A method for correlation of gravestone weathering and air quality (SO_2), West Midlands, UK

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Michael John Carlson

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Howard D. Mooers, Adviser

May 2017

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Acknowledgements

I would like to give thanks to my advisor Howard Mooers and my committee members Erik Brown and Laure Charleux for helping see me through to the finish on this thesis. Their guidance and knowledge was invaluable.

I also want to thank my wife for being along for the ride.

Dedication

This Thesis is dedicated to my loving grandmother Patricia Carlson. Her support through my education career was endless.

Abstract

From the beginning of the Industrial Revolution through the environmental revolution of the 1970s Britain suffered the effects of poor air quality primarily from particulate matter and acid in the form of NO_x and SO_x compounds. Air quality stations across the region recorded SO_2 beginning in the 1960s however the direct measurement of air quality prior to 1960 is lacking and only anecdotal notations exist. Proxy records including lung tissue samples, particulates in sediments cores, lake acidification studies and gravestone weathering have all been used to reconstruct the history of air quality.

A 120-year record of acid deposition reconstructed from lead-lettered marble gravestone weathering combined with SO_2 measurements from the air monitoring network across the West Midlands, UK region beginning in the 1960s form the framework for this study. The study seeks to create a spatial and temporal correlation between the gravestone weathering and measured SO_2. Successful correlation of the dataset from 1960s to the 2000s would allow a paleo-air quality record to be generated from the 120-year record of gravestone weathering. Decadal gravestone weathering rates can be estimated by non-linear regression analysis of stone loss at individual cemeteries. Gravestone weathering rates are interpolated across the region through Empirical Bayesian Kriging (EBK) methods performed through ArcGIS® and through a land use based approach based on digitized maps of land use. Both methods of interpolation allow for the direct correlation of gravestone weathering and measured SO_2 to be made.

Decadal scale correlations of gravestone weathering rates and measured SO_2 are very weak and non-existent for both EBK and the land use based approach. Decadal results combined together on a larger scale for each respective method display a better visual correlation. However, the relative clustering of data at lower SO_2 concentrations and the lack of data at higher SO_2 concentrations make the confidence in the correlations made too weak to rely on. The relation between surrounding land use and gravestone weathering rates was very strong for the 1960s-1980s with diminishing correlations approaching the 2000s. Gravestone weathering of cemeteries is highly influenced by the

amount of industrial sources of pollution within a 7km radius. Reduced correlation of land use and weathering beyond the 1980s is solid grounds for the success of environmental regulation and control put in place across the UK during later parts of the 20th century.

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1. Introduction

From the onset of the Industrial Revolution until the environmental revolution of the 1970s (Sale, 1993; McCormick, 2013), Britain was plagued by air pollution from industrial, urban, and residential sources. The largest contributors to air pollution were particulate matter (smoke) and acid in the form of NO_x and SO_x compounds (Marsh, 1978; Bricker and Rice, 1993). Since about 1960, air quality monitoring networks have been in place. These air quality measurements are of great interest in studies of ambient environmental conditions (Urone and Schroeder, 1969; Eggleston et al., 1992; Leck and Rodhe, 1988; Fenger, 2009), efficacy of environmental regulation, and health related studies of mortality and morbidity related to acute and chronic respiratory ailments (Macfarlane, 1977; Spix et al. 1993; Ito et al. 1993; Greenstone, 2004). Prior to 1960, however, air quality measurements are generally lacking with only anecdotal notations, particularly during severe air quality events. The few significant exceptions are records of electric potential gradient at Kew Observatory, London, and Eskdalemuir Observatory, Scotland (Harrison, 2006; Harrison and Aplin, 2002). For most areas, proxy records are used to reconstruct air quality; these may include physical descriptions (Allen 1966; Allen 1994; Auliciems and Burton, 1973; Fenger, 2009), lung tissue samples (Hunt at al. 2003), particulates in sediment cores (Kelly and Thornton, 1996), and lake acidification studies (Battarbee and Renberg, 1990; Battarbee et al., 1990).

Another proxy that has been used successfully to evaluate historical trends in air quality is gravestone weathering (Cooke 1989; Cooke et al., 1995; Cota-Guertin, 2012; Dragovich, 1991; Inkpen, 1998, 2013; Inpken and Jackson, 2000; Meierding, 1981;

Mooers et al., 2006, in review). Mooers et al. (2016) report on a 120-year record of acid deposition in the West Midlands, UK, reconstructed from lead-lettered marble gravestone weathering. Their record is compiled from over 1400 individual weathering measurements on 591 lead-lettered marble tombstones in 33 cemeteries recorded between 2005 and 2010 (Putz et al., 2005; Mooers et al., 2006; Cota-Guertin, 2012; Mooers et al., 2016). The results from their study show gravestone weathering to be a robust measure of acid deposition with spatial sensitivity on the order of a few kilometers and temporal sensitivity of a decade or less. Although gravestone weathering is directly related to rates of acid deposition, the correlation between acid deposition and air quality is uncertain.

In this study, we use gravestone weathering recorded at 33 cemeteries in conjunction with air quality data (SO_2) for the period 1960 – 2005 reported from 27 sites across the West Midlands to create a spatial and temporal correlation between gravestone weathering and air quality. It was therefore necessary to interpolate gravestone weathering at air quality monitoring sites and then quantify the relationship between weathering and air quality. The gravestone weathering data and the recorded air quality data independently vary in both time and space. The spatial and temporal variation of these datasets created the overall framework of this study. Each dataset would be parceled and analyzed based on decadal time scales to appropriately correlate them spatially on the same timeframe. Gravestone weathering is interpolated using multiple techniques including ordinary Kriging, Empirical Bayesian Kriging, and land use analysis to determine the spatial correlation of gravestone weathering and air quality. Sensitivity and optimization analysis were used to determine the optimum radius of influence of land use on gravestone weathering and weighting factors for interpolating intermediate values of gravestone weathering.

2. Study Area

The study area encompasses West Midlands County, including Birmingham, and surrounding portions of Staffordshire, Shropshire, Worcestershire, Warwickshire, and Leicestershire (Figure 1). The industrial history of the area is well documented and there are a large number of cemeteries with lead-lettered marble gravestones. In addition, numerous air quality monitoring stations were established as early as the late 1950s (Figure 1). The air quality monitoring network and its history across the UK is described by Mosley (2009, 2011).

Coal was the primary fuel for industrial and residential uses until severe air pollutions issues forced the conversion to natural gas beginning in the early 1960s (Allen 1966; Brimblecombe, 1987). The widespread burning of coal associated with industrialization increased anthropogenic emissions and led to decreased air quality throughout much of England (Gauri and Holdren, 1981; Metcalfe and Whyatt, 1995) including emissions leading to the formation of corrosive gas and acid rain (Meierding, 1993b and Tecker, 1999).

The abundance of cemeteries and church yards across the West Midlands containing lead-lettered Carrara marble gravestones combined with a documented air quality dataset provides a unique opportunity to study both acid deposition through a time of changing industrial economy and the correlation of acid deposition with air quality.

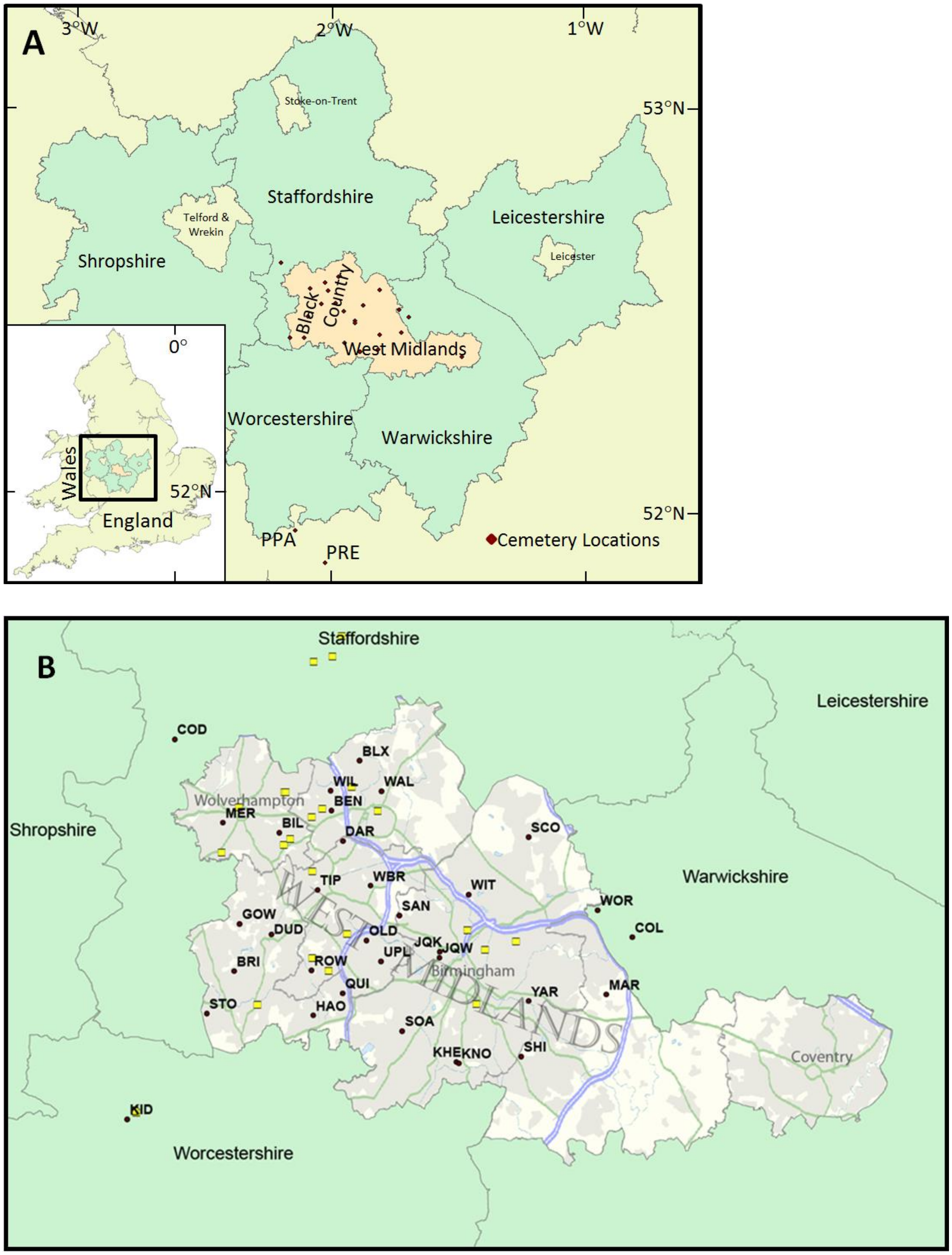


Figure 1. A. Broad view of the study area in West Midlands and surrounding counties in the UK. B. Close up study area. Cemeteries studied in this investigation are identified by their three-letter codes (Table 1). Monitoring stations locations are identified by squares. Base map courtesy of Open Street Map

2.1 Environmental Monitoring

2.1.1 Marble gravestones and acid deposition

Meierding (1993a, 1993b), Cooke and Inkpen (2000), Inkpen (2013), and Mooers et al. (2016, 2017) provide excellent summaries of the use of gravestone weathering for studies of degradation of cultural stone and assessment of acid deposition and air quality, however, a brief review of gravestone weathering studies is in order.

The use of stone deterioration for studies of weathering goes back at least to the 1880s (Goodchild, 1890; Geikie, 1880), and there is a significant body of research on the impact of acid deposition on gravestones in general (e.g. Livingston and Baer, 1990; Meierding, 1981, 1993a, 1993b) and particularly in the UK (Cooke et al., 1995; Inkpen, 1998, 2013; Inkpen and Jackson, 2000; Inkpen et al., 2000, 2001, 2008). These studies use a variety of techniques for analyzing the weathering of gravestone lettering and surfaces. Qualitative assessment or quantitative measure of lettering depth, width, and sharpness are widely used. Rahn (1971) and Meierding (1993a) describe a lettering alteration index, which qualitatively categorizes inscription lettering legibility as a result of acid deposition. Others studies have used close-range photogrammetric analysis for quantitative measurement of weathering on stone surfaces (Inkpen et al., 2000) or measurement of stone slab thickness (Meierding, 1993b).

The use of lead-lettered Carrera marble stones has been described in detail by Cooke et al. (1995). This method provides a robust and repeatable method for determining gravestone weathering (Cooke et al., 1995; Dragovich, 1986, 1991; Inkpen and Jackson, 2000). Cooke et al. (1995) and Inkpen and Jackson (2000) established criteria for the use of the lead-lettering index.

Mooers et al. (2016) found that measurement of weathering on individual gravestones is remarkably consistent. Putz et al. (2005) and Mooers et al. (2006) report weathering rates as low as 0.1 mm/century at a rural cemetery isolated from residential or industrial activities to as much as 3 mm/century in the Jewellery Quarter in the Birmingham City Center. After about 1975, implementation of pollution control measures dramatically reduced acid deposition (Mooers et al., 2016, 2017).

Mooers et al. (2016) conducted an investigation of the spatial and temporal variability of weathering of marble gravestone throughout West Midlands County. Through their findings they were able to establish the natural background rates of weathering, the effects of urban/residential expansion, and the efficacy of environmental regulations. Data were also used to convert monument corrosion to acid deposition rate and estimate the amount of acid deposition on a decadal basis from 1890-2010.

2.1.2 History of air quality monitoring

As early as the 1840s there were efforts to measure air pollution in British cities (Moseley, 2009) and Smith (1876) determined that the burning of coal was the principle source of “acid rain.” It was not until about 1960 that the monitoring network was greatly expanded with the establishment of the National Survey, which measured daily smoke and sulfur concentrations at over 500 locations (Moseley, 2009). Prior to 1960, air quality measurements were limited in spatial and temporal coverage and often described anecdotally, particularly during severe air quality events.

