CLOSING THE WATER CYCLE AND RECOVERING WATER, ENERGY, NUTRIENTS AND OTHER RESOURCES IN THE CITIES OF THE FUTURE

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Professor Emeritus Marquette University, Milwaukee, WI
Northeastern University, Boston, MA

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Central States WEA, Madison, WI
Cities of the Future – Utopia or Unavoidable Reality

- “Urbanites now outnumber their rural cousins – and that’s surprisingly good news for the environment”
- “The average New Yorker uses far less water and produces just 30 per cent of the greenhouse emissions of the average US citizen”

Barley 2010, *New Scientist* 2785, 32-37

Model of Tianjin Ecocity, China

COF – an international movement towards urban water, energy and resources sustainability
Historic Paradigms

I.
Water from springs and wells
Surface drainage by gravity

II.
Long distance water transport by aqueducts and lead and baked clay pipes
Sewers were invented
Rainwater harvesting
Primitive treatment

III.
Industrial Period:
Dramatic increase of pollution
Rivers caught on fire epidemics
Streams converted to sewers
Later mostly primary treatment

Post Clean Water Act (1972) period:
Heavy investments in infrastructure
Deep tunnel storage and CSO controls
Use water, collect it by fast underground conveyance, end of pipe treatment and dumping
**Drivers for Change towards Sustainability**

- Population increase and resulting migration of population into cities, emergence of megacities

<table>
<thead>
<tr>
<th>YEAR</th>
<th>World</th>
<th>US</th>
<th>UK</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Urban</td>
<td>Total</td>
<td>Urban</td>
</tr>
<tr>
<td>1960</td>
<td>3 041</td>
<td>180.6</td>
<td>52.3</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>4 452</td>
<td>227.7</td>
<td>56.3</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>6 084</td>
<td>282.3</td>
<td>59.5</td>
<td>46.3</td>
</tr>
<tr>
<td>2010</td>
<td>6 895</td>
<td>310.3</td>
<td>62.0</td>
<td>49.2</td>
</tr>
<tr>
<td>2030</td>
<td>8 321</td>
<td>361.6</td>
<td>69.3</td>
<td>56.9</td>
</tr>
<tr>
<td>2050</td>
<td>9 306</td>
<td>403.1</td>
<td>72.8</td>
<td>60.3</td>
</tr>
</tbody>
</table>

Source: UN World Population Prospect. 2010

- Megalopoli and Megaregions (Guanzhu-Hong Kong-Shenzen megaregion will have 120 million people in 2050)
Urban Metabolism

A  Linear needs to be changed to

B  Cyclic or Hybrid
Current urban systems are mostly linear

- Excessive water volumes are withdrawn from mostly distant surface and groundwater sources
  - Inside the community water is used only once and wastefully, e.g., treated drinking water is used in landscape irrigation for growing grass
  - Only about 5% of treated potable water is used for drinking and cooking
  - Great losses of water by leaks and evapotranspiration
- Water is transferred underground to distant large wastewater treatment plants
  - The WWTPs use energy excessively, emit carbon dioxide and often methane which are greenhouse gases
  - The WWTPs remove but rarely recover nutrients for reuse
  - The receiving water bodies become effluent dominated after discharge
A “footprint” is a quantitative measure showing the appropriation of natural resources by human beings.

- **Ecological** - a measure of the use of bio-productive space (e.g., hectares (acres) of productive land needed to support life in the cities).
- **Water** - measures the total water use on site and also virtual water (usually expressed per capita).
- **Carbon** - is a measure of the impact that human activities have on the environment in terms of the amount of GHG emissions measured in units of carbon dioxide.
<table>
<thead>
<tr>
<th>Year</th>
<th>World Population</th>
<th>Available productive land</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ha/person</td>
</tr>
<tr>
<td>1995</td>
<td>&lt; 6 billion</td>
<td>1.5</td>
</tr>
<tr>
<td>2040</td>
<td>10 billion</td>
<td>&lt;&lt;1</td>
</tr>
</tbody>
</table>

