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A New Paradigm of Sustainable Urban Drainage and Water Management

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ABSTRACT

The current paradigm of urban water, stormwater and wastewater management and related infrastructure is unsustainable in most medium and large cities. It leaves the water resources damaged by various water quality, habitat and flow stresses, it results in water wasting and threatens the use of resources by the future generations. The current water/ stormwater/wastewater management infrastructure is not resilient to extreme events such as flooding or droughts that are expected to increase as a result of global warming. A new *fifth paradigm,* emerging from past successes and failures of the current and previous paradigms of controlling urban pollution and floods, offers a promise of adequate amounts of clean water for all beneficial uses. This emerging paradigm is based on the premise that urban waters are the lifeline of cities and the focus of the movement towards more sustainable "green" cities. The concepts of the new sustainable urban water management systems and the triple bottom line (TBL) criteria, by which their performance will be judged, are summarized and outlined. The paradigm considers microscale green development concepts and links them with macroscale watershed management, water/stormwater/wastewater infrastructures and landscape preserving or mimicking nature. Urban water management of the future ecocities may be based on implementing interconnected semiautonomous water management clusters, requiring less energy for pumping, heating and cooling. Macroscale TBL measures of sustainability must be considered. The new systems will combine sustainable infrastructure and ecologically and hydrologically functioning landscape. Significant energy reduction of green house emissions may be achieved.

Key Words: Sustainable urban drainage, Water conservation, Green urban design, watershed management, Paradigms of urbanization, Urban landscape, Urban planning, Triple bottom line

Sustainable Urban Water Management - Paradigms

During the Wingspread Workshop on "Cities of the Future – Bringing Blue Water to Green Cities" held in July 2006 experts from several countries discussed and defined future integrated management of water, stormwater, and wastewater systems (Novotny and Brown, 2007). In the preface to the monograph from the workshop the history of urban water and wastewater management was described, starting with the first systems of water supply (city wells) and drainage/waste disposal (streets and waste haulers) to the current fourth paradigm (see also Novotny, 2007). The current paradigm can be characterized as one relying on interbasin

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transfers of water, causing the rivers from which water was taken to have insufficient and sometimes no flow; high imperviousness dramatically reducing groundwater recharge; unsustainable use of water resources; fast underground conveyance drainage of stormwater providing marginal protection against flooding and backwatering effects by sewage; and large regional treatment plants downstream of urban centers that overwhelm the river with treated or partly treated effluents that may be reused in an uncontrolled way for water supply downstream in another urban area. The current paradigm of drainage and water/wastewater management infrastructure is clearly unsustainable because it leaves water resources severely damaged and often unusable for future generations. These systems are not resilient to large (extreme) precipitation events that are expected to increase as a result of forecasted global warming (ICCP. 2007; Karl et al, 1995). It forces planners and engineers into a cycle of implementing ever increasing imperviousness, larger interceptors and tunnels, longer transmission distances for water and wastewater, and lining, fencing off and burying the urban streams.

In the current *fourth paradigm*, attempts to control pollution originating from diffuse (nonpoint) sources were added to the growing complex of structural water management infrastructures. This paradigm could also be called the *"fast conveyance - end-of-pipe control"* because the predominant point of control of both point and diffuse pollution is where the polluted flow is conveyed by fast conveyance systems (sewers or lined channels) to an end-of-pipe pollution control facility or, without a treatment, is discharged into a receiving water body.

Pollution by urban runoff and other diffuse sources was recognized as a problem only about thirty to forty years ago. The proponents of the Clean Water Act in the US Congress noted this type of pollution and included in the Act passed in 1972 provisions for unregulated voluntary controls of nonpoint pollution. During the last century many best management practices (BMPs) had been developed to control the pollution by urban and rural runoff. Most of the BMPs were designed and implemented after the fact, i.e., after the high volumes of urban runoff were generated from impervious surfaces, pervious bare lands or construction sites controls with varying success were implemented to reduce runoff volumes, peak flows and pollution. At the end of the twentieth century the European Parliament enacted the Water Framework Directive. The period between the enactments of the Clean Water Act in the United States and the Water Framework Directive in Europe until the beginning of this century comprises the *fourth paradigm* of urban water management and protection in which both point and increasingly diffuse sources of pollution were considered and addressed in many separate and discreet initiatives.

The fast-conveyance drainage infrastructure conceived in Roman times to eliminate unwanted, highly-polluted runoff and sewage has produced great gains in protecting public health and safety. And yet, in spite of billions spent on costly "hard" solutions like sewers and treatment plants water supplies and water quality remain a major concern in most urbanized areas. A large portion of the pollution is caused by the typical characteristics of the urban landscape: a preference for impervious over porous surfaces; fast "hard" conveyance infrastructure rather than "softer" approaches like ponds and vegetation; and rigid stream channelization instead of natural stream courses, buffers and floodplains. Because the hard conveyance and treatment infrastructure under the fourth paradigm was designed to provide only five to ten year protection, these systems are usually unable to safely deal with the extreme events and sometimes failed with serious consequences (Novotny and Brown, 2007).

In the US after the passage of the Clean Water Act in 1972, the new massive building program of treatment plants was based on the "economy of scale" that prefers large regional treatment facilities with long distance transfers of wastewater over smaller local plants. Local treatment plants built before 1970 were mostly rudimentary primary only plants or low efficiency trickling filter facilities or aerobic/anaerobic lagoons. In most cases these plants were unable to meet the goals of the Clean Water Act. The new large scale activated sludge treatment facilities offered better efficiency capable of meeting the more stringent effluent standards and were managed by highly skilled professionals.

The long distance transfers of water and wastewater dramatically changed the hydrology of the impacted surface waters, which became flow deficient after withdrawal and the water body receiving the effluent then became effluent dominated. However, even today with long distance water and sewage transfers and sewer separation, the problems with combined and sanitary sewer overflows (CSOs and SSOs) have not been and most likely will not be fully mitigated in the near future. The long distance water/wastewater transfers from source areas over large distances also require electric energy for pumping, treatment (e.g., aeration) and transporting treatment residuals to their point of disposal. This use of energy contributes to green house emissions. The volume of "clean" groundwater water infiltration and illicit inflows (I-I) into sanitary sewers has to be pumped and treated with the sewage. The I-I inputs could during wet weather more than triple the volume of dry weather wastewater flows in sewer systems and overwhelm treatment plants (Metcalf & Eddy, 2002; Novotny et al., 1989). They have to be captured and stored in expensive mostly underground facilities. Many large wastewater interceptors and CSO/SSO storage tunnels are deeply underground and pumping energy requirement is high. For example, many kilometers of twelve meters diameter interceptors known as "deep tunnel" in Milwaukee (WI) and Chicago (IL) storing millions m^3 of mixture of stormwater and wastewater from CSOs and SSOs are located 100 m bellow the surface near the location of the treatment plants in which the sewage/water mixture is pumped (Table 1). Each underground pumping station uses several pumps that are the largest ever built.

Figure 1 Deep tunnel storage in Milwaukee drilled in the dolomite rock. A longer tunnel was drilled in Chicago by a similar mining drilling machine.

Table 1 Parameters of the Milwaukee and Chicago deep tunnel storages for CSOs and SSOs (various sources by the Milwaukee Metropolitan Sewerage District and Metropolitan Water Reclamation District of Greater Chicago)

System	Milwaukee (WI)	Chicago (IL)
Capacity (million m^3)	1.8	9.1
Length (Km)	42.6	175.3
Diameter (meters)	5.2 - 9.7	5.2 – 9.7
Depth underground (meters)	100	73 - 106
Cost (US$ - 1990 level)	1 billion	3 billion

Defining sustainability of urban water/stormwater/wastewater systems – The Fifth Paradigm of Urban Water Management

Sustainable development has been defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987). Mays (2007) presented several definitions of water resources sustainability that comply with Brundtland more general definition, for example

> *Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life.*

Another similar working definition of sustainability was formulated by the American Society of Civil Engineers (ASCE 1998). Unlike the ASCE definition that focuses only on sustainability the above definition implies that urban water systems, in addition to protecting and maintaining the water resources and their ecology for future generations, should be also resilient to extreme upsets and be capable to return to the pre-disturbance status in a relatively short time. Due to the high demand for water in some cities, and excessive development, water supply systems in many parts of the United States are often facing shortages of surface water in the reservoirs, dropping groundwater table and increasing outbreaks of high pollution. Predominantly subsurface stormwater drainage by storm sewers was designed to accommodate flows with the recurrence interval of five to ten years and larger storms result in flooding. The capacity of combined sewers is even less, these conduits were designed to overflow (without storage) when the total flow exceeds approximately 6 times the dry weather sewage flow (Novotny and Olem, 1994). Without expensive underground storages combined sewers generate highly polluted overflows in humid parts of the US and Europe thirty to fifty times per year. Such systems are neither sustainable nor resilient to large storms and hurricanes.

