

## Ozymandias in the Anthropocene:

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# 1 Ozymandias in the Anthropocene: The city as an emerging landform

2

## 3 Abstract

4 The extent of urban areas is rapidly expanding across the globe, both horizontally and  
5 vertically. Whilst natural and social scientists have examined the impacts of this urbanisation  
6 upon earth system and social processes, to date researchers have largely overlooked how in  
7 turn earth system processes can act upon this urban fabric to produce hybrid landforms.

8 Unique pseudokarst landforms are found within the urban fabric, including urban stalactites  
9 and urban sinkholes. Additionally, both the chronic and acute degradation of urban buildings  
10 can form rubble and dust which if left in situ will be shaped by fluvial and aeolian processes.

11 For many of these urban geomorphological processes the neglect or abandonment of parts of  
12 the urban network will facilitate or accelerate their influence. If there are economic, climatic  
13 or social reasons for abandonment or neglect these processes are likely to reshape parts of the  
14 urban fabric into unique landforms at a range of scales. We contend that researchers need to  
15 explicitly consider the urban fabric as an Anthropocene landform and that by doing so  
16 important insights can be gained into urban hazards and geomorphological processes.

17 Shelley's Ozymandias, in which the eponymous king failed to account for the effects of earth  
18 system processes acting on "mighty" urban structures over time, serves as an important  
19 reminder of the impermanence of our urban works and the need to recognize and understand  
20 the processes acting upon them.

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26 **Ozymandias**

27 I met a traveller from an antique land  
28 Who said: Two vast and trunkless legs of stone  
29 Stand in the desert. Near them, on the sand,  
30 Half sunk, a shattered visage lies, whose frown  
31 And wrinkled lip, and sneer of cold command  
32 Tell that its sculptor well those passions read  
33 Which yet survive, stamped on these lifeless things,  
34 The hand that mocked them and the heart that fed.  
35 And on the pedestal these words appear:  
36 "My name is Ozymandias, king of kings:  
37 Look on my works, ye Mighty, and despair!"  
38 Nothing beside remains. Round the decay  
39 Of that colossal wreck, boundless and bare  
40 The lone and level sands stretch far away. (Percy Bysshe Shelley, 1818)

41

42

43 The number of people living in cities now exceeds those who do not. It is estimated that 54  
44 percent of the world's population reside in urban areas and this is expected to rise to 66  
45 percent by 2050 (United Nations, 2015). Coincident with a rise in urban population is an  
46 increase in rate of expansion of densely populated areas, with an expected tripling of urban  
47 areas between 2000 and 2030 from 0.5% to 1.5% of the planet's land area (Angel et al., 2011,  
48 Seto et al., 2012). Turning attention from horizontal to vertical sprawl, researchers have also  
49 considered how cities are expanding into new strata where technologies allow for deeper  
50 excavation (Graham, 2016). Researchers working in both physical and human geography

51 have sought to understand the effects of this urbanisation on both the planet and on human  
52 society (e.g. Chin, 2006, Dye, 2008, Gong et al., 2012, Hamel et al., 2013, Pile and Thrift,  
53 2000, Singh et al., 2002, Tatem et al., 2013). Less research has given consideration to how  
54 the fundamental physical processes which shape landforms in nature interact with the built  
55 urban environment.