**Current ecological footprint**

<table>
<thead>
<tr>
<th>Countries with 1 ha/person or less</th>
<th>Most cities in undeveloped countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Countries with 2-3 ha/person</td>
<td>Japan and Republic of Korea (democratic)</td>
</tr>
<tr>
<td>Countries with 3-4 ha/person</td>
<td>Austria, Belgium, United Kingdom, Denmark, France, Germany, Netherlands, Switzerland</td>
</tr>
<tr>
<td>Countries with 4-5 ha/person</td>
<td>Australia, Canada and USA</td>
</tr>
</tbody>
</table>

If the cities in the currently rapidly developing countries (China, India, Brazil) try to reach the same resource use as that in developed countries, conflicts may ensue.
In Nairobi (Kenya) and other megalopolis of the developing world urban water use is < 50 liter/capita-day
### Top ten countries in the CO₂ emissions in tons/person-year in 2006

<table>
<thead>
<tr>
<th>Country</th>
<th>Emissions (tons/person-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qatar</td>
<td>56.2</td>
</tr>
<tr>
<td>UAE</td>
<td>32.8</td>
</tr>
<tr>
<td>Kuwait</td>
<td>31.8</td>
</tr>
<tr>
<td>Bahrain</td>
<td>28.8</td>
</tr>
<tr>
<td>Aruba</td>
<td>23.3</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>22.4</td>
</tr>
<tr>
<td>USA</td>
<td>19.1</td>
</tr>
<tr>
<td>Australia</td>
<td>18.8</td>
</tr>
<tr>
<td>Canada</td>
<td>17.4</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>15.8</td>
</tr>
</tbody>
</table>

### Selected world cities total emissions of CO₂ equivalent in tons/person-year

<table>
<thead>
<tr>
<th>City</th>
<th>Emissions (tons/person-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washington DC</td>
<td>19.7</td>
</tr>
<tr>
<td>Glasgow UK</td>
<td>8.4</td>
</tr>
<tr>
<td>Toronto CA</td>
<td>8.2</td>
</tr>
<tr>
<td>Shanghai, China</td>
<td>8.1</td>
</tr>
<tr>
<td>New York City</td>
<td>7.1</td>
</tr>
<tr>
<td>Beijing China</td>
<td>6.9</td>
</tr>
<tr>
<td>London UK</td>
<td>6.2</td>
</tr>
<tr>
<td>Tokyo Japan</td>
<td>4.8</td>
</tr>
<tr>
<td>Seoul Korea</td>
<td>3.8</td>
</tr>
<tr>
<td>Barcelona Spain</td>
<td>3.4</td>
</tr>
</tbody>
</table>

### Selected US cities domestic emissions of CO₂ equivalent in tons/person-year

<table>
<thead>
<tr>
<th>City</th>
<th>Emissions (tons/person-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Diego CA</td>
<td>7.2</td>
</tr>
<tr>
<td>San Francisco</td>
<td>4.5</td>
</tr>
<tr>
<td>Boston MA</td>
<td>8.7</td>
</tr>
<tr>
<td>Portland OR</td>
<td>8.9</td>
</tr>
<tr>
<td>Chicago IL</td>
<td>9.3</td>
</tr>
<tr>
<td>Tampa FL</td>
<td>9.3</td>
</tr>
<tr>
<td>Atlanta GA</td>
<td>10.4</td>
</tr>
<tr>
<td>Tulsa OK</td>
<td>9.9</td>
</tr>
<tr>
<td>Austin TX</td>
<td>12.6</td>
</tr>
<tr>
<td>Memphis TN</td>
<td>11.06</td>
</tr>
</tbody>
</table>

1 Wikipedia (2009); 2 Dodman (2009); 3 Gleaser and Kahn (2008)

Values include transportation (private and public), heating, and electricity.

