MODELING WATER FLUX AT THE BASE OF THE ROOTING ZONE FOR SOILS WITH VARYING GLACIAL PARENT MATERIALS

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Introduction

Aquifer sensitivity analysis, groundwater-resource planning, and understanding climate-change impacts all require reliable approaches for estimating water fluxes in the unsaturated zone. This research seeks to answer the following questions related to quantifying water fluxes in the vadose zones of glaciated environments in the Midwestern United States:

-What is the optimal approach to efficiently determine unsaturated-zone saturated hydraulic conductivity? Guelph Permeameter field measurements and the Rosetta pedotransfer function are compared.

-What numerical models are most appropriate for estimating 1-D fluxes and groundwater recharge below the rooting zone? This question is addressed initially using objective model simulations with measured and fixed parameters applied to a soil water balance model and HYDRUS 1-D.

-How can reference evapotranspiration be partitioned into actual evaporation and transpiration components with limited datasets related to transpiration? Time-dependent leaf area indices (LAI) are estimated for sites with lawn and prairie / conservation vegetation for input into the models, which rely on the parameter to calculate AET.

Monitoring sites and data

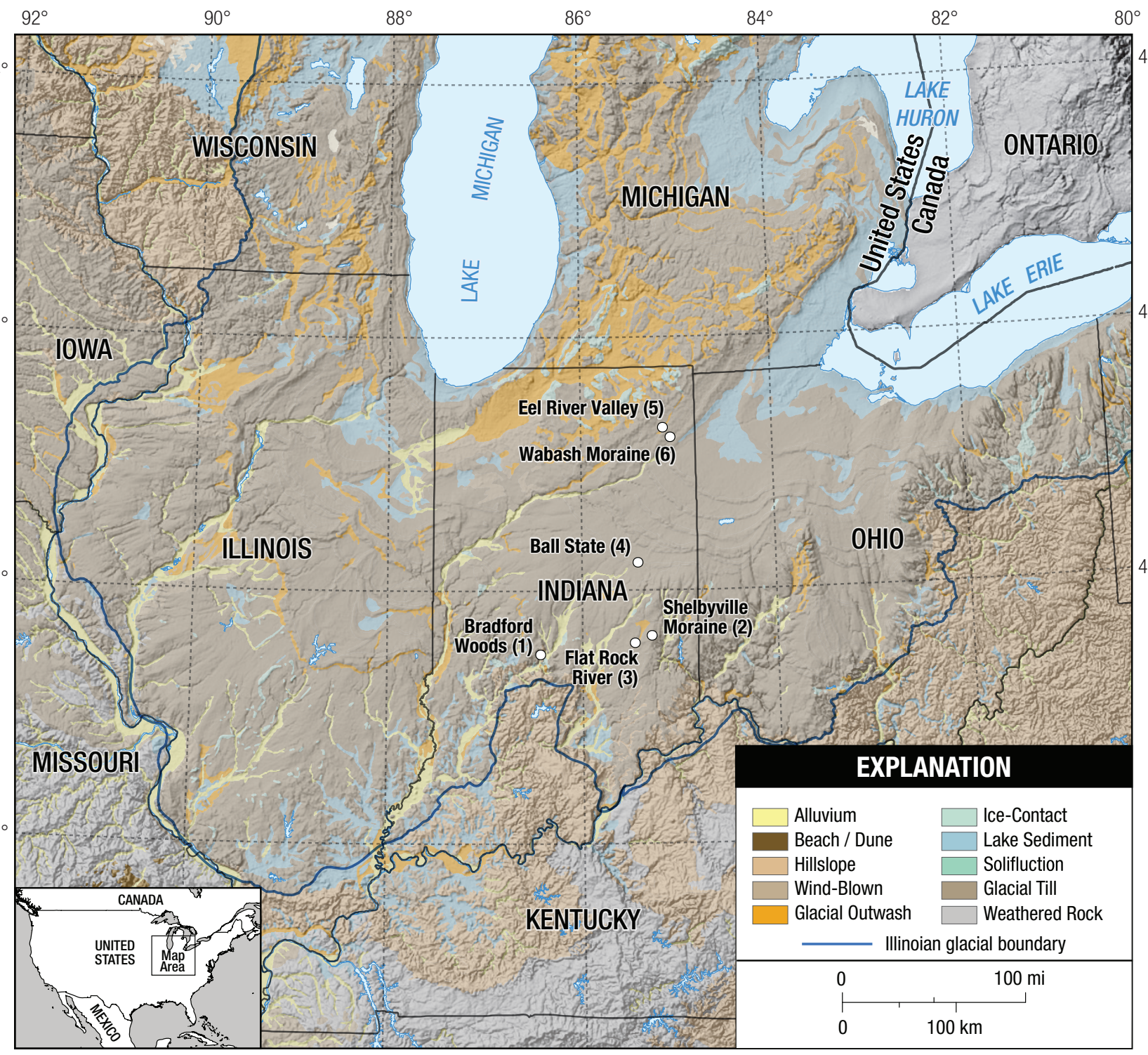
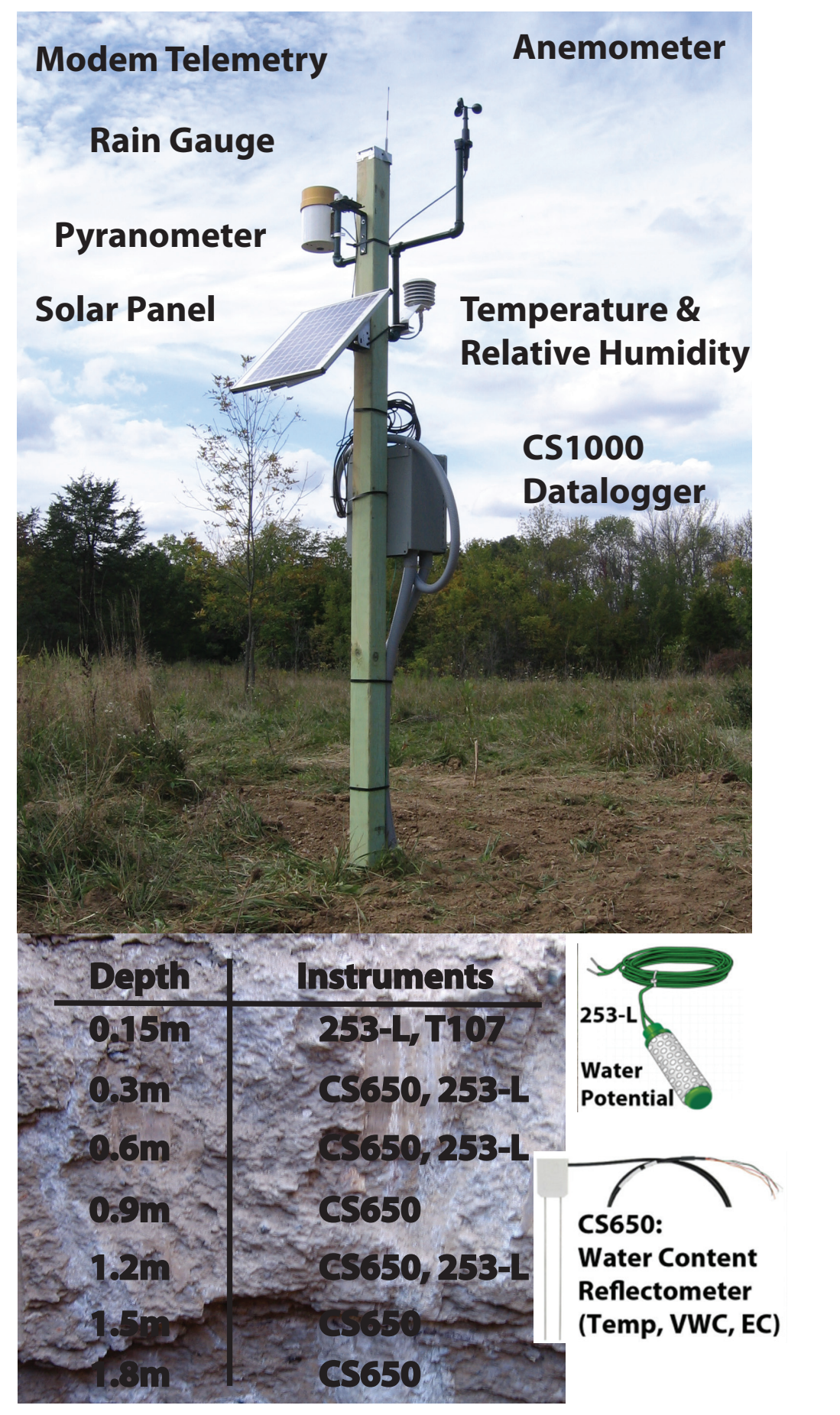


Figure 1. Map showing the location of six monitoring sites and surficial geology in the Great Lakes region. Surficial geology is from Fullerton, et al., 2003.

