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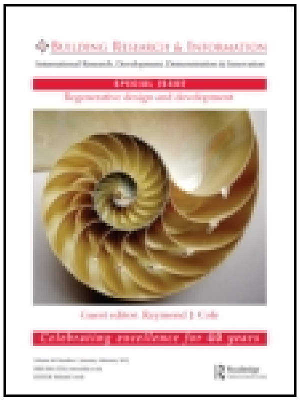

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Water-energy nexus: retrofitting urban areas to achieve zero pollution

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INFORMATION PAPER

Water–energy nexus: retrofitting urban areas to achieve zero pollution

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A major paradigm shift is examined for building new and retrofitting historic communities striving towards appropriate consumption of resources and reduced pollution: reusing and recycling water; recovering energy, nutrients, and other resources from used water and solids; attaining a sustainable use of water resources; and attaining net zero greenhouse gas (GHG) emissions targets. The key global and regional footprints identifying the trends towards the sustainable water–energy nexus in future ecocities are defined. Three scales are examined: domestic (individual building), cluster (ecoblock) and regional levels. An integrated approach to urban design and the use of water resources is presented. The future hybrid (partially closed) system would reclaim clean water, nutrients and other resources, and produce additional energy. Methane- and hydrogen-based energy recovery and conversion to electricity in an integrated resource recovery processes are proposed. The triple bottom line analysis and willingness to pay can be used to determine quantitative social values of non-market commodities (*i.e.* ecological enhancement, sustainability, improvements in water quality and aesthetic assets, and the reduction of GHGs emissions). Urban retrofit solutions are outlined for reducing water use, creating net zero GHGs, eliminating pollution, and generating financial revenue through the recycling and recovery of resources.

Keywords: cities, drainage, retrofit, sustainable urban design, urban planning, water conservation, water–energy nexus, watershed management

Il est examiné un changement de paradigme important concernant la construction de collectivités nouvelles et la rénovation de collectivités historiques visant à obtenir une consommation adaptée des ressources et une réduction de la pollution : en réutilisant et en recyclant l'eau ; en récupérant l'énergie, les nutriments et les autres ressources provenant des eaux et des matières solides utilisées; en parvenant à une utilisation durable des ressources en eau ; et en atteignant les objectifs nets zéro relatifs aux émissions de gaz à effet de serre (GES). Sont définies les principales empreintes mondiales et régionales identifiant les tendances allant dans le sens d'une interaction durable eau-énergie dans les éco-cités du futur. Trois échelles sont examinées : les niveaux du ménage (bâtiment individuel), de l'ensemble (éco-immeuble) et de la région. Une approche intégrée de l'aménagement urbain et de l'utilisation des ressources en eau est présentée. Le futur système hybride (partiellement fermé) récupèrerait l'eau propre, les nutriments et les autres ressources, et produirait de l'énergie supplémentaire. Sont proposées la récupération d'énergie à partir du méthane et de l'hydrogène et sa conversion en électricité dans des processus intégrés de récupération des ressources. L'analyse sous l'angle du triple résultat et la volonté de payer peuvent être utilisées pour déterminer les valeurs sociales quantitatives des produits non marchands (c'est-à-dire la valorisation écologique, la durabilité, les améliorations apportées à la qualité de l'eau et aux atouts esthétiques, et la réduction des émissions de GES). Des solutions de rénovation urbaine sont exposées pour réduire la consommation d'eau, créer des GES nets zéro, éliminer la pollution, et générer des revenus financiers par le recyclage et la récupération des ressources.

Mots clés: villes, système d'écoulement des eaux, rénovation, aménagement urbain durable, urbanisme, conservation de l'eau, interaction eau-énergie, gestion des bassins versants

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Introduction

The world is undergoing rapid urbanization driven by population increase and migration. According to United Nations (2010) statistical projections, the world population will increase from 7 billion in October 2010 to 9.3 billion by 2050, with 68% living in urban areas. In China, the total population between 2010 and 2050 is actually expected to drop by 46 million to 1.295 billion, but the urban population by migration and resettlement will increase by an astounding 400 million to 1.038 billion, 80% of the total. According to Vidal (2010), the emergence of large megalopoli and the trend of population growth and migration in the next 40 years will give a rise to urbanized 'mega-regions' with more than 100 million people. The first such mega-region is the Hong Kong–Shenzen–Guanzhou area in China. The financial wealth of most countries will be concentrated in the cities, but wealth in rural areas will also increase because urbanites will be purchasing the food and materials from the rural areas.

At end of the last millennium, experts realized that if urban development continued as usual, then the pressure on resources and the demand on water and associated energy use would be unsustainable. The current paradigm of 'fast mostly underground water/wastewater conveyance and end-of-pipe storm and wastewater controls' uses a large amount of energy and is responsible for excessive greenhouse gas (GHG) emissions from power plants using fossil fuel. A major paradigm shift is examined for building new and retrofitting historic communities striving towards reduced consumption of limited resources and reduced pollution.

The worldwide average energy use attributed directly to water supply and wastewater is about 3% (Intergovernmental Panel on Climate Change (IPCC), 2007). The UK level (Department of Energy and Climate Change (DECC), 2012) is approximately the same. However, the US average is about 7% of total energy consumption for treating and delivering water to the population and for disposing of used water and solids residues. The water-related energy use is even larger in some US states with water shortages, reaching 19% in California. Far more energy (which is unaccounted in the IPCC, 2007; 3% GHG estimate) is for heating water which normally is included in statistics as 'building' use (DECC, 2012; Meda, Lensch, Schaum, & Cornel, 2012). In addition, urban water systems cannot cope with extreme precipitation events which are expected to increase as a result of forecasted global warming (IPCC, 2007). A more detailed analysis of water use, water conservation and the impact on GHG emissions is published by Novotny, Ahern, & Brown (2010).

The current urban paradigm has forced planners and engineers to implement an increasing proportion of impervious surfaces, larger interceptors and tunnels, longer transmission distances for water and wastewater, and lining, fencing off and burying the urban streams. Generally, older underground storm and combined sewer infrastructures in developed countries were designed to accommodate flows generated by storms with a return period of five to ten years, with a maximum of 30 years. Such systems are usually unable to deal with the extreme events predicted to increase due to global warming. The systems sometimes fail, now with serious consequences such as the 2012 Hurricane Sandy causing flooding and pollution in the New York City metropolitan area. During wet weather the infiltration–inflow (I-I) inputs may more than triple the volume of dry weather wastewater flows in sanitary sewer systems and overwhelm treatment plants (Metcalf & Eddy, 2003). Large wastewater interceptors and storage tunnels for combined sewer overflows (CSO) and sanitary sewer overflows (SSO) are typically located deep underground and the energy requirement for pumping is high.

The need to create new models of urban design that link landscape and technology with water and energy are currently being recognized and realized in China, Singapore, Japan, Australia, several Western European countries (the UK, Sweden and Germany), the Middle East (Israel and the United Arab Emirates), and in Canada (Dockside Green in British Columbia and developments in Toronto, Ontario). In the United States, scientists and architects participated on the development of concepts (*e.g.* Massachusetts Institute of Technology and Harvard University, University of California), but applied them in cooperation with architectural firms and consultancies in the UK and other countries. Examples of such US–UK cooperation are in China (Dongtang, Tianjin) and the Middle East (Masdar in the United Arab Emirates). The United States is beginning to plan its first sustainable communities, *e.g.* in portions of Milwaukee (Wisconsin), Philadelphia (Pennsylvania), Portland (Oregon), or San Francisco (California).

