INTEGRATING GROUNDWATER OBSERVATIONS WITH MODELS OF SOIL-WATER DYNAMICS TO EXAMINE RECHARGE PATTERNS THROUGH GLACIAL SEDIMENTS IN A HUMID CONTINENTAL CLIMATE

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Introduction

Existing groundwater recharge estimates for the glaciated humid continental Great Lakes region (GLR, USA) vary greatly and are primarily based on indirect methods:

- Walton (1965) combined hydrograph separation and a water balance approach to derive estimates between 6 and 24% of annual precipitation (P) for aquifers in Illinois.
- Arnold and Allen (1996) also used hydrograph separation to obtain recharge estimates between 10 and 28% of P in Illinois.
- Nolan (2007) combined chloride-tracer and Darcy pedotransfer methods to estimate groundwater recharge between 0.3 and 63% of P in the GLR.
- Delin et al. (2007) estimated recharge between 16 and 26% of P for glacial sediments in Minnesota using the water-table fluctuation method.

Note that none of these studies used direct physically-based methods to arrive at groundwater recharge estimates and all integrate recharge over the year without considering the seasonality of recharge mechanisms.

This research integrates soil laboratory characterization with measurements of groundwater levels, vadose-zone water content, and micrometeorological data to support a physically-based analysis of shallow groundwater recharge and water-table dynamics at six unique sites in the GLR.

Data collection

Table 3. Groundwater-monitoring details. Aquifer types are classified into unconfined or semi-confined based on water-level observations and the presence of macroporosity in overlying layers with low permeability.

Glacial terrain	Site*	Monitoring period	Well depth (m)	Screened interval (m)	Texture / aquifer type
Supraglacial	AL	6/15/2013-present	3.1	2.4 - 3.1	Silt loam / unconfined
	OT	10/1/2012-present	21.3	19.8 - 21.3[1]	Sand / unconfined
	SGT	10/1/2012-present	3.7	3.1 - 3.7	Sand and gravel / unconfined
Moraine	GM	6/21/2013-present	6.0	4.5 - 6.0[1]	Sandy loam / semi-confined
	EM1	4/11/2014-present	2.1	1.8 - 2.1	Sandy loam / semi-confined
	EM2	4/29/2014-present	3.8	3.2 - 3.8	Sandy loam / semi-confined

* AL=alluvium, OT=outwash terrace, SGT=supraglacial till, GM=ground moraine, EM=end moraine
[1]estimated

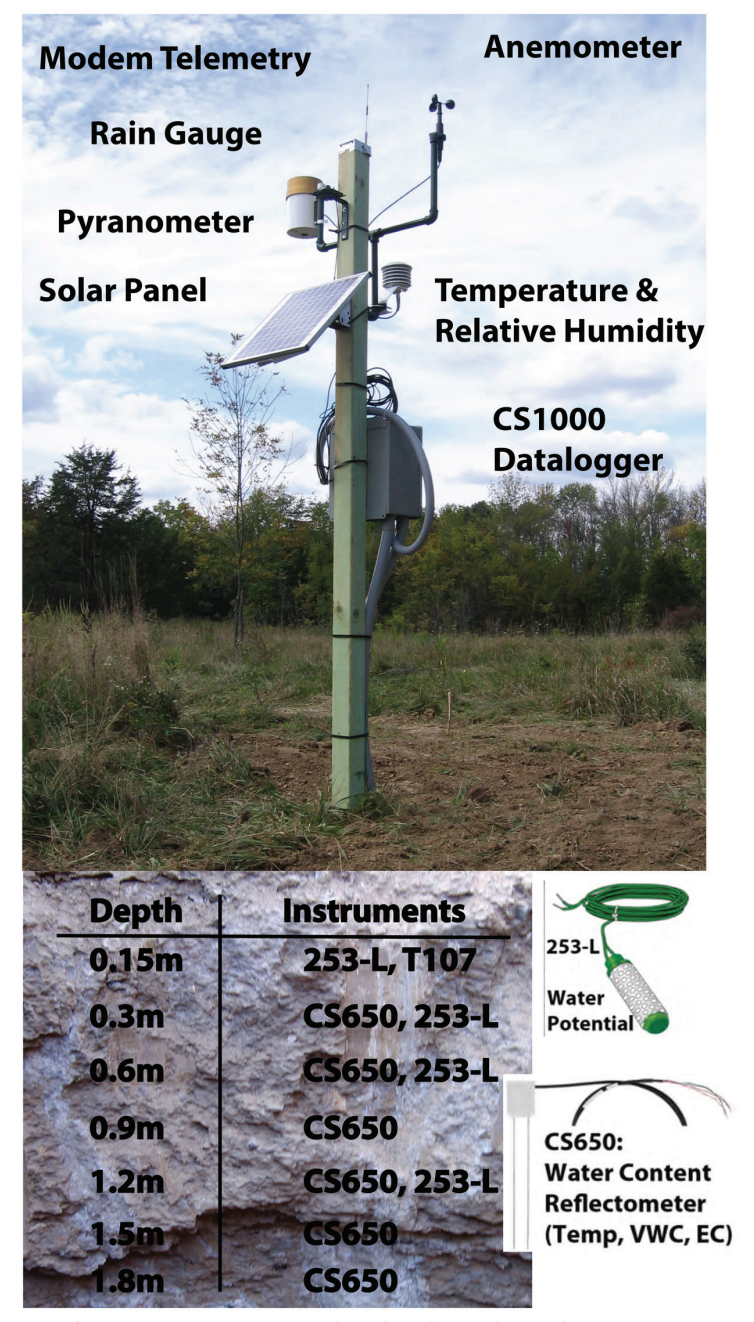

Figure 3. Meteorological and vadose-zone instruments installed at each site.