Site name (#)	Geologic setting	Depth to groundwater (cm)	Vegetation	Max. root depth (cm)
Bradford Woods (1)	**alluvial terrace**	**250**	**conservation / prairie**	**155**
Shelbyville Moraine (2)	**moraine crest**	**215**	**turfgrass / lawn**	**30**
Flat Rock River (3)	low-level outwash terrace	260	corn / soybean rotation	~60
Ball State (4)	ground moraine	226	turfgrass / lawn	30
Wabash Moraine (5)	moraine crest	2100	conservation / prairie	92
Eel River Valley (6)	**high-level outwash terrace**	**1050**	**conservation / prairie**	**62**

Table 1. Hydrogeology and vegetation for each site (modeling results are presented for the sites listed in bold).



Depth	Instruments
0.15m	253-L, T107
0.3m	CS650, 253-L
0.6m	CS650, 253-L
0.9m	CS650
1.2m	CS650, 253-L
1.5m	CS650
1.8m	CS650

Figure 2. Meteorological and vadose-zone instruments installed at each site.

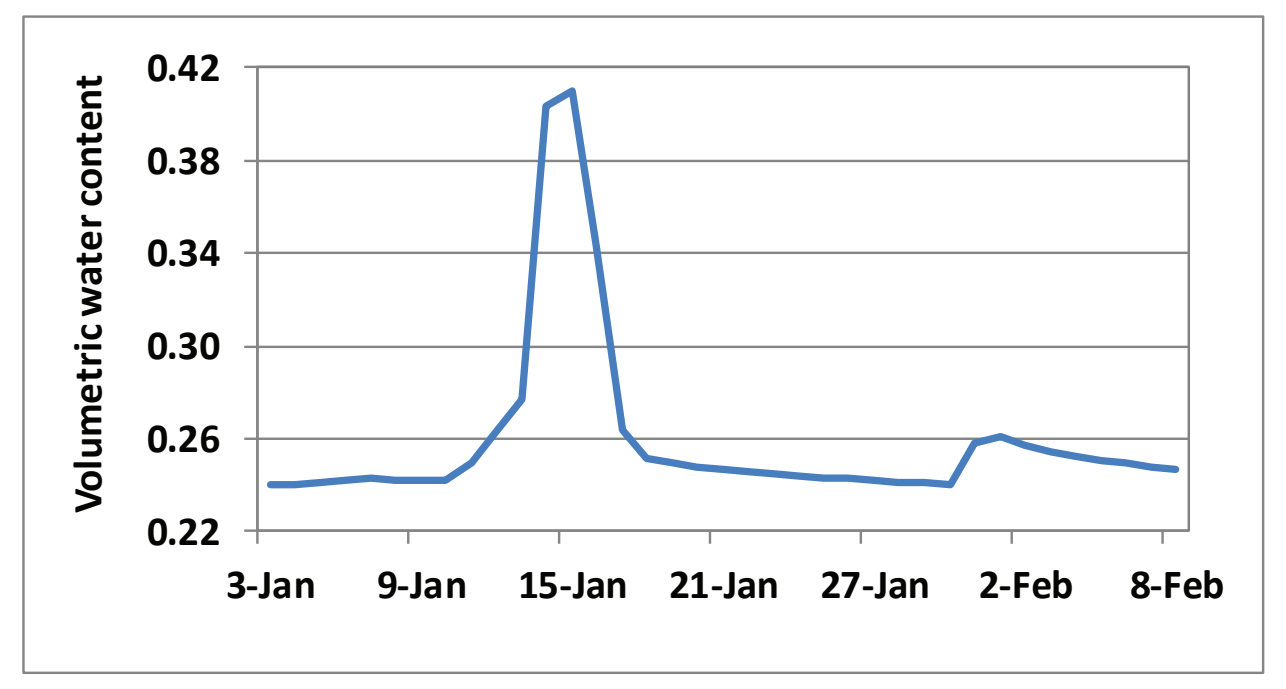


Figure 3. Visual field capacity determination at 1.8m depth at the Eel River Valley site (sandy loam). The profile is draining following a winter wetting front and field capacity is estimated to be 0.24 based on where the curve flattens.