3. Methods

The primary goal of this research is to correlate gravestone weathering with air quality data. Gravestone weathering data from Mooers et al. (2017) forms the foundation of the data used in this investigation and includes 1417 individual measurements on 591 tombstones in 33 cemeteries collected between 2005 and 2010. Whereas Mooers et al. (2016) emphasized temporal and spatial patterns of acid deposition over a 120-year period, the current investigation assesses the correlation of acid deposition and air quality and is more restricted in both space and time. Therefore only the cemeteries within the vicinity of the air quality monitoring stations were chosen for analysis. The methods of this study involve; (1) augmenting the gravestone weathering dataset of Mooers et al. (2016) to better constrain weathering since 1950 (the time period of interest here), (2) deriving gravestone weathering rates at an adequate resolution for comparison with air quality, (3) spatially correlating gravestone weathering rates to intermediate sites where air quality data are available, (4) correlating the predicted weathering rates to measured concentrations of SO_2.

3.1 The Dataset

3.1.1 Gravestone Dataset

30 of the cemeteries reported by Mooers et al. are used in the present study (Table 1). Bilston (BIL) Cemetery was revisited and additional data were acquired to constrain recent (post 1950) weathering rates. During July of 2014 an additional 485 inscriptions were measured from 227 tombstones in 10 additional cemeteries with emphasis on post 1950 inscriptions. These additional data were collected to enhance the resolution of

Identifier	Cemetery Name	UTM30 Easting	UTM30 Northing
BIL	Bilston Cemetery	561866	5825044
BLX	Bloxwich Cemetery	567804	5830398
BRI	Brierly Cemetery	558519	5814794
COL	Coleshill Parish Church/Cemetery	588007	5817313
DAR	Fallings Heath Cemetery	566570	5824432
DUD	Scot's Green Cemetery	561285	5817504
GOW	Gornal Woods Cemetery	558912	5818302
HAO	Halesowen Cemetery	564377	5811518
JQK	Key Hill Cemetery	573743	5816222
JQW	Warstone Lane Cememtery	573730	5815781
KHE	Brandwood End Cemetery	574978	5808054
KNO	Saint Nicholas Cemetery	575167	5807964
MAR	Marston Green Burial Grounds	586086	5813062
MER	Merridale Cemetery	557690	5825788
OLD	Olbury Cemetery	568314	5817067
QUI	Quinton Cemetery	566553	5813148
ROW	Rowley Regis Cemetery	564247	5814857
SAN	Handsworth Cemetery	570750	5818928
SCO	Sutton Coldfield	580327	5824737
SHI	Robin Hood Cemetery and Crematorium	579776	5808467
SOA	Lodge Hill Cemetery and Crematorium	570966	5810346
YAR	South Yardley Cemetery and Crematorium	580324	5812585
STO	Stourbridge Crematorium	556494	5811652
TIP	Tipton Cemetery	564697	5820810
UPL	Uplands Cemetery	569384	5815531
WAL	Ryecroft Cemetery	569438	5828132
WOR	Saint Peter and Saint Paul Parish Church	585444	5819309
WBR	Heath Lane Cemetery	568630	5821123
WIL	Willenhall Cemetery	565666	5828171
WIT	Witon	575877	5820467

Table 1. List of cemeteries used during this investigation. Corresponding three letter code for each cemetery is displayed in the first column. Locations are given in UTM Zone 30.

gravestone weathering estimates over the past 60 years, which overlap with the air quality monitoring data.

Gravestones were selected for measurement following the criteria of Mooers et al. (2016), which closely follow the criteria of Cooke et al. (1995). Gravestones chosen for this study were standing vertically, had planar surfaces, used lead lettering, had limited ornamentation, and contained two or more inscriptions per stone. In addition, inscriptions had to be in chronological order and there had to be visible evidence that the stone had been resurfaced at the location of each new inscription. Measurements were made with an electronic digital caliper.

3.1.2 Air Quality Data

Sulfur dioxide and smoke (particulates) began to be measured throughout the UK in the early 1950s. However, the most reliable records start around 1960. Despite the expansion of the air-quality monitoring network after 1960, there is still a general lack of temporal and spatial continuity of records. The period of record from each of the monitoring stations is highly variable because many stations were only in operation for short periods of time (Figure 2). Where possible, decadal SO_2 averages were calculated at the monitoring sites by averaging the available annual SO_2 concentrations over the respective decade (Table 2). Because of the short-term nature of the records at monitoring sites it was only possible to calculate decadal SO_2 values for specific stations during each decade. The total number of monitoring stations available for each decade is summarized in Table 3.

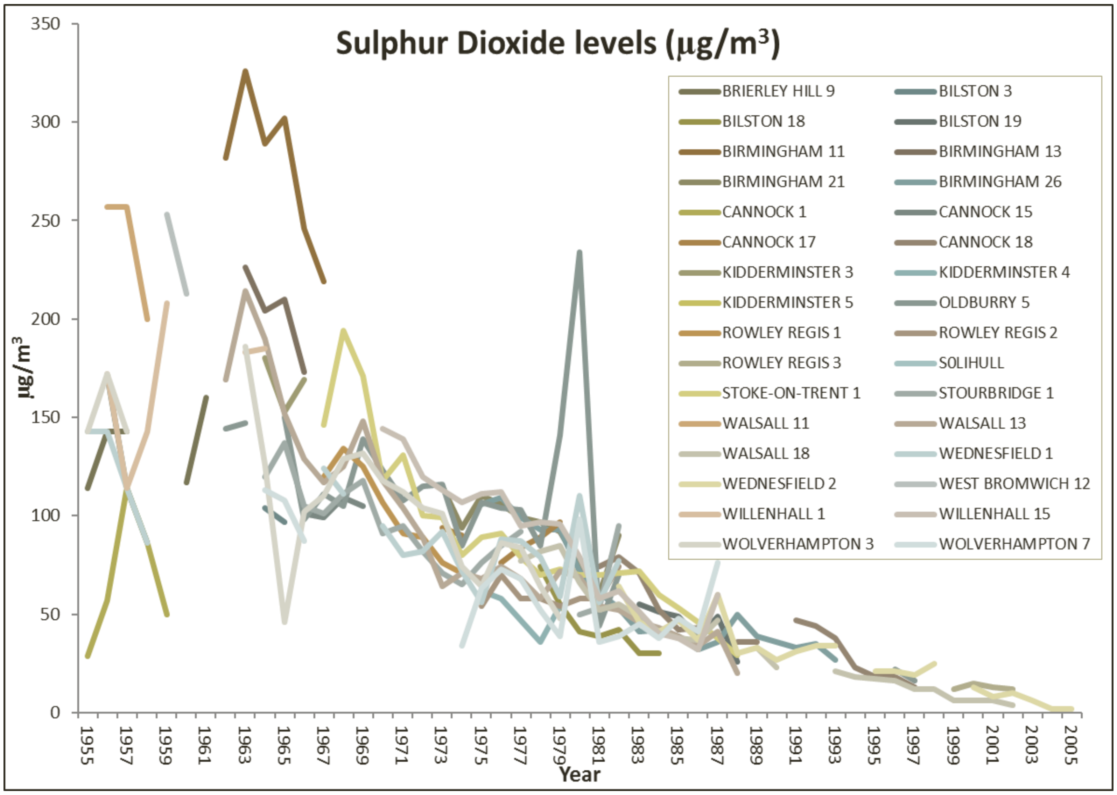


Figure 2. SO_2 levels measured at each monitoring station across the entire West Midlands monitoring network. Each line represents the period of record for an air quality monitoring station, clearly demonstrating the degree of spatial and temporal discontinuity.

Site Name	UTM30 Easting	UTM30 Northing	Y2000s	Y1990s	Y1980s	Y1970s	Y1960s
BILSTON 18	562183	5824182	-	-	40.67	64.50	-
BILSTON 19	564311	5822211	-	-	42.60	-	-
BILSTON 3	562677	5824589	-	-	-	-	99.00
BIRMINGHAM 11	577095	5816387	-	-	-	-	277.33
BIRMINGHAM 13	576450	5812377	-	-	-	-	202.40
BIRMINGHAM 21	575774	5817869	-	-	75.00	101.86	-
BIRMINGHAM 26	579387	5817019	-	32.75	46.50	100.00	-
CANNOCK 15	565790	5838135	-	-	-	101.00	103.50
CANNOCK 17	564396	5837716	-	-	-	88.33	-
CANNOCK 18	566470	5839645	-	28.71	54.13	-	-
KIDDERMINSTER 3	551255	5804326	-	-	-	-	167.33
KIDDERMINSTER 4	551153	5804525	-	-	-	47.14	60.00
KIDDERMINSTER 5	551154	5804425	-	-	-	72.00	-
OLDBURY 5	566876	5817545	-	22.33	116.00	108.70	127.71
ROWLEY REGIS 1	565513	5814826	-	-	-	86.80	126.33
ROWLEY REGIS 2	565513	5814826	-	-	63.33	58.80	-
ROWLEY REGIS 3	564299	5815809	13.33	12.00	-	-	-
STOURBRIDGE 1	560246	5812353	-	-	66.00	82.13	115.33
WALSALL 13	567225	5828453	-	-	44.22	79.33	155.50
WALSALL 18	569150	5826679	5.75	15.63	46.44	81.33	-
WEDNESFIELD 1	562229	5828084	-	-	81.00	79.00	117.50
WEDNESFIELD 2	562329	5828085	6.83	26.50	44.75	-	-
WILLENHALL 1	565047	5826822	-	-	-	-	159.67
WILLENHALL 15	564255	5826211	-	-	52.50	113.40	-
WOLVERHAMPTON 3	558844	5826936	-	-	-	85.50	118.71
WOLVERHAMPTON 7	557590	5823618	-	-	52.63	54.83	102.67

Table 2. Monitoring stations and location given in UTM Zone 30. Decadal SO_2 data for each monitoring station is presented where available. Data is presented in μg/m^3.

	Number of Stations Available
1960s	14
1970s	17
1980s	14
1990s	6
2000s	3

Table 3. Total number of monitoring stations available for each decade.

3.2 Generating Weathering Rates

In order to correlate the last 5 decades of SO_2 data to gravestone weathering, gravestone weathering rates needed to be determined from gravestone weathering data. Mooers et al. (2016) used non-linear regression to analyze weathering rates. However, their technique provides only one uniform rate up to an established break point (Figure 3). This technique results in only one or two established rates for the most recent decades (1950-2005) when SO_2 data are available. Although the technique worked well to examine the spatial and temporal dependence of gravestones weathering over the past

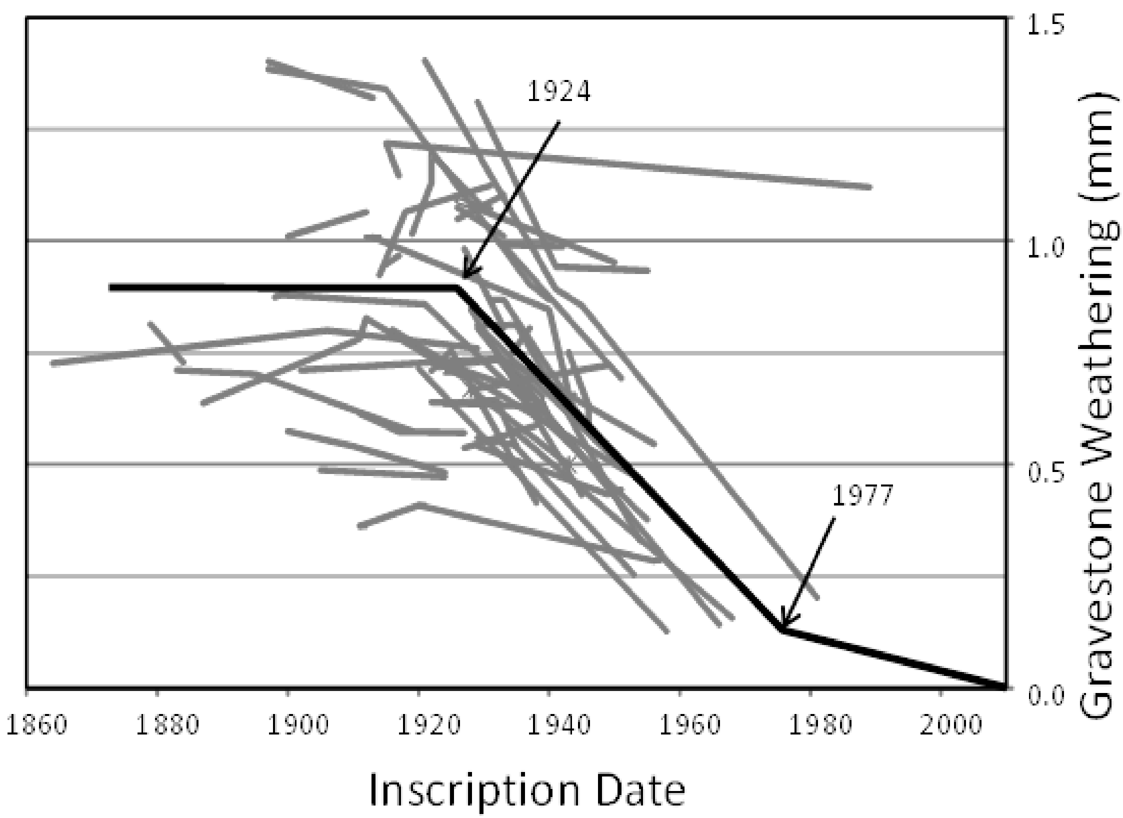


Figure 3. Non-liner regression analysis performed by Mooers et al. (2016) to analyze weathering rates. Adjusted weathering measurements plotted for each stone (individual grey lines) at Bilston Cemetery. Black line is the fitted weathering rate from the non-linear regression with break points at 1924 and 1977.

