

Health risk associated with airborne particulate matter and its components in Jeddah, Saudi Arabia

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HEALTH RISK ASSOCIATED WITH AIRBORNE PARTICULATE MATTER AND ITS COMPONENTS IN JEDDAH, SAUDI ARABIA

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43 **ABSTRACT**

44 Samples of PM_{2.5} and PM₁₀ have been collected in all of four seasons at seven sites within the city
45 of Jeddah, Saudi Arabia. The samples have been analysed for a range of trace elements. There is a
46 large loading of wind-blown dust and the majority of elements are predominantly associated with
47 coarse particles. Enrichment factors, however, show that some elements are markedly enriched
48 above crustal abundance. Using mean data for the PM_{2.5} and PM₁₀ fractions from each of the seven
49 sampling sites, health risks have been estimated for particulate matter mass, the elements Cr, Mn,
50 Ni, Pb, As, Cd and V measured in this study, and polycyclic aromatic hydrocarbons using data from
51 an earlier study within Jeddah. Cancer risks are calculated from mean airborne concentrations and
52 cancer slope factors for the carcinogenic metals and PAH, but the cancer risks are relatively modest
53 compared to the lifetime risk of mortality due to PM_{2.5} exposure. The risks associated with
54 exposure to V and Mn are considered to be small, while concentrations of cadmium far exceed the
55 European Union Limit Value and World Health Organisation guideline. Cadmium shows a very
56 high crustal enrichment factor but is present predominantly in the coarse particle fraction suggesting
57 that local soils and surface dusts are unusually enriched in Cd relative to the global average. Using
58 national data for mortality rates, the excess mortality due to PM_{2.5} exposure has been calculated and
59 amounts to over 1100 deaths annually for the city of Jeddah.

60

61 **Keywords:** Particulate matter; PM_{2.5}; PM₁₀; health risk

62 1. INTRODUCTION

63 Saudi Arabia is a country with a fast growing population enumerated as 30.8 million in 2014. The
64 population is heavily focussed on the major cities and especially Riyadh and Jeddah. The city of
65 Jeddah is located on the Red Sea coast of Saudi Arabia and has a population of 3.98 million (in
66 2014). In addition to its resident population, the sea port and airport of Jeddah act as a gateway for
67 pilgrims entering Saudi Arabia for the traditional Hajj and Umrah in the Holy City of Makkah.
68 Jeddah extends considerably further from north to south than from east to west (see Figure 1) with
69 the Red Sea on its western border. However, to the north, south and east of Jeddah lie large areas of
70 desert which provides an extensive source for wind-blown dusts.

71

72 While there have been air quality studies in the inland city of Makkah (Al-Jeelani, 2009; Simpson et
73 al., 2014), and the coastal town of Yanbu to the north of Jeddah (Khalil et al., 2016), these have
74 focussed largely on gas phase pollutants and only the latter study provides limited data for
75 particulate matter concentrations. Mean concentrations of PM_{10} and $PM_{2.5}$ in Yanbu based on six
76 years of observations are reported as $70 \mu\text{g m}^{-3}$ and $60 \mu\text{g m}^{-3}$ respectively (Khalil et al., 2016). The
77 small differential between $PM_{2.5}$ and PM_{10} measured between 2000 and 2005 in Yanbu is rather
78 surprising and diverges from the experience of many other sites in western Saudi Arabia (e.g.
79 Khodeir et al., 2012).

80

81 There have been a number of studies within and close to the city of Jeddah. Kadi (2014) reports
82 measurements of total suspended particulate matter (TSP) collected with high volume samplers
83 together with analyses of Al, Ba, Ca, Cu, Mg, Fe, Mn, Zn, Ti, V, Cr, Co, Ni, As and Sr. These were
84 made at seven sites within Jeddah, and concentrations of the various metallic components and
85 crustal enrichment factors are reported. Enrichment factors of elements at the more polluted sites
86 range approximately from 10-60 whilst for Cu and Zn, these are much higher at some of the sites
87 with a peak value of over 700 for Cu at a site influenced by light industry and road transport

88 activities. The data show very large inter-site differences for the majority of the elements analysed.
89 In another paper, the same author (Kadi, 2009) also determined soil composition and reports a
90 strong elevation in lead and zinc content at heavily trafficked sites.

91
92 Khodeir et al. (2012) report data from seven sampling sites within Jeddah from samples collected in
93 2011. They report overall mean mass concentrations of $28.4 \pm 25.4 \mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$ and $87.3 \pm$
94 $47.3 \mu\text{g m}^{-3}$ for PM_{10} with considerable spatial and temporal variability. The average ratio of $\text{PM}_{2.5}$
95 to PM_{10} of 0.33 appears typical of data from western Saudi Arabia but is very different from the
96 pattern of behaviour reported above from Yanbu. Khodeir et al. (2012) provide a factor analysis
97 model with Varimax orthogonal rotation to determine the sources contributing to concentrations of
98 $\text{PM}_{2.5}$ and PM_{10} . These include heavy oil combustion, resuspended soil and a mixed industrial
99 source for both $\text{PM}_{2.5}$ and PM_{10} , and for $\text{PM}_{2.5}$ road traffic and a second industrial source, and for
100 PM_{10} , marine aerosol. The main contributor to $\text{PM}_{2.5}$ was identified as heavy oil combustion while
101 for PM_{10} it was wind-blown soil. Crustal enrichment factors relative to Fe in $\text{PM}_{2.5}$ were very high
102 for S (average 3000), Se (14000) and Cd (8800). The same elements were enriched in PM_{10} , with
103 Se (2400) and Cd (15000) showing the highest enrichment.

104
105 Alghamdi et al. (2015a) sampled PM_{10} , $\text{PM}_{2.5}$ and PM_1 fractions and measured the elemental
106 composition of $\text{PM}_{2.5}$ in Jeddah during March 2012. The data were disaggregated into dust storm
107 and non-dust storm periods. Based upon enrichment factors, it was concluded that in both non-dust
108 storm and dust storm periods, the main sources of Na, Mg, Si, K, Ca, Ti, Cr, Mn, Fe, Rb and Sr are
109 of a crustal type whereas S, Cl, Co, Cu, Zn, Ga, As, Pb and Cd as well as V and Ni are
110 predominantly anthropogenic. The conditions giving rise to dust storms were also considered.
111 Crustal enrichment factors relative to aluminium in $\text{PM}_{2.5}$ were highest for S (average 2792), As
112 (2581), Cd (28,699) and Pb (5879). Enrichment factors were highest during non-dust storm
113 conditions but the same elements also showed enrichment during dust storm conditions. From

114 samples collected in Riyadh, Alharbi et al. (2015) found that concentrations were considerably
115 higher in summer than winter which was attributed to dust storm activity. Crustal species such as
116 Fe, Mn, Ti, Ca and Mg were found at appreciably higher concentrations in summer.

