

Speaker Profile: mike g.

- Education History:
 - 1970s: Our Lady of 115th Street parochial school
 - 1980s: Lakeport High School, same as Neil Peart (late drummer of **RUSH**)
 - 1990s: U of Toronto (Bachelor's) and then U of Guelph (Master's)
- Professional History:
 - 1990-1995: Stantec (Cambridge ON) and then I became a starving grad student of Bill's
 - 1995-2005: CDM-Smith (Tampa FL & Cleveland OH)
 - 2005-2015: AECOM (Kitchener ON)
 - since 2015: CHI (Guelph ON)



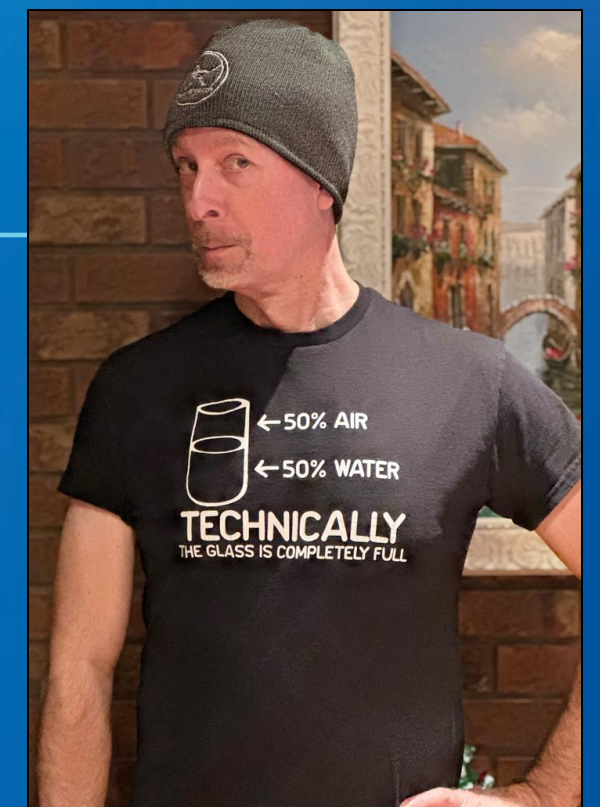
they used to call me "Bubbles"



Water Budget Analyses: Lucid Liquid Ledgers for Stormwater Modeling

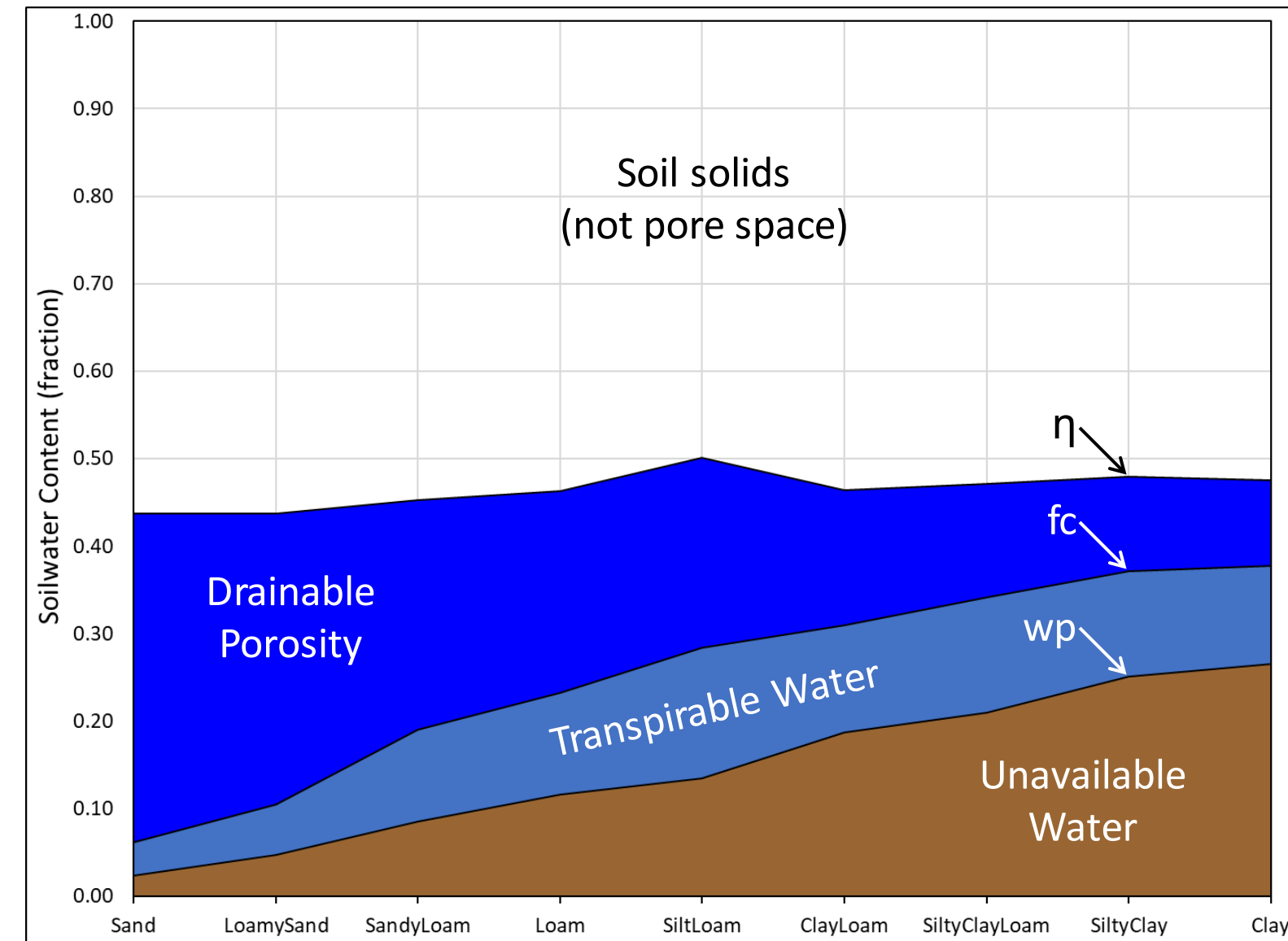
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Toronto, Canada

Mike Gregory, P.Eng., PE (CHI-Guelph, Canada)



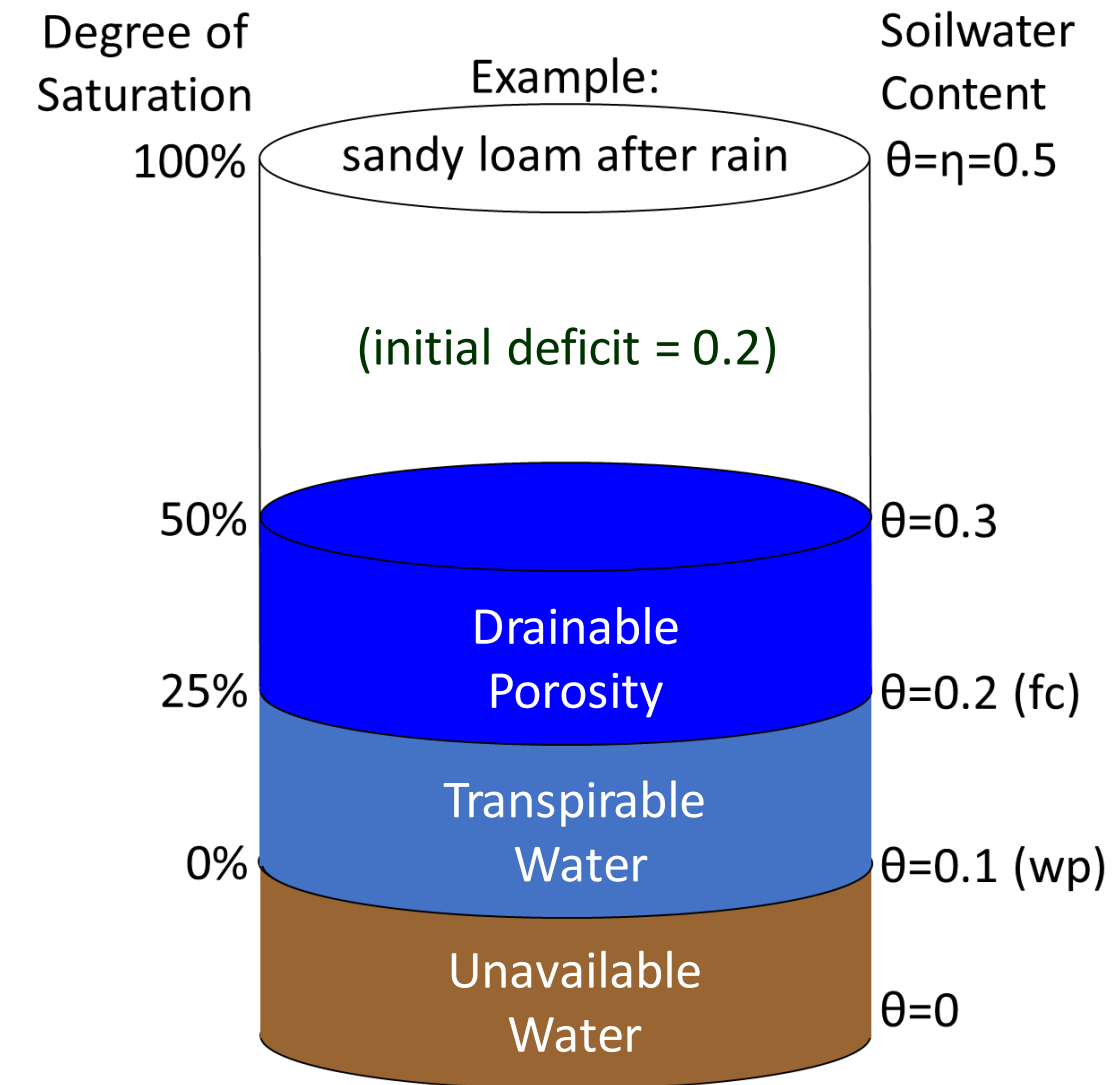
Pore Space, Exposed

- A mixture of water & air fills the porosity, η
 - Soilwater content = θ
 - Soilwater deficit (i.e., soil air content) = $\eta - \theta$
- Pore space has three components:
 - Drainable porosity, between η and fc
 - Transpirable water, between fc and wp
 - Unavailable water, below wp
- Degree of saturation is typically referenced between wilting point and porosity
 - At 0% saturation, soilwater content is at the wilting point ($\theta = wp$)
 - At 100% saturation, all of the pore space is full of water ($\theta = \eta$)
 - Field capacity is somewhere in between (θ depends on soil properties)



Specifying Initial Soilwater Content

- In SWMM5, data entry is context-sensitive:
 - Subcatchment: initial soilwater deficit (Green-Ampt)
 - Groundwater Aquifer: initial soilwater content
 - LID Usage: initial degree of saturation



Soil Texture Class	Hydraulic Conductivity (in/hr)	Suction Head (in)	Porosity (fraction)	Field Capacity (fraction)	Wilting Point (fraction)	Initial Deficit (by Degree of Saturation)					Initial Content (by Degree of Saturation)				
						0% sat'n	25% sat'n	50% sat'n	75% sat'n	100% sat'n	0% sat'n	25% sat'n	50% sat'n	75% sat'n	100% sat'n
Sand	4.74	1.93	0.437	0.062	0.024	0.413	0.310	0.207	0.103	0.000	0.024	0.127	0.231	0.334	0.437
LoamySand	1.18	2.40	0.437	0.105	0.047	0.390	0.293	0.195	0.098	0.000	0.047	0.145	0.242	0.340	0.437
SandyLoam	0.43	4.33	0.453	0.190	0.085	0.368	0.276	0.184	0.092	0.000	0.085	0.177	0.269	0.361	0.453
Loam	0.13	3.50	0.463	0.232	0.116	0.347	0.260	0.174	0.087	0.000	0.116	0.203	0.290	0.376	0.463
SiltLoam	0.26	6.69	0.501	0.284	0.135	0.366	0.275	0.183	0.092	0.000	0.135	0.227	0.318	0.410	0.501
SandyClayLoam	0.06	8.66	0.398	0.244	0.136	0.262	0.197	0.131	0.066	0.000	0.136	0.202	0.267	0.333	0.398
ClayLoam	0.04	8.27	0.464	0.310	0.187	0.277	0.208	0.139	0.069	0.000	0.187	0.256	0.326	0.395	0.464
SiltyClayLoam	0.04	10.63	0.471	0.342	0.210	0.261	0.196	0.131	0.065	0.000	0.210	0.275	0.341	0.406	0.471
SandyClay	0.02	9.45	0.430	0.321	0.221	0.209	0.157	0.105	0.052	0.000	0.221	0.273	0.326	0.378	0.430
SiltyClay	0.02	11.42	0.479	0.371	0.251	0.228	0.171	0.114	0.057	0.000	0.251	0.308	0.365	0.422	0.479
Clay	0.01	12.60	0.475	0.378	0.265	0.210	0.158	0.105	0.053	0.000	0.265	0.318	0.370	0.425	0.475
example wetted sandy loam, $\theta > fc$			0.500	0.200	0.100	0.400	0.300	0.200	0.100	0.000	0.100	0.200	0.300		