Urban metabolism

The urban metabolism is defined by Kennedy, Cuddihy, & Engel-Yan (2007, p. 44) as the:

> sum of the technical and socio-economic processes that occur within the cities, resulting in growth, production of energy, and elimination of waste.

Figure 1 illustrates a transformation of inputs of raw materials, food, energy, water and chemicals into environmentally relevant outputs which can be linear or cyclic or hybrid. The metabolism relates the amounts of inputs (which impact on the resources) to the outputs affecting citizens' well-being and ecological

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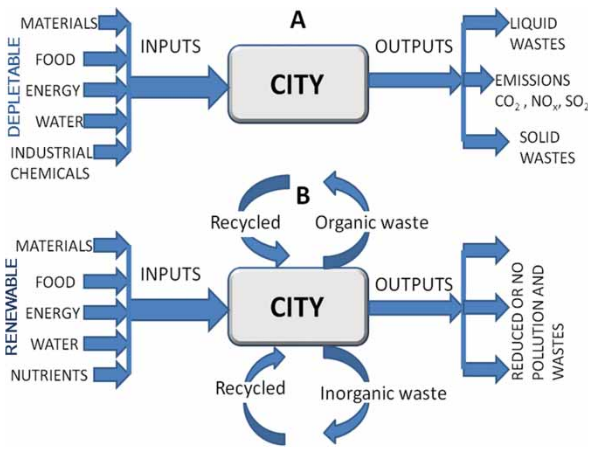

Figure 1 (a) Linear and (B) circular urban metabolism systems. Source: Novotny, Ahern, & Brown (2010)

health (Newman, 1999). Current urban systems are mostly linear. Daigger (2009), Novotny (2008) and others argue the 'linear' approach, sometimes called the *take, make, waste* approach, has become unsustainable and cannot continue. It discourages reuse because the source of reclaimed water is far downstream from the city and the traditional economic benefit–cost or minimum cost evaluations do not consider important social and environmental costs and benefits classified as intangible. The balance between the inputs, accumulation and growth, on the one hand, and waste resulting in emissions of undesirable pollutants, on the other hand, are the key determinants of the sustainability of the city. Urban metabolism is affected by ongoing and future global climatic changes caused by emissions of GHGs, and future population increases and migration.

Urban metabolism footprints

A 'footprint' is a quantitative indicator of urban metabolism showing the appropriation of natural resources by human beings (Hoekstra & Chapagain, 2008). Footprints can be local or regional to global. Three major footprints have been identified: water, carbon and ecological.

Water footprint

The per capita water use in cities has been accepted as a water footprint (Figure 2). It includes direct water use for domestic and commercial water purposes and virtual water, which includes water needed to grow and produce food, industrial products, energy and other commodities needed to sustain human life in the urban communities. The water footprint has a regional significance. In the United States, direct domestic indoor water use is relatively constant among the major urban areas (Heaney, Wright, & Sample, 2000), averaging 242 litres/capita/day for a household without water conservation and 136 litres/capita/day for a household practising water conservation (Heaney *et al.*, 2000). The US total water use is exaggerated by extensive outdoor irrigation (using potable water), leaks and swimming pools and reaches almost 650 litres/capita/day, which is the highest in the world, a factor of two to three compared with Europe. This is a consequence of the typical US urban sprawl development preferring single low-density family housing on relatively large plots requiring irrigation of grass (even in desert environments).

Critical water shortages and poor quality of available water must be vigorously addressed in developing countries as well as in many developed countries

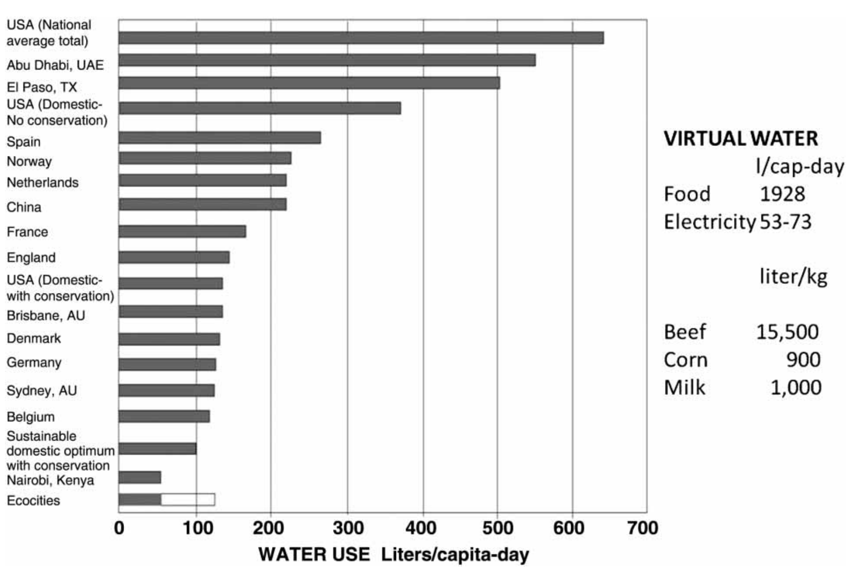

Figure 2 Per capita water use in selected countries. Source: adapted from Novotny, Ahern, & Brown (2010)

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anticipating severe drought conditions (*e.g.* Australia, the Southwest United States, Israel and the Middle East). Today shortages exist even in the humid United States where surface and groundwater sources are insufficient to sustain high water use (*e.g.* Atlanta in Georgia or Tampa in Florida). Billions of the world's poorest people subsist on fewer than 20 litres/person/day and more than 46% of people do not have access to a nearby running drinking water tap or well.

'Virtual water' transfers and trading is a concept that refers to the water use outside the city that is used to produce food, materials, and other goods and services to satisfy the needs of the people living in the city. This concept was originally developed by Allan (1993). Such water-demanding production activities outside the city include agriculture, the production of electricity, construction materials, paper, biofuel (from corn or sugar cane), or oil derived from tar sands and shale natural gas by fracking. The virtual water footprint in cities in developed countries is about three times as large as the onsite household use (Hoekstra & Chapagain, 2008). The current Cities of the Future (COF) goal and criterion of sustainability, especially in the high water-use countries, is to cut the water use to less than 50% of the today use (World Wide Fund for Nature (WWF), 2008). However, in countries with a very high per capita use, water savings could be greater. For example, by implementing water conservation and separating used water into black (containing faecal matter) and grey flows, and reusing most of the grey water, the water savings can be as much as 70% with accompanying reduction of energy use and GHG emissions (Novotny *et al.*, 2010; Novotny, 2012). Furthermore, energy and nutrients can be recovered from black water.

