Hydrological Functionality of Plants
And its Application to
Stormwater/Wastewater Management

Anton Skorobogatov
Why Plants?

- Plants are unique living organisms that play a pivotal role in our environment.

- Plants are abundant and diverse. Over 90% of all visible living matter is plant life.

- Plants directly influence natural processes that are critical to life. These include the biogeochemical cycles of water, oxygen, carbon dioxide, and nutrients.

- Plants can have a pronounced impact on the hydrological cycle both directly and through their impact on soil properties.
There are three key aspects of hydrology that are plant-related:

1. Interception
2. Infiltration
3. Evapotranspiration
Infiltration

- Infiltration refers to water entering the soil from the soil surface.
- Soil texture is usually utilized to predict infiltration.
- Engineered coarsely textured soils are assumed to have high hydraulic conductivity.
- Hydraulic conductivity of native soils is a function of soil structure and porosity.

**Soil Texture**
- Clay: <0.002 mm
- Silt: 0.002-0.05 mm
- Sand: 0.05-2.00 mm

**Soil Structure**
- Granular
- Blocky
- Prismatic
- Columnar
- Platy
Soil Porosity

- There are two defined types of pores that exist in soils:
  - Micropores < 3mm
  - Macropores 3-100 mm

- Macropores make up 0.23 - 2% of total soil volume, yet can carry 74 - 100% of total infiltration flow

- Macropores can be formed by abiotic processes, such as soil freezing/thawing, wetting/drying, and cracking, or by living organisms
Plant Roots and Macropore Formation

- All plants form soil macropores as their roots proliferate.
- Roots physically penetrate the soil, and radial expansion of the roots compacts the soil in their immediate vicinity.
- Organic compounds are secreted from the plant roots into the surrounding soil and they bind soil particles together.
- Woody species produce macropores of high resilience due to the lignin lining.
- Plant roots transform the soil from a collection of particles into a network of stable channels, capable of carrying water to greater depths of soil profile.
A plant-induced increase in soil hydraulic conductivity has been demonstrated by agricultural studies.

*Figure 1. Changes in infiltration rate under alfalfa culture with time*
The Effect of Woody Species on Soil Hydraulic Conductivity

- Isolated anthropogenic woody vegetation plantings set within uniform soil and topography - shelterbelts, tree beds in urban parks, tree rows in urban golf courses

- Measure saturated soil hydraulic conductivity with Guelph Hydraulic Permeameter within the planting and compare it to the surrounding area
Guelph Hydraulic Permeameter

- Measures saturated soil hydraulic conductivity
- Constant level of water is maintained in the well by the vacuum inside the reservoir
- The steady-state discharge rate refers to the intrinsic properties of the soil and is independent of pre-existing soil moisture
- Less impacted by capillary forces than conventional ring infiltrometer
- More mobile and less invasive than double ring infiltrometer
Alberta Shelterbelt Nursery, Bowden

- Mixed Shelterbelt

- Salix sp.
- Syringa villosa
- Caragana arborescens
- Caragana arborescens
- Picea glauca
- Picea glauca
- Caragana arborescens
- Cotoneaster lucidus

N=1

<table>
<thead>
<tr>
<th>1 m</th>
<th>Salix sp.</th>
<th>Syringa villosa</th>
<th>Caragana arborescens</th>
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<th>Caragana arborescens</th>
<th>Cotoneaster lucidus</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm/hr</td>
<td>0.734</td>
<td>12.7</td>
<td>2.80</td>
<td>13.1</td>
<td>6.34</td>
<td>34.4</td>
<td>24.0</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Glenmore Park Tree Beds, Calgary
Woody Vegetation and Soil Hydraulic Conductivity

Saturated Hydraulic Conductivity, mm/hr

- **tree stand**
- **control**

N=3

- Willow
- Poplar
- Larch
- Spruce
Plant physiology

- Root physiology dictates the nature of macropores that get formed by the plant.

- Grass roots are not capable of significant radial expansion, which would compact the surrounding soil.

- Roots of woody plants have an additional layer of complex organic polymer surrounding the root and making the resulting macropore more resilient.

- Deciduous woody species have short-lived roots, which would facilitate abundant macropores.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Root longevity (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Malus</em> sp.</td>
<td>0.02 - 0.04, 0.2 - 0.26</td>
</tr>
<tr>
<td><em>Tsuga</em> sp.</td>
<td>3.5</td>
</tr>
<tr>
<td><em>Pinus</em> sp.</td>
<td>4</td>
</tr>
<tr>
<td>Prairie</td>
<td>4</td>
</tr>
</tbody>
</table>

Data from Waisel et al 1996
Evapotranspiration

- Deciduous species tend to have greater transpiration rates per leaf unit area

- Intrinsic transpiration rates are proportional to leaf conductance rates

- Leaf conductance rates are proportional to stomatal conductance rates

<table>
<thead>
<tr>
<th>Species</th>
<th>Transpiration rate (mm/day)</th>
</tr>
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<tbody>
<tr>
<td>Hybrid Poplar</td>
<td>2.3 - 3.5</td>
</tr>
<tr>
<td>Cottonwood/willow</td>
<td>4.8</td>
</tr>
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<td>Norway spruce</td>
<td>0.90 - 0.97</td>
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Data from Chang 2006

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<th>Species</th>
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<tr>
<td>Northern Red Oak</td>
<td>1245</td>
</tr>
<tr>
<td>Yellow Poplar</td>
<td>976</td>
</tr>
<tr>
<td>Loblolly Pine</td>
<td>508</td>
</tr>
</tbody>
</table>