117

118 Porter et al. (2014) analysed PM₁₀ data collected in 2010-2011 in sites in and around Jeddah and at
119 a remote background site for comparison. Data were collected with automated beta gauges making
120 diurnal variations in concentrations available. The PM₁₀ concentrations do not show a very
121 consistent seasonal pattern with major differences between the various sites. PM₁₀ showed a
122 reduced concentration at weekends relative to weekday concentrations clearly indicating an
123 anthropogenic influence. Data from Yanbu (Khalil et al., 2016) showed marked diurnal variations
124 that do not link clearly with road traffic activity and appear more likely to be influenced by the
125 speed of local winds.

126

127 Shaltout et al. (2013, 2015) have reported concentrations of PM_{2.5} and trace elements in the city of
128 Taif in western Saudi Arabia. In the more recent study (Shaltout et al., 2015) they report PM_{2.5}
129 concentrations of 50, 57 and 37 $\mu\text{g m}^{-3}$ respectively at traffic, industrial and residential sites.

130

131 Measurements of particulate matter made at a rural background site (Hada Al-Sham) about 60 km
132 east of the Red Sea coast and the city of Jeddah are reported by Lihavainen et al. (2016). Mean
133 PM₁₀ concentrations were $109 \pm 89 \mu\text{g m}^{-3}$ and PM_{2.5}, $38 \pm 68 \mu\text{g m}^{-3}$ hence showing a clear
134 dominance of coarse mode particles. PM₁₀ concentrations were markedly higher in January to June
135 than in July to December, but given the limited duration of sampling, it is difficult to attach any
136 significance to this. The mass fraction of PM_{2.5} was around 0.35 and showed maxima in February
137 and December with minimum concentrations in March, June and July. PM₁₀ and PM_{2.5} showed
138 diurnal variations which appeared to be related to traffic activity with reduced concentrations at the
139 weekend. The strength of the diurnal variation, apparently connected with traffic, is rather

140 surprising given that it was a rural site. However, the authors speculate that the strong sea breeze
141 circulation with diurnal changes in wind direction and speed may have been an important influence.
142 The fact that black carbon showed a very different diurnal pattern peaking at night suggests that
143 road traffic was probably not the cause.

144

145 Two studies have reported concentrations of particulate and vapour phase polycyclic aromatic
146 hydrocarbons (PAH) sampled at sites within and north of Jeddah (Alghamdi et al., 2015; Harrison
147 et al., 2016). Alghamdi et al. (2015) carried out a source apportionment study reporting that the
148 major identifiable sources of PAH were gasoline vehicles (17%), industrial sources, particularly the
149 oil refinery (33%) and diesel/fuel oil combustion (50%).

150

151 **2. EXPERIMENTAL**

152 Full details of the sampling sites and analytical methods are given by Khodeir et al. (2012). In the
153 interests of completeness, brief details are provided here. The sampling sites and brief details of
154 their characteristics are provided in Table 1, while Figure 1 shows their location within the city of
155 Jeddah and in relation to major local sources. In particular, the desalination plant is notable as it
156 burns heavy fuel oil and emits through two elevated chimneys. The older parts of Jeddah lie to the
157 south, where there is a concentration of light and heavy industries, mainly concentrated around the
158 port and refinery area (see Figure 1). In contrast, the north of Jeddah is more recently developed,
159 with less industry and lower population density. Hussein et al. (2014) provide a valuable map
160 which shows the distribution of light and heavy industries and major facilities in the city.

161

162 PM_{2.5} and PM₁₀ were sampled using an automated cartridge collector unit (ACCU) sampler in the
163 period June 2011 to June 2012. Daily samples of 24 hours duration were collected on alternate days
164 on 37 mm, 0.2 µm pore size Gelman Teflo filters. Chemical analysis was by energy dispersive x-

165 ray fluorescence after filter mass had been determined on a micro-balance (Mettler-Toledo Model
166 MT5).

167

168 Samples were collected through all seasons of the year, the number at each site appearing in Table
169 2.

170

171 **3. RESULTS AND DISCUSSION**

172 The sampling sites used in this study were the same as those used by Khodeir et al. (2012) for their
173 receptor modelling work, but the study now reported differs in important ways from the work of
174 Khodeir et al. (2012). Firstly, a substantially larger number of samples was collected, and at all
175 sites, samples were collected in all of the four seasons of the year. This was in order to estimate
176 annually-averaged exposure, rather than that in just one season of the year. The seasonal variations
177 have not been analysed as they are not directly relevant to the topic of this paper, which focusses on
178 the consequences of long-term exposure. Secondly, Khodeir et al. (2012) pooled their data and did
179 not look at it on an individual site basis. We now look at site-specific information for PM mass and
180 selected health-relevant trace constituents.

181

182 A large number of elements was analysed and the data are summarised for individual sites in
183 relation to means and standard deviations in Tables S1 to S7 in the Supplementary Information. As
184 this study is focussed upon the health risk associated with particulate matter exposures within the
185 city of Jeddah, the data analysis has focussed upon PM_{2.5} and PM₁₀ mass and a number of specific
186 chemical constituents for which there are significant health concerns, and for which regulatory
187 guidelines and standards are available. Those elements are chromium (Cr), nickel (Ni) and arsenic
188 (As), which are of concern because of their carcinogenicity, lead (Pb) which is a potent neurotoxin,
189 manganese (Mn) which can affect neuro-behavioural function, vanadium (V), which is a potent
190 respiratory irritant, and cadmium (Cd) which leads to an increased risk of renal dysfunction.