Energy-carbon footprint

It is now generally accepted that the earth is undergoing a long period of adverse global climatic changes caused by excessive emissions of GHGs from natural and anthropogenic sources. The density of the urban area can vary over a wide range from urban sprawl type developments of fewer than 25 people/ha to densely populated megalopoli with populations in hundreds or even thousands of people per hectare. Figure 3 shows the impact of density on the carbon footprint. The optimum population density in the context of the energy footprint is the medium density between 80 and 200 people/ha, which is the density typical for current or planned ecocities and also typical for many European urban areas. The figure also includes a comparison of estimates of lowest GHG emission limits for sustainable urban drainage systems (SUDS) known in the United States as low impact developments (LID) and the COFs.

Most people living in less developed countries have their carbon footprint below 1 tonne of CO_2/capita/year (*e.g.* Nairobi in Kenya). Data from Barcelona (Spain) and San Francisco indicate that if urban communities are designed with green goals and optimum density with good public transportation, then a footprint of 3–4 tCO_2/capita/year, or about one-third of the average US urban emission, is realistic.

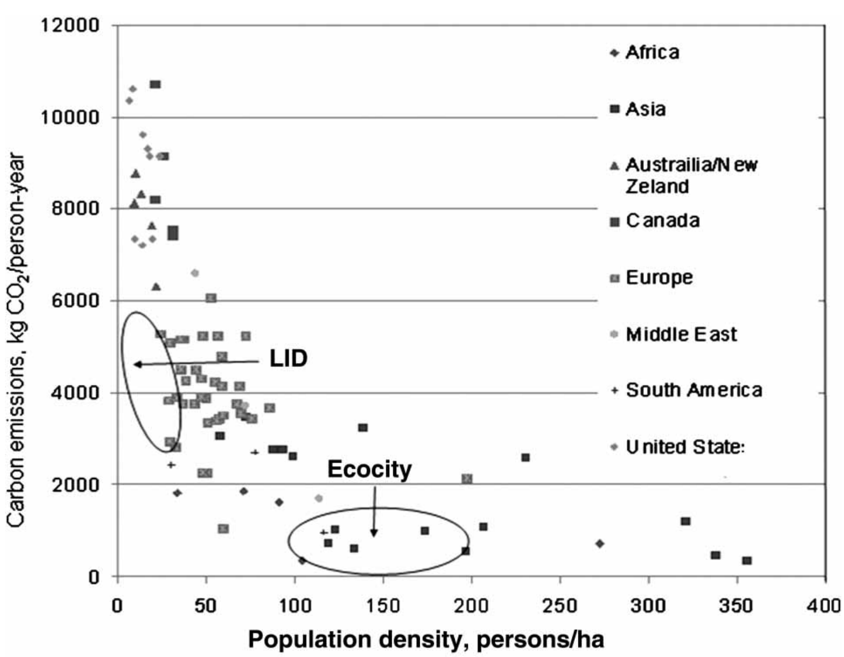

Figure 3 Effect of population density on the carbon footprint of urban areas.
Sources: Novotny & Novotny (2012) and Novotny, Ahern, & Brown (2010)

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In the area of water management, achieving the global goal of reducing GHG emissions implies water (energy) conservation, the reuse of used water and storm water, implementing surface drainage for storm water, the development and use of renewable energy, a reduction in energy use in urban and suburban transportation and building infrastructure, and a reliance on local and sustainable agriculture.

The ecological footprint

This has been defined as the total area of productive land and water required to produce, on a continuous basis, all the resources consumed by the city and to assimilate all the wastes produced by its population, wherever on earth the land may be located (Rees, 1992, 1996, 1997).

Rees (1997) and Wackernagel & Rees (1996) calculated the ecological footprint of a 'typical North American city' (Vancouver in British Columbia) as being 4.8 ha/person, which, if multiplied by the expected population 20–30 years in the future, will be three to four times the total productive land area on earth. This is clearly unsustainable, especially in rapidly growing cities in water-short developing countries. Hence, the COF goal is to reduce a high ecological footprint, which requires a decentralized hybrid water and energy management.

Urban water-centric sustainability

COF is an international movement working towards a major paradigm shift in the way new cities will be built or older ones retrofitted to achieve a change from the current unsustainable status to sustainability. The 11 principles defining the COFs were declared at the September 2010 International Water Association (IWA) World Water Congress in Montreal, Canada (Anon., 2012). An 'ecocity' is a more general term coined by urban planners and architects. A working definition of an ecocity was included in Register (1987). Novotny *et al.* (2010) outlined the goals of future new sustainable urban development as well as retrofitting the historic communities. The key components of water-centric sustainable communities pertinent to the development and retrofitting are outlined below.

Decentralized cluster water/storm water management

The concept of distributed complete water management has been evolving (Daigger, 2009; Heaney, 2007; Lucey & Barraclough, 2007) (Table 1). Water and energy conservation, resources recovery, reuse, and recycle are hierarchical and accomplished at three levels:

- house or building level (including appliance/fitting/water and energy fixtures)
- cluster/neighbourhood (ecoblock) level
- city/regional level

At the building level water, energy-saving devices are installed along with the outdoor sustainable landscape – xeriscape. Significant water and energy savings can be achieved by installing appliances such as shower heads, low-flush toilets, low-energy clothes-washing and dish-washing machines, or tankless water heaters, but also by efficient light bulbs. Passive house or building energy savings include insulation, sun exposure during winter, shading on hot, sunny summer days, and, wherever possible, green roofs. Irrigation is the largest water use in a typical US household and significant water and related energy savings will result by change of the house landscape from grass lawn to xeriscape in which native plants and mulching dramatically reduce or eliminate potable water use. Water separation into black and grey flows can be implemented. Most future houses will be expected to install solar hot water panels. Urine separation may be implemented because urine contains 75% of nitrogen and 50% of phosphorus load in 1% of the total used water flow and the nutrients from urine are easily recoverable.

A cluster or an ecoblock is a semi-autonomous water management/drainage unit that receives water, implements water conservation inside the structural components of the cluster and, throughout the cluster, reclaims sewage (separated or unseparated) for onsite reuse, such as toilet flushing, irrigation and providing ecological flow to restored existing or daylighted streams, recovers heat energy from used water, and possibly recovers biogas or (in the future) hydrogen from organic solids. Clusters may range from a high-rise building, shopping centre or a subdivision (neighbourhood) to a portion of a city (Furumai, 2007; Lucey & Barraclough, 2007). Figure 4 presents a concept of such interconnected hybrid systems with connections to a centralized integrated resource recovery facility (IRRF).

The goal of treatment at the cluster level is 'fit for reuse'. If reclaimed water in the cluster is used for landscape irrigation, removing nutrients does not make sense because the nutrients eliminated from reclaimed water would have to be replaced by industrial fertilizers with a high virtual energy use, which would defy the purpose of reclamation and reuse. Toilet flushing may require reduction of turbidity, disinfection (primarily to control bacterial growth and odour in the toilets and urinals), and adding some colour, if needed. To provide ecological flow to lakes or streams, nutrients should be recovered (*e.g.* by recovering struvite or urine separation) and not just removed (*e.g.* in sludge deposited in a landfill). On the local cluster/ecoblock scale, aquifer recharge is accomplished by infiltration of captured storm water. SUDS/LID concepts include enhanced rainwater infiltration (rain gardens), pervious pavements and infiltration ponds (Novotny *et al.*, 2010). Lastly, most heat energy in grey water can be recovered by heat pumps and used for heating/cooling at the cluster or building level.