120 years the gravestone weathering rates do not provide adequate sensitivity for this study. The SO_2 data suggest that atmospheric concentrations of these pollutants decrease exponentially over the period of record (Figure 2). Close examination of the data of Cota-Guertin (2012) and Mooers et al. (2016) suggests that an exponential function may better describe the post 1950 trend in gravestone weathering (Figure 4). Cemeteries typically display a similar pattern in gravestone weathering over the past 60 years. Cemeteries show high weathering early on and then the trend decreases rapidly between about 1970 and 1990 (Figure 4). Therefore we explored three additional methods for determining weathering rates.

3.2.1 Integrative Rate Calculation

A recent study by Inkpen (2013) outlined methods for obtaining decadal weathering rates using an integrative calculation approach. Rates are calculated based on the idea that the losses on a stone are integrative of all the losses experienced by the stone since established (Inkpen, 2013, p. 324). With this approach, a weathering rate for each decade can be extracted by subsequently removing loss data (amount of weathering) from prior decades (or time periods)(Inkpen, 2013). An example of this method attempted with our data is provided in Figure 5. For simplicity only the first few steps of the procedure are shown. Weathering rates are calculated for each time period based on the initial loss over

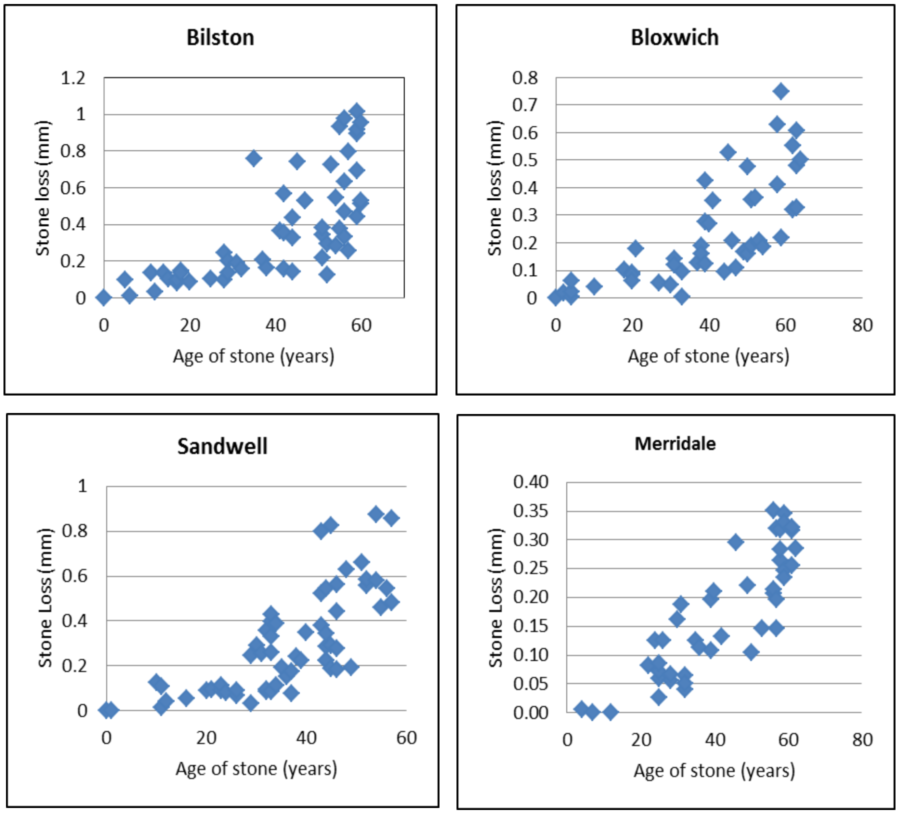


Figure 4. Typical signal of total gravestone weathering through time on four different cemeteries in the study area. Each point represents one inscription measurement with stone loss presented in mm.

time. The loss from the oldest time period is then subtracted from the loss of the more recent time periods to derive the adjusted loss 1 and adjusted rate 1. The step of removing the oldest loss from earlier decades is repeated until an adjusted rate for each time period is derived (Figure 5).

3.2.2 Moving Average

Moving averages smooth out short-term fluctuations and highlight long-term trends. Gravestone weathering data were ordered from oldest to youngest. A moving average was calculated in several ways. First the raw stone loss data was plotted over

Period	Number of Inscriptions	Initial Loss	Initial Rate	Adjusted Loss 1	Adujsted Rate 1	Adjusted Loss 2	Adujsted Rate 2	Adjusted Loss 3	Adujsted Rate 3
1970-1979	13	0.217	0.007	0.205	0.007	0.171	0.010	0.091	**0.012**
1980-1989	6	0.126	0.005	0.114	0.006	0.080	**0.009**		
1990-1999	8	0.046	0.003	0.034	**0.003**				
2000-2005	5	0.012	**0.004**						

Losses in mm; rates in mm per year; rates in bold are those for each time period
Adjusted loss 1 = (initial loss - (2000-2005 loss)) for each time period
Adjusted loss 2 = (adjusted loss 1 - (1990-1999 adjusted loss 1)) for each time period
Etc...
* Example Figure templated from Inkpen, 2013, p. 324.

Figure 5. Inkpen (2013) method attempted on our Selly Oak Cemetery data. Removing subsequent loss data results in an adjusted weathering rate for each time period. Each adjusted rate is displayed on the far right of each row in bold.

time. Then the moving average was conducted using both time intervals and point intervals. The first method used moving average intervals of 5, 10 and 20 years. The second method ignored the date of the inscriptions and focused on the number of inscriptions. Moving average trials were run at 5, 10 and 20 inscription intervals.

3.2.3 Regression Analysis

The third method of determining weathering rates from gravestone weathering data was with the use of least-squares regression analysis. Post 1940 gravestone weathering data were plotted vs. time. Data were fit with an n^{th} order polynomial trendline to calculate gravestone weathering rates as a function of time (Figure 6). Primarily second order polynomials were fit to the cemeteries while third order polynomials were used in a couple of occasions where it visually fit the data better, resulted in a higher correlation coefficient, and helped avoid negative y-intercepts. Rates for each decade were estimated by taking the derivative of the best-fit polynomial at the midpoint of each respective decade (i.e. derivative of the polynomial at 1965 for the weathering rate of the 1960s decade).

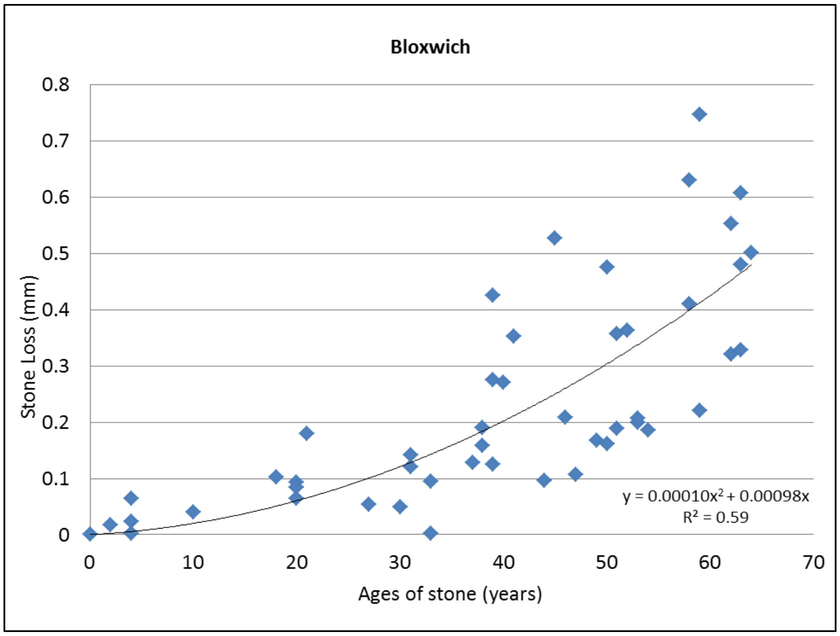


Figure 6. Second order polynomial curve fitted to the raw stone loss data at Bloxwich cemetery. Equation and corresponding correlation coefficient for the polynomial curve are displayed on the chart. Each point represents one inscription measurement with stone loss presented in mm.

3.3 Interpolation of Gravestone Weathering

3.3.1 Empirical Bayesian Kriging

An attempt was made to grid and contour decadal averaged gravestone weathering data in ArcGIS® using simple kriging. Variograms were produced and various theoretical models fit to the data. Evaluation of results suggested little or no spatial correlation suggesting the process is non-stationary and anisotropic and would require another technique of spatial correlation. Empirical Bayesian Kriging (EBK) was chosen because it is better suited for small datasets and relatively non-stationary data (Chiles and Delfiner, 1999; Pilz and Spock, 2007). The default EBK parameters in ArcGIS

Geostatistical Wizard were used. A separate interpolation grid of weathering rates was generated for each decade (1960s-2000s) using EBK.

3.3.2 Land use based approach

Because acid deposition is directly related to emissions of SO_2 and NO_x, which in turn are a function of proximity to sources and related to land use, a land-use approach for correlation of weathering data was employed. This approach was explored as an alternate and comparative approach to the EBK method of interpolating gravestone weathering rates across the study area. Land use was organized into three categories; 1.) urban areas with high concentrations of factories, large buildings and heavy automobile traffic, 2.) residential areas with dense housing and moderate automobile traffic and 3.) rural/green space with few residences and light traffic. Land use maps were digitized from recent aerial photography obtained from Google Earth® (Figure 7). Air quality at each cemetery was assumed to be related to its surrounding land use, with an optimum radius of influence and an optimum weighting factor for each land use type. To evaluate this assumption, we chose an inverse distance weighting (IDW) function. The IDW function would allow for the adjustments of the following parameters: the values to assign each land use type, the radius of influence, and the exponent of the IDW function. A sensitivity analysis was done to evaluate each of the three parameters individually to determine the optimum combination to best correlate weathering and land use.

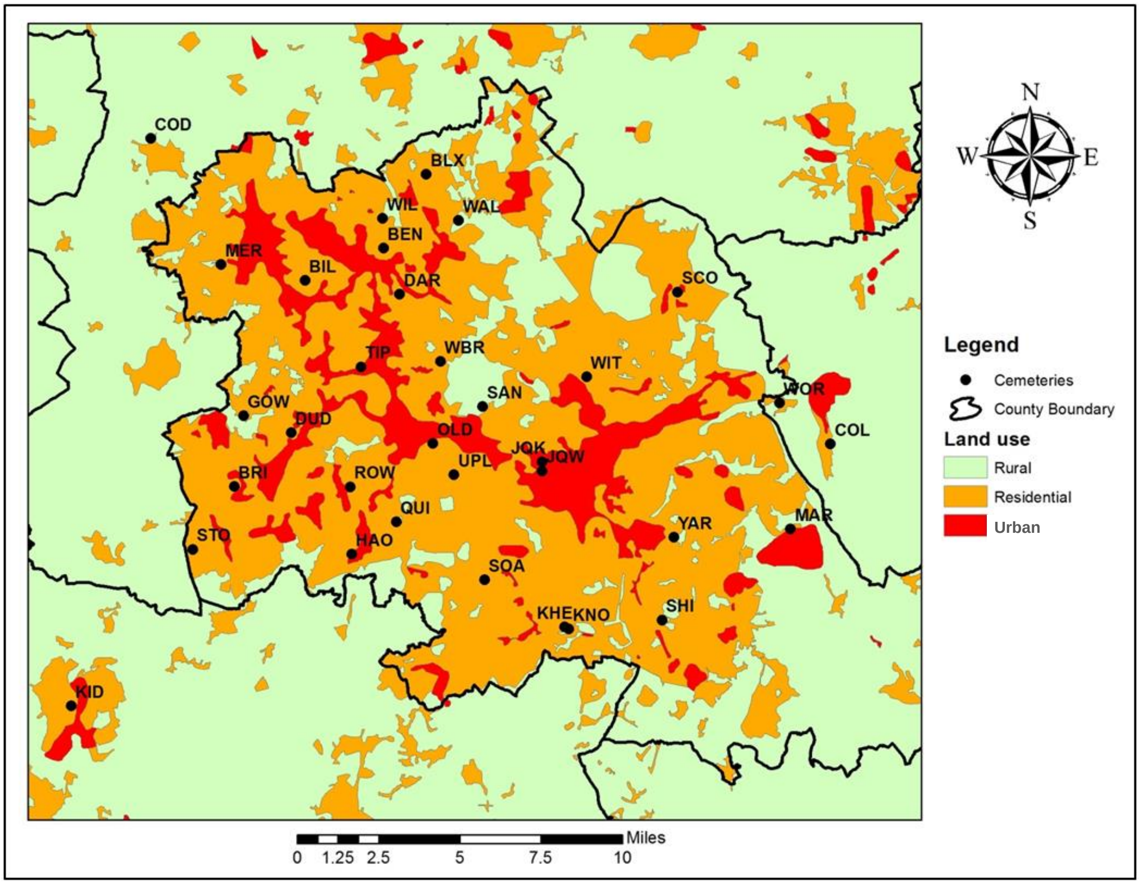


Figure 7. Land use map digitized based on aerial imagery in Google Earth®. Land use classified into three categories: Rural, Residential, and Urban. Cemeteries are shown as black dots with their three-letter code.

Digitized land use was converted into a 200m grid. Grid cells were assigned an indicator value between zero and one based on land use. Green space generates essentially no pollution and was assigned a value of 0.0. The relation between urban and residential is less clear. Initially urban areas were assigned a value of 1.0 and residential a value of 0.5. This scheme allows sensitivity analysis by simply varying the intermediate (residential) value. The IDW function was used to determine a land use value on a spatial grid for each trial. The predicted land use value at each cemetery was plotted against decadal gravestone weathering rates for each trial. Best fit least-squares regressions were determined and the correlation coefficient (R^2) was calculated. Parameters were optimized based on achieving a maximum R^2 value. Optimization of parameters was an iterative process as described below.