Monitoring results

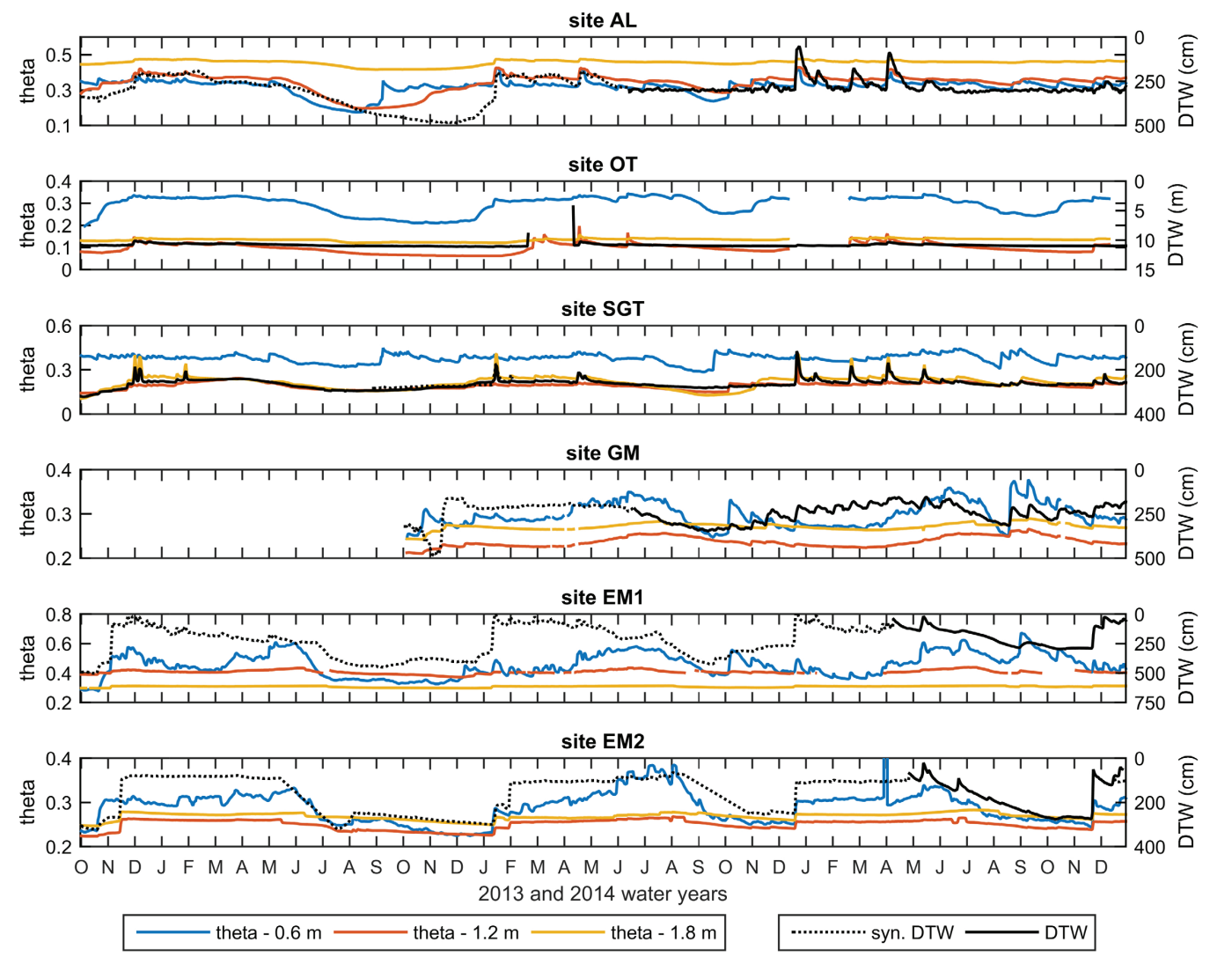

Figure 4. Measured volumetric water content (theta) and groundwater depth to water (DTW) for the monitoring period (October 2011 to December 2014). DTW measurements were not available for the early monitoring period at some sites, so a synthetic DTW (dotted line) was established by a multiple regression analysis using VWC and soil tension data from the period when DTW was measured.

