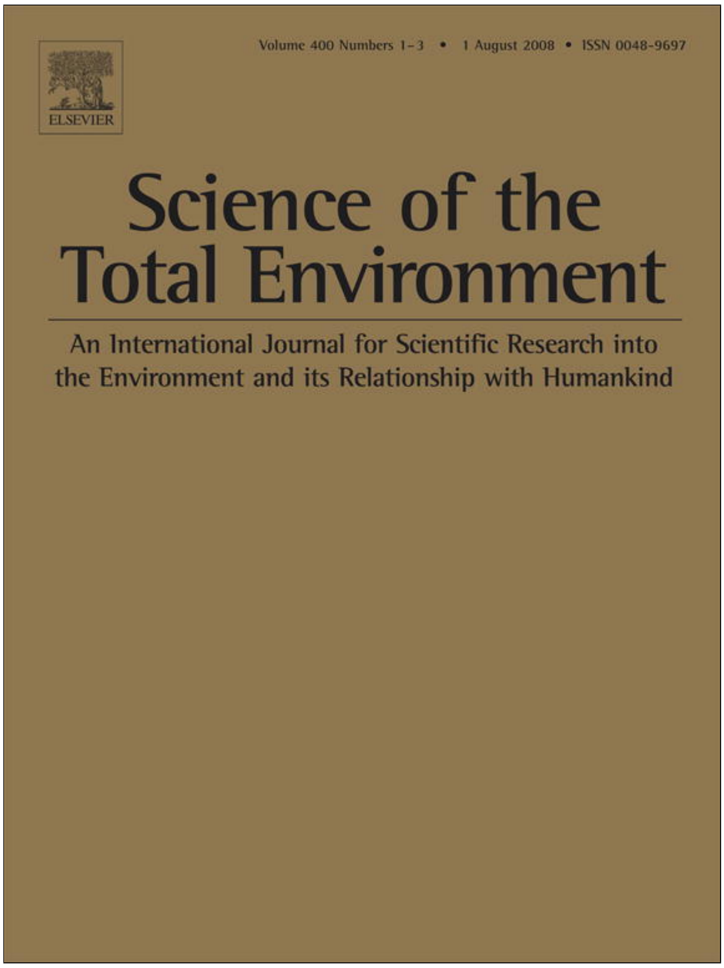

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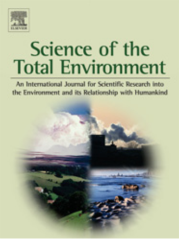

Review

Rates of urbanisation and the resiliency of air and water quality

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ABSTRACT

Global human population and urban development are increasing at unprecedented rates and creating tremendous stress on local, regional, and global air and water quality. However, little is known about how urban areas vary in their capacity to address effectively air and water quality impacts associated to urban development. There exists a need to better understanding the factors that mediate the interactions between urbanisation and variations of environmental quality. By synthesizing literatures on the relationship between urban development and air and water quality, we assess the amount of scholarship for each of these cities, characterize population growth rates in one hundred of the largest global cities, and link growth trends to changes in air and water quality. Our results suggest that, while there is a growing literature linking urbanisation and environmental quality, some regions of the globe are better represented than others, and that these trends are consistent with our characterization of population growth rates. In addition, the comparison between population growth rates and air and water quality suggest that multiple factors affect the environmental quality, and that approaching rates of urbanisation through the lens of 'resiliency' can be an effective integrative concept for studying the capacity of urban areas to respond to rapid rates of change. Based on these results we offer a framework for systematically assessing changes in air and water quality in megacities.

Contents

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1. Urban system and global change

The global population in urban areas is growing at an unprecedented rate. Since the first issue of STOTEN was published in 1972, the human population has almost doubled (from 3.8 billion to over 6.6 billion), and by 2030 more than two-thirds of the world's human inhabitants will live in urban areas (Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2007). Much of this growth is occurring in the developing world, where the pattern of growth of urban regions is often uncoordinated, more fragmented and originating from multiple nuclei. Numerous reports suggest that these changes in the number of people living in urban areas result in serious environmental and social problems and accelerate global environmental change (Bengtsson et al., 2006; Grimmond, 2007; Parnell et al., 2007). There exist multifaceted global water issues that include intermittent flows, desalination and its impact on environment, climate change and extreme events and its impacts on freshwater resources, inadequate supply, and water security and risks (see for example, Shiklomanov and Rodda, 2003; Gleick, 2006). Half the world's population lacks basic sanitation, and population growth without proper sanitation and hygienic resources currently causes over 1.6 billion child deaths each year, making water-related deaths the third leading cause of mortality in children under the age of 15 in middle- and low-income countries (WHO, 2005). In addition, every year 1.5 billion urban residents breathe air that exceeds World Health Organization standards, with over 800 thousand deaths each year due to urban air pollution. Impact of urban development also degrades local and global ecosystems by reducing and fragmenting natural habitats, introducing exotic organisms, and severely modifying energy flow and nutrient cycles (Collins et al., 2000; Pickett et al., 2001; Groffman et al., 2004; Mills, 2007).

Increasing awareness of the human and ecosystem impact of cities on global environmental conditions has been the topic of special issues of scientific journals, e.g., *Science*, Volume 319 (5864) in 2008; *Journal of Industrial Ecology* Volume 11(2) in 2007, and countless national and international meetings involving scientists, policy makers, and natural resource managers. Additionally, cities throughout the globe are actively attempting to improve living and environmental standards by, among other approaches, developing urban sustainability goals. In recent years the emergence of a small industry examining the 'greenest' or most sustainable city (see for example Sustainlane, 2006; Greenbiz, 2008; Popular Science, 2008) speaks to the active interest in understanding and mitigating adverse impacts of urban development on human welfare and ecosystems.

While laudable, the concept of sustainability as a mitigation tool contains several challenges that limit an understanding of the dynamics operating in an urban environment. While recent research suggests that several interacting factors affect urban environmental quality, there have been far more theoretical explorations than empirical studies on the sustainability of urban ecosystems (White and Whitney, 1992; Bartone et al., 1994; Mega, 1996; Register, 2006). Empirical studies examining the sustainability of cities in terms of impact on natural resources typically examine patterns of urban development (e.g. land use, land cover) at single points in time to predict changes to air or water quality, with a few exceptions in such cities as Paris and London where a large inventory of data exists (see the special issue of STOTEN on urban regeneration in London, STOTEN, 2006, volume 360, (1–3) by Leeks et al., 2006 and on the Seine River 2007, volume 375, (1–3) by Billen et al., 2007). These 'snap-shots' of urban development provide valuable information, for example, about what types of urban development may be associated with degraded environmental conditions, but the limited analysis of temporal dimensions precludes understanding time-dependent factors that contribute to or detract from the ability of urban areas to rebound from rapid rates of population growth or urban development. An empirical understanding of the dynamics (i.e., time dependence, interactions, and feedbacks) operating in an urban environment may be especially important in developing mitigation tools for urban areas where large population changes are occurring at unprecedented growth rates.

While many cities have improved their air and water quality in the past two decades, several urban areas are in need of counteractions to reduce adverse health impacts to urban ecosystems at a faster pace. In several countries such as Nigeria, Brazil, and China where urban population growth rates are associated with degradation in air and water quality, reports suggest a concomitant decrease in the overall health status of urban residents (El-Fadel and Massoud, 2000). Because a few such assessments have occurred on a global scale, it is not clear to what magnitude and at what rate the environmental degradation accompanies population growth, and at what level of growth in urban system will cause irreversible damage to human inhabitants and the natural systems. In studies of ecosystems, research suggests that natural habitats with low resiliency were susceptible to sudden, unexpected, and large changes in response to disturbance (Carpenter et al., 2001; Scheffer et al., 2001; Folke et al., 2002;

Schneider, 2004), and that an overwhelming rate of disturbance creates unpredictable system responses in ecosystems with diminishing resiliency (Sukopp and Starfinger, 1999; Jackson et al., 2001). With rapid rates of urbanisation, sudden and unexpected changes in environmental quality may be the precursor to unpredictable declines in health of urban residents. While research is beginning to address the relationship between urban environmental quality and human or ecosystem health (see for example, Rose et al., 2000; Paul and Meyer, 2001; Beasley and Kneale, 2002; Neal, 2003; Stamm et al., 2008), this area requires further research about which counter-actions are most effective and in what circumstances.

