A framework to compare water-balance components, streamflow, and nutrient export from CONUS-scale watershed models, applied to the Illinois River Basin

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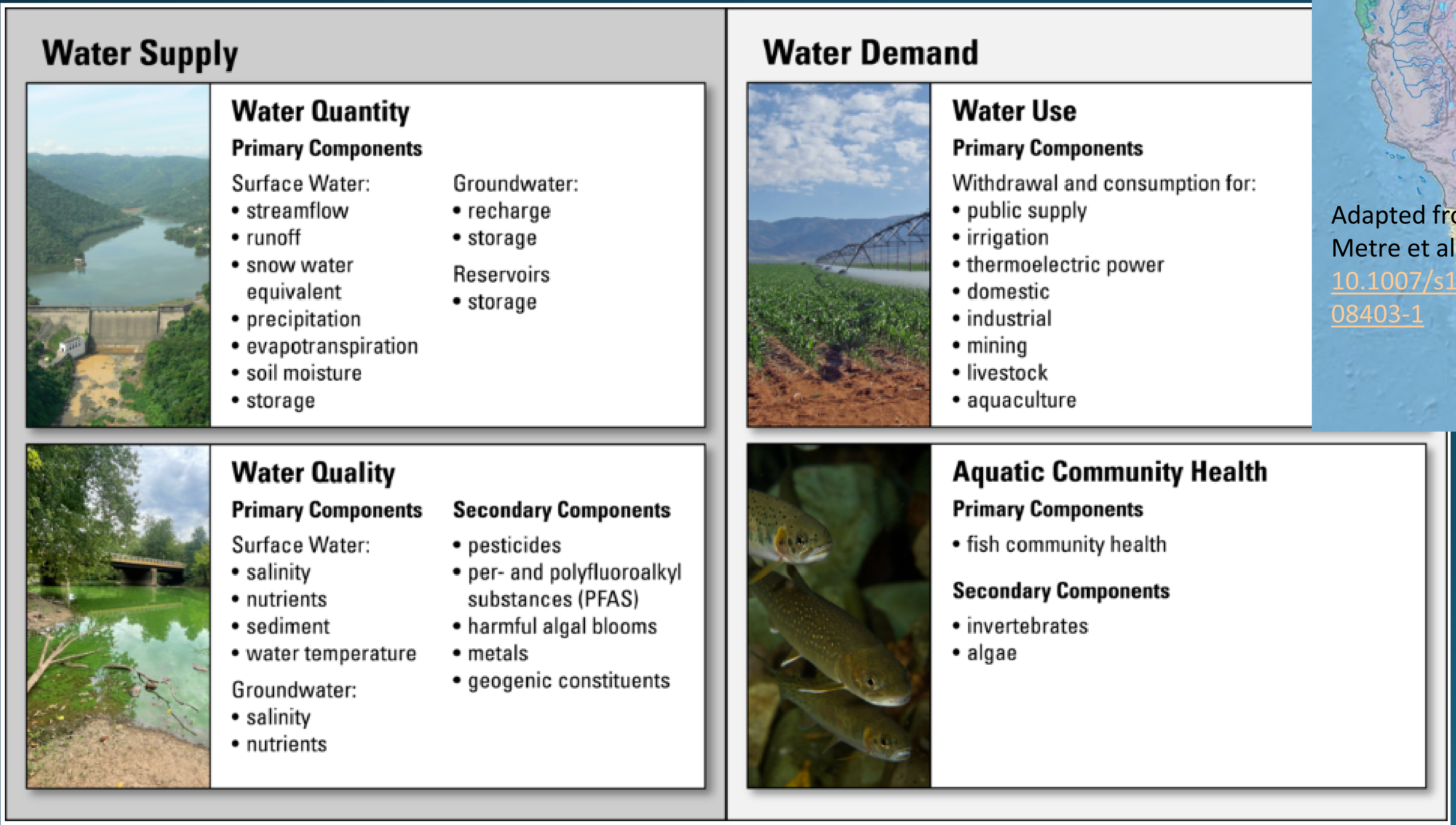
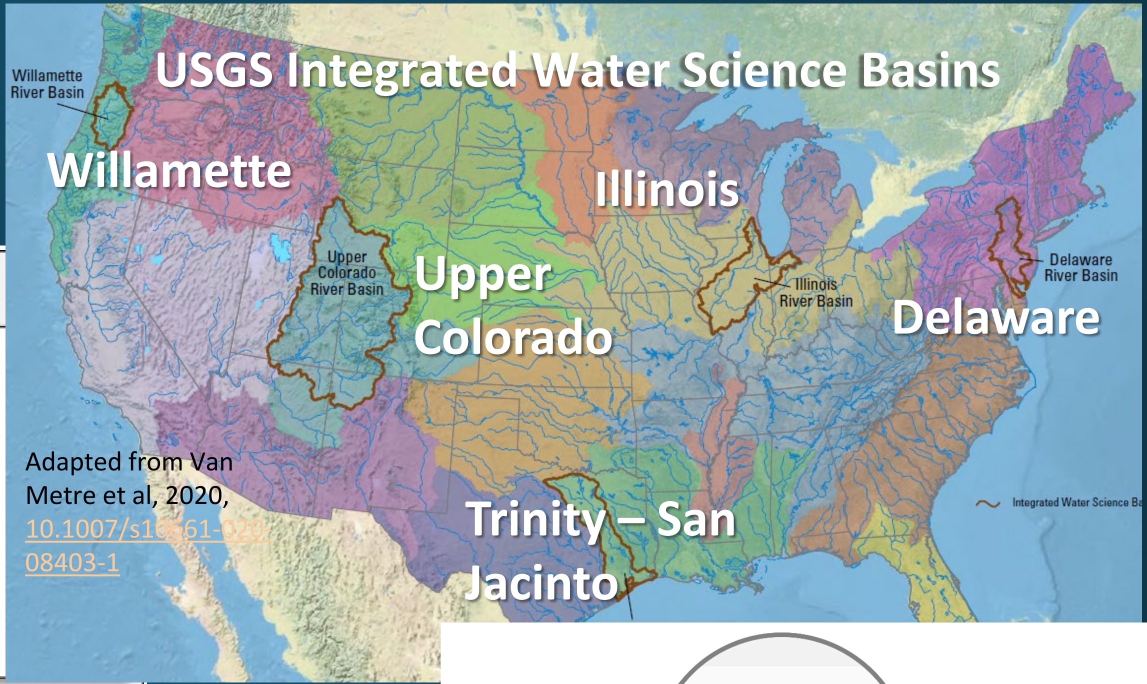
USGS Need - Methods and Tools for Assessing National and Regional Water Availability

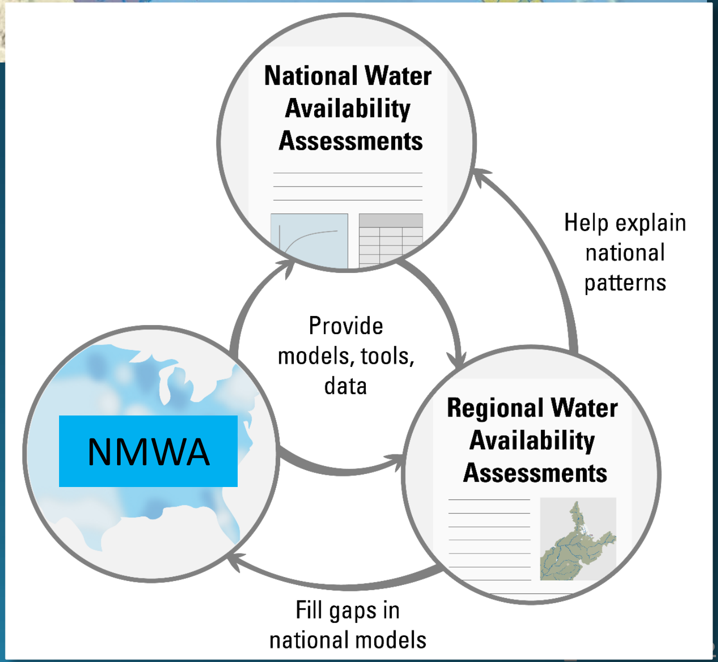
The SECURE Water Act tasked the USGS with assessing water availability - quantity and quality of water for both human and aquatic ecosystem needs



Core indicators



National Modeled Water Atlas: Water Supply and Demand Estimates in Your Watershed Through Time



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Purpose

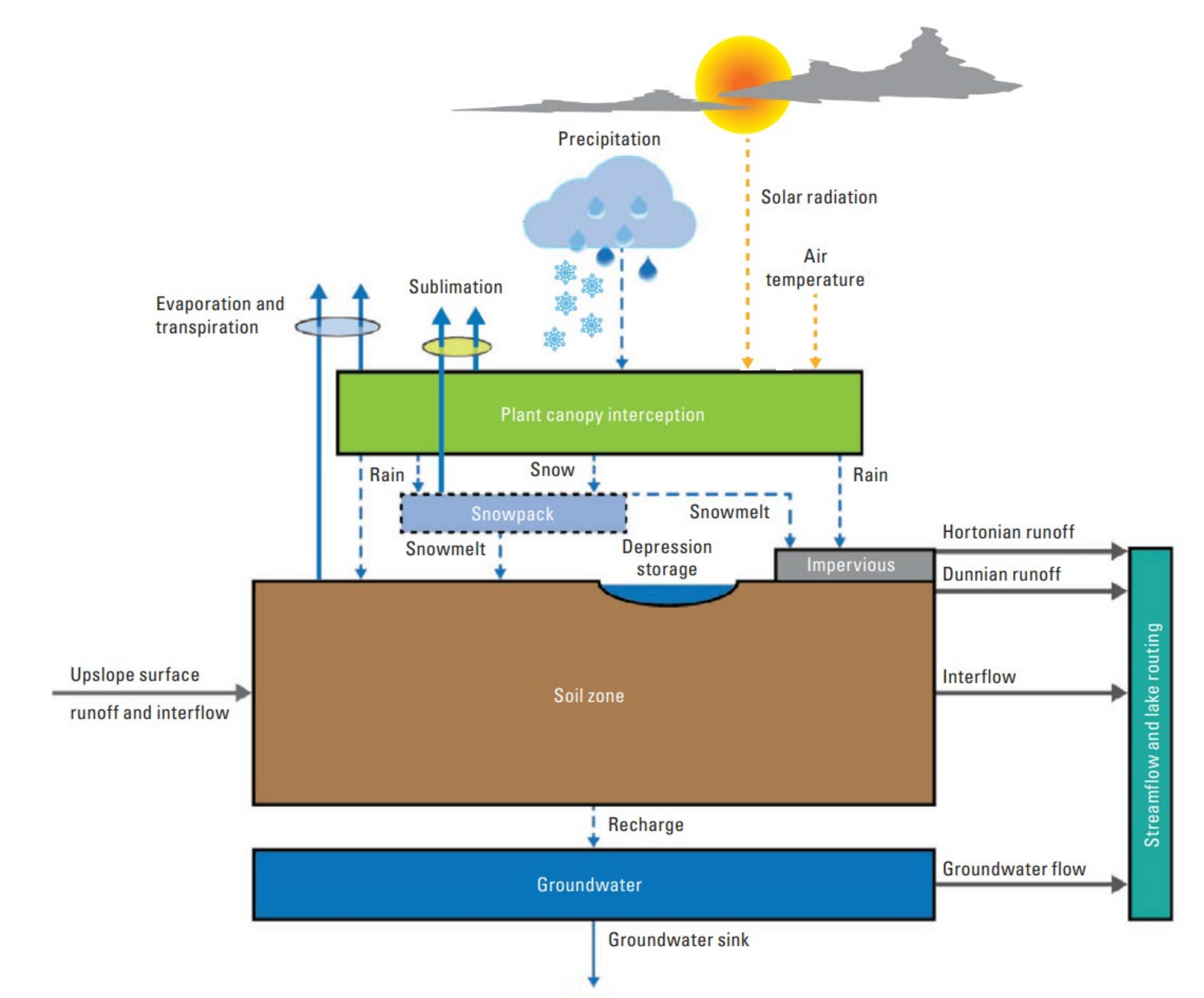
1. Develop a model evaluation framework
2. Evaluate existing National-scale or Regional-scale watershed models of the contiguous USA
3. Models:

Hydrology	Water Quality
NAM (SWAT+)	NAM
NHMv1.0 (PRMS)	Dynamic SPARROW of Illinois River Watershed
NWMv2.1 (WRF-HYDRO)	

4. Examine:
   - Differences in approach, model structure, inputs, strengths & weaknesses, possible sources of error
   - Comparisons of the model outputs at:
     1. Water balance at HUC 12 framework
     2. Observational gages

National Hydrological Model (NHM)

- Developed by USGS
- Based on the Precipitation-Runoff Modeling System (PRMS)
- Focuses only on the hydrologic cycle
- Natural flows only
  - no reservoirs, diversions, irrigation, etc.
- Inputs/outputs in English units



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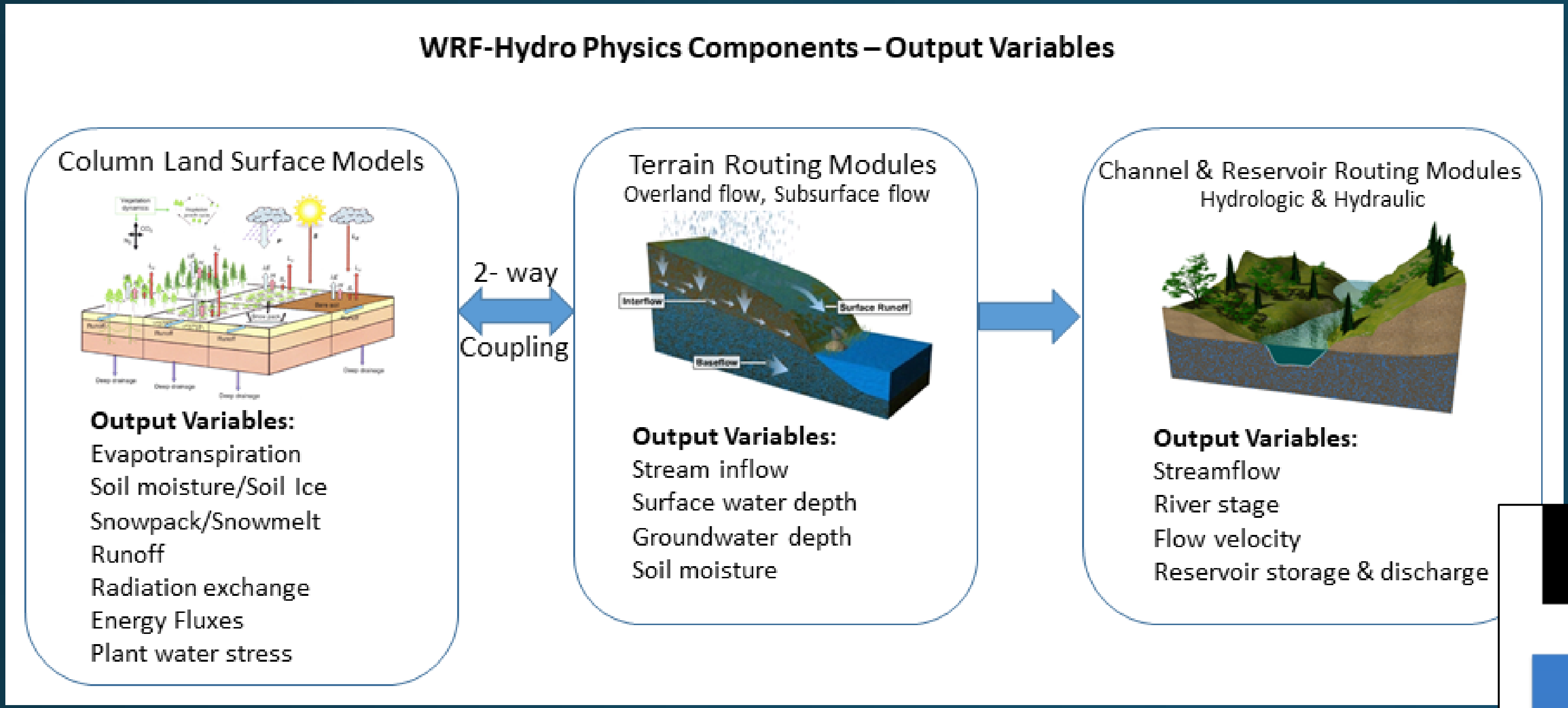
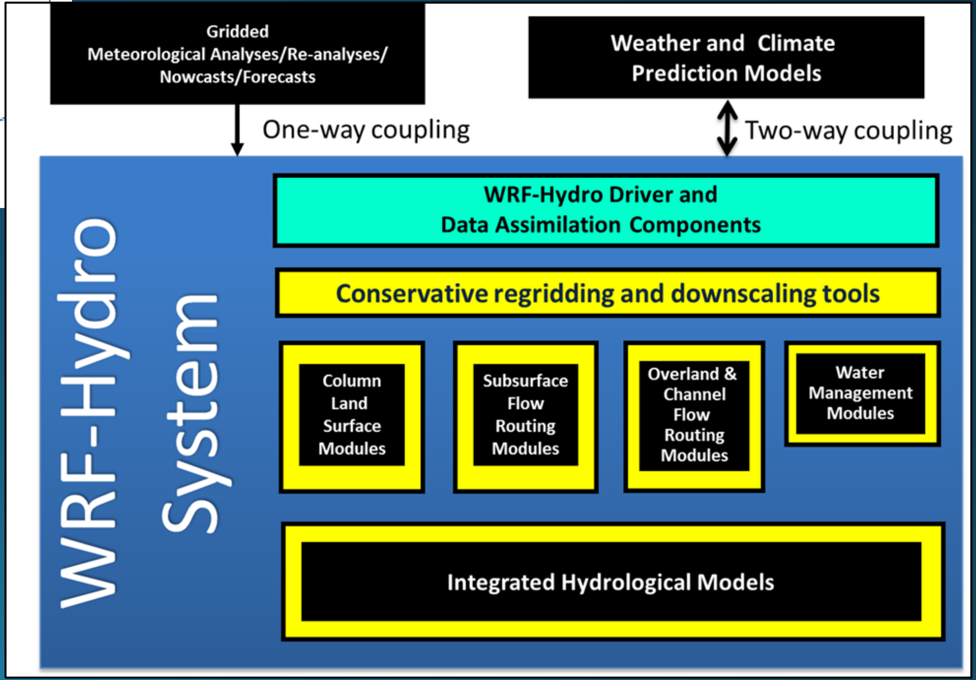
National Water Model (NWM)