Values based on typical soil properties in Rawls W.J., Brakensiek D.L., and Miller N.; January 1983; Journal of Hydraulic Engineering; Vol.109, No.1

Property	Value
Aquifer Name	Boston
Porosity	0.5
Wilting Point	0.1
Field Capacity	0.2
Conductivity	0.15
Conductivity Slope	45
Tension Slope	5
Upper Evap. Fraction	0.25
Lower Evap. Depth	18
Lower GW Loss Rate	0.02
Bottom Elevation	0.1
Water Table Elevation	2
Unsat. Zone Moisture	0.1

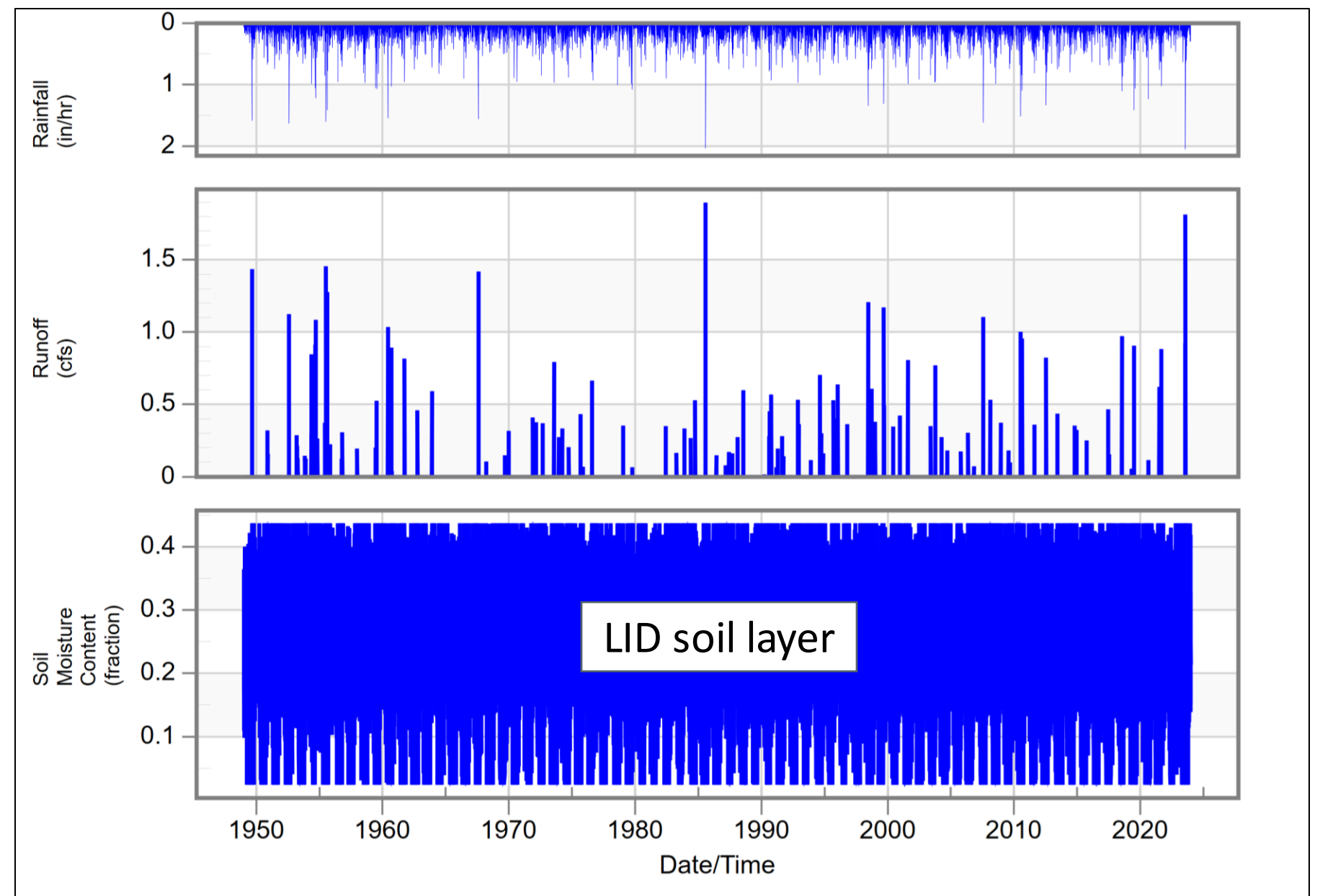
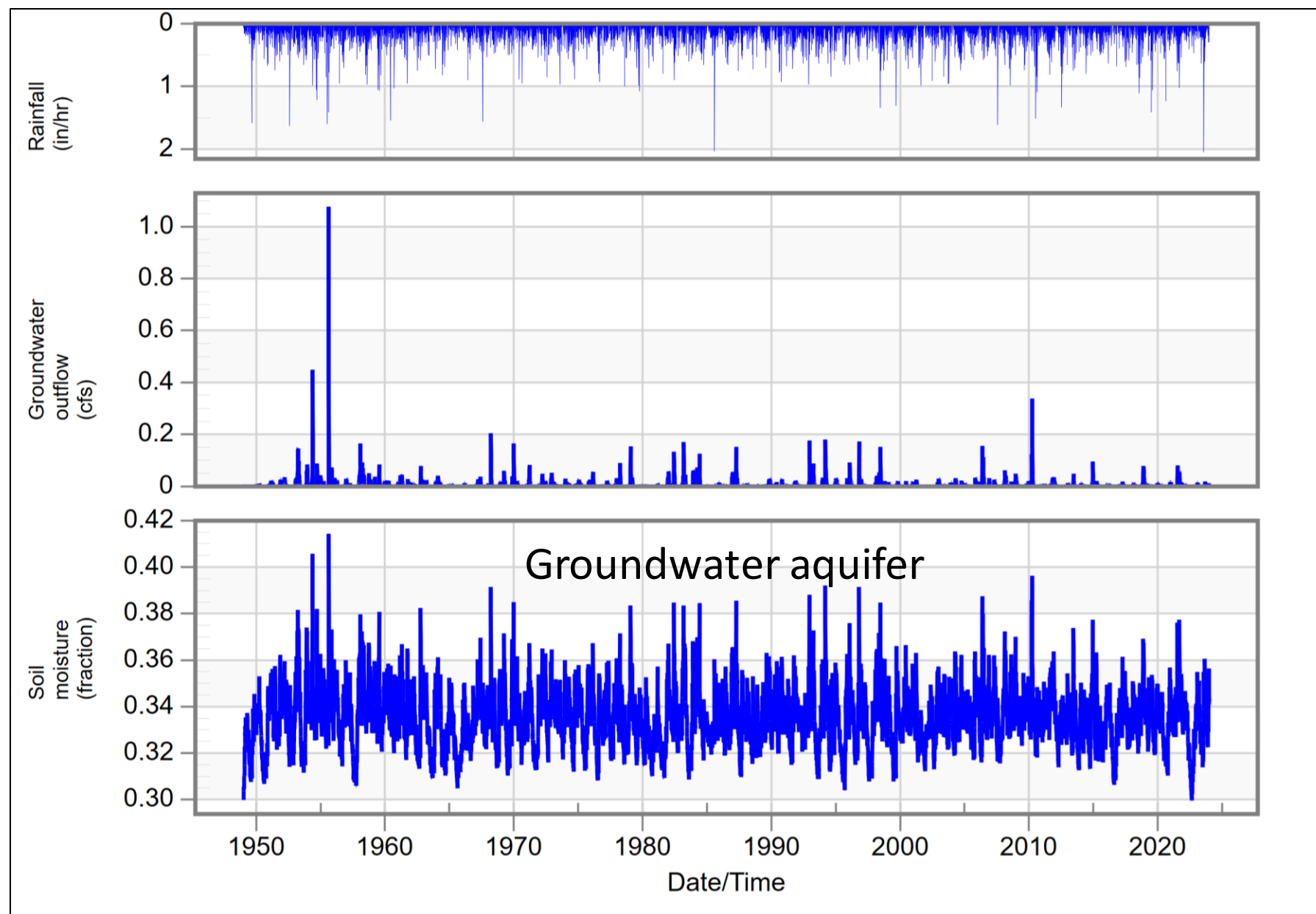
SWMM5 ($\theta = wp$, 0% saturation)

Property	Value
Infiltration Method	MODIFIED_GREEN_AMPT
Suction Head	4
Conductivity	0.5
Initial Deficit	0.4

A Different Example, Same Texture

Soilwater Content Timeseries in SWMM5

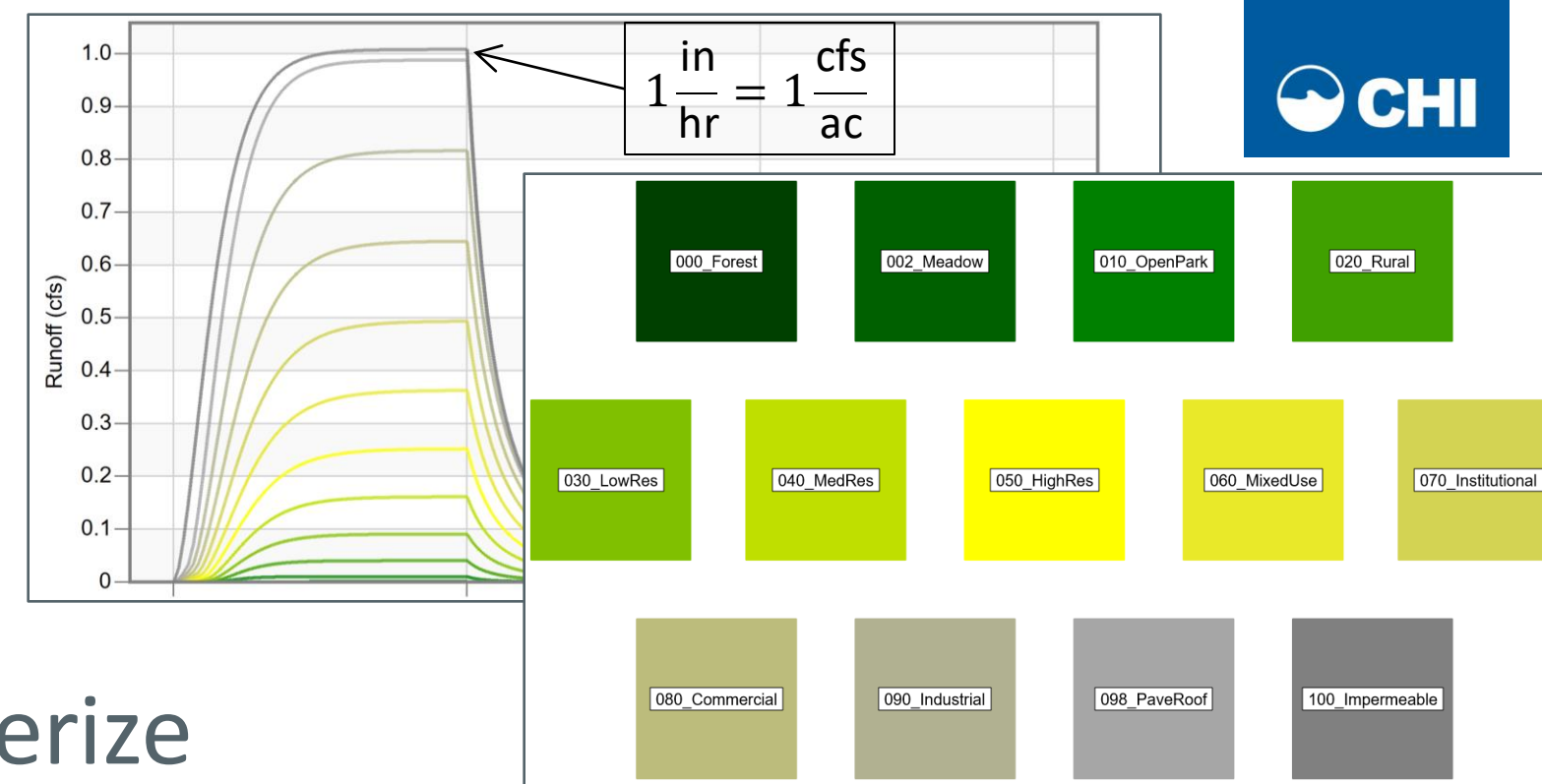
- Quantifying the amount of water that lurks beneath the surface...
 - Subcatchment: the timeseries is not computed
 - Groundwater Aquifer: computed (as “Soil Moisture”)
 - LID Usage: computed (as “Soil Moisture Content”, if Detailed Report file specified)