By characterizing rates of population growth in one hundred of the most populous global cities, assessing the amount of scholarship for each of these cities, and linking growth trends to changes in air and water quality, this study aims to better understand the factors that mediate the interactions between urbanisation and variations of environmental quality in urban areas. Many interdisciplinary, integrated studies of coupled human and natural systems define our current understanding of resiliency of urban areas, and these studies suggest that cities are the major sources of global environmental problems and also the hot spots for solutions (Cousins et al., 2007; Liu et al., 2007; Grimm et al., 2008). A holistic and integrated approach to understanding the capacity of urban areas is instrumental in responding effectively to rapid urban growth and reducing adverse human health and ecosystem impacts caused by urbanisation. While there is little disagreement that greater integration of the factors that affect urban air and water quality is needed, less consensus exists on *what* needs to be integrated and *how* that integration should be accomplished. The existing literature offers several clues about how to conduct a synthesis, and this paper offers one approach to link factors in the human and biophysical system for more effective integrative studies of urbanising areas.

In an effort to examine holistically the environmental changes occurring in cities around the globe, the paper begins by characterizing growth rates of cities and develops a typology based on growth rates. Because urbanisation causes the production and consumption of goods and services that affect air and water quality, a characterization of growth rates allows for examination of the relationships between growth rates and air and water quality for select cities. Following a discussion of this relationship, the paper describes the mechanisms currently understood to affect urban environmental quality based on a review of the literature, and the indices currently used for monitoring and assessing air and water quality. Finally, the review and analysis of the literature and existing data offer a framework for a holistic understanding of the factors that mediate the interactions between urbanisation and variations of environmental quality in urban areas.

2. Characterizing rates of urbanisation

The rates of urbanisation are characterized by creating a typology of urbanisation trends based on quantities that are indicative to the potential environmental impacts. Information on population of world cities (Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2007) is used to characterize the typology of urbanisation trend. The top 100 most populous urban agglomerations based on estimated 2005 populations were selected for analysis. As many as 60 of them will be characterized as megacities (i.e., have a population of five million or more) by 2015. We used their 1975, 2005, projected 2015 population, and population changes between 1975 and 2005 and between 2005 and 2015 in a *K*-mean cluster analysis. *K*-mean cluster analysis is a method to classify or to group objects based on attributes or features into *K* number of group. In this analysis, the population growth rate between time periods represents the object. The cluster analysis provided a means for characterizing the 100 most populous urban agglomerations into three categories: mature, transitional, and rapid urbanisation areas (Fig. 1). Mature urban areas are characterized by leveled population growth. Examples include New York City (US), London (UK), Seoul (S. Korea), Osaka–Kobe (Japan), Rio de Janeiro (Brazil), and Moscow (Russian). Transitional urban areas had rapid population growth between 1975 and 2005 but tapered projected growth between 2005 and 2015. Such urban areas include Mexico City (Mexico), Los Angeles (US), Bombay (India), Beijing (China), and Istanbul (Turkey). Regions categorized as 'rapid urbanisation' are slated to grow in population growth in both time periods, and includes cities such as Shanghai (China), Jakarta (Indonesia), Lagos (Nigeria), Delhi (India), and Atlanta (US). Tokyo (Japan) was categorized into a unique urbanisation

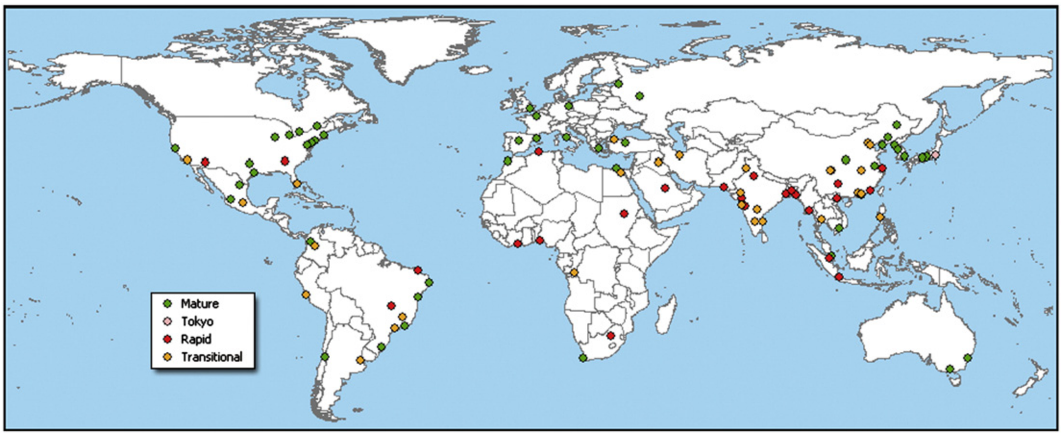

Fig. 1 – Locations of the world's 100 largest cities (based on estimated 2005 population).

type because it entailed the largest urban area of any city examined here, and was considered an outlier. Most mature cities are found in developed countries, while most rapid urbanising cities exist in developing counties. The results of the cluster analysis are consistent with current demographic understanding about the relationship between economic stages of development and rate of urbanisation around the world (Abrahamson, 2004). Further analysis revealed that the rate of population changes vary across our categories (Fig. 2).

To better understand the relationship among population, urban development and environmental conditions, a bibliometric analysis was undertaken to understand the amount of scholarship in air and water quality across the three urbanisation categories. A synthesis of the amount of scholarship occurring in specific urban regions provides an understanding of the variations in and amount of research occurring throughout the globe. To synthesize the literature, a literature search in the SCOPUS digital citation database (November 2007) was undertaken for all citations from 1960 to 2007 using the combinations of air (or water) quality or air (or water) pollution and the city name as search keywords (e.g., “air and (quality or pollution) and Delhi”). The total number of citations indicates the extent to which peer-reviewed air and water quality scholarship is occurring in each region.

The results (Appendix A) indicate that mature cities had more published papers on urban air or water quality than transitional areas, and that transitional areas had more papers than rapid areas. The average numbers of papers for mature, transitional, and rapid urbanisation areas were 283 ($N=47$), 224 ($N=28$), and 92 ($N=24$) respectively. In addition, the difference between mature and rapid was statistically significant at 0.05 level ($p=0.03$ for air and water quality papers combined). These variations reflect the amount of scholarship that exists for understanding the interactions between rates of urbanisation and variations of environmental quality in urban areas. The differences may be entirely due to the amount of time mature urban areas that have existed as pollution problems, or it may reflect the level of investment in investigating these regions (or a combination of both).

3. Urbanisation as environmental stressor

Urbanisation affects the environment in many ways. Urbanisation has been associated with introduction of exotic species, modification of landforms and drainage networks, control or modification of natural disturbance agents, and the construction of extensive infrastructure (Alberti, 2008). Literatures from industrial ecology and urban ecology provide some systematic approaches for characterizing the complex interactions between urbanisation and urban environment. Industrial ecology treats a city as an organism that relies on resource and capital investments to sustain its activities. The input and local resources and investments go through a metabolic process to become waste and pollutants that accumulated in the urban area (Brunner, 2007). Urban growth, which relies on urban metabolism processes, causes changes in urban aquifers, materials in the infrastructures, energy and heat balance, and concentration of chemical compounds.

