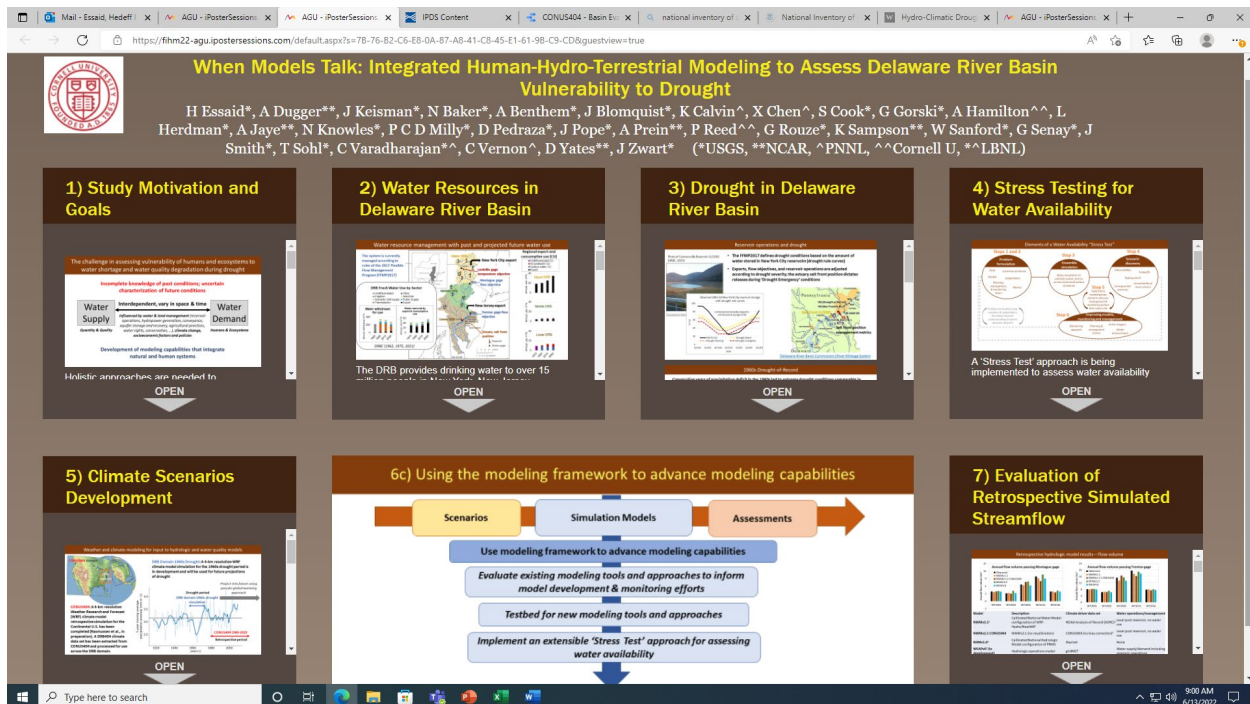


Link to live iPoster preview:

<https://fihm22-agu.ipostersessions.com/default.aspx?s=7B-76-B2-C6-E8-0A-87-A8-41-C8-45-E1-61-9B-C9-CD&guestview=true>

Static screenshot of iPoster:



iPoster Figures and Text:

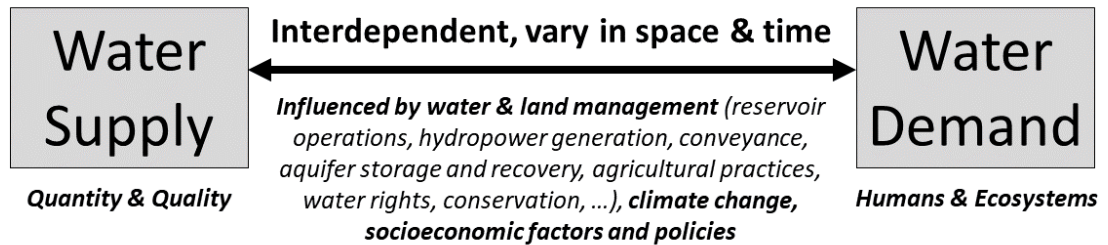
When Models Talk: Integrated Human-Hydro-Terrestrial Modeling to Assess Delaware River Basin Vulnerability to Drought

H Essaid*, A Dugger**, J Keisman*, N Baker*, A Benthem*, J Blomquist*, K Calvin^, X Chen^, S Cook*, G Gorski*, A Hamilton^^, L Herdman*, A Jaye**, N Knowles*, P C D Milly*, D Pedraza*, J Pope*, A Prein**, P Reed^^, G Rouze*, K Sampson**, W Sanford*, G Senay*, J Smith*, T Sohl*, C Varadharajan^, C Vernon^, D Yates**, J Zwart* (*USGS, **NCAR, ^PNNL, ^^Cornell U, *^LBNL)

