, is very harmful because the thin water layer formed has a very high concentration of pollutants and the reaction products subsequently formed can remain on the surface for a long time without being washed away (Hicks, 1982, 194-195 and Amoroso and Fassina, 1983, 141-143).

Water is the most important agent of damage. It induces the formation of aggressive chemicals, either acidic or alkaline, in the air or on the air/material interface ; chemical reaction is possible only in the presence of water. Moreover, impinging particles and gases adhere better to wet surfaces, whilst rough surfaces provide better deposition substrates than smooth ones.

In polluted areas, direct deposition of SO_2 (dry deposition) may well be the dominant process. On exposed surfaces located near sources, where pollution levels are high, dry mechanisms probably deposit at least as much material as wet, especially on surfaces which are protected from the direct impact of rain (Amoroso and Fassina, 1983, 135).

POLLUTANTS AND THE CULTURAL HERITAGE - THE SITUATION IN MALTA

Outdoors and indoors

The quantity of pollutants present indoors, relative to those present outdoors, depends largely on the type and amount of ventilation in the building concerned. In an air-conditioned building with filtered air, levels of particulate matter and SO_2 are much lower than those in the outside air ; however in Malta, none of the museums, churches and palaces, which house the nation's cultural heritage, are air-conditioned, and ventilation consists of throwing the windows and doors of the building wide open – in summer, windows and doors are kept open for most of the day. Thus we can safely say that, in these cases, the concentrations of air pollutants are virtually the same both indoors and outdoors, except perhaps in the case of coarse particulate matter which is hindered from entering by window sills, curtains, shutters, etc. The situation is, however, different in the case of objects which are encased, because the showcase or storage box mitigates the effects of air pollutants: practically all the particulate matter is eliminated (unless the case is especially leaky), and the levels of gases which succeed in penetrating are much lower than the ambient concentrations. However, occasionally the materials of which the showcases are made may themselves release pollutants which will then attack the material on display.

The primary pollutant which adversely affects these cultural objects is sulphur dioxide, which, in the presence of moisture, can be absorbed or adsorbed onto surfaces and can react with them (Amoroso and Fassina, 1983, 92-95). It is capable of attacking calcium carbonate (marble, limestone and frescoes), cellulose (paper, wood and many textiles), protinaceous material (silk, wool and leather) and metals. Other deleterious pollutants include the other acidic gases (nitrogen oxides), chlorides and ozone. The latter is a powerful oxidant which is capable of bringing about the deterioration of most organic materials (including paintings, textiles, archival material, furniture, ethnographic material, leather, etc.); besides, it also increases the deterioration of certain metals (e.g. silver and iron) (Thomson, 1986, 151).

Particulate matter, besides making surfaces visibly dirty, also contributes towards their deterioration because it is usually acidic (by adsorbing sulphur dioxide) and often contains trace metals such as iron which tend to catalyse deterioration (Thomson, 1986, 131-132; Amoroso and Fassina, 1983, 105).

Building materials: stone, marble, mortar and plaster

Both particulate matter and gaseous pollutants have a deleterious effect on building materials. Suspended particulate matter will dirty the surface of buildings and statuary, causing both aesthetic damage and creating ideal conditions for chemical reactions to take place, which will bring about the deterioration of the material concerned; these reactions are often catalysed by carbon particles and other trace metals present in the aerosol itself (Amoroso and Fassina, 1983, 105).

Limestone buildings and marble elements and statues in polluted atmospheres show characteristic weathering patterns consisting of black, white and grey areas. Black crusts are found in sheltered areas which are protected from direct rainfall. Here gypsum crystals are formed, binding together various materials of atmospheric origin, including black carbonaceous particles from fuel burning; these are active as catalysts in transforming limestone and marble (calcium carbonate) to gypsum (calcium sulphate) in the presence of moisture in the form of condensation, humid air or dew.