191 Regulatory standards and guidelines relating to chronic exposure to these constituents and to PM_{2.5}
192 and PM₁₀ mass appear in Table 3. This contains both concentration guidelines (listed as a
193 concentration) and cancer slope factors (presented as incremental lifetime risk per unit of
194 concentration). In the case of chromium, Cr(VI) is a potent respiratory carcinogen, while Cr(III) is
195 relatively benign, hence the cancer slope factors and concentration guideline relate only to the
196 former oxidation state.

197

198 Mean concentrations of the health-related particle size fraction masses and chemical species at the
199 seven sampling sites and the overall mean of all sites appear in Table 4. There has been no attempt
200 to elucidate seasonal patterns because of the limited number of samples collected in each season at
201 each of the sites (see Table 2). It is clear from Table 4 that PM₁₀ mass far exceeds PM_{2.5} mass at all
202 of the sites and that this is also the case for many of the elemental constituents. The split between
203 fine particles (PM_{2.5}) and coarse particles (PM_{2.5-10}) is shown for all constituents in Figure S1 and
204 for the elements of health concern, in Figure 2. It may be seen from Figure S1 that the typical
205 crustal elements, Ca, Ti, Fe, Si and Al are 90% or more in the coarse fraction consistent with a large
206 input of crustal dust to the samples as has been observed in earlier studies (Rushdi et al., 2013;
207 Hussein et al., 2014). Those elements of health concern which show a larger contribution from the
208 fine fraction indicative of anthropogenic sources are Ni, As, V and Pb, for which 40-60% lies in the
209 fine fraction. The question of anthropogenic contribution to concentrations has been further
210 examined through the calculation of crustal enrichment factors according to the method described
211 by Pant et al. (2015) and Table 5 shows averaged crustal enrichment factors for the elements of
212 concern calculated separately for the PM₁₀ and PM_{2.5} size fractions. If the enrichment factor of 5 is
213 taken as the threshold for a significant enrichment above crustal ratios, then in the PM₁₀ fraction, V
214 shows a slight enrichment, with As appreciably enriched, and Pb and Cd showing very large
215 enrichments. In the PM_{2.5} fraction, Ni now shows significant enrichment with a larger enrichment
216 of V and substantial enrichments of As, Pb and Cd.

217 Referring to Table 4, site 2 has the highest concentration of PM_{10} , but the second lowest of $PM_{2.5}$,
218 suggesting a local source of coarse dust, possibly resuspension from the dense traffic at this site.
219 Site 3 is located in a predominantly residential area, with substantial light industry locally, and a
220 visit to the site revealed recent tyre and waste oil burning. There is a marked contrast to site 1, also
221 in a residential area, but without intense vehicle traffic. Site 1 shows markedly lower
222 concentrations of both PM_{10} and $PM_{2.5}$ mass than the other sites as well as appreciably lower
223 concentrations of many of the trace elements, especially Pb and As. The site showing the highest
224 concentrations of Ni and V is site 6 which is located most closely to the oil refinery and the port and
225 shipyard, although with the prevailing winds coming predominantly from the NNW, it is unlikely to
226 have a high exposure to emissions, especially from the oil refinery. Nonetheless, the elevated
227 concentrations of these elements are indicative of a fuel oil combustion source influencing this site.
228 Some evidence of this is also seen in elevated concentrations at site 5 which is also in the area of
229 Jeddah closest to the oil refinery and port. Concentrations of Pb and As are elevated at all sites
230 except for rather lower concentrations at site 1 which is in a residential area in the north of Jeddah
231 and remote from major industrial activity. The highest concentrations of Pb in both the PM_{10} and
232 $PM_{2.5}$ size fraction appear at sites 3 and 4, and since leaded additives are not used in gasoline in
233 Saudi Arabia, must result from one or more local industrial sources.

234

235 Hussein et al. (2014) measured particle mass and number (D_p 0.25-32 μm) through the year 2012 at
236 a sampling site on the campus of King Abdulaziz University in Jeddah. The diurnal variation of
237 both PM_{10} and $PM_{2.5}$ on workdays showed a pattern typical of an influence of traffic emissions.
238 The concentration of total particle number, but not of $PM_{2.5}$ or PM_{10} mass showed a marked
239 elevation in a wind sector centred on 250° , leading Hussein et al. (2014) to infer that the industrial
240 city in the south of Jeddah is the main source of particulate matter. They also report that the PM_{10}
241 concentration shows a clear U-shaped dependence upon wind speed, which is characteristic of a
242 contribution of wind-blown dust at high wind speeds, with dilution of emissions below the

243 threshold for dust resuspension (Harrison et al., 2001). The occurrence of dust storm events in
244 Saudi Arabia is well documented (Alharbi et al., 2013; Kutiel and Furman, 2003).
245
246 Aburas et al. (2011) measured lead concentrations in the air of Jeddah in 2008-9, seven years after
247 the phase-out of leaded gasoline in Saudi Arabia. The mean lead content of PM_{2.5} was 73 ng m⁻³
248 (range 4-446 ng m⁻³), with crustal enrichment factors (relative to K) at four sites of 761 to 15080.
249 Concentrations were markedly higher at two sites in the south of Jeddah (King Abdulaziz
250 University campus and Alfayhaa district) which was attributed to very high traffic density and the
251 proximity to the industrial zone. Rushdi et al. (2013) report concentrations and enrichment factors
252 (relative to Al) for Na, Mg, Al, Si, P, S, K, Ca, Mn, Fe Ni, Cu, Zn and Ba. The mean enrichment
253 factor for Ni was 16.3. The only other analyte showing an elevated enrichment factor was S,
254 suggesting fuel oil combustion as the source. Measurements from Taif in western Saudi Arabia
255 made on samples collected in 2011-12 showed average concentrations of Mn of 34-52 ng m⁻³; Ni of
256 3.5-4.0 ng m⁻³; and Pb of 6.3-8.5 ng m⁻³ across traffic, industrial and residential sites. These are in
257 all cases lower than those measured in our study and suggest that Jeddah is subject to greater levels
258 of pollutant emissions.