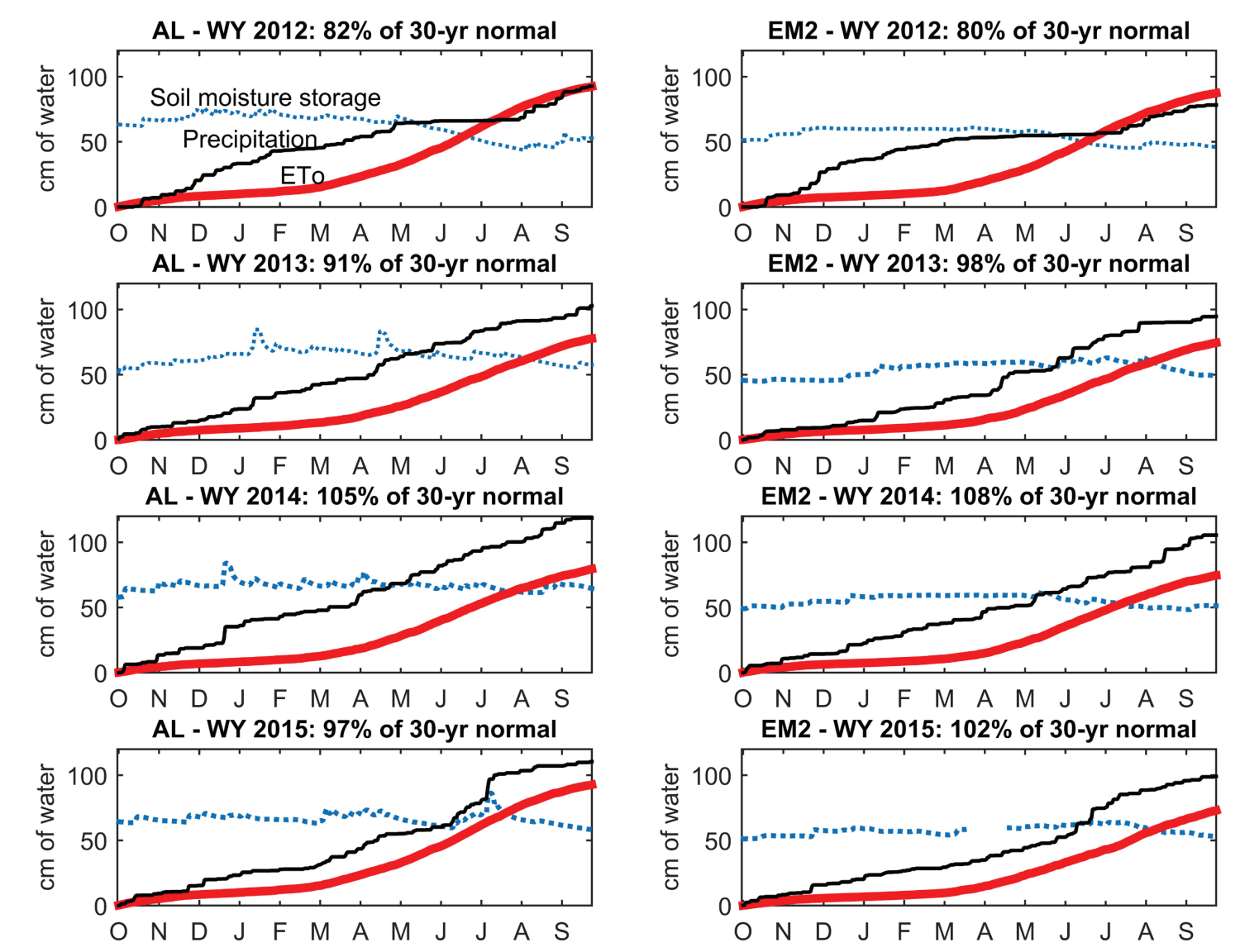

Figure 5. Precipitation, reference evapotranspiration (ET₀), and soil-moisture storage for sites AL and EM2. The 2012 water year was abnormally dry and the 2013 period was representative of more normal hydroclimatic conditions when comparing site precipitation with 30-year normals calculated at nearby long-term weather stations.

- The 2012 water year (WY 2012) included drought conditions during summer (sites averaged 14 cm of P over three months compared to 31 cm normally received based on reference site data) and soil moisture storage decreased significantly between May and August .
- Reference evapotranspiration (ET_0) equaled or exceeded P at three of five sites during WY2012.
- Extremely wet conditions existing during the summer of WY 2015 with 150-200% of 30-year normal P received at all six sites in June (air temp. was also 0.7 - 1.8 deg C less than average at five of six sites during June and July 2015).
- Soil moisture and groundwater level data (Fig. 4) show that moraine sites (GM, EM1, and EM2) have shallow water tables (<4 m) and prolonged periods of up to six months when water levels are high with less variability.

Study area / monitoring sites

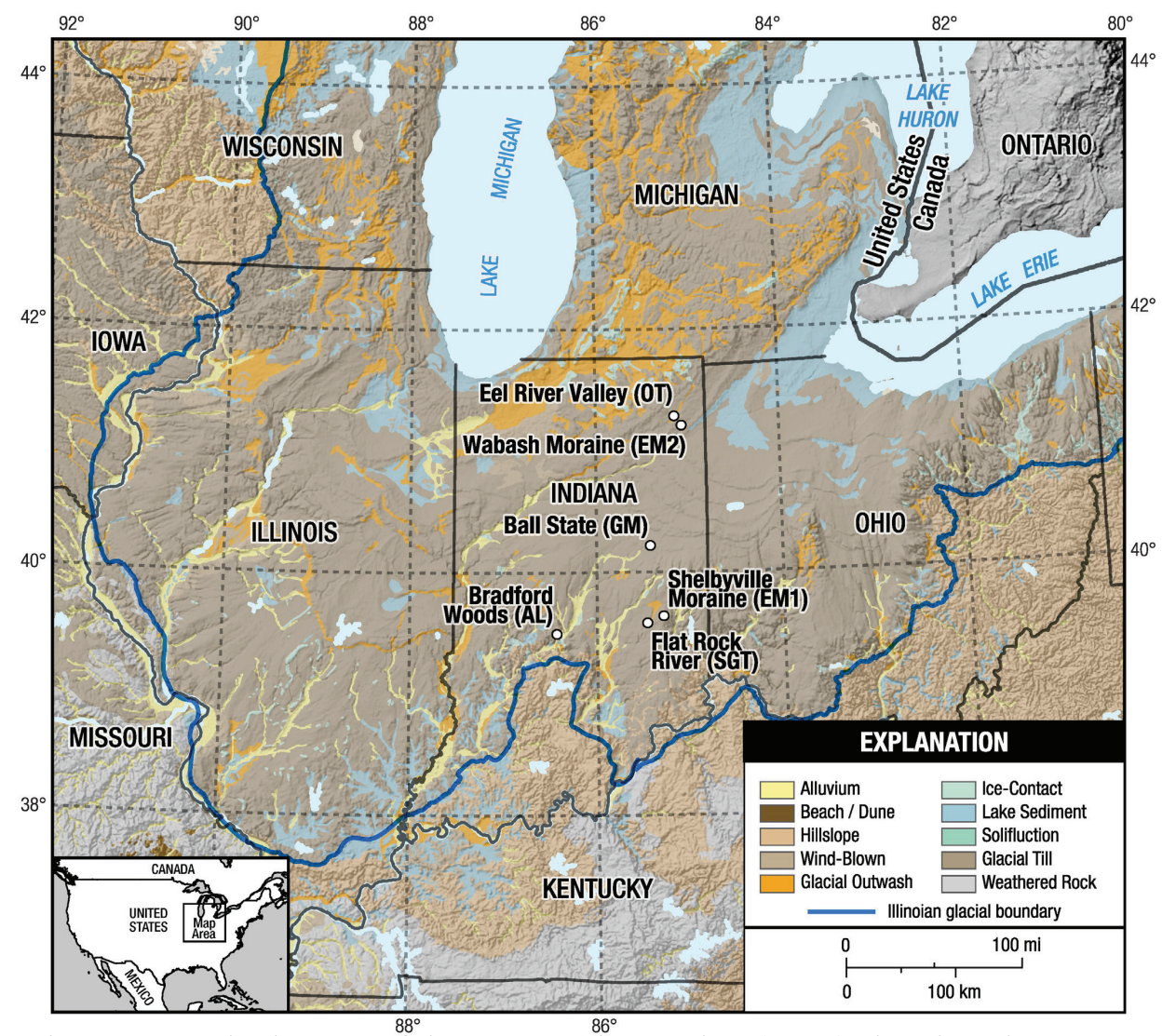

Figure 1. Geologic map of the Great Lakes region (GLR) showing site locations in Indiana. Additional details regarding the monitoring sites and data can be accessed at: http://igs.indiana.edu/CGDA/waterBalanceNetwork.cfm.

