Implications to aquifer storage from climate-driven shifts in water-balance partitioning: Indiana, Midwest USA

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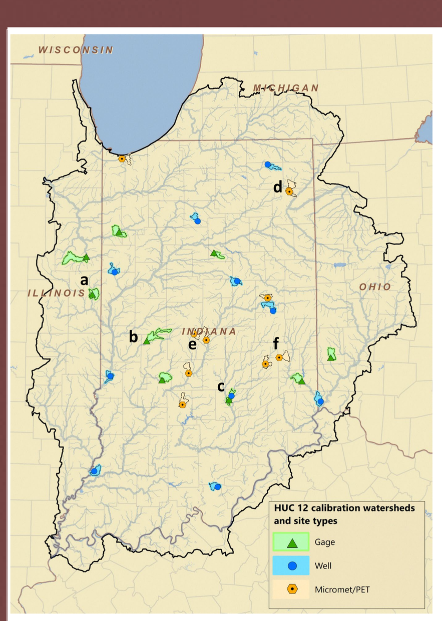
INTRODUCTION

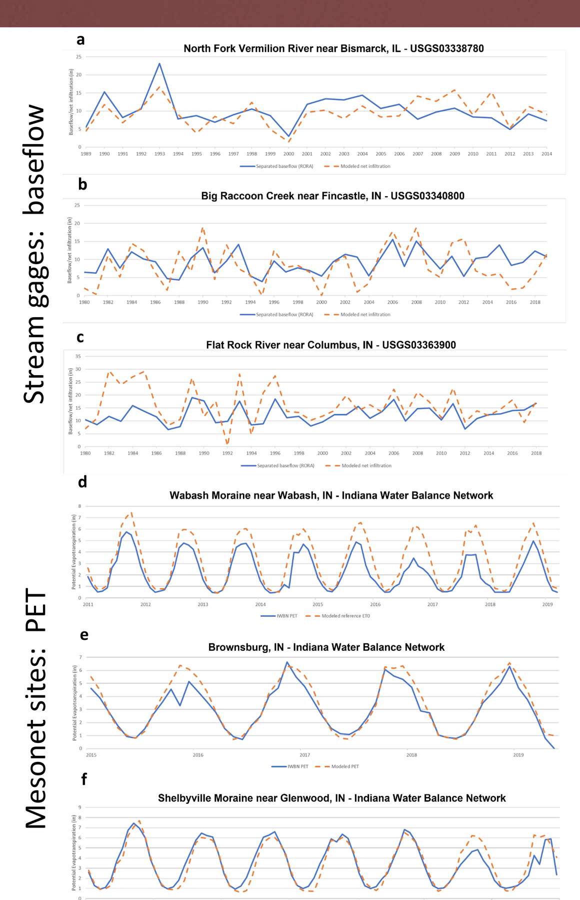
Documented trends in the timing and intensity of precipitation events have been met with associated hydrologic changes in water-balance partitioning. Changes in land use, initiation and length of the growing season and associated irrigation practices, timing of autumn leaf senescence, snow accumulation and melt, flooding, and drought all affect the hydrological processes of infiltration, evapotranspiration, and runoff. This study is an investigation of trends in groundwater recharge over space and time in the temperate climate of the Midwest USA. It tests the hypothesis that increasingly intense precipitation events resulting in extreme runoff events might be short-circuiting processes of infiltration and groundwater recharge by lowering the residence time of water in upland landscapes, while increasing infiltration in lowlands and riparian corridors.

METHODS

This in-progress study used a quasi-3D approach to assessing changes in water-balance partitioning from 1980-2019 in Indiana, USA. The 40-year spatially continuous water balance (U.S. Geological Survey Soil Water Balance v 2.0, SWB2; Westenbroek et al. 2018) model solved for potential groundwater recharge (net infiltration) at a daily time step and was analyzed at annual, monthly, and seasonal intervals. Note that observations and model output retain the original Imperial units in most cases.