56

57 The Anthropocene is an interesting frame for this line of enquiry precisely because it is a  
58 concept that straddles the line between physical and human geography where particular  
59 attention is levelled at anthropogenic effects on environmental processes (e.g. Brown et al.,  
60 2017, Brown, 1970, Goudie and Viles, 2016, Graham and Marvin, 2001, McCann and Ward,  
61 2011, Pacione, 2009, Steffen et al., 2007, Tarolli and Sofia, 2016, Thomas, 1956). Within  
62 geographical and earth sciences the focus on exploring the Anthropocene as a theoretical  
63 framework has so far been largely restricted to humans as agents of environmental change  
64 either developing new landforms, or altering earth surface processes (e.g. Brown et al., 2017,  
65 Price et al., 2011, Tarolli and Sofia, 2016). Examples of Anthropocene geomorphological  
66 forms include the large scale excavations associated with mining operations, agricultural  
67 terracing and the change in land cover associated with development of cities (Price et al.,  
68 2011, Tarolli et al., 2014, Tarolli and Sofia, 2016). In addition to direct changes to  
69 landscapes, other researchers have looked at the effects of humans upon processes, exploring  
70 ways in which land use can change hydrological (Syvitski et al., 2005, Tooth et al., 2009) and  
71 aeolian (Li et al., 2009, Mauz et al., 2005, Wang et al., 2013) processes for example. Taken  
72 one step further however, we might then consider a less anthropocentric approach where  
73 environmental process go to work on human-built structures to create hybrid landforms  
74 (Whatmore, 2002). Weisman (2008), for instance, considers how cities may change should  
75 humans vanish, however his focus was largely on the effects of plants and animals in

76 recolonizing urban space with little explicit consideration of the reshaping of the urban  
77 landscape by geomorphological processes. At much longer timescales both Weisman (2008)  
78 and Zalasiewicz (2008) consider how the remains of the urban infrastructure might be  
79 preserved in the geological record. We suggest here more explicit consideration of cities and  
80 other urban infrastructure as alternative landforms upon which geomorphological processes  
81 are acting is needed. If we frame geomorphological processes as fundamentally erosional or  
82 depositional in nature, then it follows that hybrid urban geomorphology would consider the  
83 removal of material from the urban environment and the deposition of material upon the  
84 urban fabric as a substrate. In both cases we can ask whether, given sufficient time, this  
85 would yield unique hybrid 'landforms' which have not previously existed prior to the  
86 Anthropocene.

87

88 Urban weathering and formation of Anthropocene regolith

89

90 Researchers have long studied the effects of weathering processes on man-made structures,  
91 and how these processes differ within urban, as opposed to non-urban environments (e.g.  
92 Inkpen and Jackson, 2000, Searle and Mitchell, 2006, Smith et al., 2005, Török et al., 2011).  
93 However, typically this research has been in the context of the effects upon material surfaces  
94 over management timescales on the order of  $10^1$  years. Weathering is a fundamental  
95 geomorphological process which renders rock into sediment particles (regolith) and reshapes  
96 rock surfaces, typically at very slow rates. The current focus of research on urban weathering  
97 has been on the mechanisms involved and the small scale landforms that result from this  
98 'reshaping' (e.g. alveolar weathering, surface crusting and pitting). However, if the stone  
99 fabric of the urban landscape is considered as an Anthropocene geological formation, then  
100 over decadal timescales weathering processes will develop Anthropocene urban regoliths as

101 well as more intensively reshaped surfaces. The move towards urban greening, where  
102 infrastructure is designed, or revised, to incorporate green spaces upon and within structures  
103 shows the urban fabric already acts as an alternative surficial geology hosting  
104 biogeomorphological processes. In addition to weathering, other more acute erosional  
105 processes can act upon the urban fabric to generate regolith through structural collapse, for  
106 example through earthquakes.

107

108 Although it has rarely been conceived in such a way, destructive urban warfare can be seen as  
109 a form of Anthropocene geomorphological process; as the use of high explosives in the urban  
110 environment causes the destruction of buildings and creation of rubble with a range of  
111 particle sizes (Graham, 2011, Weizman, 2012). For example warfare in the Syrian city of  
112 Aleppo between 2011 and 2014 is estimated to have caused damage or destruction to 302,000  
113 housing units, 52% of the pre-war housing in the city, the majority of which is multi-storey  
114 apartment blocks (United Nations, 2014). A UN report observed that piles of rubble and  
115 debris are accumulating in Aleppo (United Nations, 2014, 11). Typically, this material,  
116 whether formed by chronic or acute processes, will be cleared during maintenance or  
117 reconstruction of the urban infrastructure. However, if there are social conditions such as  
118 abandonment (McLeman, 2011) or neglect, which precludes removal of this urban regolith,  
119 then it would then be expected to be shaped by other fundamental aeolian, fluvial and  
120 biogeomorphological processes. The timescales over which these processes operate, the  
121 morphology of the resultant landforms and their persistence or transience in the landscape  
122 over decadal timescales are entirely unknown, yet much information could be gleaned from  
123 cities like London, where abandoned tube stations were isolated and persevered by Luftwaffe  
124 bombing runs which destroyed surface structures during the Second World War  
125 (Dobraszczyk et al., 2016, Garrett, 2015). Additionally, urban areas which have been