The paradigm of sustainable water resources in the context of water reuse and conservation, the principal building block of sustainable urban water systems, was extensively covered in the Metcalf and Eddy (2007) book. In elaborating concepts of sustainable development, the literature has emphasized that people – including city dwellers – are participants in ecosystems, and that they are ultimately dependent upon the resilience and renewability of ecosystem resources and services. Communities must therefore find ways to live adaptively within the loading capacity (waste assimilative capacity, loading capacity) afforded to them by the ecosystems of which they are a part (Rees, 1992, 1997). The linkages between socioeconomic and ecological systems mean that people must pay attention to the protection, and if necessary, the re-creation of resilient, self-organizing ecosystems that have the capacity for self-renewal in the wake of disruptions. If the definition of ecological sustainability is extended to urban ecosystems the understanding of "sustainability" does not necessarily imply a return to pre-development ecological conditions. The emphasis is on restoration of viable and resilient aquatic biota and letting the present and future generations use, enjoy and live in harmony with the urban water resources and their surroundings.

Jian and Beck (2007) summarized that the environmental performance of cities should be judged on the following categories of criteria: (1) their ecological footprint (EF- ecosustainability); (2) the total material (including water) flux and metabolism through the urban area (e.g., from water to wastewater; from clean stream water upstream to polluted downstream), and (3) the spectrum of disturbance frequencies (e.g., floods, pollution emergencies) to which the city's environment is subjected and is not resilient to. More specific criteria of sustainability have been also included in the Metcalf and Eddy (2007) book on water reuse.

The concepts of the sustainable water use and drainage/sewerage infrastructure have been evolving in research literature and laboratories since the pioneering article by Okun (2000) and recently reinforced by the inventor of the Bardenpho advanced treatment system James Barnard (2007) in his Clark award lecture, the Metcalf and Eddy (2007) monograph and others. A new *fifth paradigm* discussed at the Wingspread Workshop (Novotny and Brown, 2007) offers a promise of adequate amounts of clean water for all beneficial uses. The new paradigm of sustainable urban waters and watersheds is based on the premise that urban waters are the lifeline of cities and the focus of the movement towards more sustainable and emerging "green" cities. Summarizing the discussions at the Wingspread Workshop and literature, the concepts of the new sustainable urban water management system and the criteria by which their performance will be judged include:

- integration of water conservation, stormwater management and wastewater disposal into a one system managed on a principle of a closed loop hydrologic balance concept (Figure 2) (Novotny, 2007; Heaney, 2007);
- considering designs that reduce risks of failure and catastrophes due to the effects of extreme events and are adaptable to future anticipated increases of temperature and associated weather and sea level changes (IPCC, 2002);
- incorporating **green buildings** (LEED certified) that will reduce water use by water conservation, reduce storm runoff with best management practices (BMP's), including **green roofs, rain gardens and infiltration;**
- incorporating heat energy and cooling water recovery from sewage in the cluster water reclamation and energy recovery facilities (Engle, 2007);

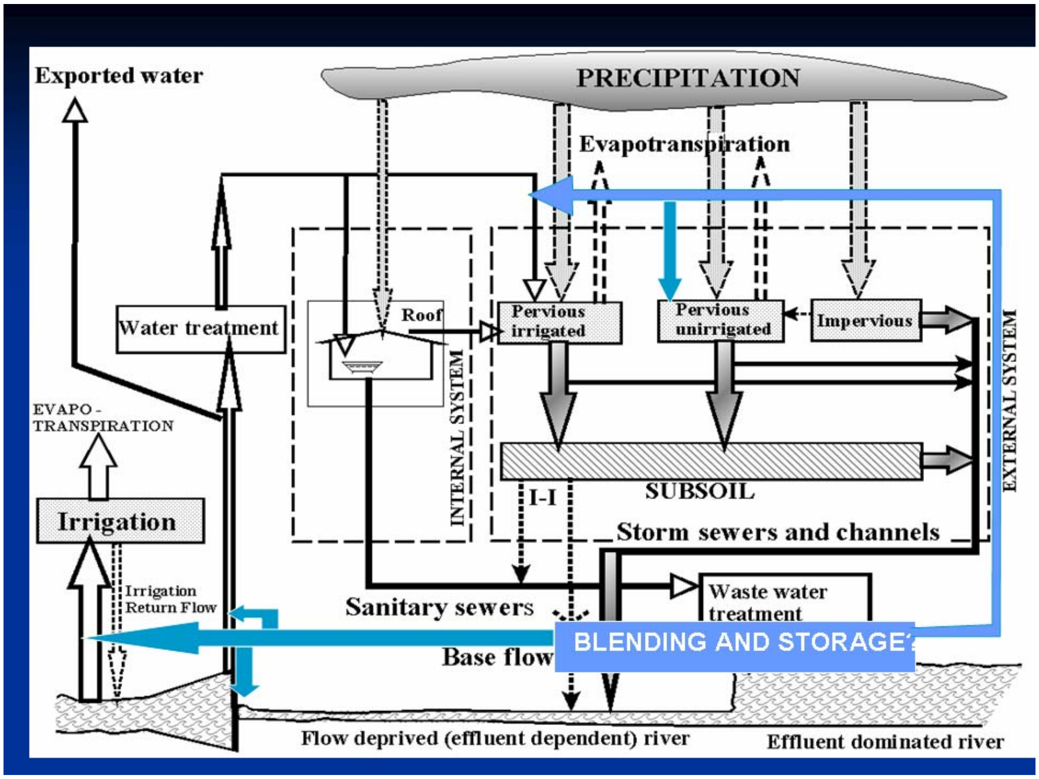

Figure 2 Total urban hydrologic cycle concept (adapted from Mitchel et al. (1996) and Heaney (2007))

- implementing new innovative and integrated infrastructure for reclamation and reuse of highly treated effluents and urban stormwater for various purposes including landscape irrigation and aquifer replenishment (Hill, 2007; Ahern 2007; Novotny, 2007; LEED criteria (USGBC, 2005, 2007);
- minimization or even elimination of long distance subsurface transfers of stormwater and wastewater and their mixtures (Heaney, 2007; Anon, 2008);
- energy recovery from waste water; environmental flow enhancement of effluent-dominated and flow-deprived streams; and ultimately a source for safe water supply (Anon, 2008);
- implementing s**urface stormwater drainage** and **hydrologically and ecologically functioning landscape,** making the combined structural and natural drainage infrastructure and the landscape far more resilient to the extreme meteorological events than the current underground infrastructure. The landscape design will emphasize interconnected ecotones containing ecologically with a viable interconnected surface water systems. Surface stormwater drainage is also less costly than subsurface systems and enhances aesthetic and recreational amenities of the area (Hill, 2007; Ahern, 2007);
- considering residual pollution loading capacity of the receiving waters as the limit for residual pollution loads (Rees, 1992, 2007; Novotny, 2007) as also defined in the Total Maximum Daily Load (TMDL) guidelines (US EPA, 2007), and strive for zero pollution load systems (Metcalf and Eddy, 2007);

- adopting and developing new green urban designs through new or reengineered resilient drainage infrastructure and retrofitted old underground systems interlinked with the daylighted or existing surface streams (Novotny 2007);
- reclaiming and restoring floodplains as ecotones buffering the diffuse (nonpoint) pollution loads from the surrounding human habitats and incorporating best management practices that increase attenuation of pollution such as ponds and wetlands (Novotny, 2007);
- connecting green cities, their transportation needs and infrastructure with drainage and receiving waters that would be ecologically based, protect the aquatic life, provide recreation and by doing so be acceptable to and desired by the public;
- decentralization of water conservation, stormwater management and wastewater treatment to minimize or eliminate long distance transfer, enable water reclamation near the use and energy recovery (Heaney, 2007; Anon, 2008);
- developing surface and underground drainage infrastructure and landscape that will
    1. store and convey water for reuse and providing ecological flow to urban flow deprived rivers, and safe downstream uses;
    2. treat and reclaim polluted flows; and
    3. integrate the urban hydrologic cycle with multiple urban uses and functions to make it more sustainable.

Urban developments do not necessarily have to be bad to the environment, human habitats can mimic the nature and preserve it as documented by urban ecotones and nature mimicking in designed parks built by Frederick Law Olmstead in New York, Boston, Chicago, Milwaukee and other cities almost one hundred fifty years ago (Hill, 2007, Novotny and Hill, 2006, Novotny, 2007; Heaney, 2007). The precipitation – runoff – groundwater recharge balance of the cities of the future can approach the natural hydrologic cycle.

Triple Bottom Line Concept

The sustainability of urban development, as any business undertaking, is today typically evaluated against the "triple bottom line" (TBL) criteria (Elkington, 1997). For consultants, utility managers, city planners and ecologically minded developers the triple bottom line criteria include (1) Environmental/ecological protection and enhancement; (2) Social Equity; and (3) Economics (Anon, 2008; Brown, 2007; Taylor and Fletcher, 2005). This trinity of sustainable objectives of urban design is show on Figure 3. Until the end of the last century, urban development was unrestricted and a single bottom line – the profit – was driving it. After its passage of the in 1972 the Clean Water Act (PL 92-500, US Congress) and other similar pollution control laws on state and local levels instituted some environmental constraints on unrestricted development. Some mandatory statutory constraints (e.g., stormwater controls, innovative approaches to treatment, water and energy conservation) have been incorporated into LEED (UCGBC, 2005, 2007) standards as "required" measures. Examples of the pre-1970s US, last century central and eastern Europe, and current expanding economies in China and other countries of South Asia and Latin America have shown the severe and often catastrophic impacts on the society and environment by developments and industrialization under a single bottom (economics) line scenario. The economic bottom line is the profit or minimizing cost on microscale and increase of the GNP on macroscale which have been extensively described in the literature. There is no established social standard against which to evaluate the social dimension (Miller, Buys and Summerville, 2007).