1) Study Motivation and Goals

The challenge in assessing vulnerability of humans and ecosystems to water shortage and water quality degradation during drought

**Incomplete knowledge of past conditions; uncertain
characterization of future conditions**



**Development of modeling capabilities that integrate
natural and human systems**

Holistic approaches are needed to investigate the capacity of current water resource operations and infrastructure to sustain water supply and critical ecosystem health under projected drought conditions. Drought vulnerability is complex, dynamic, and challenging to assess, requiring simultaneous consideration of changing water demand, use and management, hydrologic system response, and water quality.

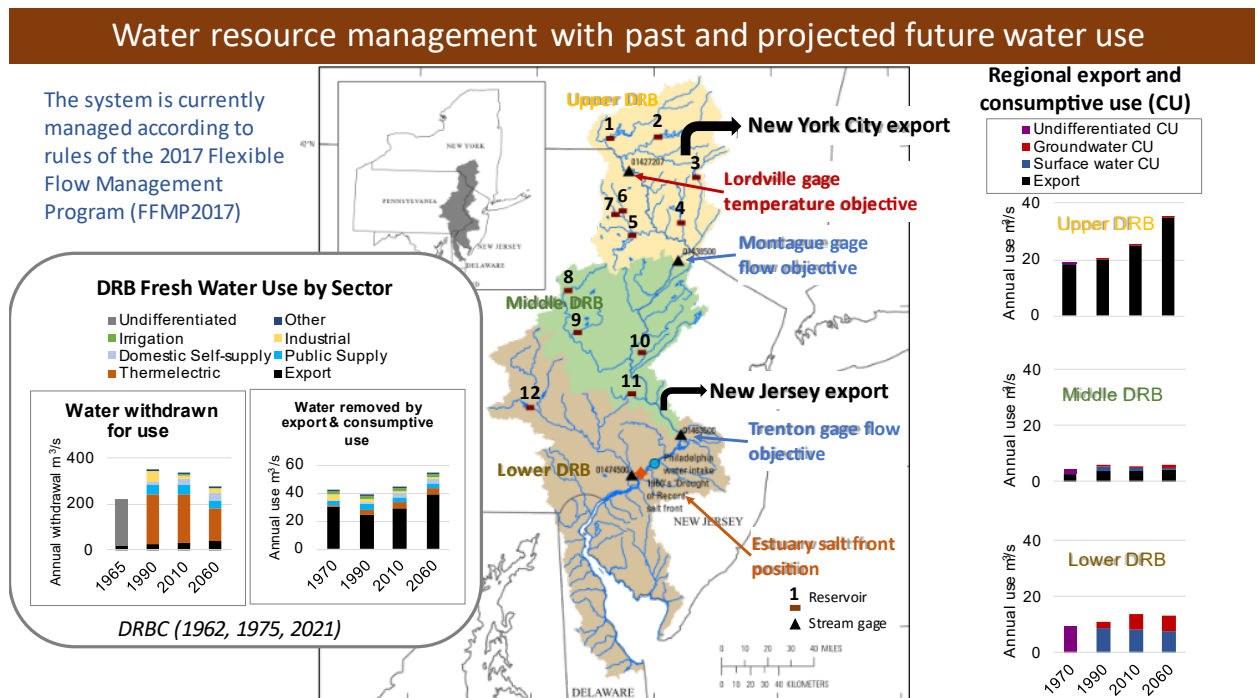
The DRB endured a major drought in the 1960s and current water resource managers do not know if present-day operations and water demands can be sustained during a future drought of comparable or greater magnitude. In response to this concern, an integrated modeling framework leveraging existing models developed by multiple institutions is being used to explore water availability and vulnerability in the Delaware River Basin (DRB). The models include inland hydroclimate and water quality models, coastal models, and water operations/management models. Model performance is being evaluated to better understand the strengths and weaknesses of current modeling capabilities and to drive future model development. A phased water availability 'Stress Test' approach is being implemented to characterize and explore future water resource availability and management options. The modeling framework and Stress Test approach will be used to examine and assess past and future water availability, including:

- The ability of existing retrospective models (2000-2016) to reproduce past observed water resource conditions
- The ability of existing models to reproduce water resource conditions during the 1960s drought of record
- Predict the impacts of a 1960s-like drought occurring today under current water management, land use land cover (LULC), and water demand conditions