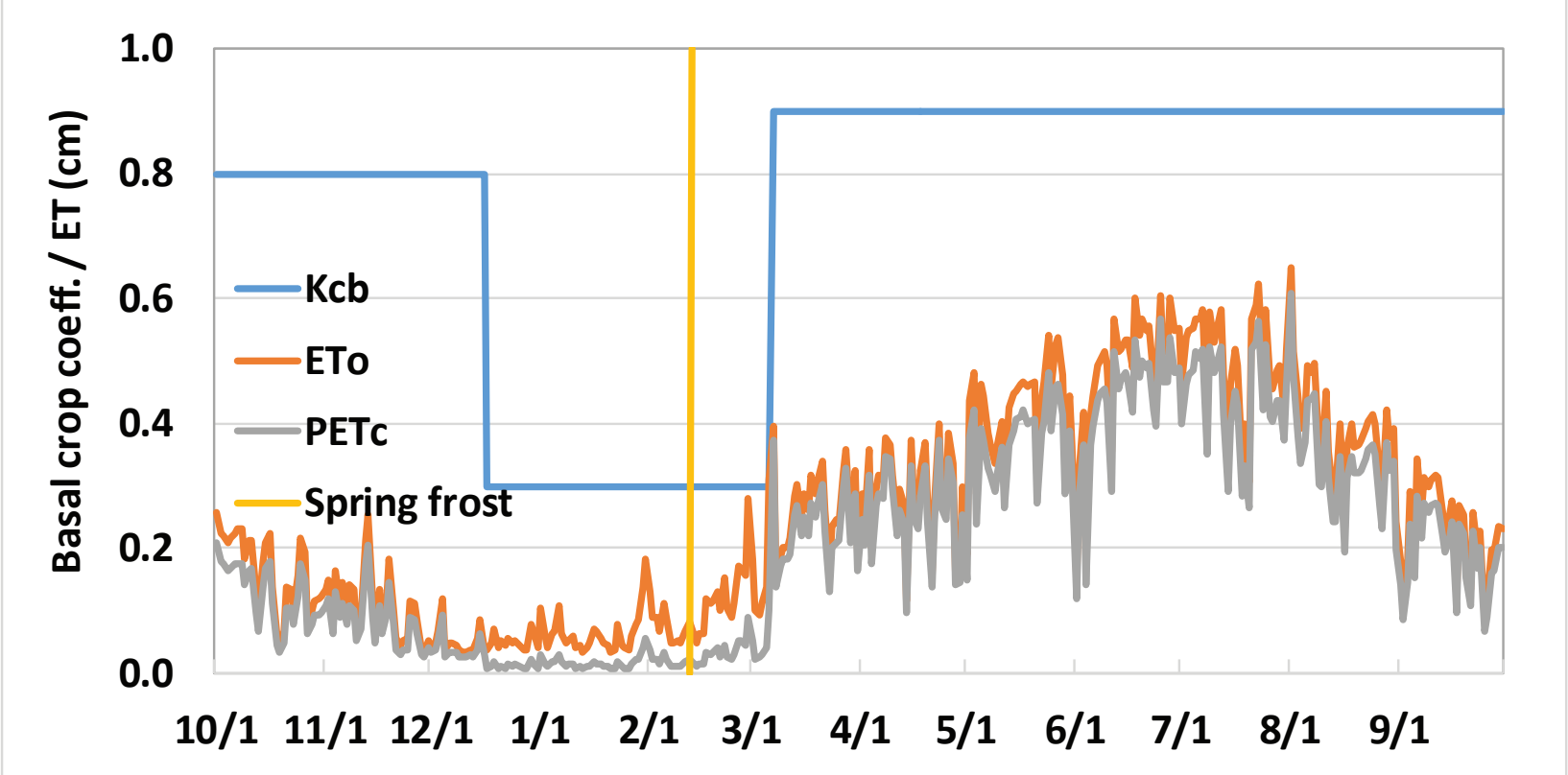


Figure 4. Basal crop coefficient (Kcb) values used to calculate compensated PET (PETc) at the Bradford Woods site. Methods outlined by Allen et al. (1998) were used to compensate the transpiration component of PETc using values for rotated grazing pasture. The evaporation component was not corrected because we assume that evaporation from the prairie sites is generally consistent with the reference surface.

Water-flux / recharge modeling approach

Model time domains and boundary conditions
-Water-year simulations were ran using daily time steps and input data for 2011/2012 and 2012/2013
-Groundwater recharge season simulations were conducted between November and February for each water year
-Daily time steps were used
-Measured soil moisture data were used to establish initial conditions
-General depth-to-groundwater measurements or estimates were used to establish the bottom of the modeled soil profile

MODEL 1: Soil water balance model (Kendy et al., 2003)
-Infiltration and evapotranspiration are treated as separate, non-sequential processes
-Hydraulic conductivity and unit gradient are used to represent vertical flux of water at the base of each soil layer
-Transpiration and evaporation ratios of potential evapotraspiration (PET) are calculated based on leaf canopy stage (i.e., LAI)
-Actual evapotranspiration (AET) is calculated from PET based on soil-layer moisture content relative to wilting point

MODEL 2: HYDRUS-1D (Simunek et al., 2013)
-Numerically solves Richard's equation for saturated-unsaturated flow.
-Flow equation includes sink term to account for water uptake by roots (inputs are LAI and root depth)
-Ratio of PET that is allocated to evaporation is determined based on a specified extinction coefficient.
-Hydraulic parameters can be specified by user or estimated using the Rosetta pedotransfer function model (Schapp et al., 2001)

Estimating LAI for turfgrass and prairie vegetation

Because each model requires daily LAI input data, we chose to estimate leaf-canopy development stages for 1 lawn site and 2 locations with praire vegetation (Table 1). Annual variation in root depth was calculated using the estimated LAI data and maximum depths listed in Table 1.