126 abandoned due to disaster such as at Chernobyl or Fukushima, or neglected due to economic  
127 downturns and/or social unrest such as Detroit (Dobraszczyk, 2010, Moore and Levine, 2010)  
128 would be useful case studies. Although building materials and styles have changed  
129 extensively throughout history, an effective understanding of these processes could also aid  
130 archaeological research; shedding light on how abandoned and destroyed urban areas are  
131 reshaped by earth surface processes and thus help interpret the forms which may be preserved  
132 in the archaeological record (DeSilvey, 2006). Such an approach, of forecasting archaeology,  
133 has many parallels with the work of Virilio (1994) on Atlantic coastal bunkers from the  
134 Second World War, where much of the monolithic concrete architecture created by Hitler's  
135 architect Albert Speer is beginning to fold into the landscape and shape, for instance, dune  
136 formation. In turn, further geomorphological insights could be gained by considering ancient  
137 abandoned cities as landforms which could potentially be used cautiously as a space-for-time  
138 substitution. Over even longer timescales, an understanding of how urban forms are reshaped  
139 by earth processes, coupled with tectonic setting (Zalasiewicz, 2008), could help to forecast  
140 their sedimentological characteristics and potential for preservation in the geological record.

141

#### 142 Urban Stalactites

143

144 Concrete has been used as a building material since at least the time of the Roman Empire,  
145 but became ubiquitous in the 20<sup>th</sup> century; first through World War II defensive structures  
146 (again, see Virilio, 1994), and then in urban developments, particularly in association with  
147 the Brutalist architectural movement (Mould, In Press). If we consider cement as a form of  
148 sedimentary rock, its high calcium oxide content of around 66% (Kosmatka et al., 2011)  
149 means it is broadly analogous to limestone and would be subject to similar geomorphological  
150 processes and could thus potentially form pseudokarst (see Eberhard and Sharples, 2013,

151 Halliday, 2007 for discussions of 'pseudokarst' formations). Specifically, it has been  
152 documented that concrete and lime mortar can be weathered by dissolution processes,  
153 leaching calcium from the concrete; these dissolved ions can then precipitate out as stalactite  
154 and stalagmite formations as shown in Figure 1A-E (Allison, 1923, Smith, 2016, Ver Steeg,  
155 1932). The process of stalactite formation from concrete leachate differs to that in natural  
156 limestone caves, as it proceeds via dissolution of calcium hydroxide and absorption of CO<sub>2</sub>  
157 from the atmosphere to produce the precipitate, whereas in limestone caverns CO<sub>2</sub> is  
158 degassed from dissolved calcite (Smith, 2016). Furthermore, the dominance of near-vertical  
159 surfaces in the urban environment will act as weathering-limited slopes and discourage the  
160 build-up of regolith and weathering products upon buildings. At the same time this will favor  
161 the vertical drainage and percolation of water and encourage pseudo-karst processes  
162 including formation of evaporites on overhanging surfaces.