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Table 1 Centralized and decentralized components of the future cities

Component	Centralized	Distributed/decentralized in clusters
Storm water rainwater management	None, storm water management is local	Best-management practices – pervious pavements, rain gardens, green roofs, surface and subsurface storage, infiltration basins and trenches
Water conservation	Reducing or replacing leaking pipes, system-wide education of citizens about water conservation, dual water distribution (potable and non-potable)	Wide variety of commercial residential water-saving plumbing fixtures and technologies for potable and non-potable use; changing from lawns to xeriscape
Treatment	Treatment for potable use and non-potable reuse	Fit for reuse treatment for local potable use (from local wells and surface sources) and non-potable reuse (from used water) in small cluster size water and energy reclamation units; storm water treatment in biofilters, ponds and wetlands, effluent post-treatment in ponds and wetlands. Possible source separation into black and grey water
Energy recovery	Methane from anaerobic treatment and digestion of residual organic solids, thermal microbial fuel cells, electricity from methane by hydrogen fuel cells	Capture and distribution of heat and cooling energy (heat pumps); geothermal, wind and solar energy. Small-scale biogas production by digestion (outdoor in developing countries)
Nutrient recovery	Land application of biosolids, struvite (ammonium magnesium phosphate) precipitation and recovery	Irrigation with reclaimed water with nutrients left in it; reclaimed irrigation water distribution to parks, golf courses and homeowners; urine separation and recovery
Source separation	Treatment of black waste water and organic solids with energy (biogas) production	Supply potable and non-potable water; treatment of black, grey (laundry and kitchen) and yellow water for non-potable reuse (irrigation, toilet flushing), concentration of residual used water flow with removed solids for further processing at the integrated resource recovery facility (IRRF)
Landscape management	Habitat restoration; fish management and restocking, wild life management in ecotones, flood-plain restoration	Stream and ecotones maintenance, installation and maintenance of best-management practices, including ponds and wetlands; on and off water recreation, incorporating flood storage and extreme weather resiliency into the landscape

Source: Adapted from Daigger (2009).

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This concept of cluster water management was implemented in the Solaire Battery Park residential complex in New York City where reclaimed water is reused for toilet flushing, irrigation and cooling, or at the Olympic sites in Beijing and London. The residual effluent is then conveyed to a central (regional) treatment plant. Olympic sites in Beijing and London are also known for implementing extensively sustainable drainage.

Restoring urban water bodies

Restored or daylighted urban surface water bodies are a lifeline of the development serving multiple purposes (Novotny *et al.*, 2010). In combination with landscape best-management practices, surface streams are more efficient conduits of flood water than underground drainage. Natural and created surface water bodies (*e.g.* manmade wetlands and ponds) and restored/daylighted water bodies attenuate peak flows and residual pollution from surrounding inhabited residential, industrial and commercial areas, and roads and highways instead of treating polluted runoff in hard infrastructure treatment plants. They also may serve as a source of non-potable water for buildings, landscape irrigation, cooling and/or street and sewer cleaning. This 'green infrastructure' along with the installation of pervious pavements and other infiltration best-management practices eliminates clean water inputs into sanitary and combined sewers which saves energy by reducing pumping mixed wastewater in the lift stations and reduces energy use of the treatment. Also, existing sewer capacity may become oversized and CSOs could be eliminated. Finally, ecologically functioning urban landscape containing surface water bodies and their interconnected green corridors provide habitat conditions for a balanced aquatic life and urban flora and fauna and sequester CO_2.

The imperviousness of urban surfaces prevents runoff from permeating into shallow aquifers which provide base flow to urban streams; hence, the restored surface water bodies may have insufficient flow, often

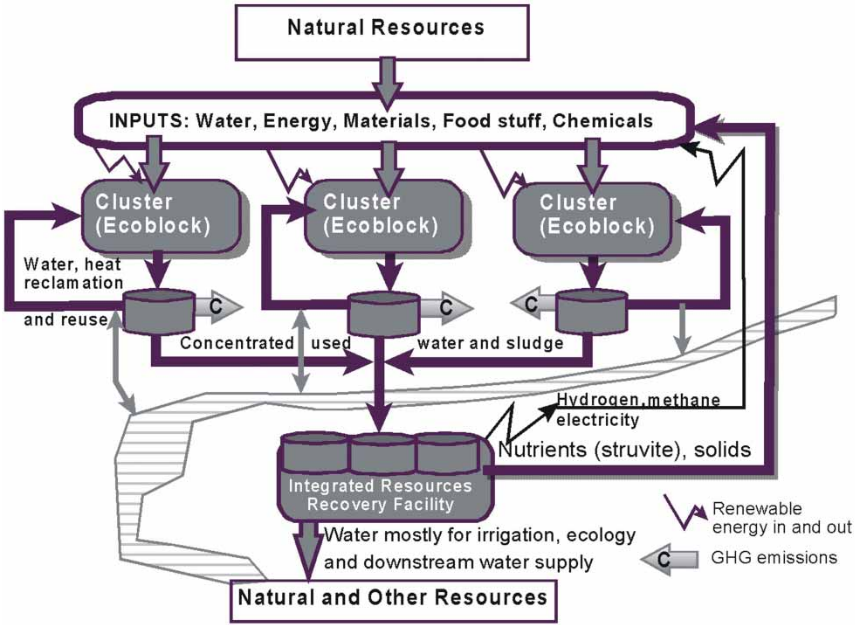

Figure 4 Distributed urban water/storm water/used water management system with an integrated resource recovery facility (IRRF)

to the point that they became ephemeral and/or effluent dominated (Figure 5a). Additional base flow can be provided by eliminating groundwater inflows into sanitary sewers, disconnecting sump pumps draining basements, tunnels and construction sites from subsurface hard infrastructure, diverting upstream flows and releasing stored urban runoff in ponds, wetlands and underground modular storage infrastructure into surface drainage. None of the above should enter underground sanitary sewers. Low flows can be supplemented/restored by ‘fit for ecological reuse’ effluent flows from cluster water reclamation plants.

Many restoration and/or daylighting projects are underway or planned throughout the world (Novotny *et al.*, 2010). One example is a project in Singapore. Despite a large annual rainfall, Singapore’s freshwater resources are very limited and the country has had to rely on imported water from neighbouring Malaysia. To increase its fresh water availability Singapore is increasingly relying on desalination, reclamation and reuse of used water (NEWater) and on augmenting its freshwater resources by changing the brackish estuary of the Singapore and Kallang Rivers, called Marina Bay, into a freshwater reservoir. This was accomplished by building a dam at the mouth of the estuary. Before 2010 the Kallang River (Figure 5a) was a concrete fast-conveyance channel discharging polluted urban storm water directly into the sea. Extensive urban storm water treatment best-management practices are being installed throughout the urban watersheds because urban runoff is now a major source of fresh water. The river is being restored to a natural status (Figure 5b) that also provides

(a)

Figure 5a Kallang River in Singapore, 2009.
Courtesy: CDM-Smith, Singapore

(b)

Figure 5b Computer-generated architectural picture of Kallong River after restoration.
Courtesy: PUB Singapore

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natural treatment. Water from Marina Bay is now pumped into the freshwater reservoirs located in the protected headwater areas which provide potable water to the city and country.