3.4 Optimizing IDW Parameters

3.4.1 Optimizing Land Use Type Indicator Values

To understand the relative contributions to gravestone weathering from each land use type we assigned weighting values to urban, residential and rural land use types respectively. Arbitrary values were assigned in an attempt to understand the relationship between the various land uses. Urban points across the region were given a value of 1 and rural points were assigned a value of 0. Residential was then assigned an intermediate value somewhere between 0 and 1. This method assumes high contribution from urban areas, low contribution from rural sources and residential will contribute somewhere between the two. Trials were run at a constant radius and IDW power while adjusting the value for residential land use.

3.4.2 Optimizing IDW Power

The weighting of the land use in a given radius highly depends on the power used in the IDW function. Often a power of 2 is the default value for IDW when gridding (Surfer, ArcGIS). However, a power of 2 gives minor weight to points at large radii. The purpose of choosing IDW was to try and weight land use in a given radius around a cemetery based on its distance. Therefore we still wanted points at very large distances to influence our prediction. In order to use IDW and still give adequate weights to points at larger distances (>1 km) a power much less than 2 should be used. Figure 8 shows the relative weight given to points based on their distance for various powers and demonstrates how even at a power of 0.3 points beyond several hundred meters receive little to no weight. To evaluate radii as large as 10 km, trials were run with powers between 0 and 0.5 for optimization. The radius used and land use indicator values were held constant while IDW was adjusted for each trial.

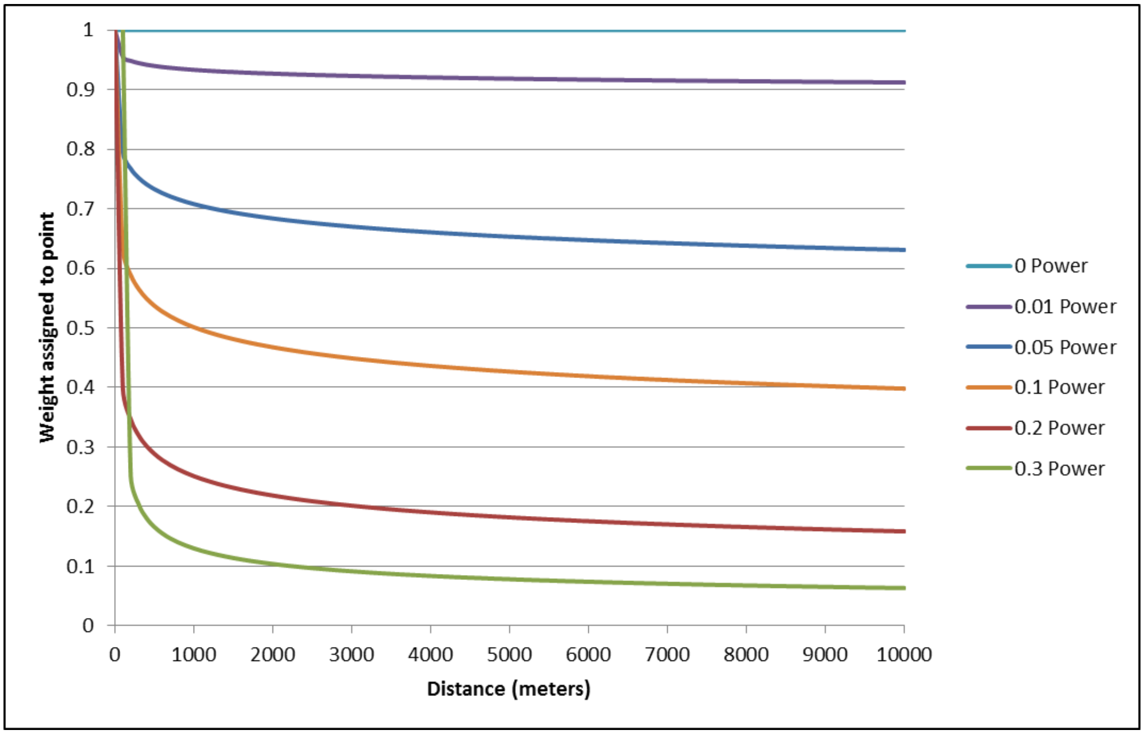


Figure 8. Weights assigned to points based on distance while using the IDW function. Chart shows weights based on different powers specified in the IDW function. As the power approaches zero higher weights are assigned to points further away from the prediction location.

3.4.3 Optimizing Radius

If gravestone weathering is a signal of the surrounding land use, there should be an optimum, or maximum, radius at which land use type has significant influence. Early phases of investigation using various combinations of IDW power and land use values continually suggested an optimum radius near 7 km. Once the IDW power and land use values had been optimized we performed the final radius optimization trials. Radius was adjusted from 3 km to 10 km while maintaining a constant IDW power and constant land use indicator values.

3.5 Correlation of gravestone weathering rates and measured SO_2

Two separate sets of interpolated grids of gravestone weathering rates were generated. The first set of grids came from results using EBK on each respective decade's weathering rates from each cemetery. The second set of grids was created using the land use based approach by generating a 200 m grid of interpolated gravestone weathering rates based on the relationship between land use and weathering rate for the respective decade. If no relationship existed between land use and weathering rates for a specific decade an interpolated grid was not able to be generated. The interpolated gravestone weathering rates were plotted against their respective decade of recorded SO_2 for each method. Best fit least-squares regressions were fit and the correlation coefficient (R^2) was calculated to evaluate the relationship between gravestone weathering rates and air quality (SO_2). In addition to individual decade correlations the data from each decade was combined onto one plot for both EBK and the land use based approach respectively to analyze the correlation on a larger scale.

4. Results/Discussion

4.1 Decadal weathering rates

The first two attempts at deriving decadal gravestone weathering rates involved the methodology of Inkpen (2013) and evaluation using a moving average (Figures 9 and 10). A curious artifact arose in both analyses. An unusual "saw tooth" patterns arose in the plots of weathering rate through time. Periods of time characterized by negative slopes indicate negative weathering, or accretion of material to the stone. Clearly this is not the case and the trend must be an artifact of the data. This periodic trend is also noted in an evaluation of the data of Inkpen (2013). The periodicity of the integrative rate calculation is similar to the average difference in age between successive inscriptions on gravestones. Mooers et al. (2016) document a large natural variability in the erodibility of Carrera marble gravestones, with "soft" stones weathering up to three times faster than "hard" stones. Periods of time where weathering measurements on "hard" stones are more abundant lead to lower weather calculations. The opposite is true when "soft" stones dominate a particular interval. The wide range of stone variability in the data set may also be a contributing factor to the shortcomings of these two methods. Because of the "saw tooth" patterns arising in the previous attempts at deriving rates, fitting polynomial curves to the measured gravestone loss was deemed the most suitable approach for obtaining rates at the scales desired. The wide range in stone variability and limited data makes this the most reasonable approach to obtaining those rates.

Time-dependent weathering rates were therefore determined by least squares regression using a second-order or third-order polynomial. Results for each cemetery are summarized in Table 4 with regression equations and their corresponding regression coefficients.

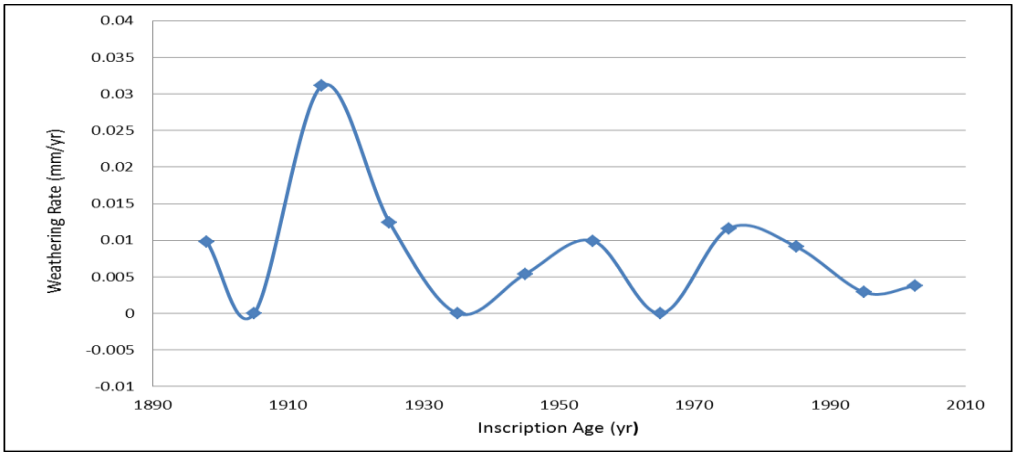


Figure 9. An example of the adjusted gravestone weathering rates calculated using the integrative method outlined by Inkpen (2013). The data displayed a "saw tooth" pattern where negative slopes unfeasibly represent accretion to the stone.

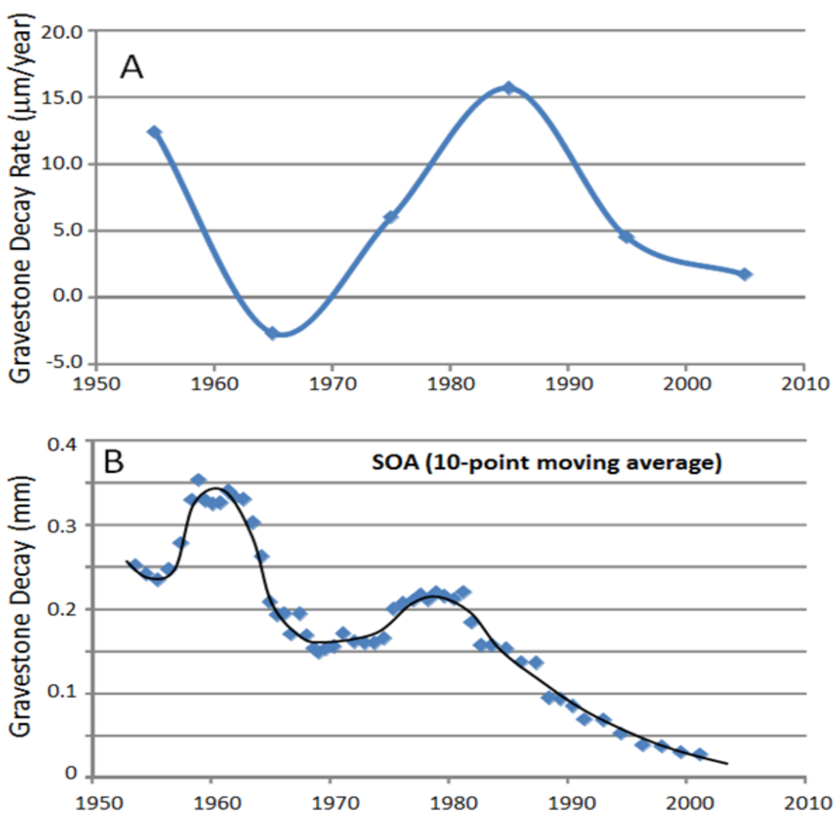


Figure 10. Examples of a 10 year moving average (A) and a 10 inscription moving average (B) performed on gravestone weathering data at Selly Oak Cemetery. A "saw tooth" pattern similar to the Inpken (2013) method was displayed.

ID	Regression Equation	R^2	Weathering Rate (mm/100yrs) Y1960s	Y1970s	Y1980s	Y1990s	Y2000s
BIL	$y = 1.47E\text{-}04\ X^2 + 2.34E\text{-}03\ X + 0$	$R^2 = 0.55$	0.0167	0.0138	0.0108	0.0079	0.0050
BLX	$y = 1.02E\text{-}04\ X^2 + 9.82E\text{-}04\ X + 0$	$R^2 = 0.59$	0.0110	0.0089	0.0069	0.0049	0.0028
BRI	$y = 9.36E\text{-}05\ X^2 - 6.09E\text{-}04\ X +$	$R^2 = 0.53$	0.0086	0.0067	0.0048	0.0029	0.0011
DAR	$y = 1.48E\text{-}04\ X^2 + 8.28E\text{-}04\ X + 0$	$R^2 = 0.56$	0.0142	0.0112	0.0082	0.0053	0.0023
DUD	$y = 3.24E\text{-}06\ X^3 - 03E\text{-}05\ X^2 + 0.002X$	$R^2 = 0.82$	0.0155	0.0094	0.0051	0.0024	0.0014
GOW	$y = 5.22E\text{-}05\ X^2 + 1.94E\text{-}03\ X + 0$	$R^2 = 0.43$	0.0071	0.0060	0.0050	0.0039	0.0029
HAO	$y = 9.26E\text{-}05\ X^2 + 21E\text{-}04\ X + 0$	$R^2 = 0.54$	0.0099	0.0080	0.0062	0.0043	0.0025
JQK	$y = 1.52E\text{-}04\ X^2 - 1.40E\text{-}03\ X + 0$	$R^2 = 0.61$	0.0123	0.0093	0.0062	0.0032	0.0001
JQW	$y = 2.48E\text{-}04\ X^2 - 1.49E\text{-}03\ X + 0$	$R^2 = 0.68$	0.0172	0.0132	0.0091	0.0051	0.0011
KHE	$y = 9.29E\text{-}05\ X^2 + 1.74E\text{-}03\ X + 0$	$R^2 = 0.87$	0.0086	0.0067	0.0048	0.0028	0.0009
KNO	$y = 4.72E\text{-}05\ X^2 + 4.37E\text{-}03\ X + 0$	$R^2 = 0.55$	0.0080	0.0068	0.0055	0.0043	0.0030
MAR	$y = 2.54E\text{-}05\ X^2 + 4.08E\text{-}03\ X + 0$	$R^2 = 0.51$	0.0074	0.0058	0.0049	0.0045	0.0048
MER	$y = 4.98E\text{-}05\ X^2 + 1.73E\text{-}03\ X + 0$	$R^2 = 0.76$	0.0066	0.0056	0.0046	0.0036	0.0026
OLD	$y = 1.48E\text{-}04\ X^2 + 2.74E\text{-}03\ X + 0$	$R^2 = 0.46$	0.0173	0.0143	0.0113	0.0084	0.0054
QUI	$y = 5.76E\text{-}05\ X^2 + 4.03E\text{-}03\ X + 0$	$R^2 = 0.44$	0.0097	0.0085	0.0074	0.0062	0.0051
ROW	$y = 1.10E\text{-}04\ X^2 + 2.04E\text{-}03\ X + 0$	$R^2 = 0.44$	0.0128	0.0106	0.0084	0.0062	0.0040
SAN	$y = 2.02E\text{-}04\ X^2 + 1.85E\text{-}05\ X + 0$	$R^2 = 0.59$	0.0182	0.0141	0.0101	0.0061	0.0020
SCO	$y = 5.85E\text{-}05\ X^2 + 4.90E\text{-}03\ X + 0$	$R^2 = 0.75$	0.0088	0.0074	0.0061	0.0047	0.0033
SHI	$y = 6.34E\text{-}05\ X^2 + 1.88E\text{-}03\ X + 0$	$R^2 = 0.54$	0.0076	0.0063	0.0050	0.0038	0.0025
SOA	$y = 5.07E\text{-}05\ X^2 + 3.65E\text{-}03\ X + 0$	$R^2 = 0.34$	0.0080	0.0070	0.0060	0.0050	0.0040
YAR	$y = 1.27E\text{-}04\ X^2 + 2.05E\text{-}03\ X + 0$	$R^2 = 0.58$	0.0135	0.0109	0.0084	0.0059	0.0033
STO	$y = 1.10E\text{-}04\ X^2 + 1.18E\text{-}03\ X + 0$	$R^2 = 0.56$	0.0098	0.0076	0.0053	0.0031	0.0008
TIP	$y = 2.11E\text{-}04\ X^2 + 1.97E\text{-}03\ X + 0$	$R^2 = 0.88$	0.0184	0.0141	0.0099	0.0057	0.0014
UPL	$y = 3.94E\text{-}05\ X^2 + 7.03E\text{-}03\ X + 0$	$R^2 = 0.42$	0.0109	0.0101	0.0093	0.0085	0.0077
WOR	$y = 6.28E\text{-}05\ X^2 - 3.71E\text{-}04\ X + 0$	$R^2 = 0.87$	0.0053	0.0040	0.0028	0.0015	0.0003
WBR	$y = 1.26E\text{-}04\ X^2 + 1.24E\text{-}03\ X + 0$	$R^2 = 0.61$	0.0126	0.0100	0.0075	0.0050	0.0025
WIL	$y = 1.40E\text{-}04\ X^2 + 3.64E\text{-}04\ X + 0$	$R^2 = 0.59$	0.0130	0.0102	0.0074	0.0046	0.0018
WIT	$y = 2.28E\text{-}04\ X^2 - 5.44E\text{-}04\ X + 0$	$R^2 = 0.83$	0.0177	0.0134	0.0092	0.0049	0.0007