More regional results for the glaciated Midwest USA obtained by Trost et al. (2018) using SWB2 have been presented. This study seeks to provide a high-resolution (250-m spatial scale) analysis of water-component trends and likely future of water resources across Indiana.



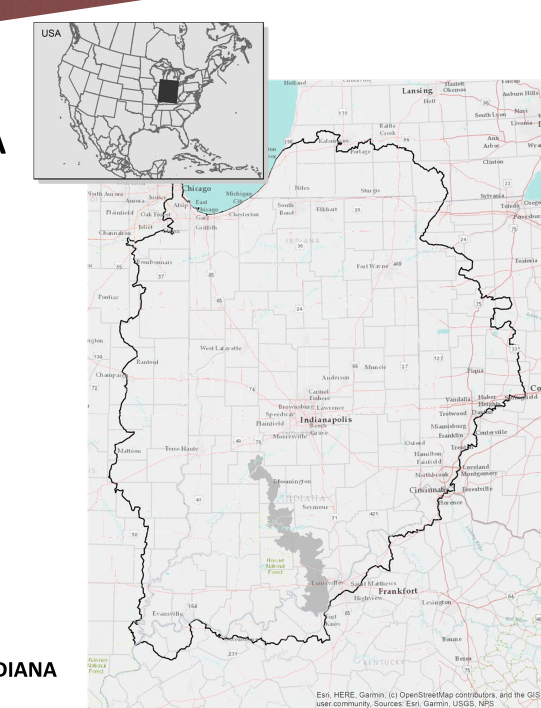


MODEL CALIBRATION

A diversified approach to model calibration employed three different observation platforms to compare to modeled water-balance components. USGS stream gage discharge data was processed using the Rorabaugh method (RORA; Rutledge, 2007) to estimate baseflow to net infiltration, and mesonet micromet sites were used to compare Penman-Monteith PET estimates to modeled reference ET_0. Current work is ongoing to extract recharge from observation well data using the water-table fluctuation method.

LOCATION

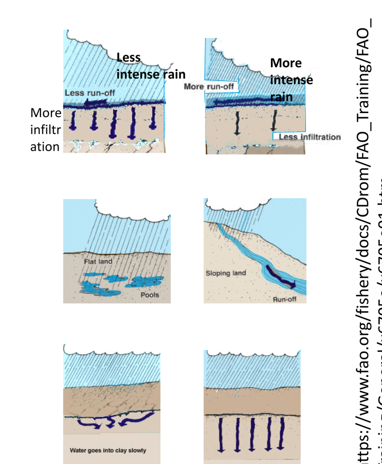
HUMID MIDWEST USA



INPUT DATA, PARAMETERS

Type	Variable	Source	Original Scale
Physical Characteristics	Temperature, precipitation	Daymet (NASA/ORNL DAAC)	1-km
	Growing degree day	Baskerville and Emin 1969	---
	Evaporation-to-rainfall ratio	McDonald 1961	1-km
	Flow direction (D8)	National Elevation Dataset (NED) derivative	200K (100-m)
	Dynamic rooting depth	Various	ft
Soils	Hydrologic Soil Group (classified)	Natural Resources Conservation Service (NRCS) STATSGO	250K
	Available water content 100cm (in/ft)	Natural Resources Conservation Service (NRCS) SSURGO	12K – 20K
	Initial Soil Moisture – January long-term mean (percent)	National Weather Service (NWS) Climate Prediction Center (CPC)	0.5 degree
Land Cover	Land cover (classified, multiple years)	National Land Cover Dataset (NLCD)	24K (30-m)
	Crop type	USDA NASS Cropland Data Layer	24K (30-m)
	Crop coefficient method	FAO-56	---
	Impervious surface (percent)	National Land Cover Dataset (NLCD)	24K (30-m)
	Initial snow storage (SWE) – Jan 1980	Daymet (NASA/ORNL DAAC)	1-km
Parameters	Interception method	Bucket	---
	Evapotranspiration method	Hargreaves	---
	Soil moisture method	FAO-56 two stage	---
	Runoff method	Curve number	---
	Continuous Frozen Ground Constant	Molnau and Bissell 1983	---
	CFGI Lower/CFGI Upper	Molnau and Bissell 1983, Follum et al., 2018	---
	Growing season start/stop	Various: NWS, EPA, Indiana Dept Ag	---
Irrigation	Irrigation locations (wells) – classified by use (crops, urban grasses)	Indiana Dept Natural Resources, Division of Water	24K
	Irrigation method	FAO-56	---

