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Water and Energy Footprints for Sustainable Communities

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Abstract The framework for sustainability of urban areas is tied to the patterns of urban metabolism in which resources (water, food, energy, materials and chemicals) are delivered to an urban area, metabolized and changed to outputs. Under the current linear concept water, energy and other inputs generate waste and pollution. Furthermore, lack of conservation and waste within the city leads to shortages and, in the near future, to exhaustion of resources. There is a need to change the current linear metabolism to one that would reuse and recycle and in which used water and solids would become a resource. This would be a paradigm change of building and retrofitting the cities.

The footprints are quantitative measures of sustainability and metabolism. Footprints covered in this article are water, energy/greenhouse emissions, and ecology. When the footprints are defined, development of sustainability criteria should follow. The footprints may be global, regional or local and can be hierarchically interconnected.

Keywords Urban metabolism, Urban footprints, Water reuse, Recycle, Global warming, Resources availability, Water shortages, Sustainable development, Cities of the Future

INTRODUCTION

The impetus to develop sustainable cities (Cities Of The Future - COTF) has emerged because of the realization of anticipated consequences of business as usual progression of cities under the major stresses of (1) population increases and migration, (2) threats of adverse impacts of global climatic changes, and (3) increasing water shortages in many highly populated regions of the world. Also, it has become evident the worldwide goals of adequate water supply and sanitation, of the last decade of the twentieth century, have not been met in many cities of developing countries and the problem of poor public health and inadequate water supply may be worsening as populations increase. There is now an almost uniform agreement among professionals in many disciplines (environmental engineering and science, urban planning, architecture, urban and suburban ecology) that the current infrastructure and urban planning paradigm relying on fast surface and underground conveyance of water and waste water, regional water and wastewater management systems, energy overuse for sustaining living processes, commerce, transportation and use of other resources in the cities have become impediments to achieving sustainable urban development and living including addressing the impacts of global climatic change. A paradigm shift from the current unsustainable urban development and living to sustainable future ecocities is needed.

URBAN METABOLISM

Sustainability of the cities, pollution, and social qualities and other attributes and amenities are related to “urban metabolism” (Wolman, 1965; Kennedy, Cuddihi, and Engel-Yan, 2007). Wolman in his pioneering article compared the overall fluxes of energy, water, materials, and wastes in a hypothetical one million population urban community. He used the concept to address “evident shortages of water and pollution of water and air” (Pamminger and Kenway, 2008) and was concerned, forty five years ago, about the deteriorating state of the urban environment, high pollution, and overuse of resources. Wolman was the first to define urban metabolism, also stating that it must be sustainable (Hermanowitz and Asano, 1999). Cities and interconnected surroundings are complex systems consisting of nonliving infrastructure, machinery, roads and ecosystems with living organisms. Humans are part of the ecosystem. The urban system receives inputs which are accumulated and grow, cycled, attenuated and transformed within the system, and produces outputs (Figure1). Urban metabolism can be defined as the "sum of the technical and socio – economic processes that occur within in the cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007). The balance or imbalance between the inputs, accumulation and growth, and waste resulting in emissions of undesirable pollutants determine the sustainability or unsustainability of the city.

Generally, the inputs can be categorized into five groups

Materials (raw materials for buildings and production of goods and services within the city)

Food (homegrown and imported)

Water (potable and nonpotable from the grid, harvested rainwater, groundwater and surface)

Energy (coal, natural gas, gasoline, electricity from renewable and fossil fuel sources)

Chemicals (such as industrial fertilizers, pesticides, road and highway deicing chemicals, pharmaceutical products and other drugs, household and commercial cleaners and solvents.