Integrated resources recovery

The preceding section defined the concept of a hierarchical three-level management of water, energy and resource recovery at the building, neighbourhood cluster/ecoblock and regional levels. Such recycling hybrid systems will need a supply of clean water to prevent the accumulation of salts and of 'new' contaminants (pharmaceuticals, nanopollutants and endocrine-disrupting compounds) in the system. This implies the safe disposal of reject water from microfiltration and reverse osmosis (RO).

While simpler, smaller cluster water/energy reclamation plants may be built efficiently in the neighbourhoods (ecoblocks), sludge management may not be advisable locally and would be objectionable to citizens living nearby. A regional IRRF is visualized to become a new complete recovery and management facility. It would accept organic solids and concentrated excess used (black) water and it would recover water, nutrients, solids, electric energy and heat in much greater quantities than it is possible in the current 'water reclamation plants'. The IRRF is based on existing technologies and those under development and may become feasible and economic soon. Some technologies have been used for decades, *e.g.* anaerobic treatment in digesters or lagoons, but new developments led to anaerobic treatment and the digestion of organic liquid and solids in upflow anaerobic sludge blanket (UASB) reactors (Lettinga & Hulshoff-Pol, 1991; Verstraete, van de Caveye, & Diamantis, 2009) or anaerobic fluidized bed membrane bioreactors (AFBMR) that require a much smaller volume and hydraulic residence time than traditional digesters and produce more biogas. These new processes also work in lower temperatures and require less heating energy than traditional digesters. Co-digestion of sludge with other organic solids and high-strength liquids (*e.g.* food and beverage production, airport de-icing fluids, vegetation residues and manure) is also being implemented (Zitomer, Adhikani, Heisel, & Dineen, 2008). These anaerobic processes produce biogas methane. High efficiencies of removing pollutants with much less space than traditional secondary clarifiers is achieved by membrane systems located in the biological reactor (Water Environment Federation (WEF), 2006).

For renewable energy production, heat (cooling) energy recovery from water is enabled by heat pumps and other heat reclamation devices. Solid organic waste, including residual sludge from liquid treatment and recovery processes, can be converted to biogas syngas (a mixture of carbon monoxide (CO) and hydrogen) by pyrolysis, which can also produce a liquid biofuel and nutrient and carbon-containing char. CO can be converted into hydrogen in the hydrogen fuel cell concurrently with methane to hydrogen conversion. The first step in steam reforming methane to hydrogen in the hydrogen fuel is converting it to syngas.

Finally, the main final by-product of these processes is a concentrated hot outflow of CO_2 gas which can be used in production of algal biomass and subsequently more biofuel or hydrogen (James, Baum, Perez, & Baum, 2009) using also nutrients emitted from used water and sludge processing units. New and more efficient capture of renewable solar energy by concentrated solar panels, and photovoltaics and wind energy by wind turbine power plants could be an integral part of the new water, nutrient and energy recovery facilities. Solar and wind power and heat will replace fossil fuel that otherwise would be needed to heat reactors and buildings.

Some of these processes have been or are being implemented in sustainable 'ecocities' of Qingdao in China, Masdar in the United Arab Emirates, Hammarby Sjőstad in Sweden, and other developments (Novotny *et al.*, 2010).

Nutrient recovery

Progress has been made in the production of nutrient-rich solids from sludge (Verstraete, Bundervolt, & Eggermont, 2010). Phosphorus can be and has been for long removed chemically by precipitation into sludge by adding iron salts. A process simultaneously recovering both nitrogen and phosphorus without energy is available by struvite precipitation from liquid used water and digester supernatant rich in nutrients (Barnard, 2007; Cecchi, Battistoni, & Boccadoro, 2003; Parsons, Wall, Doyle, Oldeing, & Chuerley, 2001). Struvite is chemically an ammonium magnesium phosphate ($NH_4MgPO_4 \times 6H_2O$). Magnesium (Mg) is added to the treatment/recovery process as magnesium hydroxide or magnesium chloride. Because struvite precipitates at pH > 9, pH could be adjusted after precipitation back to neutral by CO_2 produced in the treatment process. Struvite is recovered in fluidized bed or pellet reactors.

There are virtual energy savings and potential reduction of GHG emissions from the recovery of ammonium and phosphate (instead of disposing them in sludge or as nitrogen gas). As quoted by McCarty, Bao, & Kim (2011), the virtual energy requirement for production of nitrogen fertilizer by the Haber–Bosch process is 19.4 kWh/kg of N produced (Gellings & Parmeter, 2004) and that for phosphate is 2.11 kWh/kg of P, respectively. Struvite

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precipitation may recover most of phosphorus (70–90%), but because struvite contains equivalent molar amounts of phosphate and ammonia and a typical quantity of used water contains about 14 g-N/(person/day) and 2.6 g-P/(person/day), respectively (Henze & Ledin, 2001), only about 10% of ammonium is recovered. A new less energy-demanding process for removing (not recovering) ammonium from used water and digester supernatant is the patented Anammox process (McCarty *et al.*, 2011). Ammonium N can be also effectively recovered at building level by the separation of urea, which contains 75% of N in only 1% of used water flow. Based on current knowledge, the main capabilities and features of the IRRF could be:

- treating and reclaiming water for:
  - ecological flow of the recipient body of water
  - irrigation, water supply from alluvial deposits and recreation
  - groundwater aquifer recharge after additional treatment
  - recovering phosphorus and nitrogen as struvite or other chemically precipitated phosphate and high nutrient content solids
  - providing water, nutrients and CO_2 (alkalinity) to algal aquaculture producing biomass and energy
- recovering and producing energy for heating the anaerobic treatment and fermentation units as well as the facility and surrounding urban areas
- producing biogas that may include methane and/or syngas (O'Riordan, Lucey, Baraclough, & Corps, 2008) and/or hydrogen
- producing organic solids and char for soil conditioning
- converting biogas and hydrogen into electricity
- deriving all energy needs from on-site energy recovery, additional renewable sources (solar and wind) and sequestering carbon

Such facilities would generate no pollution, produce excess electricity and will be net sequesters of carbon (Verstraete *et al.*, 2009). Good reviews of the state of the art and future outlooks have been presented by Verstraete *et al.* (2009), Novotny *et al.* (2010), and McCarty *et al.* (2011).