Urban ecology, which examines urban system functions through spatial patterns and changes in hierarchical spatial heterogeneity (Pickett et al., 2008), attributes the major environmental stressor of urbanisation to the physical changes in the landscape (Forman and Godron, 1986; Turner, 1989; Alberti et al., 2007). Landscape change rescales natural disturbances by reducing or increasing their magnitude, frequency, and intensity. It homogenizes natural patterns by changing land use and modifying the natural processes that maintain diversity. For example, the conversion of natural land cover to impervious surfaces reduces the amount of infiltration of stormwater, and leads to increased overland flows, more rapid runoff of rainfall, and flashier hydrological responses (Booth and Jackson, 1997). The overland flows are affected by the conditions of the surface (e.g. temperature, organic and inorganic compounds), and are directly discharged into the stream system through artificial drainage network. As a result, the chemical, hydrological, and biological

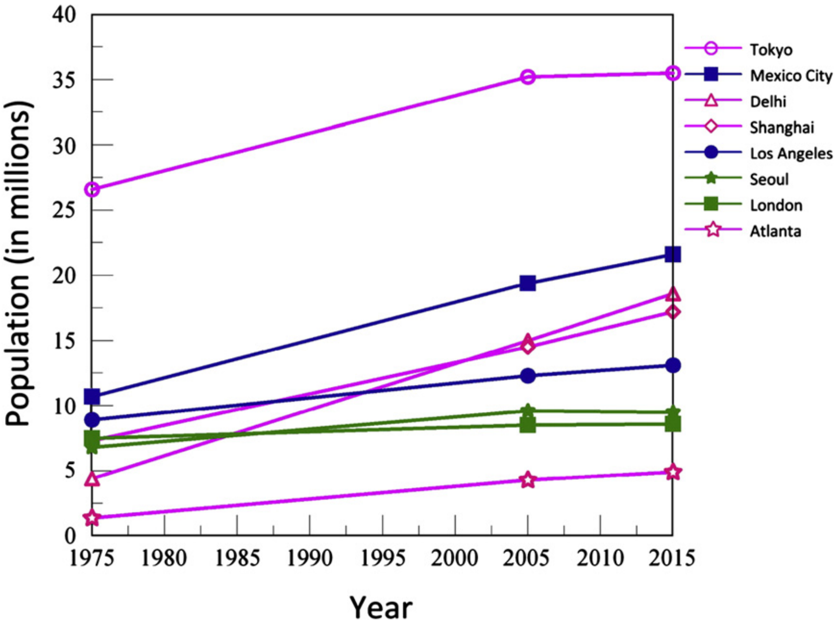

Fig. 2 – Population trends in various types of urban agglomerations.

conditions of the stream are affected by the amount and spatial patterns of impervious surface in a watershed.

In many instances, mechanisms that affect one medium also affect others in an interconnected system of feedbacks. For example, as urban impervious surface increases, vegetated surface decreases and air temperature rises. Increases in air and ground temperatures lead to rise in water temperature, which then reduce dissolved oxygen content and accelerate in-stream biogeochemical processes. In addition, combustion of fossil fuels that contain nitrogen oxide and sulfur dioxide increases atmospheric depositions of acid rain water (Hegde, 2007) and nitrate fallout (Forti et al., 2007; Lee et al., 2008). The geographical extent of these pollutant fallouts could be wider than that of the source area as regional or local atmospheric circulation works as a major agent of diffusion.

The process by which urban development affects air and water quality is described in more detail below. A synthesis of the air and water quality parameters that are affected by urban development is helpful for developing robust frameworks for empirically studying the capacity of urban areas to withstand faster rates of urbanisation.

3.1. *Air quality indices*

Activities and processes at the Earth's surface generate emissions in the form of gases and particulate matter that either directly, or through secondary processes (i.e., chemical reaction, phase change, dissolution, etc.) cause harm to human health or the ecosystem. Emissions are produced from human activities (anthropogenic), the biosphere (biogenic) and geosphere (geogenic). Globally, the pollutants of concern in the troposphere are nitrogen oxides, sulfur dioxide, volatile organic compounds (as precursors to ozone), carbon monoxide, lead, ozone and particulate matter (Barrie, 2005; SEC, 2005; WHO, 2005; US EPA, 2008). Particulate matter is typically categorized by size and mass loading although chemical speciation and other physical parameters are possible (McMurry, 2000) and desirable for assessment of human health (Harrison and Yin, 2000; Lighty et al., 2000; Dominici et al., 2007; Samet and Krewski, 2007) and ecosystem effects (Lu and Schroeder, 1999; Campo et al., 2001; Marques et al., 2001; Neff et al., 2002; Grantz et al., 2003; Krupa, 2003; Steinnes et al., 2005; Hageman et al., 2006).

Although there is general agreement about target air pollutants, there are some differences globally in health-related standards (see Table 1). Lack of continuous and accurate measurements of even key air quality indicators is a significant issue for air quality management in newly industrializing countries (Baldasano et al., 2003; Barrie, 2005; Rappengluck et al., 2006). Furthermore, the complexity of substances in the atmosphere and their relationship to harmful effects does not lend itself to effective public communication (Longhurst, 2005). Air quality indices (AQIs) are a mechanism for assessing relative risk from key air pollutants in a communicable format. In the United States the AQIs take into account ambient levels of ozone, $PM_{2.5}$, carbon monoxide, nitrogen dioxide and sulfur dioxide levels and compare them to dose–response relationships (US EPA, 2006). Although, these are the pollutants generally considered in constructing AQIs for many countries, globally, there is no common formula for obtaining AQI values (Stieb et al., 2005; Cairncross et al., 2007). There is considerable debate related to improving the accuracy of AQIs with respect to risk by taking into account multiple and simultaneous exposures, time-exposures and threshold effects (Stieb et al., 2005; Cairncross et al., 2007; Gurjar et al., 2008). Nevertheless, the AQI parameters (ozone, nitrogen dioxide, carbon monoxide, particulate matter and sulfur dioxide) first determined by regulatory agencies in "mature" and developed countries have become the first monitoring and control targets for newly industrializing countries.

3.2. *Water quality parameters and indices*

Like air quality, the sources of water contamination can be either anthropogenic or natural. In some regions, natural geology or soils contain high background concentrations of phosphorus (e.g., Tualatin River in Oregon, USA, cited in Boeder and Chang, 2008) and arsenic (e.g., India and Bangladesh cited in Spallholz et al., 2004), threatening human and ecosystem health. As shown in Table 2, water quality varies depending on natural background or the degree of development. Urban and industrial development, accompanied with higher wastes inputs from factories, transportation (Nixon and Saphores, 2007, see also STOTEN, 2004, volume 334–335), typically contribute to water pollution. While there is no single dominant and global standard water quality index, many researchers attempted to incorporate physical, chemical, and biological parameters in making water quality index. One standardized method for comparing the water quality of various water bodies is the Water Quality Index (WQI) developed by the US National Sanitation Foundation based on 142 experts' opinion (1970). Nine water quality parameters, including temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), fecal coliform, phosphates, nitrates, turbidity, and total suspended solids (TSS), were chosen to develop WQI.

While the US national and local agencies use these parameters when monitoring water quality, international and national environmental standards for water quality parameters vary from one country to another (Table 3). The UK standard is based on the general quality assessment scheme that is designed to provide the state of water quality and changes in the state over time. The South Korean standard is similar to the UK standard but the classification system is based on the purpose of water for specific use of water, either humans or environment. These differences in regulation standards reflect complex political and management decisions on water quality (e.g., effluent regulation for wastewater discharge, regularly targets for heavy metals). In addition, regulations are evolving based on the availability and developments in scientific understandings (Brauman et al., 2007). Drinking water quality standards are of course much higher than for river water, particularly for issues with regards to bacteria for drinking waters (WHO, 2005).