In water resource development, the concept of the triple bottom line concept is not new and the trinity of criteria have been incorporated (in a slightly different form) in the guidelines by the Harvard group for developing and assessing water resources systems (Maas et al., 1062). Hence, TBL concept and criteria are build on the previous economic concepts of incorporating social and environmental cost into the total cost of producing goods and accounting for all social and tangible and intangible benefits of preserving and improving environment/ecology and providing aesthetic and recreational amenities to the population. In he sustainable urban development the macroscale triple bottom line measures of sustainability must be considered and accounted for a multiplicity of components in the following categories

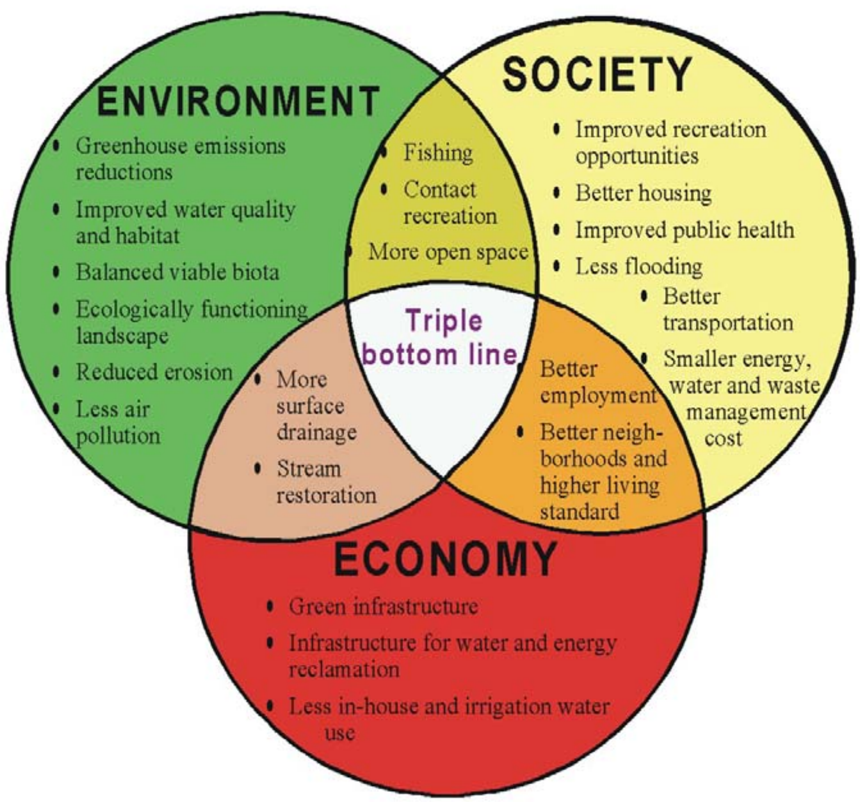

Figure 3 Trinity (triple bottom line) of goals and benefit accounting for the urban sustainable development

- Water supply
  - Quality and quantity of the sources water body
  - Protection zones
  - Distance of water transmission and energy use (pumping)

    - Impact of the withdrawal on the downstream uses including loss of flow, propagation of aquatic biota and providing conditions for fish migration
    - Water treatment (chemicals use, energy, waste byproducts and their disposal)
  - On-site water and energy use recovery and management
    - In-house water use and water conservation
    - Reduction of energy use in–house (energy saving appliances, green roofs, house insultation) and ensuing green house gasses emissions
    - Irrigation water demand reduction or elimination and rainwater harvesting
    - Green roofs to reduce runoff and energy losses of the buildings (a practice known in Scandinavia for centuries)
  - Stormwater management
    - Reduction and control of pollution loads from impervious surface (streets, parking lots and highways)
    - Reduction of imperviousness
    - Clean water inputs into underground conduits and storages and cost of pumping
    - Storage and treatment of stormwater in surface ponds and wetlands for further reuse
    - Stormwater infiltration (rain gardens, infiltration ponds) and groundwater recharge
    - Stormwater treatment units (swirl concentrators, stormwater separators)
    - Hydrologically functioning landscape, recreational use, wild life habitat
  - Wastewater management and water, fertilizer and energy reclamation
    - High efficiency cluster treatment plants
    - Heat and cooling energy recovery by heat pumps and other energy recovery units
    - Possible energy supplement from geothermal sources to provide most of the heat/cooling energy need of the cluster
    - Biogass recovery and use
    - Fertilizer recovery
  - Stream restoration and daylighting - ecotones
    - Urban stream and lake restoration/rehabilitation, restoring the stream continuum and removing fragmentation (culverts impassable by biota, large drops and dams)
    - Daylighting previously buried streams (often converted to storm or combined sewers)
    - Riparian buffer/flood zone restoration and preservation – urban water ecotones

Connecting Green Concepts to Sustainable Water Resources

Green Developments – Smart Growth

Mayors of many major cities, county executives of urban counties, USEPA, environmental activists (e.g., Sierra Club), and other community interests have been promoting the Green City - Smart Growth ideas and programs. In many respects, it is a grass roots effort to incorporate ecological principles into urban planning and development. Sustainable cities of the future will combine concepts of “smart/green” developments; their landscape with natural systems; and the control of diffuse pollution and stormwater flows from the landscape. They will be based on water conservation and reuse of highly treated effluents and urban stormwater for various purposes including landscape and agricultural irrigation, groundwater recharge to enhance groundwater resources and minimize subsidence of historic infrastructure; environmental flow enhancement of effluent-dominated and flow deprived streams; and ultimately for water supply.

Currently, the US Green Building Council has proposed and is developing standards for "green" buildings and neighborhoods (USGBC 2005, 2007) that are becoming a standard for building and development. For example, each federal, state and city owned building in Chicago (Illinois) is expected to comply as close a possible with the LEED (Leadership in Energy and Environmental Design) standards and install a green roof and implement water conservation. Green roofs reduce runoff and provide substantial savings on the energy use, which again reduces green house emissions. New green tall buildings are showcased in New York. Most consultants and city planners try as best as they can to adhere to LEED's concepts and standards (USGBC, 2005, 2007). "Green" subdivisions and satellite cities are now sprouting throughout the world and in the design studios of landscape architects. In Alston (Boston) the entire one billion plus US$ new campus development of Harvard University will be "green" and comply with the LEED standards to the highest degree. The concept and designs of one million plus inhabitants "Ecocities" are now being implemented in the United Kingdom, Sweden, Singapore, China, Australia, and elsewhere.

The USGBC standards for "green" certification were formulated for homes, neighborhood development and commercial interiors (http://www.usgbc.org). The new construction and reconstructions standards (USGBC, 2005) include the following categories:

- *Sustainability of the sites* such as site selection and development, brown field development, transportation, or stormwater design;
- *Water efficiency* in landscape irrigation, innovation in wastewater technologies and reuse and water use reduction;
- *Energy and atmosphere*
- *Material and resources* such as construction materials and waste reuse and recycling
- *Indoor environmental quality*
- *Innovation and design*

Under the pilot LEED Neighborhood Rating System (USGBC, 2007) added categories are

- *Smart Location & Linkage* which include, among others, required indices of proximity to water and wastewater infrastructure, flood plain avoidance, endangered species protection, wetland and water body conservation, and agricultural land conservation;
- *Neighborhood Pattern and Design* such compact development, diversity and affordability of housing, walkable streets, transit facilities, access to public spaces, or local food production;
- *Green construction & technology,* essentially LEED building certification; and
- *Innovation & design process*

This comprehensive list of standards is a potpourri of many "good sense" ideas. The LEED standards are aimed at buildings and small neighborhoods. They are not *a priory* related to natural resources and the value (total number of points) for the natural resource protection and water resources conservation is relatively small; only 10% of the points are credited for reducing water use and potential contribution to improving integrity of waters and natural resource. There are no credits for restoration of water bodies or wetlands as a part of the neighborhoods. Maximum two points are available for implementing sound stormwater management strategies and diffuse pollution controls. The standards were developed by volunteers of various nongovernmental organization and developers. It is becoming clear that the scientific basis and of ecological sustainability have not been sufficiently incorporated in the LEED standards.