GHG = Green House Gases (CO₂, methane, nitrogen oxides and other gases)
New Threats to Water Supplies and Ecology

- Large increases of losses of fertilizers from agricultural lands, urban lawns and continuing nutrient discharges from point sources
  - Hyper-trophic water – Harmful algal blooms by cyanobacteria
    - Toxins
    - Loss of oxygen and biota
    - Loss of recreation
- New chemicals accumulate in the environment
  - Endocrine disruptors
  - Pharmaceutical
    - Antibiotics
  - Nanoparticles
We are running out of phosphorus

Virtual energy for producing fertilizer

\[
\begin{align*}
19.4 \text{ KW-h} & \quad \text{Kg N} \\
2.11 \text{ KW-h} & \quad \text{Kg P}
\end{align*}
\]

For N produced by Haber/Bosch

GHG emissions in US

\[
0.61 \text{ kg CO}_2/\text{KW-h}
\]

Phosphate rock (2010): 119.6 $/mt
Diammonium phosphate (2010): 482.6 $/mt

Currently (2010): 1.1 – 1.6 $/kg-P


Source P. McCarty et al. 2011
Energy from Used Water and Solids via Syngas \((\text{H}_2 + \text{CO})\) and Oil Production

- **SEWAGE SLUDGE** leads to **PYROLYSIS**
  - Charcoal (Biochar)
  - Ash
- **DRY BIOMASS**
- **ADDITIONAL HEATING & CATALYST**
  - Oil
- **SYNGAS**
  - Combustion and turbine
  - GHG
  - Electricity

This traditional energy recovery will provide less than \(\frac{1}{2}\) of energy needs of an aerobic/anoxic WWTP
The Fifth Paradigm

GOAL:

WATER CENTRIC SUSTAINABLE COMMUNITIES
Definition/Vision of an Ecocity:

An ecocity is a city or a part thereof that balances social, economic and environmental factors (triple bottom line) to achieve sustainable development. A sustainable city or ecocity is a city designed with consideration of environmental impact, inhabited by people dedicated to minimization of required inputs of energy, water and food, and waste output of heat, air pollution - CO2, methane, and water pollution. Ideally, a sustainable city powers itself with renewable sources of energy, creates the smallest possible ecological footprint, and produces the lowest quantity of pollution possible. It also uses land efficiently; composts used materials, recycles or converts waste-to-energy. If such practices are adapted, overall contribution of the city to climate change will be none or minimal below the resiliency threshold. Urban (green) infrastructure, resilient and hydrologically and ecologically functioning landscape, and water resources will constitute one system.

Adapted from R. Register UC-Berkeley
One Planet Living (WWF) Goals

- WATER – Reduce water demand by 50% from the national (state) average
  - Water conservation (more efficient water fixtures), xeriscape
  - Using additional sources (stormwater, desalination)
  - Reclamation and reuse
- SOLID WASTE - Zero solid waste to landfills, recycling
- ENERGY – Carbon neutrality
  - Minimization or elimination use of fossil fuels
  - Renewable energy sources
  - Passive energy savings (Energy STAR)
  - Water conservation (reduction of pumping energy, CO₂ emissions)
  - Energy and resource recovery from water, used water and solids
Reduce, Reclaim, Reuse and Restore - 4 Rs

1. Reduce - Water and energy conservation
2. Reclaim
   1. Treat for safe discharge into environment – TMDL
   2. Reclaim energy (heat), nutrients, solids
3. Reuse after additional treatment
4. 4th R – Restore water bodies as a resource

Separate, Sequester and Store- 3 Ss

1. Separate Blue, White, Gray, Yellow, and Black Water
2. Sequester GHGs and remove/detoxify toxics
3. Store reclaimed water on the surface and/or underground

Toilet to Tap – 2Ts (is it needed?)

- Reclamation with or without 3S for potable reuse
RESILIENT CITY

- Nested semi-autonomous
  - Buildings
  - Neighborhoods
  - Cities

Source: Steve Moddemeyer
Concept of Integrated Water Management in a Cluster/Ecoblock

Synergy of Landscape and Infrastructure
If water is needed for local reuse, sewers can be the source.