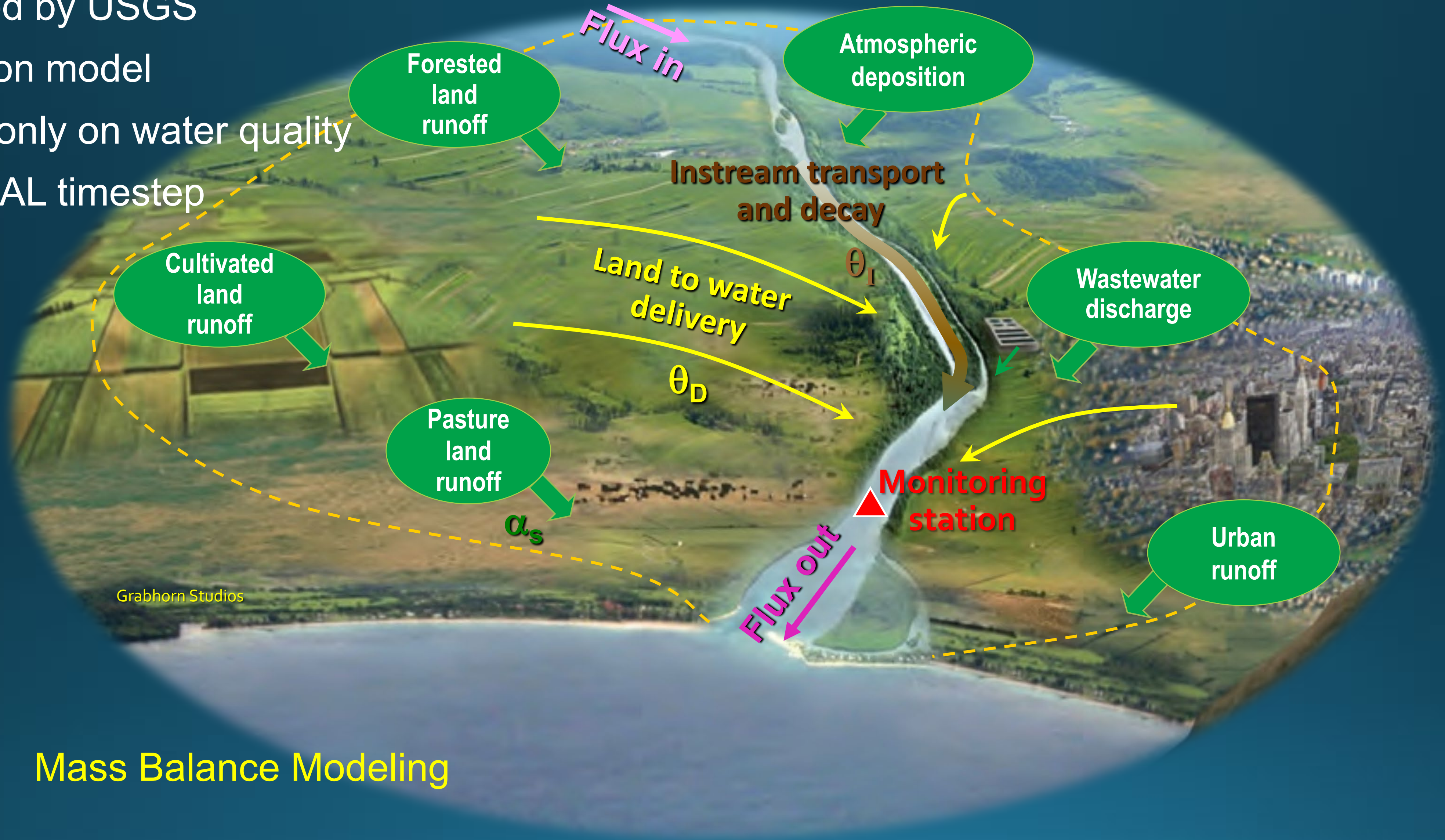


- Developed by National Oceanic and Atmospheric Administration (NOAA) National Center for Atmospheric Research (NCAR)
- Based on Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro)
- Open Source
- Hydrology model; flooding



SPARROW: SPAtially Referenced Regression on Watershed attributes Watershed Model

- Developed by USGS
- Regression model
- Focuses only on water quality
- SEASONAL timestep



Mass Balance Modeling

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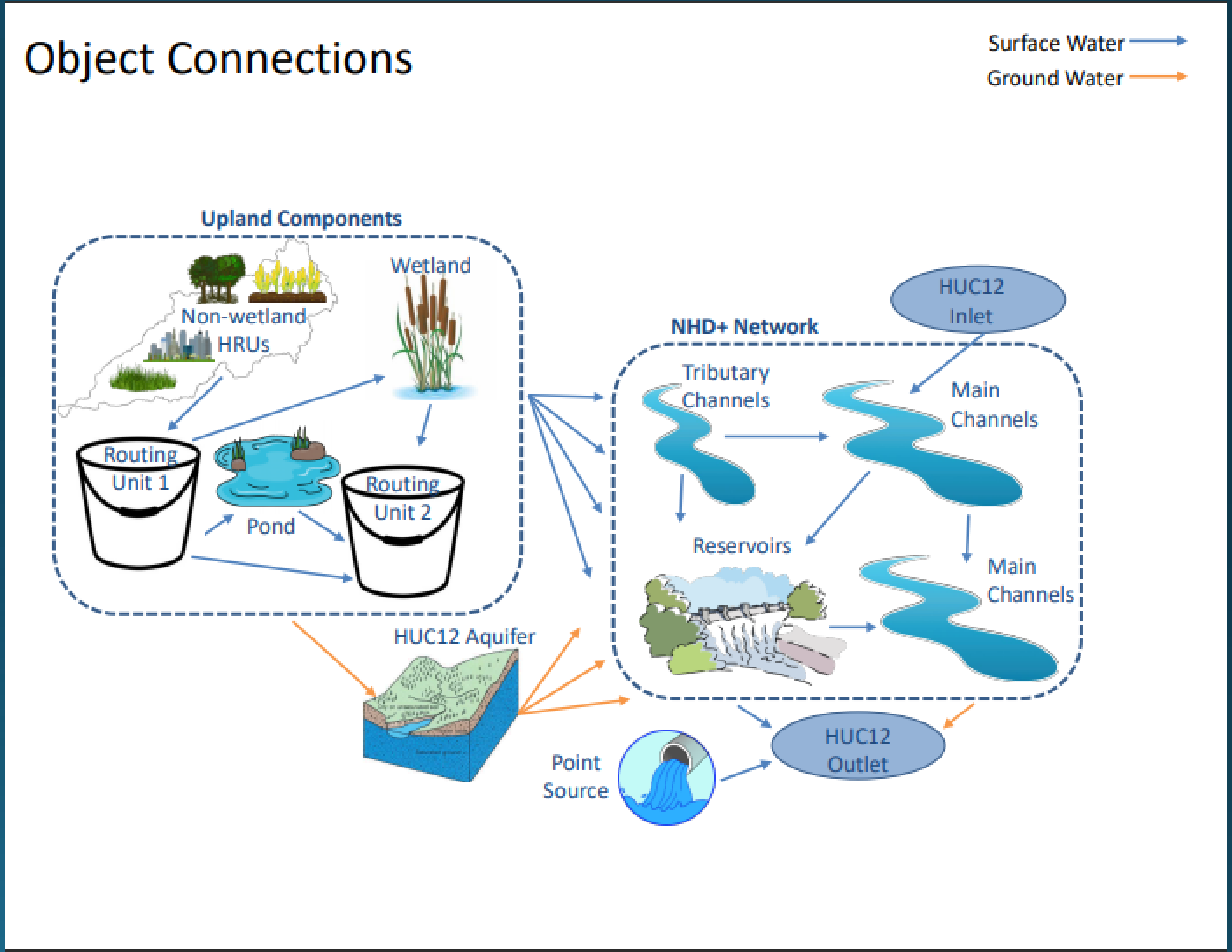
Target = Flux out = Flux in + (α_s Sources x θ_D Delivery) – θ_I **Instream Decay**

National Agroecosystems Model (NAM)

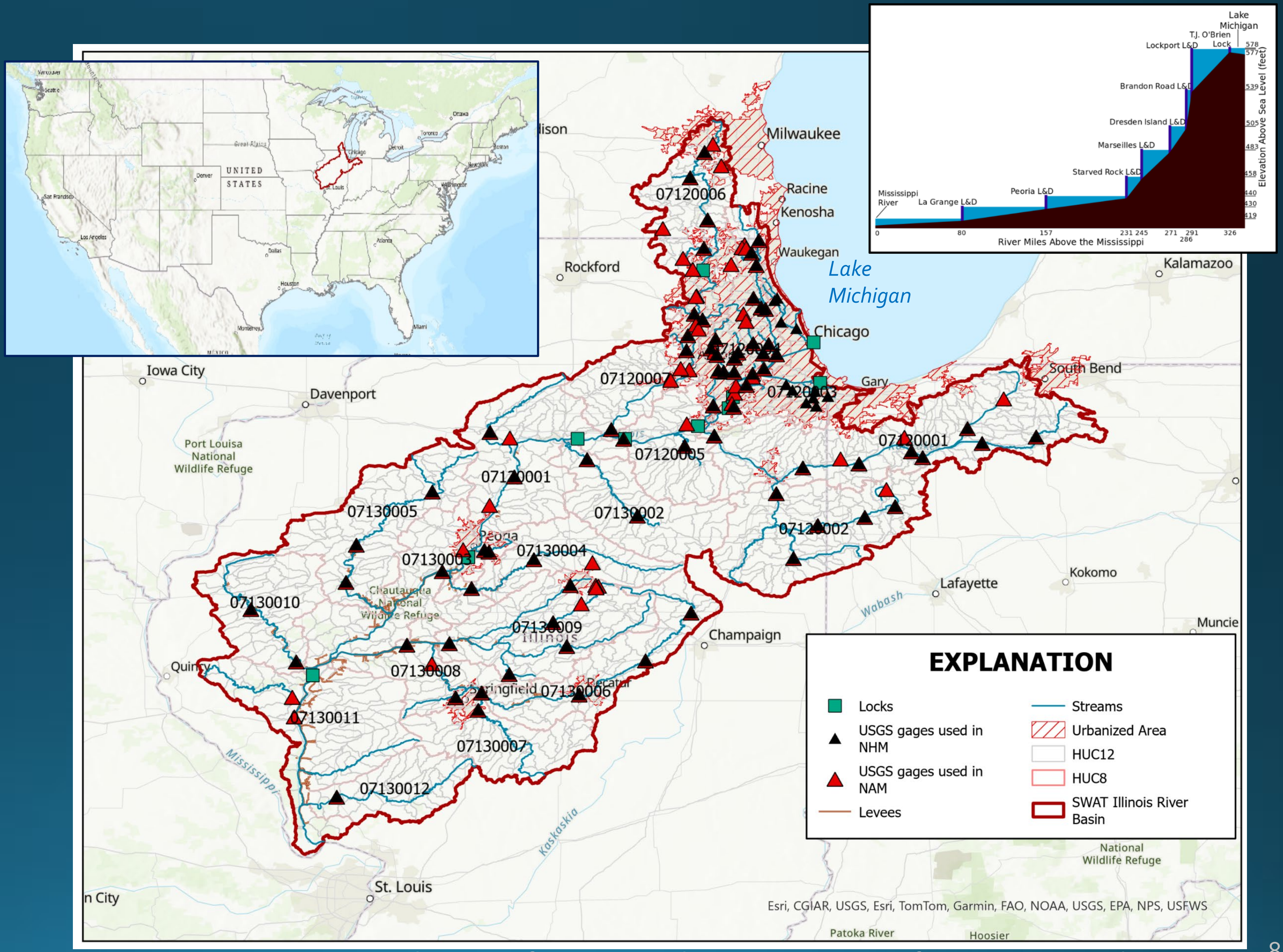
- Developed by USDA/ TX A&M
- Based on SWAT+
- Hydrology and water quality model

- still in development/undergoing calibration – results are preliminary



Study Area: Illinois River Watershed

- 4,920 km^2 (44% state of IL)
- 925 HUC12's
- 19 HUC8s
- 10 Locks and dams (7 on IL River)
- 1,303 km of levees
- Change in elevation of 578 ft (176 m) between Lake Michigan and the Mississippi River
- Urbanized in the area around Chicago
- Corn and soybeans downstate