259
260 The results for Cd are quite surprising. This shows substantial enrichment relative to crustal
261 abundance in both the PM₁₀ and PM_{2.5} size fractions (Table 4) and the predominant presence in
262 coarse particles (see Figure 1) seems to suggest either that the local soils have an abnormal
263 geochemical enrichment of Cd or that there is a widespread source of coarse Cd arising from an
264 industrial process. However, such a process would need to be widespread in order to cause such an
265 extensive enrichment across all of the sites. It is notable that Alharbi et al. (2015) measured
266 concentrations of Cd in PM₁₀ in Riyadh of ca. 180 ng m⁻³ during dust storm periods which exceeded
267 the non-dust storm concentrations by a factor of 2.3-fold. Such concentrations are broadly
268 consistent with those in our measurements from Jeddah which strongly suggests an abnormal

269 enrichment of cadmium in surface soils in Saudi Arabia. Alghamdi et al. (2015a) also report very
270 high enrichment factors for Cd in PM_{2.5} sampled in western Saudi Arabia with average
271 concentrations in this size fraction in excess of 10 ng m⁻³, and appreciably higher on dust storm than
272 non-dust storm days. Unfortunately, Cd concentrations were not reported by Kadi (2014) and Cd
273 was not included in the factor analysis conducted by Khodeir et al. (2012), and consequently that
274 work does not shed light on the likely sources of Cd.

275

276 **3.1 Health Risk Assessment**

277 Comparing the mean concentrations in Table 4 with the standards and reference concentrations in
278 Table 3, it is clear that concentrations of V are not a matter of concern. However, concentrations of
279 Cd, even those in the PM_{2.5} fraction, exceed the recommendation of WHO (2000) and the EU Limit
280 Value of 5 ng m⁻³. The likely health consequences of such an exceedence are very hard to estimate
281 particularly as there are no quantitative exposure-response functions relating airborne
282 concentrations of Cd to the progression of kidney disease. There seems to be ample evidence for
283 high concentrations of Cd in the atmosphere of Saudi Arabia and this warrants further study in
284 relation to potential risks for human health. Concentrations of PM₁₀ far exceed the WHO and EU
285 requirements for this size fraction, and those for PM_{2.5} exceed the WHO (2006) recommendation at
286 all sites and exceed the EU recommendation of 25 µg m⁻³ at site 3, but not the other sampling sites.

287

288 In Table 6, health risks associated with the mean exposures have been calculated for those
289 pollutants for which there are quantitative exposure-response functions available. In addition to the
290 pollutants in Table 4, polycyclic aromatic hydrocarbons have been included using the cancer slope
291 factor recommended by WHO (2000) and a mean concentration from three sites within Jeddah
292 reported by Alghamdi et al. (2015b). The concentration used is for benzo(a)pyrene, which
293 following the guidance of WHO (2000), is taken as a marker compound for the PAH mixture. As
294 recommended by WHO the unit risk has been applied to the concentration of this compound, but

295 the risk estimation applies to the entire PAH mixture. Considering the chemical carcinogens, the
296 highest risk appears to apply to Cr, but the value is an upper limit which assumes that all of the Cr
297 exposure is in the form of Cr(VI) which is very improbable. This therefore represents an upper
298 limit to the risk associated with Cr exposure. The risk is quite high and studies of the oxidation
299 state of Cr in local airborne dusts would be well justified. Risks associated with exposure to As and
300 PAH are of somewhat lesser magnitude but still exceed those calculated for Ni exposure.

301

302 In the case of PM_{2.5}, a coefficient for all cause mortality has been taken from WHO (2006), and
303 rather than the usual mortality burden calculation, an incremental risk has been estimated for the
304 mean concentration exposure assuming a mean life expectancy of 74.5 years. This reveals a risk
305 associated with PM_{2.5} exposure which substantially exceeds the risks associated with the chemical
306 carcinogens, which is logical as the PM_{2.5} exposure includes exposure to the associated chemical
307 carcinogens which present a subset of the mortality risks associated with PM_{2.5} exposure. The work
308 of Pope et al. (2002) and Lepeule et al. (2012) has shown a significant association between PM_{2.5}
309 exposure and lung cancer mortality in the ACS cohort, but the lung cancer risk is only a component
310 of the overall all cause mortality risk. Harrison et al. (2004) considered whether exposure to the
311 chemical carcinogens within PM_{2.5} could explain the carcinogenicity demonstrated by Pope et al.
312 (2002). Their conclusion was that it was quite plausible that the chemical carcinogens present could
313 explain the observed carcinogenicity, which serves to confirm the view that the risk associated with
314 exposure to the specific chemical carcinogens is only one part of the overall risk to health from
315 PM_{2.5} exposure which has been associated with a range of cardiopulmonary diseases. The mean
316 concentration of Ni in the Jeddah samples falls significantly below the EU and EPAQS
317 recommendation of 20 ng m⁻³ serving to confirm that the cancer risks associated with Ni exposure
318 are not excessively high. However, the recommendations of the EU and EPAQS for As of 6 ng m⁻³
319 and 3 ng m⁻³ respectively are appreciably exceeded in Jeddah and there is a good case for further
320 investigating the source of emission of this element and seeking to take action to mitigate the risk.

321 The USEPA IRIS reference concentration of 50 ng m⁻³ for manganese is a highly precautionary
322 value designed to protect against impairment of neuro-behavioural function. It is exceeded by a
323 factor of up to almost four-fold at the Jeddah sampling sites, but this factor is relatively small
324 compared to the large in-built margin of safety and it seems unlikely that manganese presents an
325 important risk to public health. The crustal enrichment factors in Table 5 show little evidence for
326 anthropogenic emissions and hence the majority of exposure is from crustally-derived material in
327 which the manganese may be significantly less bio-accessible than in the industrial exposures used
328 as the basis for setting the reference concentration. In the case of lead, the exposure concentrations
329 in PM₁₀ at many of the sites exceed the USEPA (1996) and EPAQS (1998) recommendations. Air
330 quality standards for lead are designed to protect the developing infant from neuro-developmental
331 effects which have been shown to lead to a reduction in IQ. The fact that the concentrations in
332 Jeddah exceed the regulatory guidelines from these jurisdictions is a matter of some concern. The
333 lead concentrations reported by Aburas et al. (2011) are considerably exceeded by the recent
334 measurements suggesting that there is a significant industrial source or sources in the south of
335 Jeddah which is responsible for the substantial elevation of concentrations at sites in this part of the
336 city. It is notable that lead concentrations at the most northerly site (site 1) are very much lower and
337 within the acceptable range.

338

339 Very few studies have provided data on the effects of mixtures of pollutants, and it is not possible to
340 comment on the possible interactions. It can reasonably be expected that the effects of the chemical
341 carcinogens are additive, but as noted above this effect is included in the overall toxic effect of
342 PM_{2.5} as an exposure metric.