Temperature is fundamental to the health of water system as it affects the solubility of DO and in-stream biochemical processes. Warm water, often originating from urban areas, holds less DO than colder water and increases the rate of chemical reactions, which then dissolves more substances. Acidic water (pH lower than 6) dissolves more ions in water, including heavy metals (e.g., dissolved aluminum) that threaten fish survival. DO content is not only important for the taste of drinking water but also for aquatic fauna that use gills to breath. BOD, as an indirect

Table 1 – Comparison of current air quality limits/guidelines (in μg/m^3) [a]

	EU	USA	Japan	WHO	India (residential areas)	China (residential areas)
SO_2						
1 h mean	350	–	262	500 (10 min avg)	–	500
3 h mean		–	–	–	–	–
24 h mean	125	366	105	20	80	150
Annual mean		79	–	–	60	60
NO_2 or NO_x						
1 h mean	200	–	–	200	–	120
Daily avg. of 1 h		–	–		80	80
Annual mean	40	100	–	40	60	40
PM_{10}						
Hourly	–	–	200 [b]	–	–	–
24 h mean	50	150	100 [b]	50	100	150
Annual mean	40	–	–	20	60	100
$PM_{2.5}$						
Hourly	–	–	–	–	–	–
24 h mean	–	35	–	25	–	–
Annual mean	–	15	–	10	–	–
CO						
8 h mean	10,000	10,000	22,904	9000	2000	–
1 h mean	–	40,000	–	26,000	4000	10,000
Daily avg. of 1 h	–	–	11,452	–	–	4000
Ozone						
8 h mean	120	147	–	100	–	–
1 h mean	–	–	118 [c]	–	–	160
Benzene						
Annual	5	–	3	–	–	–
Lead						
Annual	0.5	1.5	–	0.5	0.75	1
PAH						
Benzo-*a*-pyrene	0.001	–	–	–	–	0.01

Sources:
EU — http://ec.europa.eu/environment/air/quality.htm.
USA —http://epa.gov/air/criteria.html.
WHO — http://whqlibdoc.who.int/hq/2006/WHO_SDE_PHE_OEH_06.02_eng.pdf.
Japan — http://www.env.go.jp/en/air/aq/aq.html.
India — http://cpcbenvis.nic.in/airpollution/standard.htm.
China — http://www.epa.gov/oia/airandclimate/byregion/us_china_aqm_report.pdf.

[a] The values are nominal levels of concern. Regulatory actions are generally not based on one time exceedances of these values. Please refer to the regulatory documents for details.

[b] Suspended particulate matter.

[c] Photochemical oxidants.

measure of organic matter, has been used frequently as it is one of the most popular water quality measures. Phosphates and nitrates are agents for eutrophication, the process of excessive plant growth, including algae that deplete oxygen. Turbidity and TSS measure the suspended particles in water. High turbidity and TSS increase the treatment cost for drinking water and are harmful for fish habitat, particularly for juveniles. In addition, as these particles could be organic in content, they also require oxygen demand (Davie, 2003).

4. Environmental quality trends

To directly link air and water quality trends, over time, to population growth rates of the 100 selected cities is not possible due to the lack of relevant data. The variation in reporting standards in different countries, and missing long-term data also preclude such analysis for all 100 cities. As a result, air and water quality trends are examined here for only those cites where sufficient data are available. These trends provide a perspective for understanding factors potentially mediating the interactions between urbanisation and variations of environmental quality.

Urban air quality data released by the Organization for Economic Cooperation and Development (OECD, 2008) indicates that, out of the 152 cities, only 22 were in the top 100 largest cities based on the 2005 population. The 22 cities include Tokyo, 3 transitional cities (Mexico City, Los Angeles, and Istanbul), and 18 mature cities. No records matched the rapid cities identified in the cluster analysis. This pattern consistently agrees with the aforementioned literature review — there exists a disproportionate amount of environmental research in large and mature cities. To illustrate the relationship between air and water quality and population growth rates, 8 cities were selected – representing all three of our categories – and acquired from various sources to link population growth to air and water quality data (Table 4).

Table 2 – An illustration of the differences in average water quality for a rural, an urban/industrially impacted and a rural/agricultural river in the UK

		Tweed (rural river)	Aire (urban/ industrial river)	Thames (rural/ agricultural river)
Na	mg l^{-1}	7.60	55.9	36.0
K	mg l^{-1}	1.30	7.70	7.14
Ca	mg l^{-1}	17.6	42.9	120.4
Mg	mg l^{-1}	5.10	10.80	5.82
NH_4	mg-N l^{-1}	0.03	0.08	0.05
Cl	mg l^{-1}	13.60	73.90	51.68
SO_4	mg-SO_4 l^{-1}	9.60	81.40	85.70
NO_3	mg-N l^{-1}	1.34	3.69	8.00
DOC	mg-C l^{-1}	4.08	5.65	4.28
Si	mg-Si l^{-1}	4.31	6.89	3.91
SRP	µg-P l^{-1}	30	350	1063
TDP	µg-P l^{-1}	110	490	1081
TP	µg-P l^{-1}	270	840	1153
DHP	µg-P l^{-1}	90	140	18
PP	µg-P l^{-1}	150	350	72
pH		7.78	7.37	8.15
Alk	µEq l^{-1}	54.93	93.67	4382.58
Sus. sed.	mg l^{-1}	15.31	53.40	10.93

SRP = soluble reactive phosphorus (phosphate), DHP = dissolved hydrolysable phosphorus (organophosphates and polymeric phosphates), PP = particulate phosphorus. Data are from Neal et al. (2000).

The air quality parameters include the concentrations of lead (Pb), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and suspended particles. Water quality parameters include concentrations of total phosphorous (TP), dissolved oxygen (DO), and biochemical oxygen demand (BOD).

The data (Fig. 3) indicate that, in general, increase in population is not accompanied by a decrease in air quality. The concentration of PM_{10} and SO_2 decreased nonlinearly, while NO_2 oscillated but remains at the same level, over the same time period, in Seoul, Shanghai, and Mexico City. The NO_2 levels for Delhi and Shanghai, though with some decreases around 2000, showed signs of rising, while other pollutants either decrease or are relatively at a low concentration. London, Los Angeles, and Tokyo all showed relatively low levels of SO_2 and PM_{10} from 1985 to 2005.

Water quality trends were also not explained by a simple function of population growth (Fig. 3). There are no discernable trends in DO for all four cities during the study period. While BOD concentrations decreased in Shanghai since the late 1980s, they have continued to grow in London since the late 1990s. There are no significant trends in BOD in Atlanta or Seoul. TP concentrations show a general declining trend in London. Although there are no significant trends in TP concentrations in other cities, there are signs of declining trends in TP in Shanghai since the 2000s.

Clearly, although many cities have experienced and still experience high levels of air and water pollution during some period of their history, these results suggest a general trend is toward cleaner air and water. Such improvements in air or water quality appear to be associated with the introduction of new technology that stems from new environmental policy. In another words, urban air and water quality seem to be resilient to urbanisation. Perhaps active manipulation of the

Table 3 – Environmental water quality standards in the UK and South Korea

UK

GQA grade	Likely uses and characteristics	DO (% saturation)	BOD (mg/L) 90%	Ammonia (mg-N/L) 90%
A: Very good	All abstractions Very good salmonid fisheries Cyprinid fisheries Natural ecosystems	80	2.5	0.25
B: Good	All abstractions Salmonid fisheries Cyprinid fisheries Ecosystems at or close to natural	70	4	0.6
C: Fairly good	Potable supply after advanced treatment Other abstractions Good cyprinid fisheries Natural ecosystems, or those corresponding to good cyprinid fisheries	60	6	1.3
D: Fair	Potable supply after advanced treatment Other abstractions Fair cyprinid fisheries Impacted ecosystems	50	8	2.5
E: Poor	Low grade abstraction for industry Fish absent or sporadically present, vulnerable to pollution Impoverished ecosystems	20	15	9.0
F: Bad	Very polluted rivers Severely restricted ecosystems	<20	–	–

South Korea

Class	Purpose	DO (mg/L)	BOD (mg/L)	SS (mg/L)
I	Drinking (1st class) Environmental protection	>7.5	<1	<25
II	Drinking (2nd class) Fishing (1st class) Swimming	>5	<3	<25
III	Drinking (3rd class) Fishing (2nd class) Industry (1st class)	>5	<6	<25
IV	Industry (2nd class) Agriculture	>2	<8	<100
V	Industry (3rd class) No nuisance	>2	<10	No trash

Source: UK Environment agency (2008) & Korea Ministry of Environment.

Table 4 – Urbanisation trends and sources of air and water quality data of selected cities

City	Country	Urbanisation trend	Air data sources	Water data sources
Atlanta	USA	Rapid	US EPA	US EPA
Delhi	India	Rapid	CPCB (2008)	N/A
London	UK	Mature	OECD (2008)	NERC, 2008
Los Angeles	USA	Transitional	OECD (2008), US EPA	N/A
Mexico City	Mexico	Transitional	OECD (2008)	N/A
Seoul	N. Korea	Mature	OECD (2008)	Korea Ministry of Environment
Shanghai	China	Rapid	OECD (2008)	Shanghai EPA
Tokyo	Japan	Outlier	OECD (2008)	N/A

factors that contribute to resiliency may in fact accelerate progress. This aspect will be discussed in detail later in the paper.