163

164 To date, calcium carbonate formations; referred to as urban stalactites or calthemite (Smith,  
165 2016), have been studied from a geochemical perspective (Smith, 2016, Sundqvist et al.,  
166 2005) and the morphology of stalactites has been described at two sites (Smith, 2016, Ver  
167 Steeg, 1932), but there is almost nothing documented about how these formations differ in  
168 morphology to stalactites in natural karst systems. Stalactites of “soda straw” type have been  
169 most commonly described (Allison, 1923, Smith, 2016, Ver Steeg, 1932), but Smith (2016)  
170 also documents flowstone and coralloid type formations. The only quantitative measurements  
171 of urban stalactite growth rates we are aware of give a typical range of 3-29 mm/yr (Smith,  
172 2016, Sundqvist et al., 2005, Ver Steeg, 1932), however Smith (2016) found one example  
173 with an equivalent growth rate of 160 mm/yr. The chemistry of concrete leachate  
174 precipitation favors more rapid formation, with calcium hydroxide around 200 times more



175 soluble in water than calcite which forms limestone cave formations (Sefton, 1988 in Smith,  
176 2016).

177

178 We can consider whether differences in processes, rates and controls on dripstone formation  
179 in urban environments are likely to result in differences in morphologies compared to natural  
180 cave systems. In human built tunnels for example, there is a prevalence of straight lines and  
181 sharp angles, which do not exist in natural karst systems (Macfarlane, 2013). and wide  
182 seasonal ranges of temperate and thus seasonal variations in evaporation and resulting  
183 stalactite growth rates (Ver Steeg, 1932), compared to near constant temperatures in natural  
184 caves. Lastly, the caves of karst systems are typically sheltered and have little or no moving  
185 air, whereas in urban environment there may be prevailing, strong air currents (Kanda, 2007).  
186 These currents could influence the formation of stalactites, particularly in subterranean  
187 tunnels, such that they form at an angle non-normal to gravity (Figure 1B), potentially readily  
188 forming dendrite; stalactites which are rare in natural systems. Alison (1923) postulates that  
189 faster drip rates would favor the formation of thinner stalactites, and that asymmetry in  
190 morphology, including the formation of stalactite curtains, could be a result of changes in  
191 growing conditions, including seasonality.

192

193 It is possible, given sufficient time that pseudo-karst systems could form upon an  
194 anthropogenic substrate, where abundant depositional formations create entire systems which  
195 resemble natural limestone caves. The early onset of such a phenomenon has been  
196 documented in the book *Explore Everything: Place-hacking the City* by Bradley Garrett,  
197 where he recounts an ethnographic vignette relayed to him by a recreation trespasser in  
198 London who had gained access to the 'Mail Rail', a 6.5-mile subterranean railway that had  
199 been mothballed by the Post Office for almost a decade:

200

201 *The stories emerging from the trip were like something out of the Royal Geographical Society*  
202 *archives: miles of tunnels running right underneath central London that almost no one knew*  
203 *about. The crew made multiple trips into the Mail Rail that June, walking from Paddington to*  
204 *Whitechapel. As 'Gary' explained:*