343

344 **3.1.1 *Premature mortality due to PM_{2.5} exposure***

345 The latest demographic information available for Jeddah relates to the year 2014. It lists
346 populations for 60 areas of the city, which have been classified according to their similarity to the

347 areas represented by the sampling sites in Figure 1 and Table 1. The land use types are shown
348 diagrammatically in Figure 3, and are listed in Table S8, both of which include population data.
349 Table 7 shows a calculation of premature mortality according to the different district types for
350 Jeddah, using both the 2014 population data for the districts listed in Table S8, as well as the total
351 Jeddah population, including districts beyond the boundaries shown in Figure 3, making the
352 questionable assumption that growth in the population is distributed in the same way as the 2014
353 population within Table S8.

354

355 In the approach used to estimate the burden of premature mortality, the burden is linearly related to
356 both the exposure concentration and the population exposed. Thus for a similar concentration of
357 $PM_{2.5}$, the overall number of premature deaths will be greater in a larger city, while in a city of
358 similar size to Jeddah, the burden will be greater if the mean $PM_{2.5}$ concentration is higher. The
359 World Health Organization has recently reviewed air quality data from around the world (WHO,
360 2016). While measured data for PM_{10} are plentiful, measurements of $PM_{2.5}$ are far less abundant,
361 and in many cases have been crudely estimated from the PM_{10} data. Measured concentrations vary
362 greatly between countries. Australia reports some of the lowest $PM_{2.5}$ concentrations, with annual
363 means ranging from 5-10 $\mu g m^{-3}$. European concentrations are typically a little higher with annual
364 means mostly in the range of 10-20 $\mu g m^{-3}$ in western Europe and 20-40 $\mu g m^{-3}$ in eastern Europe.
365 Concentrations in China and India are typically higher, with most in the range of 30-100 $\mu g m^{-3}$ and
366 some exceeding 100 $\mu g m^{-3}$. The mean of 10 sites in Delhi in 2013 was 122 $\mu g m^{-3}$. The WHO
367 data for $PM_{2.5}$ concentrations in Saudi Arabia are all estimated from PM_{10} measurements and range
368 from 65 to 156 $\mu g m^{-3}$ in 2014. These include a mean for Jeddah of 68 $\mu g m^{-3}$. This concentration
369 well exceeds those reported for Jeddah in Table 4, but this may be due, at least in part, to the
370 calculation method of WHO as opposed to direct measurement. This wide range of $PM_{2.5}$ data
371 implies that many countries will have considerably lower mortality rates per million of population

372 due to PM_{2.5} exposure than calculated in this work for Jeddah, while in others the rates will be
373 higher.

374

375 A further factor to be considered is that almost all buildings and cars in Jeddah are air conditioned.
376 Janssen et al. (2002) have shown that in the United States there appear to be lower rates of some
377 diseases associated with PM₁₀ exposure in areas with a high percentage of homes with air
378 conditioning, as this can reduce exposures. This implies that the estimated premature mortality
379 shown in Table 7 may be an over-estimate, but this effect has not to date been established for PM_{2.5}
380 exposure.

381

382 **4. CONCLUSIONS**

383 It is clear from the high concentrations of the crustally-related elements such as Ca, Fe and Si that
384 crustal material in the form of wind-blown soil and dust makes up a substantial proportion of
385 particulate matter in Jeddah. It is predominantly in the coarse (PM_{2.5-10}) size fraction, but a
386 significant proportion lies also in the fine fraction. Of the health-related elements, only Ni, Pb, As,
387 Cd and V show significant anthropogenic enrichment which is most marked in the fine particle
388 fraction, except for Cd. Comparison with health-related guidelines suggest that the risks associated
389 with exposure to Mn and V are very modest or wholly negligible, while the chemical carcinogens
390 Ni, Cr and As present a smaller risk from chronic exposure than does exposure to PM_{2.5}. This is
391 unsurprising as PM_{2.5} exposure has been shown to be associated with a range of cardiopulmonary
392 diseases, including lung cancer which is only a sub-component of the overall health impact of PM_{2.5}
393 exposure. Inclusion of data for PAH from an earlier study shows that these also do not represent a
394 large risk in relation to the overall risk of PM_{2.5} exposure. The largest potential risk from the
395 chemical carcinogens relates to Cr, but the calculated risk is an upper limit which makes the
396 pessimistic and probably unrealistic assumption that all of the Cr is present in the Cr(VI) oxidation
397 state. Were this oxidation state to make up only a small proportion of the Cr content, then the

398 estimated risk would be greatly reduced. The enrichment factor for Cr is very small indicating that
399 most Cr arises from the local soils and dusts and could not readily be abated. One unexpected
400 finding is the very high enrichment factor for Cd. The concentrations measured in this study are not
401 dissimilar from those reported in earlier studies from both Jeddah and Riyadh, and the fact that the
402 enrichment is broadly similar in both the fine and coarse particle fractions suggests that there is an
403 abnormal geochemical abundance of Cd in local surface soils which could be readily verified by
404 chemical analysis. The calculated Cd exposures exceed health-based guidelines by a small factor in
405 the PM_{2.5} size fraction and a much larger factor in PM₁₀. However, if the Cd is associated with
406 surface soils, it seems likely that its bio-accessibility is limited and hence the risk to health may be
407 relatively modest.

408

409 The health risk associated with chronic exposure to PM_{2.5} has been estimated in the form of
410 premature mortality. This shows that total deaths influenced by chronic exposure to PM_{2.5} exceed
411 1100 for the 2014 population of Jeddah, making this a very significant public health problem.

412

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538 **TABLE CAPTIONS**

539

540 **Table 1:** Characteristics of sampling sites.

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542 **Table 2:** Seasonal distribution of sample numbers at the seven sites.

543

544 **Table 3:** Air quality standards, reference concentrations and cancer slope factors for chronic
545 respiratory exposure to relevant aerosol components.

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547 **Table 4:** Mean concentrations of health-relevant size fractions and chemical species at the
548 seven sites.

549

550 **Table 5:** Average crustal enrichment factor for the elements of concern.

551

552 **Table 6:** Health risk associated with the mean exposures.