- Explore how drought vulnerability will evolve in the future:
 - Explore drought vulnerability for a prescribed subset of potential future climate, LULC, water demand, and management conditions
 - Conduct large-scale exploratory modeling over a wide range of future conditions using stochastic hydrology, model error sampling, water demand and LULC scenario sampling
 - Explore alternative water planning and management alternatives that can reduce vulnerability

This information is preliminary and is subject to revision. It is being provided to meet the need for timely best science. The information is provided on the condition that neither the U.S. Geological Survey nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

2) Water Resources in Delaware River Basin

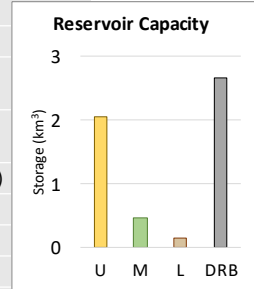


The DRB provides drinking water to over 15 million people in New York, New Jersey, Pennsylvania, and Delaware. Critical water management decisions within the system are coordinated through the Delaware River Basin Commission (DRBC), comprised of members from four states and the federal government, and must meet requirements set by prior litigation. New York City has rights to divert water from the upper basin for water supply but must manage reservoir releases to meet downstream flow and temperature targets. The US Geological Survey Office of the Delaware River Master (ODRM) administers provisions of the 2017 Flexible Flow Management Program designed to manage reservoir releases to meet water supply demands, habitat, and specified downstream minimum flows to repel upstream movement of saltwater in the estuary that

threatens Philadelphia public water supply and other infrastructure. There are 12 major reservoirs in the basin that are used for water supply, power generation, flood control, recreation, and replacement of summer season hydroelectric cooling evaporative water loss.

Reservoirs in the Delaware River Basin

Map no.	Reservoir (dam name if different from reservoir)	Year dam completed	DRB Region (State)	Storage Capacity km ³	Owner (Primary use(s))
1	Cannonsville	1964	U (NY)	0.54	NYC (WS)
2	Pepacton (Downsville)	1954	U (NY)	0.75	NYC (WS)
3	Neversink	1953	U (NY)	0.18	NYC (WS)
4	Mangaup River System ⁵ dams, 3 power stations	1930	U (NY)	0.10	Private Utility (HE21.6 M, R)
5	Wallenpaupak (Wilsonville)	1926	U (PA)	0.33	Public Utility: (HE44.0 MW, R)
6	General Edgar Jadwin	1960	U (PA)	0.06	USACE (FC)
7	Prompton	1961	U (PA)	0.09	USACE (FC)
8	Francis E. Walter	1961	M (PA)	0.20	USACE (FC, R)
9	Beltzville	1969	M (PA)	0.13	USACE (FC, WS, R)
10	Merrill Creek	1988	M (NJ)	0.06	Private Utilities: (Replace HE cooling evaporation, R)
11	Nockamixon	1973	M (PA)	0.09	PA DCNR (R, FC)
12	Blue Marsh	1977	L (PA)	0.16	USACE (FC, WS, R)



Information from [USACE National Inventory of Dams](#)