A future possible IRRF alternative is shown in Figure 6 (based on Novotny, 2010, 2012). Other anaerobic systems were proposed by Lettinga, van Velsen, Hobma, de Zeeuw, & Klapwijk (1980) and McCarty *et al.* (2011). This facility would accept both concentrated liquid used water flows from the clusters and organic solids and liquids. The produced biogas could be converted to electricity by a combustion engine and

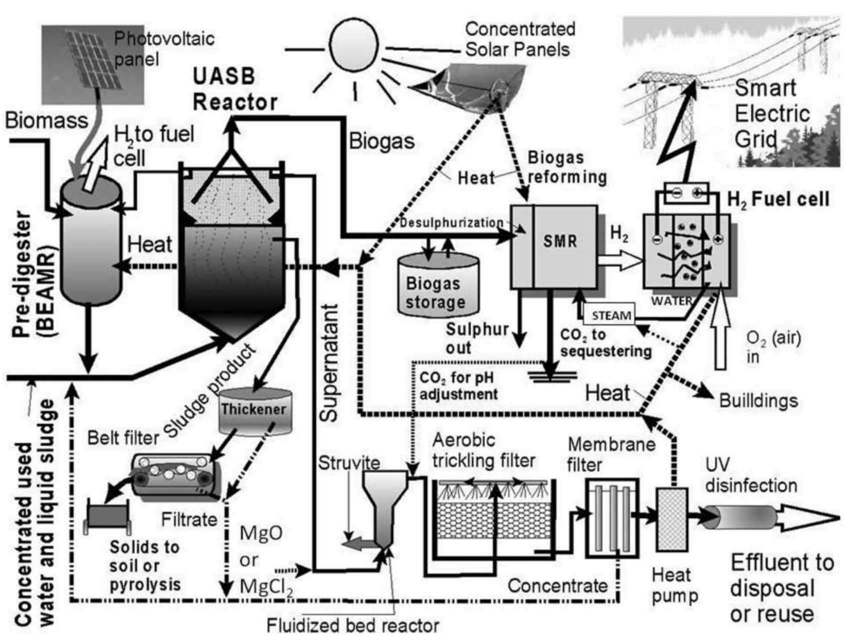

Figure 6 Integrated resources recovery facility (IRRF) for concentrated used water and organic solid waste.
Sources: Novotny (2010) and Novotny, Ahern, & Brown (2010). BEAMR, bio-electrically assisted microbial reactor (Logan, 2008); SMR, steam methane reforming

generator, or, in a more distant '2050' future, biogas and hydrogen would be generated and could be converted to electricity in a hydrogen fuel. Hence, energy can be recovered in a form of biogas (methane), syngas (CO and hydrogen), heat or hydrogen.

In Figure 6, UASB is an upflow anaerobic sludge blanket reactor as originally proposed by Lettinga *et al.* or, in a modified arrangement, a more modern and efficient two-tanks anaerobic fluidized membrane reactor (AFMBR) (McCarty *et al.*, 2011). Pre-digester (bio-electrically assisted microbial reactor – BEAMR) is an enhanced anaerobic fermentation reactor that in future is expected to produce more hydrogen (Call & Logan, 2008; Logan, 2004, 2008) directly from organic matter and concentrated wastewater (Wagner, Regan, Oh, Zuo, & Logan, 2009). Logan and co-workers and other researchers discovered that if a small amount of electricity is added to the reactor by DC current, then the hydrogen production by electrogenesis in a microbial fuel cell can be much greater than that in the fermentation process without electricity assistance. Anaerobic AFBMR treating typical municipal used water (COD $\geq$ 500 mg/l) can remove more than 90% COD and suspended solids with energy expenditure of less than 10% of a typical aerobic membrane bioreactor (Kim *et al.*, 2011; McCarty *at al.*, 2011). Current regional wastewater treatment plants can be converted/retrofitted into IRRFs and the current capacities of the tanks and pipes would be more than sufficient to accept these flows as well as the organic solids even when the connected population is moderately increased.

Attaining net zero pollution

Novotny (2012) analysed three alternative systems to illustrate the water and energy use and associated GHG emissions (Table 2). Water demand and its division into domestic (kitchen, bathroom, dishwasher, laundry, etc.) and outdoor (irrigation) components for average US households with and without water-conserving appliances and practices were based on the study of the American Water Works Association Research Foundation reported by Heaney (2007). Methods and parameters for the calculation and original reference sources are included in Novotny *et al.* (2010). The energy needed to extract, treat and deliver potable water from the water grid was based on the US estimate of 3–4% of the total energy use (US Government Accountability Office (GAO), 2012), which in 2010 was 12 146 kWh/capita/year (World Bank, 2012) and average water use based on the US Environmental Protection Agency (USEPA, 2012) data of 500 litres/capita/day, which yielded an estimate of 2.2 kWh/m^3. The average GHG CO_2 emissions equivalent from the US power plants is 0.61 kg CO_2/kWh (Novotny *et al.*, 2010). If the water is provided by desalination, then energy use may increase by 0.75–4.5 KWh/capita/day, based on 150 litres/capita/day water use and energy use for desalination ranging from 5 to 15 kWh/m^3 (Asano, Burton, Leverenz, Tsuchihashi, & Tchobanoglous, 2007).

- *Alternative I*
  Alternative I is based on average US household with sprinkler lawn irrigation water demand practising no water and energy conservation and discharging its wastewater into a conventional sewer system connected to an activated sludge treatment plant with nitrification that deposits residual sludge on land or in a landfill. Water demand is 550 litres/capita/day (an increase by 10% over the national average) of which 313 litres/capita/day is for outdoor irrigation. Heated water was 106 litres/capita/day and there was no heat energy recovery.

- *Alternative II*
  Alternative II is based on near future (10–15 years) household practising indoor water conservation and outdoor xeriscape planting with minimal irrigation located in a cluster which has a capability to reclaim some water and reuse it for toilet flushing. It is estimated that irrigation water need would be cut by half. Water conservation reduced the total water demand to 166 litres/capita/day, similar to a typical demand in Europe and Japan. On the cluster level a portion of heating energy can be recovered by heat pumps. Reclaimed water for toilet flushing was treated by microfiltration and ozonization and the rest of used water delivered to a regional activated sludge treatment plant with nitrification producing methane from sludge for heating of the digesters and buildings. This alternative needed separate piping, storage and a pump with a pressure tank for delivering reclaimed water to the toilets.

- *Alternative III*
  Alternative III is based on a 'visionary 2050' hybrid distributed system. The cluster (eco-block) level separates water into black and grey water cycles, as shown in Figure 7. This double-loop cycle was originally proposed by Harrison Fraker for the ecocity in Qingdao, China. The black water cycle (BWC) includes solids separation and treatment of a portion of the BWC flow for the local supplement of the grey water cycle (GWC) which needs make-up water to replace water lost in backwash and rejects water from the filtration (including RO) units of the GWC and for irrigation and ecological outdoor flow. Implementing the double-loop reuse reduced the daily volume of fresh water from the grid provided by freshwater sources to 50 litres/capita/day. A part of the BWC

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Table 2 Water and energy balance of three alternative water/used water management

Parameter	Alternative I Traditional linear system with no conservation	Alternative II Mostly a linear system with water conservation and partial reuse	Alternative III Hybrid system with energy recovery and conversion to hydrogen
Water flow from the grid (litres/capita/day)	551	166	50
Energy to deliver and use water kWh/capita/day)	0.55	0.17	0.113
Energy use for heating (kWh/capita/day)	3.88	2.60	2.60
Energy to treat recycle (kWh/capita/day)	0	0.015[a]	0.160[b]
Heat recovery from grey water (kWh/capita/day)	n.a.	n.a.	−1.00
Methane recovery from UASB (kg/capita/day)	n.a.	n.a.	−0.02
Hydrogen from UASB methane conversion by SMR (kg/capita/day)	n.a.	n.a.	−0.035
Hydrogen from BEAMR fermenting solids (kg/capita/day)[c]	n.a.	n.a.	−0.02
Total energy from hydrogen (kWh/capita/day)	n.a.	n.a.	−1.50
Heat recovery from effluent (kWh/capita/day)	0	−1.78[d]	−1.20[d]
Total energy expenditure (production) (kWh/capita/day)	4.75	1.05	(−0.89)
Carbon GHG emissions (credit) (kg CO_2/capita/year)	1263	234	(−198)
GHG credit with half solar heating (kg CO_2/capita/year)	n.a.	(−55.5)	(−710)