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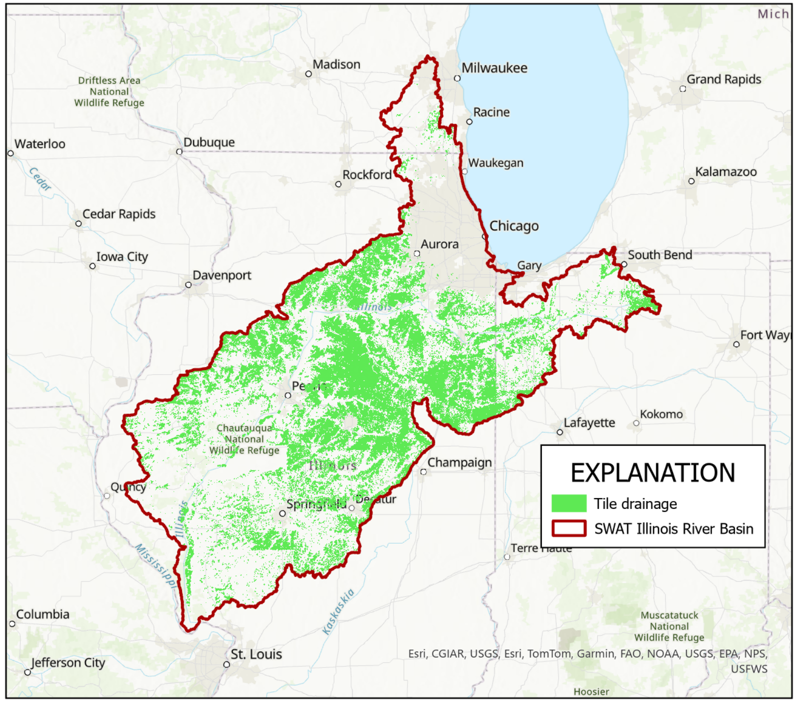
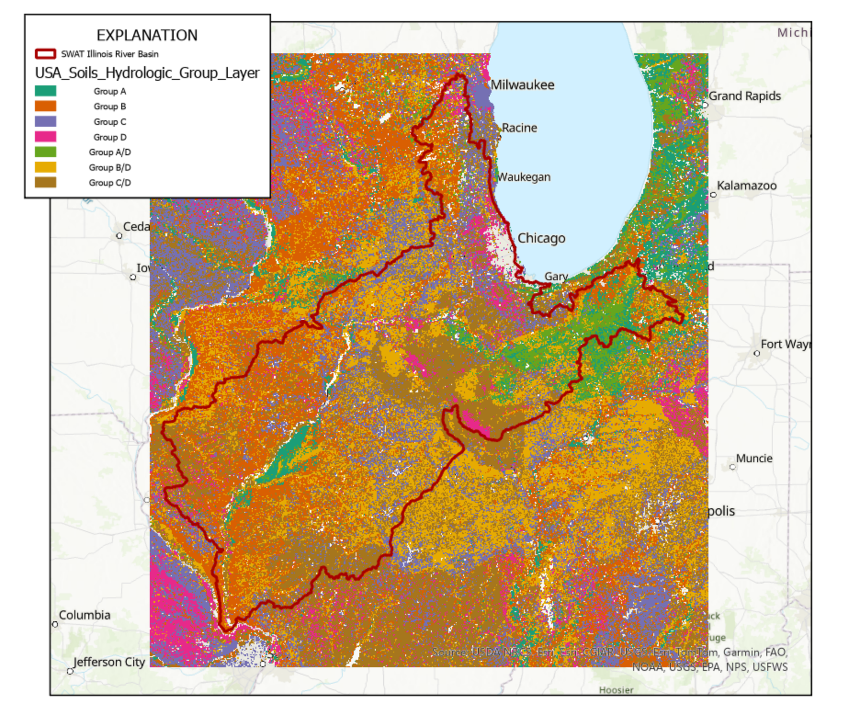
Study Area: Illinois River Watershed

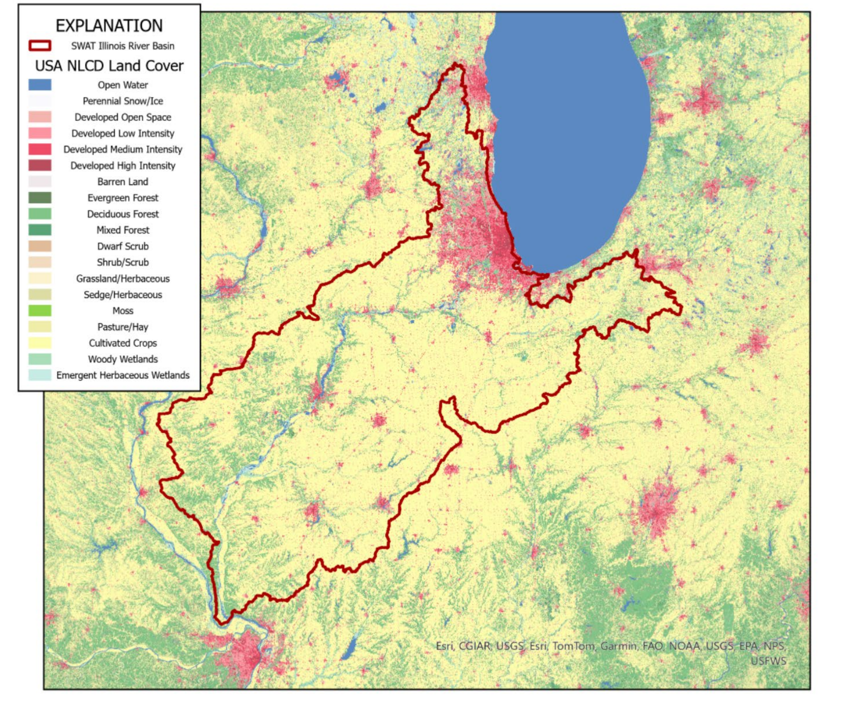
Tile Drainage (AgTile-US)



SSURGO soils



Land use – NLCD2021



Spatial framework summary → translate to HUC12s

	NAM	NHMv1.0	NWMv2.1	SPARROW
Cell resolution	Ag Field boundaries. Cell size variable	HRUs from [1]National Geospatial Fabric v1.1	NWM hydrofabric 1 km surface grid 250m stream routing grid	Catchments based on NHD+ streams ~ 2 km^2
HUC12 dataset	[4]Modified 2015 WBD HUC12	Recompiled by spatial weighting to HUC12s ([2,3]NHDPlusV2 snapshot from 10-26-202)	Recompiled by spatial weighting to HUC12s (NHDPlusV2)	Catchments compiled to the nearest HUC12
Number of HUCs	925	925	925/917*	918**
Model run timestep	Daily	Daily	Hourly	Seasonal

*Streamflow, baseflow, and surface runoff is excluded from the NWMv2.1 due to the lack of flow directions of the flowlines in 8 HUC12s.
**Compilation of flowlines to HUC12s in the SPARROW model lacked flowlines in 7 HUC12s.

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Model Inputs

	NAM (SWAT+)	NHM (PRMS)	NWM (WRFHYDRO)	SPARROW
DEM	X	X	X	X
Soils	X	X	X	If significant
Hydrography	X	X	X	X
Weather/Climate	X	X	X	If significant
Point Sources (location, outflow, loading)	X	X	X	X
Atmospheric deposition data	X			If significant
Tile drainage extent and depth	X			If significant
Septic extent, type, depth	Optional			If significant
Land use/land management	X	X	X	X
CAFO	X			
Wetlands, pond	X			If significant
Reservoirs, canals	X		X	X
Water use: irrigation, water transfer	X	X		If significant
Bathymetry	X		X	
Surficial geology	Optional			If significant
Geology WQ	Optional			

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Model Inputs

	NAM	NHMv1.0	NWMv2.1	SPARROW
Climate dataset	Modified GHCN; PRISM in western states Daily	Daymet version 3 1km resolution Daily	AORC 1km resolution hourly	NCEI nClimGrid 48.28 km resolution daily
Streams	NHDPlus Version 2	NHDPlus Version 1.0	NHDPlus Version 2 Medium Resolution	NHDPlus Version 2 Medium Resolution
Landuse	CDL 2012; Management from 2014, 2015, and 2016 CDLs	NLCD 2001	NLCD 2016	NLCD linear interpolation on a quarterly basis between the 5-year data.
Soils	gSSURGO	SSURGO	STATSGO	SSURGO and STATSGO

Model Algorithms

	NAM	NHMv1.0	NWMv2.1	SPARROW
Surface runoff	SCS Curve number	nonlinear variable-source-area method allowing for cascading flow	fully-unsteady, explicit, finite-difference, diffusive wave formulation like that of Julien et al. (1995) and Ogden et al. (1997).	Calculated from a Monthly Water Balance Model (McCabe and Wolock, 2011)
ET	Hargreaves PET	Jensen-Haise PET	Penman PET	
Snow processes	Snowmelt is controlled by a temperature index method. Snowpack is based on changes in accumulation	depletion processes by using an energy-budget approach	a multi-layer snow pack with liquid water storage and melt/refreeze capability and a snow-interception model describing loading/unloading, melt/refreeze capability, and sublimation of canopy-intercepted snow	--
Canopy interception	function of canopy storage and is normalized by the maximum plant leaf area index (LAI)	Computes volume of intercepted precipitation, evaporation from intercepted precipitation, and throughfall that reaches the soil or snowpack	a two-stream radiation transfer approach along with shading effects necessary to achieve proper surface energy and water transfer processes including under-canopy snow processes	--

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Model Algorithms continued

	NAM	NHMv1.0	NWMv2.1
Streamflow routing	Muskingum	Muskingum–Mann	Muskingum-Cunge
Baseflow/ groundwater	Baseflow occurs if groundwater storage exceeds a storage threshold	Sums inflow to and outflow from groundwater reservoirs; outflow can be routed to downslope groundwater reservoirs and stream segments	non-linear, conceptual baseflow bucket model Boussinesq Approximation - Simple exponential decay
Soil Zone	Kinematic storage model is in each soil layer. Accounts for variation in conductivity, slope, and soil water content	Computes inflows to and outflows from soil zone of each HRU and includes inflows from infiltration, groundwater, and upslope HRUs, and outflows to gravity drainage, interflow, and surface runoff to downslope HRUs	Boussinesq approximation -- effective 2-dimensional calculation of saturated subsurface lateral transport.
Reservoirs	[1]Generalized methods for (i) reservoir capacity; (ii) reservoir release; (iii) climate conditions; (iv) reservoir storage and release.	--	passive storage and releases from waterbodies – no active management

Hydrology Calibration Procedure

	NAM	NHMv1.0	NWMv2.1
Calibration POR	2000 to 2013	odd water years from 1981 to 2010	water years 2008 to 2013
Validation POR	--	even water years from 1982 to 2010	water years 2014 to 2016
Calibration points	1. Water yield @ HUC8s 2. ~150 gages for SS, TN, and TP	1. Water balance components 2. Statistically generated 7,265 headwater watersheds (DA < 3,000 km^2) 3. observed gaged streamflow at 1,417 stream gage	a subset of 14 soil, vegetation, and baseflow parameters to streamflow in **1,378** gaged, predominantly natural flow basins.
Calibration method	1. Soft calibration: water balance components, crop yield, flow duration curves 2. Dynamically Dimensioned Search Algorithm	Uses a multiple objective, stepwise approach to identify an optimal parameter set that balances water budgets and streamflow	Dynamically Dimensioned Search algorithm to optimize parameters to a weighted NSE of hourly streamflow (mean of the standard NSE and log-transformed NSE).

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Water Quality Inputs

	NAM	SPARROW
Atmospheric deposition	National Atmospheric Deposition Program	
Point Sources	2002 – (USGS) Maupin and Ivahnenko, 2011* 2012 – (USGS) Skinner and Maupin, 2019 Compiled from U.S. Environmental Protection Agency Integrated Compliance Information System (ICIS) and Permit Compliance System (PCS) databases	2018 – (USGS) Skinner et al. 2024 (*in prep)* Compiled from U.S. Environmental Protection Agency Integrated Compliance Information System (ICIS) and Permit Compliance System (PCS) databases
Fertilizer application - quantity	US Agricultural Census fertilizer application data from 2012	1. Falcone, J. 2020. Estimates of County-Level Nitrogen and Phosphorus from Fertilizer and Manure from 1950 through 2017 in the Conterminous United States, USGS Report. 2. Sekellick, A.J. and Sherr, C.E., 2024, Nitrogen and phosphorus inputs from fertilizer and manure in the Continental United States, 2002-2012: U.S. Geological Survey data.
Manure production	2012 US Agricultural Census at HUC6 Gollehon et al. 2016	
Fertilizer application - timing	management templates using dates from White et al. 2016	seasonal application based on monthly estimation of nitrate emissions from Community Multiscale Air Quality modeling
Geologic parent material	--	Background release from natural soils (Robertson and Saad, 2019)

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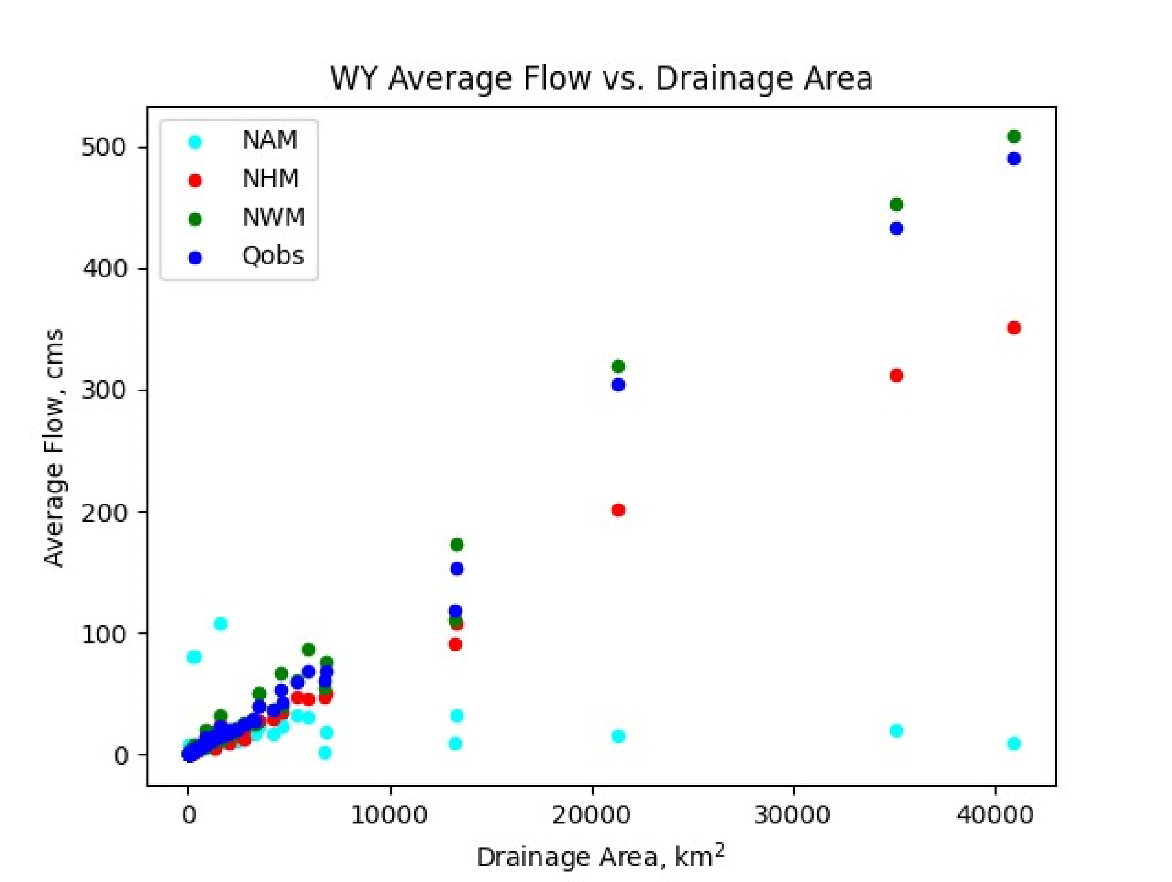
Model evaluation statistics computed for Hydrology (at USGS gages)

1. Nash-Sutcliffe (NSE)
2. Percent bias (PBIAS)
3. Kling-Gupta Efficiency (KGE)
4. Log NSE
5. Mean Squared Error (MSE)
6. Root Mean square error (RMSE)
7. Pearson Correlation coefficient
8. Spearman Correlation coefficient
9. Ratio of standard deviation
10. PBIAS in flow duration curve mid-slope segment
11. PBIAS in flow duration curve high-segment volume
12. PBIAS in flow duration curve low-segment volume