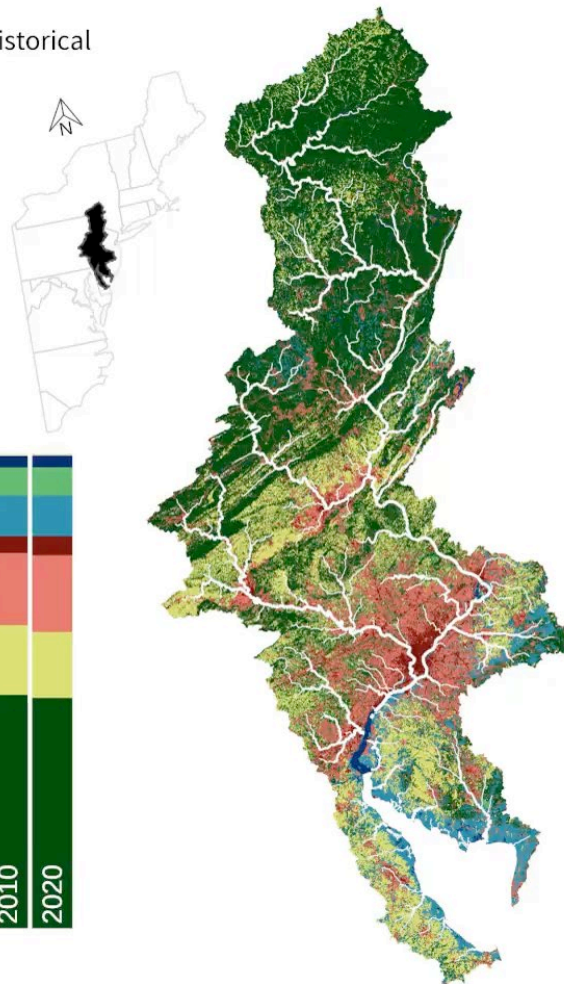
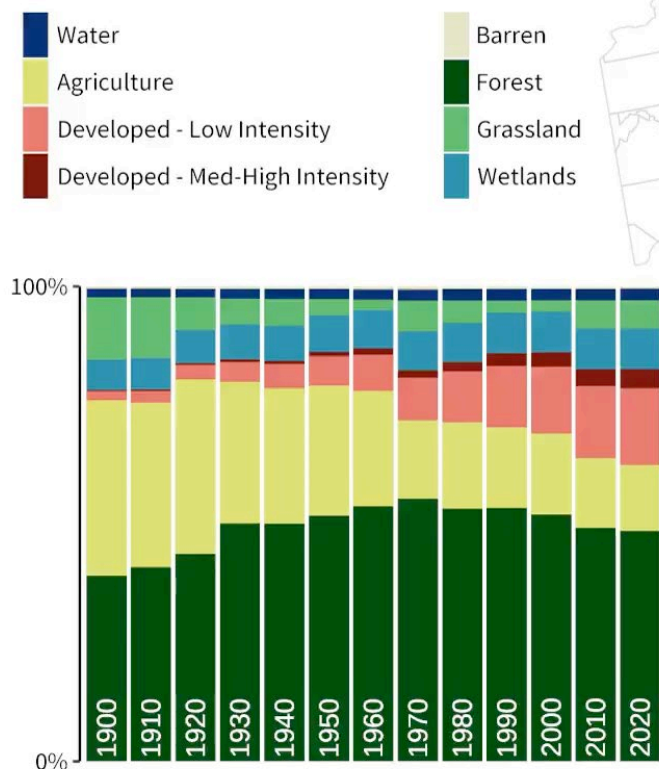
Abbreviations: U-upper; M-middle; L-lower; NY-New York; PA-Pennsylvania; NJ-New Jersey; NYC-New York City; WS-water supply; HE-hydroelectric; MW-megawatts; R-recreation; USACE-US Army Corps of Engineers; FC-flood control; PA DCNR-Pennsylvania Department of Conservation and Natural Resources

Hydrologic response to drought is influenced by change in water use and land use/land cover (LULC). Water withdrawn for thermoelectric use has decreased and is anticipated to continue to decrease. Likewise, water used for irrigation has decreased as agricultural land has been developed. This change in LULC is illustrated in the animation below (Sleckman, 2022) that visualizes FORE-SCE model results (Dornbierer et al., 2021).

Land cover change in the Delaware River Basin

Reconstructed timeseries made using modeled historical landscapes from the USGS FORE-SCE model.

Data: doi.org/10.5066/P93J4Z2W



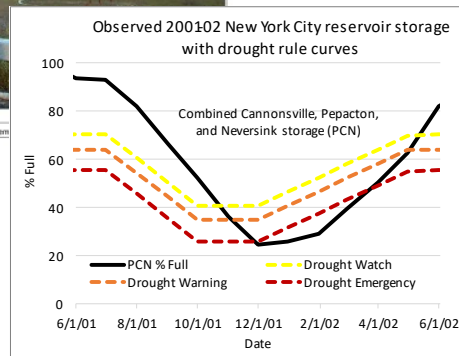
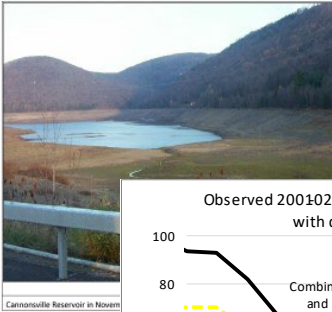
Margaux Sleckman, USGS

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3) Drought in Delaware River Basin

Reservoir operations and drought

Photo of Cannonsville Reservoir 11/2001 (DRBC, 2019)



- Drought conditions are determined by the amount of water stored in New York City reservoirs (drought rule curves)
- Exports, flow objectives and reservoir operations are adjusted according to drought severity the estuary salt front position dictates releases during 'Drought Emergency' conditions