Notes: [a]Water recycle was treated by microfiltration and ozonization.
[b]Grey water recycle was treated by microfiltration, reverse osmosis and ozonization.
[c]Per US Environmental Protection Agency (USEPA) (2010), food and yard organic waste is 0.68 kg/capita/day and the recovery is 60%.
[d]Total effluent for Alternative II; integrated resource recovery facility (IRRF) effluent for Alternative III.
BEAMR, bio-electrically assisted microbial reactor; GHG, greenhouse gas; n.a., not available; SMR, steam methane reforming; UASB, upflow anaerobic sludge blanket.
Source: adapted from Novotny (2012).

with all solids separated and a significant portion of nutrients in BWC and GWC is conveyed to the regional IRRF (Figure 8). Admittedly, this is a visionary concept still lacking prototype testing and parameter derivations.

Discussion

- *Alternative I*
  Alternative I would result in 1.26 tonnes of CO_2 emissions/capita/year, which represents about 12% of the average US per capita emissions (including also traffic and home space heating). Its average water use was unsustainable and could not be repeated in most countries and arid regions.

- *Alternative II*
  Alternative II incorporates reasonable water and energy-saving measures with a reuse and rain water reclamation which would bring the per capita water use to the levels common in European countries and Japan. By these measures the CO_2-equivalent emissions can be reduced by 75%. Furthermore, the net-zero carbon emissions goal would be achievable if about 50% or more of water heating energy is derived from

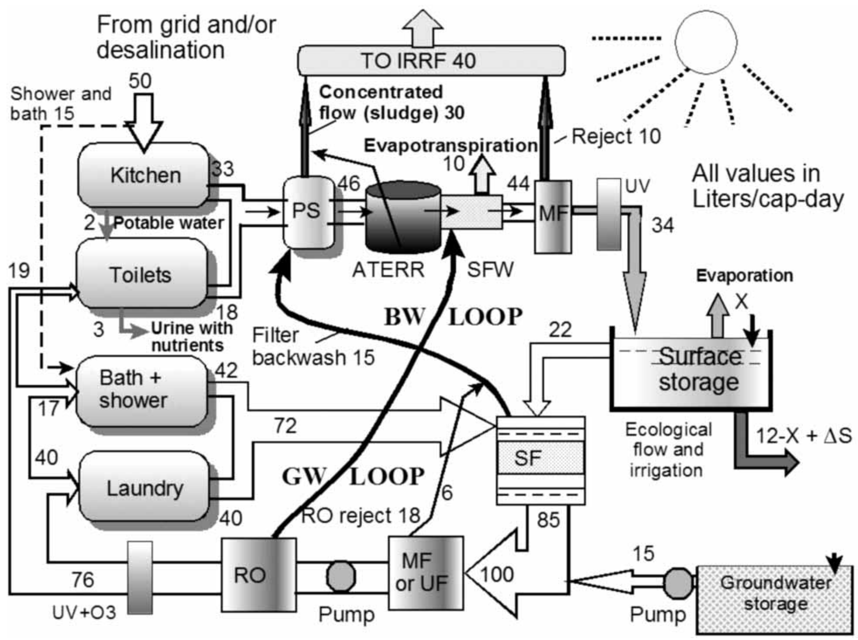

Figure 7 Double-loop hybrid cluster (ecoblock) system that recycles grey water (GW) and some black water (BW) on a dry day based on Qingdao Ecoblock (Fraker, 2008)
Source: Novotny, Ahern, & Brown (2010)
Note: ATERR = a generic anaerobic treatment and energy (methane) recovery reactor; HWT = hot water tank; MF, = membrane filter; UF = ultrafine filter; O_3 = ozone addition; PS = primary settler with solids removal; RO = reverse osmosis; SF = sand filter; SFW = subsurface flow multi-cell wetland with vertical flow; UV = ultraviolet disinfection

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renewable sources by installing concentrated heat solar panels.

- *Alternative III*
  Alternative III has a double-loop separating grey water and black water flows and on site cluster/ecoblock treatment (Figure 7). As documented by Novotny (2012), the water demand of this alternative could be very low at 50 litres/capita/day, which is deemed to be the lowest limit needed for providing an adequate water supply and water-based sanitation and providing water for some irrigation and ecological flow. However, there was not enough energy in the used water to satisfy the needs for the high recycle rate without co-digestion of organic solids and/or using renewable (solar) energy for heating water. With the co-digestion of food and other organic wastes Alternative III would create excess energy as well as the production of hydrogen, electricity and nutrients. The process also provides carbon sequestering. Implementing solar power for water heating would further improve the energy balance. For a community of 10 000 people, the IRRF energy production would be approximately equivalent to a 1 MW power plant which would provide, based on average 2010 electricity consumption (12 146 kWh/capita), electric power to 720 people. With improved future energy conservation, more people could be served.

Retrofitting

The conversion of historic cities to sustainability and water/storm water/used water decentralization will require a long-term plan that will first subdivide the urban area into semi-autonomous water management clusters, which also determines their surface drainage. Hence, a water-centric cluster is a low-order natural or created catchment. The daylighted and/or restored water body including the interconnected nature areas surrounding it (floodplain parks and nature trails and preserved forests) is the centrepiece of the community. The cluster water management, in addition to homes and commercial establishments, will then provide base flow to the water bodies, which, in turn, will provide fit-for-reuse reclaimed water for some uses within the cluster (*e.g.* irrigation) and provide resilience to extreme storms.

The measures that could retrofit the existing higher density communities and bring them towards sustainability begin with identifying buried historic streams, canals and filled wetlands and designating those that could be daylighted and made a backbone of the gradually surfaced storm water drainage, essentially separating storm drainage from combined sewers and eliminating storm sewers (*e.g.* Malmö, Sweden;

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Stahre, 2008). This activity will delineate storm water/used water management clusters (high-rise buildings, commercial clusters, residential communities, catchments and sewersheds).

If the system is linear, the first focus should be elimination of CSOs and SSOs by implementing (1) pervious pavements on side streets, back alleys and car parks; (2) green roofs; (3) infiltration of storm water and recharging groundwater; and (4) including underground and surface storage designed to provide water, not just storing it, and releasing it rapidly after the wet weather event.

Water conservation is the best and most efficient measure to reduce water and energy use in any community. In the traditional European (and European type, *e.g.* San Francisco or New Orleans) cities, private water use for irrigation is mostly restricted to flowerbeds in public parks and small garden plots. Development of urban agriculture on empty dedicated plots relying on irrigation water from the restored urban streams fed by reclaimed water should be encouraged. Irrigation by treated water from the public water supply should be either prohibited wherever possible or discouraged.