Package and small high efficiency treatment units can be installed to provide locally water for:

- Ecological flow of restored streams
- Toilet flushing
- Landscape irrigation
- Street flushing

Idea: Concentrate used water for centralized resource recovery

Adapted from Asano et al. (2007)
Treatment in the cluster is “fit for reuse”

- **IRRIGATION**
  - Secondary treatment - Nutrients stay in the effluent
- **FLOW SEPARATION**
  - Black, Gray, White and Yellow
- **ECOLOGIC FLOW** – Secondary treatment with membranes, phosphorus removal, disinfection with UV
- **TOILET FLUSHING**
  - Filtration with disinfection and “adding color”
- **INDIRECT POTABLE REUSE**
  - Secondary + tertiary (microfiltration + reverse osmosis) + long storage in aquifer or surface + more treatment
Water reclamation and reuse for toilet flushing and possibly irrigation

Rainwater harvesting and reuse for irrigation is also practiced

Battery Park Solaire development in New York - a semiautonomous water/used water management cluster

Designer Alliance Environmental
Need for reuse

It could be energy demanding

Microfiltration

Reverse osmosis

UV radiation
Water Energy Nexus
Implement water conservation first; it also concentrates used water for better energy recovery

Energy delivered from the grid
In the US 1 kW-hr = 0.6 kg CO₂ emissions
In France 1 kW-hr = 0.22 kg CO₂
Energy use of treated volume of municipal used (waste) water and corresponding CO$_2$ emissions. Raw data from Asano et al. (2007) and from Novotny et al. (2010)

<table>
<thead>
<tr>
<th>Treatment process</th>
<th>Daily flow volume of treated used water m$^3$/day)</th>
<th>Energy use kw-hr/m$^3$ (CO$_2$ emissions kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Activated sludge without nitrification and filtration</td>
<td>0.55 (0.33)</td>
<td>0.38 (0.23)</td>
</tr>
<tr>
<td>Membrane bioreactor with nitrification</td>
<td>0.83 (0.51)</td>
<td>0.72 (0.44)</td>
</tr>
<tr>
<td>Reverse osmosis desalination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brackish water (TDS 1 – 2.5 g/L)</td>
<td>1.5 (0.91) – 2.5 (1.52)</td>
<td></td>
</tr>
<tr>
<td>Sea water</td>
<td>5 (3.05) – 15 (9.15)</td>
<td></td>
</tr>
<tr>
<td>Ozonization (ozone produced from air)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtered nitrified effluent</td>
<td>0.24 (0.15) – 0.4 (0.24)</td>
<td></td>
</tr>
<tr>
<td>Desalination by evaporation (using waste heat)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical water domestic water heating (recoverable)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Switch from aerobic treatment in linear systems to water, energy and other resource recovery

- 3 Ss- Separate, Store and Sequester (Gray and Black water, CO₂)
- 3 R-s, Reclaim, Reuse, Recycle (Blue and White water)
- No 2 Ts
- Distributed water and energy reclamation/recovery (Gray, Blue, White and Black water, heat, methane)
- Concentrate Black water and with sludge send it to the regional Integrated Resource Recovery Facility

Anaerobic Processes are Key
Distributed recycle needs urban runoff

Losses by evapotranspiration, ecological flow and reject water – Qingdao Ecoblock
(Prof. H. Fraker – University of California-Berkeley)

The number of cycles without make up water is very limited.
Make up water comes mainly from treated (and stored) storm water

PS – primary settler
MF - microfiltration (membrane filter)
O₃ - Ozonation
UV ultraviolet disinfection
ST storage
RO reverse osmosis
SFW – subsurface flow wetland
SF – sand filter
ATERR – anaerobic treatment and energy recovery reactor - concentrator
More centralized resource recovery

- Characteristics of integrated resource recovery facility
  - More concentrated influent (COD > 3000 mg/L desirable)
  - Urine may be separated (contains 50% of P and >75% N) in 1% of flow
  - Inflow and input contains sludge and other solids (shredded food and other organic solids). Other organic biodegradable solid waste may be trucked in (co-digestion)

- Because of high COD, a conventional (energy demanding) activated sludge treatment is not feasible and should be replaced by an anaerobic processes
  - Conventional sludge digester requires large detention and high concentrations of solids and COD
  - Use Upflow Anaerobic Sludge Blanket (UASB) reactor
We can do better in the future  
Examples of new technologies