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554 **Table 7:** Estimated premature mortality due to PM_{2.5} exposure in Jeddah.

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558 **FIGURE CAPTIONS**

559

560 **Figure 1:** Location of sampling sites (stars) and major industrial sources (circles) in Jeddah,
561 Saudi Arabia.

562

563 **Figure 2:** Average coarse and fine percentages of the health-relevant elements and particulate
564 matter (PM) mass.

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566 **Figure 3:** Map of Jeddah, showing the districts according to land use type (colour), population
567 (circles) and the air sampling sites (stars).

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569 **Table 1:** Characteristics of sampling sites.

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	District	Population	Type	Characteristics
1	Al-Muhammadiyah	28315	Residential	Typical residential with no intense traffic
2	Al-Rehab	43400	Residential	Influenced by heavy traffic from the nearby highway and the crowded Tahleya street
3	Al-Rughama	38437	Suburban	Heavy traffic, open burning of batteries, electric wires, and tyres. Some significant marble workshops
4	University	141277	Urban	Dense traffic
5	Al-Nuzlah/Al Yamaneyyah	53602	Urban	Dense traffic, some car repair workshops
6	Pitrumin	41774	Urban	Refinery emissions
7	Al-Alfiyyah	43037	Residential	Refinery emissions (less affected than Pitrumin)

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572 **Table 2:** Seasonal distribution of sample numbers at the seven sites.

Site/Season	1	2	3	4	5	6	7	All sites
Spring	7	8	7	6	7	7	50	92
Summer	7	2	5	7	6	7	37	71
Autumn	6	7	7	7	7	7	37	78
Winter	6	9	5	7	7	5	47	86
Totals	26	26	24	27	27	26	171	327

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575 **Table 3:** Air quality standards (annual mean), reference concentrations and cancer slope factors for
 576 chronic respiratory exposure to relevant aerosol components.
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Constituent	WHO (2000)	WHO (2006)	USEPA (1996)	EU (2016)	EPAQS (1998; 2009)
PM _{2.5}		10 µg m ⁻³	12 µg m ⁻³	25 µg m ⁻³	
PM ₁₀		20 µg m ⁻³		40 µg m ⁻³	
Cr(VI)	4 x 10 ⁻⁵ /ng m ⁻³		1.2 x 10 ⁻⁵ /ng m ⁻³		0.2 ng m ⁻³
Mn			50 ng m ⁻³		
Ni	3.8 x 10 ⁻⁷ /ng m ⁻³			20 ng m ⁻³	20 ng m ⁻³
Pb			150 ng m ⁻³	500 ng m ⁻³	250 ng m ⁻³
As	1.5 x 10 ⁻⁶ /ng m ⁻³		4.3 x 10 ⁻⁶ /ng m ⁻³	6 ng m ⁻³	3 ng m ⁻³
Cd	5 ng m ⁻³			5 ng m ⁻³	
V	1000 ng m ⁻³				

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Table 4: Mean concentrations of health-relevant size fractions and chemical species at the seven sites.

Site/Analyte	1	2	3	4	5	6	7	All sites
PM₁₀ fraction								
PM ₁₀ mass (µg m ⁻³)	69.8	143	120	112	110	104	94.0	108
Cr (ng m ⁻³)	4.9	12.1	14.2	10.3	10.5	7.4	8.1	9.6
Mn (ng m ⁻³)	56.4	153	137	105	85.6	100	95.7	105
Ni (ng m ⁻³)	6.6	12.1	12.6	12.6	12.4	15.0	11.6	11.7
Pb (ng m ⁻³)	38.6	595	695	695	84.6	379	440	450
As (ng m ⁻³)	3.3	26.5	19.7	19.7	5.8	11.4	15.2	15.2
Cd (ng m ⁻³)	80.2	194	145	145	100	231	98.4	140
V (ng m ⁻³)	20.6	32.6	27.8	27.8	34.2	43.5	26.8	30.7
PM_{2.5} fraction								
PM _{2.5} mass (µg m ⁻³)	14.2	17.5	21.6	21.6	23.4	24.2	21.8	20.7
Cr (ng m ⁻³)	0.5	1.1	1.7	1.7	1.6	0.9	1.2	1.2
Mn (ng m ⁻³)	5.3	9.7	12.2	12.2	9.8	9.5	8.4	9.4
Ni (ng m ⁻³)	2.6	2.8	3.6	3.6	4.6	7.2	3.6	4.1
Pb (ng m ⁻³)	31.3	256	443	443	59.8	137	209	248
As (ng m ⁻³)	0.8	15.6	10.3	10.3	1.8	5.3	6.9	8.4
Cd (ng m ⁻³)	9.5	13.5	9.4	9.4	9.8	11.9	6.7	11.0
V (ng m ⁻³)	9.1	8.8	9.5	9.5	16.3	25.8	11.7	13.4

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586 **Table 5:** Average crustal enrichment factor for the elements of concern * .
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Element/ Size fraction	Cr	Mn	Ni	Pb	As	Cd	V
PM ₁₀	1.4	3.0	3.4	810	88	20,200	5.9
PM _{2.5}	1.8	2.7	12.0	4533	491	16,100	26

* Relative to Al

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Table 6: Health risk associated with the mean exposures.

Pollutant	End Point	Coefficient	Mean Concentration	Lifetime Risk
PM _{2.5} ^a	Mortality (all cause)	4%/10 µg m ⁻³	22.5 µg m ⁻³	1.2 x 10 ⁻³
Cr ^b	Cancer	4 x 10 ⁻⁵ /ng m ⁻³	9.6 ng m ⁻³	3.8 x 10 ⁻⁴
Ni	Cancer	3.8 x 10 ⁻⁷ /ng m ⁻³	11.7 ng m ⁻³	4.4 x 10 ⁻⁶
As	Cancer	1.5 x 10 ⁻⁶ /ng m ⁻³	15.2 ng m ⁻³	2.3 x 10 ⁻⁵
PAH (B(a)P) ^c	Cancer	8.7 x 10 ⁻⁵ /ng m ⁻³	0.23 ng m ⁻³	2.0 x 10 ⁻⁵

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Notes:

- (a) Calculation based upon a life expectancy of 74.5 years (World Health Rankings, 2016)
- (b) Calculation assumes all Cr is present as Cr(VI) which is extremely unlikely, and hence this is an upper limit to risk
- (c) B(a)P concentrations measured in Jeddah by Alghamdi et al. (2015); mean of particulate concentration at three sites