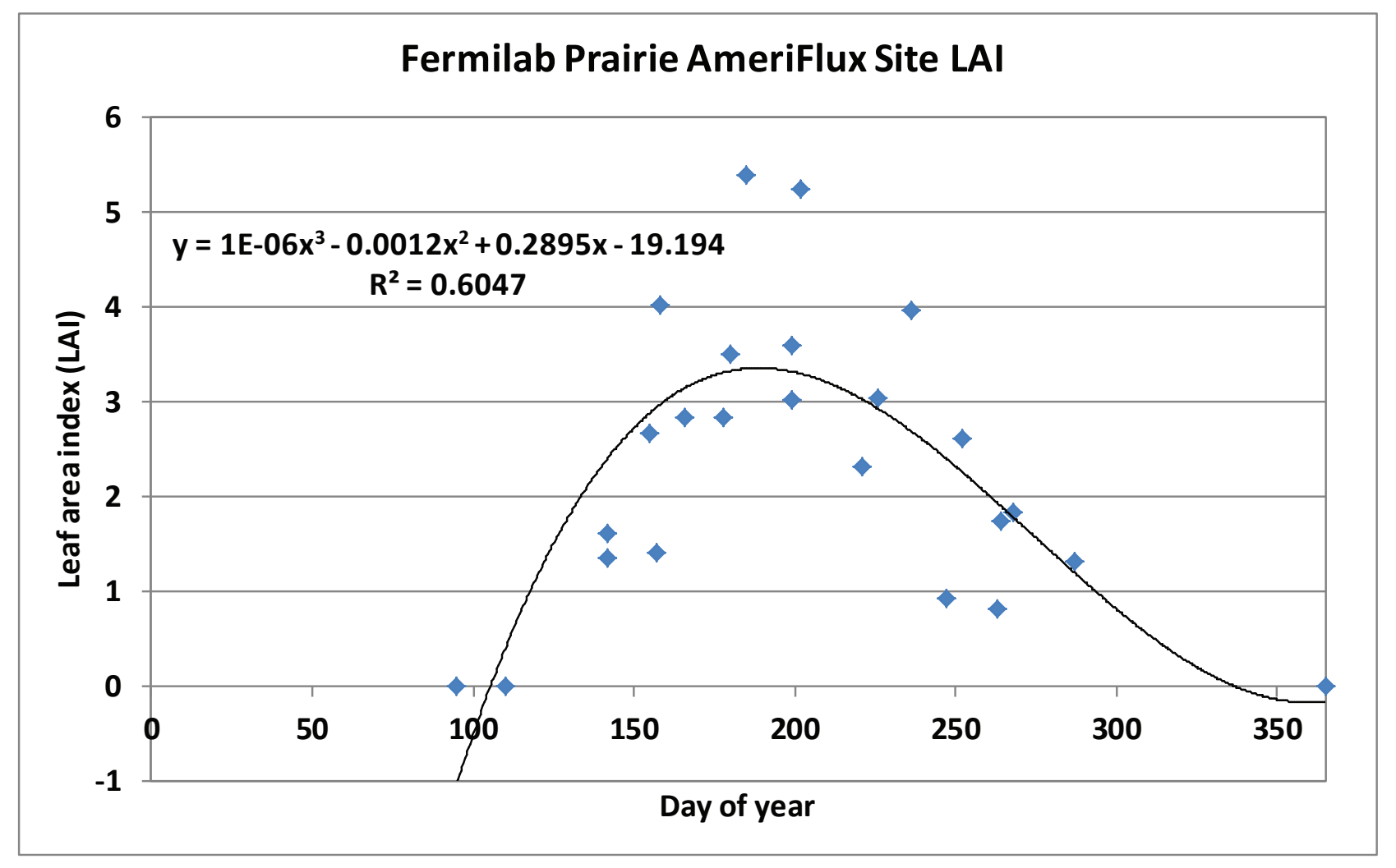


Figure 5. Leaf area index (LAI) data from the Fermilab Prairie AmeriFlux station (north-central Illinois) collected between 2005 and 2007. We fit a polynomial function to the data to estimate a daily LAI for our sites with conservation / prairie vegetation. The minimum LAI was set to 0.5 during winter months because green foliage persisted at each site.

