Mapping Groundwater Recharge Rates Under Multiple Future Climate Scenarios in Southwest Michigan

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Introduction

Primary Objective:

Model the water table of Kalamazoo County, Michigan under various future scenarios of climate change, urbanization, and expanded agricultural production.

Sub Objective (primary for this presentation):

Use SWAT to simulate and map (at field scales) groundwater recharge under future scenarios of climate change.

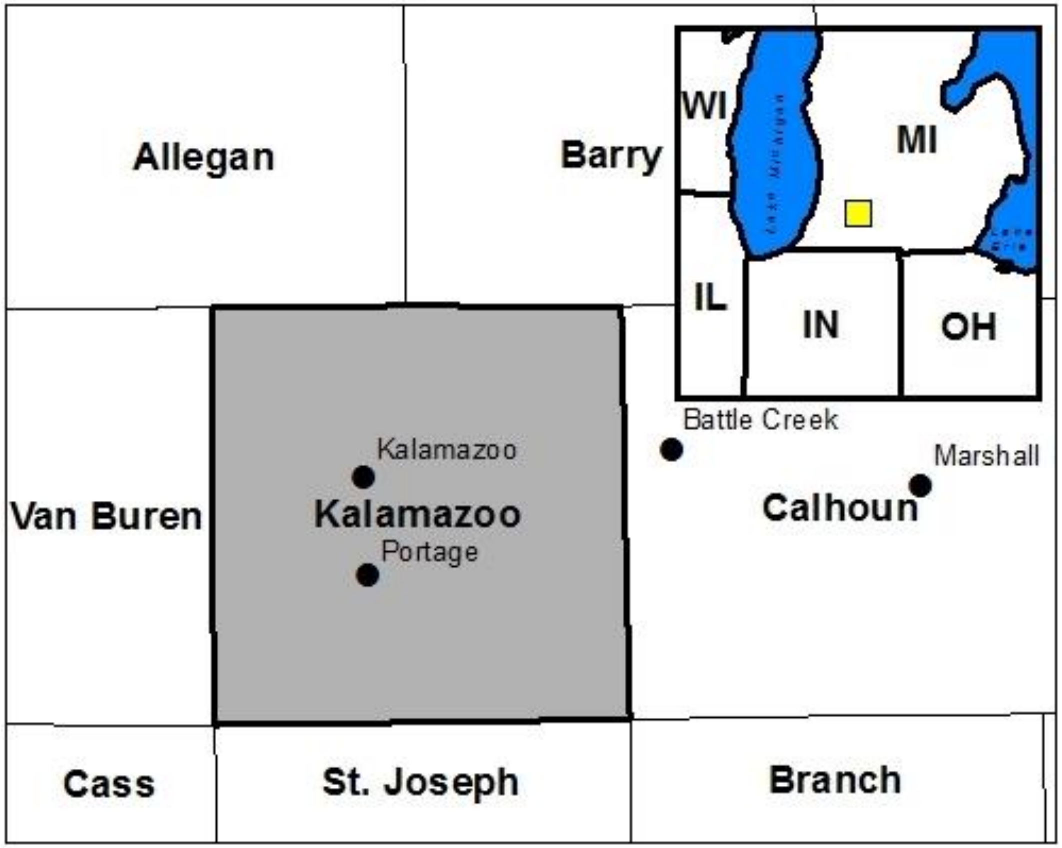
Expectations:

Evapotranspiration will increase due to higher temperatures.

Subsequent decrease in groundwater recharge.

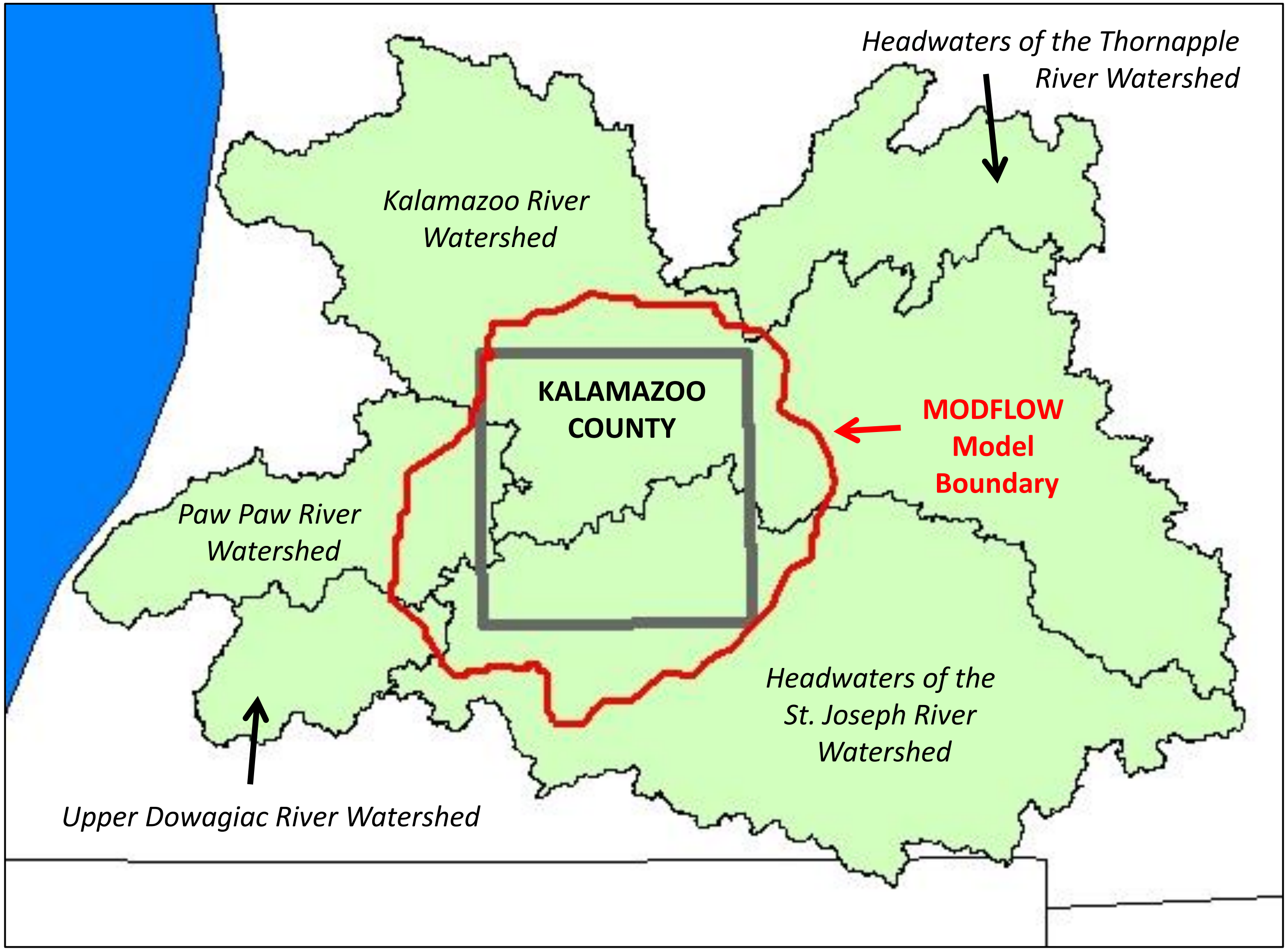
Primary Study Site

- Kalamazoo County, Michigan
- Existing MODFLOW model by USGS (Luukkonen et al. 2004)
- 40% agriculture, 21% forest, 20% urban
- well draining soils
- moderate topographic relief
- precipitation 36 in./yr.
- population 254,000, growing
- average annual water use
    - ag: 26 MGD
    - industry: 5 MGD
    - City of Kalamazoo: 19 MGD
    - City of Portage: 6 MGD



SWAT Study Site

Intersecting watersheds of MODFLOW model boundary.

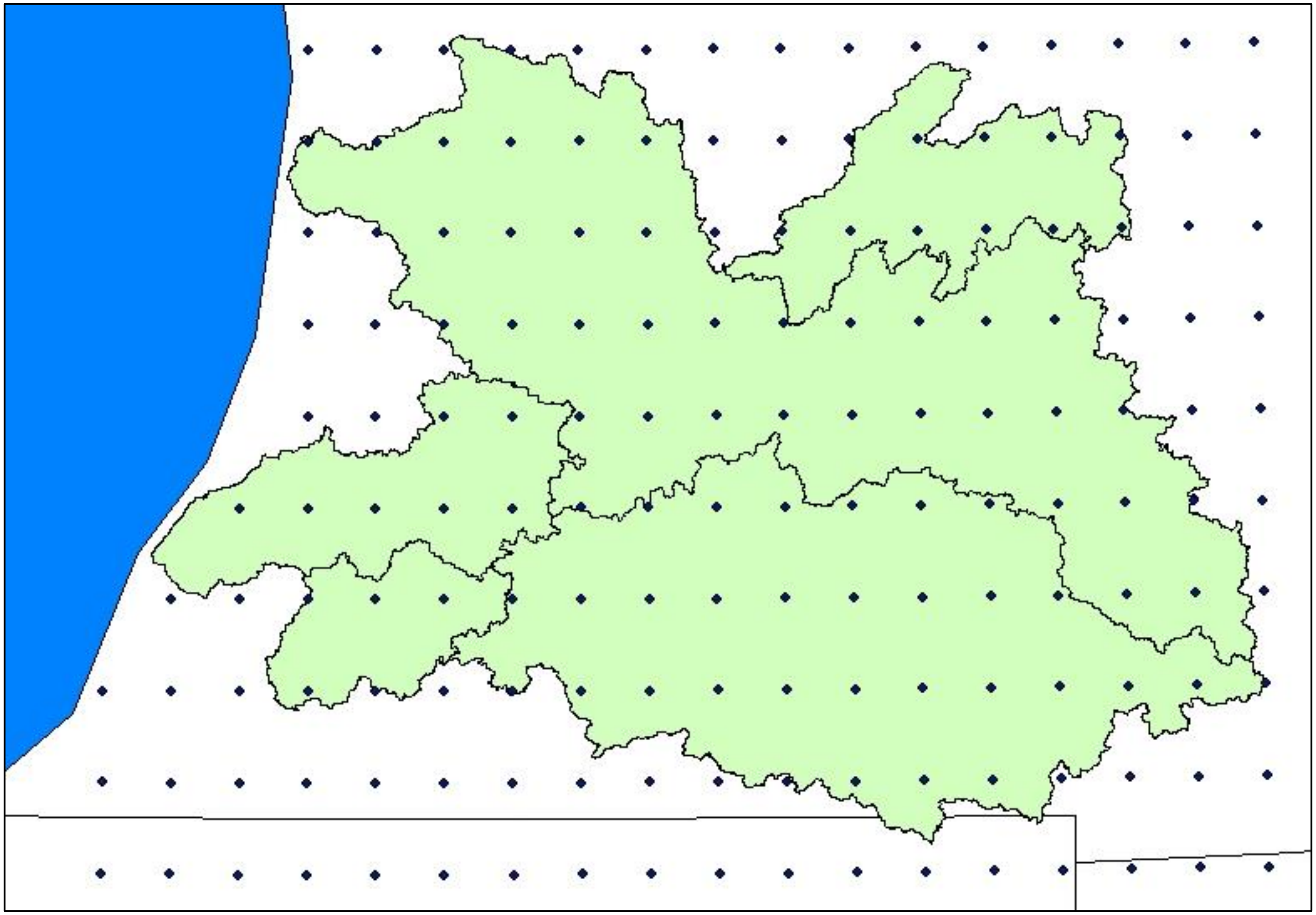


SWAT Inputs

Data	Source
Land cover	Cropland Data Layer (2009-2013)
Soils	SSURGO
Topography	USGS 10-meter DEM
Irrigation	Michigan DEQ, well logs
Consumptive water use	Michigan DEQ
Point sources	Michigan DEQ, US EPA
Dams	USACE National Inventory of Dams
Weather	Maurer et al., 2002.