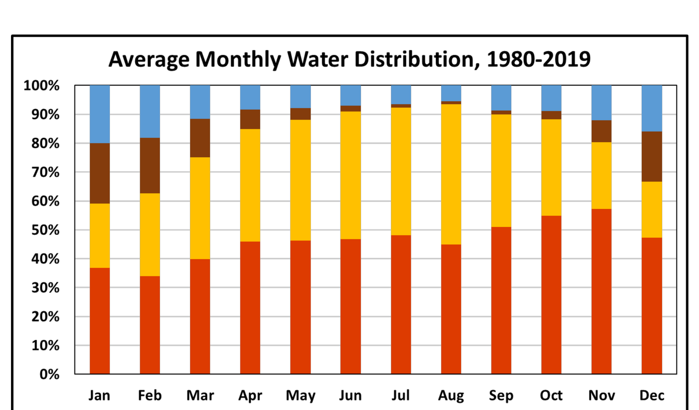
SWB2 (Soil Water Balance model v2; Westenbroek et al., 2018) was the modeling framework for this study. Daily temp/precip inputs drive the boundary conditions, while topography, land cover, land use, and soil properties describe ground conditions that govern the amounts, rates, and location of infiltration across the landscape. The conceptual sketches below (FAO, 2006) illustrate how the same amount of precipitation can result in different amounts and rates of infiltration.



https://www.fao.org/fishery/docs/CDrom/FAO_Training/FAO_Training/General/x6705e/x6705e01.htm

AVERAGE WATER-BALANCE 1980-2019

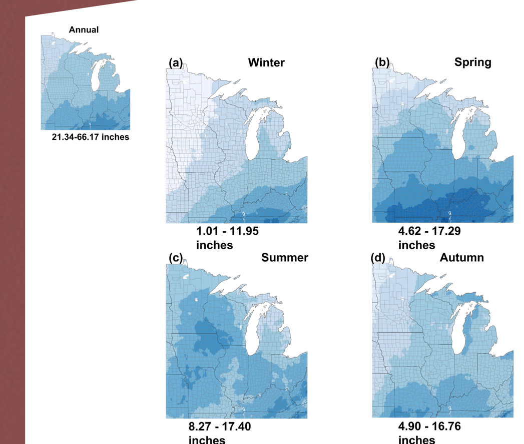
Annual: 1980-2019	Max Temp (°F)	Min Temp (°F)	Precip. (inches)	Reference ET0 (inches)	Actual ET (inches)	Net Infiltration (inches)	Runoff (inches)
Mean	62.4	42.0	39.2	41.7	31.4	3.5	8.0
Min	54.2	34.5	15.9	32.7	-154.5	0.3	0.0
Max	71.6	49.7	77.4	51.0	61.0	8.7	452.8
Std Dev	2.9	2.4	8.0	2.8	6.7	2.2	10.7
Variance	8.4	5.7	64.6	7.8	45.4	4.6	114.1



Average values for water-balance components for the 40-year 1980-2019 simulation. Although the values are very generalized, they show a humid climate that is occasionally water limited in some locations in some years. ET by crops and forest is a controlling factor in the timing of (potential) recharge to the subsurface.