<table>
<thead>
<tr>
<th>UASB Reactor</th>
<th>Hydrogen fuel cell with biogas reforming</th>
<th>Microbial fuel cell</th>
<th>Bioelectrochemically Assisted Microbial Reactor (BEAMR)</th>
</tr>
</thead>
</table>
| • 0.4 L CH₄/g COD removed  
• 9.2 kW-hr/m³ of methane | • Converts methane into hydrogen, electricity and water  
• Greater efficiency than methane combustion | Converts organic biomass directly into electricity (from Rabaey and Verstraete, 2005) | Converts organic biomass directly into hydrogen by adding small electricity to the reactor (from Liu, Grot and Logan, 2005)  
95 % energy recovery from produced acetate |

SMR = Steam methane reforming
There is not enough energy in used water to compensate for energy use for delivery, treatment, and (above all) heating.

Typical biodegradable solid (food and yard) recoverable waste production in the US is about 0.5 kg/cap-day that can be codigested with the sludge.

Nutrients in the effluent and CO₂ from IRRF can be used for growing algae for more energy.

Codigestates: Food waste, deicing fluids, yard waste, oil and hydraulic fluids, meat production waste, yeast, and many others.

Solar and wind energy can be implemented in IRRF and in clusters to provide more energy for heating the reactors and buildings and (in the future) to enhance fermentation.

CODIGESTION

Co-digestates

Waste
(PS and/or WAS)

PS-Primary Sludge
WAS-Waste Activated Sludge

Biogas

Credit Dan Zitomer
Integrated Resource Recovery Facility – IRRF (Future)

IRRF produces
- Reclaimed water for reuse
- Heat for heating reactors and buildings
- Struvite (ammonium-magnesium phosphate) fertilizer
- Biogas and hydrogen
- Electricity
- Organic solids
- Carbon sequestration

BEAMR = Bioelectrochemically assisted microbial reactor - Logan (2008)
Comparison of Three Alternatives

- **ALTERNATIVE 1**
  - US household on irrigated lot – water use 550L/cap-day
  - Linear system with no reuse
  - Traditional activated sludge treatment

- **Alternative 2**
  - Hybrid system with cluster recovery of heat and water for toilet flushing and irrigation; household practicing water conservation – water use 166 L/cap-day
  - Conventional regional Bardenpho system removing nutrients

- **Alternative 3**
  - Hybrid system with double loop ecoblock recovery of heat and water – water use from grid 50 L/cap-day
  - Black water and solids sent to the IRRF for recovery of energy (methane electricity), fertilizer, biosolids, and water
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Alternative I</th>
<th>Alternative II</th>
<th>Alternative III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flow from the grid</td>
<td>L/cap-day</td>
<td>551</td>
<td>166</td>
</tr>
<tr>
<td>Energy to deliver and use water</td>
<td>kW-h/cap-d</td>
<td>1.245</td>
<td>0.375</td>
</tr>
<tr>
<td>Water used for irrigation from grid</td>
<td>L/cap-d</td>
<td>313</td>
<td>301</td>
</tr>
<tr>
<td>Energy use for irrigation</td>
<td>kW-h/cap-d</td>
<td>0.169</td>
<td>0.016</td>
</tr>
<tr>
<td>Total heating water flow</td>
<td>L/cap-d</td>
<td>106</td>
<td>71</td>
</tr>
<tr>
<td>Energy use for heating</td>
<td>kW-h/cap-d</td>
<td>3.876</td>
<td>2.60</td>
</tr>
<tr>
<td>Total wastewater (WW) flow</td>
<td>L/cap-d</td>
<td>297</td>
<td>116</td>
</tr>
<tr>
<td>Pumping WW in the sewers</td>
<td>kW-h/cap-d</td>
<td>0.030</td>
<td>0.012</td>
</tr>
<tr>
<td>COD content of used water</td>
<td>g/cap-day</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Energy used to treat WW</td>
<td>kW-h/cap-d</td>
<td>0.125</td>
<td>0.072</td>
</tr>
<tr>
<td>Methane recovery from sludge</td>
<td>kW-h/cap-d</td>
<td>0</td>
<td>-0.05</td>
</tr>
<tr>
<td>Gray water (GW) recycle</td>
<td>L/cap-d</td>
<td>0</td>
<td>20^6</td>
</tr>
<tr>
<td>Energy to treat recycle</td>
<td>kW-h/cap-d</td>
<td>0</td>
<td>0.015^7</td>
</tr>
<tr>
<td>Heat recovery from GW</td>
<td>kW-h/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Concentrated BW flow to IRRF</strong></td>
<td>L/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Pumping BW to IRRF</td>
<td>kW-h/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Methane recovery from UASB</td>
<td>kg/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>H\textsubscript{2} from UASB methane conversion</td>
<td>kg/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>H\textsubscript{2} from BEAMR fermenting solids</td>
<td>kg/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total energy from hydrogen</td>
<td>kW-h/cap-d</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Heat recovery from effluent</td>
<td>kW-h/cap-d</td>
<td>0</td>
<td>1.78^10</td>
</tr>
<tr>
<td><strong>Total energy expenditure (production)</strong></td>
<td>kW-h/cap-d</td>
<td>5.45</td>
<td>1.26</td>
</tr>
<tr>
<td>Carbon GHG emissions (credit)</td>
<td>kg CO\textsubscript{2}/cap-year</td>
<td>1263</td>
<td>281</td>
</tr>
</tbody>
</table>
Struvite production