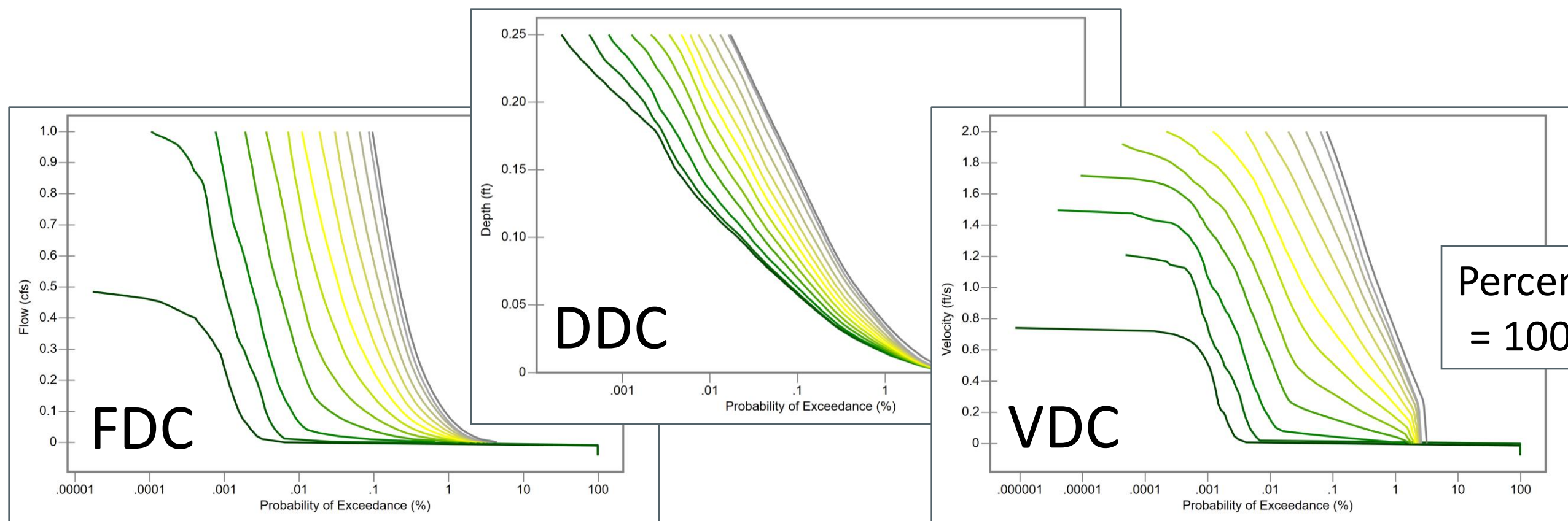
Water Quantity Analyses



- Hydrologic Response Units translate rainfall to runoff for specific surface cover materials
- Percentiles, trends, and other statistics characterize long-term timeseries results
- Flow/Depth/Velocity Duration Curves quantify impacts
- HRU approach can quantify impacts in another way...

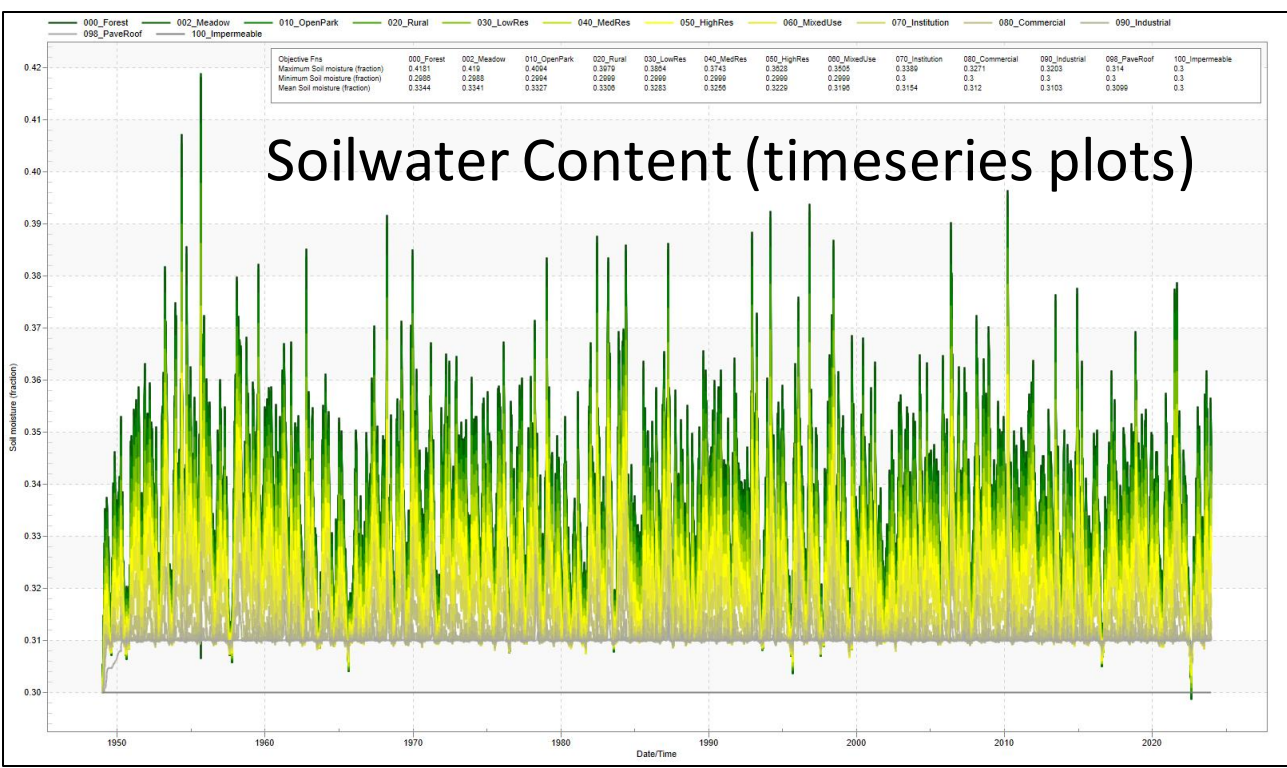
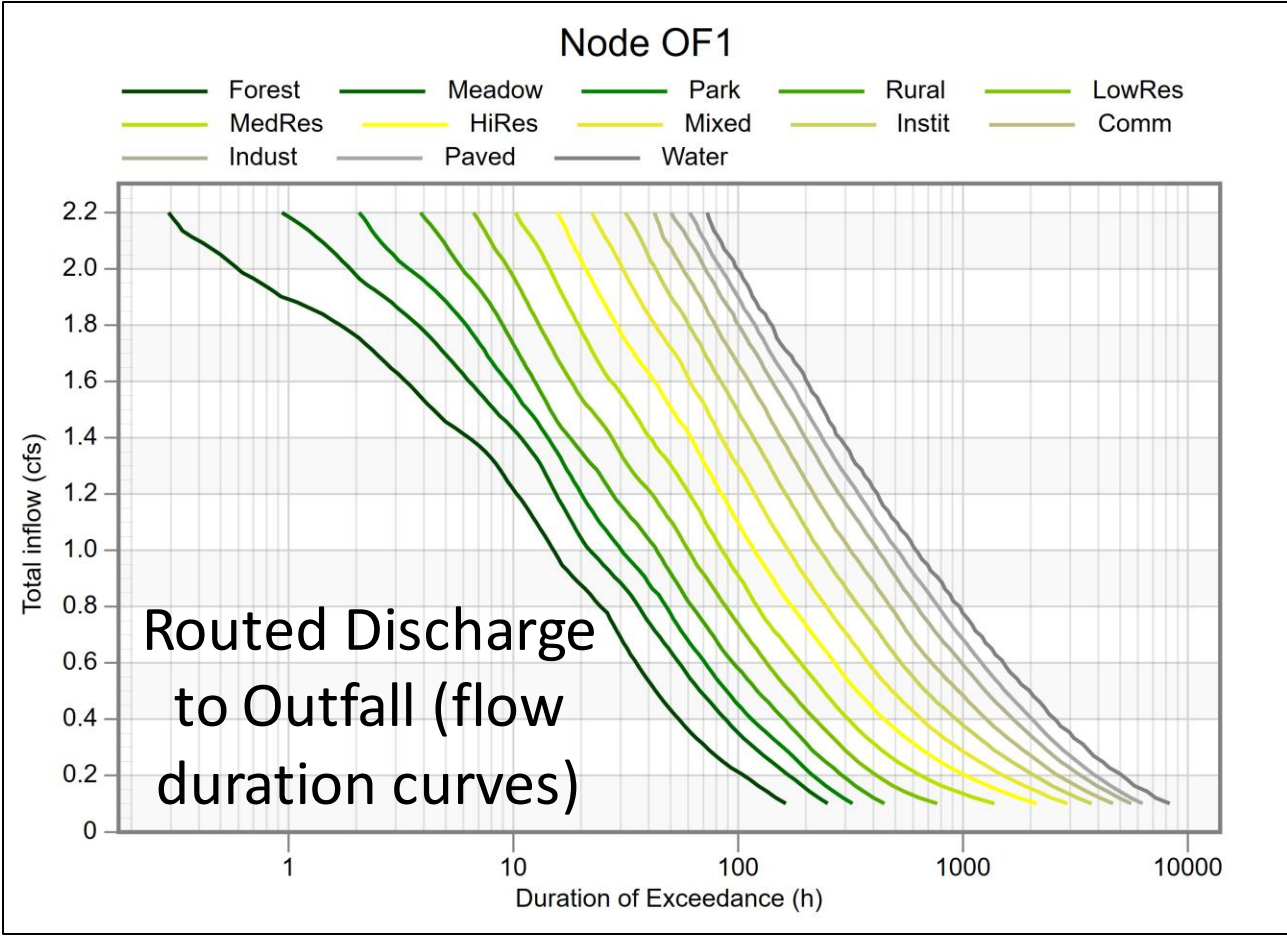
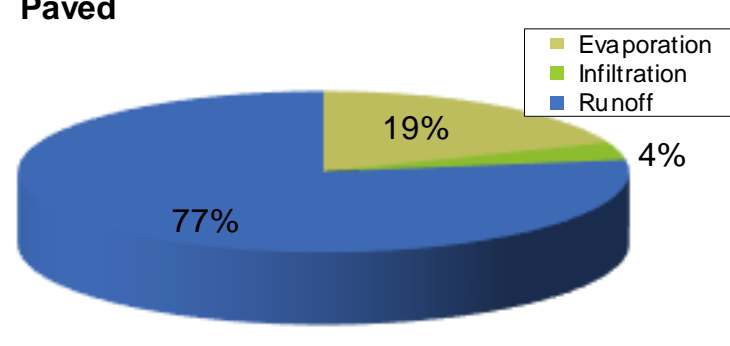
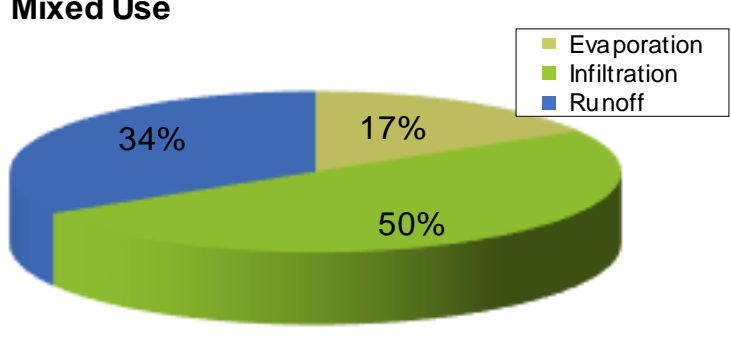
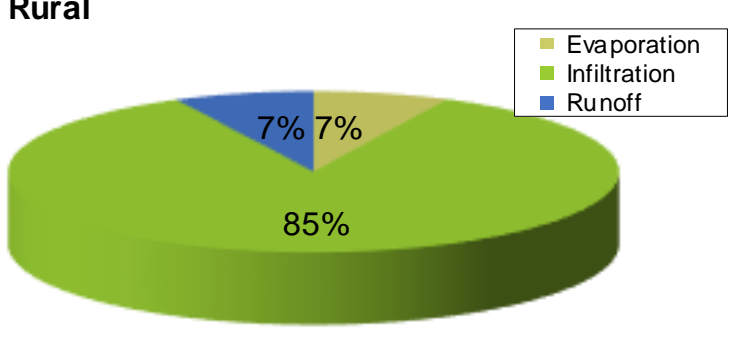
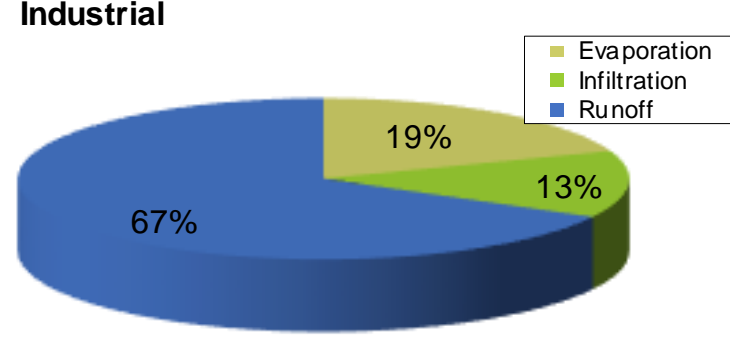
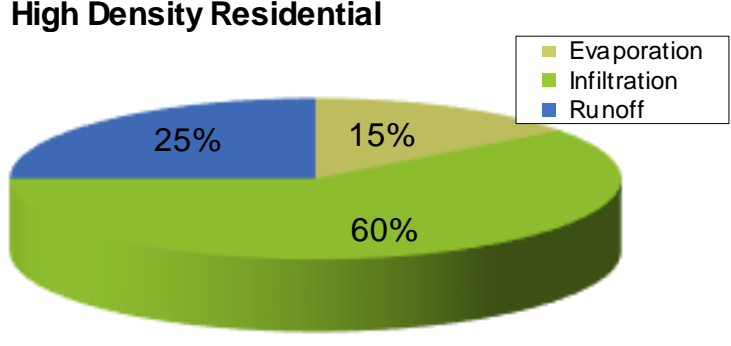
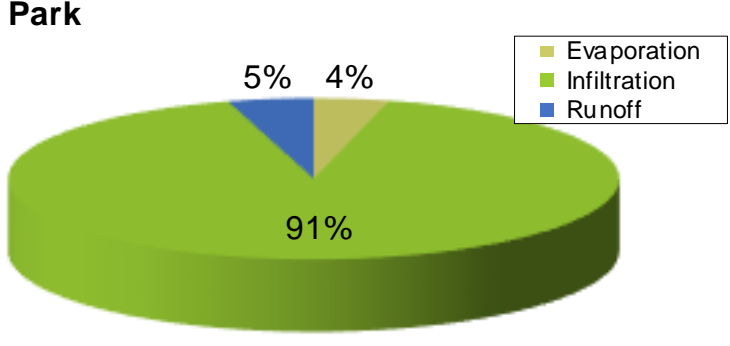
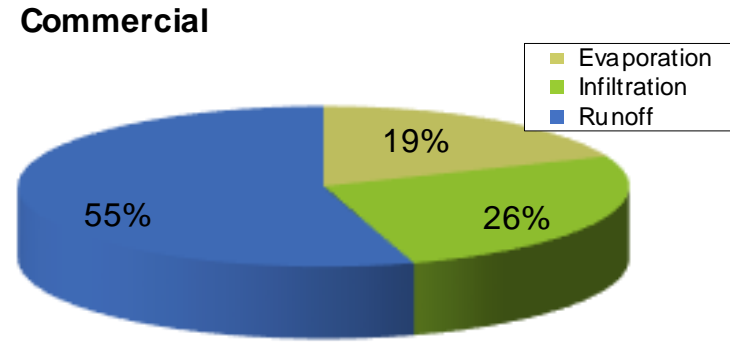
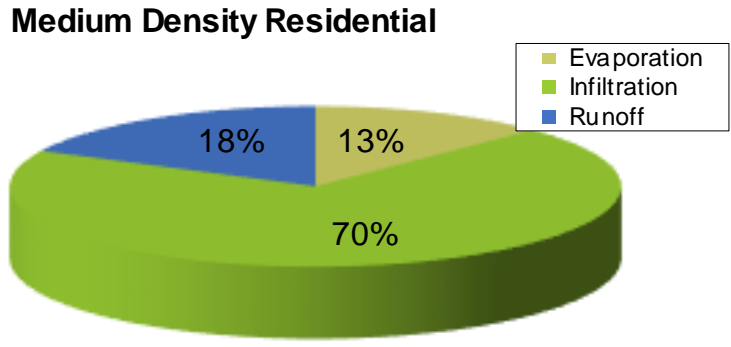
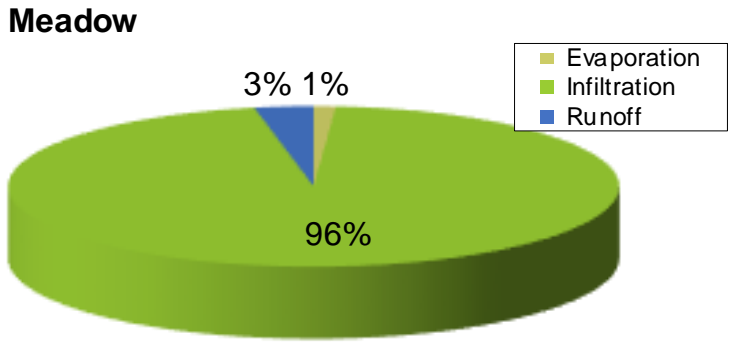
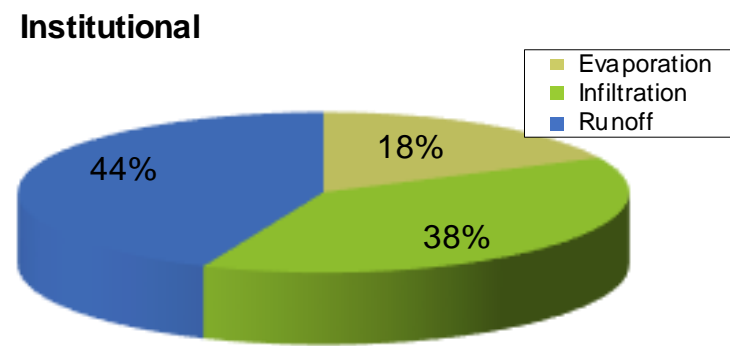
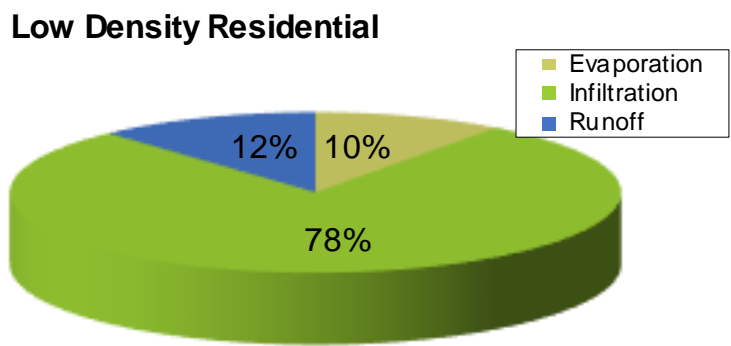
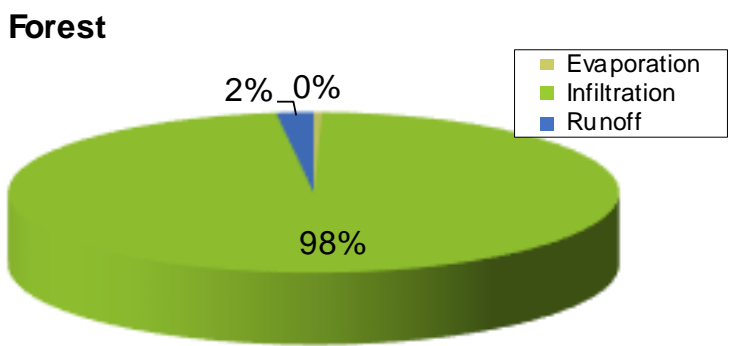