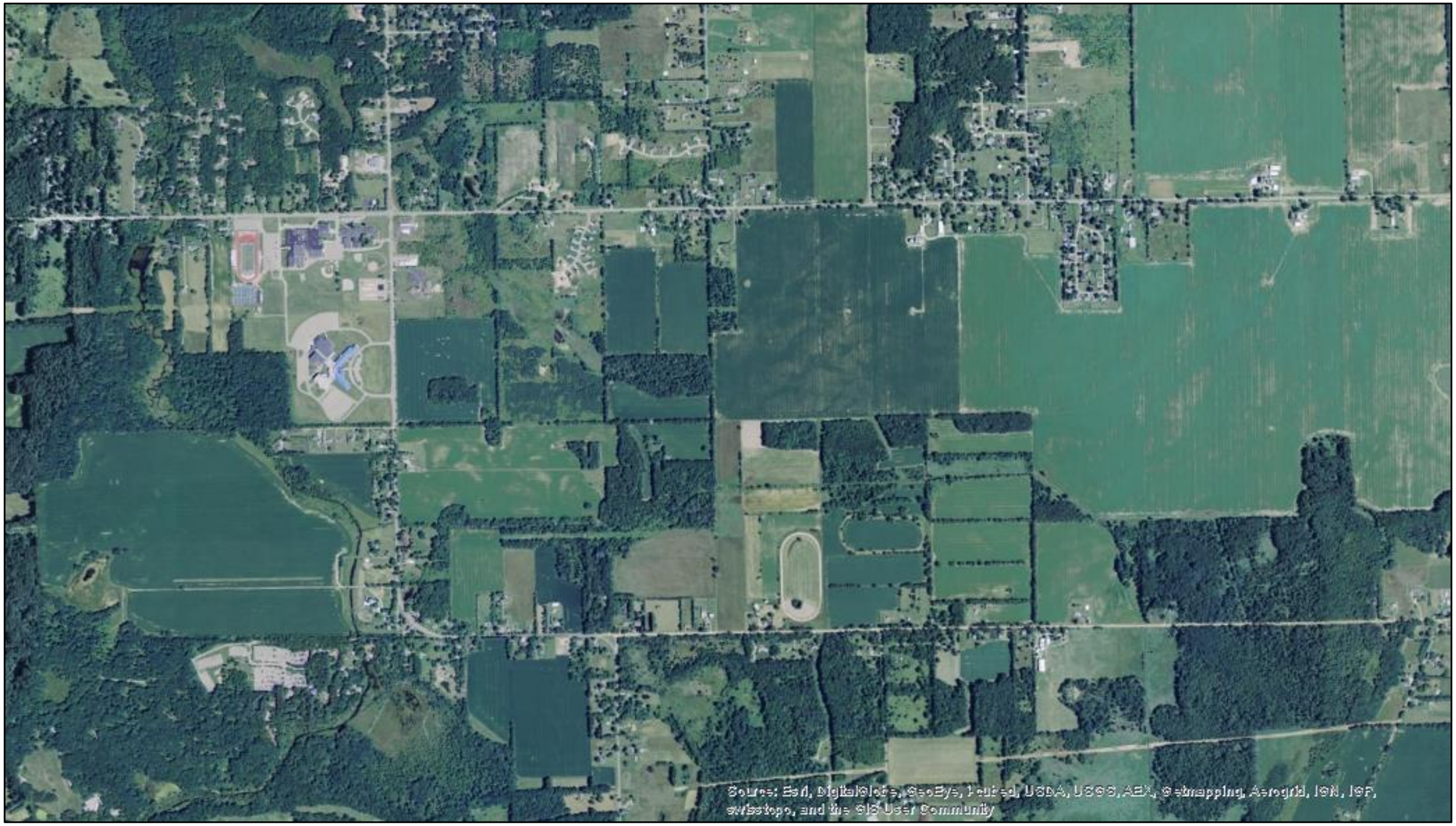
SWAT Inputs

- Observed weather data interpolated to grid points
- 1/8 deg. resolution.
- Daily precip, min. temp., max temp.
- 1940 - 2010



HRU Mapping

- HRU thresholds: Land cover – 3%, Soil – 3%, Slope – 3%.
- Back-mapped to raster format.
- Resulted in 256 sub-basins, 76,281 HRUs.



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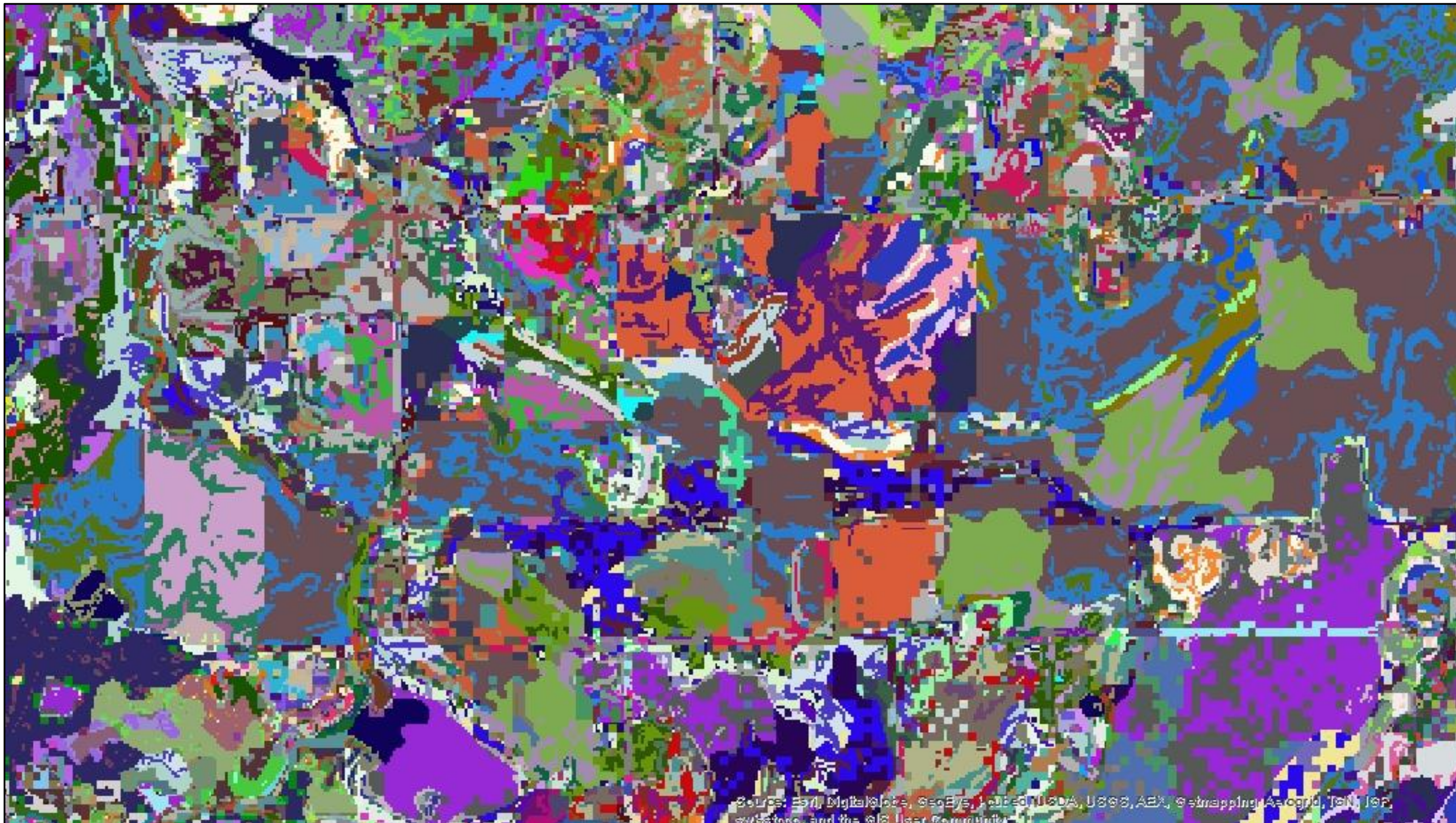
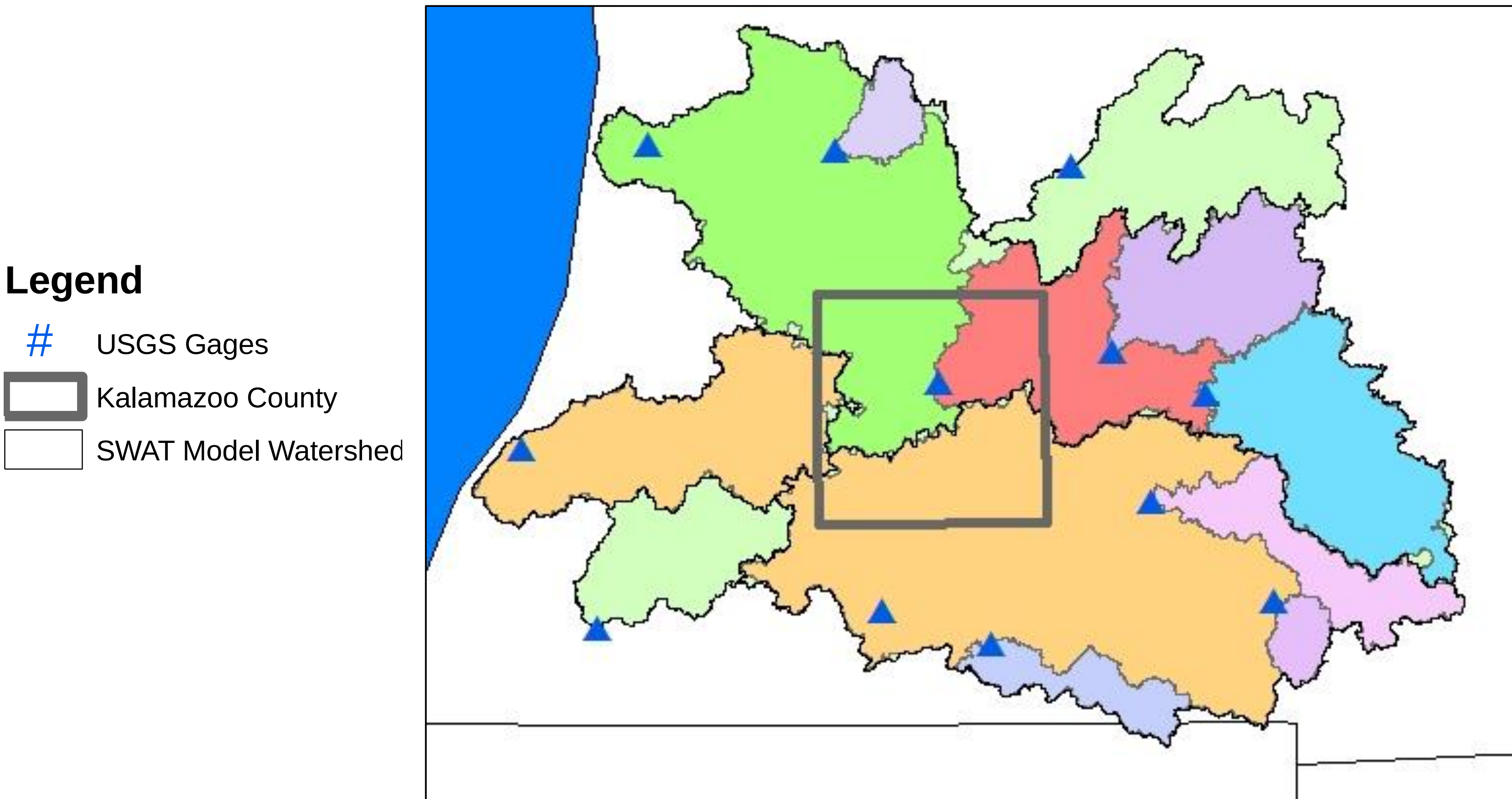