205

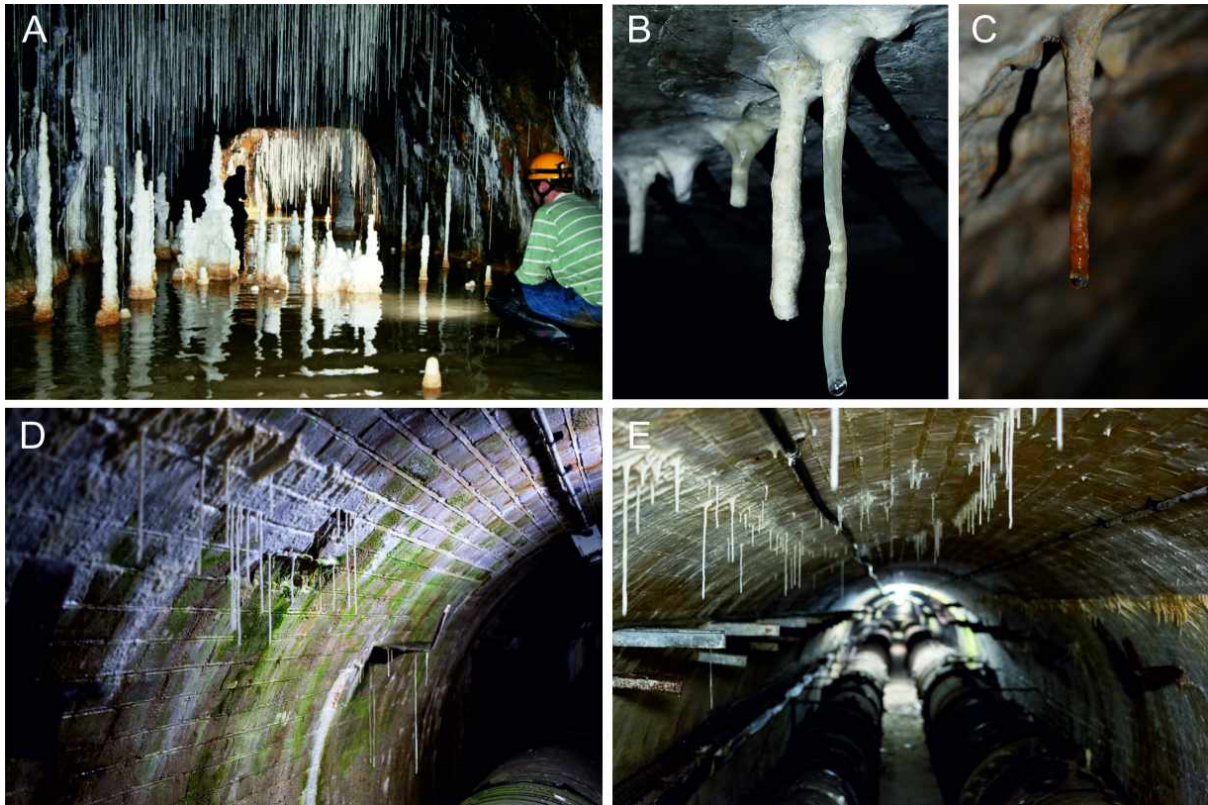
206 *The tunnels become tighter approaching the stations, meaning stooping was required at*  
207 *regular intervals throughout the trip. Towards the eastern end of the line, calcium stalactites*  
208 *were more abundant, hanging from the tunnel ceilings, and gleaming under the fluorescent*  
209 *light. This produced a very real feeling of adventure, like we were in an Indiana Jones movie,*  
210 *in some kind of mine or cave system with wooden carts and the smell of damp throughout*  
211 *(Garrett, 2014: 153-154).*

212

213 Abundant urban stalactites have also been documented in a disused railway tunnel (Hartland  
214 et al., 2010) (Figure 1A), believed to be formed by hyperalkaline drip water from dissolved  
215 carbonate cement or mortar (Hartland et al., 2010), and in an abandoned cellar in Uppsala,  
216 Sweden (Sundqvist et al., 2005). In another 150-year old utility tunnel under the (very damp)  
217 north embankment in London, Garrett also encounter early straw cone formations (Figure 1D  
218 and 1E).

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Figure 1 – Subterranean urban stalactite formations; A) Disused railway tunnel in Britain (J.Gunn in Hartland et al, 2010), B) Calthemite formation which has been shaped by air currents (Garry K. Smith), C) an orange stalactite, likely stained by iron oxide, inside the Fort du Salbert, France (Thomas Bresson, wikimedia commons under a cc-by-2.0 license), D & E) utility tunnels under the north embankment, London (Bradley Garrett)

### Urban sinkholes – an emerging Anthropocene geohazard

A final example of geomorphological processes acting upon and within the urban fabric is the formation of “urban sinkholes” (Figure 2). Such formations pose a risk to life and infrastructure and occur due to a variety of processes (Banks et al., 2015). Obtaining accurate numbers for the occurrence of urban sinkholes is problematic as there are very few published studies on the phenomenon. The city of Guangzhou in China is built within a karst region and studies report an estimated 17 urban sinkholes formed between 1995-2005 (Liu et al., 2005 in