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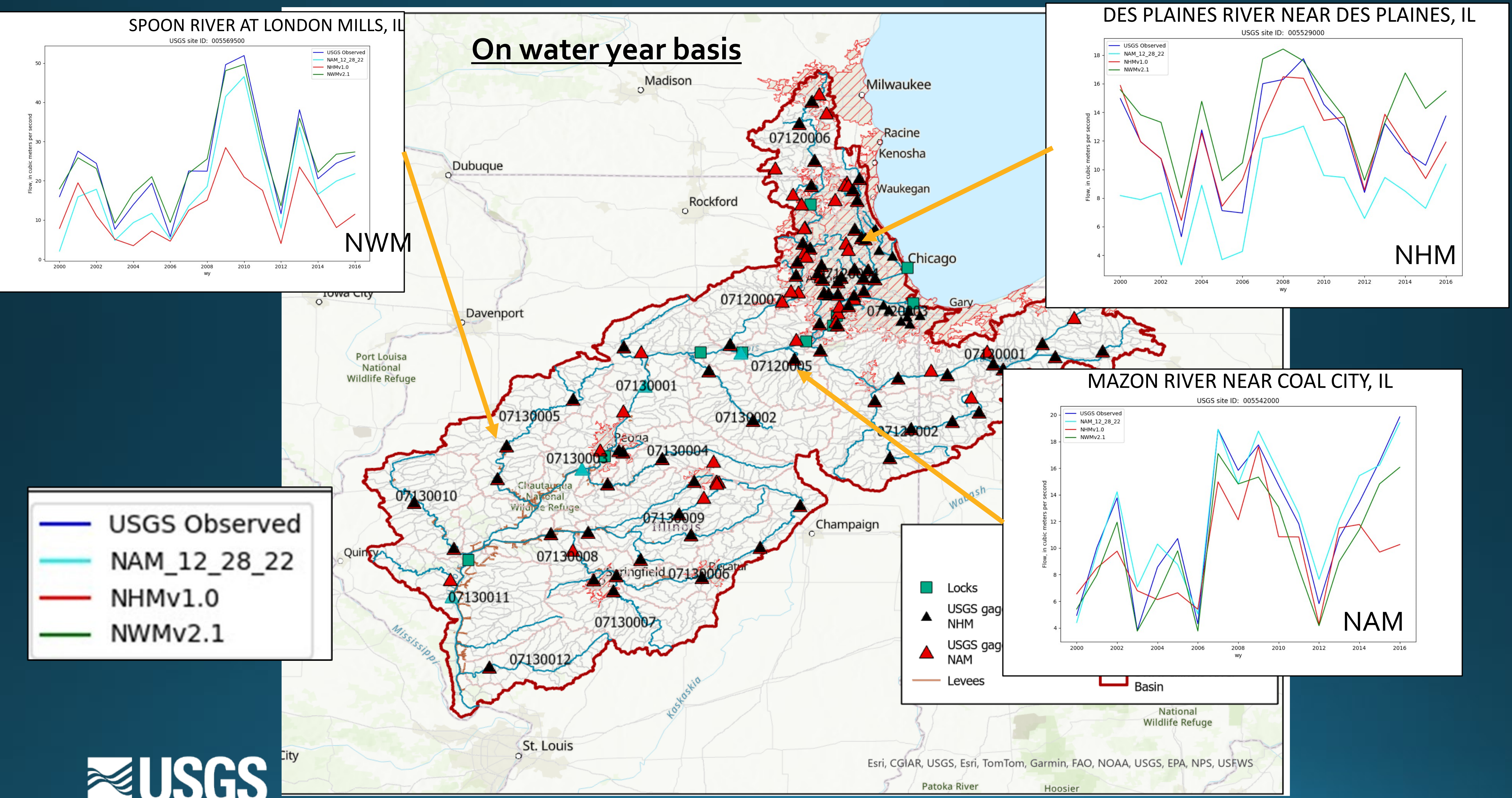
On water year basis
SPOON RIVER AT LONDON MILLS, IL
USGS site ID: 005569500
NWM
DES PLAINES RIVER NEAR DES PLAINES, IL
USGS site ID: 005529000
NHM
MAZON RIVER NEAR COAL CITY, IL
USGS site ID: 005542000
NAM
USGS Observed
NAM_12_28_22
NHMv1.0
NWMv2.1
Flow, in cubic meters per second
wy
Locks
USGS gag
NHM
USGS gag
NAM
Levees
Basin
Madison
Milwaukee
Racine
Kenosha
Waukegan
Dubuque
Rockford
Chicago
Gary
Davenport
Iowa City
Peoria
Champaign
Quincy
Springfield
Decatur
St. Louis
Port Louisa National Wildlife Refuge
Chautauqua National Wildlife Refuge
National Wildlife Refuge
07120006
07120007
07120005
07120001
07120002
07120003
07130001
07130002
07130003
07130004
07130005
07130006
07130007
07130008
07130009
07130010
07130011
07130012
Mississippi
Kaskaskia
Wabash
Patoka River
Hoosier
Esri, CGIAR, USGS, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS

Model Results

HUC12 Water Balance Components

Comparison of Model Output: Water Balance Components at HUC12's

Definition	NAM (SWAT+) in mm	NHM (PRMS) in inches	NWM (WRFHydro) in mm
precipitation	Precip	Ppt	Precip
actual evapotranspiration	et	Aet	ET
Streamflow	flo_out (m^3/s) in channel_sd_mon.txt	lateral_flow	Streamflow
Surface runoff	surq_gen	Sroff	SurfRunoff
Flow from the groundwater reservoir to the stream network per unit area	flo in aquifer.txt	gwres_flow	Baseflow
average of water held in soil matrix	sw_ave	--	SoilMois_avg
change of water held in soil matrix	sw_final- sw_init	--	SoilMois_delta
interflow	Latq	ssres_flow	--
average snow water content	Snopack	Snowpack_water_equivalent	SWE_avg
change in snow water content	sno_final-sno_init	--	SWE_delta
recharge	Rchrg in aquifer.txt	Recharge	Recharge
GW storage	Stor in aquifer.txt	change_in_gw_storage	--

Statistics

a. Maximums
b. Minimums
c. Medians
d. Quantiles
    a. [10,25,50,75,90]
e. Standard deviation
f. Coefficient of variation
g. Skew

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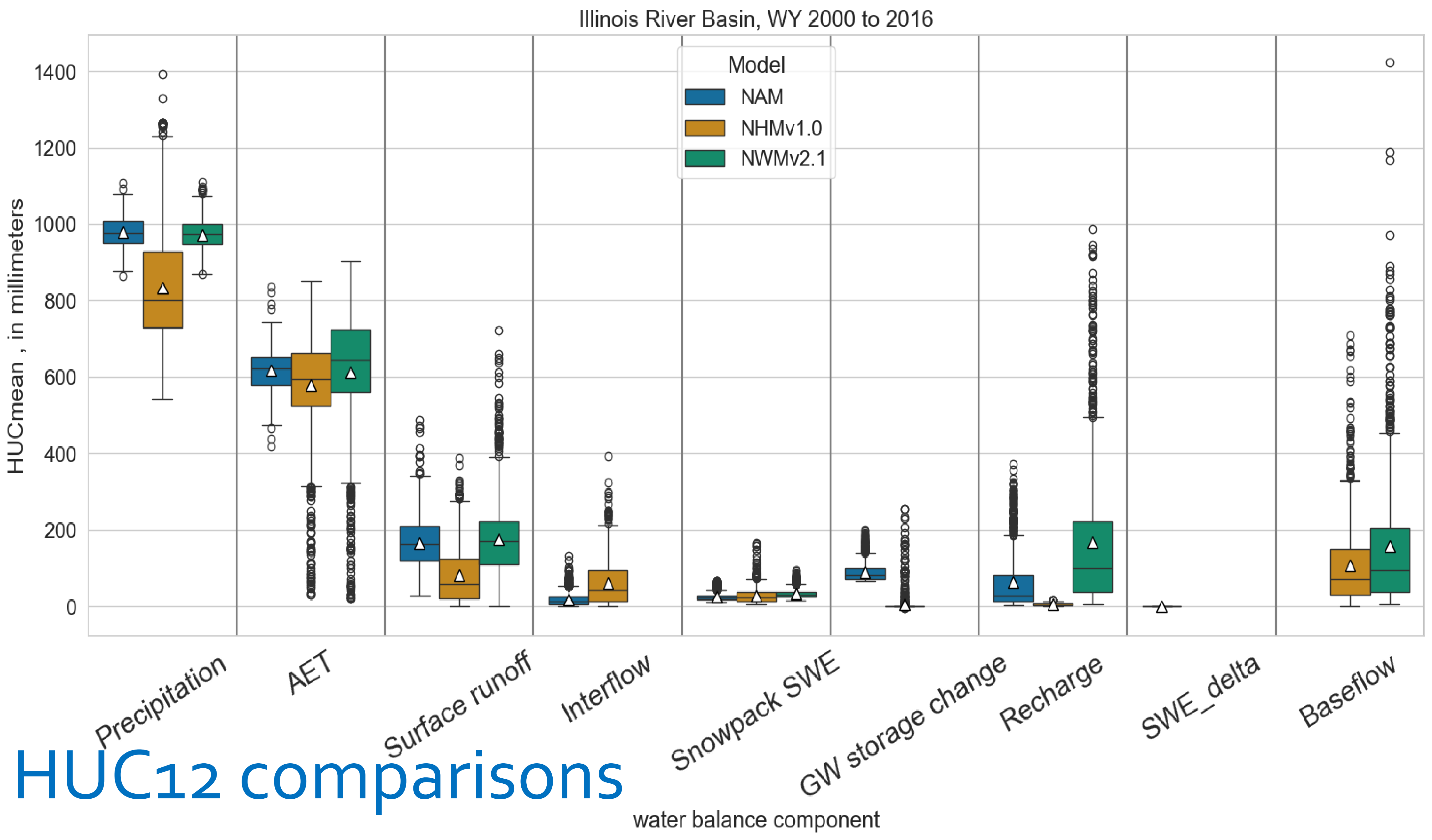
HUC12 comparisons