SWAT Calibration

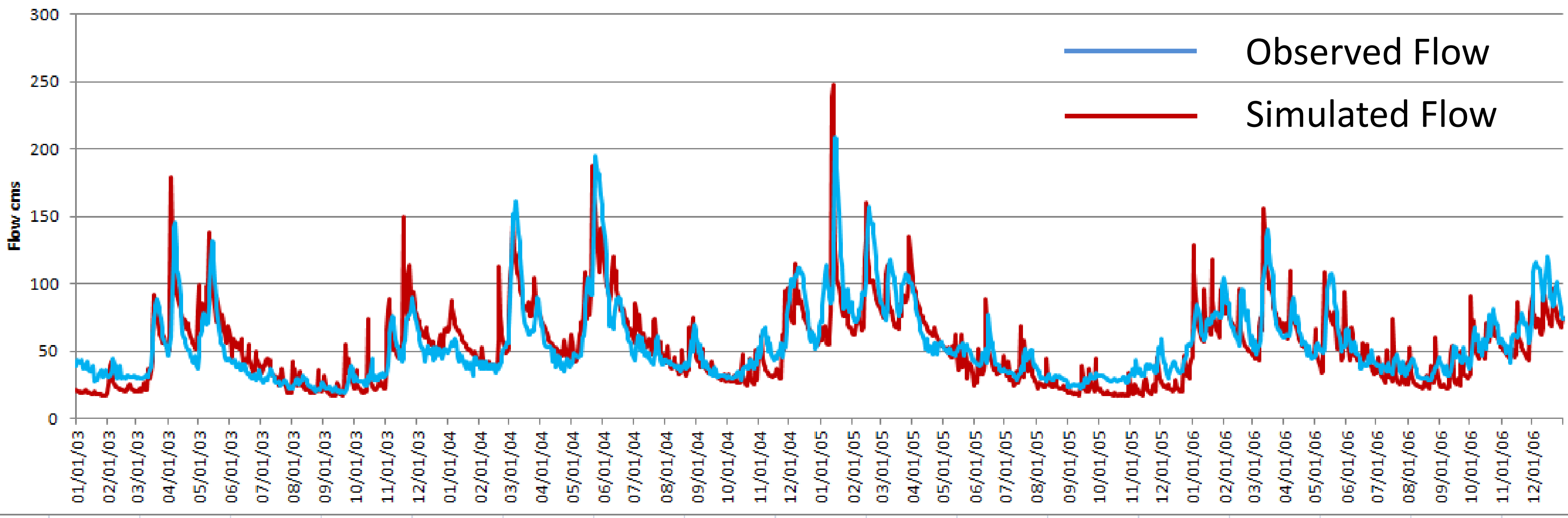
To best simulate ground water recharge, SWAT was calibrated to baseflow conditions.



SWAT Calibration

USGS baseflow separation program identified days where 75% of flow was from ground water.

Kalamazoo River – USGS Gage 04108660



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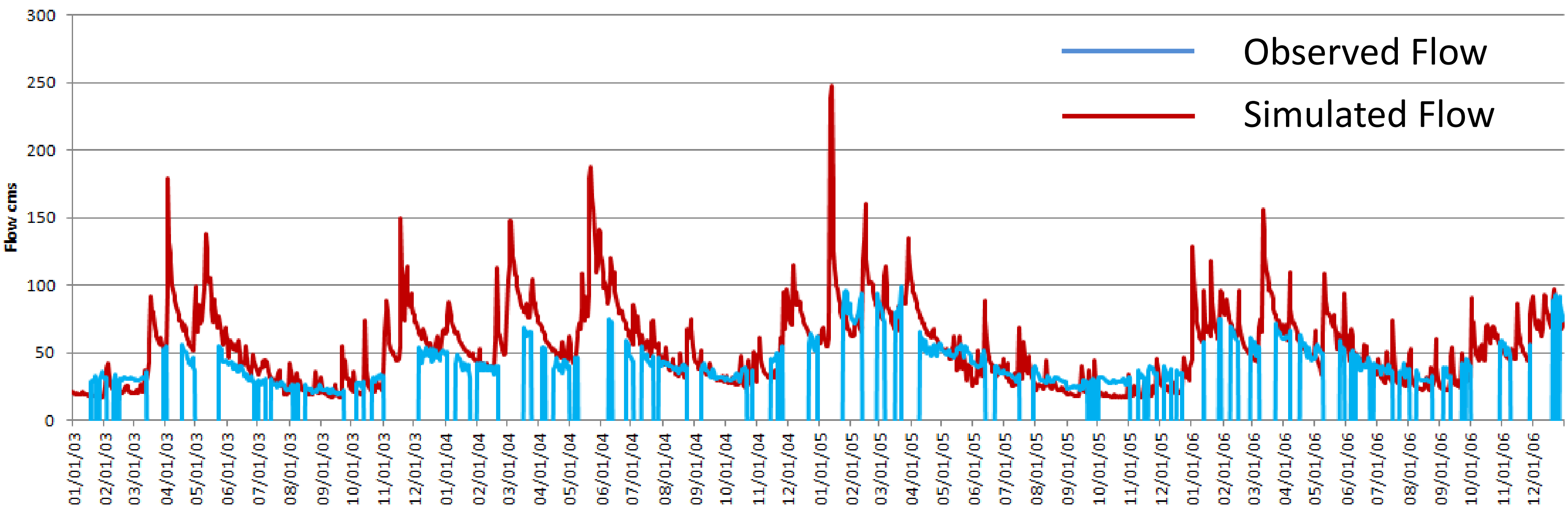

Climate Change Simulation

11 different models, each under various CMIP-3 scenarios, downscaled to Maurer grid points by Hayhoe, et al. (2013).

Daily values for precipitation and temperature through 2100.

Climate Models

1. CCSM
2. CGCM3-T47
3. CGCM3-T63
4. CNRM
5. ECHAM5
6. ECHO
7. GFDL-2-0
8. GFDL-2-1
9. HADCM3
10. HADGEM
11. PCM

Climate Scenarios

1. A1FI – rapid population growth, levels off mid-century, heavy fossil fuel use
2. A1B – rapid population growth, levels off mid-century, balanced fossil fuel use
3. A2 – continuous population growth, regional economic growth
4. B1 – population growth levels off, efficient energy technologies adopted

Climate Change Simulation

Run SWAT in 10-year increments, for each decade:

- adjust .wgn files
- adjust CO2 concentrations (ppm) from IPCC*
  - A1Fi: 420 (2020) – 970 (2100)
  - A1B: 403 (2020) – 717 (2100)
  - A2: 417 (2020) – 856 (2100)
  - B1: 412 (2020) – 549 (2100)
- run the model
- grab the outputs

* http://www.ipcc-data.org/ancilliary/tar-isam.txt

SWAT Calibration

- Calibrated SWAT models from 2000-2005
- Validated from 2006-2010
- Moriasi et al. (2007) provided guidance on flow metrics

	Nash-Sutcliffe Efficiency	Percent Bias
Very Good	0.75 - 1.0	< 10%
Good	0.65-0.75	10 – 15%
Satisfactory	0.5 – 0.65	15 – 25%
Unsatisfactory	< 0.5	> 25%

SWAT Calibration

- Model performance for monthly baseflow

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SWAT Model / Gage	Calibration NSE	Calibration % Bias (negative value = more simulated baseflow)	Validation NSE	Validation %Bias (negative value = more simulated baseflow)
04108660 (Kalamazoo)	.69	-1%	0.55	10%
04108600 (Kalamazoo)	0.02	-20%	0.89	-36%
04106000 (Kalamazoo)	0.66	-4%	0.69	-8
04105000 (Kalamazoo)	0.64	1%	0.48	<1%
04103500 (Kalamazoo)	0.86	-4%	0.58	8
04097500 (St. Joe)	0.66	-14%	0.55	3%
04097540 (St. Joe)	0.83	-16%	0.18	-13%
04096515 (St. Joe)	0.99	-50%	0.99	-65%
04096405 (St. Joe)	0.97	-6%	0.94	7%
Paw Paw	0.53	7%	0.50	-9%
Thornapple	0.61	1%	0.80	8%
Upper Dowagiac	0.49	3%	0.50	-6%

SWAT Calibration

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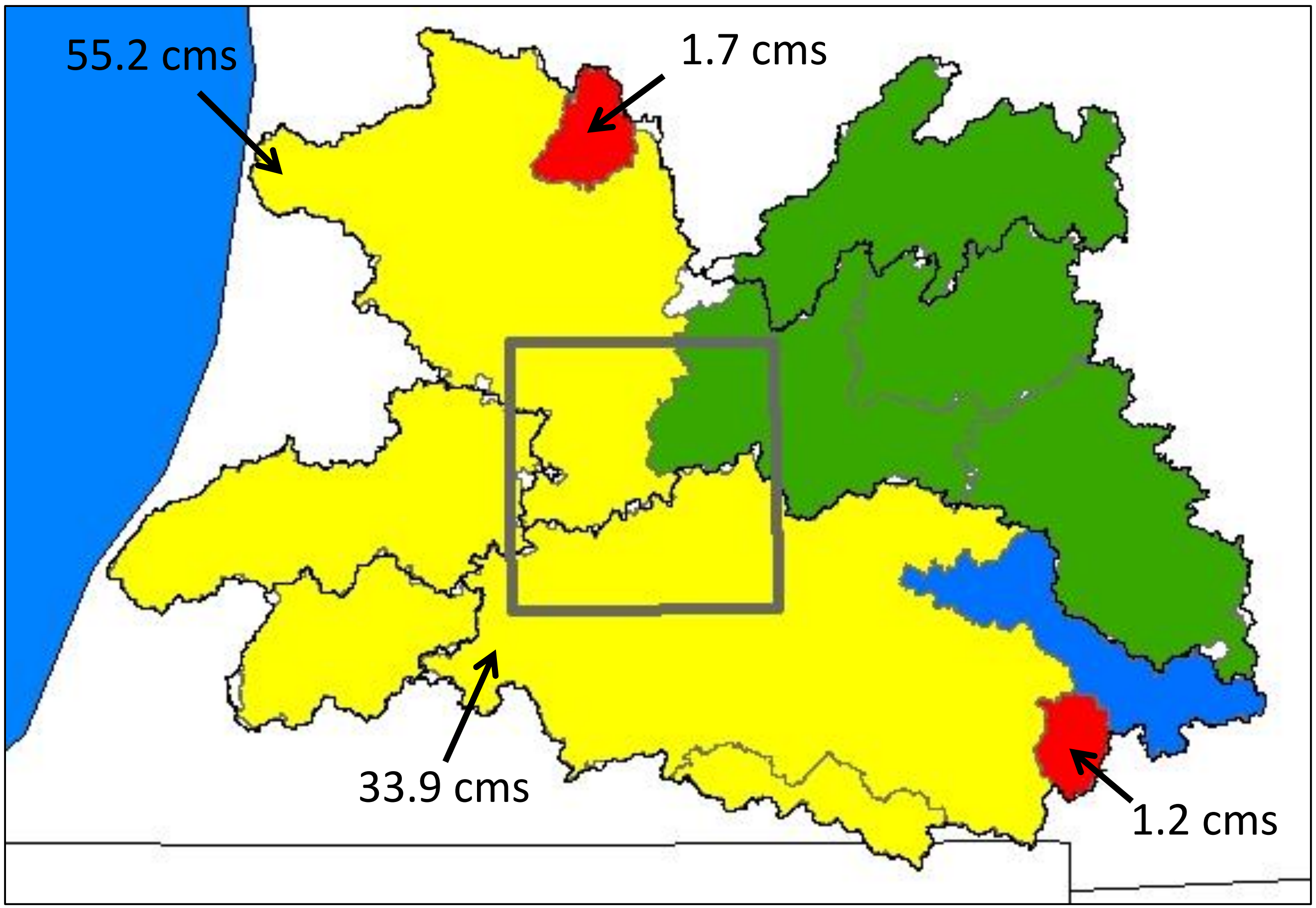
Map of Nash Sutcliffe Efficiency Values