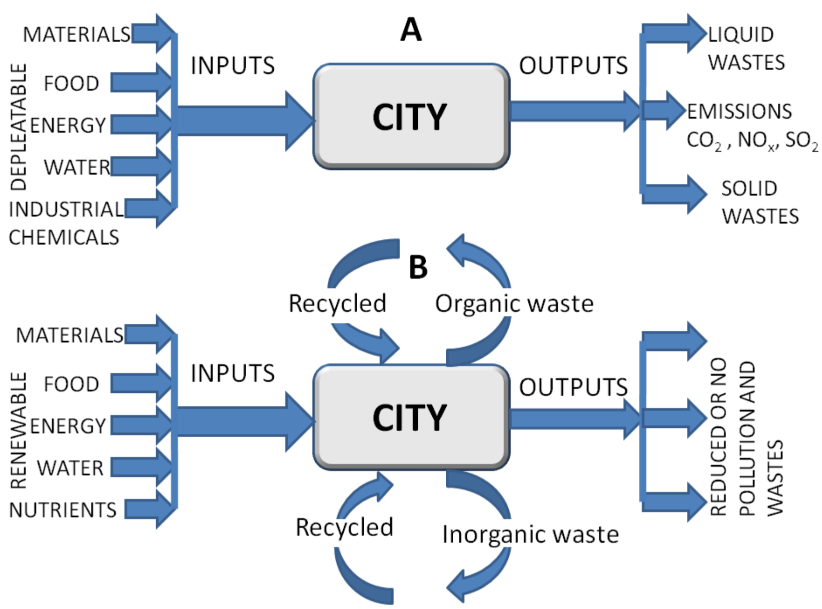

Figure 1 Linear (A) and circular (B) urban metabolism systems

There are many outputs. The examples of undesirable environmental outputs are:

liquid sewage, industrial wastewater and combined sewer overflows (point sources) containing suspended solids, organics, toxic compounds and pathogens that impairs the integrity of the receiving waters, often far downstream from the city;

polluted urban construction sites and highway runoff (diffuse sources) also contain solids, toxic compounds and pathogens. Because of the changed hydrology of the cities, peak flows and volume of urban runoff increases flooding and enlarges floodplains. The response of city planners (an undesirable output) was to channelize the streams or convert them to underground sewers and culverts (Novotny, Ahern, and Brown, 2010);

air pollution emissions with local, regional and global impacts (including regional and global green house gases (GHG), ozone layer destroying chemicals (fluorocarbons), polychlorinated bi-phenyls that contaminate fish and can be detected as far away as in Greenland and Antarctic glaciers, and acid forming oxides of sulfur and nitric oxides from power production and traffic); and

rubbish and other solid waste such as demolition and construction materials, newspapers, packaging solids, woodchips and other landscaping solids, discarded TVs, computers, etc.

The linear system has also other drawbacks and adverse environmental impacts. Because water use in the linear system withdraws excessive volumes of water from the surface and groundwater resources the urban streams for long distances, including the urban sections, have insufficient or no flow. The effluent flow from large regional treatment plants is added at a long distance downstream, converting the receiving water body into an effluent dominated stream (Novotny, 2007). This natural low flow deficiency of urban streams is exasperated by the modified hydrology of the cities that greatly increases urban surface runoff and minimizes infiltration.

"Urban metabolism" does not consider only mass and energy. People are a part of the urban system, their well being and behavior are strongly affected by the mass and energy balances and the consequences (pollution, water shortages, more warmer, hot and catastrophically turbulent weather). Other undesirable inputs of unbalanced urban metabolism in the past were famine, diseases or malnutrition of disadvantaged population, increased flooding, deteriorating neighborhoods. For example, in the last thirty years Detroit (Michigan) lost ½ of its population and has embarked on demolishing a significant portion of its area.

The concept of urban metabolism is derived from the more general concept of the ecosystem analysis. In an ecosystem, production of organic matter begins with photosynthesis which converts inorganic mass (carbon dioxide, water and nutrients) into organic living organisms that are at the bottom of the food web. The output of one organism is the input to other species, organic matter provides energy and elements of growth, and in the final outcome the matter is broken (decomposed) to its original mineral forms and organic residues (e.g., humus). In ecological metabolism, organic and inorganic mass and energy undergoes several cycles.

Current urban systems, on the other hand, have been mostly linear. Daigger (2009), Novotny (2008) and others agree the current "linear" approach, sometimes called the *take, make, waste* approach in the sustainability literature, when applied more broadly to natural resources use and global climatic change, has become increasingly unsustainable. The most obvious causes and effects are increasing demands for energy, food and water by population increase and increasing living standards which then results in pollution, shortages and overuse of resources throughout the world. The major concerns are the ecologic status of the water bodies impacted by urban development, resource consumption, the dispersion of nutrients resulting in severe algal blooms are increasing, and GHG emissions leading to adverse global climatic changes. A linear system relies on an unrestricted availability of resources and energy and, without strong regulations and enforcement, disregards the adverse impacts of waste and GHG emissions on the environment and society. In the prevailing current linear water system, water is taken from upstream sources, delivered to the urban area by underground conduits, used and polluted, then delivered by underground conduits to a regional wastewater treatment facility many kilometers downstream from the points of potential reuse, and finally overwhelming the receiving water body by the effluent discharge, creating often an effluent dominated water body. Traditional simple economic cost analysis for water systems based on economy of scale dogma was leading planners to building large regional facilities and (in the 1970s after the passage of the Clean Water Act in the US and elsewhere) to abandoning smaller community based treatment plants that were deemed uneconomical and inefficient.