Timeseries Statistical Analysis	Lake Huron Water Levels	Tidewater, OR Streamflows	Int'l Falls, MN Rainfall	Tampa, FL Tides
Data Type	mean	mean	cumulative	instantaneous
Recording Interval	monthly	daily	hourly	6-min
Units	ft-IGLD1985	cfs	in	ft-NAVD 1988
Data Exclusions	none	none	remove zeroes	none
Missing Data Flag	none	-9999	999.99	none
Missing/Null Values	do not include	do not include	replace with zero	do not include
Period of Record (yr)	103.0	61.0	65.0	1.2
Count	1,236	22,281	35,134	109,420
% of records	100.0%	100.0%	6.2%	99.8%
Minimum	576.02	47	0.01	-3.12
Maximum	582.35	36,100	2.84	4.65
Average	578.88	1,490	0.04	0.02
Median	578.87	650	0.02	0.07
Mode	579.30	88	0.01	0.34
Standard Deviation	1.34	2,320	0.09	0.90
Kurtosis	-0.8	23.7	130.8	-0.09
Skewness	0.1	3.9	8.6	-0.13
Coeff. of Variation	0.0	1.6	2.0	51.7
Percentiles				
10%	577.17	99	0.01	-1.20
25%	577.76	172	0.01	-0.61
50%	578.87	650	0.02	0.07
75%	579.89	1,800	0.04	0.65
80%	580.12	2,240	0.05	0.78
85%	580.37	2,840	0.07	0.96
90%	580.64	3,850	0.09	1.17
95%	581.17	5,700	0.16	1.45
99%	581.76	11,600	0.41	1.89
99.5%	581.96	14,300	0.58	2.03
99.9%	582.21	20,700	1.07	2.67
99.95%	582.27	22,300	1.29	3.55
99.99%	582.33	30,635	1.89	4.49



Example Impact Analyses using HRUs

Surface Water Balance (pie charts) = focus of my presentation



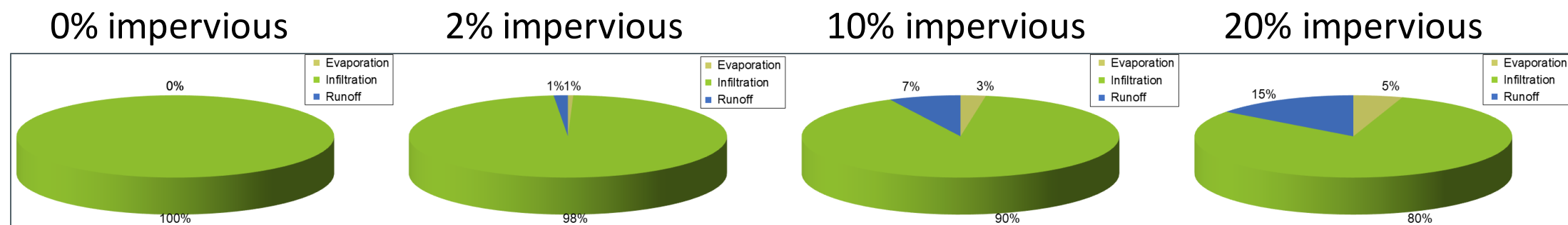
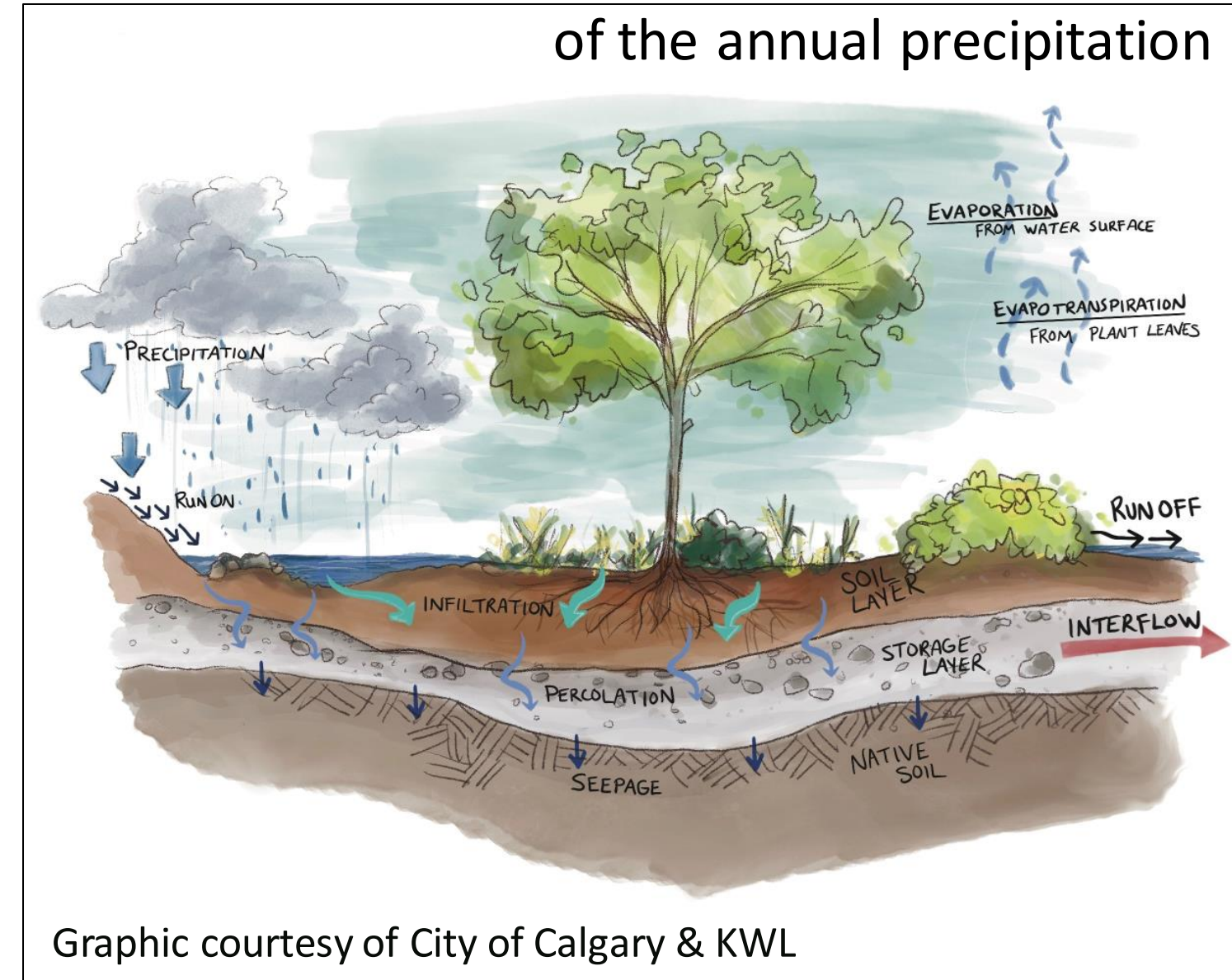
When Water & Energy Meet...