Table 1. Monitoring sites, soil parent materials, topographic settings, and land use.

Site label	Soil parent material	Terrain	Land use / vegetation
AL	alluvium / lacustrine	floodplain	prairie / mixed grasses and wildflowers
OT	glacial outwash	terrace	conservation / mixed grasses
SGT	glacial till (supraglacial)	terrace	row crop / corn and soybean rotation
GM	glacial till (ground moraine)	plain	turf grass
EM1	loess / glacial till (end moraine)	hill crest	turf grass
EM2	glacial till (end moraine)	hill crest	prairie / mixed grasses and wildflowers

Model development

Soil-water dynamics simulated with HYDRUS 1D (Šimůnek et al., 2005)

- Numerically solves Richards equation for unsaturated flow
- Flow equation includes sink term to account for water uptake by roots (inputs are leaf area index and root depth)
- Surface infiltration is simulated when P exceeds potential evapotranspiration
- Runoff is simulated when P exceeds infiltration during wet periods when surface is saturated
- Hydraulic parameters were determined using an inverse modelling approach described in Naylor et al. (2015). Soil moisture data used for model calibration (Fig. 6) shows good correspondence with model results at all sites except the GM (ground moraine) location.

Integrating water-table measurements

- Treatment of the lower boundary condition is important for this study of shallow groundwater systems because we define groundwater recharge as infiltrating water that percolates below the root zone and increases storage in the underlying saturated zone.
- Lower boundary conditions are defined as either variable head (head established by the water-table position) or free drainage (unit vertical gradient at the base of the model domain). Measured hydrologic regimes at each site (Fig. 4) provide a context to define the lower boundary conditions for each site. The outwash terrace site (OT) has a deep water table (~10 m) and a free drainage boundary condition is applied; whereas, the other five sites have water tables that rise within the model domain (Table 4) so variable head conditions are applied for those models.

Table 4. Srizons and laboratory data used to establish HYDRUS 1D model layers.

Type	Site*	Soil horizon	Parent material	Depth (cm)	ρ_s (g/cm³)	Lab ϕ	Sand %	Silt %	Clay %	Guelph (Rosetta) K_s (cm/d)
Supraglacial	AL	Ap ^+	alluvium	0 - 40	1.67	0.37	69	24	7	27.7 (29.8)
		Bw ^+	alluvium	40 - 208	1.43	0.46	10	75	15	1.11 (21.31)
		2Cu	lacustrine	208 - 250	-	-	-	-	-	-
	OT	Ap ^+	loess	0 - 46	1.64	0.38	62	33	5	0.43 (29.4)
		2Bt ^+	outwash	46 - 108	1.74	0.35	50	32	18	0.18 (5.87)
		2Bw ^#+	outwash	108 - 200	1.57	0.41	62	27	11	0.92 (26.8)
		2Cu	outwash	200 - 300	-	-	-	-	-	-
	SGT	Ap ^+	supraglacial till	0 - 40	1.61	0.39	57	27	15	4.31 (15.2)
		Bt ^#+	supraglacial till	40 - 105	1.57	0.41	52	19	29	10.9 (9.42)
		Bw #+	supraglacial till	105 - 180	1.42	0.47	56	21	23	(24.0)
		2Cu #+	outwash	180 - 260	-	-	63	23	14	(29.8)
Moraine	GM	Ap	loess	0 - 32.5	1.66	0.39	11	60	29	0.58 (2.83)
		2Bt	basal till	32.5 - 60	1.65	0.39	16	44	40	(2.31)
		2Cu	basal till	60 - 230	1.77	0.35	18	50	32	(1.47)
	EM1	Ap ^+	loess	0 - 32	1.48	0.44	6	71	23	237 (9.35)
		Bt ^#+	loess	32 - 130	1.52	0.44	3	68	29	11.8 (5.19)
		2Cox #+	basal till	130 - 215	1.88	0.31	34	44	22	(1.72)
	EM2	Ap ^+	loess	0 - 35	1.58	0.40	31	50	19	0.32 (6.88)
		2Bt ^#+	basal till	35 - 86	1.64	0.39	18	42	40	4.19 (2.49)
		2Cu #+	basal till	86 - 250	1.82	0.33	22	49	29	(2.49)

* AL=alluvium, OT=outwash terrace, SGT=supraglacial till, GM=ground moraine, EM=end moraine
^Guelph permeameter measurements; #Franzmeier comparison horizon; +Rosetta comparison

Modeled recharge

- Groundwater recharge values are determined from the models using a water-table flux estimation approach for the variable-head scenarios. Because water tables rose to within the lower portion of the model domains at these sites, water-table flux is taken as the first occurrence of downward flux (starting deeper in the profile) between 1.8 m and the rooting zone for each model (1.8 m is the lowest model output node used for comparison with measured data).
- Recharge is estimated using the flux at the base of the model domain for the OT site with a free drainage lower boundary.