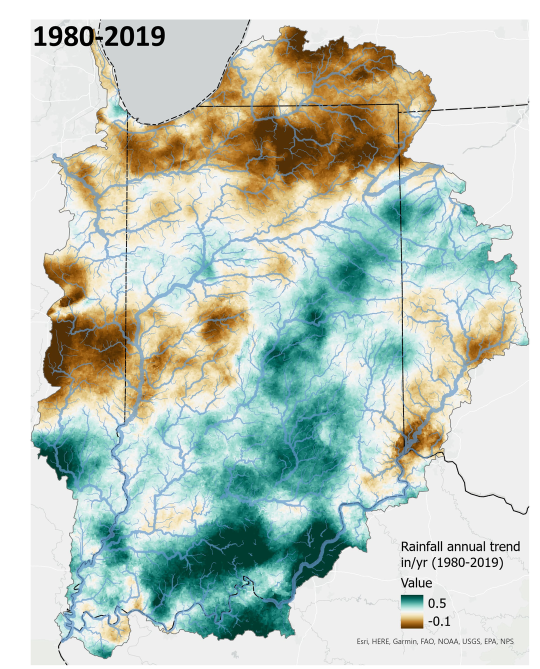
ANNUAL/SEASONAL DISTRIBUTION OF WATER

Using estimates of annual net infiltration from the SWB2 model, 40-year temporal trends calculated on space-time cubes suggest that over 50% of the model domain is experiencing statistically significant increases ($p < 0.006$) in potential groundwater recharge (mean of 0.06. Trend analyses of unconfined water levels from 1980-2019 were conducted, finding that water levels in 8 (out of 9) climate divisions in the state are increasing (rising) in 6 of the 8 climate divisions. The distribution of increasing water tables reflects the same spatial distribution as the annual estimates of recharge generated by the SWB2 model.

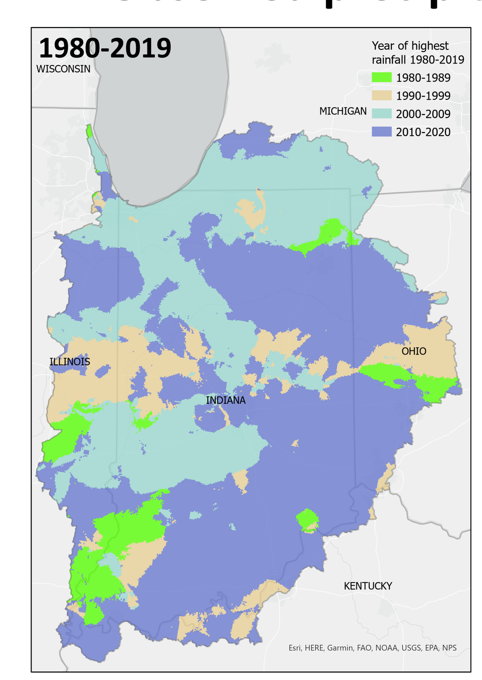


Distribution of annual and seasonal distribution of precipitation in the Midwest USA. The spatial distribution changes seasonally, affecting patterns of net infiltration (data from NCEI using 1991-2020 climatology baseline).

Observed precipitation trends



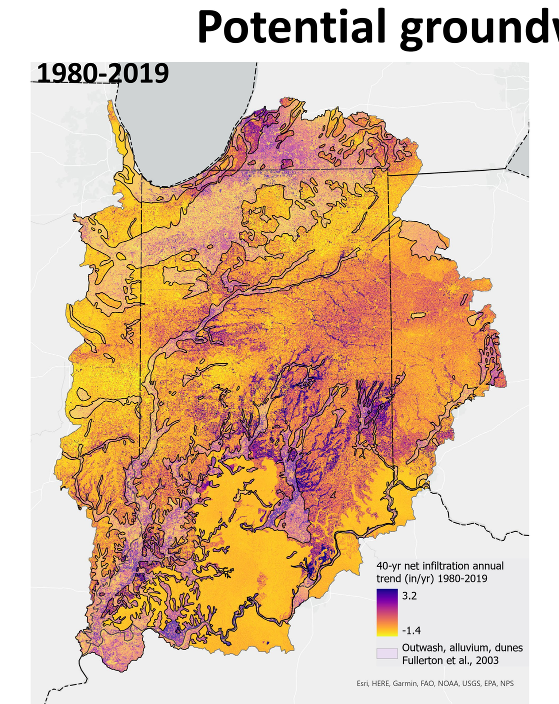
Rate of change = +0.18 in/yr (18 in/century)