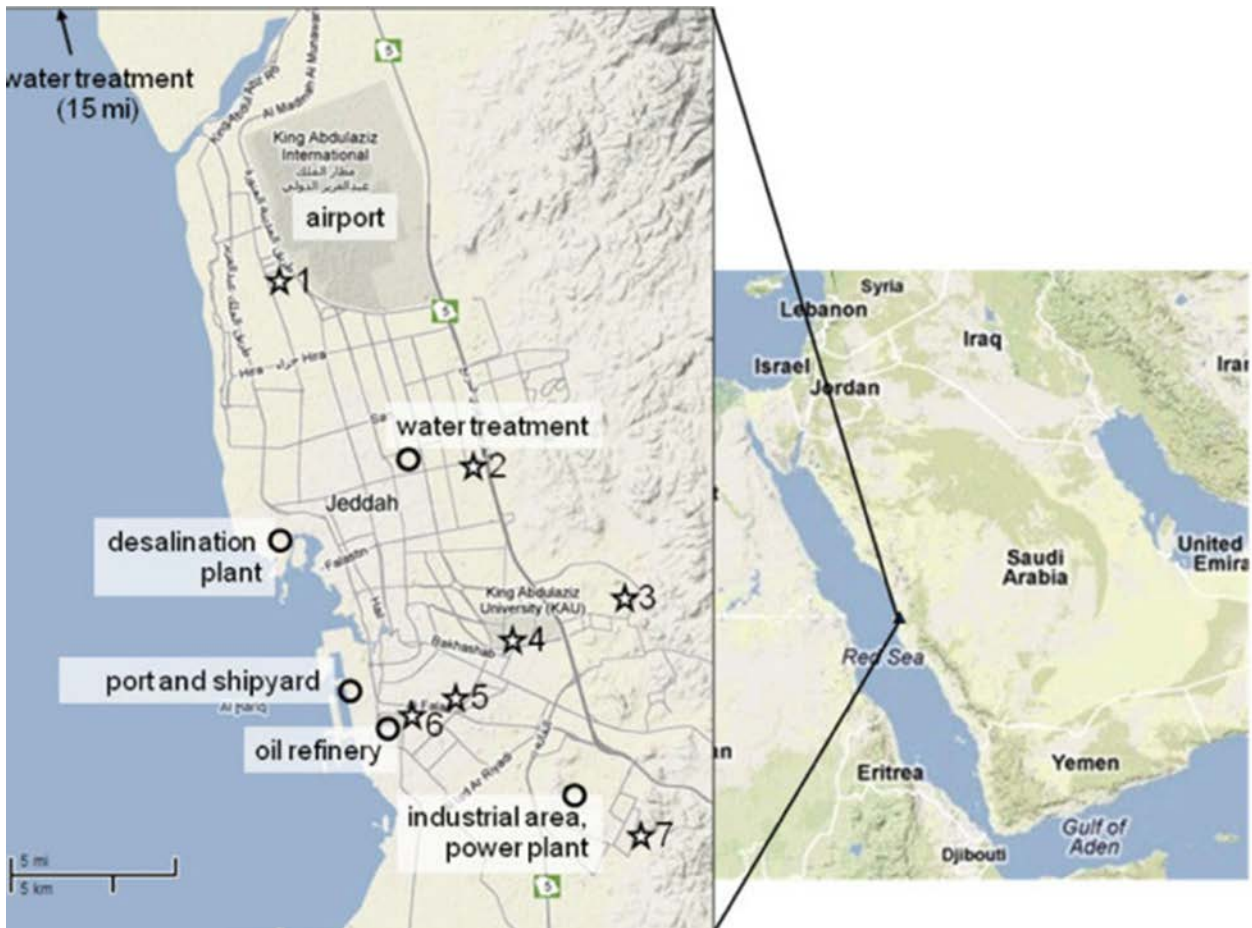
Table 7: Estimated premature mortality due to PM_{2.5} exposure in Jeddah.

District Type	PM _{2.5} (µg m ⁻³)	Total Population (2014) (thousand) ^a	Premature Deaths ^{b,c}	Total Premature Deaths ^{b,d}
Residential (1)	14.2	274	53	77
Residential (2)	17.5	392	94	136
Residential (3)	21.8	211	63	91
Suburban	21.6	173	51	74
Urban (1)	21.6	1153	341	494
Urban (2)	23.4	307	98	142
Urban (3)	24.2	234	77	112
TOTAL		2744	777	1126

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Notes:

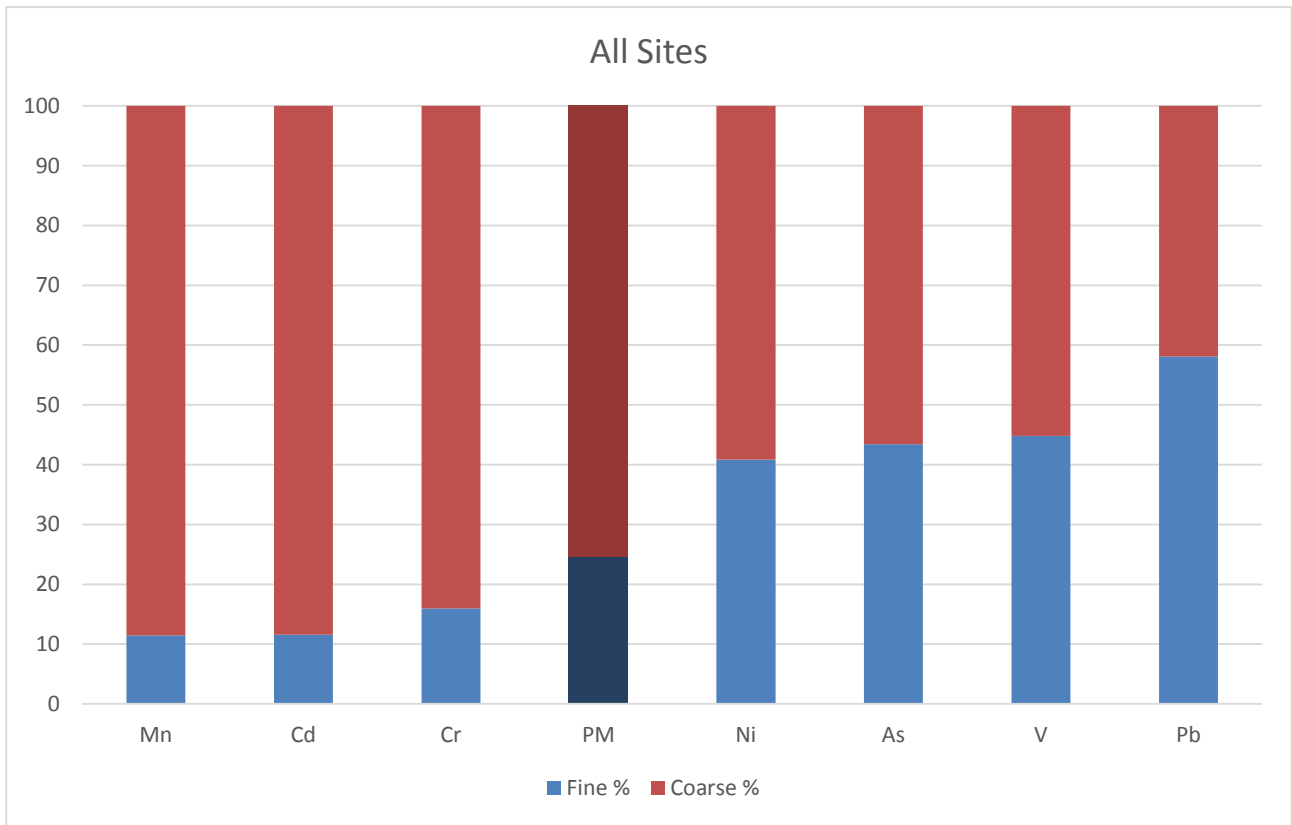
- ^a Population data from Jeddah Council (personal communication).
- ^b Based upon a crude death rate of 3.42 per 1000 in 2015 (Index Mundi, 2016).
- ^c Based on population for 2014 from districts listed in Table S8.
- ^d Extrapolated to total population of Jeddah in 2014.



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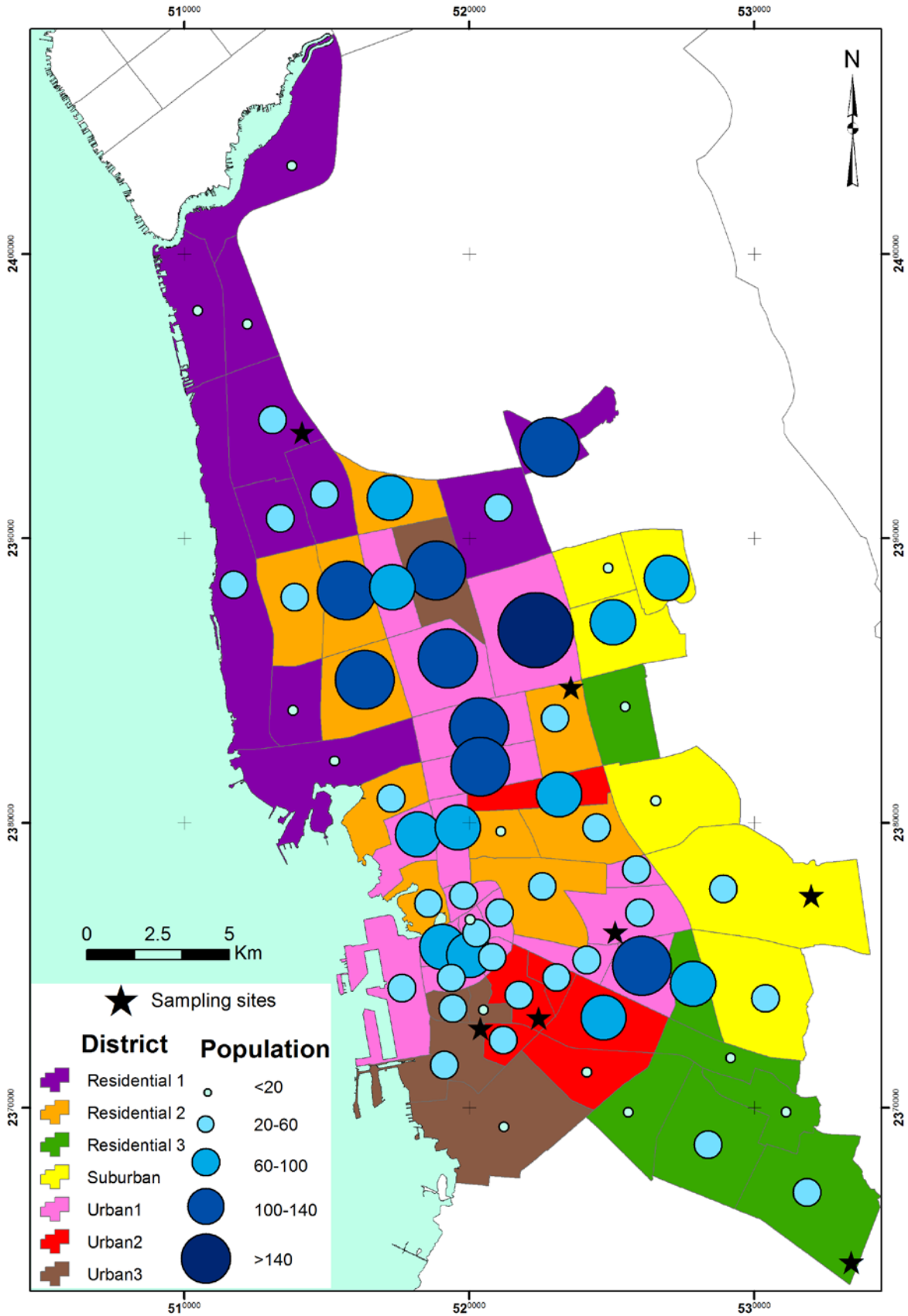
Figure 1: Location of sampling sites (stars) and major industrial sources (circles) in Jeddah, Saudi Arabia.

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Figure 2: Average coarse and fine percentages of the health-relevant elements and particulate matter (PM) mass.



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Figure 3: Map of Jeddah, showing the districts according to land use type (colour), population (circles) and the air sampling sites (stars).