Grey areas, also present on sheltered surfaces, generally consist of a thick, compact deposit of dust particles and deterioration products overlying the stone surface. White areas are the washed out surfaces which are directly exposed to rain fall. Rain-water acidified by carbon dioxide and sulphur dioxide from the air slowly dissolves limestone and marble and washes away the dirt (Amoroso and Fassina, 1983, 145-147).

In Malta, where all buildings are constructed of the local limestone, the above situation is often evident, especially so in Valletta and Cottonera; here the facades of most buildings are heavily blackened, and in many areas, the black crusts are falling away to reveal the deteriorated stone beneath.

In fact, a study of prehistoric and other monuments located both in Valletta and elsewhere has revealed the presence of gypsum in several surface samples. Thus it was found that a sample from the Auberge de Provence, which is located in the heart of Valletta, had 3 % gypsum, whereas a sample from St John's Bastion (also in Valletta), had 1 % gypsum and 2 % halite. Samples from the Vilhena Palace in Mdina were also found to contain varying amounts of gypsum (up to 1 %) (Cassar and Vannucci, 1983, 103). This clearly shows the presence of air pollutants (especially SO_2) on Malta, and their greater concentration in the Valletta area. The prehistoric temple of Mnajdra (located on the south coast of Malta) also showed traces of gypsum in stone samples analysed during the same study.

A further study carried out on the lantern of the church of St James, also in Valletta, clearly showed the relationship between the location and presence of sulphates. Thus it was found that samples taken from the columns facing the Grand Harbour (and hence also the power station) had the highest content of both sulphates and chlorides. These were also the columns which showed the greatest deterioration (Cassar, 1990).

In a limestone country such as Malta, much of the SO_2 which arrives from neighbouring countries, as well as part of that generated locally, is neutralised by the outcropping rock; in addition, some of the polluting gas is retained by the alkaline soil, and clouds of limestone dust which are produced during quarrying and on construction sites, though annoying to humans, also help in removing this aggressive gas from circulation. Unfortunately, however, in the case of the power station which is located in a heavily built-up environment, it is the buildings and monuments which receive the full impact of this gas when the wind blows inland, and it is the limestone utilised as a building and decorative material which « neutralises » the SO_2; hence many important monuments are suffering greatly from this pollutant. The moving of the energy generating plant to the south-east coast of the island will help alleviate matters, at least as far as Valletta and Cottonera are concerned; a power station located in the southern part of the island will, in fact, be much less deleterious than the one in its the present location.

Nitrogen oxides, another primary pollutant, give rise to photochemical smog and acid rain ; in the latter role it too attacks and dissolves limestone and marble. Besides, there also appears to be a synergistic effect of NO_x on the SO_2 attack on stone, whilst transition metal oxides (present in the effluents from combustion processes) play a catalytic role in the oxidation. Hence the aggressiveness, of pollutants such as N and S oxides (Haneef et al., 1990, 14-15).

Mural paintings

As a material, a fresco is a lime-based plaster. Hence, as for normal lime-based mortars and plasters, deterioration occurs in the presence of SO_2 : this can also occur inside buildings. The calcium carbonate ($CaCO_3$) of the fresco is converted to calcium sulphate ($CaSO_4$) which brings about a deterioration and loss of cohesion in the fresco. The situation in Malta with respect to mural paintings has not been adequately studied so far, although such paintings occur in many of the churches of the island, as well as in palaces. A detailed study of the deterioration of a set of important Medieval frescoes in a country church is now in progress. This has so far revealed the presence of sulphates in several areas ; although the source cannot be attributed with any certainty to air pollution, it is suspected that this must have had some part to play in their deterioration (University thesis, currently being researched).

Metals

Gaseous pollutants, and in particular SO_2, corrode metals. This includes the rusting of iron and the corrosion of certain bronze alloys, steel and zinc. The tarnishing of silver (by H_2S) is also a well-known phenomenon ; this is accelerated in the presence of ozone, as is the rusting of iron. Other metals appear not to be affected by atmospheric pollutants, except with regards to the dirtying of surfaces whenever dust and other matter settles on them. Chlorides are also serious contaminants for metals, accelerating certain processes such as the rusting of iron. Malta is greatly affected by this problem, due to the presence of both types of contaminant ; exposed ironwork deteriorates rapidly, and bronze rapidly tarnishes and some alloys may also deteriorate. Metal objects in museums are, however, usually less affected because they are practically always displayed inside showcases ; outdoor bronze statuary, on the other hand, tends to experience this problem quite acutely.