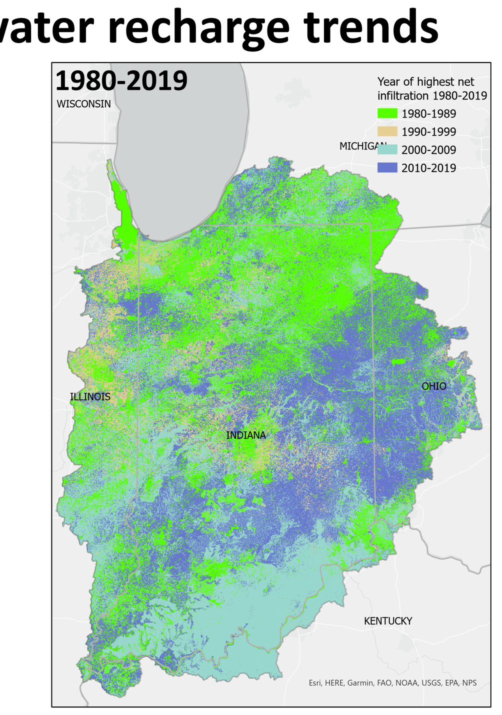
Left map is the 40-year annual trend (Sen slope) for **PRECIPITATION**. Lower precipitation in areas of this highly agricultural state require intensive irrigation to meet crop requirements. Although irrigation is included in the SWB2 model, it is largely used as an input; groundwater withdrawals are not accounted for in this model. During the last 40 years, over this domain, the average rate of increasing precipitation is 0.18 in/yr (18 in/century). As the map shows, the distribution of precipitation is not uniform over the state.

Right map is the date (year) of the highest values of precipitation over the last 40 years. Most of the state has seen the highest values in the last 20 years.

Potential groundwater recharge trends



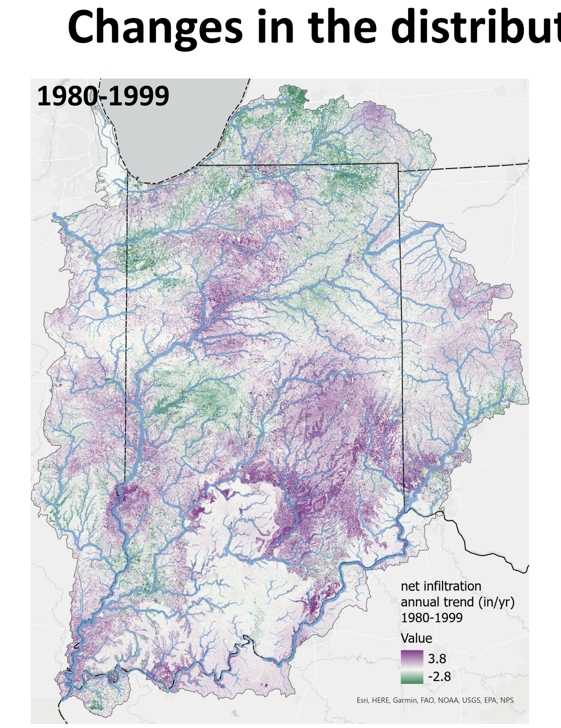
Rate of change = +0.06 in/yr (6 in/century)