Missing Links – Macroscale (watershed wide) goals

Architects, builders, developers, local governments and consultants are pushing as best as they can for implementing “sustainable” and “green” infrastructure, land and resources development. LEED index with its metric is a well meant step forwards towards the better developments and more sustainable urbanization. These microscale LEED standards are aimed at individual buildings, small neighborhoods and commercial establishments. However; the impact of these LEED certified and similar developments and infrastructure on sustainability of water resources, their water quality, increasing resilience against extreme events such as floods or catastrophic storms, as well as protection and enhancement of natural terrestrial resources is fuzzy at best and some could be found irrelevant, at worst when macroscale scale, for example, watershed scale hydrological and ecological goals and impacts are considered. The development of the cities of the future, the ecocities, requires a comprehensive and hierarchical macroscale approach to the microscale and often fragmented piecemeal transformation (Hill, 2007) of the current unsustainable urbanization to the new eco friendly and sustainable urban areas and finally entire cities. There is strong rational for integrating urban water management concepts into the Green Cities concepts and vice versa. The convergence of efforts to improve the quality of life in urban communities and the campaign to improve our water quality offer potential synergies that could overcome the often confrontational encounters that can occur between environmental regulation and economic development.

The macroscale goal of the fifth paradigm is to develop an urban watershed and its landscape that mimics but not necessarily reproduces the processes and structures present in the predevelopment natural system. A goal should also include protection of the existing natural systems. Eco-mimicry includes hydrological mimicry, where urban watershed hydrology imitates the predevelopment hydrology, relying on reduction of imperviousness, increased infiltration, surface storage and use of plants that retain water (e.g., coniferous trees). It will also contain interconnected green ecotones such as surviving and new/restored nature areas, especially those connected to water bodies, that provide habitat to flora an fauna, while providing storage and infiltration of excess flows and buffering pollutant loads from the surrounding inhabited, commercialized, and traffic urban areas. (Hill, 2007; Ahern, 2007).

Daylighting and restoring lost urban streams.

The urban waters have been for millennia the lifelines of many cities. Paris has its Seine River, Rome has had the Tiber River, London is on the Thames River, Shanghai has the Yangtze River, Boston has the Charles River, Milwaukee has the Milwaukee River, etc. In all cases these water bodies spurred the city development in the distant past and city core demise occurred when some of these rivers became highly polluted. The revival of the Milwaukee’s downtown as a place of living concentrated around the river is closely linked to the clean- up the river after 1990s. These rivers provide multiple uses such as transportation, fishing, recreation (boating), and water supply for industries and the city populace. Before the industrial revolution the urban rivers were recipients of the pollution, mainly washoff of dirt, manure, feces, and rubbish from paved and unpaved streets. The polluted stormwater runoff was an impetus to the ancient government of Rome to build the Roman Cloaka Maxima (Large Sewer) two thousand years ago that diverted pollution to the Tiber River. Despite pollution of medieval streets, medium and larger rivers in these cities were reasonably clean so that they, at the onset of industrial revolution in the nineteen century, could provide for fishing and water supply for the new industries that were located on their banks. For example, at the beginning of the nineteen century the Capital of

Czech Republic Prague had a viable fishery on the Vltava River in the center of the town. In Boston (Massachusetts), a smaller size river (watershed area of 36 Km^2) called Stony Brook was a vital and important water resource that spurred the development of a large area west of the historic center of the city and also attracted high quality residential development.

Daylighting. However, at the end of the nineteen century (or two thousand years in Rome) with the invention of flushing toilets, pollution of urban rivers became unbearable and smaller rivers became open sewers. The urban rivers were so polluted that in summer they were devoid of oxygen and emanating pungent odor (hydrogen sulfide) resulting from anaerobic decomposition of BOD and heavily pollutant laden sediments. In the fist half of the twentieth century, summer sessions of the parliament in London had to be cancelled due to the strong odor emanating from the Thames River. In many cases, decision was made to put these rivers out of sight and underground. Today, only the names of streets or squares in the cities often remind the people that there was historically a viable water body in that place. A several hundreds years old remnant of a little stone bridge was archeologically discovered during the building of the subway (metro) station at the lower part of the Wenceslaus's Square in Prague (CZ) called "Mustek" (Little bridge) where today are no signs of a water body. Referring to Stony Brook in Boston, in the late 1800s, because of regulation for sewer discharge points, lowlands in the neighborhoods into which the brook was discharging became terminal sewage pools. Periodic epidemics swept through the city regularly. Raw sewage from the Stony Brook flowed directly into the tidal Back Bay, with environmentally destructive results. Historian Cynthia Zaitzevsky (1982) describes the effect of sewage on the Back Bay: "...the residue lay on the mud flats, baking odiferously in the sun. Eventually it became incorporated into the mud. Under these conditions, the last vestiges of the salt marsh could not remain healthy for long. When the park commissioned surveyed the area in 1877, animal life was no longer able to survive in the waters of the Back Bay," As a result, a 12 km stretch of the brook through the city was buried and converted into large single (4.7x 5.2 meter) of double box culverts. Only names such as Stony Brook Park or Stony Brook subway and train station remain and most of the Boston population does not even know that a medium size historic river existed in the city one hundred fifty years ago. Also, the entire Back Bay tidal marsh was filled and converted to residential and commercial mostly impervious are. Figure 4 shows the disappearance of streams in Tokyo metropolitan area.

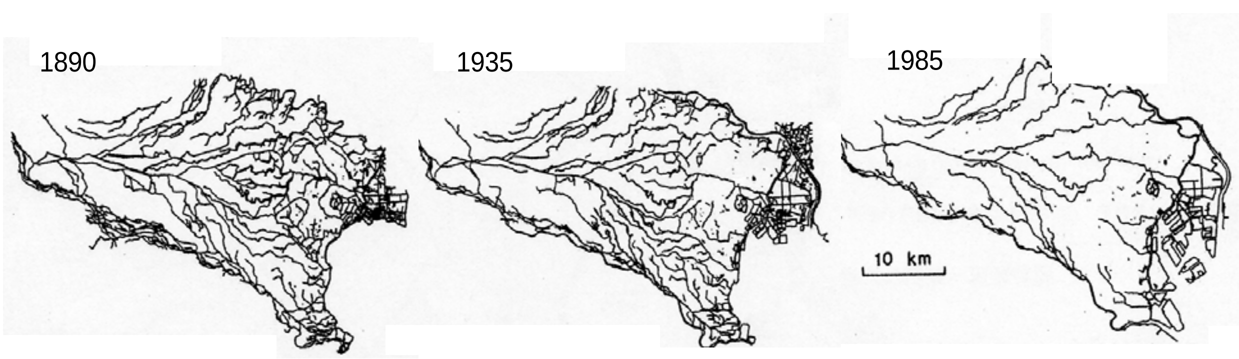

Figure 4 Disappearance of small streams in the Tokyo Metropolitan area. Courtesy Hiraoki Furumai (2007)

In the cities, in the last one hundred to one hundred fifty years almost all streams that remained on the surface were converted to concrete lined ecologically nonfunctional channels (Figure 5, fenced off, or put underground to disappear in culverts. This blight of the cities was due to the effort of city planners, one hundred years ago and before, to keep devastating water borne epidemics under control, reduce unsightliness and pungent odors cause by anoxia, and cope with increased flooding. Covered streams also provided space for traffic and impervious surface for parking. Underground culverted or sewered streams generally do not provide resiliency to extreme events. Their capacity is generally limited and undersized because the early designers did not anticipate the hydrologic the hydrology of the current conditions of very high imperviousness and greatly diminished groundwater recharge that greatly increased the peaks and volume of urban runoff. Typically, underground storm sewers were designed to carry flows resulting from storms that have a recurrence interval of five to ten years but urbanization can increase the magnitude of peak flow in this recurrence range three times or more times (Hammer, 1972; Hollis, 1975; Bledsoe and Watson, 2001; Novotny, 2003). Extreme precipitation events can render existing underground urban drainage with a capacity to handle a five year precipitation inconsequential, as exemplified by the hurricane Katrina in New Orleans and frequent flood events in many other cities. More generally, in urban areas, the hydrologic connection with the landscape is fragmented or nonexistent and provides little buffering protection from diffuse pollution. Scientific predictions indicate that the frequency and force of extreme hydrologic events (hurricanes, typhoons) will increase with global warming (IPCC, 2007). The consequences of flooding by Katrina in New Orleans were thousands of lives lost, dislocation of survivors, and billions of dollars in damages (Van Heerden et al, 2007).

Figure 5 The Los Angeles River. Once a viable water body the river was converted into a flood conveyance channel without a base flow and with no aquatic life.

Restoration of streams damaged by urbanization, often to the point of conversion into underground sewer, should be a key component of the green development. Today, raw sewage inputs into surface streams or underground culverts carrying the buried streams have been or are being eliminated and the buried stream are becoming storm sewers; however, in most cases with insufficient capacity to handle flows from extreme storms. The restored and daylighted streams will become technically a part of the surface drainage system but should be ecologically viable and functioning, pleasing to the public and providing recreation as well as enjoyment. Surface drainage is also more resilient to flooding as documented on case of the buried Stony Brook branch under the campus of the Northeastern University (Figure 6). Most of the buried Stony Brook today is not a combined sewer anymore; it carries relatively clean water from upstream nature reservation and storm water from the city. One of the key requirements of daylighting and urban stream restoration is to provide and recreate good base flow that can be, if available, from natural sources (springs, wetland) or created or supplemented by highly treated effluent from nearby high efficiency treatment plants or stormwater runoff stored in ponds and wetlands and recharged shallow aquifers. Base flow of urban stream has been lost because of high imperviousness of the surrounding watershed and shallow groundwater infiltration into sanitary sewers, basement dewatering into sanitary sewers and leaks into other underground infrastructure (underground garages, subway and freeway tunnels).