- Evaporation and Transpiration are related, often conflated, always abbreviated ET
- Energy causes water to:
 - Evaporate from open water bodies and depressions on impervious surfaces/bare soils
 - Transpire from openings in leaf surfaces and from vegetation roots
- The evaporative regime (i.e., evapotranspiration):
 - Dominates the water balance during dry weather periods (i.e., >95% of the time)
 - Drives the soilwater content down, while rainfall/snowmelt/irrigation replenish it
- Definitions: Potential ET (PET) is the possible ET rate when soilwater isn't limiting, whereas Actual ET is the actual/computed rate at which water is lost to the atmosphere under the actual/computed soilwater, energy, and climate conditions
- It is disappointing that the ET process is oversimplified, even in sophisticated hydrologic models... including the regular subcatchment routing of SWMM5!

Surface Water, Exposed

Typical ET range is 40-95% of the annual precipitation

- Hydrology doesn't end with infiltration!
 - I repeat... the evaporative regime often dominates the water budget (overwhelmingly in arid regions)
 - Also... interflow is critical for analyzing wetlands
- Back to the HRUs... have you ever tried to do a water balance which resulted in results like this?

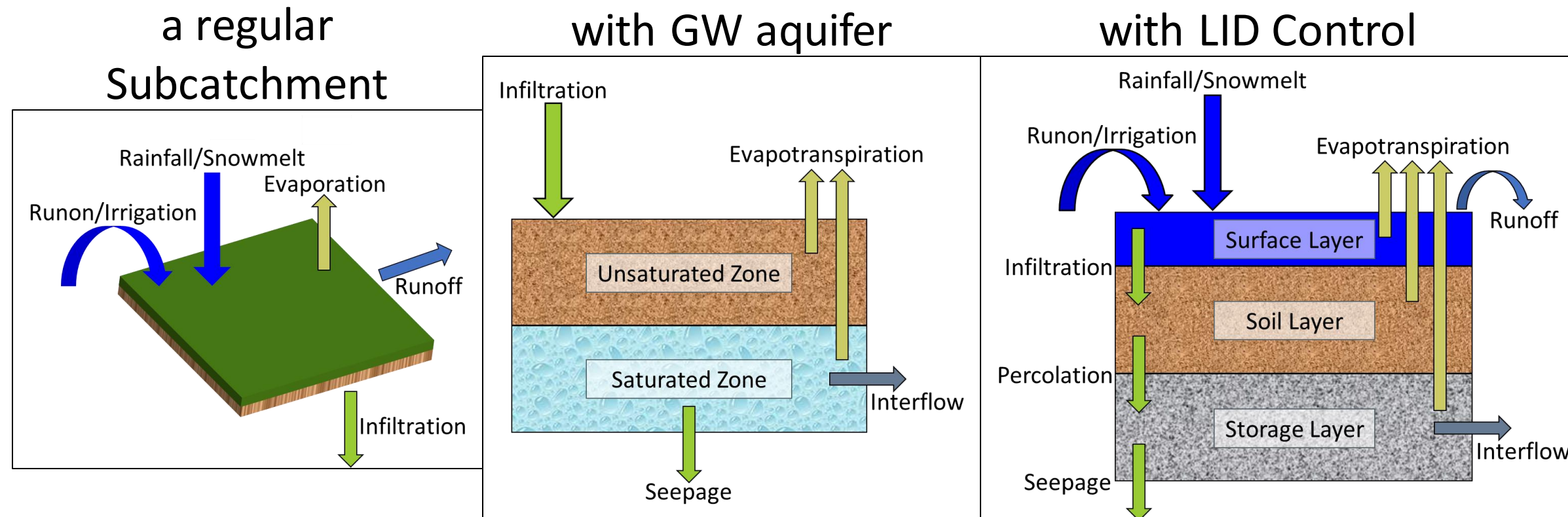
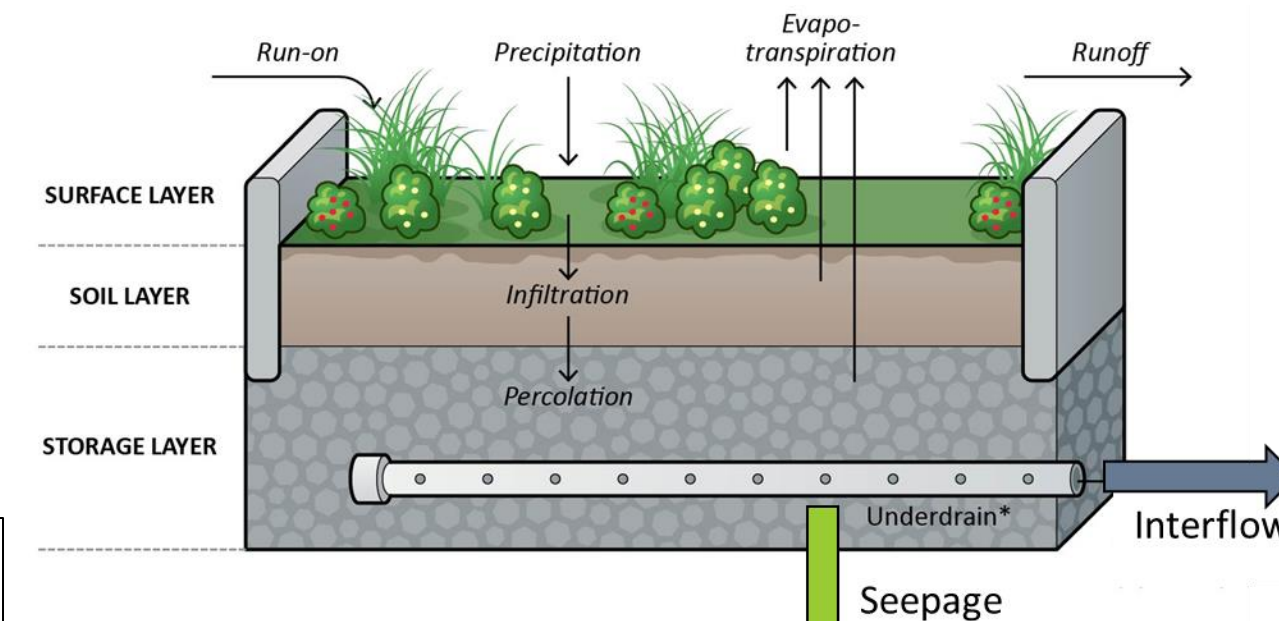
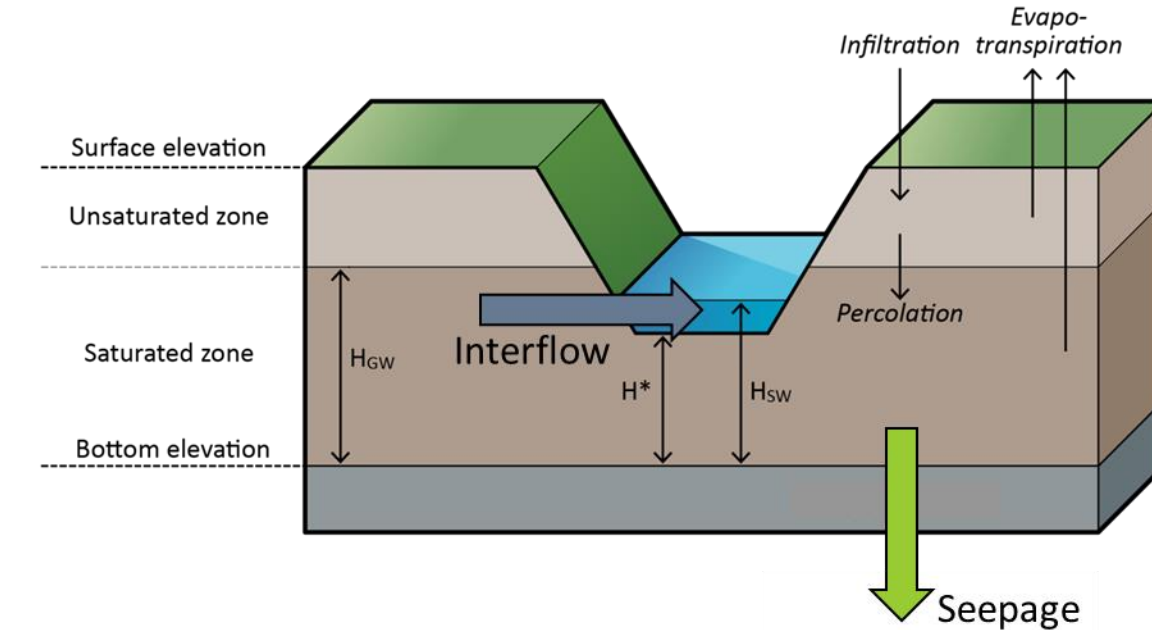


- That is, rural land uses suggest ET is only 0-10% of the annual water balance – this is not correct