237 Zhao et al, 2009) and a further 20 between 2007-2012 (Gao and Lei, 2013), which reflects a  
238 general reported increase in sinkhole collapses in Chinese urban areas (Lei et al., 2015). In  
239 the absence of academic studies the use of news media reporting of sinkholes can be a useful  
240 alternative for recording occurrences and estimating abundance (Banks et al., 2015). In 2016  
241 there were six separate sinkholes reported in roads in the Greater Manchester urban area in  
242 news media (ITV, 2017), whilst Japanese media reported transport ministry figures of nearly  
243 3300 sinkholes occurring in Japan during the 2014 financial year, most in urban areas  
244 (Nikkei, 2016). In early 2017, a large sinkhole opened in the concrete spillway of Oroville  
245 dam in northern California, forcing the evacuation of nearly 200,000 people and causing an  
246 estimated \$200,000 of damage to the spillway (Chambers, 2017).

247

248 Many urban sinkholes have been found to occur via the same processes observed in karst  
249 systems for collapse or cap rock sinkholes, namely the collapse of a capping layer of rock  
250 over an erosional void (Waltham et al., 2007). Additionally, some occur as a result of the  
251 collapse of abandoned mine workings (Pepe et al., 2013) or other man-made subterranean  
252 tunnels (Eberhard and Sharples, 2013). An example of this type is the Paris catacombs in the  
253 late 18<sup>th</sup> century where collapses of uncharted limestone quarries swallowed buildings and  
254 necessitated the formation of a city inspectorate which still exists to map and maintain them  
255 (Garrett, 2011, Shea, 2011). A class of sinkhole which may be almost unique to urban  
256 environments is one in which a void space is created by soil piping (Banks et al., 2015,  
257 Stafford et al., 2013) and in which the capping layer is formed of asphalt or similar  
258 anthropogenic building materials (Figure 2). In effect the urban development has created a  
259 new, and unusual surficial geological profile, in which a highly labile earth stratum, is  
260 overlain by an impermeable and erosion resistant layer, e.g. asphalt or concrete. Urban  
261 development, either through its effects on proximal surficial geology or through the failure of

262 urban drainage systems has created the water flow conditions which directly lead to the soil  
263 piping removing the material below the capping layer via flowing water/dissolution, which  
264 subsequently leads to collapse of the capping layer into the void.

265



266

267 Figure 2 – Urban sinkholes attributed to soil piping resulting from broken or leaking water  
268 pipes removing material with subsequent collapse of asphalt capping layer. A) collapse at  
269 corner of Montrose Avenue and Honore Street, Chicago, caused by broken water transfer  
270 pipe (TheeErin on Flickr under a cc-by-2.0 licence), B) Large sinkhole in Fukuoka, Japan in  
271 November 2016 (Muyo on wikimedia commons under a cc-by-sa 4.0 license), C) Sinkhole  
272 in St Mary’s Avenue, Omaha, attributed to leaking pipe (Courtney “Coco” Mault on Flickr  
273 under a cc-by-2.0 license).

274

275 It is debatable whether these ‘urban sinkholes’ are true sinkholes (c.f. Brinkmann et al., 2008,  
276 Eberhard and Sharples, 2013), but their existence is due to anthropogenic changes to geology  
277 and hydrology, and their appearance in urban environments is likely to be in contrast to the  
278 extreme rarity of piping derived sinkholes in natural systems. Without fully understanding the  
279 mechanisms behind the formation of sinkholes in urban environments it is not possible to  
280 design effective mitigation measures. Urban sinkholes are hazards with the potential to cause  
281 economic losses through direct damage and indirect impacts on service and transport  
282 networks as well as loss of life and there is a pressing need to understand their mechanisms,  
283 particularly in light of 75% of recorded sinkholes in China being attributed to human

284 activities (Lei et al., 2015). Indeed, in 2014 the UK Government Chief Scientific Adviser  
285 called for more information on the hazard susceptibility and processes associated with the  
286 formation of urban sinkholes (Banks et al., 2015).