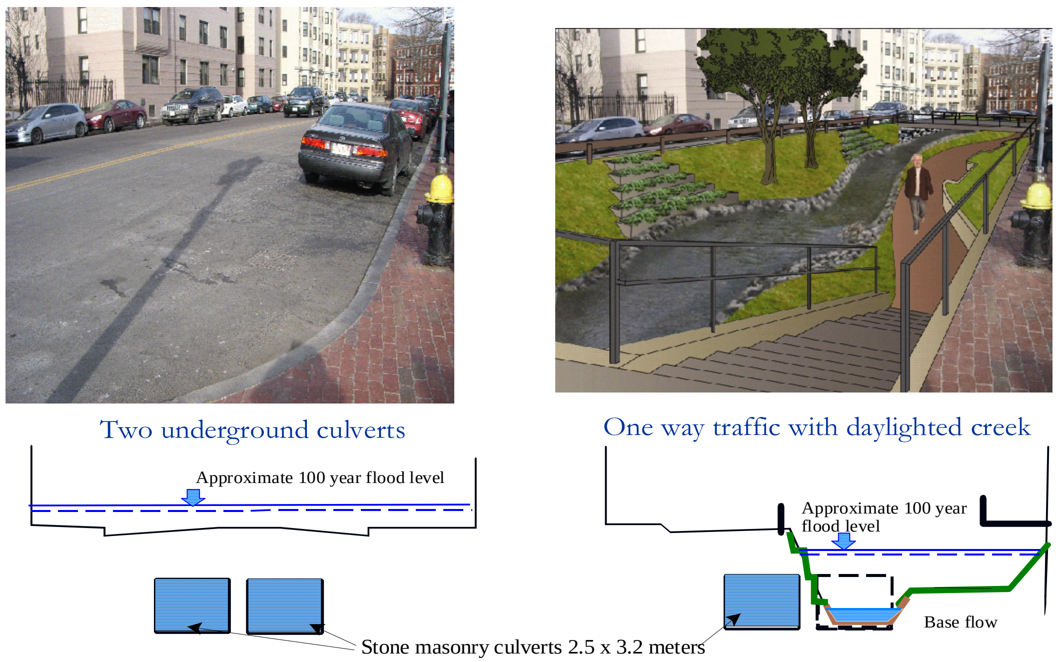

Figure 6 Proposal for daylighting of the historic Stony Book buried under the streets of Boston about one hundred years ago on the Northeastern University (Boston, MA) campus. Left is current situation, right is daylighting proposal by the capstone design student project. The left culvert will carry sewage flows with portion of stormwater runoff. The channel on the right will carry portion of the "clean" Stony Brook.

Stream restoration. Straightening and lining the lining of urban streams with concrete, ripraps or gabions has been another practice of mid twentieth century and before that was designed to compensate for the increased peak flows and volumes. In the same time, development in the floodplain was allowed all the way to the stream bank.

After the point sources have cleaned up and by long distance transfers sent to regional treatment plants outside of the watersheds of streams flowing through the city, the streams often lost their base flow and those streams that were subjected to bank erosion and habitat degradation by increased magnitude and frequency of stormwater flow inputs. Habitat degradation is the primary causes of the impairment of the integrity of urban streams (Manolakos et al., 2007; Novotny et al., 2008). Furthermore, the quality of urban streams in northern climates is adversely impacted by winter deicing chemicals (for a summary see Novotny et al., 1999) and toxic contamination of sediments.

Restoration of urban streams is only possible after the major point source of pollution have been eliminated. It is a complex process that begins with the identification of the cause of impairment (impaired habitat, insufficient base flow and erosive high flows) implementation of best management practices to control the stormwater flow and pollution inputs, removal of lining, restoration of natural sinuosity, pool and riffle sequence and habitat restoration, removal of stream fragmentation (bridges, culvers, channel drops and small dams impassable to fish and other aquatic organisms), and riparian (flood) zone restoration (Novotny, 2003).

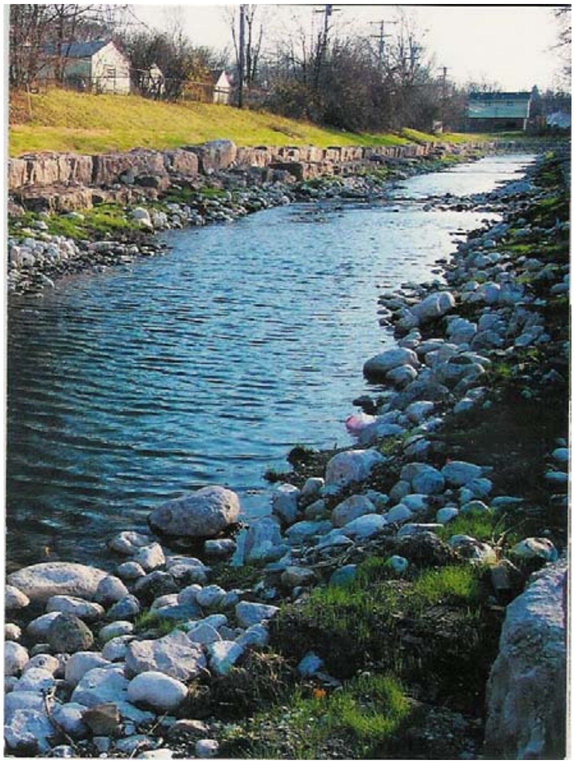

Figure 7 Restored Lincoln Creek in Milwaukee. The creek was lined with concrete before the 1980s but was fully renaturalized by 2002.

Figure 7 shows restored Lincoln Creek in Milwaukee (Wisconsin). The creek was converted to a lifeless concrete lined flood conveyance channel because of enlarged floodplain due to upstream urbanization and ensuing increased frequency of flooding affected about 1800 properties. In the late 1980s the political attitude changed and the Milwaukee Metropolitan Sewerage District (MMSD) began to renaturalize the creek, starting with the removal of lining, removal some bridges or widening of bridge openings causing flood bottlenecks, enlarging flood plain storage and including several off line detention ponds and a large wetland. In 1990s, the CSOs were eliminated by diverting them into the Milwaukee's deep tunnel underground storage. Concurrently, in-stream habitat was restored and stream bank erosion was controlled. The project was finished in 2002 at a cost of more than US$ 80 million and fish and aquatic biota have returned. The restoration and integrated management of the Lincoln Creek in Milwaukee (WI, USA) has been impressive but partially failed because the restoration was not based on the total hydrologic balance; the creek is lacking sufficient base flow that was reduced by urbanization within the watershed and the pollutants present in the stormwater runoff entering the creek have not been fully controlled (e.g., salt from road deicing operations and toxic compounds in urban runoff). Consequently, the biota and oxygen levels crashed due to excessive growth of alga *Cladophra* stimulated by these deficiencies. The restoration is still more or less an art rather than a science.

Stormwater pollution and flood abatement

Since the late 1970s scientists and urban planners have been developing and implementing best management practices (BMPs) for controlling pollution and peak flow of urban runoff. Prior 1970, urban runoff was considered as clean and a "diluter" of more concentrated point source pollution. Sewer separation was a general solution to the problem. An extensive US Environmental Protection Agency (1983) study, the National Urban Runoff Project (NURP), disputed this notion and found that urban runoff contains high concentrations of pollutants, including extreme concentrations of pollutants from deicing chemicals (Novotny et al, 1999) such as salinity, sodium, chlorides, metals and cyanides in winter flows, and suspended solids, oil and grease, COD, pathogens, toxic metals and organics in the non winter runoff.

BMPs to control diffuse pollution in the last thirty years can be categorized as (Novotny, 2003):

1. Source control measures (control of atmospheric deposition, reduction of urban erosion especially from construction, street sweeping, switching from irrigated laws using large quantities of fertilizers to non-irrigated xeriscape)
2. Hydrologic modification focusing on infiltration (porous pavements, landscape infiltration, infiltration trenches)
3. Reduction of delivery (silt fences at construction sites, buffer strips, grass swales, in line solids separation in sewers)
4. Storage and treatment (wetlands, ponds, underground storage basins with a follow-up treatment).

The BMPs listed above can be divided into structural (hard) and nonstructural (soft). Most structural BMPs implemented till the end of the last century were "engineered" and did not blend with the natural environment nor did they try to mimic the nature. Since one of the requirements of the sustainable development is to restore and protect nature, most of the structural BMPs were not sustainable nor were they appealing.