Two-Layer Hydrology Options in SWMM5

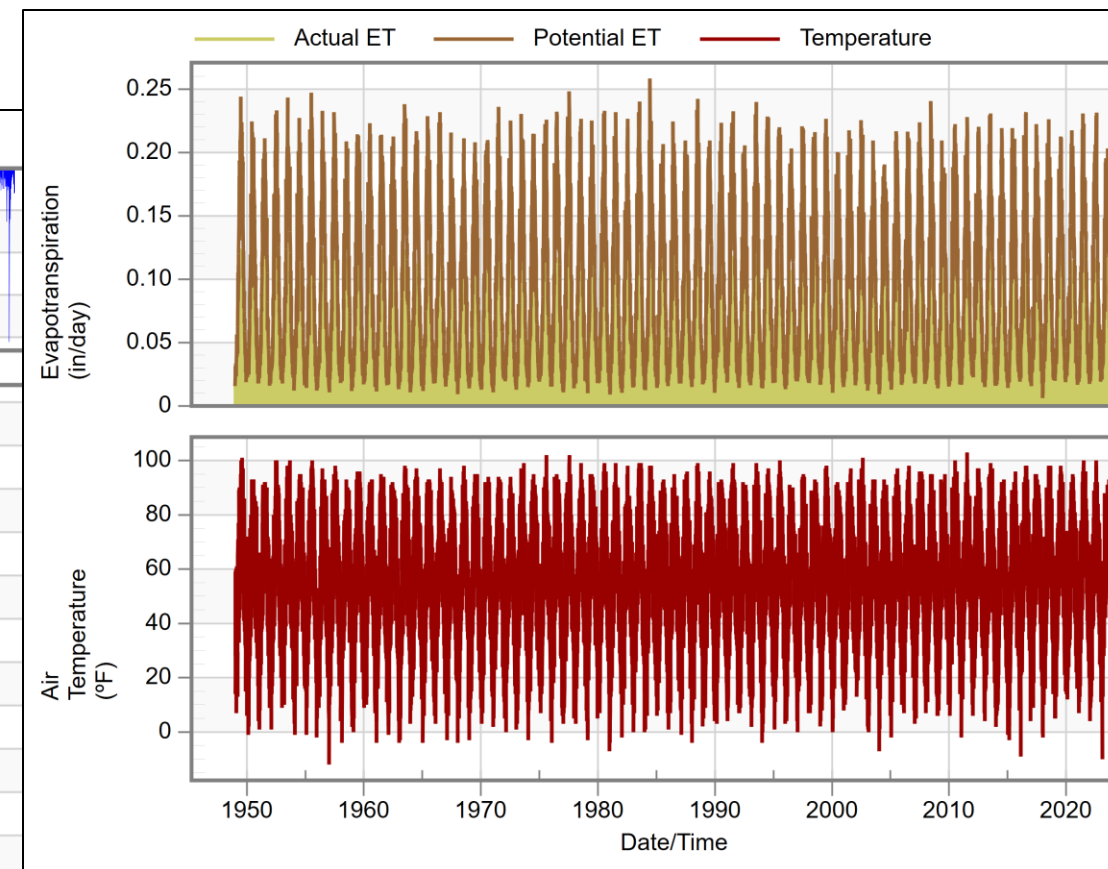
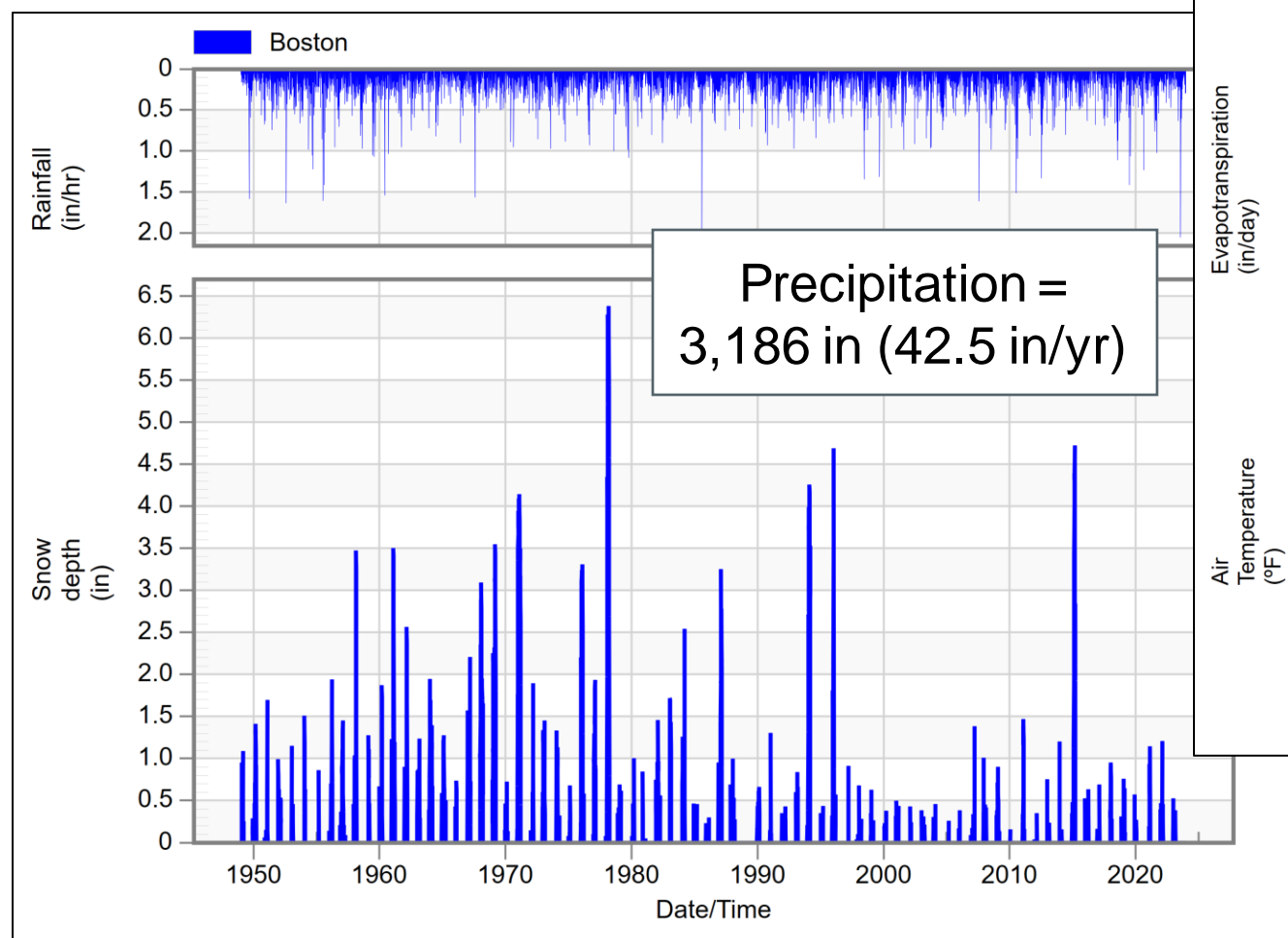
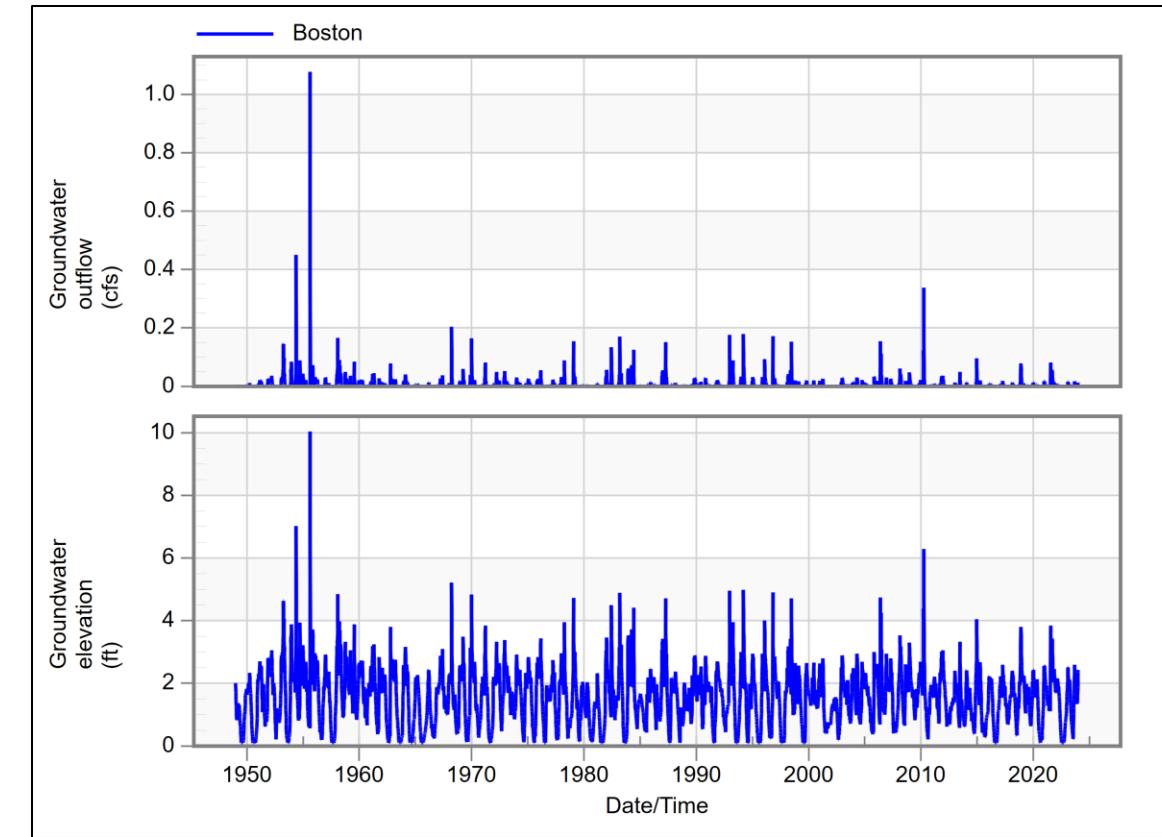
- Solution 1: Add a Groundwater aquifer
 - Two layers (saturated + unsaturated zones)
 - ...but only one soil type can be specified
- Solution 2: Add an LID control
 - Two layers (Soil + Storage) can represent two soil types
 - ...but note Soil layer applies Green-Ampt infiltration, in Storage layer, water rises from bottom like a reservoir



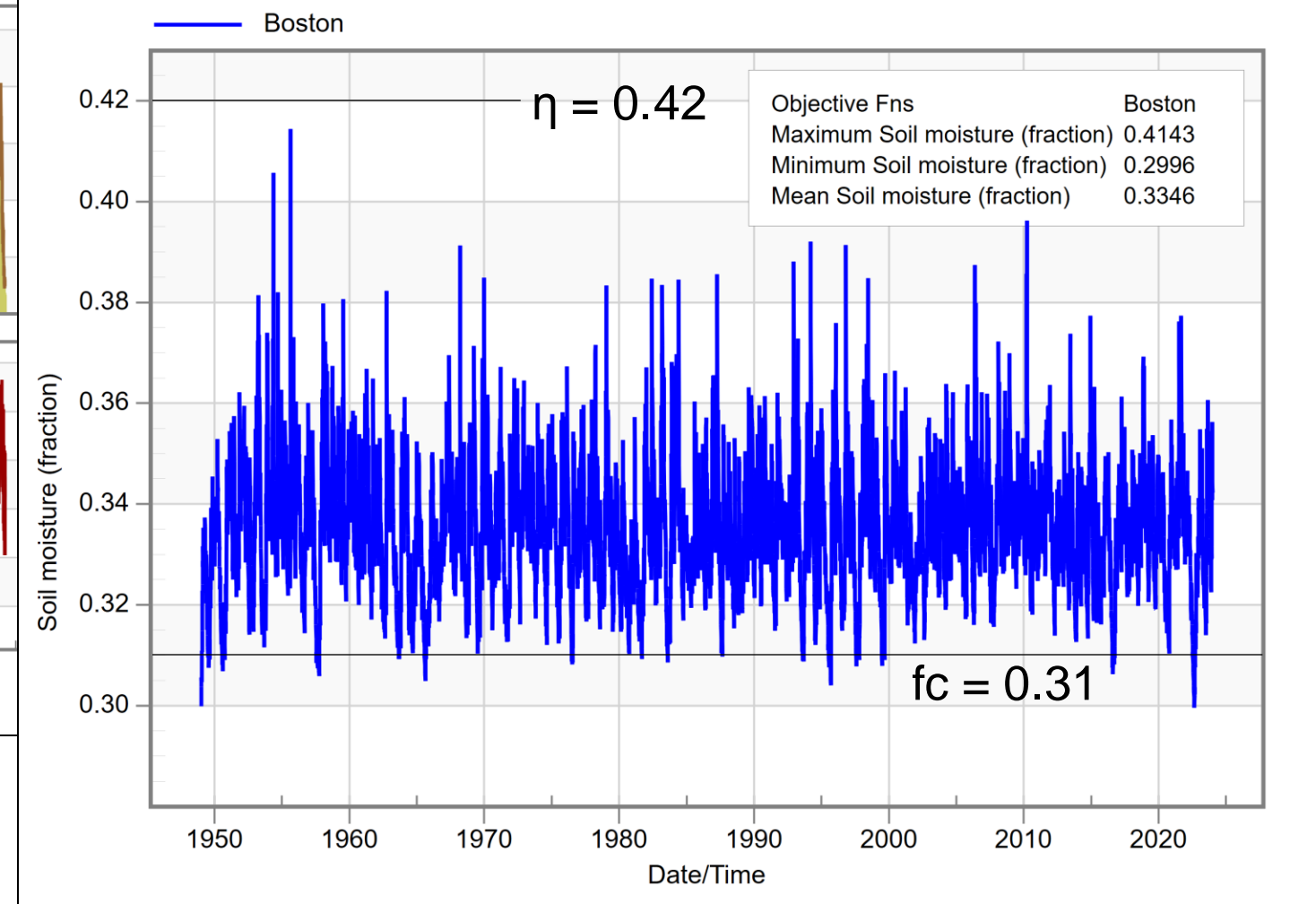
My understanding of the practical applications of the groundwater approach is courtesy of Nandana; the LID approach is courtesy of City of Calgary, MPE, KWL, and Matrix Inc.