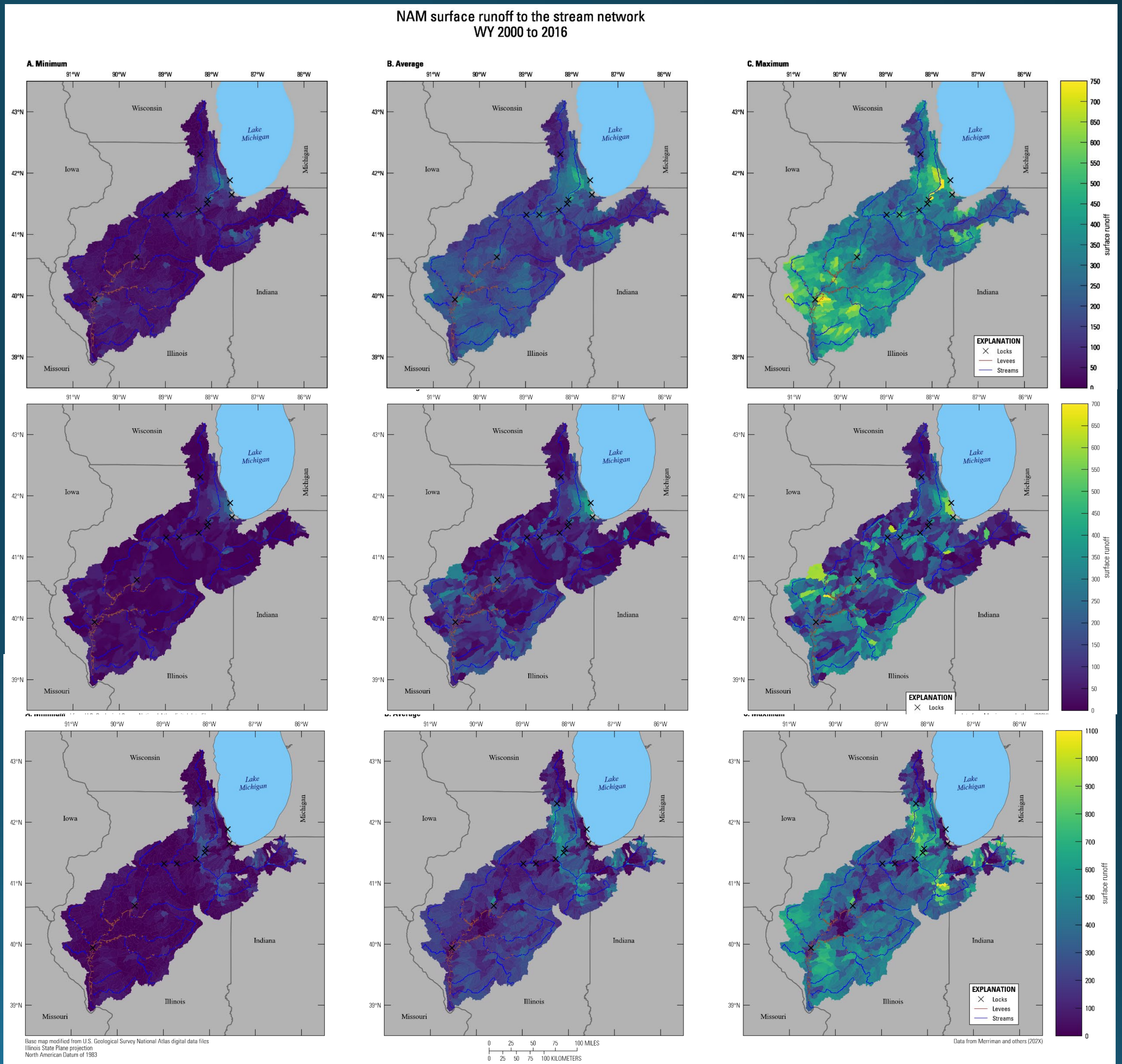


HUC12 maps: Surface Runoff by WY

NAM

NHM

NWM



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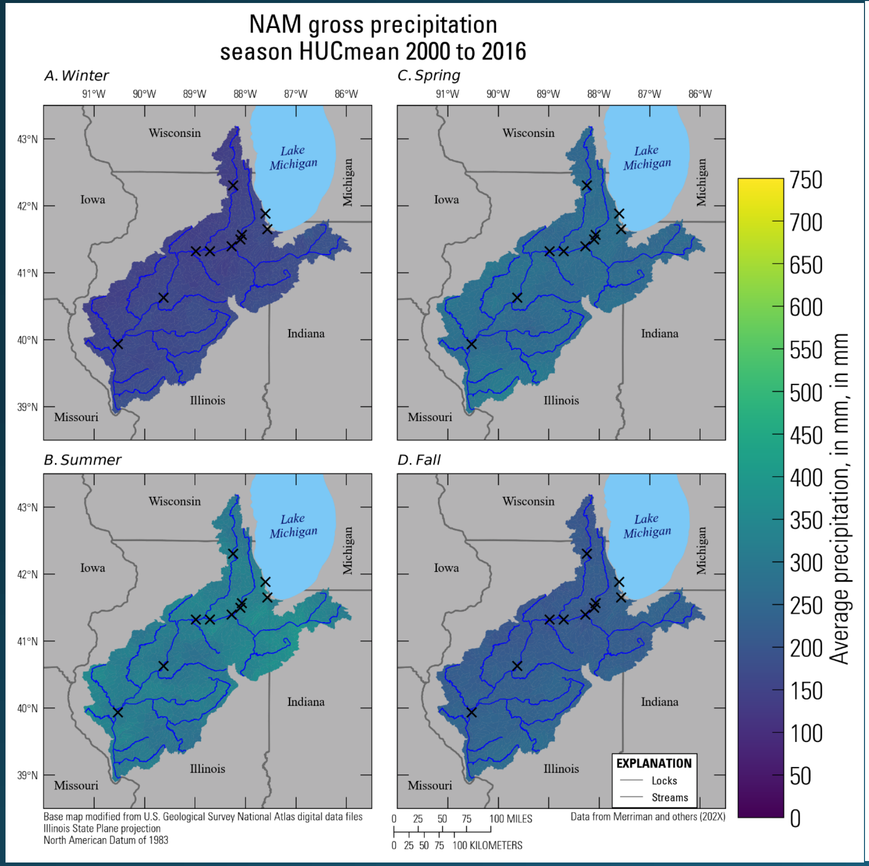
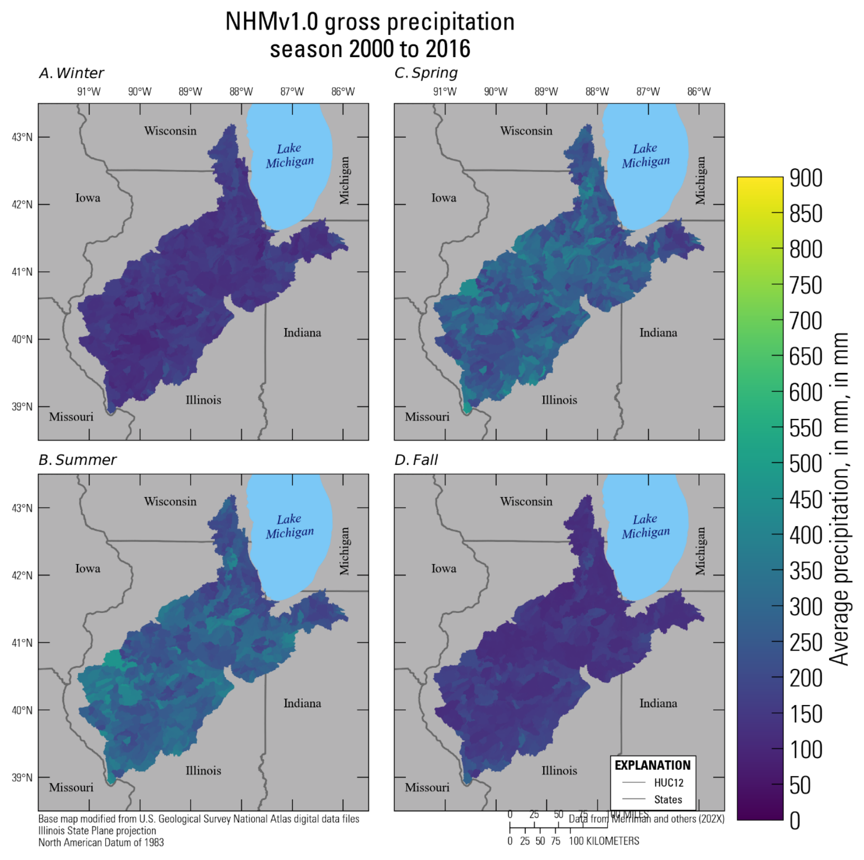
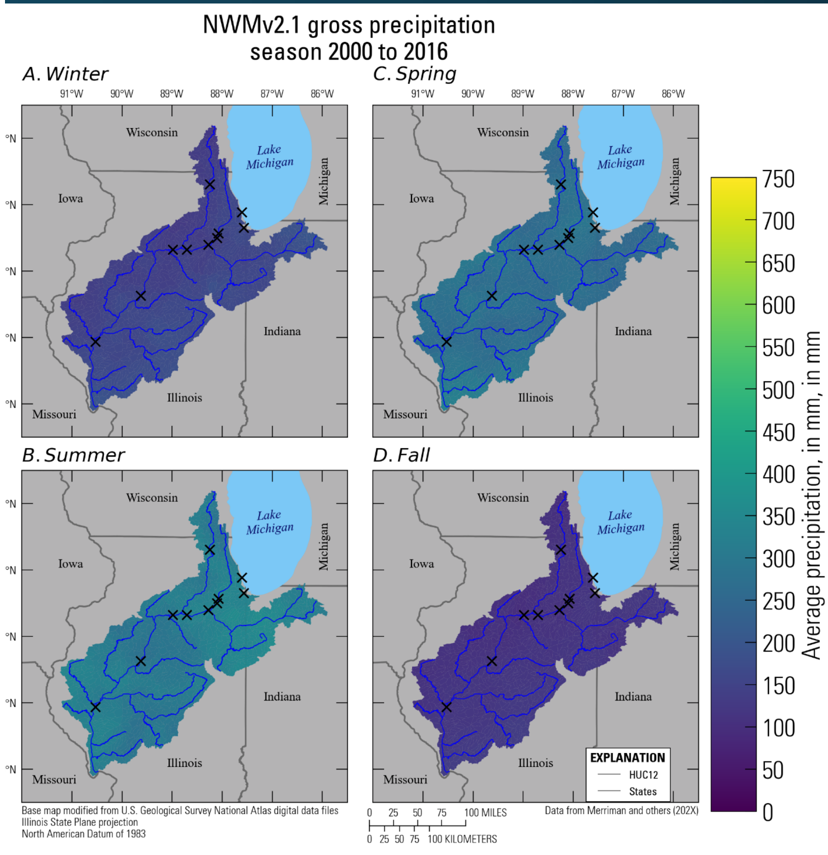
HUC12 maps - Seasonal Average Precipitation

NAM NHM NWM

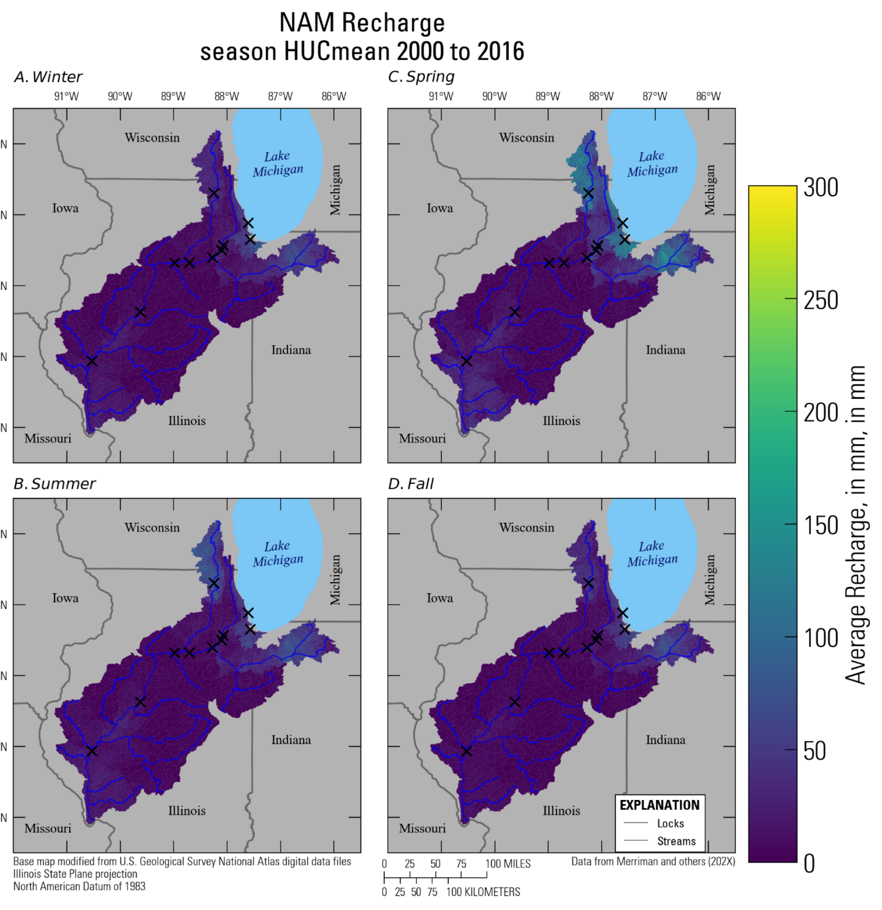


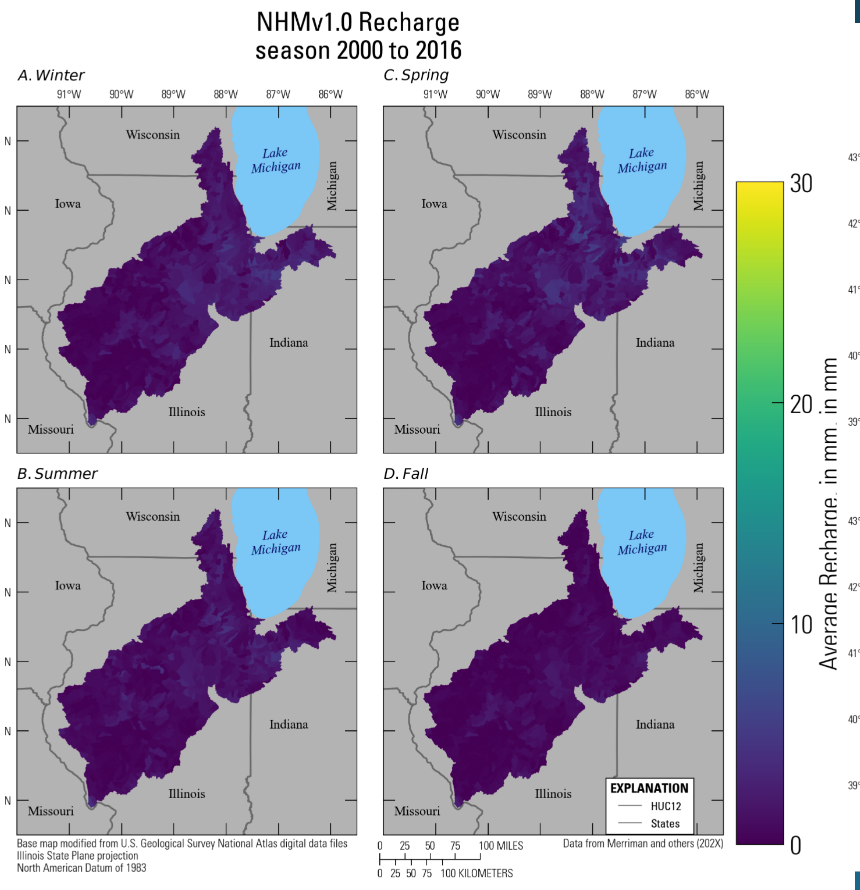


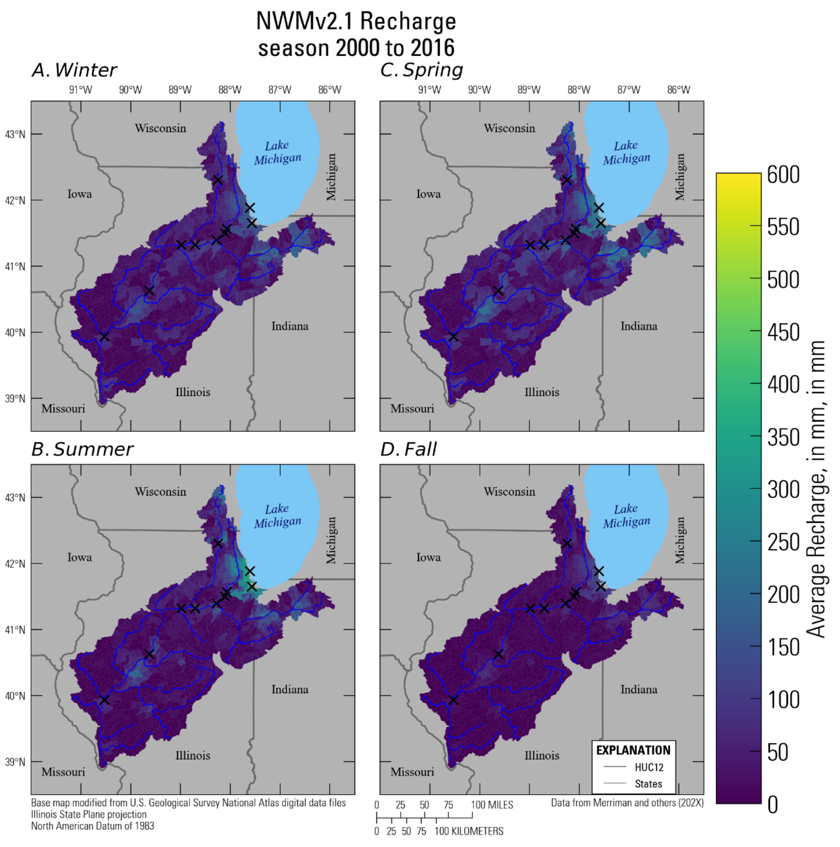


HUC12 maps – Seasonal Average Recharge

NAM NHM NWM

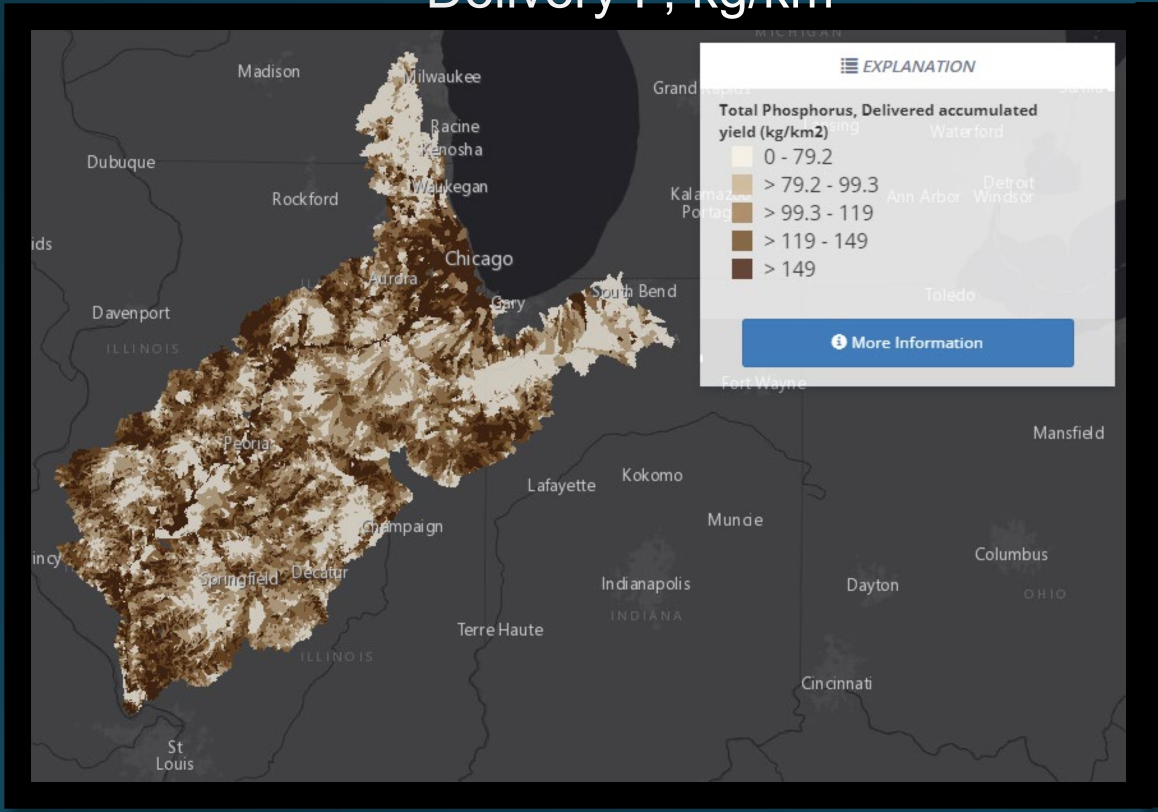




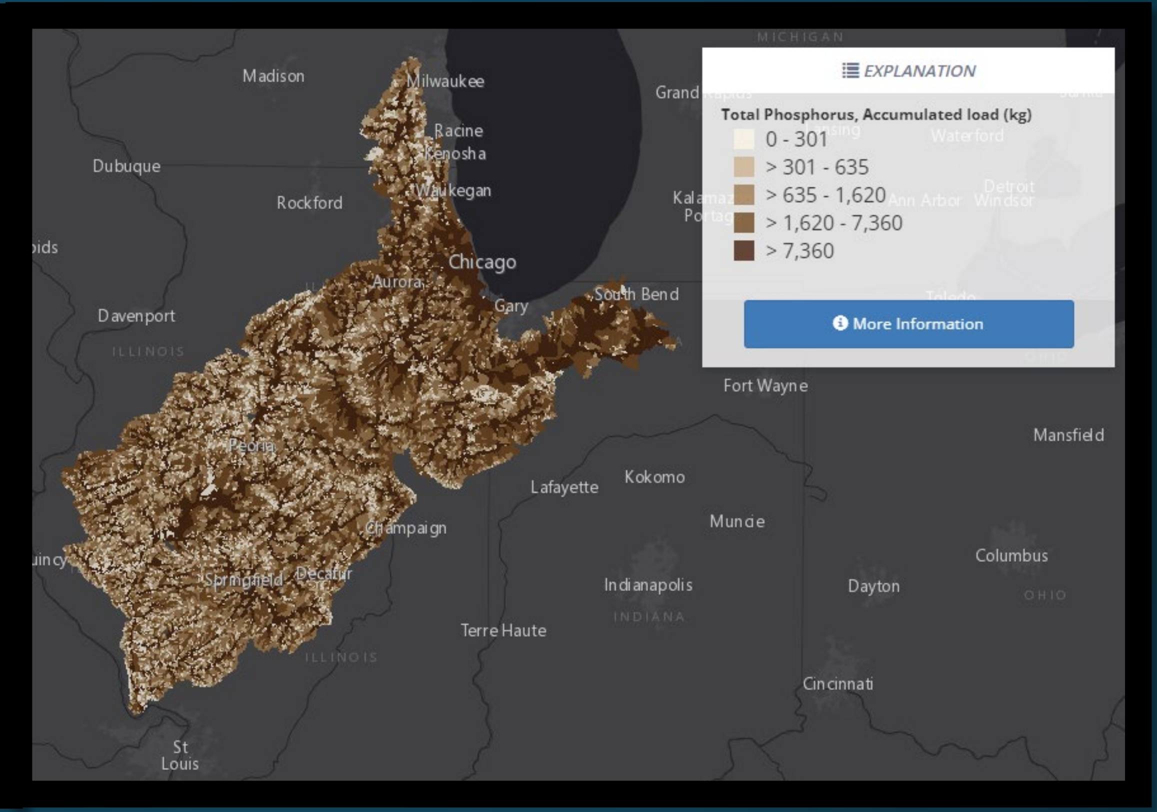


Future Water Quality Comparisons–
Preliminary WQ SPARROW results

Predicted Incremental Downstream Delivery P, kg/km²



Predicted Total Accumulated TP load, kg



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Still waiting for calibrated NAM results…