- Struvite is ammonium magnesium phosphate (MgNH₄PO₄)
  - Magnesium is added in a form of MgOH₂ or MgCl₂ and pH is adjusted (if needed) to pH>9.
  - Struvite is a precipitate separated from flow, for example, in upflow fluidized be reactors
  - pH can be adjusted back to normal by waste CO₂ from the treatment process which sequesters carbon
  - Struvite has a commercial value as a slow release fertilizer
  - While struvite precipitation can recover over 90% of phosphorus, less than 10% of ammonium N in typical municipal used water is incorporated into struvite. About 50% of N or more can be removed by ammonia stripping at pH >9

Ammonium recovery beyond struvite to be developed

- Inonexchangers, possibly in a combination with struvite production

Local Nutrient Recovery

<table>
<thead>
<tr>
<th>Typical nutrient load in used water and urine *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Used water</td>
</tr>
<tr>
<td>Urine (%)</td>
</tr>
</tbody>
</table>


- Use of fit-for-irrigation reuse reclaimed water
- Urine separation and collection for centralized treatment
  - Dual or triple pipes and collection tank
    - Realistic even today for public and commercial buildings and schools
    - Sterilization 6 months storage @ 20° C; otherwise energy demanding heat, pressure, UV, etc
    - Volume reduction by evaporation or freezing – energy demanding
    - Nutrient extraction – struvite (N and P – no pH adjustment is needed)
    - ionexchange (N)
Summary and Conclusions

- Water conservation is the best alternative solution to a water availability problem. There is a direct relationship between water use and energy reductions.
- Reuse with high efficiency solids and pollutant removals (e.g., microfiltration and reverse osmosis) in a closed cycle requires more energy because of the energy requirement in the treatment. This energy should and could be provided by renewable sources.
- Reuse/recycle needs make-up water to offset losses by reject water and liquid content in sludge and possibly by evaporation.
- A new paradigm of urban drainage and used water reuse with resource recovery needs to be developed and implemented.
- Net zero GHG emissions, or better systems recovering and producing energy, fertilizer, solids, and water are technically feasible and achievable.
Summary and Conclusions – cont.

- Under current paradigm, nutrients are removed but rarely recovered.
- Switching from removal to recovery is needed
  - Using industrial fertilizer has a significant virtual carbon footprint that should not be overlooked
  - The world mineral phosphate ore (apatite) reserves are diminishing and may be exhausted in this century
  - The production of industrial nitrogen fertilizer in Haber–Bosch process and phosphate mining and processing require a lot of energy
  - Struvite recovery and production of needed magnesium hydroxide do not require much energy
Dockside Greens, BC (courtesy P. Lucey)

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