Delaware River Basin Commission | River Mileage System

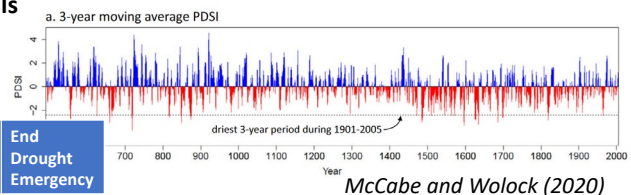
1960s Drought-of-Record

Consecutive years of precipitation deficit in the 1960s led to extreme drought conditions comparable in duration and severity to droughts of previous centuries, as identified by tree ring-based reconstruction of the Palmer Drought Severity Index (PDSI) (McCabe & Wolock, 2020). Drought conditions experienced in the 2000s have been less severe. Impacts of the 1960s drought included:

- Cessation of New York City reservoir releases on 6/4/1965 to preserve storage; a downstream water supply emergency declaration on 7/7/1965 requiring NYC to resume releases
- Upstream encroachment of the estuary salt front threatening Philadelphia and Camden water supply; neither experienced serious contamination issues
- Increased salinity and corrosion problems that led to industrial shutdowns; decreased dissolved oxygen in the estuary that led to extensive fish kills

DRBC (2019)

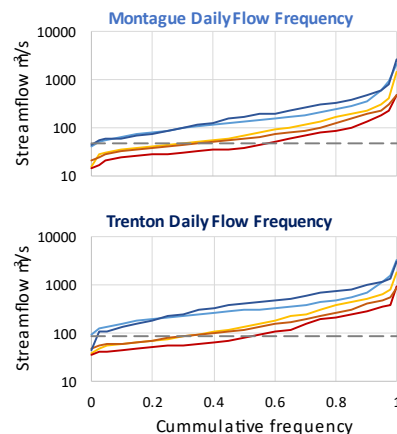
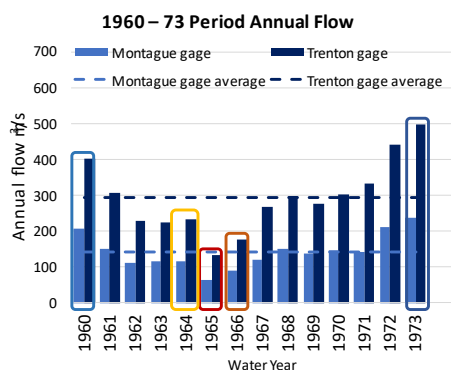
Period	Enter Drought Watch	Enter Drought Warning	End Watch/Warning	Enter Drought	Declare Drought Emergency	End Drought Emergency
1960s					7/7/65	3/15/67
2001-02	10/29/01	11/4/01		12/1/01	12/18/01	11/25/02
2016-17	11/23/16	--	1/18/17			



McCabe and Wolock (2020)

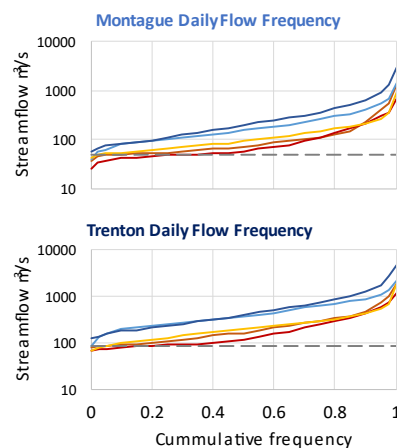
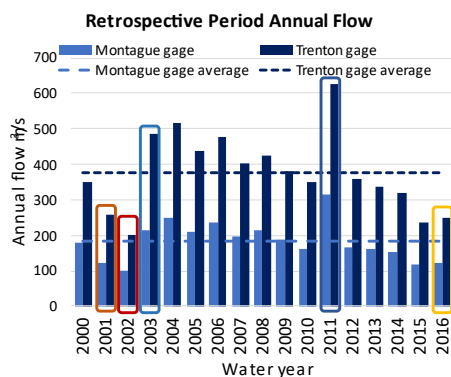
Streamflow during the 1960s Drought-of-Record

During the drought emergency of **WY1965** flow fell below the non-drought flow objective at Montague (49.6 m³/s) 56% of the year, and at Trenton (85.0 m³/s) 52% of the year