5. Resiliency factors of urban systems

The aforementioned literature associates urbanisation and population growth alone to decreases in air and water quality. However, an examination of air and water quality trends around the world over the last 25 years did not match this prediction, indicating the existence of other factors mediating environmental quality response to stressors, such as urbanisation. This does not suggest that urbanisation and population growth do not degrade air and water quality; rather these trends indicate the existence of other factors mediating environmental quality. These results suggest that studying impacts of urbanisation and population growth on air and water quality alone, without explicit consideration of the human dimensions, does not accurately reflect the interactions of managements systems, and cultural conditions that also affect urban environmental quality. Such an interpretation is consistent with the general understanding that human and natural domains are no longer viewed as separate but rather as connected and embedded entities in webs of interaction (Liu et al., 2007). The following synthesizes relevant literature to develop a framework for use in empirical assessments of the coupling of human and natural systems.

Several salient examples of factors that affect the resiliency of urban environmental conditions exist. Carpenter et al. (2001) have provided, perhaps the most germane example about the relationship between human and biophysical conditions that affect the quality of lakes in Wisconsin, USA. In another research, Liu et al. (2007) suggested that the impact on environmental conditions is mediated by the nesting of local systems in regional and global systems, and that the cumulative effects of local processes can have global consequences, and vice-versa. As a result, the improvement of air and water quality during rapid urbanisation depends both on the local conditions and the regional and global changes occurring. In other examples, population (Ehrlich et al., 1970; de Sherbinin et al., 2007), land consumption rate and type (Chen et al., 2006), and urban metabolism (Brunner et al., 1994; Bergbäck et al., 2001; Kennedy et al., 2007) are identified as the primary stressors of an urban environmental conditions.

These literatures provide the basis for developing an integrative resiliency framework to better understand the relationship between an environmental stressor, such as urbanisation, and water and air quality. This framework articulates factors that have a significant role in determining the resiliency of urban environment based on our review of the literature. These resiliency factors are: 1) anthropogenic emissions/effluent mix, 2) natural emissions and biological mitigation, 3) urban form and land-cover change, 4) geography, 5) environmental policy, 6) access to technology, and 7) risk perception. The purpose of identifying these factors is not to provide an exhaustive framework that fully integrates the universe of factors affecting air and water quality, but to draw from select literatures and offer a mechanism for empirically studying the coupling of human and natural systems.

To effectively conduct studies across multiple urban environments with varying biophysical, management, historical, and cultural conditions, an integrative framework is required for the creation of a theoretical opportunity to examine the interaction of each of these factors over time and space. Due to the expansive scope of research required to assess each of these factors, it is no wonder that to date few studies have empirically examined the mix of factors. The concept of "resiliency" holds tremendous value as mechanism for integration *across* these multiple factors, interrelationships between factors, and a means for assessing any surprises or system renewal for developing robust management systems (Nelson et al., 2007).

5.1. Anthropogenic emissions/effluent mix

Anthropogenic emissions are generally characterized by source type, such as industrial *point sources*, transport related *mobile sources*, and individually small but numerous and widely dispersed *area sources*. As the industrial economy of a city increases, all three source categories increase. Point source emissions increase as a by-product of producing goods. Point sources of particulate matter, nitrogen oxides, volatile organic compounds, sulfur dioxides, etc. have increased dramatically in Asia over the last 20 years (Tsai, 2005; Ohara et al., 2007; Gurjar et al., 2008). Mobile source emissions increase as transportation of goods increase and as the population shifts transportation modes from human powered to petroleum powered (Potera, 2004). Demand for the use of light-duty vehicles is related to per capita income (Schafer and Victor, 2000). Increasing rates of urban development along with rises in per capita income has produced unprecedented increases the concentration of pollutants related to vehicle exhaust and vehicle use (Molina and Molina, 2004; Srivastava, 2004; Srivastava et al., 2005) in the developing world. In contrast to industrialization in the West, both mobile and industrial emissions are increasing both rapidly and simultaneously.

Anthropogenic sources of water pollution in urban areas are also either point or nonpoint source. Point sources of water pollution include industrial effluent or municipal sewage inputs. While the industrial and municipal sources of pollution have been generally controlled in cities of developed countries (Taebi and Droste, 2004), they are still the major sources of water pollution in Southeast Asia and Africa, including in the Surma River (Alam et al., 2007), in the Brahmaputra River (Girija et al., 2007), in the Bagmati River (Kannel et al., 2007) and Lagos, Nigeria (Ikem et al.,

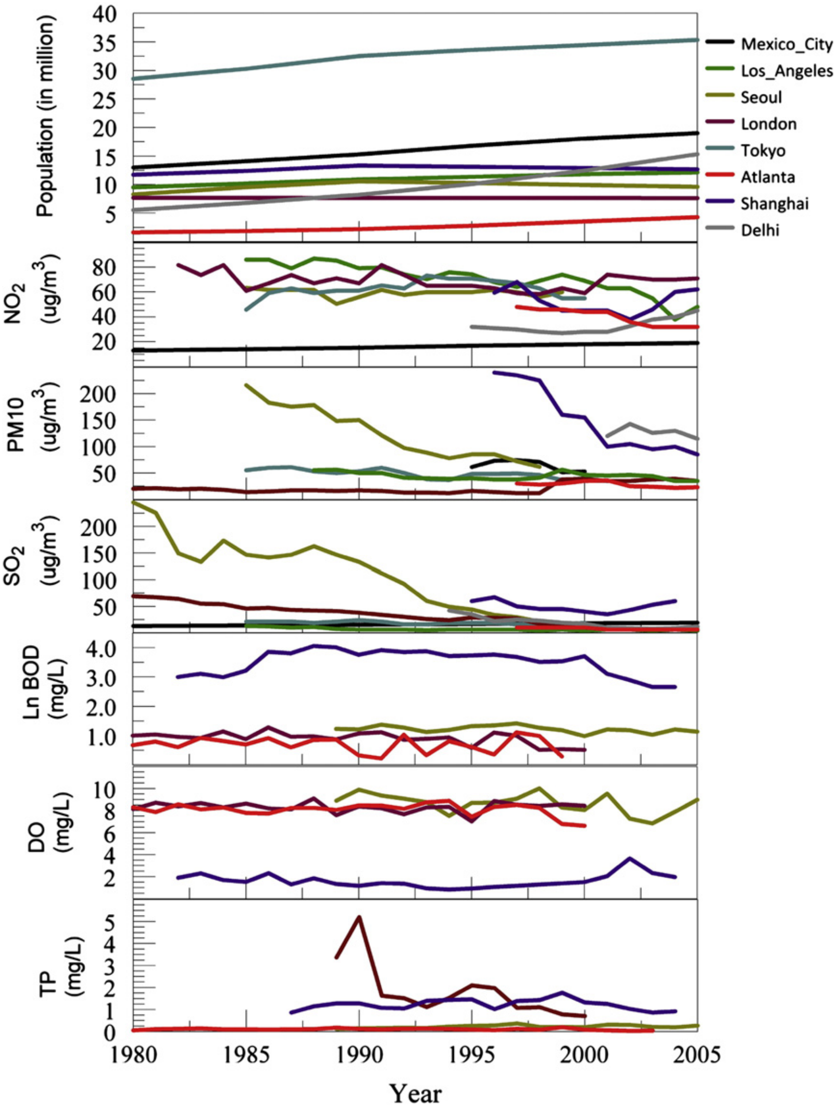

Fig. 3 – Population and air and water quality trends of eight urban areas. BOD is plotted in natural log scale.