287

288 Abandonment and neglect as drivers of change

289

290 A key consideration in the theoretical framework of the city as an emerging landform is that  
291 society has infrastructure in place to mitigate or arrest these Anthropocene urban  
292 geomorphological processes; streets and buildings are cleaned of deposits, sinkholes are filled  
293 in and drainage issues causing soil piping are corrected. However, in the event that such  
294 support frameworks are absent there will be nothing arresting the development of  
295 Anthropocene urban geomorphologies and therefore the occurrence and scale of these  
296 features will increase. This idea parallels those of Weisman (2008) who considered the  
297 degree to which humanity arrests the effects of nature upon cities, and how nature would  
298 recolonize cities should humankind disappear. We therefore need to consider abandonment  
299 and neglect of the urban environment as an agent of urban geomorphological change in the  
300 Anthropocene. The extensive underground infrastructures of many large cities, many of  
301 which are neglected or abandoned (see Garrett 2015) offer ample opportunity to explore these  
302 biogeomorphological and hybrid urban geomorphological processes.

303

304 In the context of neoliberal policies of infrastructural privatisation and cuts to government  
305 budgets for construction and maintenance, the need to understand how material and  
306 environmental hybrid landforms develop could not be more pressing. Further, as “smart  
307 cities” continue to be constructed with infrastructures networked to a host of domestic and  
308 civil functions, understanding urban failure like flooding events and collapses takes on new

309 weight as their impacts ripple through other networks. In a sense, the deeper cities sink and  
310 the more complicated their tangles of tunnels and infrastructural threads become, the more  
311 important and interesting it is to extrapolate from empirical case studies and speculate at  
312 wider geomorphological scales. Further, from the perspective of human geography's drive  
313 toward an expanded sense of "GeoHumanities", these new hybrid formations offer an  
314 opportunity to rethink the environment around us, both horizontally and vertically, when we  
315 stretch thinking about material spatial amalgamations into deeper temporalities where new  
316 environmental aesthetics are being formed (Dixon et al., 2012a, Wiles, 2014).

317

## 318 Conclusions

319

320 Reimagining the city as an emerging hybrid Anthropocene landform provides opportunities  
321 and challenges for natural science research and challenges human geographers to consider  
322 less anthropocentric "cultural" landscapes. As outlined above, although the underlying  
323 physical processes remain the same, the unique materials and morphologies of the city may  
324 require revisions or additions to current geomorphological theories. Therefore, by studying  
325 fundamental interactions within the emerging urban landscape new insights may be gained  
326 into underlying geomorphological processes. The great opportunity here is to undertaken  
327 inter-disciplinary work between natural and social scientists (c.f. Castree, 2014, Castree,  
328 2015, Dixon et al., 2012b), since the morphological and societal drivers and impacts of  
329 Anthropocene urban geomorphologies cannot be disentangled or dealt with in isolation.

330

331 The application of the Anthropocene as a theoretical framework has so far had a clear focus  
332 on how humans shape the natural environment directly and how they interact and change  
333 geomorphological processes. However, in doing so the research community has not fully

334 considered how fundamental geomorphological processes will alter, shape and potentially  
335 destroy anthropogenic infrastructure and form new hybrid Anthropocene landscapes. To fully  
336 investigate the processes, drivers, and implications of these Anthropocene urban  
337 geomorphologies will require interdisciplinary teams of earth scientists, social scientists,  
338 archaeologists, urban planners and civil engineers. We contend that only by considering the  
339 urban landscape as an Anthropocene landform and studying both the processes and social  
340 drivers can we avoid falling into the trap of Shelley's Ozymandias who neglected to consider  
341 the effects the twin processes of time and geomorphology would have to reshape the  
342 landscape around and upon the urban structures he had created.



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