Inverse model optimization

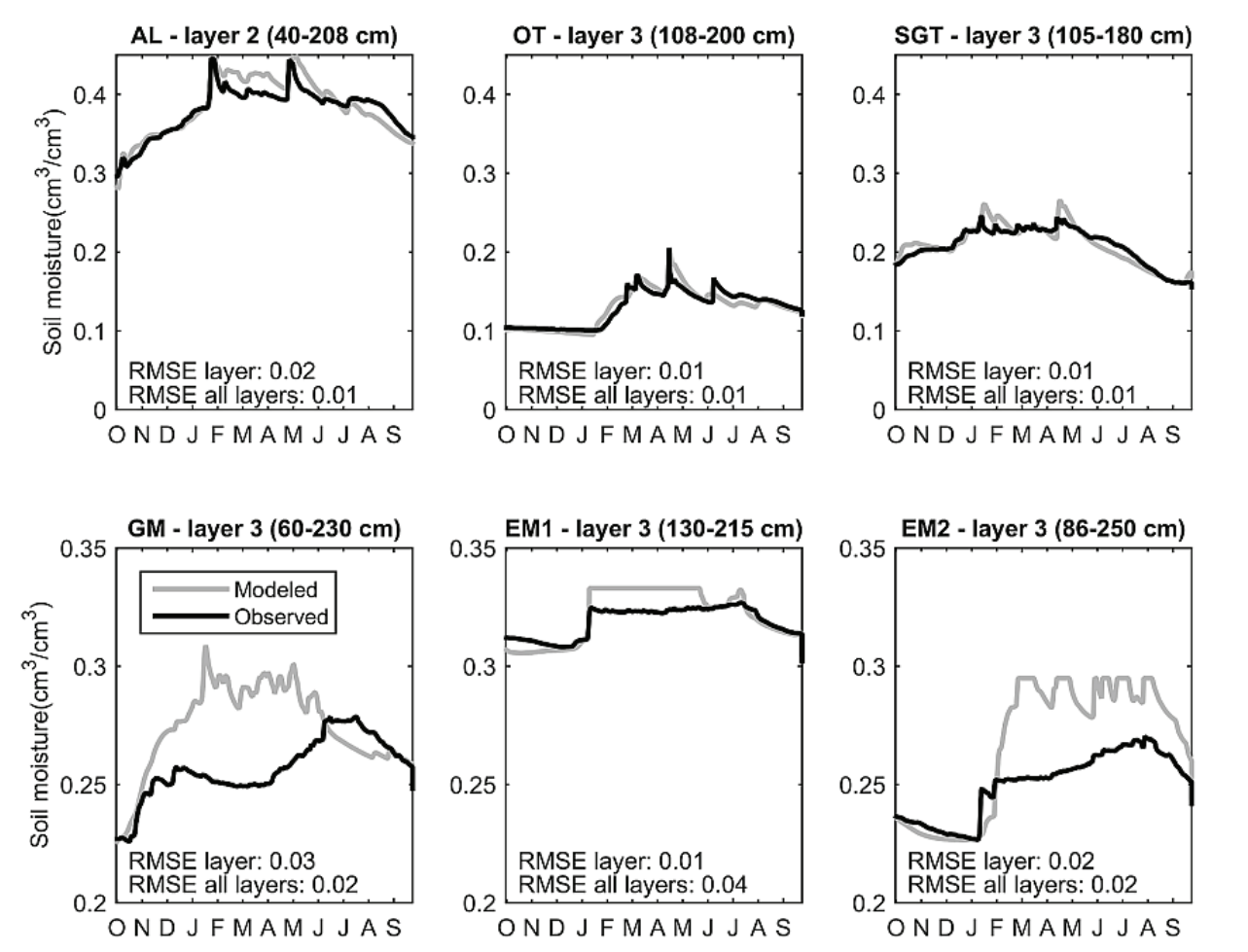

Figure 6. Measured and predicted soil moisture (VWC) for the deepest monitored soil layer at each site during WY 2013. Averages were taken for layers with multiple soil moisture sensors. Root mean square error (RMSE) is shown for average observed vs. average modeled VWC for the model layer as well as the entire profile (all layers). Forward modeling was not conducted for the GM site because the timing of water movement through the lower layer did not appear to be accurately depicted by the HYDRUS model.