2002). Nonpoint sources of water pollution are widespread and difficult to track, although the transportation sector is a major contributor. For example, one study in the northeastern USA found increases in chloride concentrations (applied on roads for deicing) in stream systems due to the presence of impervious surfaces (Kaushal et al., 2005). The levels of toxic water pollutants (e.g., lead, zinc, PAH) are strongly associated with the amount of land allocated to transportation in the United States (Hascic and Wu, 2006). The concentrations of these pollutants typically increase during the rising limb of hydrograph during storm events (Chang and Carlson, 2005; Sansalone et al., 2005), but the dynamics of changing chemistry often exhibit very complex patterns, which cannot solely be explained by first-flushing effect (Old et al., 2003; Lawler et al., 2006). Additionally, the relative contribution of point versus nonpoint source water pollution depends on the spatial scale of analysis. For example, while point source inputs of fecal coliform are more important than diffuse sources at the whole watershed scale, diffuse sources become more important than point sources at the local scale analysis in the Seine River basin (Servais et al., 2007).

5.2. *Natural emissions/biological mitigation*

Biogenic emissions come from a wide variety of vegetation types and produce numerous hydrocarbons that will oxidize to form products that are precursors to ozone formation and/or secondary aerosols. (Kesselmeier and Staudt, 1999; Steiner et al., 2002; Chang et al., 2005; Aghedo et al., 2006; Geron et al., 2006; Guo et al., 2007; Zunckel et al., 2007). The relative contribution of biogenic volatile organic compounds to formation of urban pollutants has been modeled extensively — to the extent to which the oxidation chemistry has been elucidated (Sillman, 1999; Bonn and Lawrence, 2005; Chen and Griffin, 2005; Cape, 2007; Shiu et al., 2007; Duan et al., 2008). However, vegetation can be a sink and/or a source of air pollutants (Bolund and Hunhammar, 1999; Nowak, 2006; Nowak et al., 2006; Cape, 2007; Escobedo et al., 2008). A recent cost–benefit analysis for Santiago, Chile, determined that urban forests and trees would provide similar abatement efficiencies for PM10 as more traditional control measures (Escobedo et al., 2008). While the exact nature of biogenic emissions in many parts of the developing world is still being assessed, the potential for mitigation is also not clear. Rapid urbanisation has generally decreased the amount of vegetation in urban areas, but the mix of remnant and newly planted vegetation and their contribution to urban air quality requires further study.

Natural sources of water contamination include background geology and biogeochemical processes. The influence geology on major ion concentrations and suspended sediments is not uniform across regions. For example, carbonate bedrocks lead to high pH due to the dissolved biocarbonate ions and base cations, but bedrocks containing high silicates result in low concentrations of total dissolved solids and low pH in the Han River basin, South Korea (Ryu et al., 2007). However, the River Tweed in the UK that drains silicate dominated rocks (ultrabasic rocks) showed pHs as high as 10.5 due to high photosynthesis (Neal et al., 1997). Additionally, when respiration is high, inorganic carbon speciation in the water readjust, so pH can be significantly depressed regardless of the presence of silicate or carbonate bedrocks. This is particularly the case in urban areas where large amounts of organic materials are produced (Neal et al., 1998).

Further, some of the highest sediment transport loads in the world come from tropical areas such as the Andes and Himalayas, and high salt content can also be associated with evaporative effects or saline intrusion. These areas are not dominated by carbonates (Berner and Berner, 1996; Drever, 1997). In-stream biochemical processes could result in substantial variations in dissolved oxygen, nitrate and ammonium content by season or location in an urban stream in Slovenia (Brilly et al., 2006). Anthropogenic activities (e.g., mining) often exacerbate the problem by perturbing the natural system. Rapid urban development on glacial deposits is particularly vulnerable to groundwater contamination in the City of Scarborough, southern Ontario, Canada (Meriano and Eyles, 2003). Nitrate concentration in groundwater is also found to be highly correlated with well depth and surficial geology in the Puget Sound basin, USA (Tesoriero and Voss, 1997).

5.3. *Urban form and land-cover change*

The relationship of urban design to air quality is a relatively new field (Marquez and Smith, 1999). Stone (2008) examined various types of urban design in the US and their statistical relationship to ozone precursor levels and ozone formation and found that ozone exceedances are more likely for US cities ranking highly on a sprawl index. Taha (1997, 2008) has modeled the impact of changing land use characteristics (surface albedo and vegetative cover) on ozone formation in southern California and found that increasing surface albedo and (low emissive) vegetative cover significantly decreases ozone formation. The recent studies in this area and further research may be of critical importance as urban heat islands in rapidly urbanising cities have been documented (Li et al., 2004; Weng and Yang, 2004; Kim and Baik, 2005; Tran et al., 2006), with occasional massive impacts on human health (Stott et al., 2004).

The relationship between urban form (as defined by land cover) and water quality has been investigated extensively in many rapidly urbanising cities, including Shanghai, China (Ren et al., 2003; Zhao et al., 2006), Xian, China (He et al., 2007; He et al., 2008), Istanbul, Turkey (Geymen and Baz, 2008), São Paulo, Brazil (Groppo et al., in press), and some US cities (Van Metre and Mahler, 2005; Lewis and Grimm, 2007). The geographical extent of the impacts of urbanisation could be extended to estuaries (Ferrier et al., 2001); higher concentrations of fecal coliform have been detected in South Carolina, USA, as inland urban land-cover increases (Van Dolah et al., 2008). The impact of different urban form on water quality, however, is an emerging research theme. Researchers are increasingly interested in developing approaches that allow new urban development to mitigate water pollution and hence sustain 'smart growth' (Bullard, 2007). While sprawl development could have lesser environmental impact per land area, they tend to spread pollution to much wider geographical areas than compact development. In addition, the rate of degradation in water quality is much greater in sub-urban areas than in central cities in eastern Massachusetts, USA (Tu et al., 2007). As water quality typically declines during storm events in urban areas, new development attempts to mitigate the negative impacts of development by introducing best management practices (BMPs). However, BMPs are not always effective as demonstrated by Hur et al. (2008) in the study of sediment runoff in urbanising catchments in South Carolina, USA.

5.4. *Environmental policy*

To minimize harm from contaminants, the control of air pollution through environmental policy is achieved through a combination of monitoring, modeling and emission control strategies (Williams, 2008). Since innumerable chemical compounds and mixtures of compounds in particulate matter are generated from surface activities, managing the quality of air is not possible on a species by species basis due in part to our inability to accurately measure and/or model most species present in the atmosphere. Fortunately, many pollutants are co-produced by similar emission sources and chemical processes, thus the remediation of one pollutant can have a salutary effect on many other pollutants. Consequently, air quality management and policy have made significant gains through the control of a few key pollutants. In the US, these pollutants are referred to as "criteria" pollutants, which include ground-level ozone, nitrogen dioxide, carbon monoxide, particulate matter, lead, and sulfur dioxide.

The components of air quality managements systems, when they exist, are similar in their frameworks — establishing standards, implementing control strategies and assessment and monitoring of progress (Pryde, 1991; Beattie et al., 2006; Longhurst et al., 2006; Leksmono et al., 2007; Symons et al., 2007). A comparison of the US and Chinese system (in this case, Shanghai) found that the principal differences in air quality management were in the timeframe for assessment (continuous in the US and at 5 year intervals in China), governance authority and responsibility for control measures (state and federal in the US, municipal and national in China) (US EPA, 1998). In addition, access to state-of-the-art modeling and monitoring was limited in China. While significant progress has been made for particulate matter in Shanghai (see Fig. 3), nitrogen dioxide levels have increased and are more difficult to control. Unfortunately, increasingly sophisticated air quality management becomes more necessary as overall air quality improves and cost effective strategies become less obvious. Modernizing air quality management generally means increasing reliance on scientific modeling, accurate emissions assessment and modern monitoring capabilities to determine control strategies. Newly industrializing regions often partner with environmental control agencies in developed countries to make use of scientific understanding, technologies and management systems that have developed in these countries over the last 30+ years. While these efforts increase global understanding of environmental technologies, there may be some significant inefficiencies that result from the adoption of air quality systems that have evolved under specific environmental, cultural and technological conditions (i.e. industrialization in the West) that progressed very differently from urbanisation processes occurring around the world now (Calef and Goble, 2007).