The current problems with the linear urban systems will get worse in the future. The reasons are population increase, depletion of cheap energy (oil), increased living standards and pressure on resources by the emerging economic giants (China, India, Brazil, etc.), global climatic change which is upsetting the hydrologic water cycle and the effects of rapid urbanization. Switching from concepts described by the terms "waste" and "wastewater" to those characterized as "resource recovery" or "used water reclamation" cannot be done under the typical prevailing linear system scenario even when the utility name is changed from wastewater treatment to water reclamation.

FOOTPRINTS

A "footprint" is a quantitative measure showing the appropriation of natural resources by human beings (Hoekstra and Chapagain, 2007). Footprints can be local as included, for example, in the LEED (Leadership in Energy and Environmental Design-USGBC (2005, 2007)) or OPL (One Planet Living – WWF (2008)) criteria or "giant" large scale regional to global (Girarded, 1996). Three major categories of footprints have been identified in the literature

- *The water footprint* measures the total water use on site and also virtual
- *The carbon footprint* is a measure of the impact that human activities have on the environment in terms of the amount of GHG emissions measured in units of carbon dioxide
- *The ecological footprint* is a measure of the use of bio-productive space (e.g., hectares of productive land needed to support life in the cities)

Water demand and shortages – Water footprint

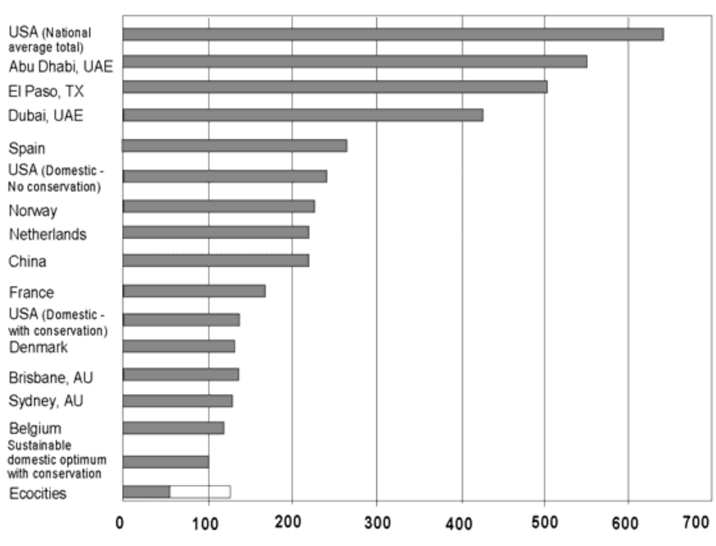

Figure 2 Per capita water use in selected urban areas and countries compiled in Novotny (2010) and Novotny et al. (2010)

Figure 2 shows the per capita water uses in several cities and countries. The per capita water use in the cities is a local footprint which usually has regional significance. In the US, domestic indoor water use is relatively constant among the major urban areas (Heaney et al., 2000), averaging 242 Liters/capita/day for a household without water conservation and 136 Liters/capita/day for a household practicing water conservation, respectively (Heaney et al., 2000).

However, the total per capita water use is magnified by outdoor irrigation (using potable water), pipeline leaks, or swimming pools and in the US reaches almost 650 Liters/capita/day. The water demand in the US is the highest in the world and, because of the high demand in the dry regions of the arid US southwest, severe water shortages have been common in many southwest US communities.

Far more severe and critical water shortages and poor quality of available water are the main problems that have to be vigorously addressed in developing countries but also in many developed countries anticipating severe drought conditions (e.g., Australia, southwest US, Israel, Middle East). During the 1990's the goal for adequate water supply and sanitation for all was established by the United Nations. This goal has not been fully met in many developing countries where it is exasperated by critical water shortages, missing or inadequate infrastructure to deliver water, poor sanitation and drainage, uncontrolled population migration to cities, and by water contamination. There are many cases throughout the world where the situation in urban water supply is critical and cities are looking for increasingly more expensive ways to provide water to citizens. Millions of the world poorest subside on fewer than 20 liters per person per day and more than 46% of people do not have access to a nearby running drinking water tap.