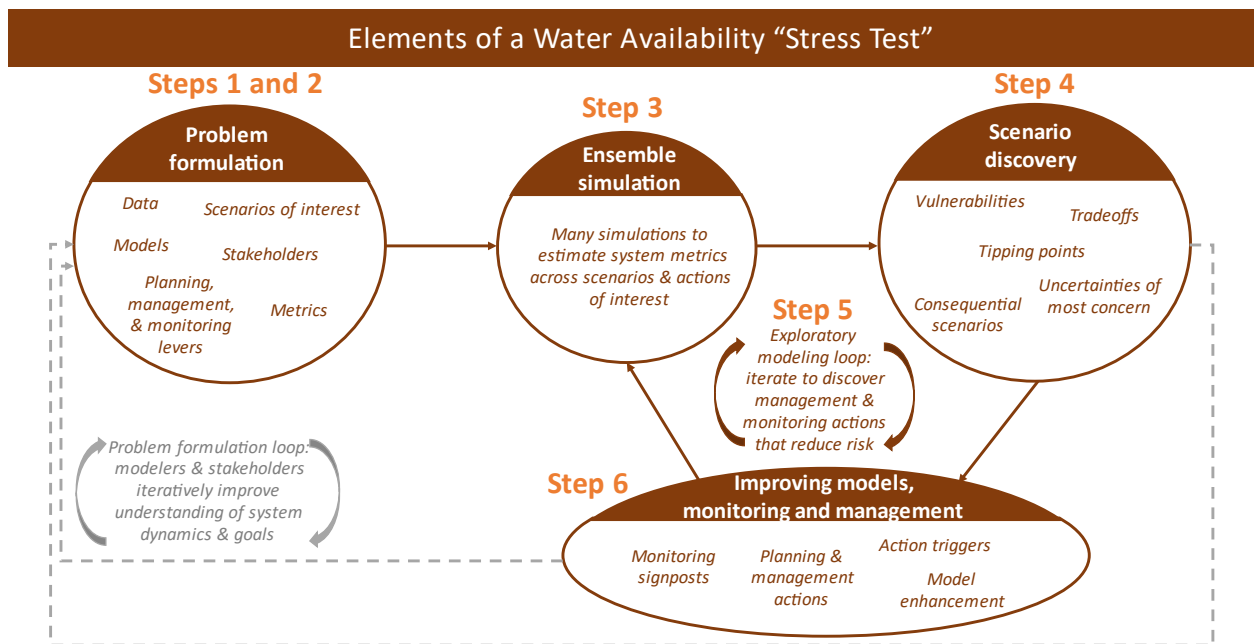
Streamflow and drought during the 2000-16 retrospective period

During the drought emergency of **WY2002** flow fell below the non-drought flow objective at Montague (49.6 m³/s) 31% of the year, and at Trenton (85.0 m³/s) 14% of the year



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4) Stress Testing for Water Availability



A ‘Stress Test’ approach is being implemented to assess water availability and vulnerability to drought in the DRB. The Stress Testing steps have been adapted from the approach of Smith et al. (2022) for long-term planning of water management in the Colorado River Basin. We are currently working on Steps 1 (see figure below) and 2 (see Section 7 - Evaluation of Retrospective Simulated Streamflow). Steps 3 through 6 will be addressed in the next phase of analysis.

Step 1 - Define key components of the analysis:

- Identify the objectives and criteria for the water availability assessment (with stakeholder input) such as the system uncertainties, potential management actions and strategies, models, vulnerability thresholds and performance metrics. These can be formulated using an XLRM Robust Decision-Making Framework (Lempert et al., 2003) as illustrated in the figure below.
- Compile climate, demand, management, and LULC information for historic conditions; characterize the range of potential future conditions.
- Identify model(s) that can simulate relationships between water supply, demand, management, and availability objectives and criteria.

Step 2 – Conduct retrospective simulation(s) of historic conditions to evaluate model performance and past water availability threshold exceedances.

Step 3 – Conduct exploratory modeling encompassing a comprehensive range of future scenarios to characterize likely future water availability.

Step 4 – Analyze simulation results to understand conditions and factors that contribute to vulnerability of water availability.

Step 5 – Explore potential adjustments to water management that could mitigate vulnerability.

Step 6 – Identify scenarios of concern and model limitations to guide further monitoring, modeling, and management actions.

Step 1 - The XLRM Robust Decision-Making Framework for a DRB ‘Stress Test’

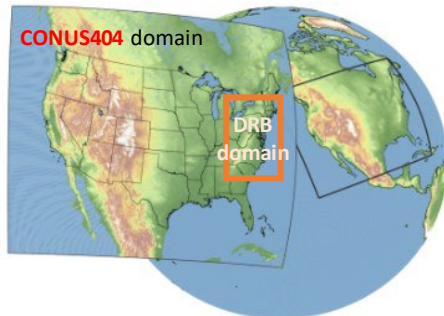
Color code: *Near-term interest*; *Longer-term potential connections depending on team interests, stakeholder connections, funding, etc.*