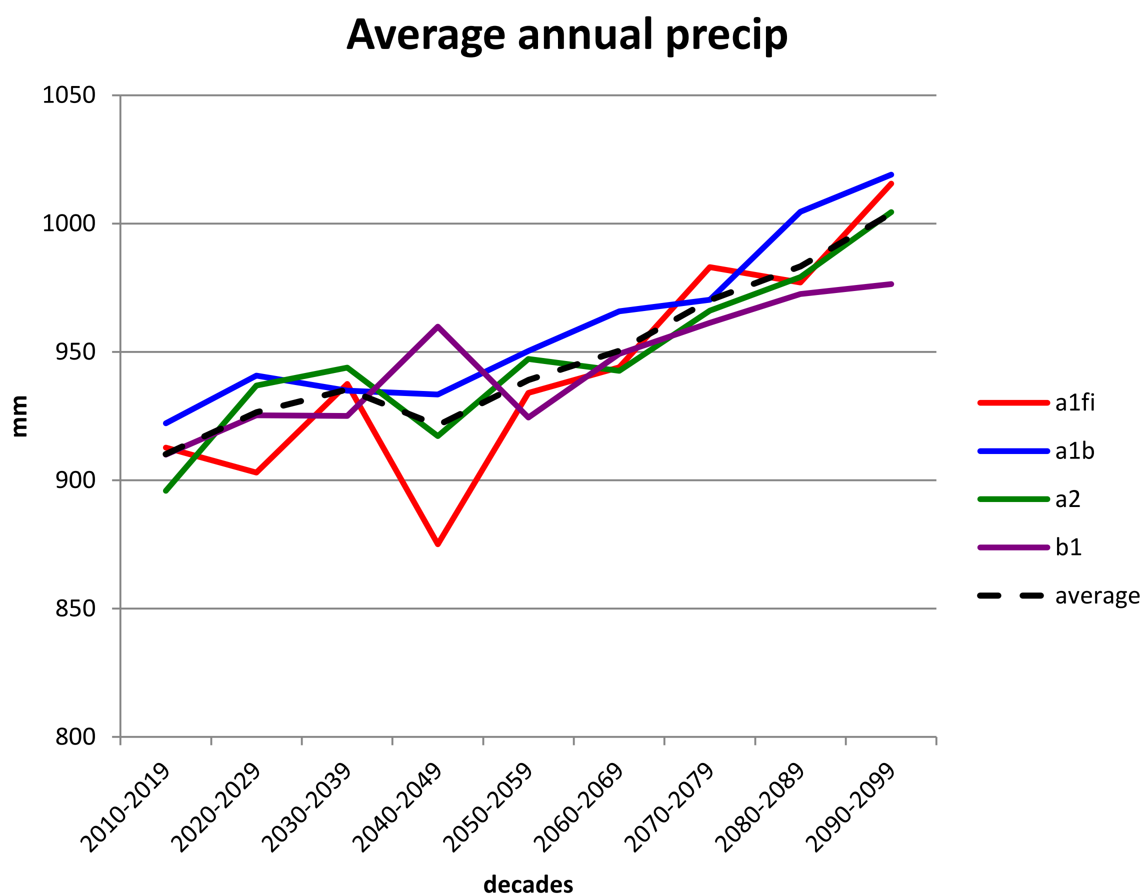
SWAT Calibration

- Did not just rely on flow.

- Compared SWAT outputs to:
    - Reported crop yields in NASS
    - USGS estimates of ET
    - USGS estimates of baseflow fraction
    - Reported irrigation rates to M-DEQ and M-DARD
    - Estimates of ground-water recharge from M-DEQ/USGS/RSGIS/IWR

SWAT Future Simulations

- SWAT Outputs for 04106000 (Kalamazoo)



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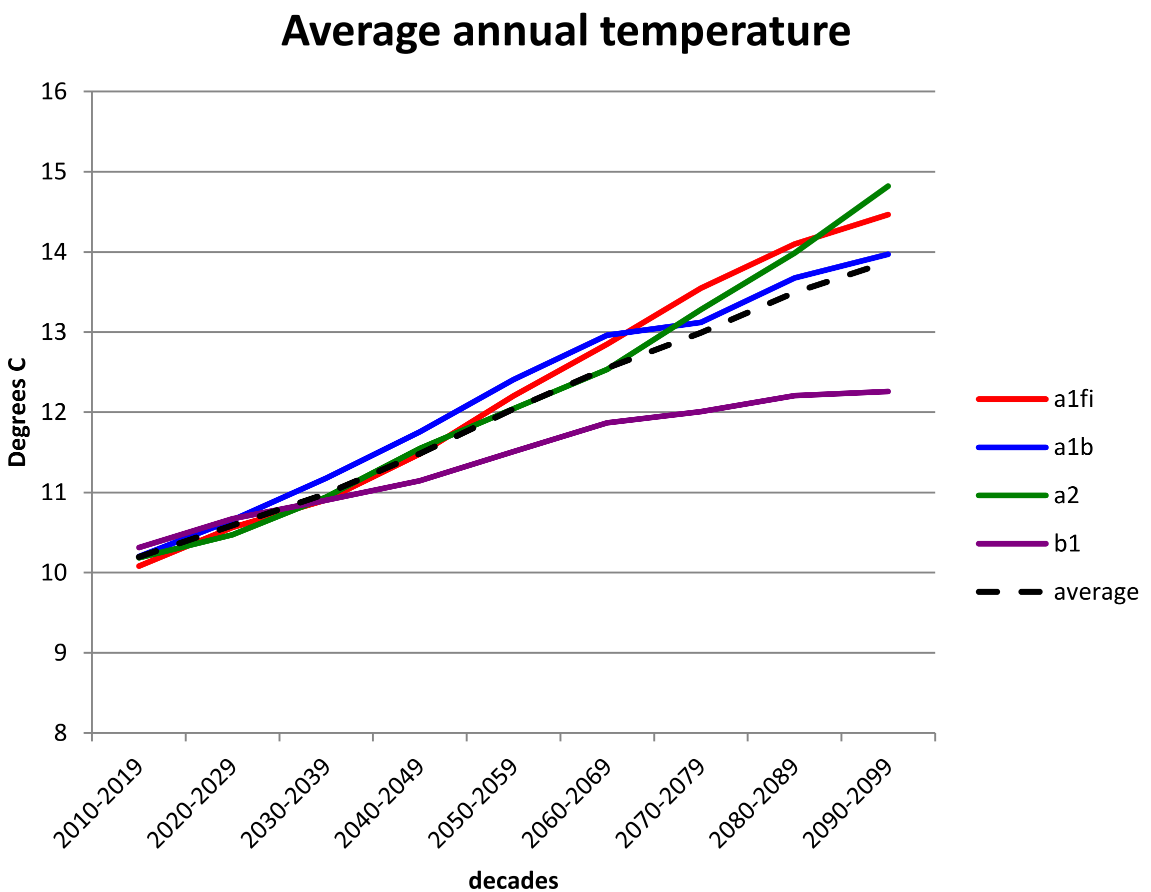

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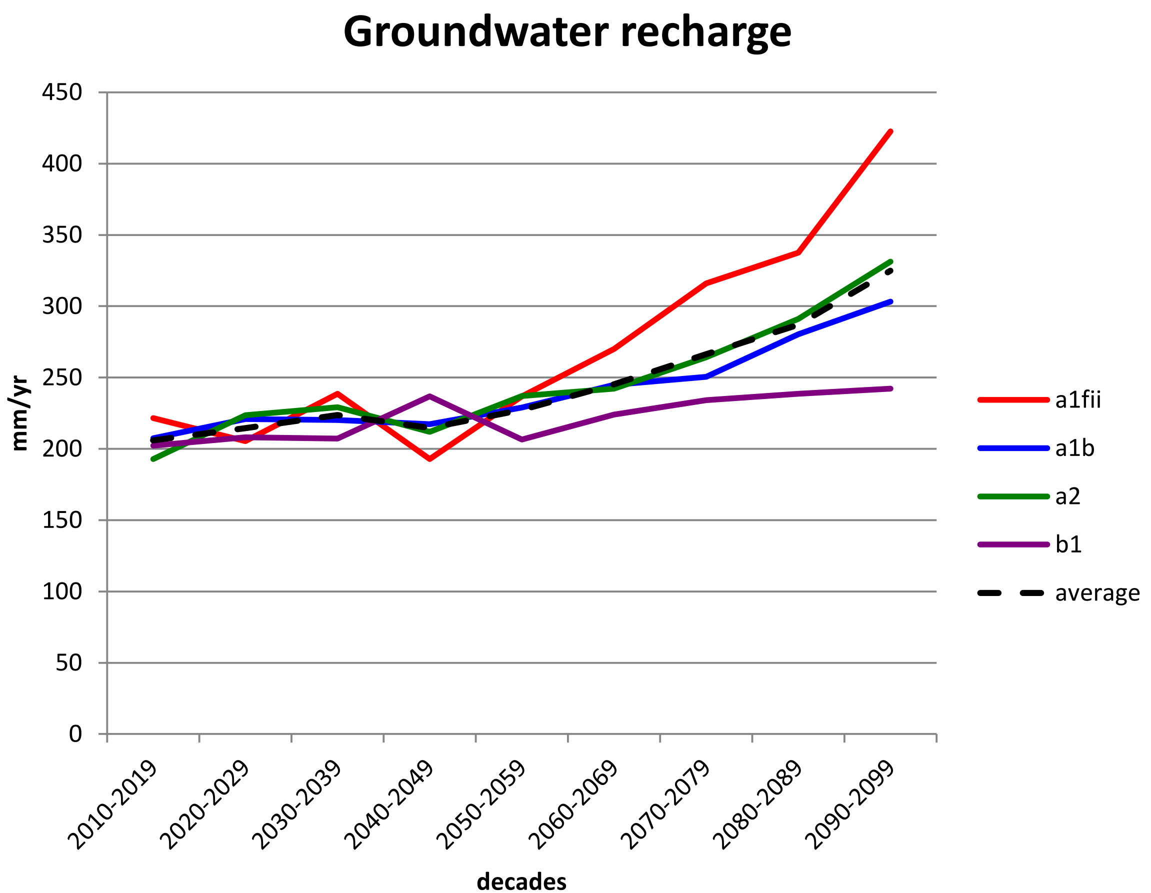