Virtual water

Virtual water transfers and trading refers to the water use outside of the city area that is used to produce food, materials and other goods to satisfy the needs of the people living in the city. Such production water demanding activities outside of the city include agriculture, production of electricity, construction materials, paper, and, today, biofuel from corn or sugar cane or oil derived from tar sands. It is a regional to global footprint which describes water use and losses in the regions providing these commodities to urban populations. For example, the water use of an average US citizen for direct household use is 242 Liters/capita/day but the water use for producing food for the same citizen, including irrigation and livestock, will require 1,928 Liters/capita/day, eight times more, of which 61% is consumptive use, i.e., water lost by evaporation and transpiration. Producing electricity requires 1780 Liters/capita/day, mostly for cooling. The consumptive loss from cooling water is about 3 to 4 %, hence, the virtual water demand for producing electricity is about 53 to 73 Liters/capita/day (McMahon, 2008; Gleick et al., 2008).

Hoekstra and Chapagain (2007) divided virtual water into

- The volume of fresh water that is lost by evapotranspiration to produce the goods and services consumed by the individual or community
- Volume of water needed to dilute pollutants generated and discharged in the production process

Pollution export – virtual pollution and externalities

Similarly to virtual water, import of goods to a large city from distant areas and countries that have lax pollution laws and abatement creates virtual pollution export from the city to areas where the goods are produced. Examples are many and the most obvious ones are imports of inexpensive goods from some developing countries that would be more costly to produce in the US and other developed countries with stringent and enforced environmental laws. Hence, the pollution that would have occurred in the area receiving the goods, if production occurred in the city, is exported to the country that produces the goods which also includes GHG emissions.

Pollution externality is another example of virtual effects. Pollution externality or external diseconomics (Novotny, 2003) occurs when pollution created by a city or industry is transferred by a physical conduit (e.g., river) downstream to another user of the water body who incurs additional costs due to more treatment or loss of the resource and the sufferer has no economic recourse to recover the cost from the upstream polluter. Externalities are regional and often transboundary. For example, in Europe upstream countries discharge nutrients into the Danube River (the second largest river in Europe after the Volga River in Russia) creating severe anoxia in the Black Sea that causes loss of fishing and problems with recreation in the nations surrounding the sea.

Global climatic change – Energy/Carbon footprint

It is now generally accepted that we are undergoing a long period of global climatic changes, indentified also as global warming, caused be excessive emissions of GHG that include carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O) and fluorinated gases. GHG emissions are natural (including living processes by humans and biota) and without them the earth would be too cold to live in. Excessive anthropogenic CO_2 and other GHG emissions from power plants, traffic, industrial operations, home heating, etc., after the onset of the industrial revolution, trap heat in the atmosphere and cause global warming.

Until recently the US was the largest emitter of GHG gases but was overtaken by China. If statistics are presented in emissions per person (Table 1), the Middle East states are the largest emitters (Table 1). Dodman (2009) found large cities emit per capita less GHG than the national average. For example, London's emissions (6.2 tons/capita/year) are 50% less than the national average (9.4 tons/capita/year).

A new paradigm shift in the COTF urbanisms can be observed in *the push for carbon neutrality* which could be considered as self - preservation of the global society from wide spread worldwide effects of predicted climatic changes if nothing or little is done to reduce emissions of GHG. Global warming solutions cut across all the major systems of the city: energy provision for buildings; energy use by transportation systems and the "discovery" by transportation engineers that land use and urban form decisions can reduce mileage (kilometers) traveled by cars and other traffic, a major contributor to transportation carbon emissions; and the dual relationship of water and energy. Energy is needed by the water/wastewater industry (biggest energy cost is for transporting water and used water) and water is needed by the energy industry, particularly for nuclear power plants. Global warming solutions are also assisted by taking a more eco-friendly approach to development. Today pressing news about the deleterious effects of increasing concentrations of CO_2 and other GHG's give added impetus for the need to make our cities more sustainable.

Water and energy nexus is also a premise of global sustainability. In the area of water management, achieving the global goal of reducing GHG emissions implies water (energy) conservation, reuse of used water and use of stormwater, development and use of renewable energy, reduction in energy use in urban and suburban transportation and building infrastructure, and reliance on local and sustainable agriculture. Figure 3 shows possible paths towards achieving the net zero GHG emissions and thereby reduce the social/energy footprint of our cities.