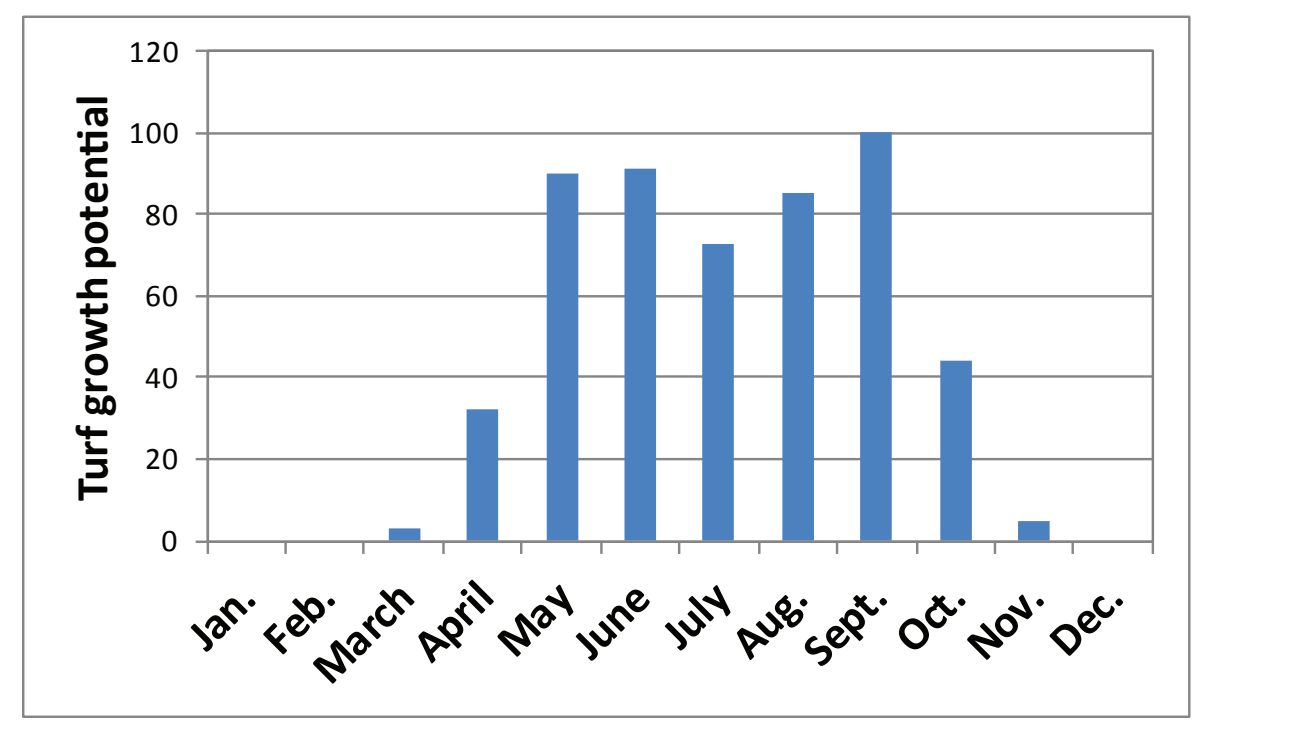


Figure 6. Cool-season turfgrass growth potential for Indianapolis, IN, from Gelernter and Stowell (2005). We converted these monthly growth potential data to percentages and multiplied them by a maximum LAI of 2.25 (a common value used for unirrigated turfgrass) to get monthly LAI values. The winter minimum turf LAI is 0.5.

Modeling input parameters and results

List of abbreviations and terms	
S&G	sand and gravel
BD	bulk density
FC	field capacity
WP	wilting point
NA	data not available
ETo	reference evapotranspiration
PETc	compensated potential evapotranspiration
Delta S	change in soil-moisture storage
AET	actual evapotranspiration
R	recharge / water flux at base of modeled profile
Theta RMSE	average root mean square error of measured and modeled soil moisture
WB	water balance
SWB	soil water balance model

General modeling approach for each site
-Guelph permeameter in-situ saturated hydraulic conductivity (Kfs) and lab porosity measurements were used for each hydrologic unit when available. Rosetta pedotransfer function saturated conductivity (Ks) and porosity values were also tested for several models to compare each parameterization approach.

-The HYDRUS lower boundary condition for all sites except the Eel River Valley location is a constant water content at saturation. Because a relatively thick unsaturated zone exists below the monitored soil profile at the Eel River Valley site, the constant water content is set at field capacity.

-The lowest hydrologic unit / soil layer in the SWB model uses the measured 1.8m water content as an initial condition.