Summary – Strengths of each Approach

NAM (SWAT+)	NHMv1.0	NWMv2.1	SPARROW (Illinois River dynamic)
Q and WQ model	Q model	Q model; flooding	WQ regression model
Highest spatial HRU resolution		higher resolution stream network; spatially-distributed modeling	
Daily timestep	Daily timestep	Subdaily time step	Seasonal timestep
	Low computational time		
Multiple approaches for reservoir management available	No reservoir management	Simplistic reservoir operations	Hydrology w/ water management is an input
Anthropogenic management, tile drains, structural BMPs	Natural flows model		good for source attribution of nutrients

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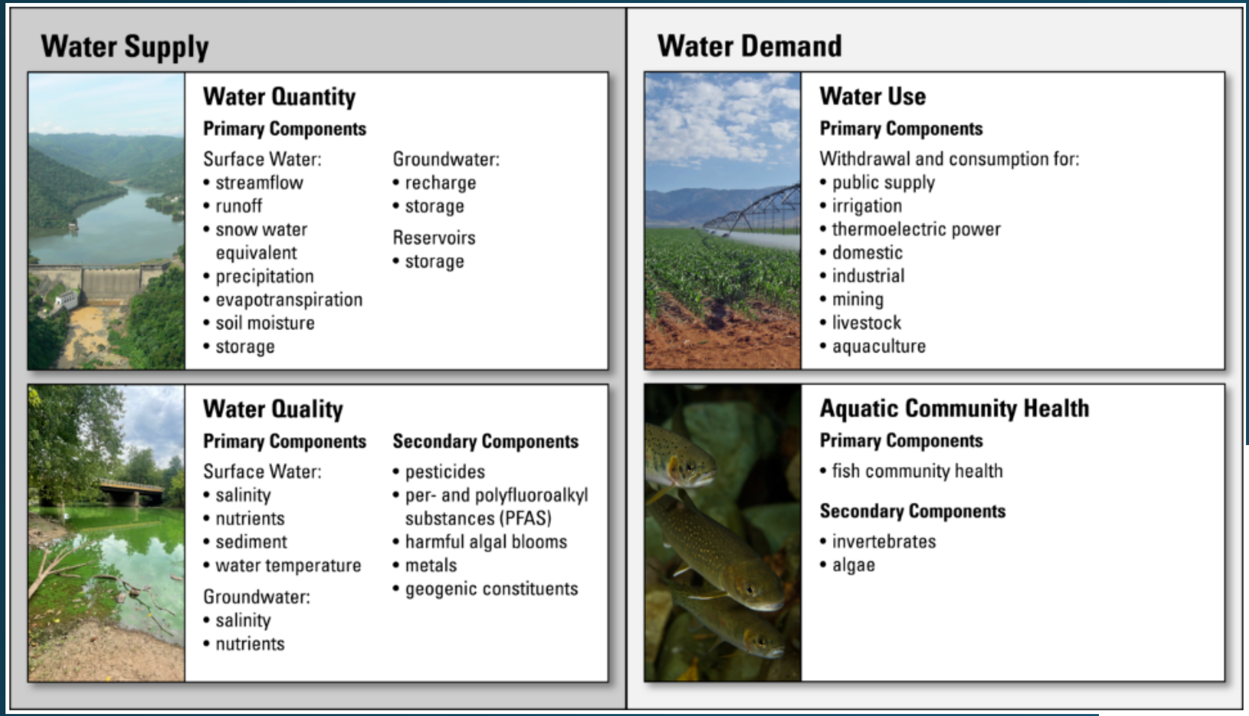
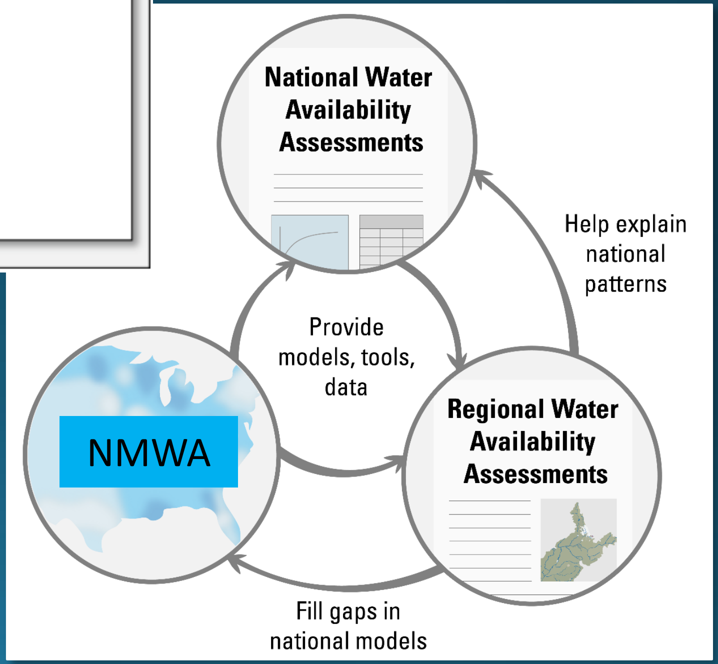
The SECURE Water Act tasked the USGS with assessing water availability - quantity and quality of water for both human and aquatic ecosystem needs



Questions?

kmerriman@usgs.gov

National Modeled Water Atlas: Water Supply and Demand Estimates in Your Watershed Through Time



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Projected Outcomes:

1. Document strengths/weaknesses for all models
2. Contrast approaches
   - Find similar areas of strengths and weaknesses; identify the trade-offs of the modeling approaches
   - Compare Model structure
4. Compare model abilities/functionality
5. Compare model input/outputs
6. Possible sources of error for all models

	NAM	NHM	NWM	SPARROW
Timestep	Daily	Daily	Hourly	Seasonal
Runoff	Computed with CN equation	nonlinear variable-source-area method	fully-unsteady, explicit, finite-difference, diffusive wave	Not computed
Nutrients	Calculates nutrient species	Not currently computed	Not currently computed	Calculates TN and TP

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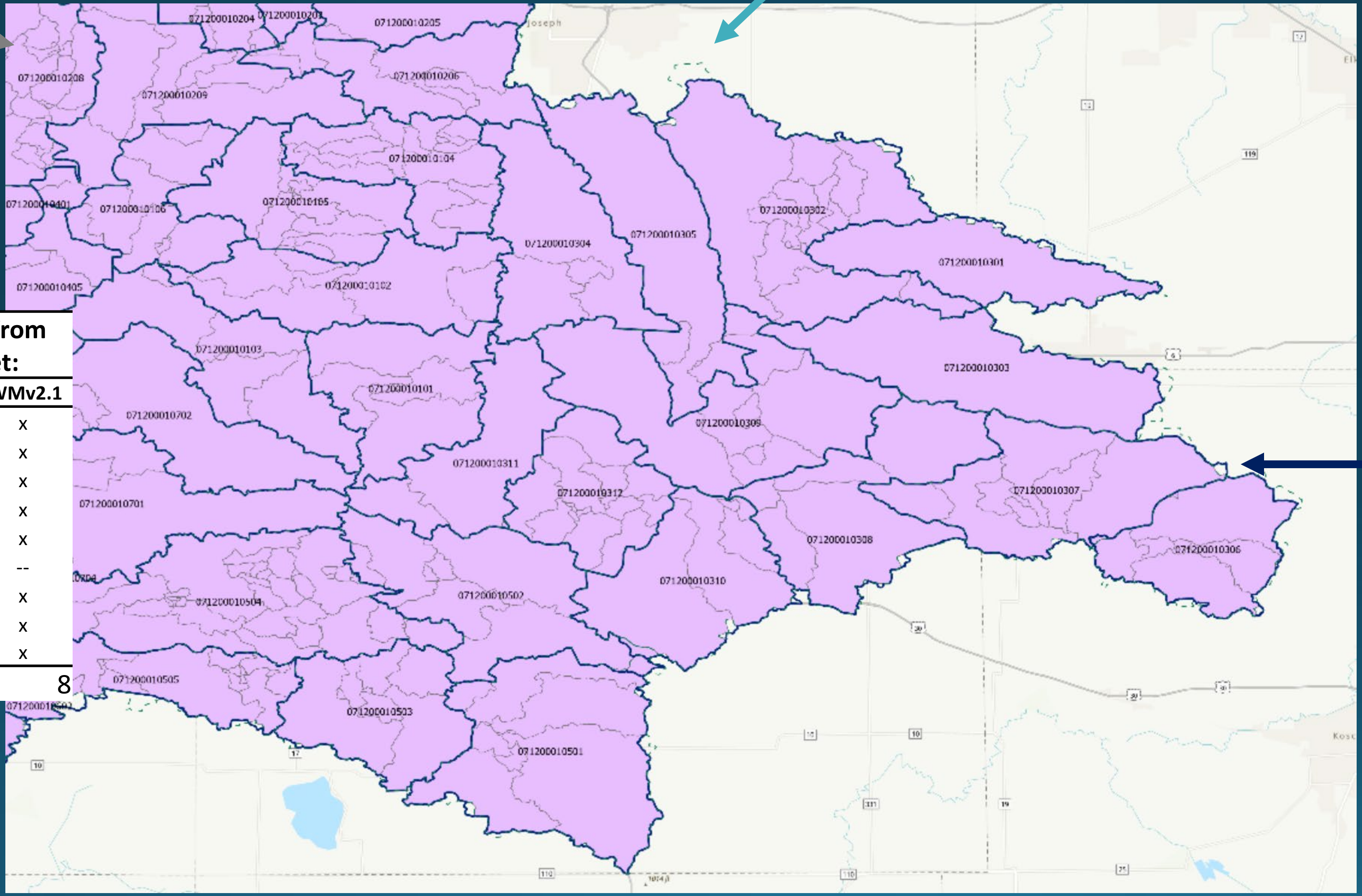
Model Structure – HUC12's!

Grey = SPARROW catchments, applied to nearest HUC12

Dashes = NAM modified HUC12s Based on 2015 WBD



Dark blue = NHM/NWM, spatially weighted to WBD from June 2021

		Missing from dataset:	
HUC12	Name	SPARROW	NWMv2.1
071200010207	Clear Lake	x	x
071200010301	Lateral Number Five	x	x
071200010303	Armey Ditch	x	x
071200010401	Breckenridge Ditch	x	x
071200010404	Salisbury Ditch	x	x
071200010705	Laramore Ditch-Kankakee River	x	--
071200011102	Wentworth Ditch-Knight Ditch	x	x
071200011201	Gregory Ditch-Mud Lake Ditch	x	x
071200060401	North Lake	x	x
COUNT		9	8

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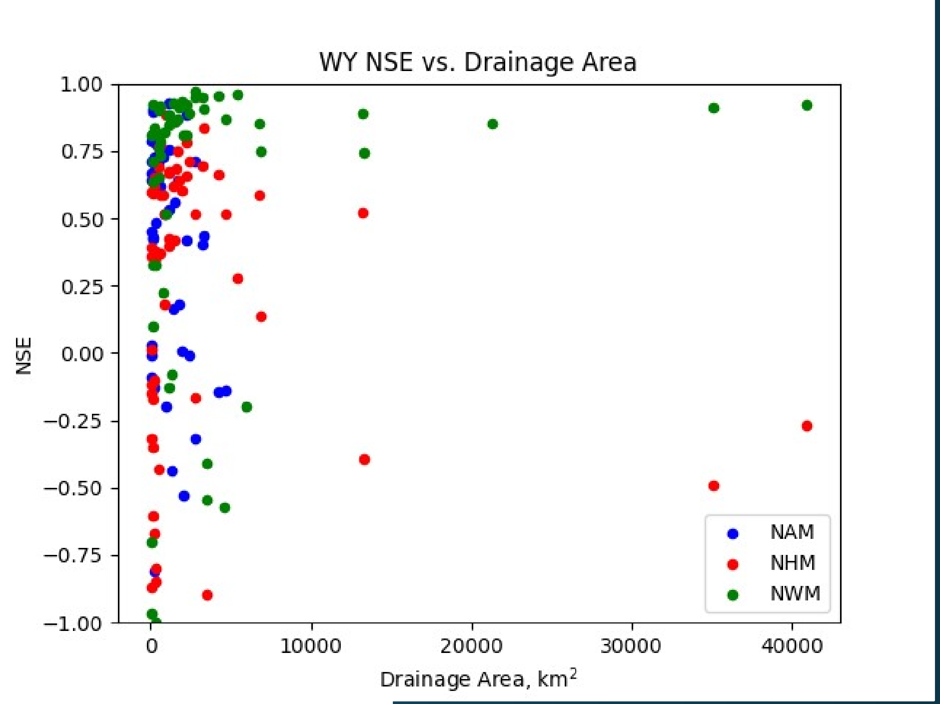
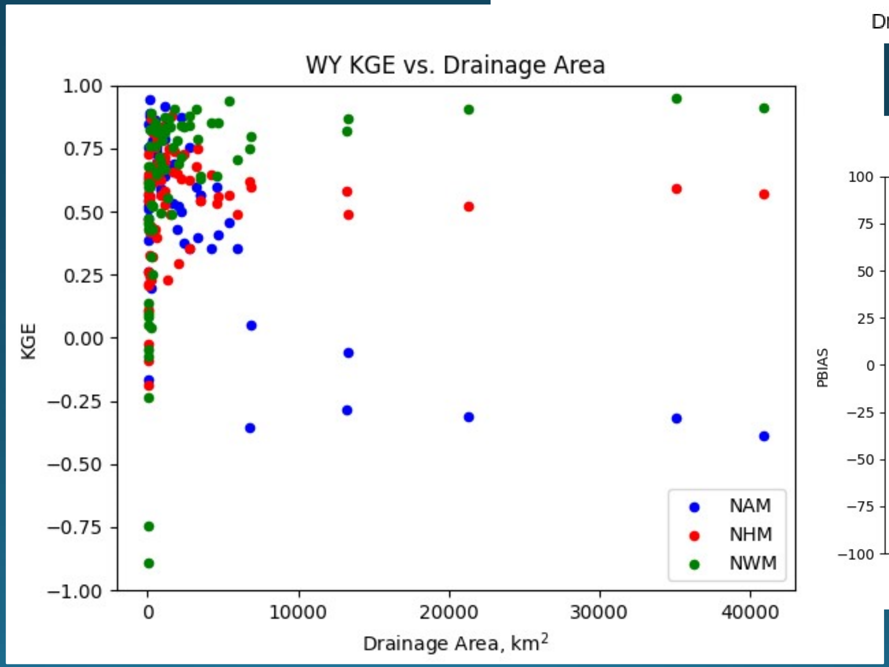
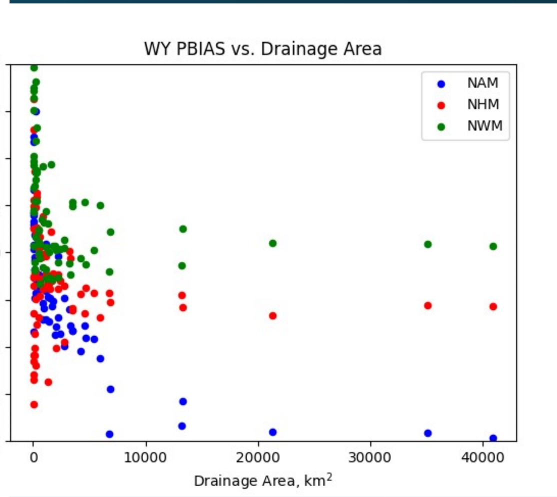
Summary of statistics