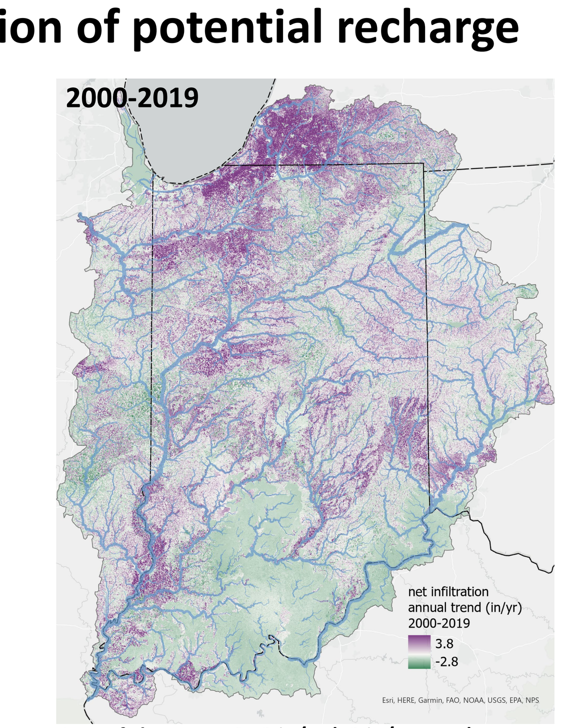
Left map is the estimated 40-year annual trend (Sen slope) for **POTENTIAL** groundwater **RECHARGE** (net infiltration). Mapped outwash, alluvium, and dune deposits are also shown to highlight the increased recharge in low-lying areas, preferentially replenishing riverside aquifers.

Right map is the date (year) of the highest values of recharge over the last 40 years. The swath of recent (2010-2019) largely coincides with the pattern of increasing precipitation.

Changes in the distribution of potential recharge



Rate of change = +0.03 in/yr (3 in/century)



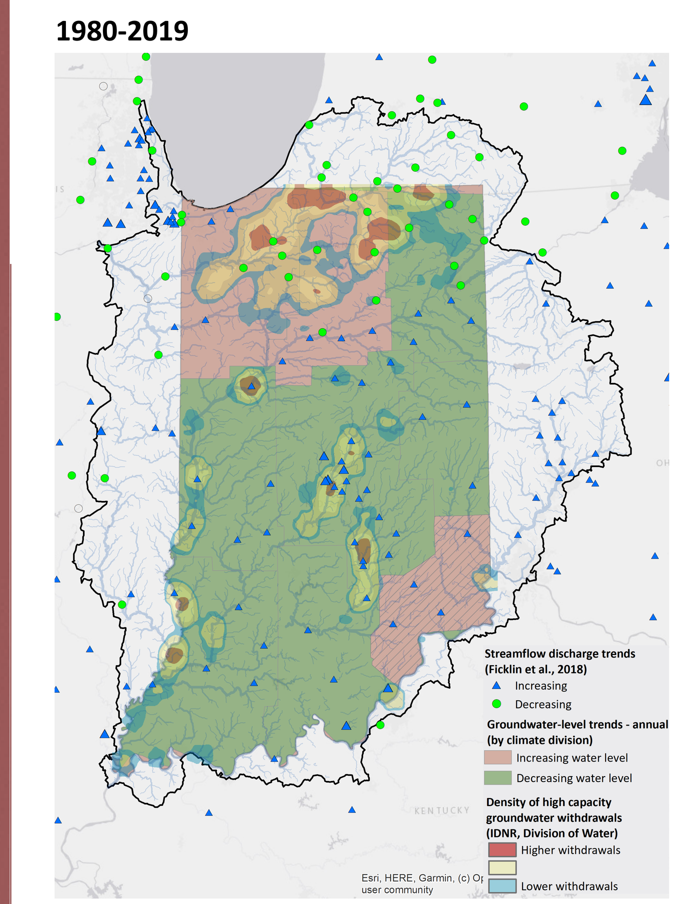
Rate of change = +0.13 in/yr (13 in/century)

Left map is the spatial distribution of the annual trend (Sen slope) of potential recharge (net infiltration) over the period 1980-1999.