Model validation and forward simulation results

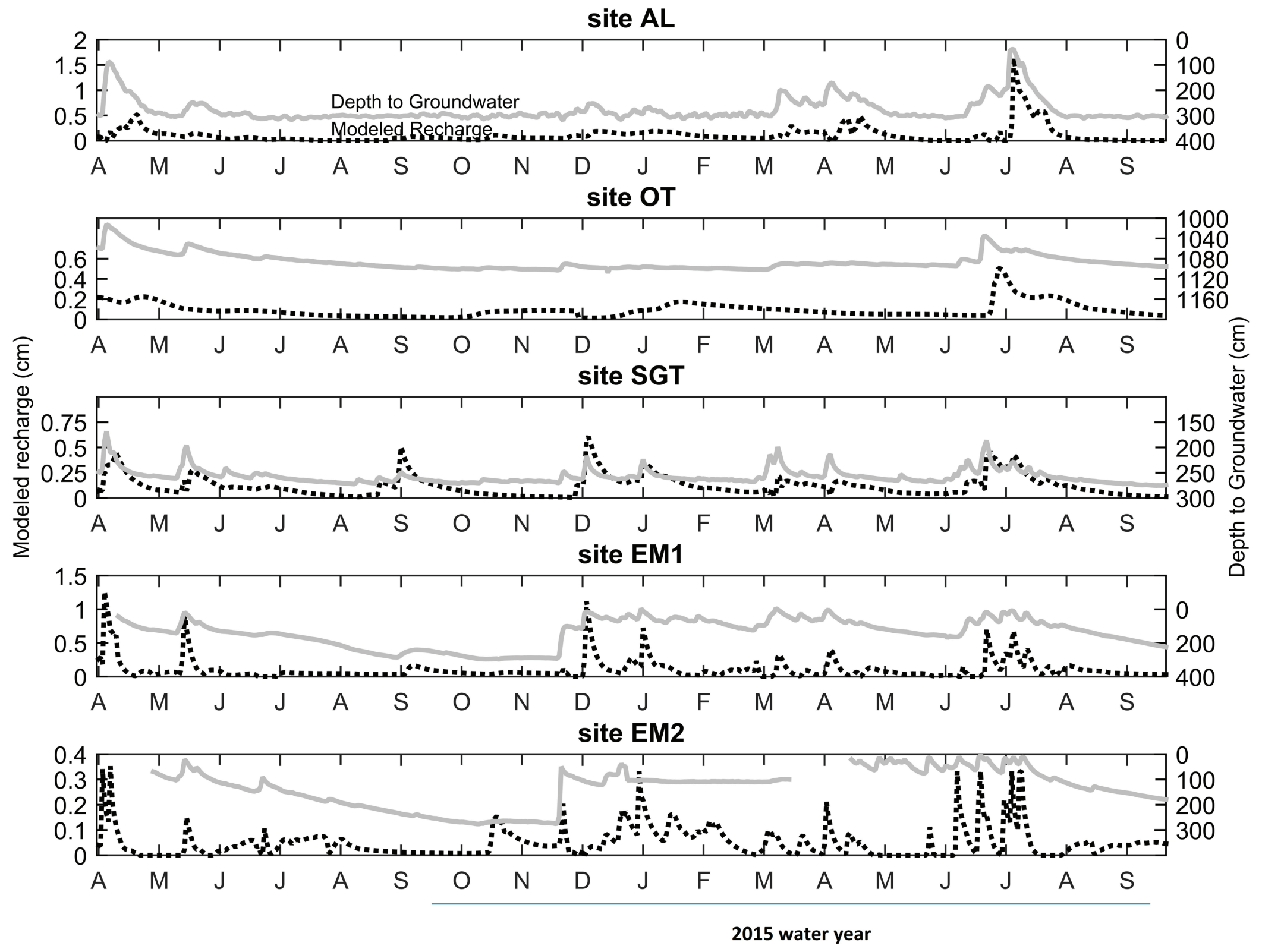

Figure 7. Measured groundwater levels and modeled daily recharge flux (cm d-1) between April 2014 and September 2015. Note that forward modeling was not conducted for site GM owing to a lack of confidence in the calibration results.

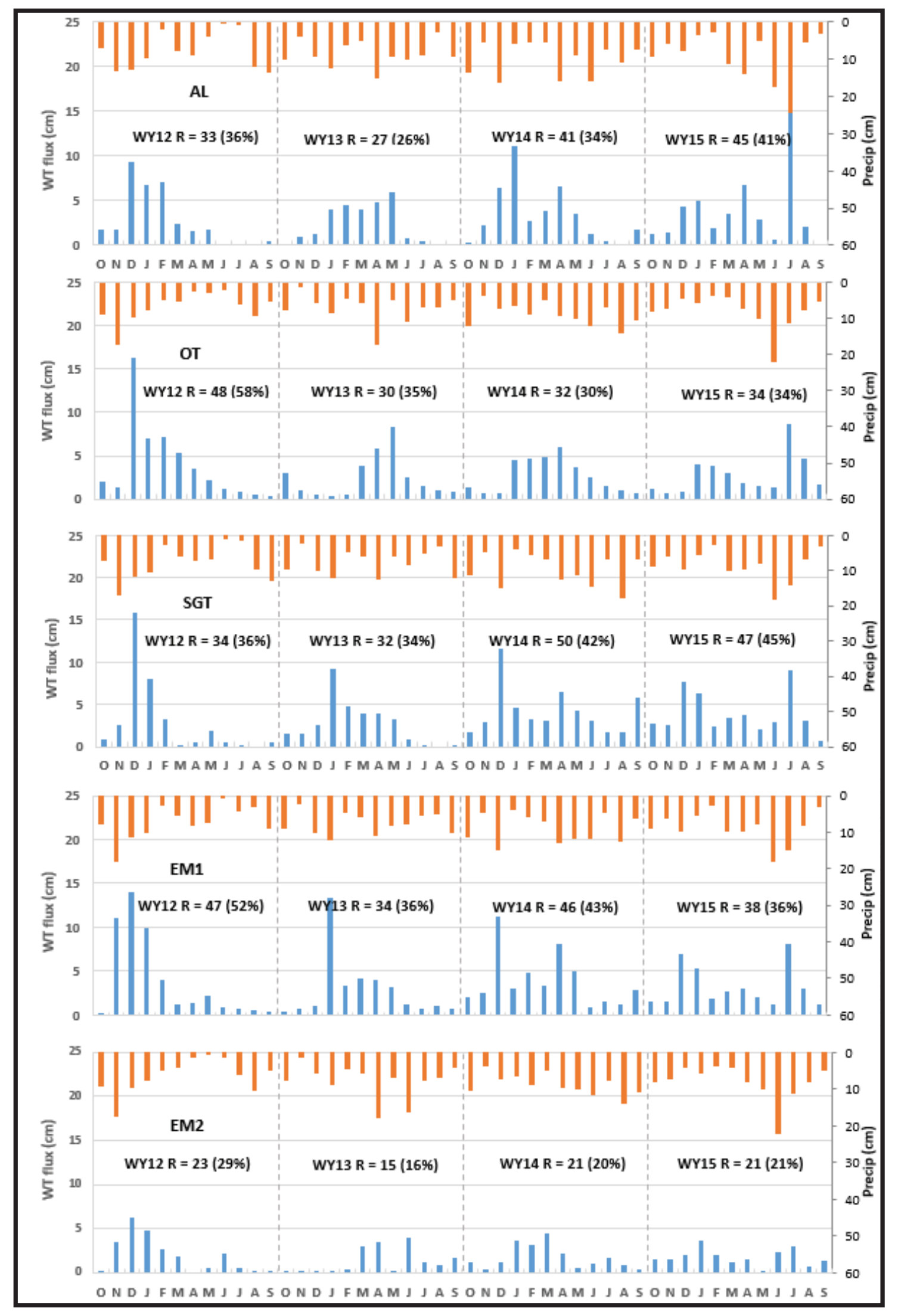

Figure 8. Monthly recharge and precipitation for the 2012 to 2015 water years (October 2011 to September 2015). The WY 2012-2015 total recharge is reported in centimeters for each site and percentage of water year precipitation is reported in parenthesis.