Changes in environmental policy also have contributed to the improvement of water quality in many developed countries. For example, in the United States, after the passage of the Clean Water Act of 1972, dramatic improvements have eliminated many public health and environmental issues associated with wastewater management (Daigger, 2007). In South Korea water quality of the main stem of the Han River has dramatically improved during the 1980s after the implementation of the comprehensive river management plan. This is concomitant with the establishment of the Ministry of Environment (Chang, 2005), which plays a central role in implementing environmental policies and enforcing these mandates. While these environmental policy and regulations have been effective in removing point sources of water pollution, few signs indicate that equal improvements have occurred in regulating nonpoint source pollution in urban areas. For example, London and Seoul, which have stabilized population and established environmental regulations, experienced an increase in nonpoint sources of water pollution (Fig. 3).

5.5. *Geography*

Geographic factors such as geomorphology, climate and meteorology are important parameters that affect the response of air and water quality to changes in emissions. The extent of the influence of these factors is unique to the specific location of the urban developments. The detailed description of the reasons that certain *urban* developments have dramatically expanded over time and their complex interactions of physical access to resources, social, cultural and political issues is beyond the scope of this paper. However, regardless of the reasons for the location of urban developments, the environmental conditions of a city may be more or less sensitive to emissions based on its geographic features.

For example, topography is closely related to the accumulation or dissipation of air pollutants (Carvalho et al., 2006; De Foy et al., 2006; Kim and Stockwell, 2007; Schaub et al., 2007). Topographic conformation favors low wind and strong inversion situations that lead to episodic conditions. Cities, such as Los Angeles (Targino and Noone, 2006), with occluded terrain, in conjunction with other factors, have the tendency to have more occurrence of episodic conditions. The seasonal variations of air quality are usually attributed to the meteorological pattern of a city. Climate determines urban air quality at a broader scale.

River ecologists have long recognized that rivers and streams are influenced by the landscapes through which they flow (Hynes, 1975; Vannote et al., 1980). Geographic conditions affect water quality through variation in the topography and location of development (Boyer et al., 2002). In recent years, the emergence of the field of watershed modeling suggests that geographic conditions matter because most models assess landscape characteristics such as topography, soil type, slope, and rainfall frequency to characterize watershed conditions. An example of this is Omernik's ecoregion scheme (Omernik, 1995), which has been used by the United States Environmental Protection Agency (US EPA, 2005) to guide the delineation of watershed categories based on specific scale, place, or region.

Although human choices and activities determine the location of urban developments, these choices historically have not had much to do with mitigating air or water pollution. Of the resiliency factors we have identified, physical geography for any given city, is the least amenable to manipulation or transformation. However, by increasing our understanding of the relative geographic resiliency of air and water quality in urban developments around the world, it is possible that future global urban developments can be more responsive to geographic factors such as locally occurring topography or climate.

5.6. *Access to technology*

Access to technology involves two key concepts, first, the actual availability of needed technologies and secondly, the ability to use these technologies (Popp, 2006; Schollenberger et al., in press; Van Niekerk, 2006). Technologies to reduce pollution include technologies that remediate effluents (such as bag houses, electrostatic precipitation, water treatment plants), technological substitutions of lower-emitting processes (solar power) and improvements in operating practices and maintenance programs (use of cleaner fuels and mobile engine maintenance). Developing cities take advantage of pollution control technologies that have developed in industrialized countries over the last 50 years (Ho, 2005). This means however, that “technology matching” must exist; pollution emission type and process must “match” existing technologies (which may, in some way, preordain the use of technologies that create emissions) (Taylor et al., 2005). Consequently, emission sources unique to new developments may await innovation or adaption of other technologies. In addition, the use of these technologies is contingent on the relative cost of using these technologies and whether or not the use of these technologies exceeds the availability of a technologically knowledgeable workforce (Saggi, 2002; US EPA, 1998). Both access and use of technology to address pollution is connected to affordability. Many researchers have suggested that as per capita incomes or GDP goes up, pollution levels decrease, a pattern described as “inverted U-shaped” curve or environmental Kuznets curve (Selden and Song, 1994; Grossman and Krueger, 1995; Harbaugh et al., 2002; Managi and Jena, 2008). Changes in an economy have an impact on the use of pollution-related technologies and therefore may explain empirical relationships between GDP and pollution (Galeotti, 2007). Ooi (2007) has pointed out that much of the literature in this area has been examined at the national scale, whereas an examination at the urban scale (for Southeast Asian cities) reveals a more complex relationship between air and water emissions and income (Ooi, 2007).

The improvement in water quality is also attributed to the introduction of a new technology that is associated with changes in economy. Many cities now have first or secondary treatments that effectively remove point source pollution. For example, Zhao et al. (2006) and Chang (2008) found declines in BOD in Shanghai and Seoul, respectively. While these waste water treatment facilities effectively remove organic pollutants, they are not so effective in removing nonpoint source pollution (e.g., nitrogen and phosphorus) as there are only a few tertiary wastewater treatment plants in these cities. Even in the cities of the most developed countries, operating tertiary treatment is costly, challenging in removing these nutrients effectively (Bowes et al., 2005; Chang, 2008).

In many parts of the USA and Europe, surface waters are generally protected through the implementation of best management practices (BMPs). BMPs may be structural or nonstructural, and are often applied at local (immediate proximity of development) or at the watershed scales (Schueler and Holland, 2000). Structural BMPs are physical undertakings and construction projects used to increase water storage capacity in the watershed. Water storage capacity is generally increased by flow attenuation, infiltration, or filtration in urban areas. Nonstructural BMPs, which may be used independently or in conjunction with structural BMPs, rely on a range from programs that increase public awareness to prevent pollution, to the implementation of control-oriented techniques (such as bioretention and stormwater wetlands) that utilize vegetation to enhance pollutant removal and restore the infiltrative capacity of the landscape (US EPA, 1984; Metropolitan Washington Council of Governments, 1992; Schueler, 1992). While some studies suggest that the lack of BMP technology is detrimental to water quality (Hamlett and Epp, 1994; Santhi et al., 2001), others suggest that the uncoordinated placement, lack of adequate maintenance, and, most importantly, the limited scientific understanding of urban hydrology may reduce their effectiveness in highly urbanised watersheds (Booth and Jackson, 1997; D'Arcy and Frost, 2001; Booth et al., 2002). Taken together, these studies suggest that the types of technology and the level to which they are integrated into the landscape and cultural context are critical for the resiliency of environmental conditions.

5.7. *Socio-cultural dimensions of risk perception*

Risk perception to environmental contamination is contingent on social and cultural factors, as well as a result of physiological responses (smell, taste, coughing, etc.) (Bickerstaff and Walker, 2003; Bickerstaff, 2004). To the extent that public perception of harm drives public policy, a feedback loop potentially exists between the level of environmental contamination and the application of environmental management practices/public policy. However, at levels near regulatory standards, a recent study in the US found that human perception of "poor air quality" is weak (Semenza et al., 2008). Even when levels are significantly above standards, resistance to acknowledging a problem can become culturally embedded (Brimblecombe and Schuepbach, 2006; Cupples et al., 2007). A case study of public perception of urban waters in Australia suggests that there is a difference between objective versus subjective assessments of water quality (Steinwender et al., 2008). Consequently, public education in urbanising environments may be critical to raise awareness about the human and ecosystem health impacts of environmental contamination.

6. Conclusions

In general, complex interactions exist among urbanisation, rates of urbanisation and environmental quality, but there is a disparity between the rate of urbanisation and the amount of literature available. While the complex interactions among these factors require further investigations, a yardstick of resiliency provides a valuable avenue for examining these interactions holistically. While other frameworks such as population impact (Ehrlich et al., 1970), ecological footprint (Rees and Wackernagel, 1996) and sustainability assessments (Pope et al., 2004) examine the impact of urban development and population on the environment, they are limited in their abilities to incorporate nonlinear feedbacks, thresholds, multiple stable states, legacy effects, and variations cross space, time and organizational units that entail our current understandings of the complex patterns and processes of urban systems (Liu et al., 2007; Grimm et al., 2008). Conceiving of the factors described above as 'resiliency factors' that affect the interaction between urbanisation rates and environmental quality allows for interactions of system components to consider nonlinear responses internal and external changes. Once general resiliency factors are identified, specific metrics can be determined and evaluated over a range of time and space scales. This strategy will allow for an integrative and holistic approach to studies of the complex interactions in human dominated landscapes that are the major sources of global environmental problems and thus must also be the hot spots for solutions.