After dividing the urban area into natural ecological clusters with restored streams, lakes and interconnected ecological landscape corridors, an important step is identifying places where used-water reclamation plants could be located. These satellite facilities would connect with the existing and/or newly installed sanitary sewers and would extract used water for reuse treatment for irrigation (no nutrient removal), cooling or ecologic (nutrient removed) base flow of the restored/daylighted streams and lakes (Asano *et al.*, 2007). No nutrient removal is needed for restored wetlands that attenuate nutrients and other pollutants. Ideally, as shown in Figure 7, the used water at the cluster level should be separated into black and grey water streams, possibly including urine separation (not shown). Black and grey water separation and urine collection can begin with wastewater from public toilets, schools and office building. The satellite water reclamation treatment plants would then treat the cluster-produced used black and grey water and send separated urine and sludge to the IRRF.

Recovering heat from used water in the clusters and from the IRRF effluent is important. The heat energy content of used water is far greater that the energy potential of the organic content of the used water measured as chemical oxygen demand (Meda *et al.*, 2012; Novotny, 2012). The cluster resource recovery units could also produce renewable electricity; hence, the anaerobic unit process could be the first unit to treat the separated black water which will recover methane and hydrogen. At the regional level, the IRRF will be also accepting other organic waste such as food and food processing wastes, grease, solids from breweries, glycol from aircraft de-icing operations, vegetation residues, and other waste that can be co-digested with the sludge produced in the IRRF (Zitomer *et al.*, 2008) and produce methane or, in future, hydrogen (Cheng & Logan, 2011). The facility should include solar and wind energy production.

The benefits of retrofitting

The triple bottom line (TBL) life cycle assessment should persuade stakeholders to implement sustainability concepts. TBL is an extrapolation of the traditional cost–benefits analysis of public and private projects by including quantitative assessment of: (1) environmental/ecological protection and enhancement; (2) social equity; and (3) economics. To evaluate resiliency to extreme events, a TBL analysis should consider: (1) precipitation-induced floods, (2) water shortages, and (3) extreme pollution, also related to global warming. The unacceptable GHG emissions footprint is mostly a societal impact related to preservation of the society and its resources and ecology.

Examples of the tangible benefits of the COF integrated resources management include:

- increased value of homes and revenues to the community
- value of electricity and heat produced by IRRF or cluster energy recovery unit and from selling the excess energy to the regional or municipal grid
- selling biogas and hydrogen to transportation companies
- savings on fuel
- economic value of businesses and employment of riverside commercial establishments
- urban restoration economic effects
- sales of recovered fertilizers and opportunity benefit (virtual) of GHG emission reduction by not using industrial fertilizers
- savings on decreased water demand
- savings on the elimination of subsurface storm sewers and rental fees obtained for the use of excess capacity of existing sewers by other utilities and private users (*e.g.* telephone and cable companies as, for example, practised in Tokyo)
- savings on pumping energy cost for transmitting water

- boat launching and excursion fees and fees for recreational and habitat use of restored water bodies (*e.g.* Ghent, Belgium)

- fees for organic solid waste processing and savings on elimination of dumping fees to landfills

- fees for reclaimed water (*e.g.* irrigation of golf courses and gardens)

- savings on waste discharge fees and profits from selling 'cap and trade' energy credits (due to carbon neutrality or net carbon sequestering) in countries that implemented nationwide payments

It is difficult to use traditional economic methods for enumerating benefits for projects which involve pollution abatement, carbon and other footprints, watershed management, aesthetic amenities, convenience of transportation, value of enjoyment and satisfaction with living in a 'green community', recreational fishery, etc. One obvious reason is that a great part of the benefits is in the category of intangibles. Another reason involves the difficulty of capturing fees and taxes paid by the citizen groups that may include both direct beneficiaries (*e.g.* riparian owners and tenants of properties surrounding the impaired water body) and citizens who use the water body for enjoyment only occasionally. A programme of recovering the benefits via public funds can be successful only if the involved citizens are *willing to pay* for the benefits. Methods for estimating willingness to pay of citizens are available (Clark *et al.*, 2001).

The benefits of daylighting and restoration of urban streams are also very high but often intangible and information is still scarce. However, the daylighting of a river in the historic downtown Seoul in Korea has been estimated to bring revitalization and tourism benefits many times larger (about US$100 billion over the life cycle of 50 years) than the cost of bringing 10 kilometres of the historic CheongGye-Cheon River back to the surface (about US$180 million) (Lee, 2004). The retrofitting/daylighting process was a part of the overall water pollution abatement and landscape restoration program.

Challenges to implementation

A change of a paradigm does not come easy. Much inertia exists in society and in the governance of the cities that prefer status quo. Existing building codes and public health regulations are rigid and difficult to change.[1]

Education of the public and the new generation of engineers is still not at a level that would make the change possible on a large scale. 'Green technology' in high schools is popular but university engineering curricula still teach urban hydrology, drainage and 'wastewater treatment' using the concepts of the last century. Courses on the sustainable water/energy systems are not yet widely available. Until recently, research funding from US funding agencies was minimal. The situation in Europe is better. Government and private funding sources in Sweden, the UK, Sweden, Singapore, and also Australia and Canada have allowed progress towards the COF vision. This also made them highly competitive in China and the Middle East.

Conclusions

The new paradigm, under the acronym Cities of the Future (COF), is evolving in this century from an interdisciplinary discourse of urban planners, landscape architects, environmental engineers and scientists, urban ecologists, and other stakeholders who realized that a previous emphasis on grey infrastructure and linearity of the urban metabolisms are unsustainable. The threats of global warming, large population increases in urban areas, the emergence of megacities and large urban agglomerations under a scenario of limited and diminishing resource along with rapidly deteriorating urban infrastructure require this paradigm change. The urban areas must also increase resiliency against the increasing frequency and magnitude of extreme meteorological events such as recent hurricanes and typhoons. Retrofitting the city will need to embrace not only energy issues, but also key resources such as water. A significant challenge is how water is managed and used, as well as how 'used' (waste) water is treated and recycled. This impacts both on the use of a limited resource as well as the energy to operate such a system.

To achieve the sustainability goals, the public must be educated about the consequences of the 'business as usual' alternative in the cities and the alternatives leading towards sustainability. 'Learning alliances' have been proposed and implemented in some cities that are built on existing formal and informal networks and are designed to optimize relationships between the different interested stakeholder groups and breaking down the horizontal and vertical barriers to the progress towards sustainability. Under the frames of the UNESCO-sponsored SWITCH project (Hove & van der Steen, 2008) such citywide alliances have been formed in Birmingham (UK), Hamburg (Germany), Lodz (Poland), Zaragoza (Spain), Beijing (China) and others. Citywide alliances have been formed in several US cities which actually compete for the 'greenest city' title.

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Endnote

[1]For example, it is very difficult to implement natural drainage and rain gardens, a core of SUDS/LID drainage, in older communities or new developments where current codes demand impermeable roads and stone or concrete curb and gutter drainage connected to storm or combined sewers. In the United States, the preference of homeowners to have water-thirsty lawns irrigated by potable water is entrenched and difficult to change, in spite of the recent widespread sprinkling bans in the country caused by severe water shortages.

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