Landscape architects (Ahern, 2007; Hill, 2007) proposed that the BMPs listed above also be divided into

- those that remedy landscape disturbance and emission of pollutants,
- those modifying the landscape and the hydrologic cycle to make it more ecologically and hydrologically sustainable, and
- those that remove pollutants from the flow.

While all BMPs aim at reducing pollution and improving water quality, some are more apt to leading towards resilient urban ecological system. Developers and landscape architects at the end of the last century realized that BMPs can be an architectural asset that can blend with the nature and mimic the natural systems. Almost every structural engineered BMP has its naturally looking, hydrologically and ecologically functioning and nature mimicking equivalent (Figures 7 and 8). Ahern (2007) and Lucey and Barraclough (2006) pointed out the differences between the traditional (civil) engineered and ecological engineering components.

With exception of source control measures mentioned above, in the past, BMPs were designed and implemented a *posteriori*, i.e., after pollution was generated from the land. BMPs provided treatment and their use as drainage was secondary. The typical drainage design preference of the fourth paradigm was to divert urban runoff and snowmelt collected by street gutters and catch basins from impervious road and parking surfaces into underground conduits (storm sewers). Subsequently, the sewer outlets were connected to a pond or a wetland or directly, without any treatment, into a receiving water body. Traditionally designed geometric ponds had the purpose to attenuate the peak flows and provide some removal of pollutants but their ecological worth was minimal.

At the end of the last millennium, the "green movement" began to change BMPs from relatively unappealing appearance with no ecologic value to attractive and desirable assets of the urban landscape. Hence, moved grass ditches, swales and dry detention ponds were converted to raingardens and bioretention facilities. Now it is being realized, that BMPs are not only additions to the drainage they could, in a modified more attractive form, become the drainage itself (Novotny, 2007). Best management practice can:

- Mimic the nature
- Provide and enhance surface drainage

Figure 7 Landscaped swale providing infiltration and pollutant removal (photo from Marriott, 2007)

- Repair unsustainable hydrology by reducing flooding and providing enhanced infiltration as well as provide some ecological base flow to sustain aquatic life
- Remove pollutants from ecological flow
- Provide water conservation and enable water reuse
- Buffer and filter pollutants and flow for restored/daylighted streams
- Enhance recreation and aesthetic quality of the urban area
- Save money and energy (expensive underground conduits and pumping may not be needed). Swale type raingardens combined with green roofs and permeable pavements of parking lots and some streets may dramatically reduce the need for underground storm sever capacity and reduce energy use.

Urban Landscape

Landscape ecologists (e.g., Forman, 1995; Forman et al., 2003; Ahern, 2007; Hill, 2007) proposed an ecologically balanced urban landscape with a river or as chain of urban lakes as a center piece. Based on these concepts the urban landscape of the future will be made of interconnected ecotones preserving or imitating the nature threaded through the inhabited space with the river corridor. The ecotones will also have in addition to supporting biota and preserving mimicking nature, hydrological and pollution buffering/attenuating functions. In most cases they contain floodplain and will provide storage of floods during extreme events.

Connectivity refers to a degree to which a landscape facilitates or impedes the flow of energy, materials, nutrients, species, and people across the landscape and it is an emergent property that results from interaction of landscape structure and functions, including flow, nutrient cycling and maintenance of biotic diversity (Ahern, 2007). Connectivity of urban ecotones and water systems is needed to provide conditions for sustainability of the aquatic biota and terrestrial ecology. If the biota is disturbed or lethally impacted by a stress (e.g., toxic spill) the biotic system can be repopulated by migration from neighboring unaffected ecotones. In urban systems, fragmentation of ecosystems, i.e., separation of ecology into isolated landscape elements is a common feature of the landscape and aquatic systems (Figure 8). Water flow connectivity and water systems are the primary examples where connectivity is important to maintain sustainable and balanced aquatic biota. Connectivity must be considered on watershed scale and include also flood plains, i.e., the entire water body corridor and contributing watershed areas.

Fragmentation is the opposite of connectivity. Fragmentation in urban environments is caused by roads (Forman, et al. 2003), culverts and drops (Figure 8) impassable by fish and other larger organisms, zones of poor water and sediment qualit6y high temperature due to cooling water discharges.

The ecomimicry of subdivision developments of the last century were piecemeal approaches restricted to the developed land and without a relation to the macroscale integrated ecological restoration and preservation goals.

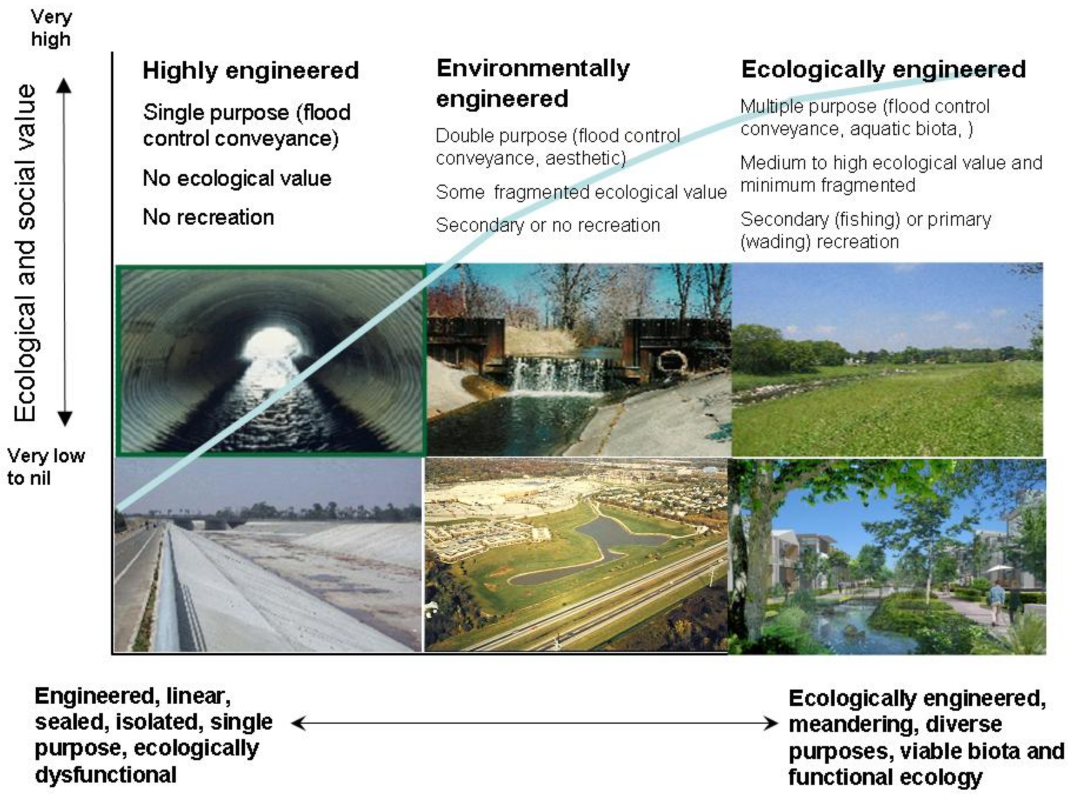

Figure 8 Engineering approaches to urban drainage from traditional to eco-engineering (adapted from Ahern (2007))

Cities of the Future – Water Centric Ecocities

Decentralized Cluster Water/Stormwater Management of the Cities of the Future

The integration of the complete water management that includes water conservation and reclamation, storage of reclaimed water and stormwater for reuse, wastewater treatment and energy from waste recovery can not be achieved in a system that incorporates long distance transfer, underground subsurface and deep tunnels and distant wastewater treatment plants. The concept of clustered distributed and decentralized complete water management has been evolving (Lucey and Barraclough, 2007; Heaney, 2007). A cluster is a semiautonomous water management/drainage unit that receives water, implements water conservation inside the structural components of the cluster and throughout the cluster, reclaims sewage for reuse, such as flushing, irrigation and providing ecological flow to restored existing or dayligthted streams, recovers heat energy from wastewater, and possibly recovers biogas from organic solids (Figure 9). The concept enables privatization (Rahaman and Varis, 2005) and commercialization (e.g., selling reclaimed water, energy and biogas). Clusters may range from a large high-rise building, larger shopping center, or a subdivision, to a portion of a city (Furumai, 2007; Lucey and Barraclough, 2007).