Similarly to water, the carbon footprint concept can be extended to include virtual energy use. For example, Geick and Cooley (2008) estimated total energy use for producing 1 liter of bottled water being on average 1.5 – 2.8 kW-hr which is 2000 times the energy cost for producing tap water.

Table 1 Per capita CO_2 emissions statistics

Top ten countries in GHG (CO_2 equivalent) emissions in tons/person/year in 2006[1]									
Qatar	UAE	Kuwait	Bahrain	Aruba	Luxembourg	USA	Australia	Canada	Saudi Arabia
56.2	32.8	31.8	28.8	23.3	22.4	19.1	18.8	17.4	15.8
Selected world cities total emissions of CO_2 equivalent in tons/person/year[2]									
Washington *DC	Glasgow UK	Toronto CA	Shanghai China	New York City	Beijing China	London UK	Tokyo Japan	Seoul Korea	Barcelona Spain
19.7	8.4	8.2	8.1	7.1	6.9	6.2	4.8	3.8	3.4
Selected US cities domestic emissions of CO_2 equivalent in tons/person/year[3]									
San Diego CA	San Francisco	Boston MA	Portland OR	Chicago IL	Tampa FL	Atlanta GA	Tulsa OK	Austin TX	Memphis TN
7.2	4.5	8.7	8.9	9.3	9.3	10.4	9.9	12.6	11.06
[1]Wikipedia (2009); [2] Dodman (2009) ; [3]Gleaser and Kahn (2008) [2,3] Values include transportation, heating, and electricity									

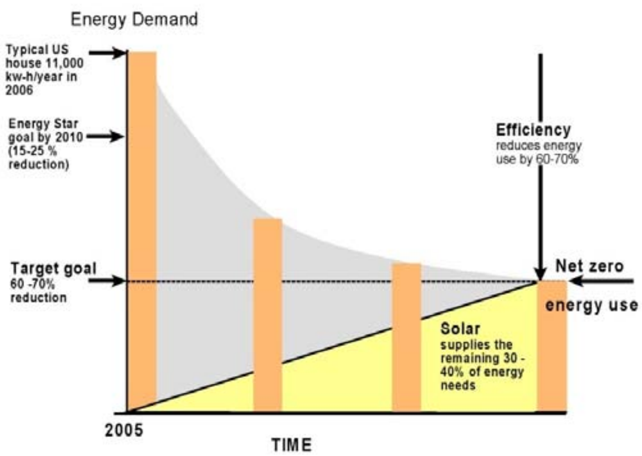

Figure 3 Water and energy nexus of ecocities with reduced water use and resource recovery can achieve net zero GHG emissions. Source NSTC (2008).

Ecological footprints

Global scale/regional ecological footprint has been proposed by Rees and his students and coinvestigators (Rees, 1996; 1997; Wackernagel and Rees, 1996). The ecological footprint was defined as the total area of productive land and water required to produce, on a continuous basis, all the resources consumed and to assimilate all the wastes produced by that population, wherever on earth the land may be located (Rees, 1996; 1997). The ecological footprint of a city is proportional to the population of that city, its population density and per capita material (plus food and water) consumption.

In 1995 with the earth population of less than 6 billion, the footprint unit area of productive land was 1.5 ha/person. In contrast, megalopoli (cities with more than five million people) in the developing world have an ecological footprint well below 1 ha/person. With the expected population to grow by 2040 to 10 billion and reduction of productive land area by urbanization, deforestation, etc., the available productive area will be less than 1 ha/person. Rees (1997) and Wackernagel and Rees (1996) calculated the ecological footprint of Vancouver (BC) called then a “typical North American city” as being 4.8 ha/person, which will be 3 to 4 times the available productive land on earth.

The ecological footprint is obviously not the same even in the cities of the developing world. Rees (1997) estimated the ecological footprint of some other cities in the developed countries as

Countries with 2- 3 ha/capita footprint
    Japan and Republic of Korea
Countries with 3 – 4 ha/capita footprint
    Austria, Belgium, United Kingdom, Denmark, France, Germany, Netherlands, Switzerland
Countries with 4-5 ha/capita footprint
    Australia, Canada, and USA

All developed countries are running an ecological deficit, i.e., the footprint is much greater than the fair share of global productive land. Large cities in developed countries have an ecological footprint hundreds times greater than the city area. The resource and productive land availability for future population growth and increased living standards that, if things go as usual, would exhaust the productive land long before the living standards in developing countries would reach levels comparable to that in the developed countries. If every person on earth living in the future cities desires to achieve the current living standard of Vancouver, the ecological footprint (i.e., the demand on resources for production and assimilation of emissions) would be more than three times the available productive land on earth. Hence, to achieve a sustainable future for all there is no other choice than to abandon linear urban systems, switch to a conservation and reuse circular system and reduce substantially the footprint. Increasing densities lead to lower land requirements, less transportation by private automobiles and generally to less energy use (Novotny and Novotny, 2010).