Right map is the spatial distribution of the annual trend (Sen slope) of potential recharge (net infiltration) over the period 2000-2019. In the last 20 years, recharge has become spatially concentrated in lowland areas likely because of more rapid runoff from higher intensity storms that characterize midwestern precipitation events in the Spring. This has resulted in a fractional shift of recharge from Spring to Winter, when water stays on the landscape longer and is not subject to vegetation uptake or transpiration.

OBSERVED GW/SW TRENDS

The climate-driven changes in precipitation events can be more easily linked to the documented increasing stream discharge trends than trends in groundwater levels. In this ongoing study, multiple methods were utilized to calculate annual and monthly, or seasonal, potential aquifer recharge amounts and trends in unconsolidated aquifers in Indiana and surrounding watersheds.

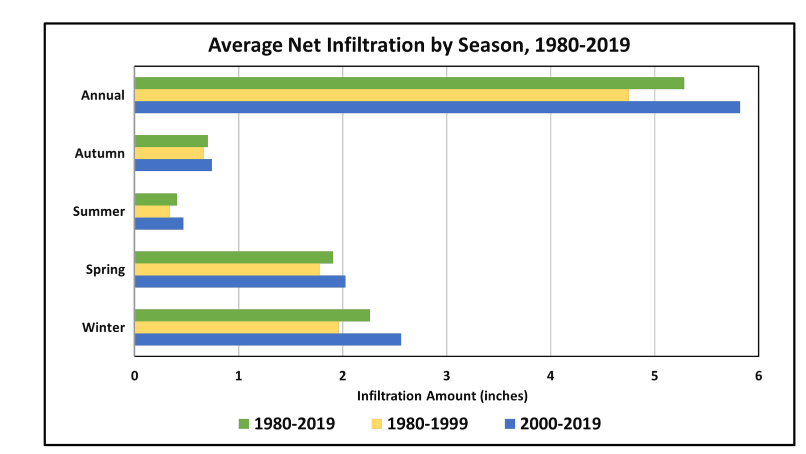


In addition to the water-balance model, observations of trends in stream flow (Ficklin et al., 2018) and groundwater-table trends from observation wells in Indiana (this study), were also examined.

Groundwater level trends were mapped to Climate Divisions to extend the interpretation of very sparse long-term observation-well data. Although very generalized, the area of increasing water levels corresponds with increasing precipitation, and declining water levels in the NW and SE parts of the state parallel slight declines in precipitation.

Much of the Midwest USA shows increasing stream flow (discharge); however, some areas of declining flows are present. These areas are located in areas with corresponding declining groundwater levels, likely influenced by a combination of declining precipitation and the anthropogenic effects of high-intensity groundwater pumping primarily during the growing season.

ANNUAL/SEASONAL TRENDS



Time span	Winter	Spring	Summer	Autumn
1980-2019	43%	36%	8%	13%
1980-1999	41%	38%	7%	14%
2000-2019	44%	35%	8%	13%

Estimated fractional shift in seasonal contribution to potential recharge (net infiltration).

CONCLUSIONS

The results presented here are largely for average modeled values or trends for the full modeled domain. This scale of analysis blurs the magnitude of spatial distribution of hydrologic processes; however, even results at this scale point to some strong signals, including:

- The later part of the time series (2000-2019) dominates the 40-year trend, indicating that we are already in a new normal
- Potential recharge (net infiltration) is shifting from spring (Mar-Apr-May) to winter (Dec-Jan-Feb)
- Spatial distribution of potential recharge is driven by precipitation patterns, but it is less evenly distributed across the landscape. Instead, topographic lows, and therefore riverside aquifers (e.g., outwash, alluvium) are receiving more recharge than upland aquifers.

Acknowledgements:
This research was funded by the Indiana Department of Environmental Management and was supported in part by Lilly Endowment, Inc., through its support for the Indiana University Pervasive Technology Institute.

Thank you to Andrew Gustin for research assistance.

2021