Case Study: Boston MA

- Coarse groundwater aquifer was added to match observed long-term average annual ET (approx. 40%)
- SWMM5 with 75-year period of record precipitation (as well as temperature + wind speed to represent snowmelt and to estimate PET per Hargreaves method)



Actual ET = 1,309 in
(17.5 in/yr, 41% of precip)

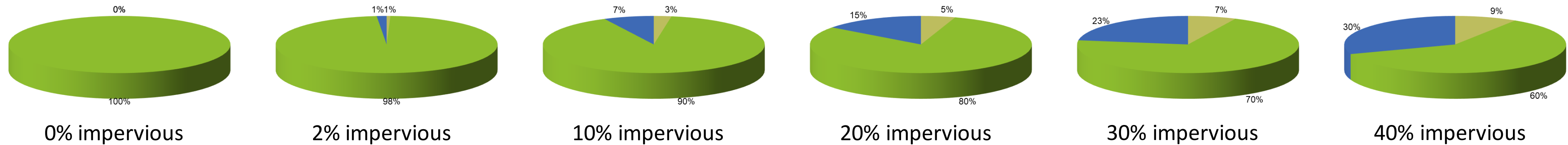


Case Study: Boston MA

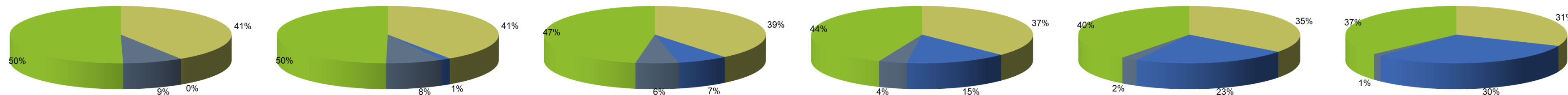
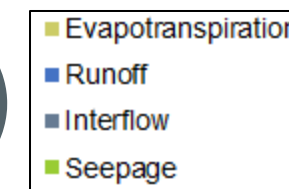
- Water budget analysis results: Subcatchments with Groundwater aquifer

Subcatchment	Precipitation (in/yr)	Evapotranspiration (in/yr)			Infiltration (in/yr)		Interflow (in/yr)		Runoff (in/yr)	
		Surface Water	Ground-water	Total	Ground-water	Total	Ground-water	Total	Surface Water	Total
000_Forest	42.5	0.0	17.5	41%	21.5	50%	3.7	9%	0.0	0%
002_Meadow	42.5	0.2	17.1	41%	21.2	50%	3.5	8%	0.6	1%
010_OpenPark	42.5	1.1	15.6	39%	20.1	47%	2.7	6%	3.1	7%
020_Rural	42.5	2.1	13.8	37%	18.6	44%	1.8	4%	6.3	15%
030_LowRes	42.5	3.0	12.0	35%	17.0	40%	1.0	2%	9.6	23%
040_MedRes	42.5	3.9	9.5	31%	15.7	37%	0.6	1%	12.9	30%
050_HighRes	42.5	4.5	7.0	27%	14.3	34%	0.2	1%	16.5	39%
060_MixedUse	42.5	5.2	5.2	25%	12.0	28%	0.0	0%	20.0	47%
070_Institution	42.5	5.6	3.9	23%	9.2	22%	0.0	0%	23.8	56%
080_Commercial	42.5	6.1	2.6	21%	6.3	15%	0.0	0%	27.5	65%
090_Industrial	42.5	6.3	1.3	18%	3.4	8%	0.0	0%	31.6	74%
098_PaveRoof	42.5	6.3	0.2	16%	1.1	3%	0.0	0%	34.9	82%
100_Impermeable	42.5	3.4	0.0	8%	0.0	0%	0.0	0%	39.0	92%

✗ One-layer hydrology (surface water only)



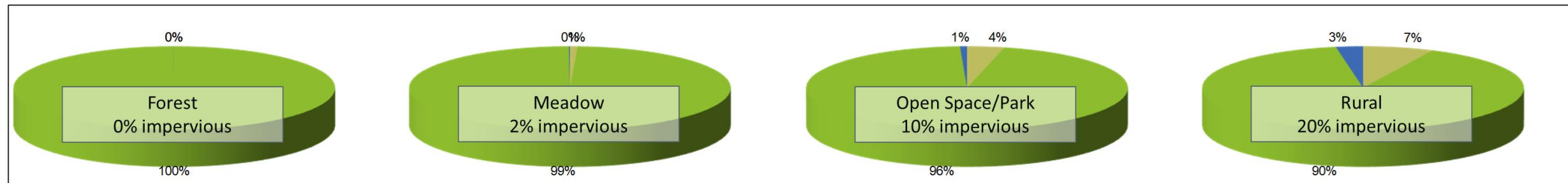
✓ Two-layer hydrology (surface + subsurface)



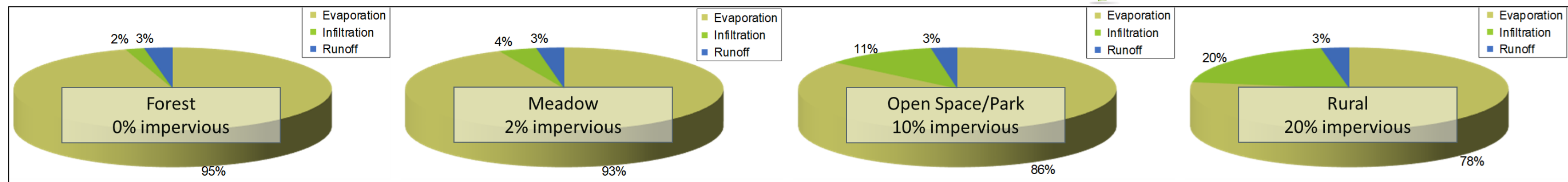
Case Study: Calgary AB

- Equivalent LID control added to match observed long-term ET (approx. 95%)
- SWMM5 applied to typical rainfall year, for the irrigation period May-September (i.e., no snowmelt)
- Used local standard PET time-series (provided by City of Calgary), derived from the Penman-Monteith equation
- Started with the HRUs...

✗ One-Layer Hydrology – Regular Subcatchments

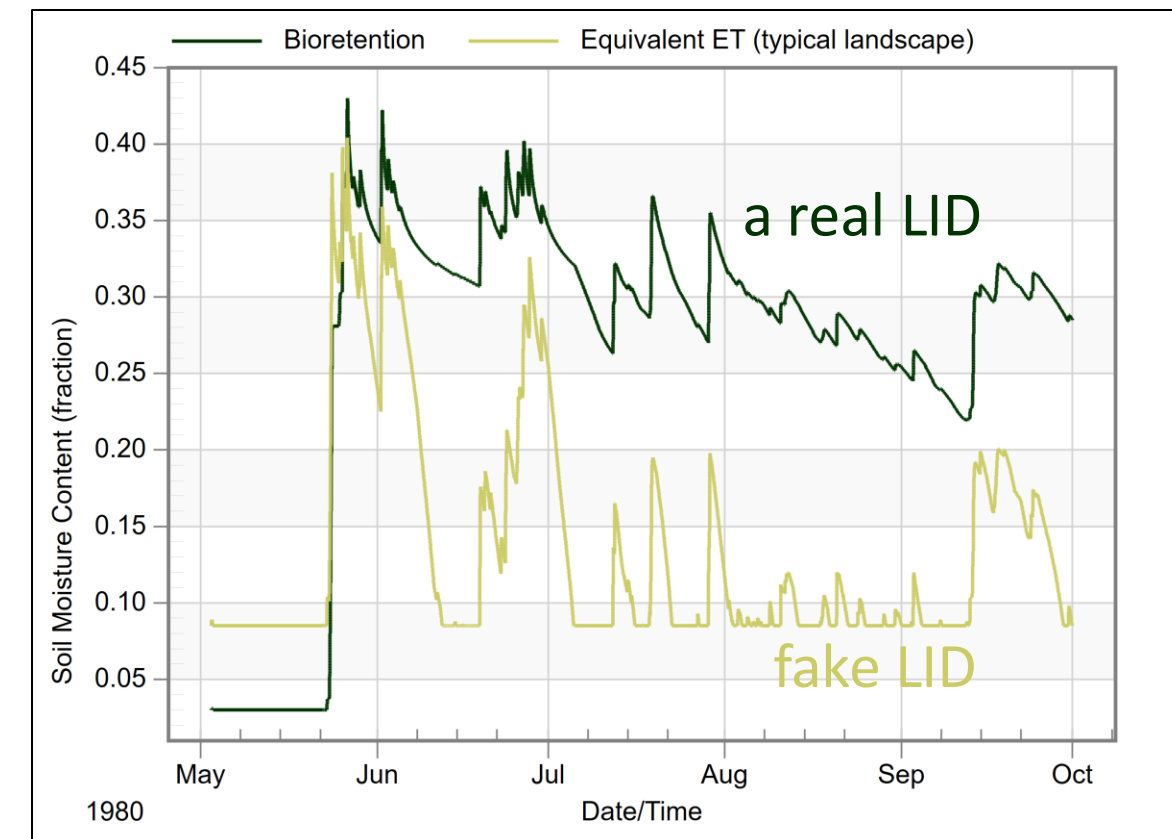
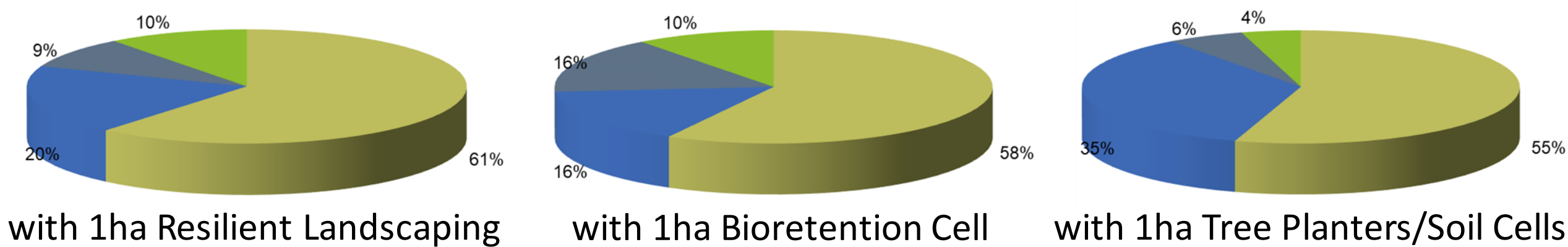
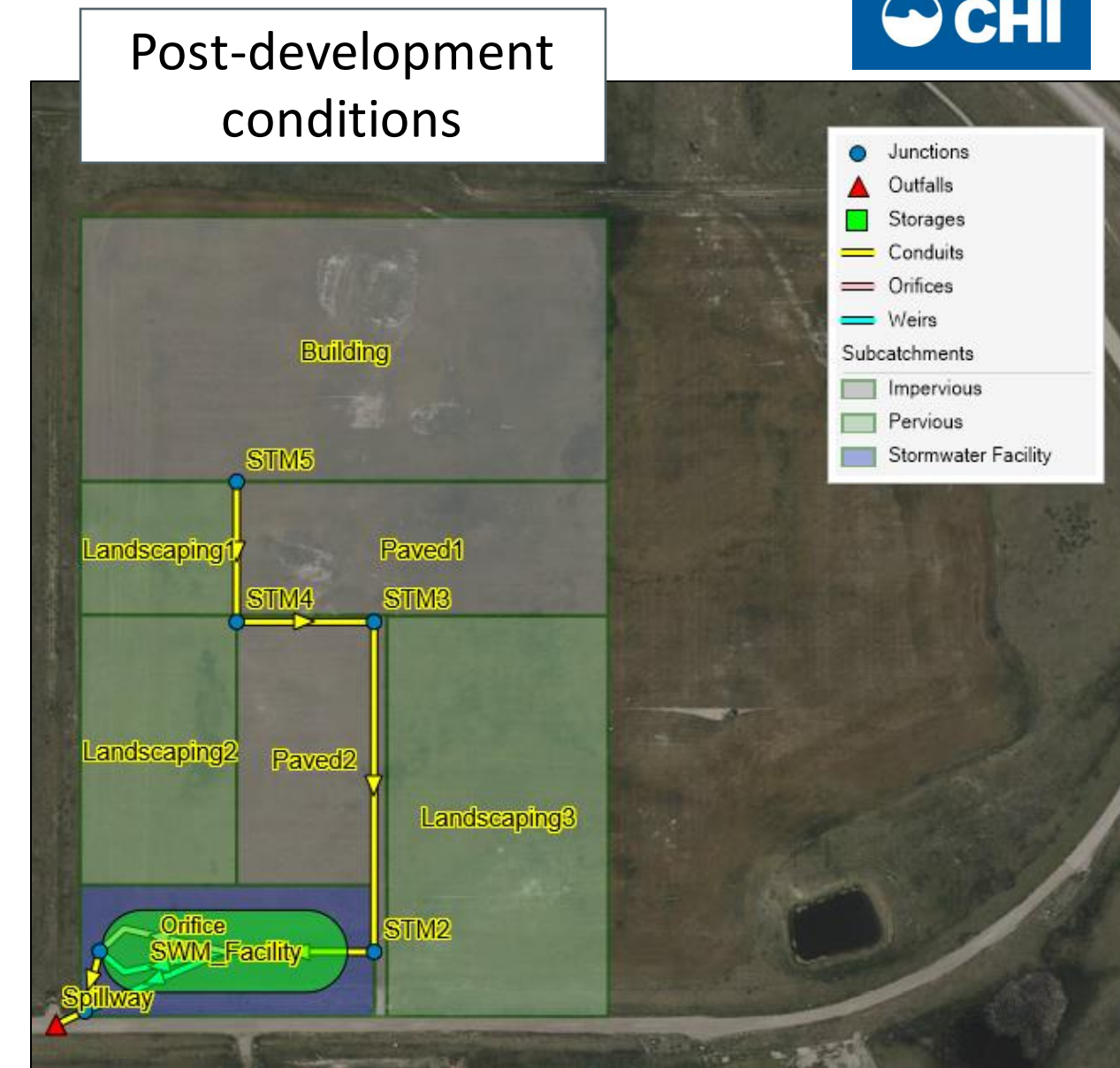
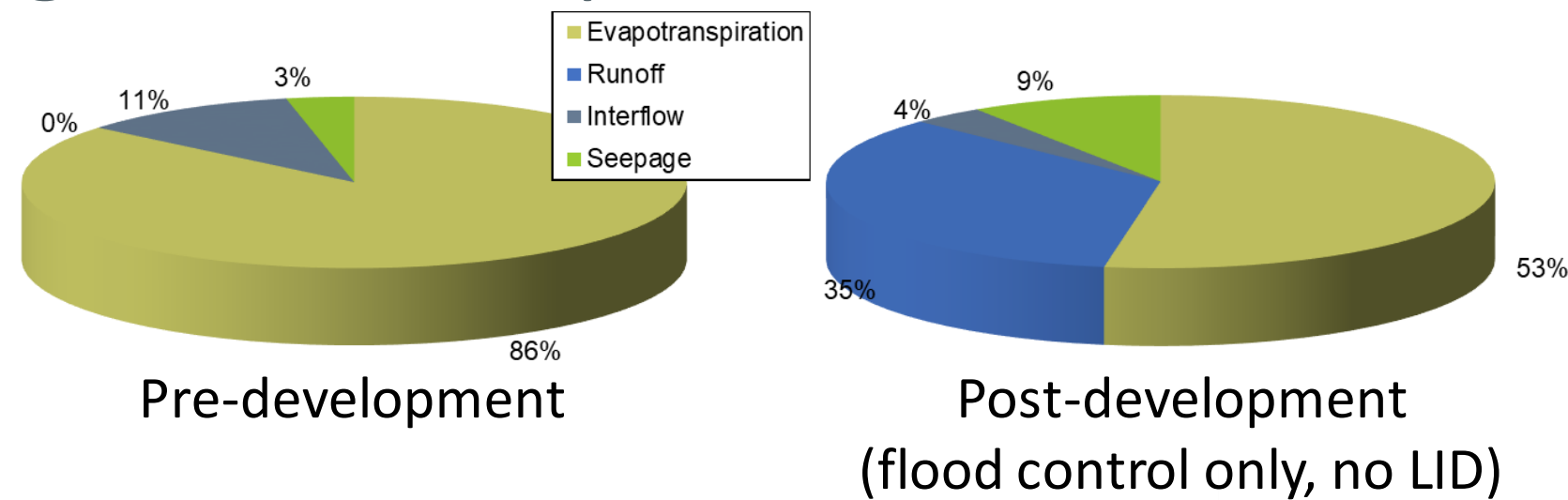