Local ecological footprints are to some degree different than global footprints focusing on sustainability of resources to provide viability to the city. The local and subregional footprints focus on sustainability of resources and ecology within the city and the region of ecological influence that is much smaller than that identified by the Rees' "giant footprint". The global virtual water, ecology and carbon footprints, in contrast, deal with the load and demand of the city on the earth's ecological resources and assimilation of pollution and waste. As pointed out by Rees (1997) "the ecological location of human settlements no longer coincides with their geographic location". Healthy ecology in and near cities is paramount for healthy living and, with the exception of mammoth water transfer from long distances, cities are connected physically with the water resources that provide drinking water, recreation, residual pollution assimilation, and happiness. Furthermore, the excessive pollution impact is most severe in or near the city that is responsible for it. The local footprint focus is on livability of cities and restoration and preservation of urban ecology. The local/subregional ecological footprints were divided into those considering (a) urban waterways and impoundments, (b) water corridors and urban open green space; and (3) urban hydrology, including surface and subsurface water resources and drainage.

Urban waterways and impoundments are the most dominant component of the local ecological footprint of the COTF. Previous practice put urban streams underground as sewers or out of sight culverts because of severe pollution decades or a century ago. In the COTF, water conservation and treatment will provide ecological flow to surface water bodies that today lack it because of overuse. Current and future used water reclamation technologies can bring water quality to levels that would support aquatic life, water supply and recreation.

Responsible nutrient management. Many water bodies, not just urban, are severely affected by eutrophication which in some cases has led to an hypertrophic status characterized by massive algal blooms of cyanobacteria. These resilient microorganisms greatly impair beneficial uses of water bodies such as fish and wildlife propagation, recreation, and water supply. The problems are caused by excessive nutrient (nitrogen and phosphorus) inputs both from urban and rural point and nonpoint sources. To make the matter worse, the world is running out of phosphorus needed to grow crops. In some countries (e.g., China, Czech Republic) hypertrophic conditions of the impoundments are decommissioning water supply during the conditions of cyanobacteria algal blooms, leading to severe problems with providing safe water from the infested sources to millions of people. Efficient and responsible nutrient management and phosphorus recovery is a COTF goal and a measurable footprint.

Ecological corridors and open space. Urban ecology consisting of green areas, water bodies and ecotones that separate nature from built habitat has to provide connectivity and passage to the urban biota and people. The opposite of connectivity is fragmentation that impedes healthy ecology and survival during the time of stress. Ecological corridors along urban surface water bodies also provide resiliency to extreme meteorological events such as floods.

Urban hydrology. Past urbanization has dramatically changed the hydrology of our cities by reducing infiltration and groundwater recharge and increasing flooding. This led not only to water shortages but also to dangerous subsidence in many communities, including Venice (Italy), Mexico City, Philadelphia, and Boston and increasing vulnerability to catastrophic flooding. Unrestricted development and climatic changes will also increase the portions of urban areas in floodplains. Restoring hydrology as close to the natural water cycle should be a goal and also one that measures the progress towards sustainability.

SUMMARY

Water, ecological, carbon/energy and economical footprints are linked to and are expressions of the urban metabolism which can be linear or cyclic. Linear urban water and energy management exert very high demand on resources and inputs (water, energy, food, chemicals, and materials) which is not sustainable. Urban metabolism and the need for change is also driven by the adverse effects of ongoing and future global warming caused by emissions of GHG into the atmosphere and future population increases. As countries currently developing at a fast pace will try to catch up with the currently developed countries, there will not be enough resources to sustain the growth and the existing resources, including water, would be rapidly exhausted.

Changing towards sustainable urban development and retrofitting the current cities will require a great degree of water conservation and partially closing the urban metabolism cycle. For this purpose developing the measurable footprints and criteria based on the important footprints will be necessary. This requires a paradigm change of how cities are built and retrofitted. The most current popular criteria and certifications are mostly local and some only loosely tied to the most important sustainability footprints.

There is a need to develop comprehensive metrics and indices of footprint measures along with better criteria defining sustainability and adherence to the Cities of the Future goals.

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