Table 2. Input parameters for the Bradford Woods site with model results for the '12/'13 recharge season.

Depth (cm)	Horizon	Parent material	S&G	Silt	Clay	USDA texture	BD	Lab porosity	Rosetta porosity	Visual FC	WP*	Guelph Kfs (cm/day)	Rosetta Ks (cm/day)
0-40	1Ap	loess / alluvium	72%	23%	5%	sandy loam	1.67	0.37	0.32	0.13	0.05	27.7	45.91
40-216	2Bw	alluvium	10%	75%	15%	silt loam	1.44	0.46	0.42	0.32	0.13	1.11	23.14
216-250	3Cu	lacustrine	NA	NA	NA	silty clay	NA	NA	0.48	0.40*	0.25	2.16*	9.61

* from Rawls et al., 1982

Time period	Total precip.	Total ETo / PETc	Delta S (measured)	Model	Simulated evap.	Simulated AET	AET % of precip.	Simulated delta S	Simulated runoff	Simulated R	R % of annual precip.	Theta RMSE	WB error
12/13 R season	31.17	8.17	13.06	SWB	0.76	2.71	9%	15.21	0.00	13.71	13%	0.05	-1.1%
12/13 R season		4.27		HYDRUS	2.28	4.26	14%	19.19	0.00	6.31	6%	0.07	-0.2%
12/13 R season				HYDRUS (Rosetta)	2.28	4.26	14%	8.35	0.00	16.96	17%	0.08	-0.2%

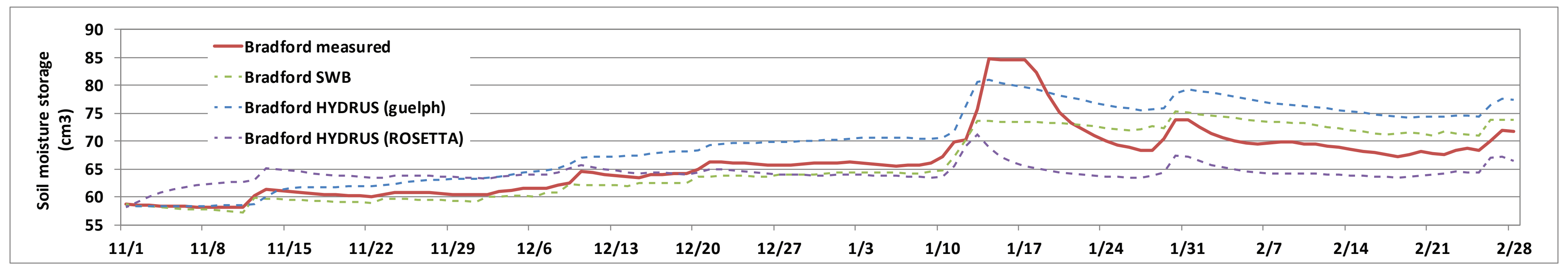


Figure 7. Soil moisture storage at Bradford Woods (alluvial terrace) during the '12/'13 recharge season. The HYDRUS model with ROSETTA porosity and Ks most closely matches the measured trend in soil moisture storage.

Table 3. Input parameters for the Shelbyville Moraine site with model results for the '11/'12 water year.

Depth (cm)	Horizon	Parent material	S&G	Silt	Clay	USDA texture	BD	Lab porosity	Rosetta porosity	Visual FC	WP*	Guelph Kfs (cm/day)	Rosetta Ks (cm/day)
0-31	1Ap	loess / plow zone	6%	71%	23%	silt loam	1.48	0.43	0.39	0.24	0.13	72.3	20.17
31-135	1Bt	loess	3%	68%	29%	silty clay loam	1.55	0.42	0.42	0.34	0.13	11.81	6.39
135-215	2Bw / Cox	lodgement/meltout till	43%	40%	17%	loam	1.85	0.31	0.29	0.22	0.12	NA^	4.55

* from Rawls et al., 1982 ^ Rosetta Ks used at this depth for each model

Time period	Total precip. / % 30-yr norm.	Total ETo	Delta S (measured)	Model	Simulated evap.	Simulated AET	AET % of Precip.	Simulated delta S	Simulated runoff	Simulated R	R % of annual precip.	Theta RMSE	WB error
11/12 WY	84.96	103.67	-0.72	SWB	4.22	36.62	43%	-7.30	0.00	55.28	65%	0.06	-0.2%
11/12 WY	75%			HYDRUS	34.82	80.45	95%	-0.94	0.00	4.56	5%	0.06	-0.2%

Table 4. Input parameters for the Eel River Valley site with model results for the '11/'12 and '12/'13 water years.