Water Year basis	NAM_12_28_22	NHMv1.0	NWMv2.1
Statistic grouping	**Count of statistic in range**		
NSE ≤ 0	28	24	26
0 < NSE ≤ 0.5	11	12	4
0.50 < NSE ≤ 0.65	7	13	2
0.65 < NSE ≤ 0.75	8	10	5
0.75 < NSE ≤ 1.00	12	6	33
KGE < -0.41	8	1	2
0 < KGE ≤ -0.41	7	3	3
0 < KGE ≤ 0.5	14	20	15
0.50 < KGE ≤ 0.75	25	42	22
0.75 < KGE ≤ 1.00	20	8	32
PBIAS ≥ ±25	44	42	27
±15 < PBIAS ≤ ±25	13	19	9
±10 < PBIAS ≤ ±15	7	13	9
PBIAS ≤ ±10%	13	10	29







Project Deliverables

- Data releases
- Code release to GitHub
- Journal article

USGS

Project Deliverables

Data releases

- Model outputs
  - NAM
  - NHM – Goodling, et al. 2022 https://doi.org/10.5066/P9TYOJKN
  - NWM
  - SPARROW – Schmadel et al. and data release forthcoming
- Calculated statistics at USGS gages
- Calculated statistics at HUC12s

Discussion Points

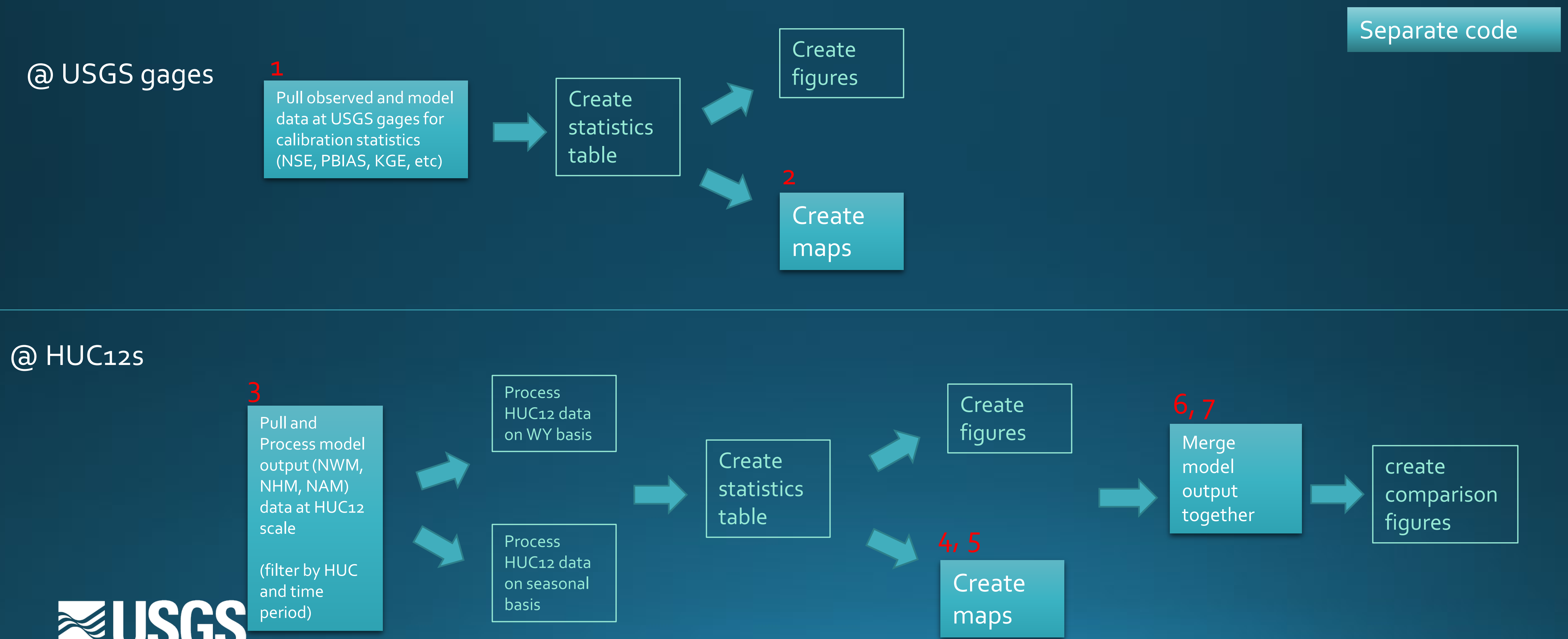
- Timeline for sharing of SWAT+ results
  - Calibration status?
- SWAT+ publication/data release availability for publication citation purposes?
- Model version control (code and application)
  - What will documented and published?
  - USGS is required to publish at minimum model results that will be cited in this effort

- Paper outline
  - Compare inputs /output
  - Contrast approaches
  - Document strength and weaknesses of national models
  - Differences in model structure
  - Contrast results and determine how best to use the different models and what questions/problems can be addressed with the different approaches
  - Possible sources of error
- Future Funding/ work
  - Goal is to have a publication this FY
    - Can frame paper that these are not final results

USGS

NAM vs. NHM vs. NWM

Hydrology comparison schematics



USGS

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NAM vs. SPARROW

Water quality comparison schematics

Separate codes

@ USGS gages

1 Pull LOADEST (NAM) and WRTDS (SPARROW) loads data at USGS gages for calibration statistics (NSE, PBIAS, KGE, etc)

→ Create statistics table

→ Create figures by model

→ 2 Create maps

@ HUC12s

3 Pull and Process model output (SPARROW, NAM) data at HUC12 scale

(filter by HUC and time period)

→ Process HUC12 data on WY basis

→ Process HUC12 data on seasonal basis

→ Create statistics table

→ Create figures by model

→ 4, 5 Create maps

→ 6, 7 Merge model (SPARROW, NAM) output together

→ create comparison figures

Comparison of Models: Water Quality Components

Definition	NAM (SWAT+)	SPARROW
Input LOADs calibration dataset calculation	LOADEST	FLUXMASTER & WRTDS
Output loads (TN & TP)		
Rank of output loads		
Model timestep	model runs on daily timestep	Seasonal
Model evaluation timestep	Daily, monthly, Seasonal, WY, Annual	Seasonal, Annual
Model evaluation statistics	Same as gage statistics	
	Statistics @ HUC12s/ HUC8s on seasonal and WY basis	

Statistics

a. Maximums
b. Minimums
c. Medians
d. Quantiles [10,25,50,75,90]
e. Standard deviation
f. Coefficient of variation
g. Skew

Water Quality Calibration Procedure

	NAM	SPARROW
POR		
Validation POR		
Calibration points		
Calibration method		

USGS

Model Calibration Data

	NHM (PRMS)	NWM (WRFHYDRO)	NAM (SWAT+)	SPARROW
Calibration Data				
Streamflow	**X**	**X**	**X**	**X**
Crop yield			**soft**	
WQ Concentrations and loads			**X**	**X**
Water levels (GW/SW)		**X**		
Sewer, tile, urban drain flows			**tile**	

Summary

- Strengths of each approach
- NAM: HRU spatial resolution is higher, reservoirs, diversions, anthropogenic management, structural BMPs, only Q and WQ
- NHM: low computational time, allows lots of exploration, no water management (natural systems only)
- NWM: subdaily timestep, stream network higher resolution, simplistic reservoir management
- SPARROW: high spatial resolution, good for source attribution of nutrients, hydrology w/ water management incorporated is an input

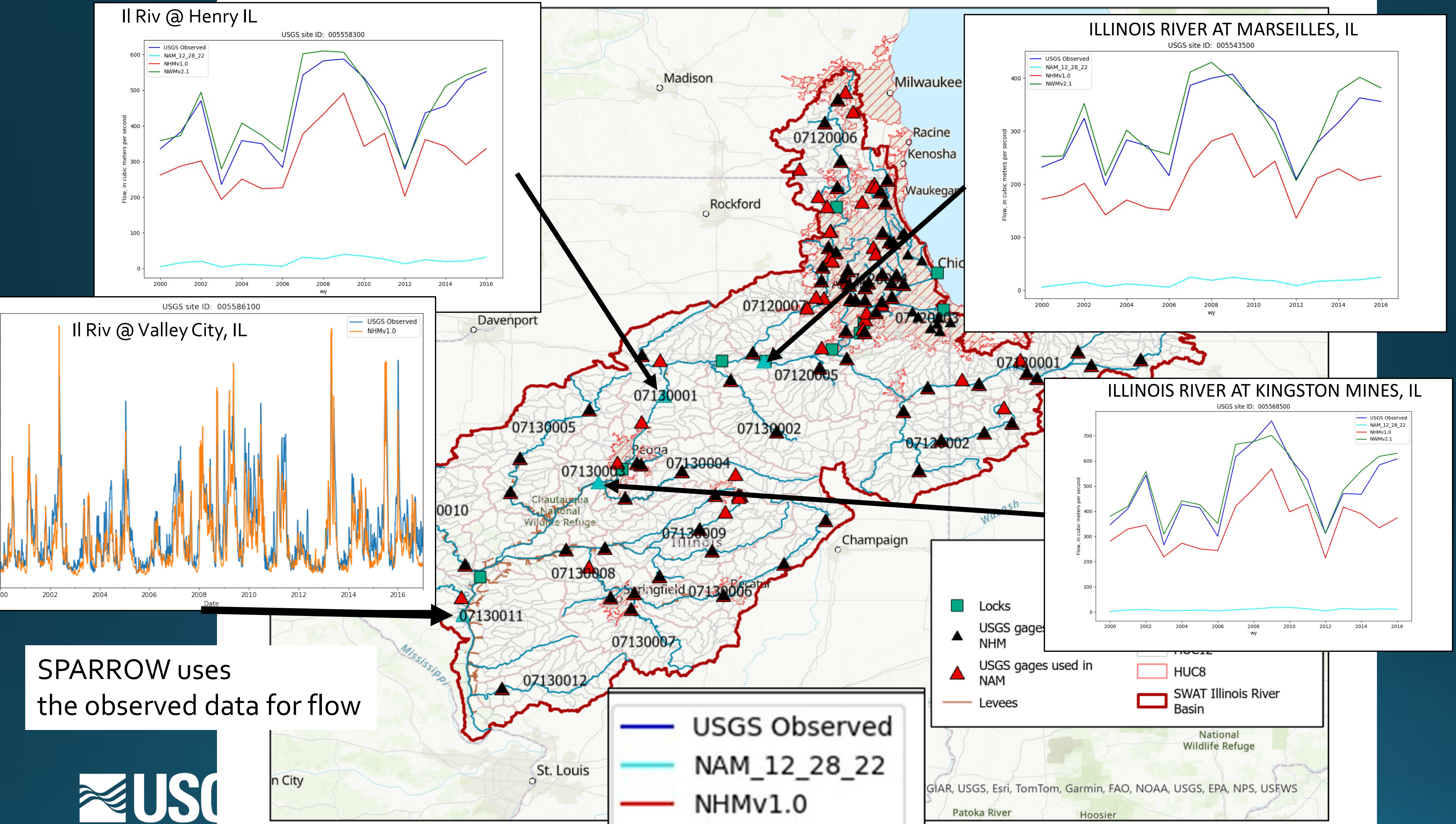
USGS

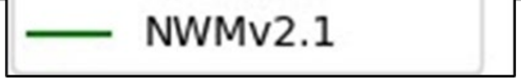
Hydrographs on the Illinois River

Model Results

USGS Site name	USGS Site no.	model	timestep	Drain area (km2)	On water year basis								
					Q Avg (cms)	Q Max (cms)	Q Min (cms)	Q Std (cms)	NSE	logNSE	PBIAS	RMSE	KGE
ILLINOIS RIVER AT MARSEILLES, IL	05543500	OBS	WY	21,349.7	303.84	407.50	198.10	68.16	--	--	--	--	--
		NWMv2.1			319.77	429.77	206.88	72.51	0.85	0.87	5.24	25.63	0.91
		NHMv1.0			202.30	295.64	135.83	46.15	-1.61	-2.42	-33.42	106.88	0.52
		NAM_12_28_22			15.44	24.69	5.99	6.57	-18.86	-183.25	-94.92	294.64	-0.31
ILLINOIS RIVER AT HENRY, IL	05558300	OBS	WY	35,074	433.34	587.07	235.68	112.83	--	--	--	--	--
		NWMv2.1			452.61	609.78	278.87	112.36	0.91	0.91	4.45	32.36	0.95
		NHMv1.0			311.83	491.87	193.64	82.54	-0.49	-0.62	-28.04	133.72	0.59
		NAM_12_28_22			20.21	39.82	4.30	10.91	-14.08	-139.87	-95.34	425.03	-0.32
ILLINOIS RIVER AT KINGSTON MINES, IL	05568500	OBS	WY	40,963.2	490.65	758.68	266.14	141.54	--	--	--	--	--
		NWMv2.1			507.79	700.75	309.40	131.13	0.92	0.92	3.49	38.72	0.91
		NHMv1.0			351.49	568.59	214.63	98.39	-0.27	-0.44	-28.36	154.77	0.57
		NAM_12_28_22			9.82	18.42	2.63	4.55	-12.21	-182.70	-98.00	499.06	-0.39