Data from Kramer and Kozlowski 2006
Evapotranspiration

- Plant water loss is usually restricted to stomata of plant leaves.
- Stomata usually occupy ~1% of leaf area, yet stomatal diffusion may be as high as 50% of open water evaporation.
- The size and number of stomatal openings determines hydraulic functionality of a particular plant.
Evapotranspiration

- Evapotranspiration refers to all the processes that transfer water from land to the atmosphere
- Water balance (Run-off, Precipitation, Storage)
- Energy balance (heat fluxes and radiation)
- Penman equation (Daily T, wind speed, humidity, and solar radiation)
- Refined by Monteith to include plant-specific parameters

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Maximum leaf conductance, (mm/s)</th>
<th>Leaf area index</th>
<th>Vegetation height, (m)</th>
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<tr>
<td>Conifer forest</td>
<td>5.3</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>Broadleaf forest</td>
<td>5.3</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>Grassland</td>
<td>8</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>Tundra/non-forest wetland</td>
<td>6.6</td>
<td>4</td>
<td>0.3</td>
</tr>
<tr>
<td>Typical crop</td>
<td>11</td>
<td>3</td>
<td>0.3</td>
</tr>
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data from Federer et al 1996
Rough Estimates based on available data

- Transpiration rates for some plants are known

- Using the LAI and Vegetation height as per land cover type

- Use variation in leaf conductance to compare intrinsic evapotranspiration efficiency of different plants

- Leaf conductance is highly dependent on stomatal pore index

- Can use ratio of stomatal pore index of a plant with known transpiration rate to calculate a coefficient to estimate transpiration rates of other plants

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Data from Federer et al 1996
Stomatal Pore Index Variation

data from Sack et al 2003
Plant Hydraulic Conductance

- Hydraulic conductance of plants is linked to their leaf conductance.
- Another limitation may come from stem and root conductance.
- Ultimately, plants that are highly conductive to water have greater transpiration rates.
- Selecting plants with higher transpiration rates can allow to remove more water faster.
Absorptive Landscaping

- Man-made systems that rely on natural processes to manage water

- One of the main goals is to minimize surface run-off (Q)

- This goal is achieved by maximizing infiltration (I) and evapotranspiration (ET)

- Depressions containing highly permeable soils and vegetation – rain gardens, bioswales, bio-retention systems
Sediment Accumulation

- Maximizing infiltration is achieved by utilizing coarsely grained media.

- Over time fine particles originating from stormwater run-off accumulate on the surface of coarsely-grained filter media.

- Resultant surface sealing prevents water from entering the soil and leading to an overall decrease in hydraulic conductivity, infiltration rate and overall system functionality.
Plants to the Rescue

- Maximizing infiltration is achieved by utilizing plants that produce abundant and resilient macropores

- Over time fine particles originating from stormwater are incorporated into the media without sealing the surface

- Large woody plants appear to be more effective than small shrubs, forbs, or grasses

<table>
<thead>
<tr>
<th>Type of Vegetation</th>
<th>Kin (4 weeks), mm/hr</th>
<th>Kfinal (60 weeks), mm/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>199</td>
<td>53</td>
</tr>
<tr>
<td>Carex</td>
<td>251</td>
<td>51</td>
</tr>
<tr>
<td>Dianella</td>
<td>232</td>
<td>88</td>
</tr>
<tr>
<td>Microleana</td>
<td>150</td>
<td>49</td>
</tr>
<tr>
<td>Leucophyta</td>
<td>231</td>
<td>66</td>
</tr>
<tr>
<td>Melaleuca</td>
<td>155</td>
<td>295</td>
</tr>
</tbody>
</table>

Data from Custumer et al 2012
Water Quality

- Plants are also capable of nutrient uptake

- Vegetated treatments each had: Banksia – a shrub/tree, Bottlebrush – a shrub/tree, Flax Lily – a tufted small lily, Swamp Foxtail Grass – a tufted grass, 3 yrs old

- Best performance is seen when plant action is combined with finely grained soils

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Annual Load kg/ha·yr</th>
<th>Media type</th>
<th>Barren retention kg/ha·yr</th>
<th>Vegetated retention kg/ha·yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Phosphorous</td>
<td>1012</td>
<td>gravel</td>
<td>146</td>
<td>446</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sand</td>
<td>391</td>
<td>679</td>
</tr>
<tr>
<td></td>
<td></td>
<td>loam</td>
<td>570</td>
<td>931</td>
</tr>
<tr>
<td></td>
<td></td>
<td>gravel</td>
<td>-87</td>
<td>212</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>639</td>
<td>sand</td>
<td>-165</td>
<td>265</td>
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<tr>
<td></td>
<td></td>
<td>loam</td>
<td>-149</td>
<td>473</td>
</tr>
<tr>
<td></td>
<td></td>
<td>gravel</td>
<td>72</td>
<td>435</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>1073</td>
<td>sand</td>
<td>125</td>
<td>545</td>
</tr>
<tr>
<td></td>
<td></td>
<td>loam</td>
<td>197</td>
<td>816</td>
</tr>
</tbody>
</table>

Data from Lucas and Greenway 2008
Conclusions

- Vegetative proliferation improves soil structure and increases soil hydraulic conductivity.
- Woody species have a significantly greater impact on soil permeability as compared with herbaceous lawn grasses.
- Plants possess various hydraulic functionalities, and some are better at increasing soil hydraulic conductivity, as well as utilizing soil water.
- Plants can have a pronounced impact on nutrient removal.
- Plants are low-maintenance living instruments that should be utilized to manage water quantity and quality as well.
Thank You!

- Questions?

- Key references