Climate and groundwater regime

- Approximately 40-69% of precipitation is lost to evapotranspiration in the GLR (Fig. 2).
- Subsurface variability greatly influences recharge in these humid settings where diffuse recharge is the dominant recharge mechanism (Scanlon et al., 2002).
- The water table is commonly less than 5 m below the ground surface in the GLR, so percolating soil water readily enters the ground-water flow system as recharge.

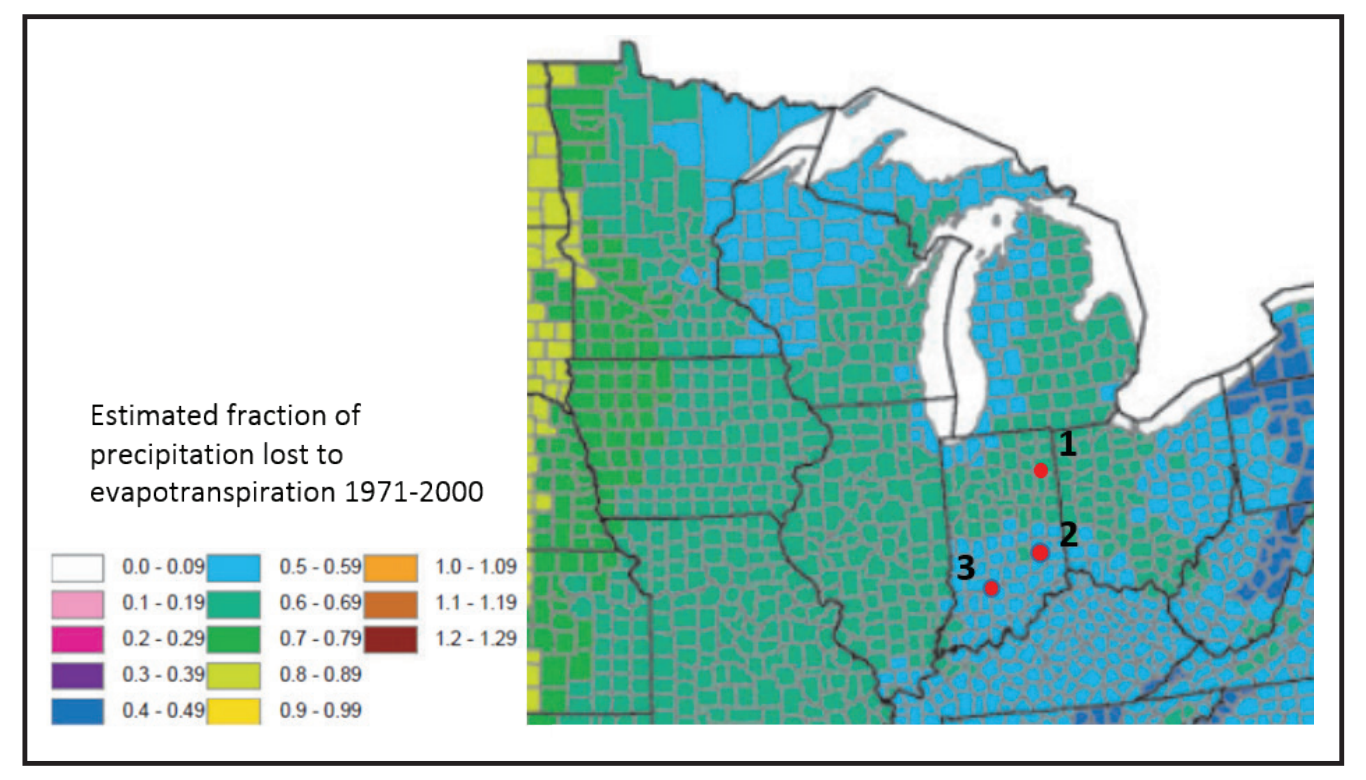

Figure 2. Estimated ratio of actual evapotranspiration to precipitation (P) for the GLR from Sanford and Selnick (2013). Reference stations that are used to compare 30-year normal P with site measurements are shown with red dots.

Table 2. 30-year normal precipitation at reference sites.

Reference station	*Corresponding map #*	*30-year normal mean annual P (cm)*	*Mean annual snow (cm)*	*Sites compared*
Fort Wayne	1	97.4	85.1	EM2, OT
Rushville	2	113.0	35.1	SGT, EM1
Martinsville	3	113.6	40.9	AL