Table 4. Decadal weathering rates (mm/100yrs) calculated at each cemetery using least squares regression along with corresponding regression equations and coefficients.

4.2 Correlation using Empirical Bayesian Kriging (EBK)

Figure 11 illustrates the spatial and temporal distribution of weathering rates across the study area from the 1960s to the 2000s using EBK. As expected, there is a decreasing trend of gravestone weathering rates as time progresses from the 1960s. The overall trend toward decreasing gravestone weathering rates after the 1960s corresponds to the establishment of environmental regulation and illustrates the efficacy of those

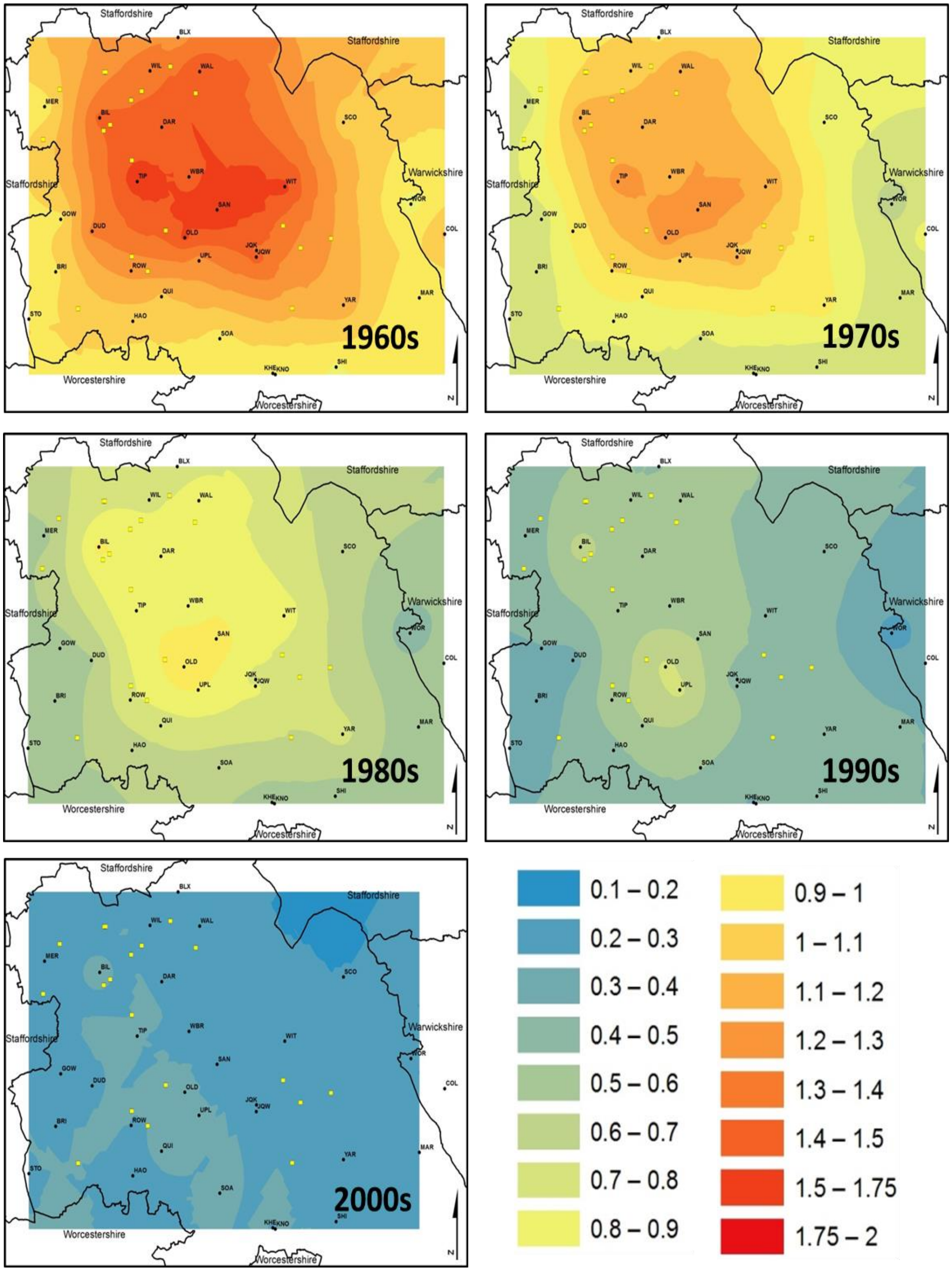


Figure 11. Spatial and temporal distribution of gravestone weathering rates (mm/100 years) from 1960s to 2000s estimated using Empirical Bayesian Kriging (EBK) in ArcGIS®. Due to inadequate variograms, the map generated for the 2000s was determined to be of little use and included for reference only.

regulations. The map generated for the 2000s was determined to be of little use and was only included for reference. EBK of the gravestone weathering rates for the 2000s did not yield adequate variograms to generate a predicted surface with a moderate degree of confidence like the other decades, which may be a result of the methods employed to obtain the decadal rates. Very little data was available for the decade 2000. Availability of data highly affects the fitting of the polynomial curves to the gravestone weathering data and the lack of data likely provides low confidence in the rates generated for the 2000s. Therefore only the 1960s-1990s was used to correlate gravestone weathering rates and measured SO_2. Gravestone weathering rates for each decade were extracted from the grids at each SO_2 monitoring station (Table 5). Where available, gravestone

Site Name	UTM30 Easting	UTM30 Northing	Y2000s	Y1990s	Y1980s	Y1970s	Y1960s
BILSTON 18	562183	5824182	0.30	0.60	0.88	1.14	1.41
BILSTON 19	564311	5822211	0.31	0.56	0.88	1.19	1.49
BILSTON 3	562677	5824589	0.30	0.61	0.89	1.15	1.42
BIRMINGHAM 11	577095	5816387	0.26	0.46	0.74	1.01	1.27
BIRMINGHAM 13	576450	5812377	0.28	0.47	0.69	0.91	1.13
BIRMINGHAM 21	575774	5817869	0.26	0.47	0.78	1.09	1.37
BIRMINGHAM 26	579387	5817019	0.27	0.44	0.69	0.95	1.21
OLDBURY 5	566876	5817545	0.31	0.64	0.92	1.18	1.44
ROWLEY REGIS 1	565513	5814826	0.30	0.59	0.80	1.01	1.24
ROWLEY REGIS 2	565513	5814826	0.30	0.59	0.80	1.01	1.24
ROWLEY REGIS 3	564299	5815809	0.30	0.55	0.78	1.03	1.29
WALSALL 13	567225	5828453	0.30	0.40	0.59	0.80	1.05
WALSALL 18	569150	5826679	0.28	0.51	0.79	1.08	1.36
WEDNESFIELD 1	562229	5828084	0.26	0.53	0.85	1.16	1.47
WEDNESFIELD 2	562329	5828085	0.28	0.53	0.78	1.02	1.27
WILLENHALL 1	565047	5826822	0.28	0.53	0.78	1.02	1.28
WILLENHALL 15	564255	5826211	0.28	0.53	0.81	1.10	1.38
WOLVERHAMPTON 3	558844	5826936	0.29	0.55	0.84	1.11	1.39
WOLVERHAMPTON 7	557590	5823618	0.27	0.48	0.67	0.86	1.09
WOLVERHAMPTON 7	557590	5823618	0.26	0.45	0.62	0.81	1.04

Table 5. Estimated decadal gravestone weathering rates at each air monitoring station using Empirical Bayesian Kriging. Rates are presented in mm/100yrs.

weathering rates were plotted against recorded SO_2 for the respective decade (Figure 12). According to the relationships, there is not a significant correlation between gravestone weathering rates and SO_2 using Empirical Bayesian Kriging. The 1970s decade indicated only a possible weak correlation between the two.

The data from the 1960s-1990s were combined and plotted on one graph to analyze the correlation of gravestone weathering rates and SO_2 on a larger scale (Figure 13). Both linear and logarithmic trendlines were fit to the data. Visually, the combined data provided a better correlation of SO_2 and predicted gravestone weathering rate than each decade represented individually. However, the effects of a few outlying points and the primary cluster of data made it difficult to be confident in the fit of a trendline. Without the addition of points at higher SO_2 levels we could not confidentially establish a correlation in this data.

4.3 Land use based approach

During the parameter optimization process it was consistently observed that the 1960s, 1970s and 1980s (early decades) displayed significantly higher R^2 values than the 1990s and 2000s (later decades). Low R^2 values in later decades made correlating weathering and measured SO_2 difficult for those time periods. Because of this, the two later decades were omitted and only the early decades were considered when optimizing parameters. This would limit SO_2 and weathering correlations to be made for only the 1980s and earlier as well. Following optimization, a final land use value grid was generated and land use was correlated to decadal average weathering rates using linear trendlines. Using the trendline functions, decadal weathering rates could be estimated at