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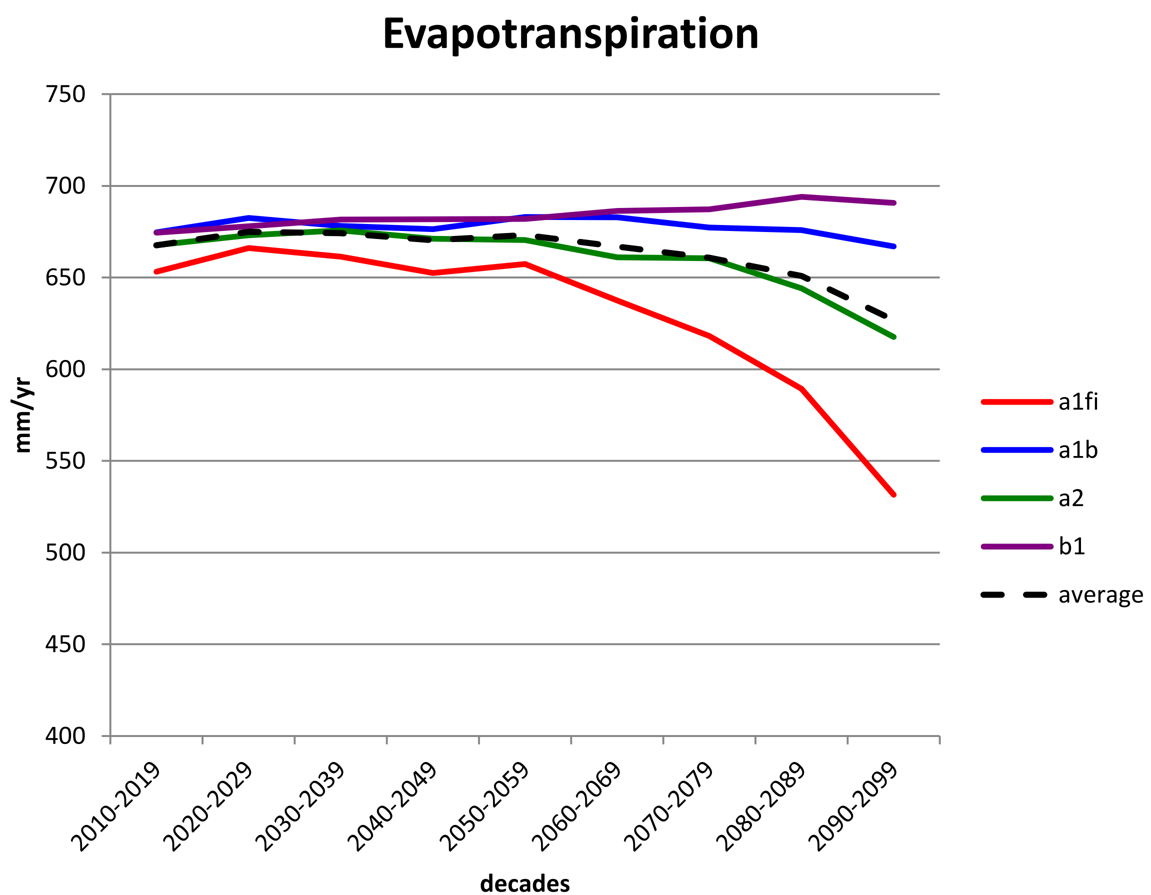

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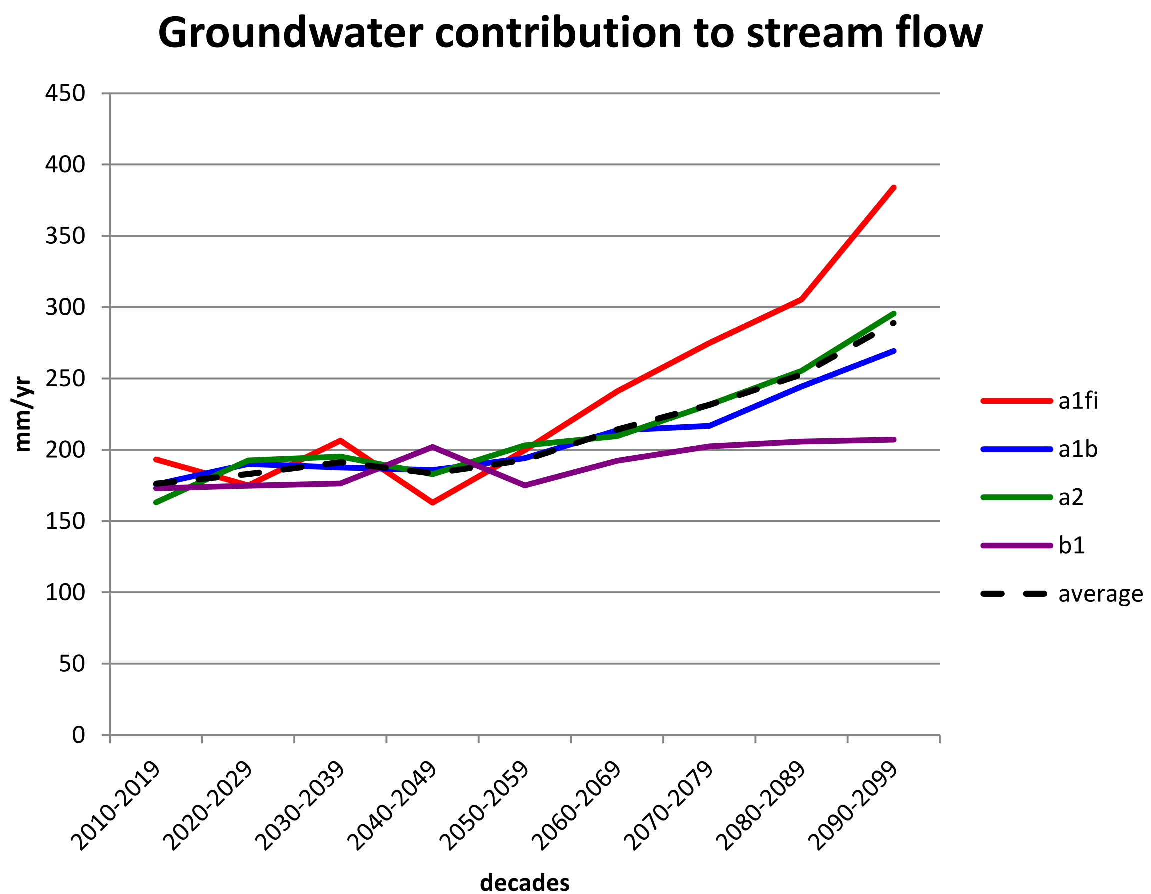

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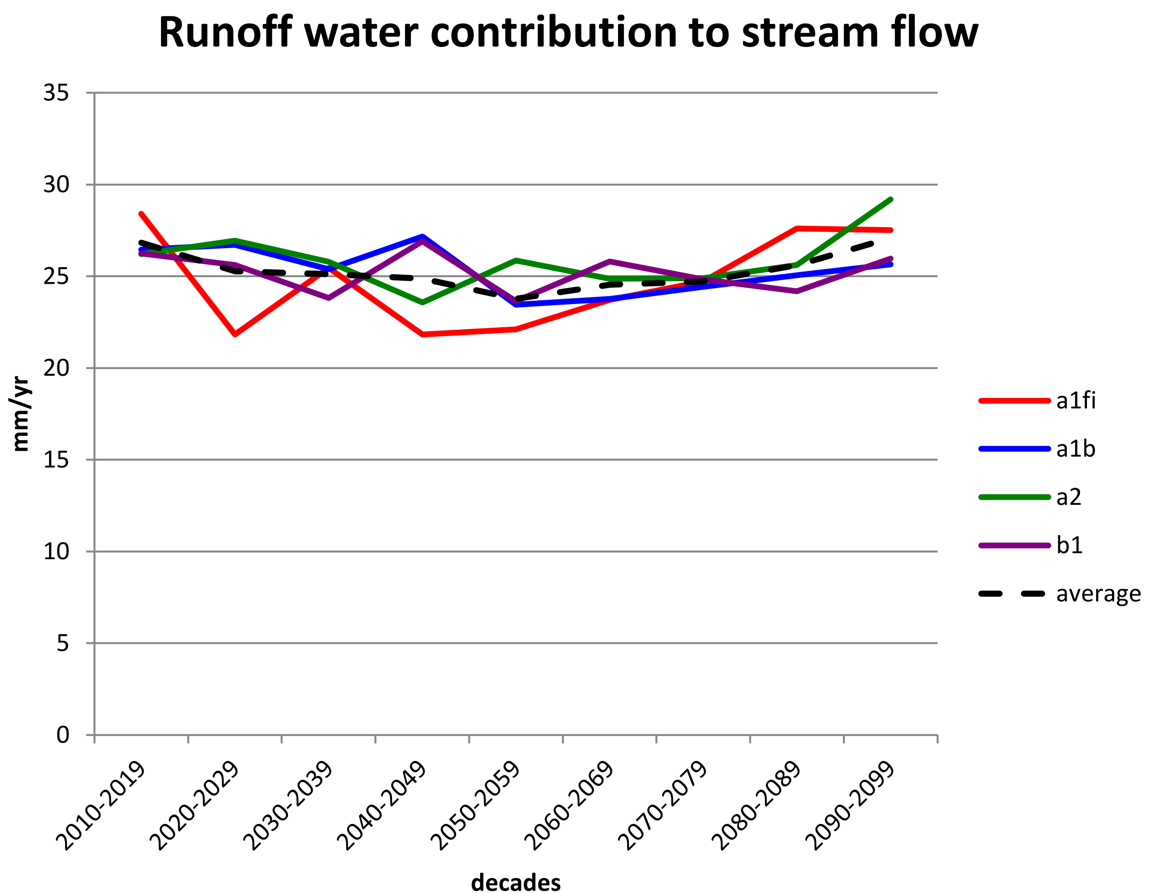

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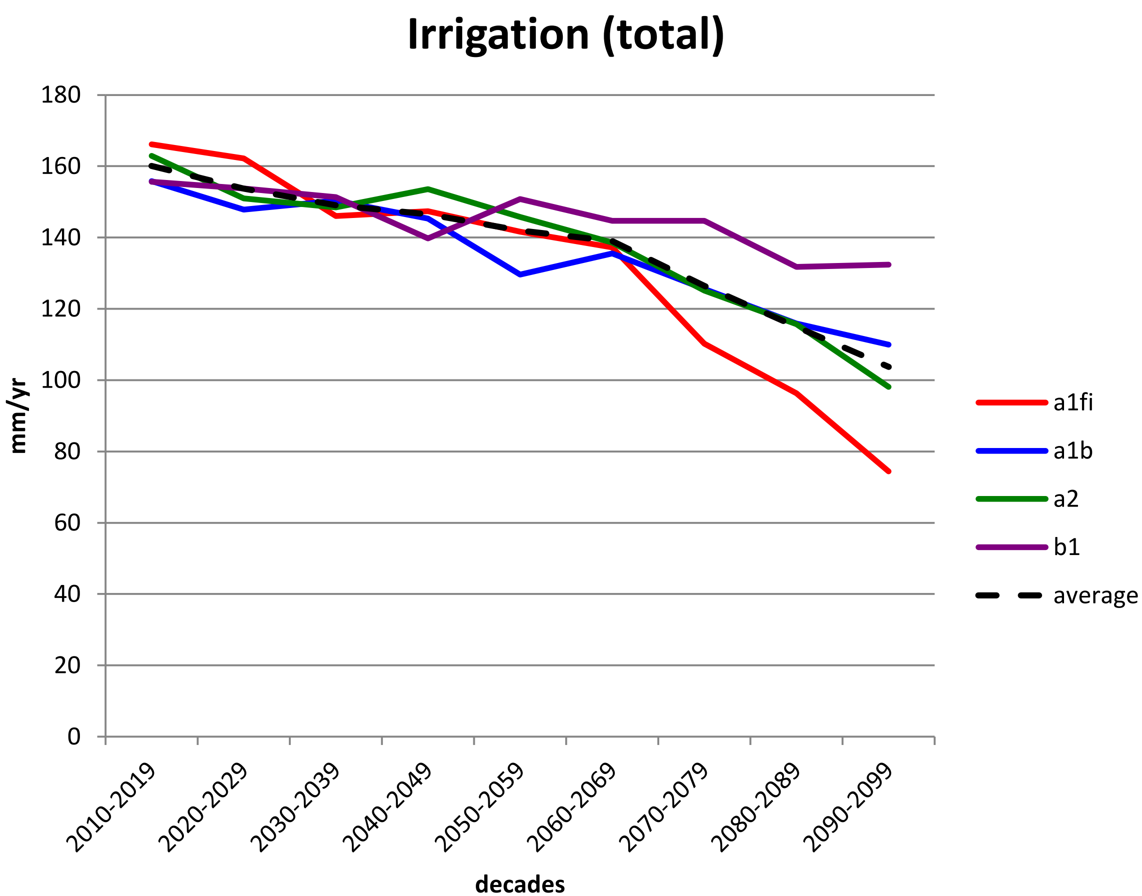