Seasonal recharge analysis

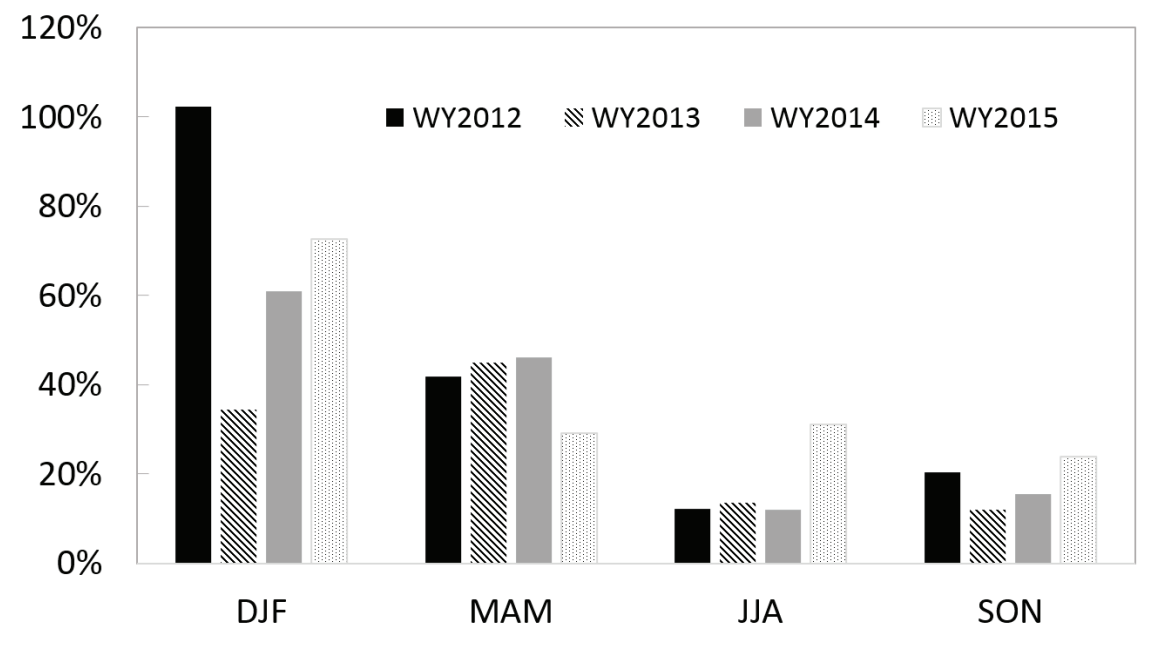

Figure 9. Seasonal mean recharge ratio (recharge expressed % of P) averaged for five forward modeled sites. Seasons are distinguished as winter (Dec, Jan, Feb), spring (March, April, May), summer (June, July, Aug), and autumn (Sept, Oct, Nov).

- Seasonal mean recharge (R) ratios (Fig. 9) indicate high and variable R during winter.
- Generally stable R ratios exist from spring to autumn but June/July 2015 anomaly of high P and cool temperatures generated summer R well above average.

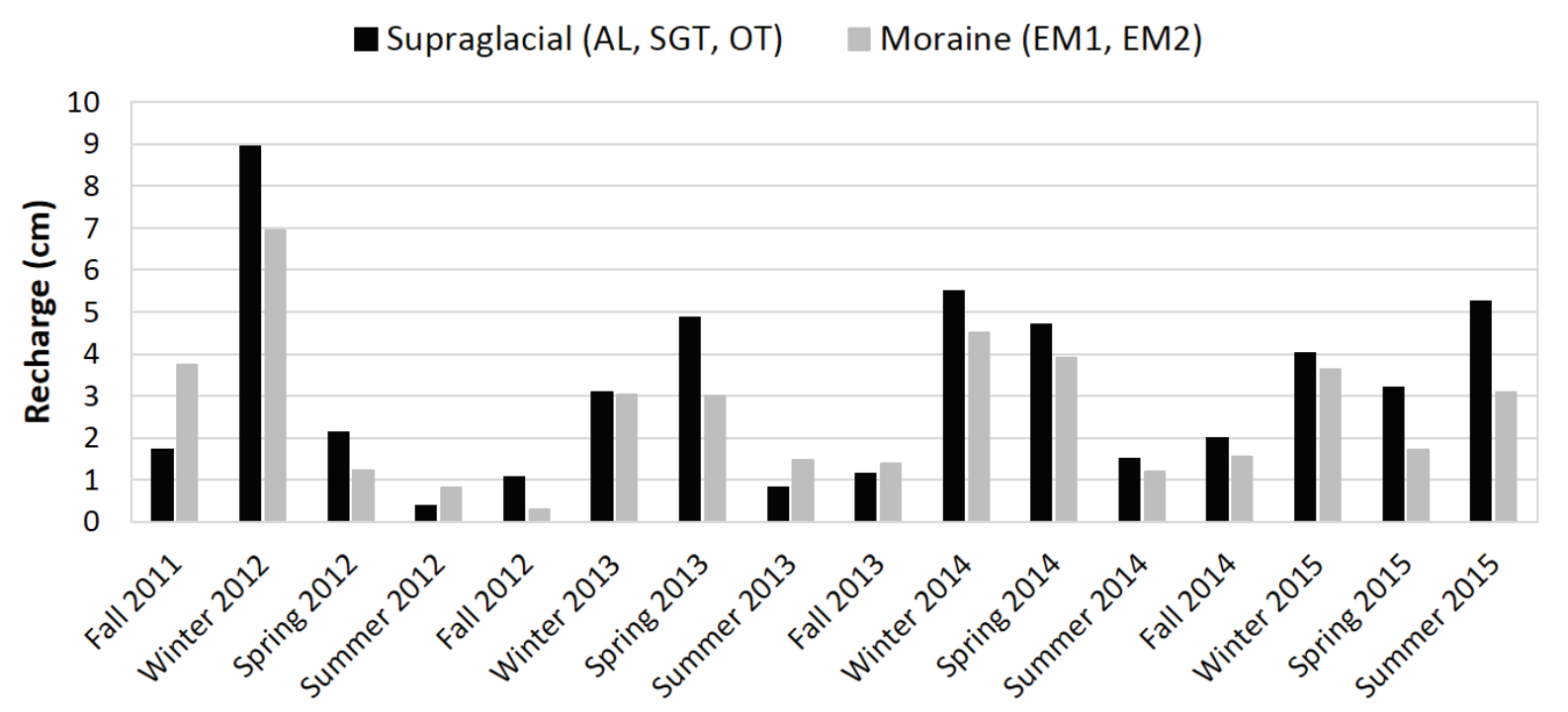

Figure 10. Seasonal recharge for sites lumped by supraglacial (soil parent materials deposited beyond and ice front) and moraine (soil parent materials deposited directly by a glacier) settings. Recharge is an average monthly value for sites within each category.

- R is generally higher for supraglacial settings / soil parent materials (Fig. 10).
- Supraglacial sites have high R in winter and spring owing to high hydraulic conductivity and low ET during these seasons.
- Fall (2011, 2012) and Summer (2012 and 2013) R was higher for moraine sites owing to higher soil-water retention and more protracted R during these periods.

Conclusions

- General seasonal R patterns exist, BUT...
- Weekly to monthly periods of increased P can create pulses of R when not expected (e.g., Dec R event during WY2012 dominated by drought and July R event during summer of WY2015)
- Diffuse R to shallow groundwater of 35% is indicated by mean of data from all sites/years
- Soil parent material and horizon characteristics have a strong influence on average annual recharge primarily through their control on Ks, with clay-rich till parent materials producing values as low as 16% and coarse-grained outwash parent materials producing values as high as 58% of P.

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