Depth (cm)	Horizon	Parent material	S&G	Silt	Clay	USDA texture	BD	Lab porosity	ROSETTA porosity	Visual FC	WP*	Guelph Kfs (cm/day)	Rosetta Ks (cm/day)
0-46	1Ap	Loess	62%	33%	5%	sandy loam	1.57	0.38	0.34	0.20	0.10	NA^	28.01
46-114	2Bt / Bw	overbank / outwash	52%	31%	18%	loam	1.74	0.35	0.34	0.30	0.12	NA^	2.08
114-?	2Cu	outwash	65%	26%	9%	sandy loam	1.57	0.41	0.35	0.15	0.10	NA^	49.04

* from Rawls et al., 1982 ^ Rosetta Ks used at this depth for each model

Time period	Total precip. / % 30-yr norm.	Total ETo / PETc	Delta S (measured)	Model	Simulated evap.	Simulated AET	AET % of precip.	Simulated delta S	Simulated runoff	Simulated R	R % of annual precip.	Theta RMSE	WB error
11/12 WY	78.03	89.14	-9.36	SWB	2.66	33.91	43%	-5.10	0.00	47.90	61%	0.04	-0.2%
11/12 WY	80%	66.43		HYDRUS	11.74	49.83	64%	-4.88	0.00	31.00	40%	0.05	-0.1%
12/13 WY	70.03	75.84	5.58	SWB	3.41	35.45	51%	4.52	0.00	27.13	39%	0.05	0.6%
12/13 WY	72%	64.82		HYDRUS	15.47	55.04	79%	6.68	0.00	4.13	6%	0.05	0.0%

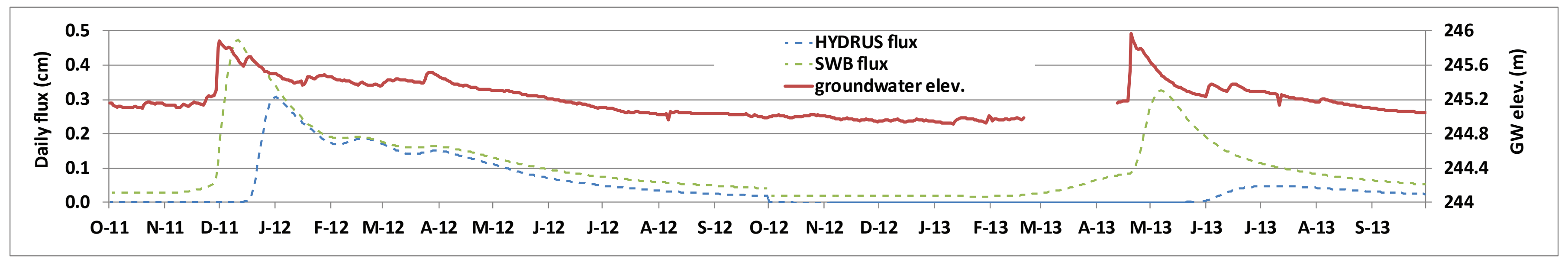


Figure 8. Measured groundwater elevation (depth to water is approximately 10m) at a monitoring well near the Eal River Valley site plotted with modeled daily flux at the base of the soil-profle domain (0-300cm). Modeled flux timing is better for the SWB model and the HYDRUS simulation appears to significantly underestimate groundwater recharge during the '12/'13 water year.

Discussion / Conclusions

Guelph vs. Rosetta K values
-The advantage of field permeameter values is that they provide a bulk conductivity estimate and can theoretically help models compensate for secondary permeability without using a dual-porosity approach. However, the guelph estimates were less than Rosetta values in some cases (Table 2), and this could be because experiments were conducted during the late summer when anticedent conditions were dry.

Evaporation/Transpiration partitioning
-Sanford and Selnick (2013) reported that AET/precip. ratios are between 0.5 and 0.7 for the study area. The SWB model appeared to significantly understimate AET for the abnormally dry '11/'12 water year (Tables 3 and 4).

Recharge estimates
-Existing recharge estimates for the Midwestern U.S. are regional in scale and difficult to compare with field-scale estimates such as those presented here. The HYDRUS model's 5% estimate for the moraine site is much more reasonable than the 65% predicted by the SWB model, especially considering it was a drought year. We attribute this descrepancy to the SWB model's severe underestimate of evaporation. Both models provided reasonable estimates for the sites underlain by silt-dominated alluvium and course outwash.
-For the site underlain by glacial outwash, the SWB model predicted the timing of groundwater recharge more closely than the HYDRUS model. However, both models indicated dynamic recharge events that were not necessarily in sync with the recharge season.

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