Glass

Moisture, especially from condensation, is the chief cause of the deterioration of glass. Some authors are of the opinion that this is accelerated by the presence of SO_2 in the air, this occurring both outdoors and indoors. In the case of stained glass windows, it is thought that the recent accelerated decay can be attributed, at least in part, to air pollution (Fitz, 1989, 45-48). Although this does not yet appear to be a local problem, a watchful eye must be kept for the initial signs of such decay, especially in the more polluted areas.

Organic materials : cellulose

This material is the primary component of wood, paper and many textiles. All cellulose materials are attacked by sulphuric acid. Exposed textiles, especially cotton and linen, are severely damaged by a combination of light and sulphur dioxide ; this applies also to paper. Archival paper is however rarely exposed to light ; yet in the presence of certain impurities, SO_2 can cause browning of the paper and brittleness of the edges. The presence of high levels of ozone is also particularly dangerous for organic materials, which are readily attacked by this gas. Wood is generally not affected by gaseous pollutants, due to its bulk, although a thin veneer can be thus attacked (Thomson, 1986, 143-144). Soiling of materials often necessitates their being cleaned ; and this is often a source of further damage, especially in the case of textiles such as tapestries.

In Malta, a precious legacy incorporated in cellulose-based materials is to be found in both textiles and paper. Amongst the former, the Gobelin tapestries of the Palace of the Grandmasters of the Order of St. John, and the tapestries of St. John's Co-Cathedral, also dating to the time of the Knights, are famous world-wide. These, and especially the latter, are now in quite an advanced state of deterioration due to the breaking of the fibres as well as a fading of the dyes, primarily because of the light levels around them but also due to handling (they are periodically moved to and fro between the Cathedral and the adjoining museum). Most certainly in recent years the high SO_2 levels (together with the presence of ozone) in the surroundings have also had some effect on these textiles, the cathedral being located in the very heart of Valletta. The archives of the Order of St. John are also housed in Valletta, in the library built by the Knights. Here, brittleness of the paper is a major problem ; leather and parchment are also often adversely affected (see below).

Organic materials : protein

This includes materials made of animal fibres, such as silk, wool, leather and parchment. Silk fibres break more easily when affected by a combination of light and SO_2, and so do wool fibres, though to a lesser extent. Leather is subject to « red rot », which is a form of deterioration brought about by sulphuric acid. Parchment, if so exposed, undergoes the same effects. (Thomson, 1986, 145). Being organic materials, these also deteriorate preferentially in the presence of high levels of ozone, which always occur when there is a high concentration of motor vehicles. This is certainly a situation often encountered in Valletta, but it has not so far been specifically studied.

CONCLUSIONS

The unique geographical conditions of the Maltese islands – their small size ; their pelagic position (separated as they are from the mainland by relatively large stretches of sea) ; and their extremely high population density – render the Maltese case one of extraordinary interest for the study of the impact of airborne pollutants on the cultural heritage.

The above account has been an attempt to list and describe the various polluting agencies, whether of foreign or local origin, that circulate in the Maltese atmosphere. The processes of deposition of these pollutants on objects of cultural significance and of the deleterious effects of these pollutants on the different types of materials involved have been explained. It has been observed that in spite of their insularity the islands are seriously affected both by particulate matter and gaseous pollutants (natural and man-made) originating in other countries.

The study of the Maltese case is seriously hampered by a next to total lack of environmental monitoring of airborne pollutants as well as of conservation studies in this and other areas. Monitoring studies of deterioration processes on architectural, archaeological and artistic monuments have only just started. It is hoped that this survey will serve to open new avenues of research that will lead to a better management of the Maltese atmospheric environment in general and of the cultural heritage in particular.

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