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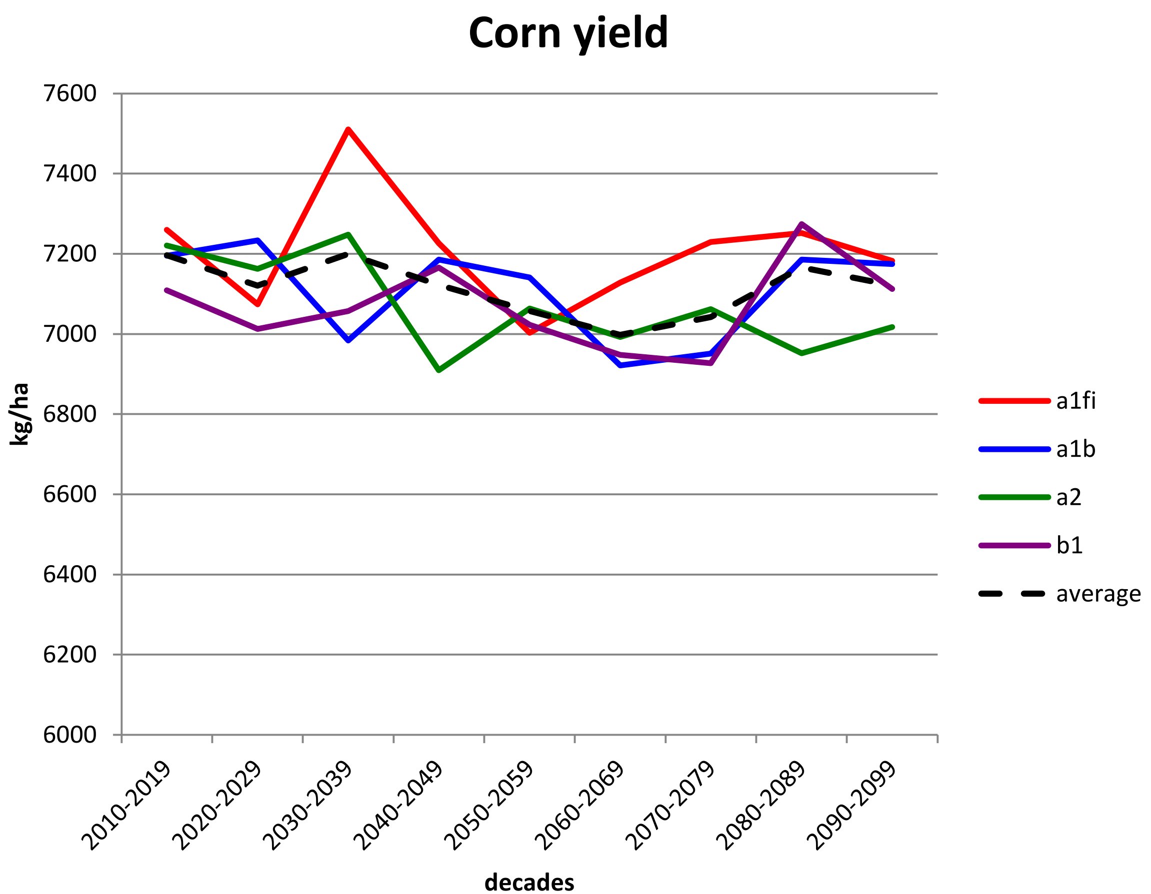


SWAT Future Simulations

- Changes in recharge (120mm, 60%) due to two primary sources:
  - Increased precip over the century (100mm, 10%)
  - Decreased ET over the century (50 mm, 8%)
- Lower ET caused by higher CO2, plants transpire less.
  - from the SWAT documentation:

> "As carbon dioxide levels increase, plant productivity increases and plant water requirements go down."
> "Morrison (1987) found that at CO2 concentrations between 330 and 660 ppmv, a doubling of CO2 concentration resulted in a 40% reduction in leaf conductance."

- CO2 is at 970 ppm by 2100 for A1Fi, 549 ppm for B1.

SWAT Future Simulations

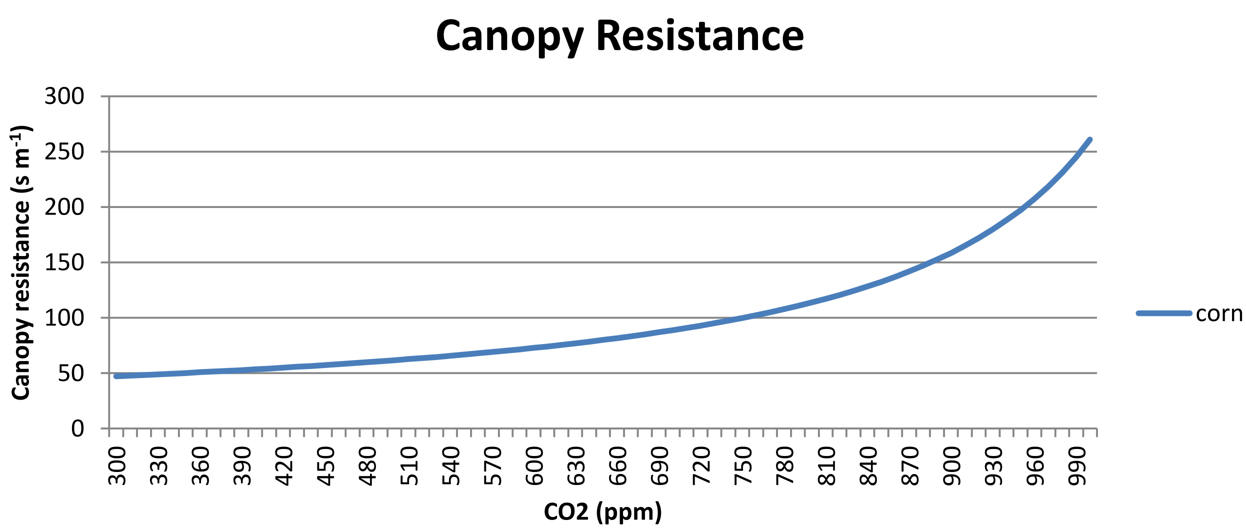
- From the SWAT Theoretical Documentation (p. 130):

$$r_c = r_\ell \cdot \left[(0.5 \cdot LAI) \cdot \left(1.4 - 0.4 \cdot \frac{CO_2}{330} \right) \right]^{-1}$$

r_c = plant canopy resistance (s m^{-1})

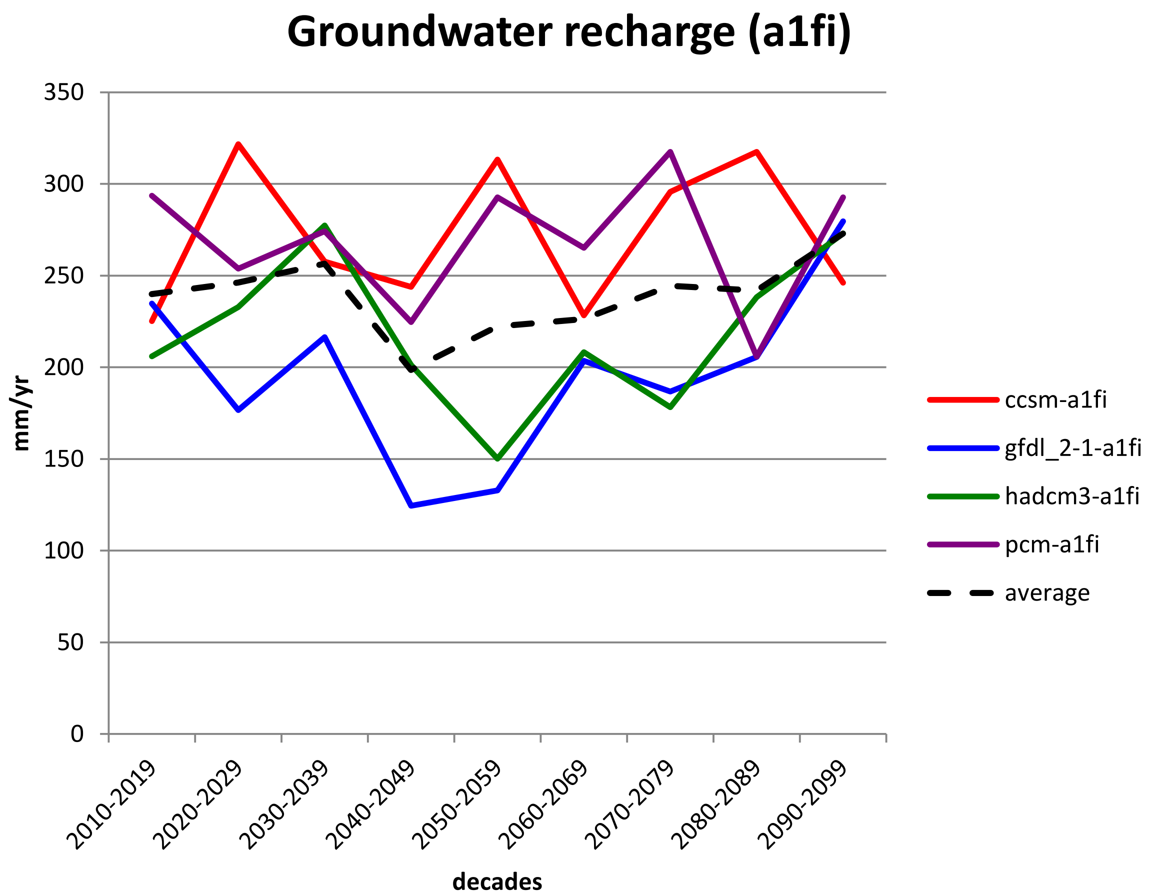
r_ℓ = minimum resistance of a single leaf (s m^{-1})

LAI = leaf area index



SWAT Future Simulations

- Holding CO2 constant in 04097540 kept recharge flat while ET rose slightly.