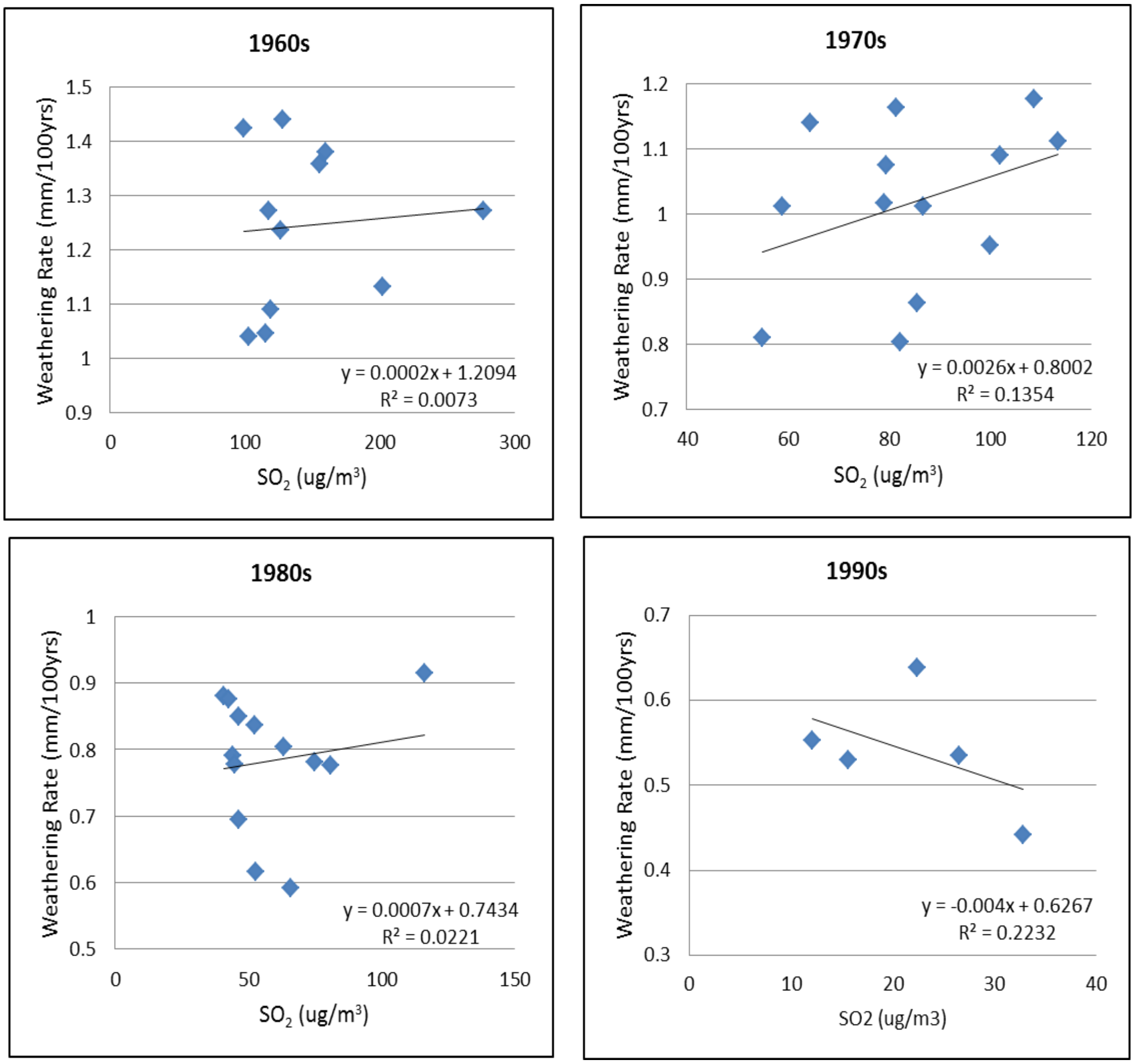
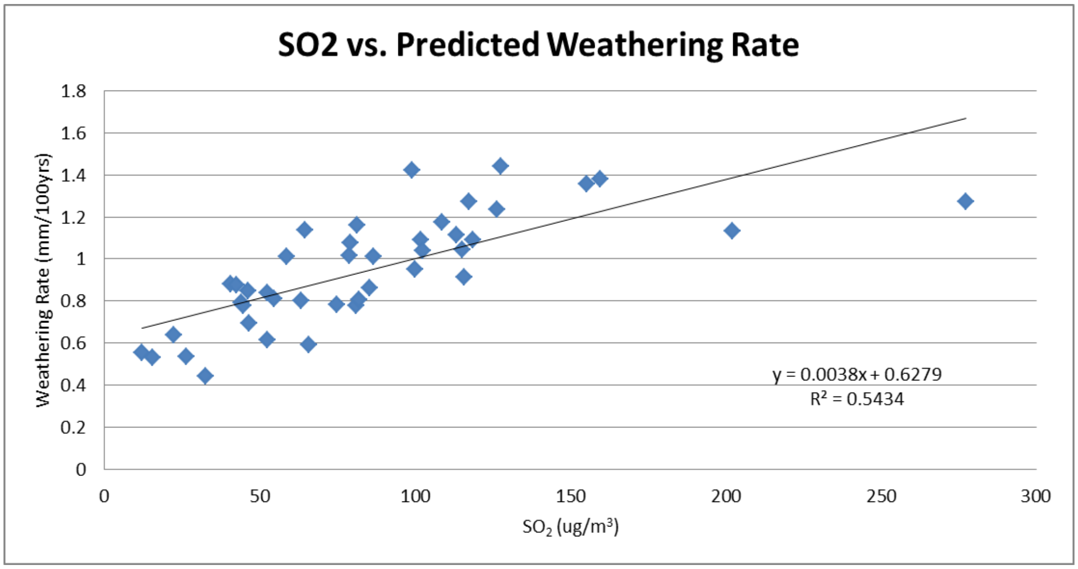


Figure 12. Correlation between predicted gravestone weathering rate and measured SO_2 using EBK. Linear regression lines and their corresponding correlation coefficients are displayed on each chart.



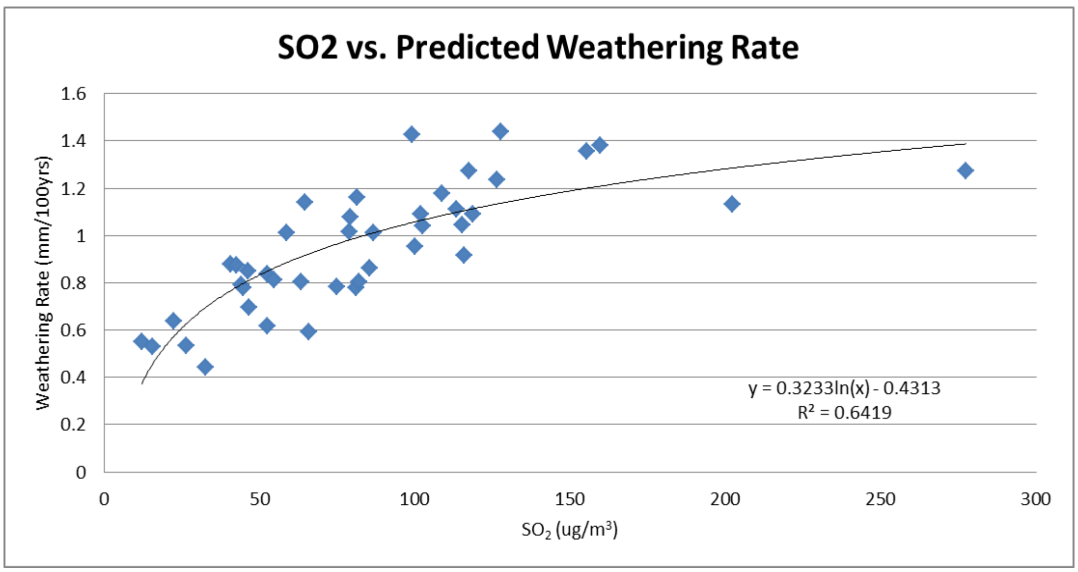
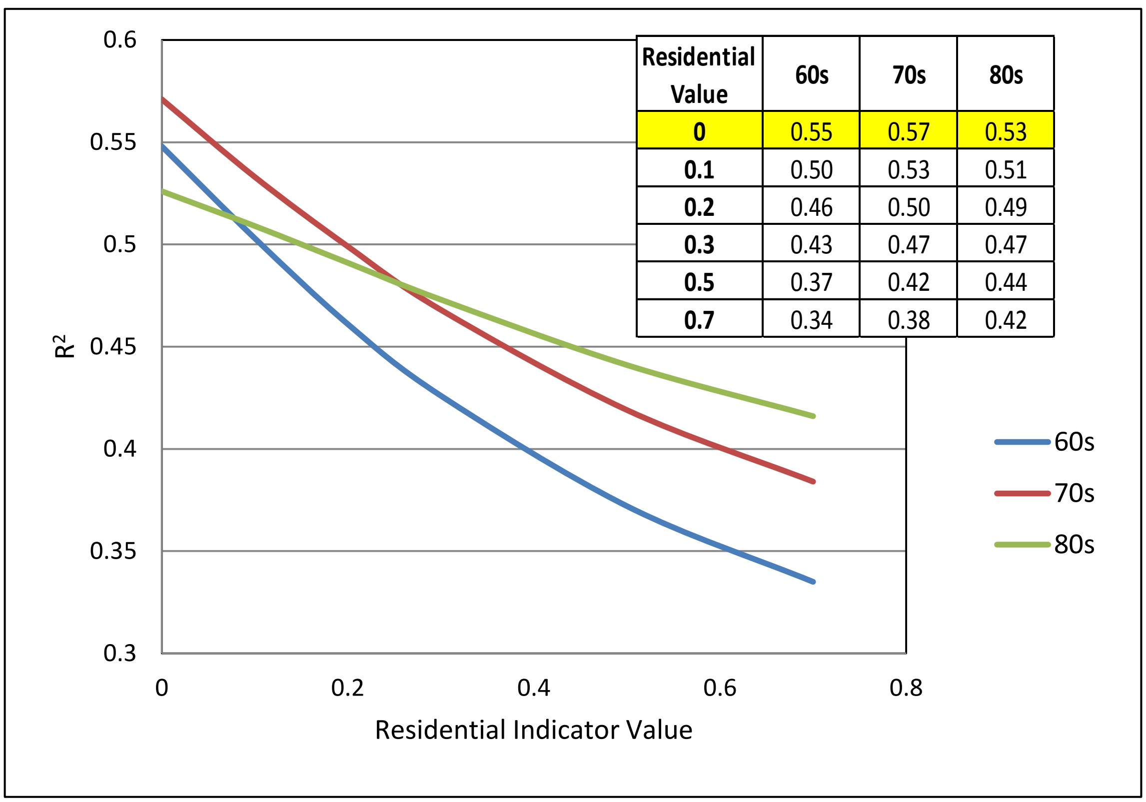


Figure 13. Correlation of SO_2 and weathering rate using EBK for the 1960s-1990s decades combined. The upper graph displays a linear trendline with its corresponding equation and correlation coefficient and the lower graph displays a logarithmic trendline with its corresponding equation and correlation coefficient.

each monitoring station based on its calculated land use value. This final estimation of decadal weathering rates allowed for the correlation between gravestone weathering and measured SO_2 concentrations.

4.3.1 Optimum land use indicator values

For early decades, 1960s-1980s, observed R^2 values decreased as the value for residential land use increased from 0.5 (half of the "urban" value) and R^2 values increased as the residential land use value approached 0 (the same as the "green space" value) (Figure 14). Results indicated that the highest R^2 value could be achieved by setting both residential and rural land use values to 0 while holding urban areas constant at 1. Setting residential and rural land use types equal was contrary to our initial



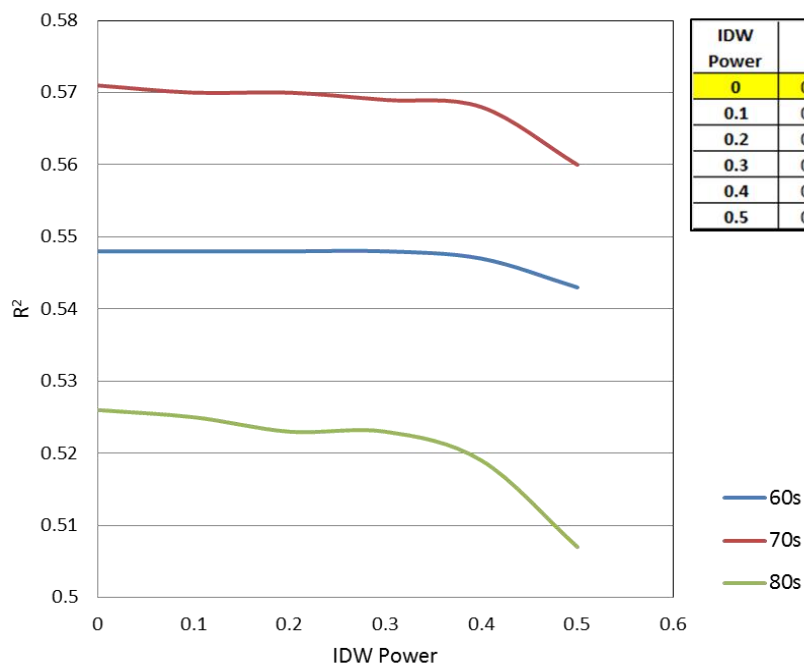
Residential Value	60s	70s	80s
0	0.55	0.57	0.53
0.1	0.50	0.53	0.51
0.2	0.46	0.50	0.49
0.3	0.43	0.47	0.47
0.5	0.37	0.42	0.44
0.7	0.34	0.38	0.42

Figure 14. Optimizing land use indicator values. The residential value was varied from 0 to 0.7 and the correlation coefficient for each decade (R^2) was plotted. R^2 for all decades was the highest at a residential value of 0.

assumption of residential contributing more influence to weathering than rural areas. We believe the results obtained can be explained by looking at the study area in which land use is being examined. It is likely that a rural area far away from the city center would indeed display lower weathering than a residential area. However, our study area is primarily a residential and urban setting with small sections classified as rural throughout. Rural areas near the city are probably not large enough or remote enough to have significantly better air quality and they are overprinted by the effects of surrounding residential and urban areas. The results indicate that weathering can be primarily determined by the amount of urban land use nearby.