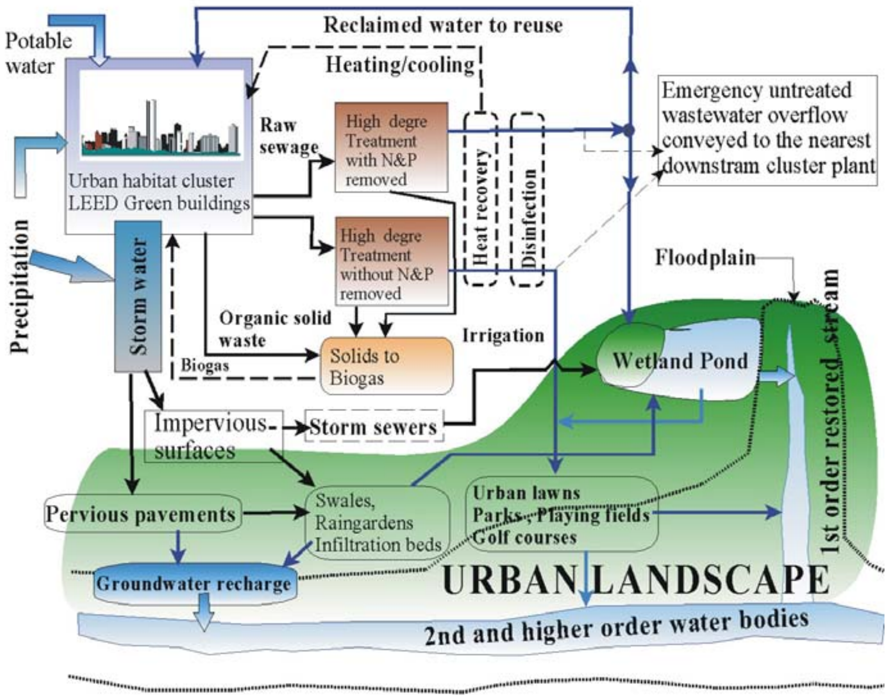

Figure 9 Cluster integrated sustainable water/stormwater and wastewater management with water reclamation and reuse

The size of the cluster and the number of people it serves must be optimized. The cost is represented by the cost of transporting wastewater and stormwater mixture towards a treatment plant, its treatment and water reclamation and transporting the reclaimed water back to the city for reuse on landscape, toilet and street flushing, and recovering energy. Benefits include fees for the recovered water and energy, savings on the size and length of sewers, savings on energy due to installation of green roofs and less pumping, benefits related to the recreational use of restored and daylighthed streams, etc. Cluster water conservation and storm water reclamation and reuse as well as energy recovery from wastewater is resource can be privatized and commercialized. In this case, the size and distance of transfer matter. The longer the distance is the more costly water and wastewater transfers are and less revenue can be derived from energy and biogass recovery. It is quite possible that cluster stormwater/wastewater management can make the deep and large interceptor sewers and tunnels obsolete. Furthermore, bringing stormwater conveyance to the surface can make existing sewers oversized and the freed space can be used for other underground conduits such as fiber optic cables and phone cables for which the water management utility can charge a fee s it is being done in Tokyo and other cities.

Water reclamation plants (WRP) and energy recovery units (ERU) could be installed in most clusters at the **points of reuse**. Sanitary sewage can be conveyed to them mostly by conventional underground sanitary sewers. A point of reuse is a reclaimed water outlet such as use for flushing in buildings, street washing, landscape irrigation, groundwater recharge and providing ecological base flow of urban streams. Since typically raw sewage is relatively warm (12 – 16°), heat can be extracted by heat pumps that could provide both warm water for heating and cold water (less than 5°C) for cooling. To minimize the energy losses it is necessary the cluster water and energy reclamation units be located in or near the cluster they serve. Compact treatment providing high BOD, suspended solids, nutrients and pathogen removals are available, ranging in size from serving few houses to population up to 20,000. These units provide effluents that could be as clean as the receiving waters into which they may be directed (Furumai, 2007). Ultimately, potable water quality is achievable (Barnard, 2007) but may not be economically justified and acceptable to the population. WRPs and ERUs can be located underground in commercial shopping areas or in basements of large commercial buildings.

Interconnectivity. Although the clusters are semiautonomous in their water, sewage and energy recovery management, they should be interconnected to increase resiliency against the failure of a cluster operating system, namely its WRP. In the case of failure there should be an option to store and send the untreated wastewater to the nearest cluster plant that has available capacity. Consequently an **on line real time optimization and control cyber infrastructure** will have to be developed.

Ecocities

An ecocity is a city or an autonomous part of a city that balances social, economic and environmental factors (triple bottom) to achieve sustainable development. An ecocity can be a cluster or contain several clusters of sustainable management. An ecocity is ecologically and hydrologically sustainable and resilient. It has become clear that the fourth paradigm of wastewater and stormwater drainage is not suitable and does not fit the ecocity concepts. The time has come to critically evaluate what has been developed during the last twenty five years in the field of urban drainage and diffuse pollution with the green city concepts and come up with a new approach to drainage that would mimic nature and the pre-development hydrology. Other trends can also be considered such as dramatically reduced emission from vehicles powered by hydrogen fuel cells, improved public transportation, energy production from wind, solar, biofuell and recycled city waste. The new drainage will make a switch from strictly engineered systems (sewers) to ecologic systems (rain gardens, surface wetlands, ponds restored and daylighted water bodies). The municipal stormwater and sewage management is expected to be decentralized into city clusters rather than regionalized (Figure 10). At some point the drainage and the buffers and flood plains will become a sequence of ecotones connected to the major receiving water body (Hill, 2007; Ahern, 2007; Novotny and Hill, 2006). Some concepts also consider organic farms surrounding the cities and significant reduction of nonpoint pollution from farms supplying food to the cities.

Ecocities are now emerging on subdivision/suburban levels in reality and on large city level (up millions of people) in planning. Singapore in South Asia is relatively small island city/state in South Asia with several millions inhabitants that does not have any significant natural and water resources. It is being converted into an ecocity. China is looking for urban housing of up to 300 million people in the next 30-50 years because of intensification of agriculture (loss of jobs of indigenous population) and a large increase of GNP being derived by industries in the cities. Essentially, it is a planned attempt to manage migration from rural to urban areas that has been so devastating in megacities of several other fast developing countries, including Brazil, Mexico, India, etc. The Cities of New Wuhan, Dongtan, Yangzhou and Changzhou on the Yangtze River and Tianjin, will be the first new ecocities in China. The intent of Chinese planers working with the Chinese Academy of Science is to make the New Wuhan City and other new cities on the

Yangtze River water centric ecocities. In November 2007, governments of China and Singapore signed an agreement under which Singapore will export its ecocity know-how and technologies and will built another ecocity in Tianjin northeast of Beijing. Concepts and plans for ecocities are fast emerging in the US, Canada, Europe (United Kingdom, Sweden, Germany), Asia (China, Japan), and Australia. Except in the US, developments and research in the other advanced countries are well funded. In the next 20 years, building new and retrofitting old cities into ecocities will become a multi trillion US$ worldwide endeavour.

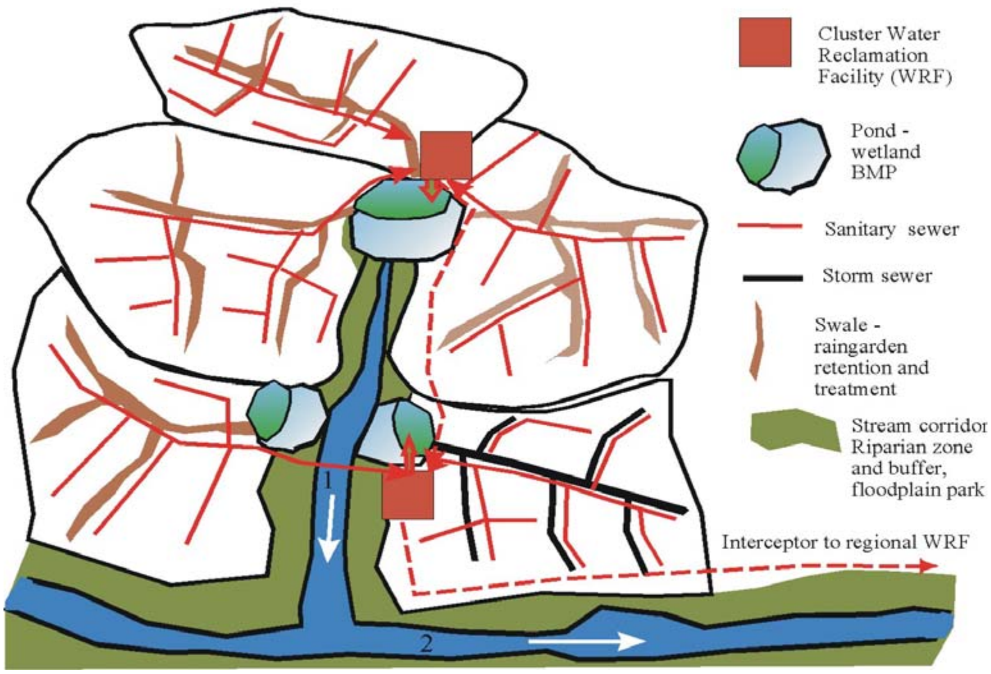

Figure 10 Concept of cluster based urban drainage in an ecocity

In developed countries, the movement towards ecocities is based on the realization that the limits of the fourth paradigm have been reached, population will be increasing, technology (e.g., high level treatment or energy recovery are available), intensity and frequency of catastrophic storms will be increasing, and population desire for these developments is rising (Novotny and Brown, 2007). On the other side, in spite of a lot of interest and work being done in academia and by NGOs, the progress in the US is still a piece meal approach mostly by individual developers or some agencies trying to use technologies that have not been yet developed and scientifically tested.