Regardless of the precise measures used to assess the coupling of human and natural systems, the current rapid pace of urbanisation is a unique opportunity to critically examine, both theoretically and empirically, the resiliency of environmental systems. Given the current state of environmental degradation in rapidly urbanising regions, and its impact on human and ecosystem health, increased research efforts in this area are vital. Using resiliency as a framework for research and analysis may accelerate our understanding of how to mitigate the air and water quality impacts from urban development.

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Appendix A. – Urbanisation typology and air and water quality peer-reviewed paper counts of the world's 100 largest cities

2005 rank	Urban agglomeration	Country	2005 population (million)	Urbanisation trend	No. of papers for air	No. of papers for water	Total no. of papers
1	Tokyo	Japan	35.2	Outlier	346	281	627
2	Ciudad de México (Mexico City)	Mexico	19.4	Transitional	564	215	779
3	New York	USA	18.7	Mature	1275	1624	2899
4	São Paulo	Brazil	18.3	Transitional	221	226	447
5	Mumbai (Bombay)	India	18.2	Transitional	153	111	264
6	Delhi	India	15.0	Rapid	225	138	363
7	Shanghai	China	14.5	Rapid	173	153	326
8	Kolkata (Calcutta)	India	14.3	Rapid	60	66	126
9	Jakarta	Indonesia	13.2	Rapid	35	47	82
10	Buenos Aires	Argentina	12.6	Transitional	54	111	165
11	Dhaka	Bangladesh	12.4	Rapid	24	40	64
12	Los Angeles	USA	12.3	Transitional	1056	350	1406
13	Karachi	Pakistan	11.6	Rapid	29	48	77
14	Rio de Janeiro	Brazil	11.5	Mature	111	161	272
15	Osaka–Kobe	Japan	11.3	Mature	123	138	261
16	Al-Qahirah (Cairo)	Egypt	11.1	Transitional	65	80	145
17	Lagos	Nigeria	10.9	Rapid	15	44	59
18	Beijing	China	10.7	Transitional	371	191	562
19	Manila	Philippines	10.7	Transitional	38	45	83
20	Moskva (Moscow)	Russian Federation	10.7	Mature	140	120	260
21	Paris	France	9.8	Mature	326	378	704
22	Istanbul	Turkey	9.7	Transitional	78	119	197
23	Soul (Seoul)	Republic of Korea	9.6	Mature	159	57	216
24	Chicago	USA	8.8	Mature	356	242	598
25	London	United Kingdom	8.5	Mature	693	374	1067
26	Guangdong	China	8.4	Transitional	71, 57	43, 81	252
27	Santa Fé de Bogotá	Colombia	7.7	Transitional	10	6	16
28	Tehran	Iran (Islamic Republic of)	7.3	Transitional	53	26	79
29	Shenzhen	China	7.2	Transitional	19	36	55
30	Lima	Peru	7.2	Transitional	14	33	47
31	Wuhan	China	7.1	Transitional	26	48	74
32	Hong Kong	China, Hong Kong SAR	7.0	Transitional	498	458	956
33	Tianjin	China	7.0	Transitional	46	78	124
34	Chennai (Madras)	India	6.9	Transitional	30, 16	43, 55	144
35	Krung Thep (Bangkok)	Thailand	6.6	Transitional	100	75	175
36	Bangalore	India	6.5	Transitional	22	27	49
37	Chongqing	China	6.4	Transitional	53	36	89
38	Lahore	Pakistan	6.3	Transitional	21	14	35
39	Hyderabad	India	6.1	Transitional	32	85	117
40	Kinshasa	Dem. Republic of the Congo	6.0	Transitional	1	1	2
41	Baghdad	Iraq	5.9	Transitional	9	24	33
42	Santiago	Chile	5.7	Mature	141	51	192
43	Madrid	Spain	5.6	Mature	159	94	253
44	Miami	USA	5.4	Transitional	40	89	129
45	Philadelphia	USA	5.4	Mature	219	124	343
46	Sankt Peterburg (Saint Petersburg)	Russian Federation	5.3	Mature	29	43	72
47	Toronto	Canada	5.3	Mature	222	144	366
48	Belo Horizonte	Brazil	5.3	Transitional	5	11	16
49	Ahmadabad	India	5.1	Transitional	0	0	0
50	Thành Pho Ho Chí Minh	Viet Nam	5.1	Mature	7	13	20
51	Barcelona	Spain	4.8	Mature	125	139	264
52	Shenyang	China	4.7	Mature	30	16	46
53	Dallas–Fort Worth	USA	4.7	Mature	49	23	72
54	(Khartoum)	Sudan	4.5	Rapid	3	153	156
55	Pune (Poona)	India	4.4	Rapid	26	32	58
56	Boston	USA	4.4	Mature	235	208	443
57	Sydney	Australia	4.3	Mature	152	306	458
58	Singapore	Singapore	4.3	Mature	146	148	294
59	Houston	USA	4.3	Mature	333	157	490
60	Dongguan, Guangdong	China	4.3	Rapid	1	6	7

Appendix A. *(continued)*

2005 rank	Urban agglomeration	Country	2005 population (million)	Urbanisation trend	No. of papers for air	No. of papers for water	Total no. of papers
61	Atlanta	USA	4.3	Rapid	187	77	264
62	Washington, D.C.	USA	4.2	Mature	117	72	189
63	Ar-Riyadh (Riyadh)	Saudi Arabia	4.2	Rapid	38	32	70
64	Hà Noi	Viet Nam	4.2	Rapid	18	32	50
65	Bandung	Indonesia	4.1	Rapid	6	5	11
66	Chittagong	Bangladesh	4.1	Rapid	2	4	6
67	Rangoon	Myanmar	4.1	Rapid	0	2	2
68	Chengdu	China	4.1	Mature	14	3	17
69	Detroit	USA	4.0	Mature	160	116	276
70	Guadalajara	Mexico	4.0	Mature	11	11	22
71	Xi'an, Shaanxi	China	3.9	Mature	4	9	13
72	Pôrto Alegre	Brazil	3.8	Mature	17	9	26
73	Al-Iskandariyah (Alexandria)	Egypt	3.8	Mature	25	104	129
74	Haerbin	China	3.7	Mature	1	1	2
75	Montréal	Canada	3.6	Mature	226	126	352
76	Melbourne	Australia	3.6	Mature	95	93	188
77	Nanjing, Jiangsu	China	3.6	Mature	26	27	53
78	Monterrey	Mexico	3.6	Mature	25	6	31
79	Abidjan	Côte d'Ivoire	3.6	Rapid	2	16	18
80	Ankara	Turkey	3.6	Mature	34	31	65
81	Surat	India	3.6	Rapid	4	9	13
82	Pusan	Republic of Korea	3.6	Mature	6	11	17
83	Recife	Brazil	3.5	Mature	3	9	12
84	Guiyang	China	3.4	Rapid	19	15	34
85	Phoenix–Mesa	USA	3.4	Rapid	169	126	295
86	Berlin	Germany	3.4	Mature	303	290	593
87	San Francisco–Oakland	USA	3.4	Mature	241	402	643
88	P'yongyang	Dem. People's Republic of Korea	3.4	Mature	0	0	0
89	Roma (Rome)	Italy	3.3	Mature	257	86	343
90	Brasília	Brazil	3.3	Rapid	7	16	23
91	Salvador	Brazil	3.3	Mature	16	30	46
92	Johannesburg	South Africa	3.3	Rapid	27	32	59
93	Fortaleza	Brazil	3.2	Rapid	1	11	12
94	Athínai (Athens)	Greece	3.2	Mature	427	78	505
95	El Djazaïr (Algiers)	Algeria	3.2	Rapid	15	15	30
96	Nagoya	Japan	3.2	Mature	39	25	64
97	Dar-el-Beida (Casablanca)	Morocco	3.1	Mature	2	8	10
98	Cape Town	South Africa	3.1	Mature	21	47	68
99	Dalian	China	3.1	Mature	9	16	25
100	Medellín	Colombia	3.1	Mature	5	1	6

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