4.3.2 Optimum IDW power

Results from trials for powers from 0 to 0.5 are shown in Figure 15. R^2 values



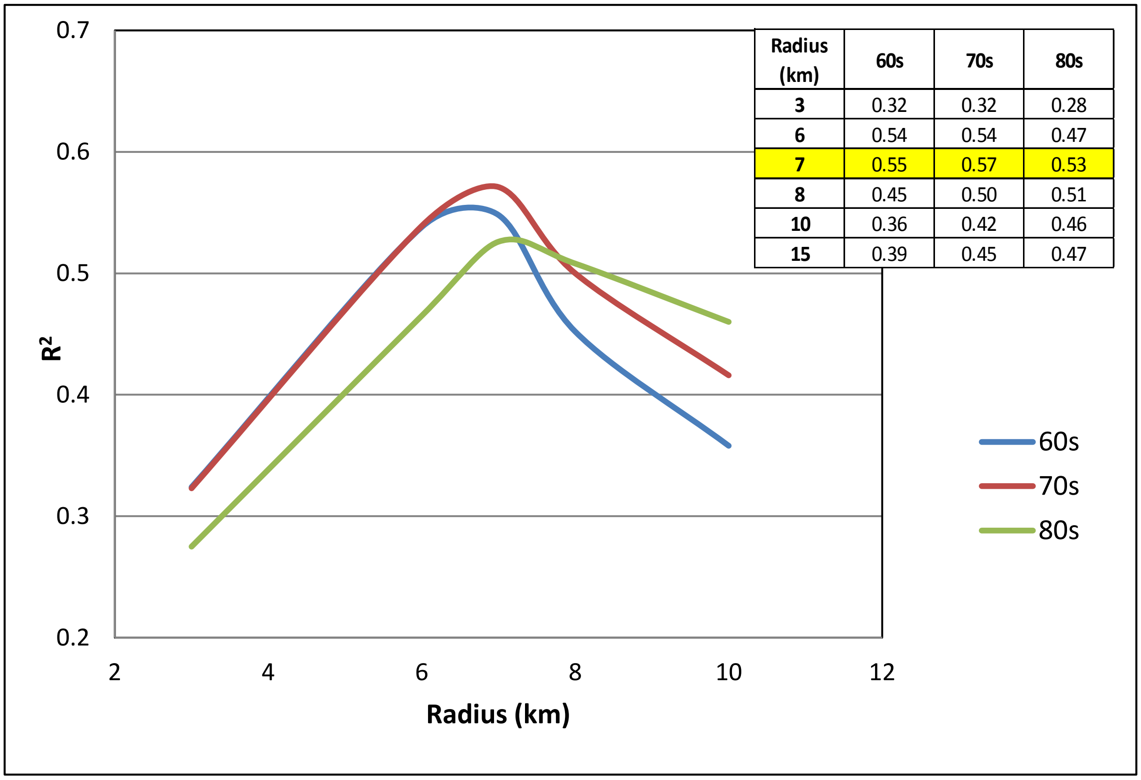
IDW Power	60s	70s	80s
0	0.548	0.571	0.526
0.1	0.548	0.57	0.525
0.2	0.548	0.57	0.523
0.3	0.548	0.569	0.523
0.4	0.547	0.568	0.519
0.5	0.543	0.56	0.507

Figure 15. Optimizing the power for the IDW function. IDW power was adjusted from 0 to 0.5 for each decade and the corresponding correlation coefficient (R^2) was plotted. Maximum R^2 achieved for all decades using an IDW Power of 0.

leveled off around 0.4, however, slightly increased as the power approached zero. The highest possible R^2 values achieved for all decades resulted from using an IDW power of zero. Several trials were also made with 1st and 2nd powers and provided results with low R^2 values. This was an intriguing result because applying a power of zero means that all points receive an equal weight regardless of their distance away from the estimation location. This was contrary to our initial belief that closer points should be more heavily weighted. One possible issue may be that IDW isn't the most effective or appropriate method for our purposes. Because the distances we are evaluating are extremely large, IDW doesn't necessarily give a smooth distribution of weights from the center to the edge of the evaluation circle. For any power, once beyond a distance of about 1000 meters weights remain relatively constant (Figure 8). Even though IDW may not be the ideal method and a power of zero negates some of the main function of the typical IDW approach, high correlations were able to be achieved operating upon the set conditions. Using an IDW power of 0 combined with the optimized land use indicator values determined in 4.3.1 simply results in the average amount of urban land use surrounding any given point.

4.3.3 Optimum radius

For early decades, R^2 values for the correlation between the derived land use value and gravestone weathering peak at 7 km (Figure 16). This indicates that the monument corrosion signal is solely based on the amount of urban area within 7km of a given cemetery using our methodology.



Radius (km)	60s	70s	80s
3	0.32	0.32	0.28
6	0.54	0.54	0.47
7	0.55	0.57	0.53
8	0.45	0.50	0.51
10	0.36	0.42	0.46
15	0.39	0.45	0.47

Figure 16. Optimized radius. Radius of influence was adjusted from 3 to 15 km for each decade and the corresponding correlation coefficient (R^2) was plotted. The highest R^2 value for all decades was achieved at a radius of 7 km.

4.3.4 Addressing later decade correlation issues

Correlation between weathering and the land use value for the later decades (1990s and 2000s) tended to display low R^2 values. We propose two possibilities for these weak correlations. There is relatively little data recorded from many of the cemeteries for the 1990s and 2000s. The lack of data from these decades may have had an influence on the calculated weathering rates. Unsound weathering rates for these time periods could lead to issues that would affect the correlation to land use. This issue would be more likely for the 2000s than the 1990s because the fit of polynomial curves is highly sensitive at early time periods based on the amount of data that is available. Although this may be the possible explanation to the poor correlation we believe our weathering rates are sound and a more robust hypothesis can be examined.

Another hypothesis to explain the decreased correlation in later decades assumes that our calculated weathering rates are valid and that the lack in correlation is a result of our methods used to address the problem. The main assumption in our most recent approach is that the weathering at a particular cemetery is related to the particular land use within a surrounding radius. We also assume that the relative density of certain land use types would cause different signals of weathering. For the early decades, this assumption is valid as land use and weathering share a strong correlation. More specifically, we were able to identify that weathering displayed a direct relationship to the amount of urban land use within a 7 km radius. However, our results indicated that weathering's dependence on land use decreases with time as we move from the early decades to the present.

The decline in the land use and weathering correlation coincides with the period of environmental pollution control measures that were taking place across the region towards the end of the 20th century. Starting with the Clean Air Act of 1965, and into the following decades, an emphasis was placed to reduce air pollution through environmental regulation (Auliciems and Burton, 1973; Greenstone, 2004). Much of this regulation was emplaced on large industry and point source polluters that are primarily located in the urban areas near the city center (Auliciems and Burton, 1973; Greenstone, 2004). As a result of the cleanup efforts, the United Kingdom decreased SO_2 emissions by 79 percent and NO_x emissions by 39 percent from 1980 to 2002 (Klein et al., 2004).

As an extreme case, we can view the “ideal” goals of environmental regulation as an attempt to eliminate effects of air pollution. In this case there would be no spatial correlation between land use, gravestone weathering, and air quality. These results may well be a representation of the efficacy of the environmental pollution control measures emplaced. As previously suggested, the cleanup would reduce effects of urban areas and essentially smooth out the contributions to weathering across the region from the varying land use types. If this was true, and as we observe with our data, we would see decreased correlation between land use and weathering as time progressed.

4.3.5 Gravestone Weathering and SO_2 Correlation

Because there was poor correlation between land use and weathering for the 1990s and 2000s only the early decades were used for the final correlation between weathering and measured SO_2. Using the optimized parameters identified, the highest possible correlation between land use and weathering was achieved by setting each land use type to a value of 0, 0 and 1 for rural, residential and urban, respectively, while using IDW with a power of 0 at radius of 7 km; the actual result then becomes simply the average amount of urban land use within 7 km of the estimation location. The predicted land use value at each cemetery (the spatial average of 7 km radius) was plotted against the weathering rate for the 1960s, 1970s and 1980s and linear trendlines were fit to each plot to determine the relationship between the predicted land use value and weathering rate for each decade (Figure 17). Each trendline provided an equation to evaluate the predicted land use value to estimate a decadal weathering rate at any given location. This was done for all air quality monitoring stations to estimate the weathering rates for each

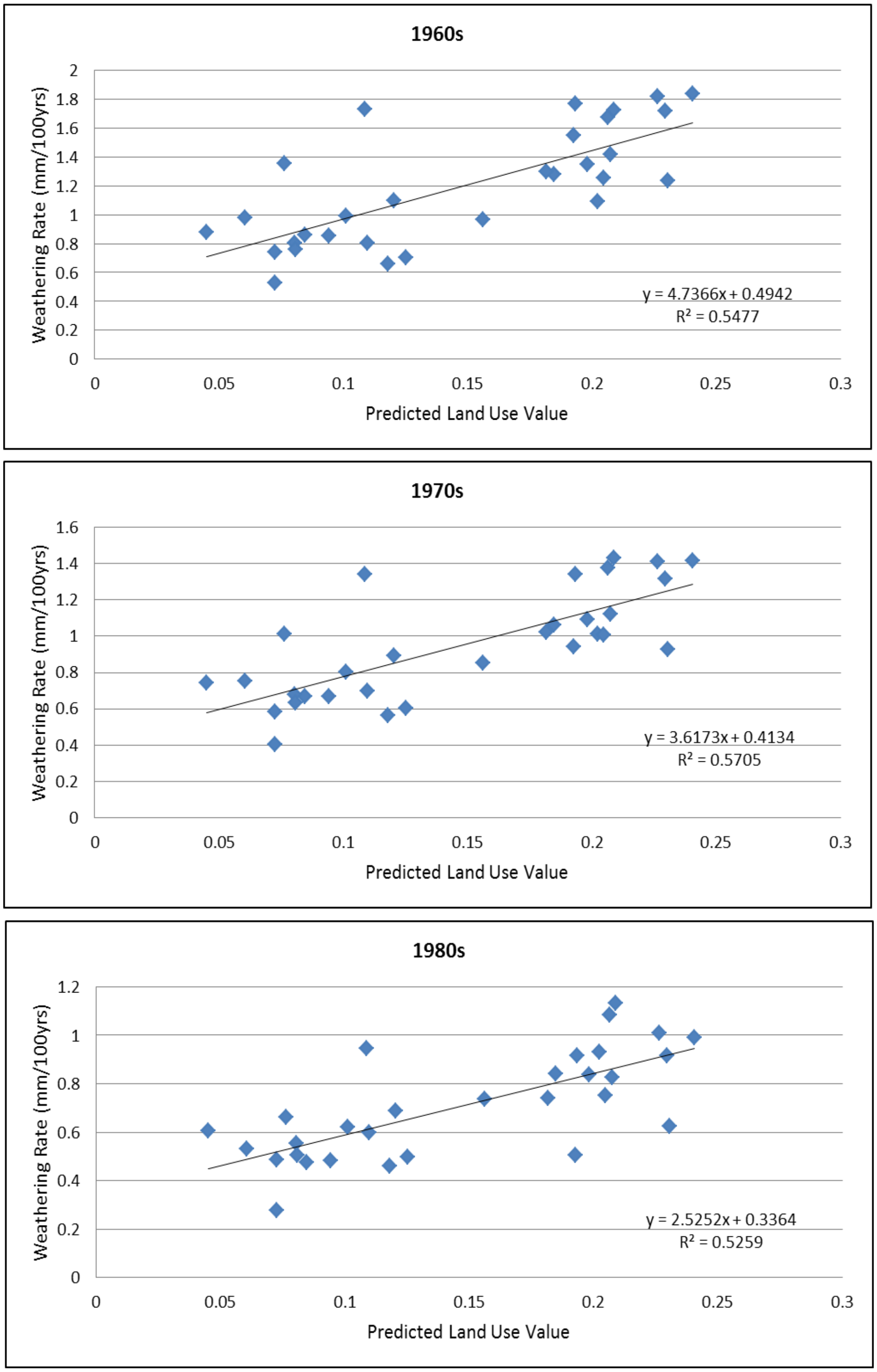


Figure 17. Correlation between predicted land use values and gravestone weathering rates (mm/100yrs) for 1960s, 19780s and 1980s. Linear trendlines and their corresponding equations and correlation coefficients are displayed on each chart.

respective decade (Table 6).

Estimated weathering rates were plotted against available SO_2 data for the respective decade (Figure 18). Based on the three decades analyzed individually, there appears to be no significant correlation between the estimated weathering rates and measured SO_2. Correlations were analyzed using both all decadal averages for SO_2 and only the decadal averages that were comprised of at least five or more annual means. Using only the confident decadal values (>5 annual means) did not improve the correlation. A possible weak positive correlation exists for the 1960s and even the 1970s however the R^2 values are very low.

As performed with the EBK method data, the 1960s, 1970s and 1980s data for the land use approach was combined onto one plot to analyze the relationship on a larger scale (Figure 19). Both linear and logarithmic trendlines were fit to the data. Again there was a stronger visual correlation at the combined scale than with each individual decade for the land use based approach. These graphs displayed similar results and problems as the combined data using EBK. The data appears fairly clustered and the trendline fits are highly influenced by a few outlying points. Without the addition of more data at higher SO_2 concentrations we cannot confidentially fit a trendline and establish a correlation between weathering rate and measured SO_2.

Weak and inconsistent correlations between the individual decades and an uncertain correlation in the combined decade analysis made it improbable to use gravestone weathering from this study to estimate an air quality record over the past century. However, our data may present some interesting observations about the relationship

Monitoring Station	Y1960s	Y1970s	Y1980s
BILSTON 18	1.53	1.21	0.89
BILSTON 19	1.71	1.34	0.98
BILSTON 3	1.57	1.23	0.91
BIRMINGHAM 11	1.54	1.21	0.90
BIRMINGHAM 13	1.36	1.08	0.80
BIRMINGHAM 21	1.55	1.22	0.90
BIRMINGHAM 26	1.48	1.16	0.86
CANNOCK 15	0.63	0.52	0.41
CANNOCK 17	0.62	0.51	0.41
CANNOCK 18	0.61	0.50	0.40
KIDDERMINSTER 3	0.62	0.51	0.41
KIDDERMINSTER 4	0.62	0.51	0.40
KIDDERMINSTER 5	0.62	0.51	0.40
OLDBURY 5	1.44	1.14	0.84
ROWLEY REGIS 1	1.38	1.09	0.81
ROWLEY REGIS 2	1.38	1.09	0.81
ROWLEY REGIS 3	1.43	1.13	0.84
STOKE-ON-TRENT 3	0.49	0.41	0.34
STOURBRIDGE 1	0.95	0.76	0.58
WALSALL 13	1.13	0.90	0.68
WALSALL 18	1.10	0.88	0.66
WEDNESFIELD 1	1.33	1.05	0.78
WEDNESFIELD 2	1.34	1.06	0.79
WILLENHALL 1	1.47	1.16	0.86
WILLENHALL 15	1.50	1.18	0.87
WOLVERHAMPTON 3	1.13	0.90	0.67
WOLVERHAMPTON 7	1.11	0.89	0.67

Table 6. Decadal gravestone weathering rates estimated at each air quality monitoring station using the land use based approach. Rates are presented in mm/100yrs.