Evaluation Statistics at IL River sites
WY basis





SPARROW uses
the observed data for flow

On water year basis

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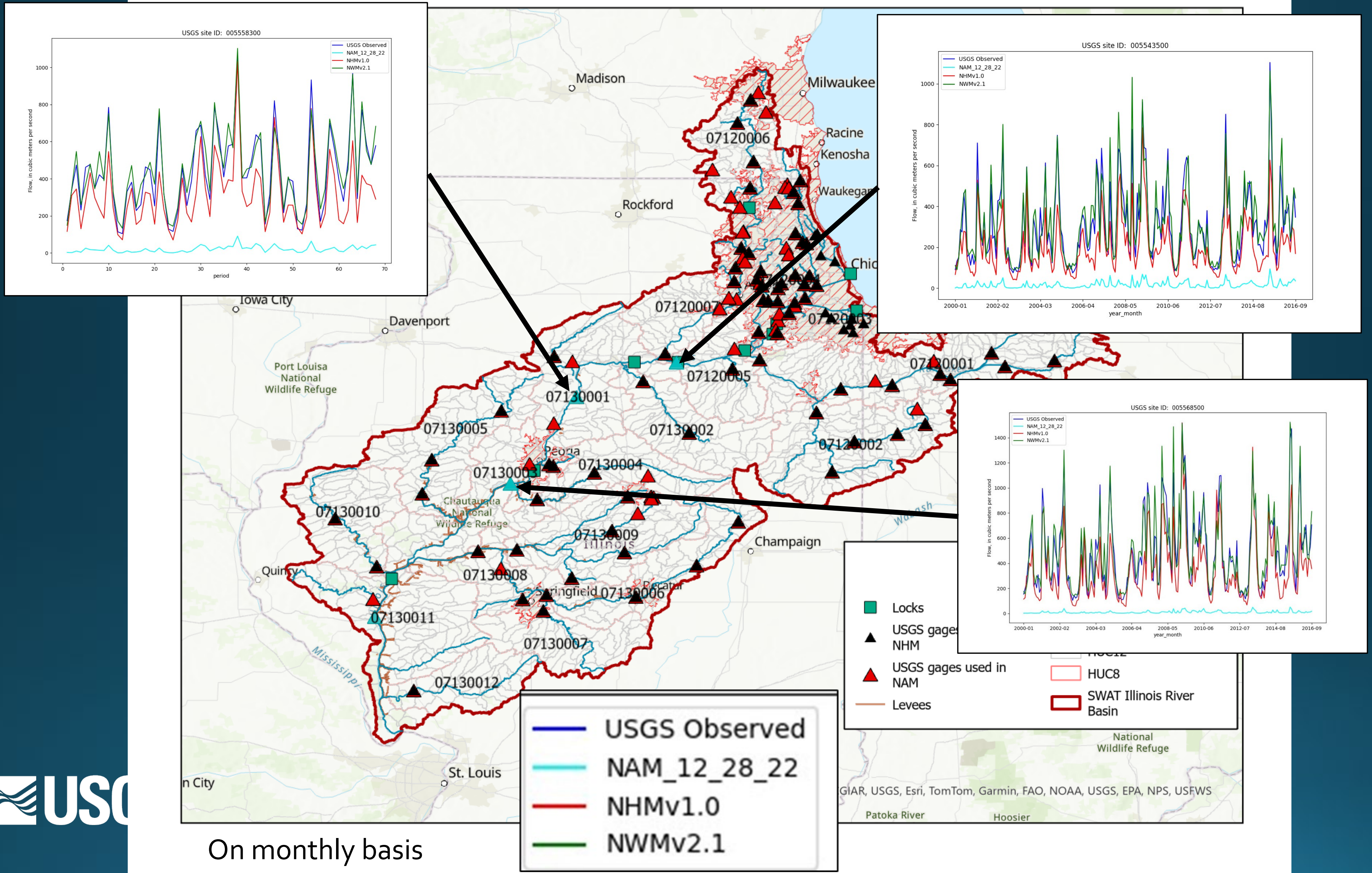
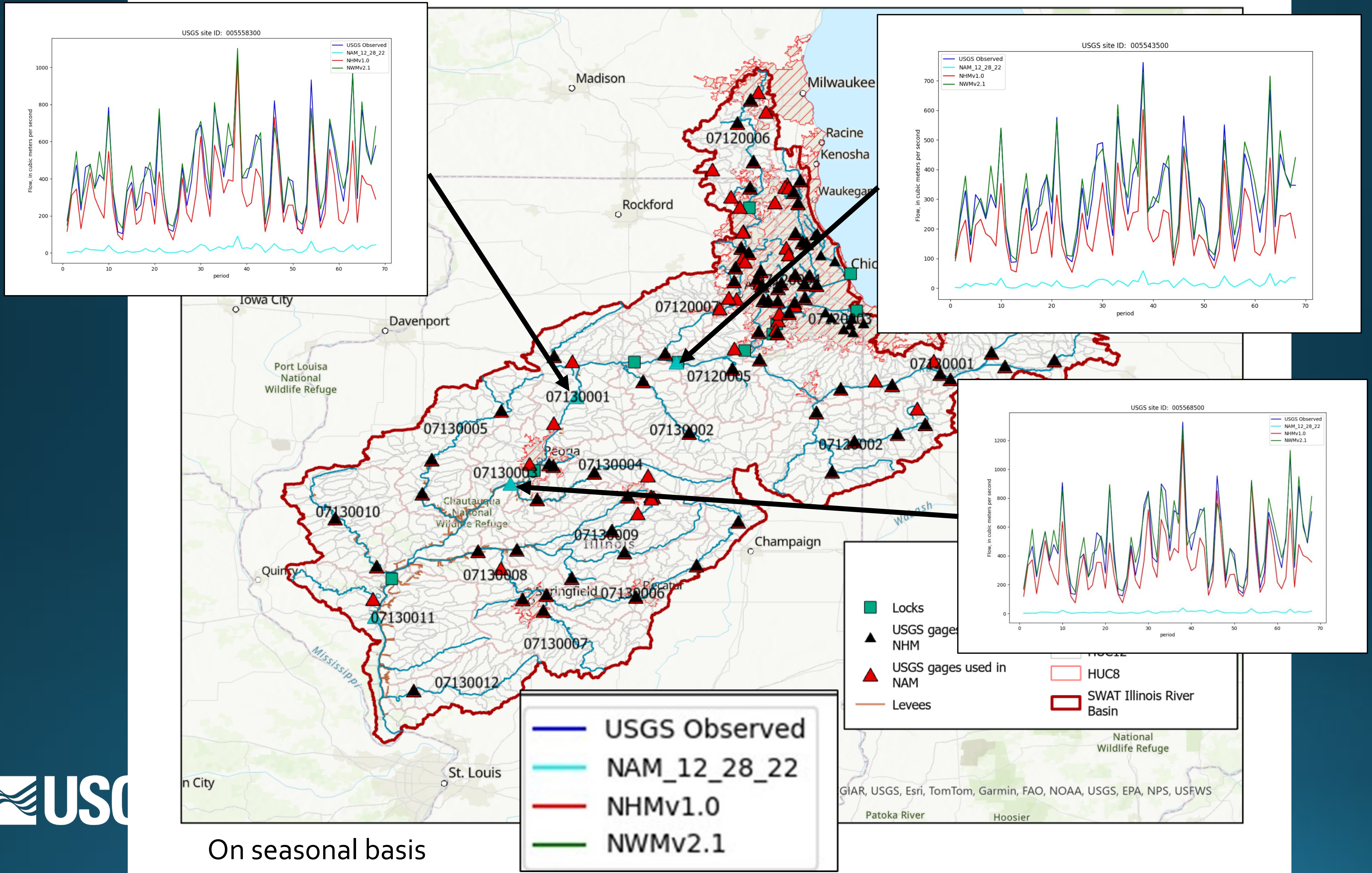
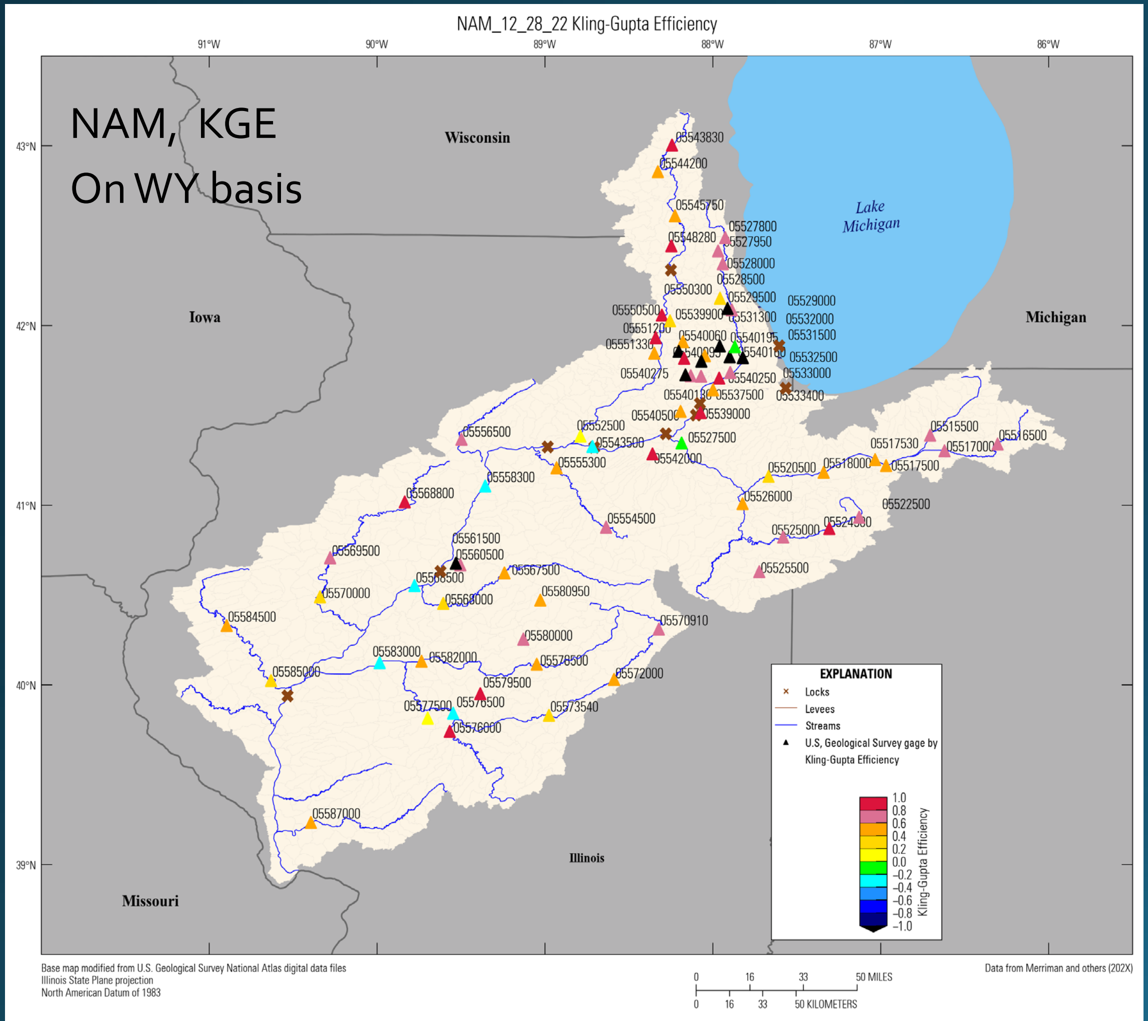


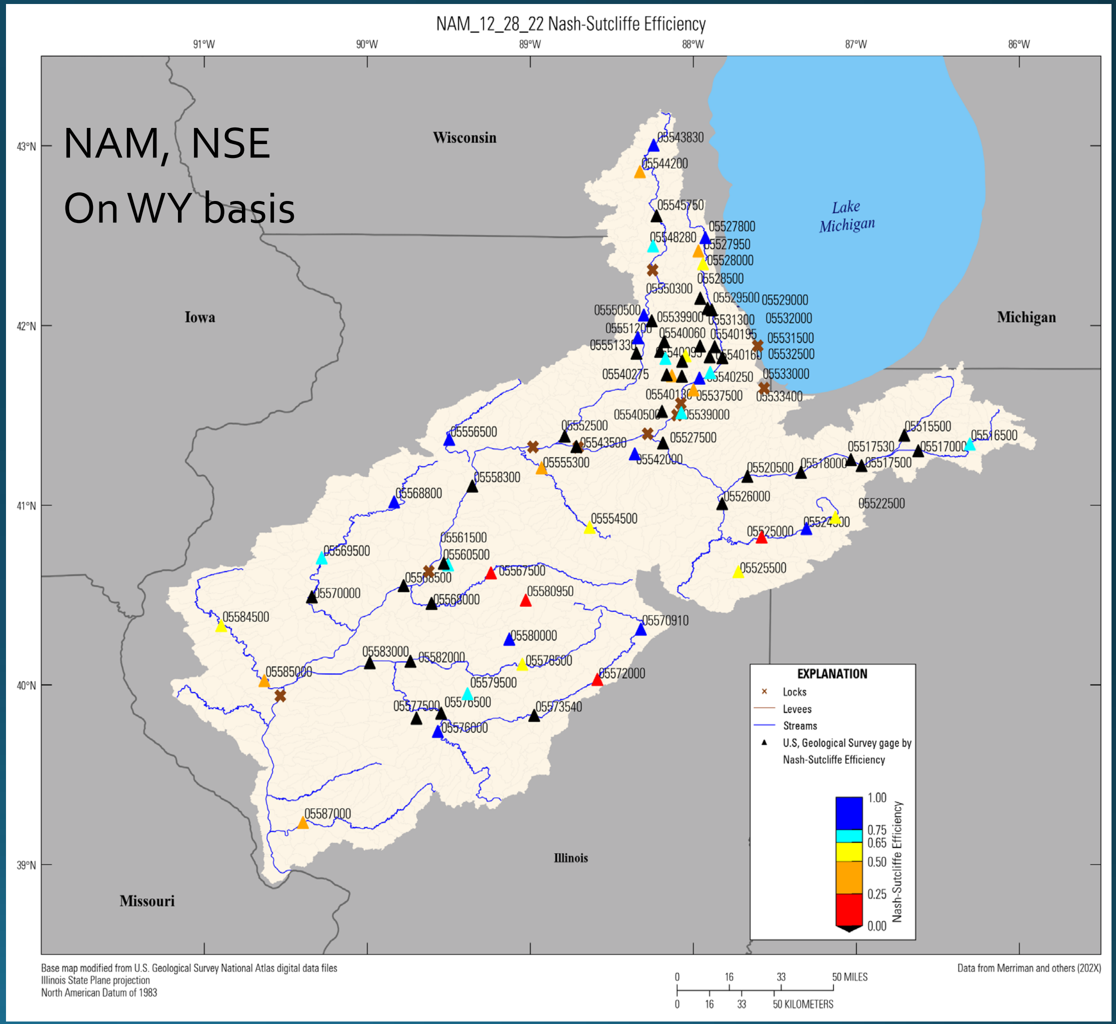
On monthly basis



On seasonal basis

Comparisons of model outputs will be on a spatial, HUC12 scale and at select gages





USGS

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USGS Site name	USGS Site no.	model	timestep	Drain area (km2)	On water year basis								
					Q Avg (cms)	Q Max (cms)	Q Min (cms)	Q Std (cms)	NSE	logNSE	PBIAS	RMSE	KGE
DES PLAINES RIVER NEAR DES PLAINES, IL	05529000	OBS	WY	943.1	12.02	17.75	5.30	3.54					
		NWMv2.1			13.95	18.42	8.01	3.13	0.52	0.55	16.00	2.39	0.78
		NHMv1.0			11.93	16.48	6.44	3.00	0.88	0.88	-0.73	1.17	0.84
		NAM_12_28_22			8.44	13.03	3.33	2.85	-0.20	-0.42	-29.77	3.76	0.64
MAZON RIVER NEAR COAL CITY, IL	05542000	OBS	WY	1,165.6	11.86	19.86	3.82	5.14					
		NWMv2.1			10.19	17.10	3.76	4.54	0.85	0.87	-14.05	1.96	0.82
		NHMv1.0			9.63	17.61	4.27	3.51	0.42	0.55	-18.81	3.78	0.58
		NAM_12_28_22			12.42	19.41	4.40	4.81	0.93	0.86	4.70	1.36	0.91
SPOON RIVER AT LONDON MILLS, IL	05569500	OBS	WY	2,773.1	24.29	51.92	5.75	12.89					
		NWMv2.1			24.89	49.66	9.21	11.35	0.97	0.93	2.47	2.09	0.88
		NHMv1.0			12.74	28.46	3.45	7.44	-0.16	-0.75	-47.54	13.48	0.35
		NAM_12_28_22			18.41	46.56	2.06	12.58	0.71	-0.06	-24.23	6.70	0.75

USGS siteno	HUC12	Forest in HUC12 (%)	Wetlands in HUC12 (%)	Urban in HUC12 (%)	Agriculture in HUC12 (%)
05529000	071200040503	15.12	7.26	73.05	1.78
05542000	071200050503	14.99	3.77	9.64	65.55
05569500	071300051004	18.31	2.09	3.87	74.1

Selected sites for high model performance

(sites with highest NSE for each model on WY basis)