Exogenous uncertainties (X)	Planning, management, & modeling levers (L)	Relationships & models (R)	Metrics (M)
Water supply <ul style="list-style-type: none"> Climate (long-term) & weather (short-term) LULC change Water demand <ul style="list-style-type: none"> Municipal & industrial Irrigation Energy (thermal cooling, hydroelectric, fracking) Ecosystems Model uncertainty <ul style="list-style-type: none"> Structural, parametric Data, assumption, & scale mismatches across model chain <p>Changing regulations & policy (ESA, carbon pricing, land use policy)</p> <p>Sea level rise & impact on salt front</p> <p>Ecosystem health & needs</p>	<p>*Note: depending on framing & stakeholder engagements, some or all of these may be reframed as uncertainties (X)</p> Reservoir operations <ul style="list-style-type: none"> Total volume of releases Timing of releases Infrastructure & BMPs <ul style="list-style-type: none"> Reservoirs, water treatment facilities, fixing leaky pipes, green stormwater infrastructure Monitoring & action triggers <p>Water transfers & banking agreements</p> <ul style="list-style-type: none"> Water purchase option contracts Drought mitigation banking <p>Insurance</p> <ul style="list-style-type: none"> Parametric contracts with payments triggered by drought 	Physical/hydrologic systems <ul style="list-style-type: none"> GCMs, WRF-NoahMP, NWM, NHM, MODFLOW, ... Water management <ul style="list-style-type: none"> WEAP/Pywr, GCAM, Fore-SCE, power systems Institutions, regulations, social history <ul style="list-style-type: none"> ODRM, DRBC, community groups, activists Water quality <ul style="list-style-type: none"> Temperature, salinity, habitat <p>Financial models</p> <ul style="list-style-type: none"> Revenues, financial risk management, affordability & equity 	<p>*Note: There are many potential metrics, see list on next page for regulatory reqs. More generally, it is helpful to break it up into sectors, types of metric, & distribution</p> Sectors <ul style="list-style-type: none"> Drinking water supply, agriculture, ecosystems, electricity Type of metric <ul style="list-style-type: none"> Reliability (i.e., likelihood of staying below some threshold). Need to define extreme quantile of interest. Cost, affordability, financial risk Distribution of benefits/costs/risks <ul style="list-style-type: none"> Upstream vs downstream In-basin vs out-of-basin Large municipalities vs small rural users

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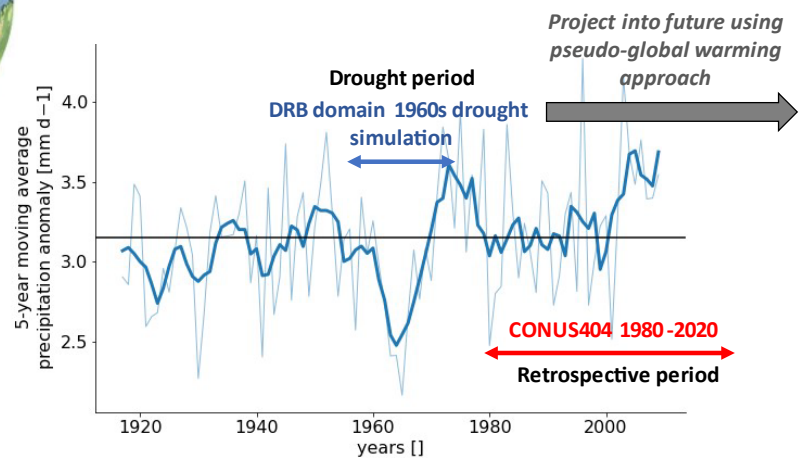
5) Climate Scenario Development

Weather and climate modeling for input to hydrologic and water quality models



CONUS404: A 4-km resolution Weather Research and Forecast (WRF) climate model retrospective simulation for the Continental U.S. has been completed (Rasmussen et al., in preparation). A DRB404 climate data set has been extracted from CONUS404 and processed for use across the DRB domain.

DRB Domain 1960s Drought A 4-km resolution WRF climate model simulation for the 1960s drought period is in development and will be used for future projections of drought



Evaluation of CONUS404 predicted precipitation and air temperature for the Mid-Atlantic region (see figures below) shows that the climate model reproduces observed interannual variability and summer diurnal fluctuations. However, there are biases in the predictions including overestimation of precipitation (particularly in summer) and underestimation of temperature (particularly in winter). Work is underway to develop and apply daily, and per-cell, CONUS404 bias adjustments using Daymet as the reference dataset. The bias adjusted dataset will be hourly and will use the CONUS404 4-km grid.