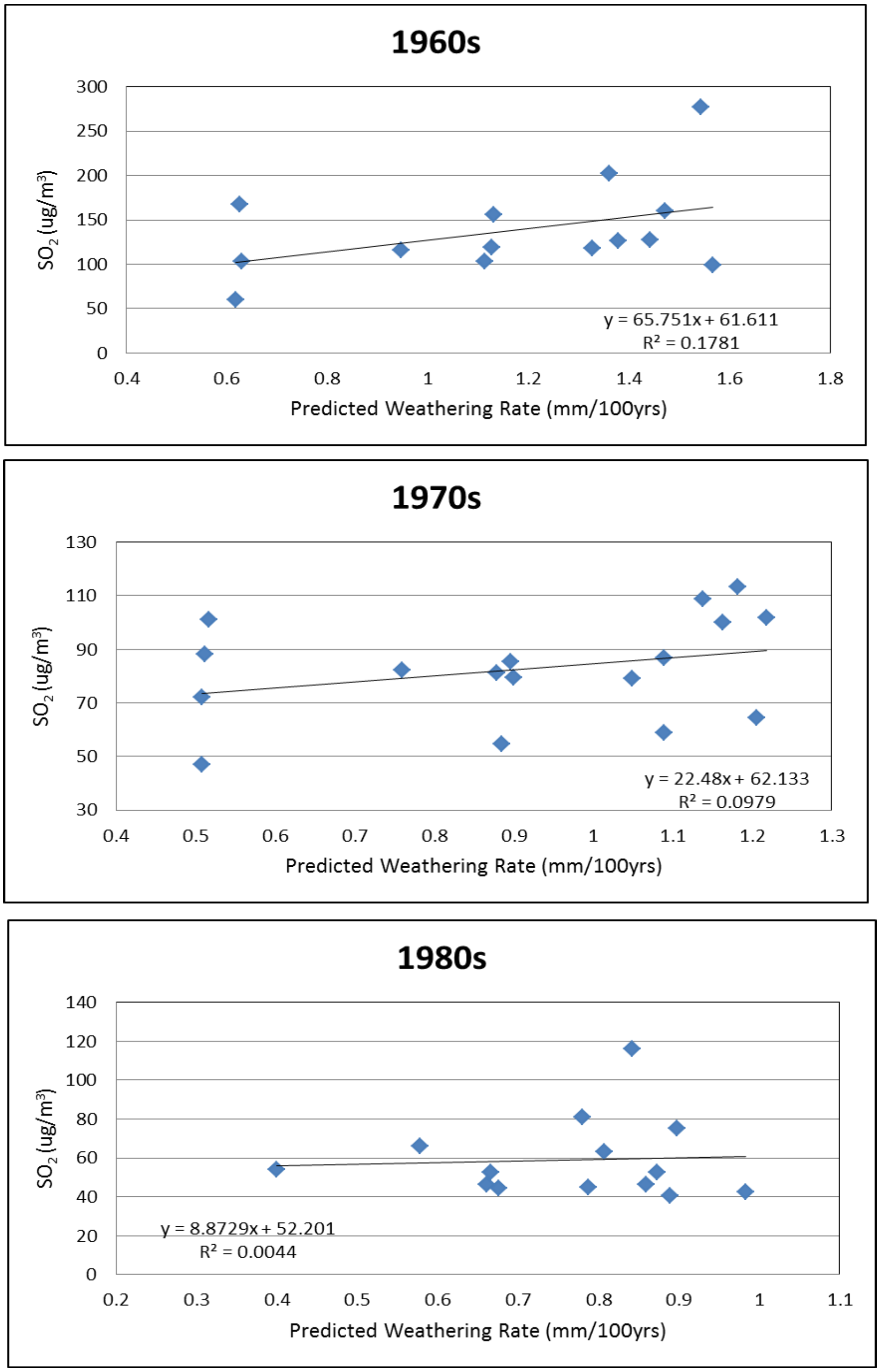
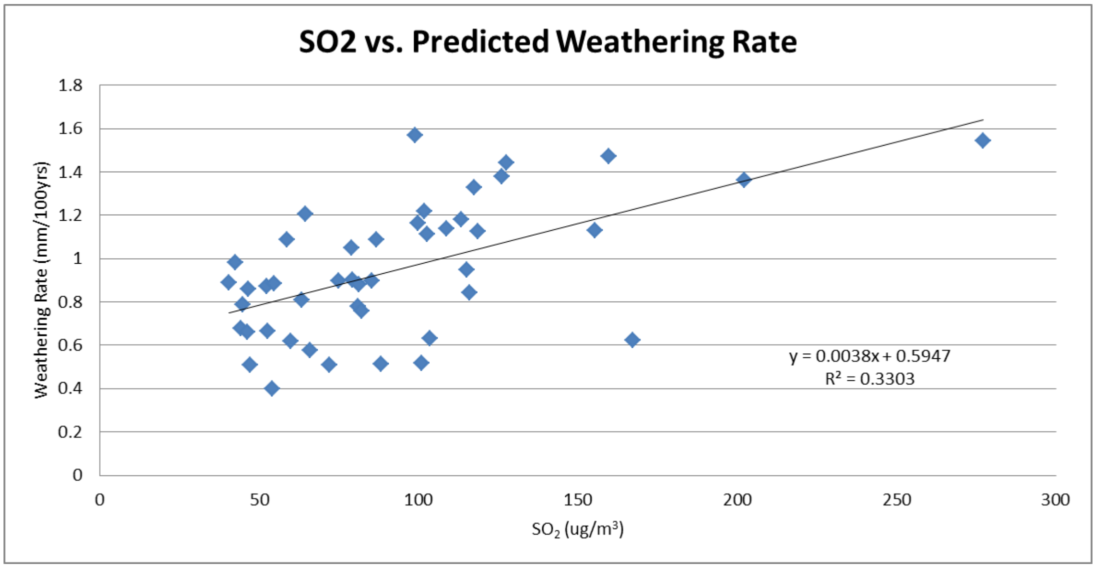


Figure 18. Correlation of predicted weathering rate (mm/100yrs) and measured SO_2 (ug/m^3) using a land use based approach. Linear trendlines and their corresponding equations and correlation coefficients are displayed on each chart.



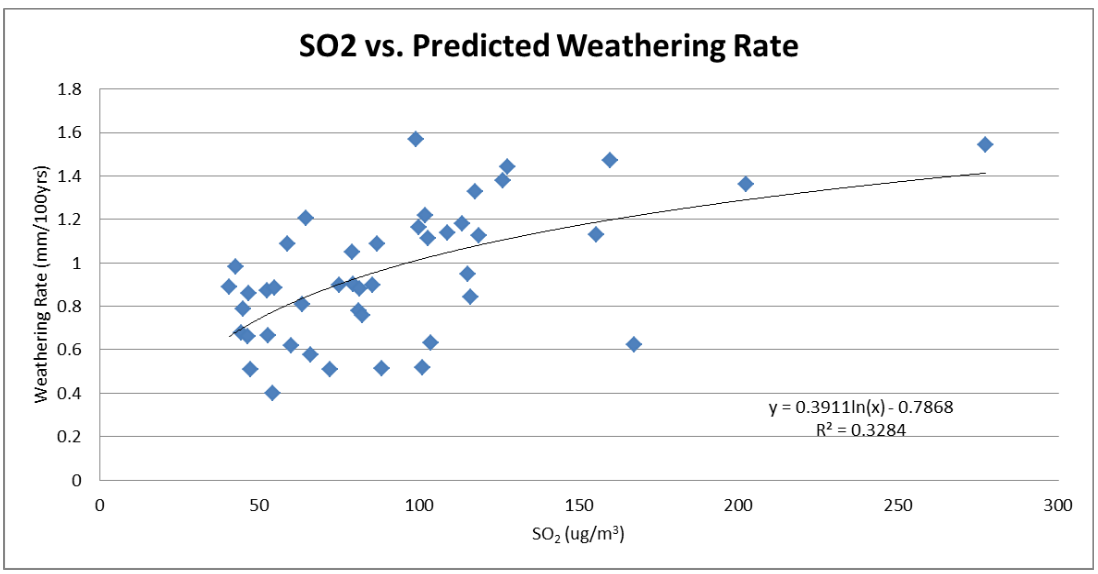


Figure 19. Correlation of SO_2 and weathering rate using land use based approach for the 1960s-1980s decades combined. The upper graph displays a linear trendline with its corresponding equation and correlation coefficient and the lower graph displays a logarithmic trendline with its corresponding equation and correlation coefficient.

between SO_2 and gravestone weathering during the 1960s, 1970s and 1980s. A weak correlation between weathering rate and SO_2 concentrations may indicate that SO_2 is only one of the various contributors (NO_x compounds) to the weathering of gravestones; therefore, weathering can't solely be estimated based on the amount of SO_2 emissions in the surrounding area. Even though all the decades have low R^2 values and weak correlations we notice that the positive correlation between SO_2 and weathering rate gets weaker (slope of trendline and R^2 values decrease) when moving from the 1960s to the 1980s. This could indicate that SO_2 has played a less important role in the weathering of gravestones as time progressed. Air quality regulation beginning in the 1960s may again be a possible explanation for weathering rate's decreased dependence on SO_2. If regulation was effectively decreasing air pollutants (with focus on SO_2 from coal burning), it is plausible for other compounds not analyzed in this study to become larger contributors to weathering in the later decades and without their consideration correlating gravestone weathering to air quality may be infeasible.

5. Conclusions

The study of stone weathering has been a useful scientific tool since the early research of weathering by Geikie and Goodchild in the late 1800s (Geikie, 1880; Goodchild 1890). More recent studies have looked at the effects of acid deposition on gravestones and even looked to gravestone weathering as an indicator of air quality (Cooke 1989; Cooke et al., 1995; Cota-Guertin, 2012; Dragovich, 1991; Inkpen, 1998; Inpken and Jackson, 2000; Meierding, 1981; Mooers et al., 2006, in review). The purpose of this study was to use a vast gravestone weathering record in conjunction with

SO_2 measurements from monitoring stations across West Midlands, England to identify a relationship between weathering and air quality. Successful correlation between air quality and gravestone weathering would allow the construction of a spatial and temporal paleo-air quality record back to the early 20th century.

Decadal weathering rates for the 1960s to present were derived from the gravestone weathering data by taking the derivative of the fitted polynomial curves at intermediate decade years (i.e. 1975 for 1970s). Attempts were made to derive the decadal weathering rates using a moving average and also the integrative rate calculation method outlined by Inkpen (2013). With both of these techniques, the weathering rates become periodically negative, an artifact that we feel corresponds to the average age difference between inscriptions on the stone. An interpolation of the derived weathering rates across the study area was necessary to obtain weathering and SO_2 data at identical locations.

Kriging is a robust and successful geostatistical method for interpolating values on a spatial grid if the data adhere to the assumptions of the technique. Our weathering data are most likely the representation of local, inhomogeneous pollution input and therefore constitute a highly non-stationary dataset (Venkatram, 1988). Empirical Bayesian Kriging was chosen as a better alternative to simple kriging to contour gravestone weathering data across the study area as it better deals with nonstaionarity (Chiles and Delfiner, 1999; Pilz and Spock, 2007). Results indicated that there was little statistical correlation between predicted gravestone weathering rates and measured SO_2 using EBK.

We hypothesize that it may also be possible to estimate weathering across the region by analyzing the land use surrounding each cemetery. Google Earth imagery was used to classify land use into three distinct categories based on visual inspection; 1.) Urban (high concentrations of factories, large buildings and heavy automobile traffic), 2.) Residential (dense housing and moderate automobile traffic) and 3.) Rural (mostly green space with few houses and light traffic). Effects of the radius of influence of land use on the weathering rate was evaluated with the use of Inverse Distance Weighting (IDW) The three factors that would affect the IDW function were the evaluation radius, the respective weight for each land use type (rural, residential and urban) and the power used within the function. Trials were run while adjusting parameters to determine the optimum combination to derive the strongest correlation between weathering rate and a predicted land use value. Results revealed good correlations for the 1960s, 1970s and 1980s (early decades) using a 7 km radius, values of 0, 0 and 1 for rural, residential and urban respectively, with an IDW power of 0. The optimized parameters identified boiled down the IDW function to a "complex" way of achieving an average but the methodology was maintained because this approach allowed for a way to get the average urban land use within 7 km of a cemetery using ArcGIS®. Correlations were weak or non-existent for the 1990s and 2000s (later decades). Decreased correlation between weathering rate and land use through time may be evidence for the success of the Clean Air Act of 1965 and subsequent environmental regulation. Air quality cleanup through the 1970s and 1980s may have created homogeneity of air pollution contributions between land use types across our region therefore effectively diminishing the relationship between land use and weathering rate through time. Poor correlation to land use in later decades only allowed the use of early decades for analyzing a possible correlation between measured SO_2 and weathering rate.

Decadal weathering rates were estimated at each air quality monitoring station using the predicted land use value at the station and the respective decade trendline function derived from the relationship between weathering rate and land use value. Weathering rates for each decade were plotted against any available SO_2 concentration data for the respective decade. There seemed to be a weak relationship between the estimated weathering rate and SO_2 that diminished with time. Weak correlations could be an artifact of the methods used in this research or again provide evidence supporting the success of environmental regulation occurring across the UK during later parts of the 20th century.

Individual decadal results were combined to analyze the relationship between weathering rate and SO_2 at a large scale for both the EBK and the land use based approach respectively. Both results, when combined to provide a bigger picture, displayed a better visual correlation than analyzing each decade individually. Linear and logarithmic trendlines were fit to try and evaluate the correlation however the lack of data at higher SO_2 concentrations and the relative clustering nature of data at lower SO_2 concentrations made it difficult to be confident in the correlation between the two variables. It is also apparent that the trendlines are highly influenced by the few outlying points and without extra data to get a true fix on the trendline fit we could not confidently use these correlations.

Because it was not possible to derive a strong and consistent relationship between weathering rates and air quality (SO_2) we were not able to use the 120 year gravestone weathering record to estimate the paleo-air quality of Birmingham in the latter parts of the 19th century and into the 20th century. The results of this research may not have allowed the construction of a paleo air-quality record; however, we were able to not only illustrate the successes of environmental regulations through gravestone weathering but also show how a land use based approach can be a useful tool in understanding and predicting the gravestone weathering rate throughout a region.

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