✓ Two-Layer Hydrology – LID Approach



Case Study: Calgary AB

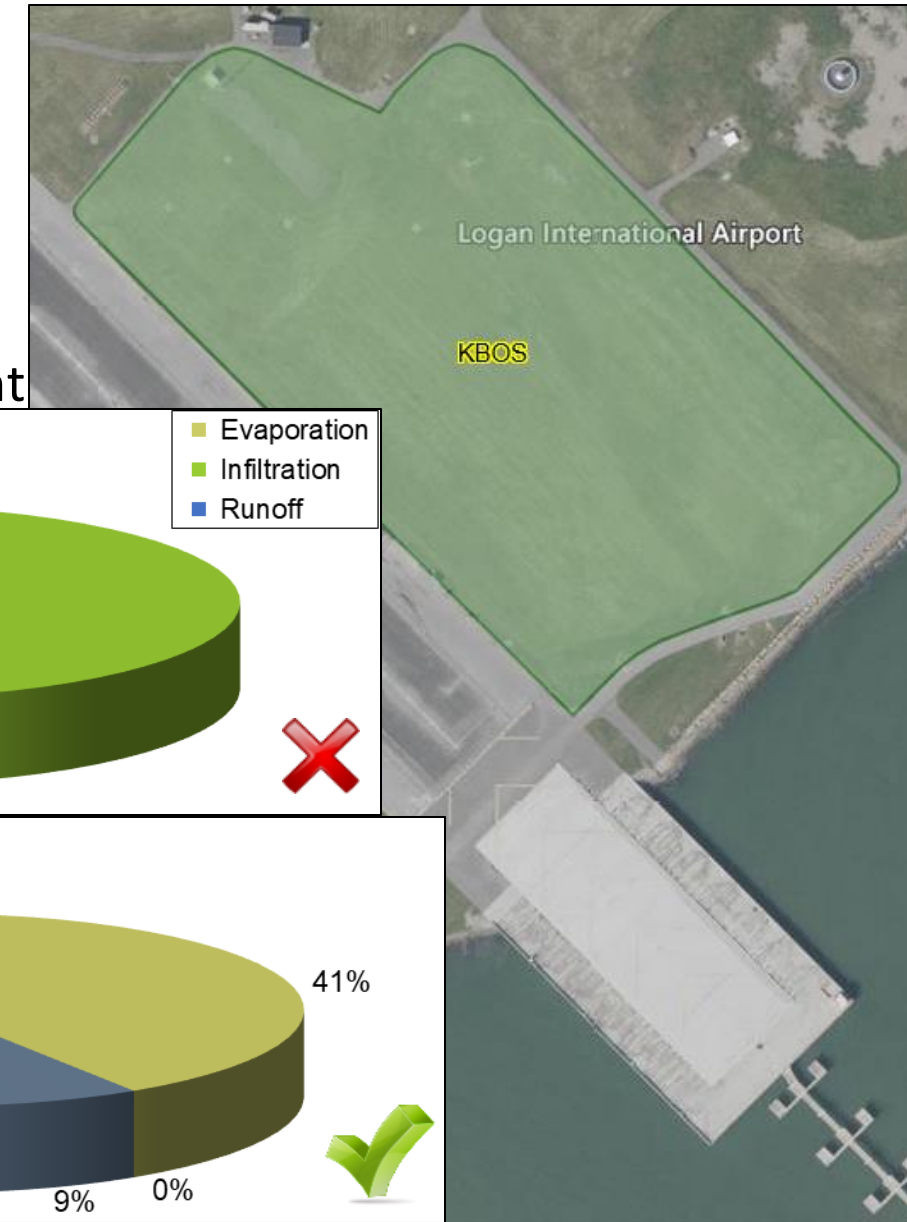
- Moved on to 10-ha site development...
- Soilwater content (compared to a real LID control)
- And again with the pie charts...



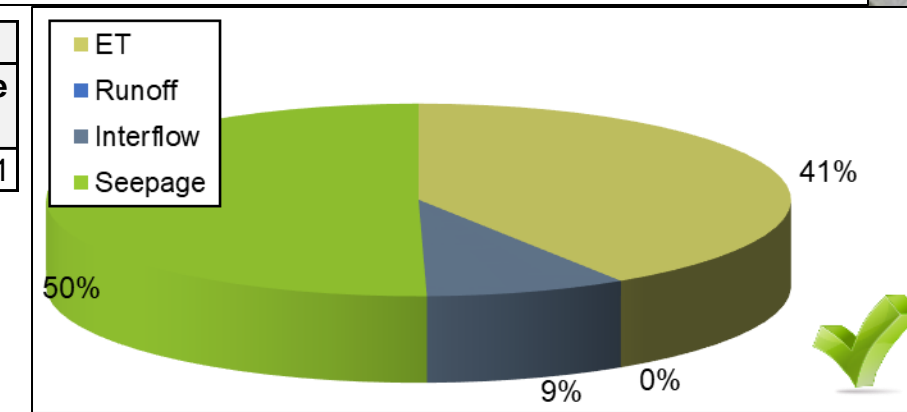
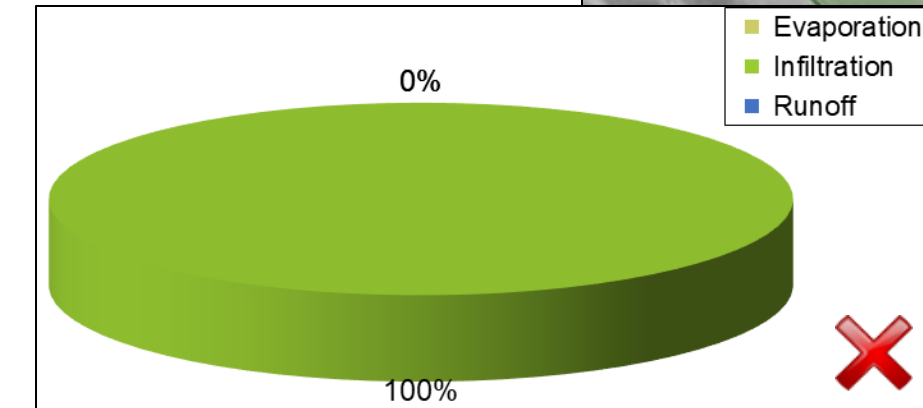
Stormwater Management System Performance	Post-Dev w/o LID	Resilient Landscape		Bioretention Cell		Tree Planters	
		value	Δ	value	Δ	value	Δ
Max. Release Rate (L/s/ac)	1.65	1.22	-26%	0.96	-42%	1.41	-14%
Runoff Volume (mm)	122.5	89.9	-27%	90.0	-27%	98.1	-20%

...meanwhile, back in Boston

- Results from 0% impervious area (GW method)
- An LID equivalent is easier to set up
 - Pick a soil type (dominant soil texture)
 - Adjust soil thickness, etc. to match long-term ET



SWMM5 Subcatchment



SWMM5 Subcatchment with Groundwater Aquifer

LID Control	Surface Layer				Soil Layer							Storage Layer		
	Berm Height (in)	Veg. Volume (fraction)	Roughness Factor	Slope (%)	Thickness (in)	Porosity (fraction)	Field Capacity	Wilting Point	Conductivity (in/hr)	Conductivity Slope	Suction Head (in)	Thickness (in)	Void Ratio	Seepage (in/hr)
ET_Equivalent	12	0.1	0.2	1	3.5	0.42	0.31	0.19	0.15	45	5.0	8	0.70	0.001

- SWMM5 results from LID Performance Summary:

Subcatchment	LID Control	Total Inflow (in)	ET	Seepage	Runoff	Interflow
			Evap Loss (in)	Infil Loss (in)	Surface Outflow (in)	Drain Outflow (in)
KBOS (Logan Airport)	ET_Equivalent	3185.82	1310.46	285.56	0	1589.62
Average (in/yr, 75-yr simulation):		42.5	17.5	3.8	0.0	21.2
			41%	9%	0%	50%



In Summary...

1. Stormwater modelers, you have a choice to make...
 - It is okay to ignore evapotranspiration for single events
 - It cannot be ignored for multiple events – any statements on long-term performance (e.g., flow duration curves, water budgets, etc.) require multi-event analysis
 - Tracking soilwater content through surficial soil layers is critical
 - The “single layer” approach of SWMM5 hydrology is inadequate
2. Stormwater model developers, please consider...
 - Adding soil moisture accounting to the top surface layer or two
3. In the meantime, go ahead and build yourself an ET machine
 - Add a coarse groundwater aquifer or “representative” LID control



Thank you for your attention!