Renaturalizing Drainage of the Cities of the Future

Natural drainage systems begin with ephemeral small vegetated channels and gullies. At some point several of these channels will form a first order perennial stream. A second order stream is formed when several first order stream join together. Springs and wetlands feed and provide perennial flows to natural streams. It is possible to do the same in the urban areas but then it would be called integrated best management practices. Table 2 presents a comparison of natural and equivalent BMP systems. In urban areas perennial base flow can be provided by highly quality effluents provided by the cluster treatment plants such as has already been done in Tokyo and elsewhere.

Table 2 Natural systems and their equivalent BMPs

Natural systems	Nature mimicking Best Management Practices
Watershed with infiltration	Pervious pavements, green roofs with French well or rain garden infiltration of downspout excess water
Ephemeral pre-stream channels	Rain gardens, buffers sand filters connected to landscaped swales or dry storage ponds for flood water
1st order perennial streams with base water flow from o Springs o Headwater Wetlands o Headwater lakes	Daylighted, restored or created streams with base flow from o Groundwater infiltration, including dewatering basements o Decentralized high efficiency treatment plant effluents o Restored or created wetlands o Wet ponds with stored storm water
2nd order streams	Restored original streams with reclaimed floodplains and riparian wetlands; floodplain converted to recreational park and buffer zones; storage in lakes and ponds in the reclaimed flood plains
3rd and higher order streams	Removal of channelization and impoundments wherever possible, providing flood storage. Significant portion of flow may originate from upstream nonurbanizaed areas.

The proposed drainage concept contains best management practices that have been covered by many urban stormwater management manuals (e.g., see Novotny, 2003). The novelty is only in using them in an integrated context of the urban landscape and the total hydrologic cycle as an alternative to the traditional fast conveyance subsurface drainage. The concepts were introduced also in Novotny and Hill (2006) and also covered in Novotny (2007).

I. Sanitary sewage conveyance mostly underground but decentralized.

1. *High efficiency treatment (water reclamation) plants* located so that they can provide reclaimed flow for (a) reuse in buildings (toilets flushing, on site energy recovery, cooling, etc.) and/or (b) ecological base flow to perennial streams, and/or (c) park, golf course irrigation. Hence, decentralized urban wastewater management could be organized into (a) clusters of one or several large (high-rise) buildings; (b) one or more subdivisions; (c) smaller urban districts (Figure 10). The quality of the effluent should be commensurate to the purpose of reuse. In the effluent reuse for irrigation, nutrients (nitrogen and phosphorus) should not be removed. For effluent used to provide base flow, a high quality effluent with removed nutrients and pathogens is desirable. Removed nutrients can be converted to bio-fertilizer and reused and heat can be extracted from the effluent. In this way, treated effluent becomes a commodity that can be commercially distributed.

2. *Energy recovery from wastewater.* Temperature of urban sewage/wastewater is warmer than that of water supply due to the addition of warm water from households and cooling water from industrial operations. Depending on geographical locations the mean annual temperature of urban sewage/wastewater varies between 10 to 20ºC (Metcalf & Eddy, 2003). Both cooling and heating energy can be recovered by heat pumps and other similar energy recovery units, still to be developed, without emitting carbon dioxide. In winter, the energy needs could be supplemented by geothermal energy sources in groundwater. Groundwater typically has a stable temperature around 12 ºC.

II. Surface drainage for stormwater and treated effluent discharges

1. *Ephemeral swales landscaped as rain gardens*. On side streets, low to medium density urban zones, less frequently traveled urban highways and parking lots, in combination with pervious pavement, no storm sewers would be needed. The swale/rain gardens will be designed to have a minimum (to prevent standing water and development of unwanted cattails and other vegetation) and maximum (to prevent erosion and gullying) slopes and engineered flow capacities. Stormwater runoff from impervious roads and streets would be filtered by grass or sand filters. Rain water from down-spouts would be directed to French wells or other infiltration devices for infiltration and/or to rain gardens.

Figure 11 Small artificial nature mimicking stream in Tokyo. The stream, stocked with fish, receives base flow from a tertiary treatment effluent. This stream was created as a response to protests of people after the original stream was polluted and converted into an underground combined sewer..

Flow form storm sewers, if installed, should be treated by various best management practices available for treatment (filters, ponds, etc).

2. *First order perennial drainage channels – streams.* In older cities the original first order streams disappeared and were converted into sewers. In new planned communities, they should be preserved. As soon as perennial flow becomes available from reclaimed effluents, from stored rainwater (in subsurface manmade basins), from groundwater pumped from basements or from wetlands, smaller natural or naturally looking channels (sinusoidal, with pools and riffles) should be created (Figure 11) or the original streams should be preserved or restored. Hydrologically, the channels and landscape could be designed with the channel capacity to hold a 2 year flow, considering also flood storage capacity, and the extended channel with vegetated banks to hold flows with a large recurrence interval, Landscape should be resilient to floods with the 100 year recurrence interval. Storage ponds and/or wetlands may be included to create water parks and enhance the landscape. The purpose of the ponds and wetlands in the first order stream systems is to store excess peak flows for longer times (not 24 hours or less as in conventional designs) so that the stored water can be used for irrigation, supplementing base flow and other purposes and also to provide post treatment of effluents discharged into them. Created wetlands are the best place for receiving treated effluents. Most first order streams may not have natural base flow unless they originate in a nature reservation within the city.

Some ponds on the first order streams may be stocked with fish but may not sustain large quality of less tolerant fish species. Surface urban runoff not infiltrated through the pervious surface (vegetated areas and porous pavement) will be filtered by grass or sand filters or, if storm sewers are used in dense settlements, by Storm separators, filters installed in sewers and other stormwater treatment units.

3. *Second and higher order streams*. These larger streams should sustain balanced viable fish population. Since these streams will consist mostly of preserved original or daylighted and restored streams, the pollution control laws in many countries will call for attaining and maintaining "a balanced indigenous aquatic biota" (in US) or have water and habitat quality achieving and preserving the "best ecologic potential" (In EU countries) of the water body. The streams should be surrounded by buffer zones encompassing the flood zone. The buffer and flood storage zones should be landscaped as interconnected parks, nature, with bike and walk trails, and picnic areas. Recent research in integrity of receiving water has been discovering the beneficial role of ecological green riparian zones surrounding the water bodies (Novotny et al., 2007).

   The difference between the second, third and higher order streams is primarily in the origin of the flow they receive. Second order stream receive flows primarily from the first order water bodies located within the urban area. Third and higher order streams carry significant proportion of flow originating from outside nonurbanized areas.

   Streams, straightened and/or channelized with lining, may have to be restored, lining removed and the channel renaturalized. Lakes on these streams would be a part of the park and the overall urban ecosystem. Long distance wastewater transfers and large effluent discharges into 2^{nd} and 3^{rd} order streams should be minimized or avoided completely. The most preferable discharge location of effluents from cluster water reclamation plants is into the first order wetlands and/or polishing ponds.

Conclusion

There is a need to develop and implement the new (fifth) paradigm of urbanization in general and water/drainage management in particular. The sustainable watershed management of urban watersheds is based on and may evolve from the following premises and concepts:

- Streams have been and will be the lifeline of the urban areas and preserving good quality of water in adequate amount and nature for future generation is necessary, which is the fundamental premise of sustainability.
- Water management of future viable sustainable cities will close the urban hydrologic cycle, i.e., the cities will practice water conservation and reuse and stormwater and waste water flows will be accounted as resources with an economic value rather than waste.
- Energy recovered by heat pumps for heating and cooling from sewage and combined waste water flows (potentially supplemented by geothermal energy from groundwater), water saved or recovered from water and stormwater, and biogass produced from organic residues of the recovery process will be considered as economic assets that can even be commercialized.
- Most of the energy recovered will be in a form that will not increase green house emissions (global warming).
- These concepts will require decentralized water/stormwater/wastewater/energy recovery systems that will be optimized and organized in semi-autonomous but interconnected clusters. Cyber infrastructure of real time control must be developed and implemented.
- Small (1^{st} and 2^{nd} order) urban streams that have not been buried in underground storm

sewers should be rehabilitated and those that were buried should be daylighted and restored. These streams, after the cleanup of pollution inputs, will become a backbone for the sustainable and resilient drainage and water recovery for ecological flows.

- Due to the insufficient groundwater discharge between precipitation events, many restored and rehabilitated 1st order urban stream will need supplemental base flow provided by reclaimed water.
- Urban drainage, runoff pollution attenuation, storage and infiltration/groundwater recharge will be a part of the hydrologically and ecologically functioning landscape consisting of interconnected green ecotones forming transition between the human habitat and aquatic systems. These multipurpose landscape units (recreation, flood mitigation, infiltration/groundwater recharge, habitat for flora and fauna) will also contain ponds, wetlands, rain gardens serving water management and as buffers for aquatic ecosystems.
- The triple bottom line accounting (economic, environment and society) is the foundation for developing the sustainable urban systems. The methods for societal accounting are not yet well developed
- Ecocities based on sustainability are already being designed and built in several countries.

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