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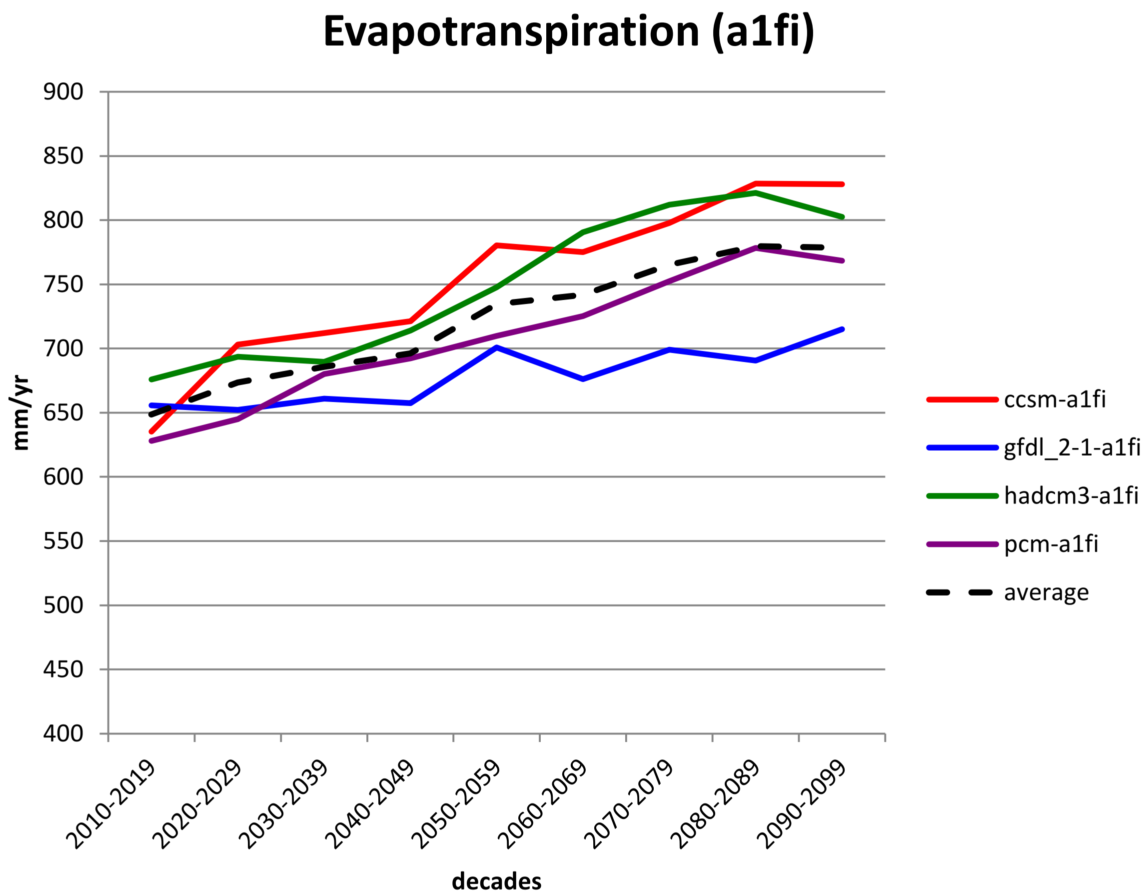
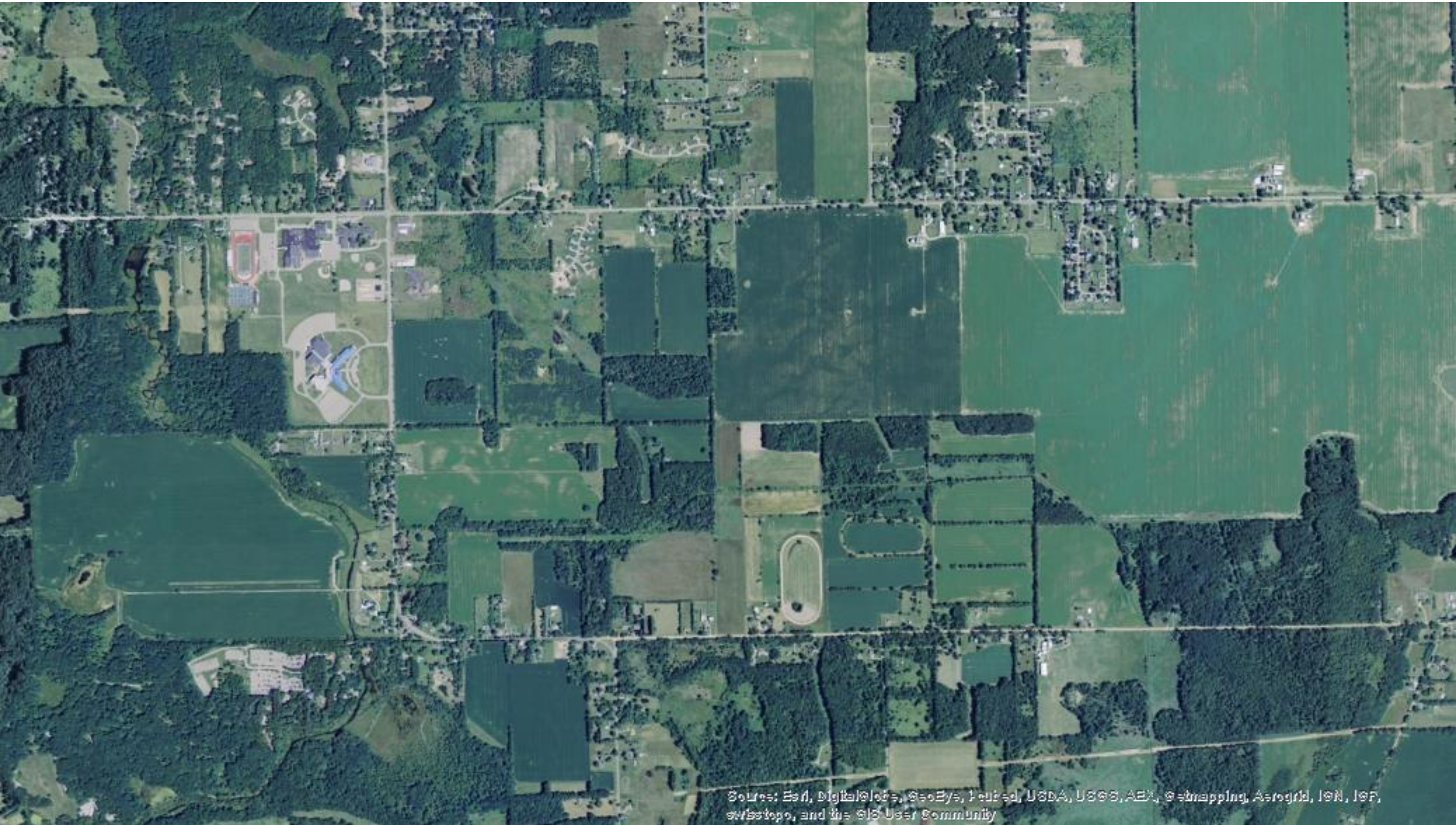


SWAT Future Simulations - Spatial differences in HRU outputs.



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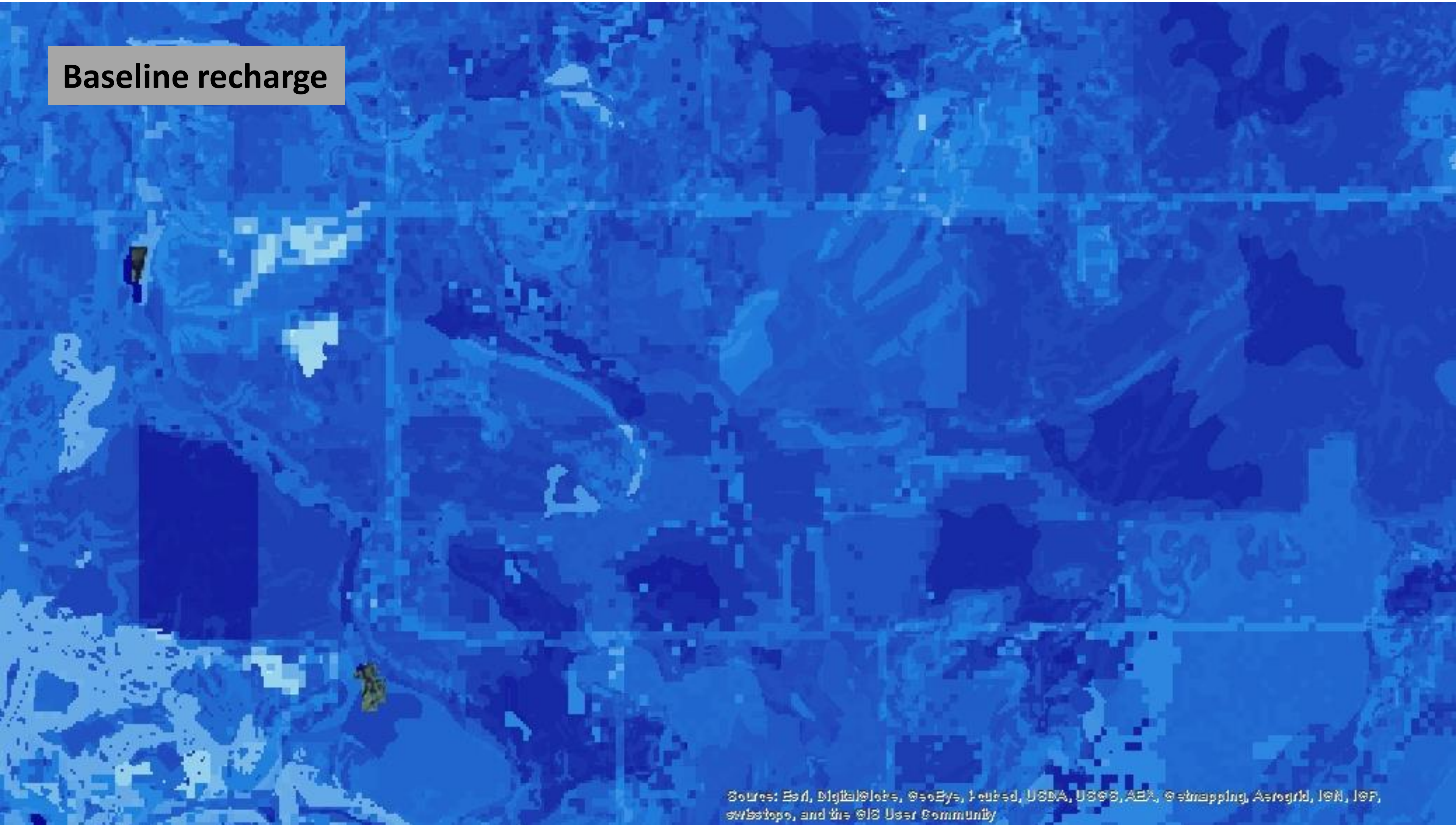

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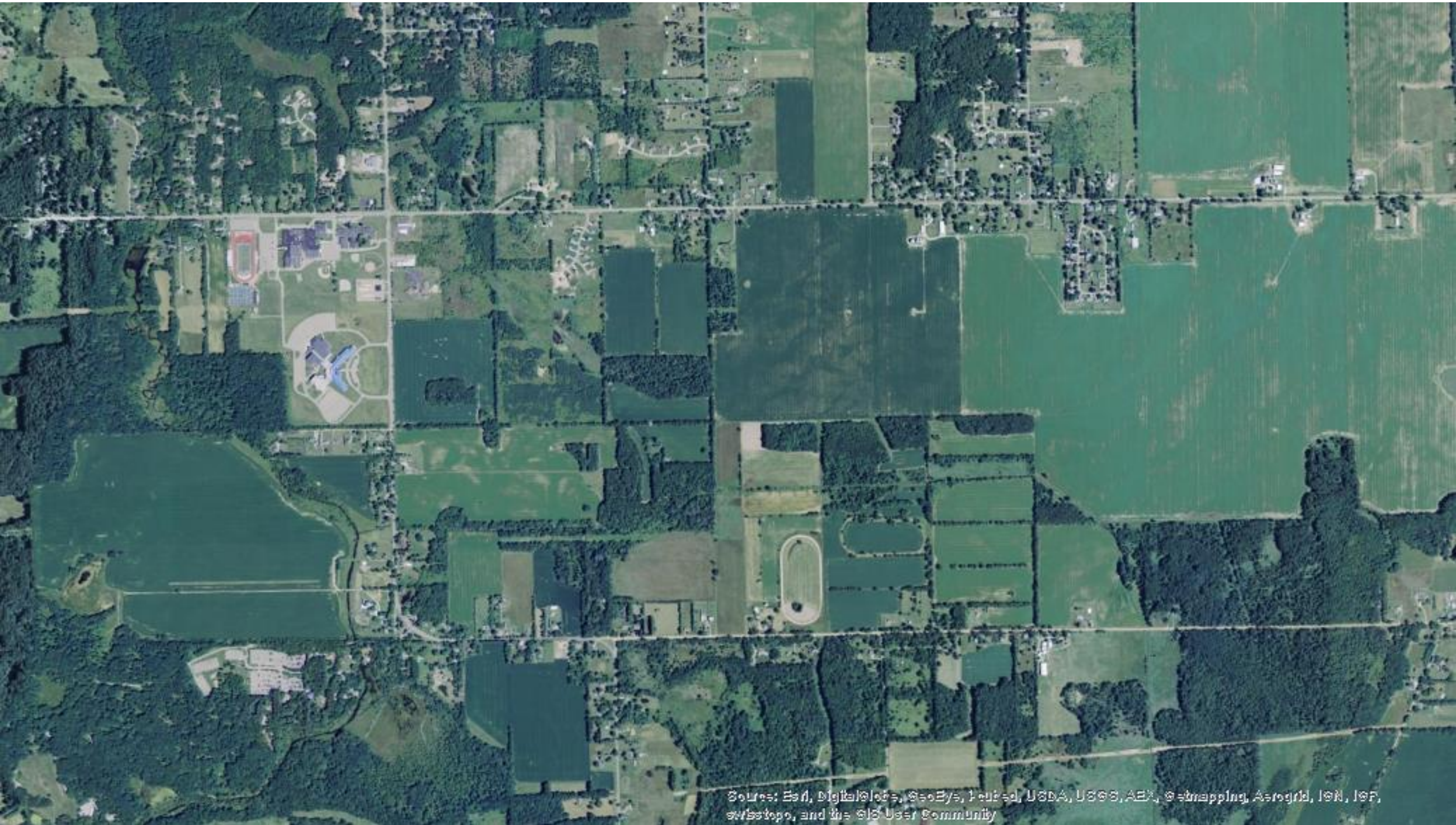

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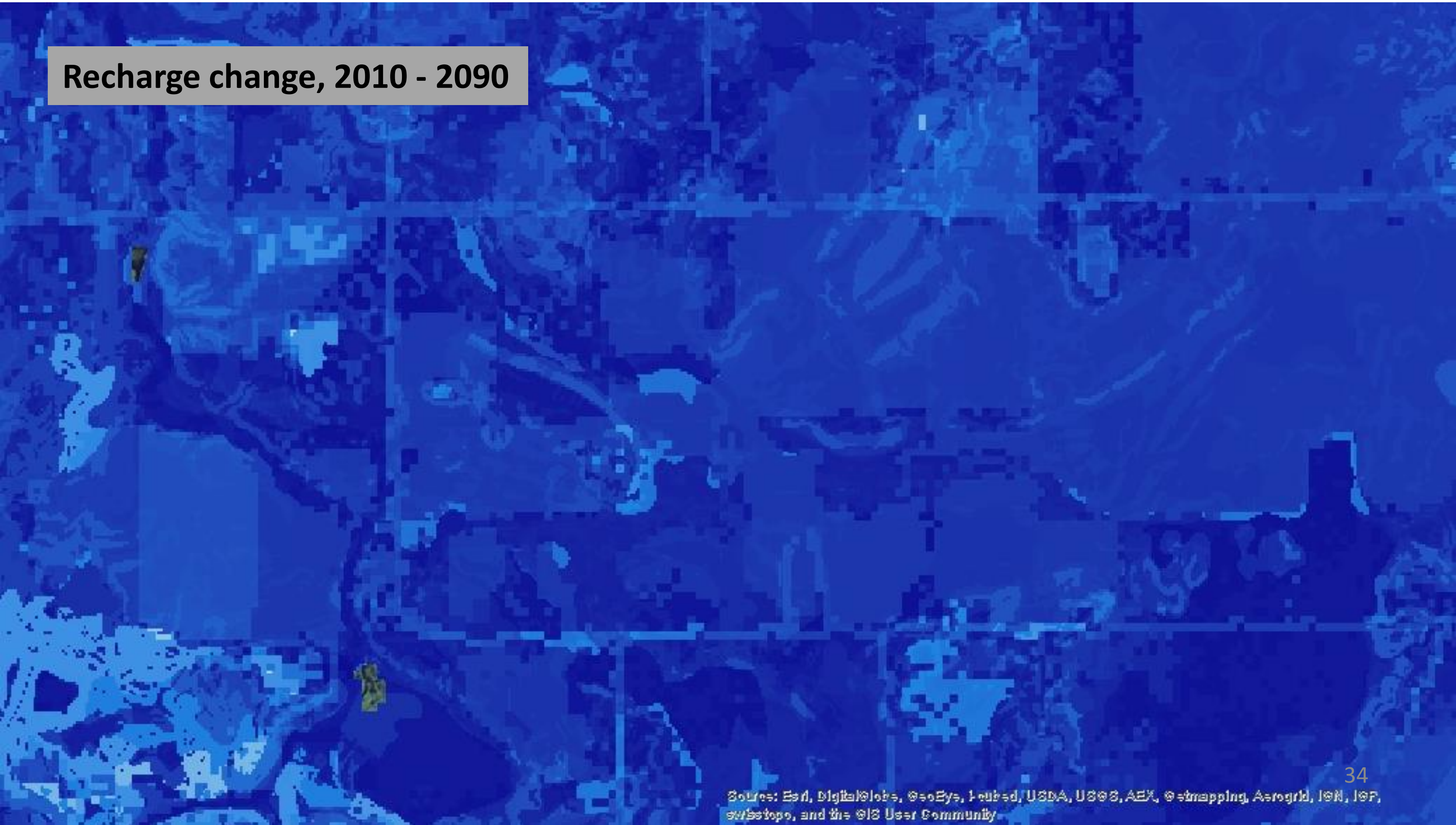
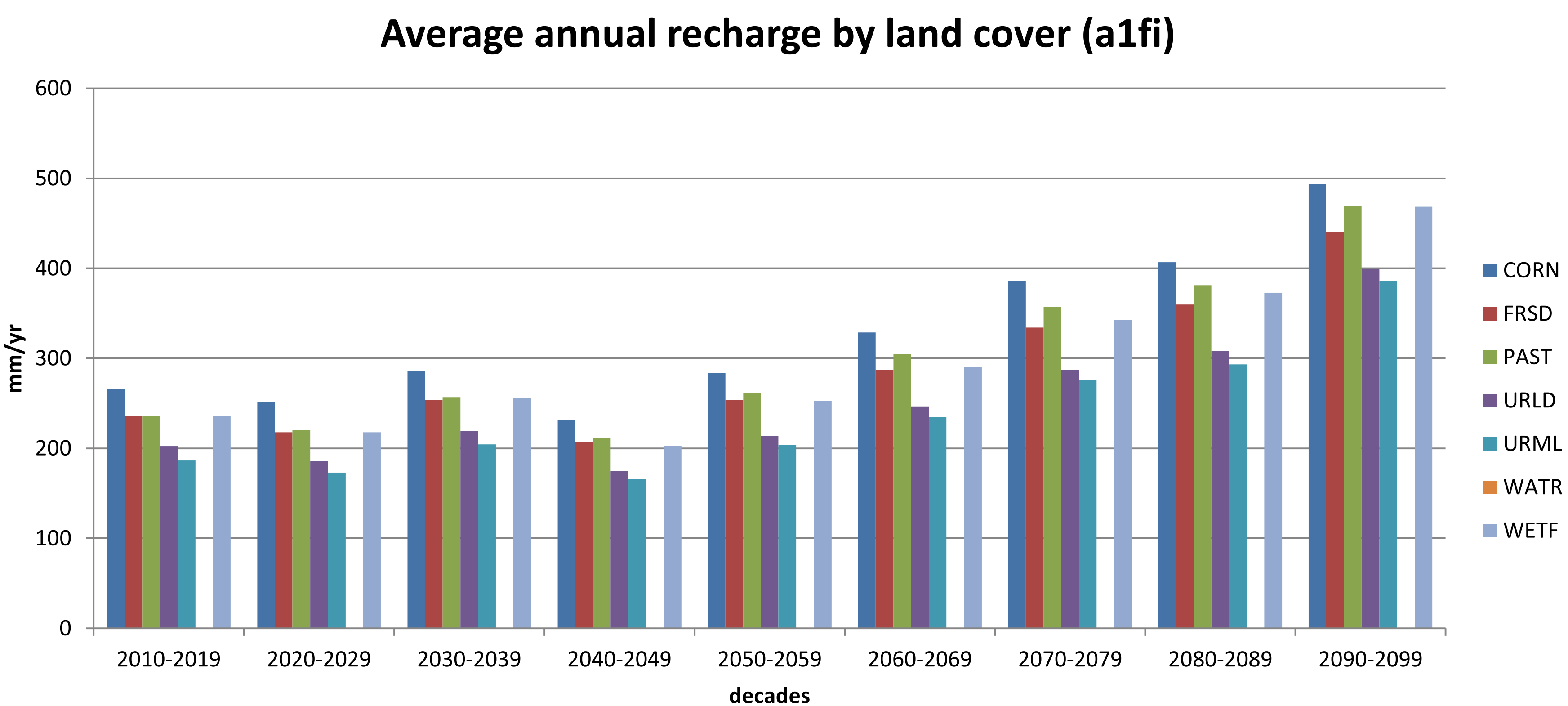


SWAT Future Simulations

- Corn areas in 04106000 recharged most, urban least.
- Pasture started even with forest, surpassed it around 2050.



Limitations

- Land cover did not change in future simulations.

- Solar radiation and relative humidity did not change.

- Growing season parameters did not change (e.g. no double-cropping).

- Did not calibrate for nutrients, may affect crop-growth.

Conclusions

- Groundwater recharge generally decreased in future climate scenarios, except for the b1 scenario.

- ET generally increased, except for the b1 scenario, due to increased CO2 levels.

- Crop yields were flat.

- Spatially, largest increases in recharge through 2100 are in forested and pasture areas.

Next Steps

- Feed the recharge maps into MODFLOW to produce steady-state head for each decade within each climate scenario.

- Run another batch of simulations for increased urbanization (more imperviousness around urban centers, more consumptive water use), with current climate conditions.

- Run another batch of simulations for expanded agriculture (marginal lands converted to corn-soy rotations, more lands implementing irrigation), with current climate conditions.

- Run a final batch of simulations combining the increased urbanization, agricultural expansion, and changing climate.

References

Hayhoe, K. 2013. Development and dissemination of a high-resolution national climate change dataset. *Final Report for United States Geological Survey, USGS G10AC00248 (Accessed online 10-08-2014 at: https://nccwsc. usgs. gov/displayproject/5050cc22e4b0be20bb30eacc/4f833ee9e4b0e84f608680df)*. http://cida.usgs.gov/thredds/catalog.html?dataset=dcp

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Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States*." *Journal of Climate* 15 (22): 3237–51. doi:10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2. http://cida.usgs.gov/thredds/catalog.html?dataset=cida.usgs.gov/new_gmo