Evaluation of WRF CONUS404 across the Mid-Atlantic Region: Bias and interannual variability

Evaluation data sets

Data set	Spatial resolution	Temporal resolution	Temporal extent	Variable (PR-precipitation, T-air temperature)
AORC	1 km	1 h	1979-present	Tmean, Tmax, Tmin, PR
Livneh	1/16°	1d	1915-2011	PR, Tmax, Tmin
PRISM	4 km	1d	1981-present	PR, Tmax, Tmin
GMET	12 km	1d	1980-2016	PR, Tmax, Tmin
ERA5	35 km	1h	1955-present	PR, Tmax, Tmin
WRF CONUS404	4 km	15 min.	1979-1995	PR, Tmax, Tmin
COOP	Station	1h	1948-present	PR

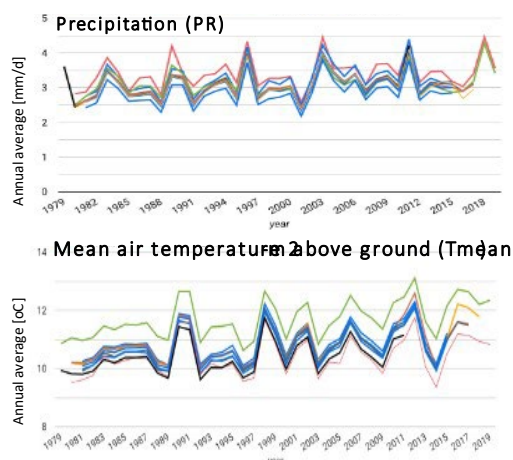
CONUS404 Mid-Atlantic Region Bias

Variable	Annual Bias
Precipitation	12.5 %
Tmin	0.9 °C
Tmean	-0.6 °C
Tmax	-2.2 °C

CONUS404 simulation results



Interannual variability

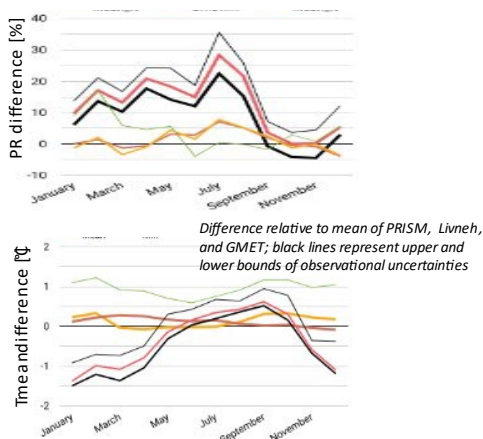


Evaluation of WRF CONUS404 across the Mid-Atlantic Region: Seasonal and diurnal variability

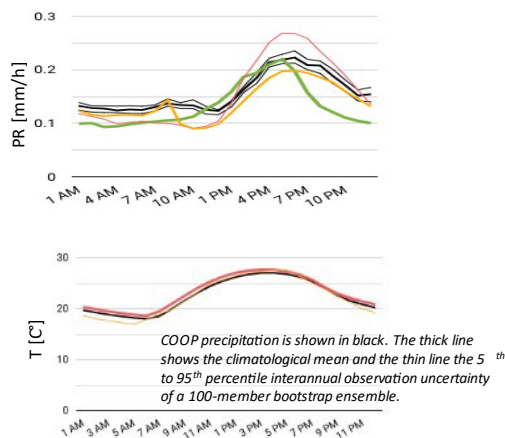
CONUS404 simulation results



Seasonal variability



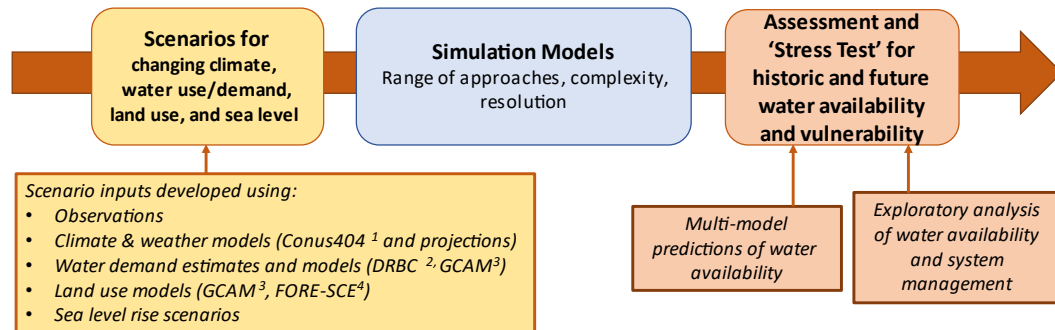
Diurnal variability (summer)



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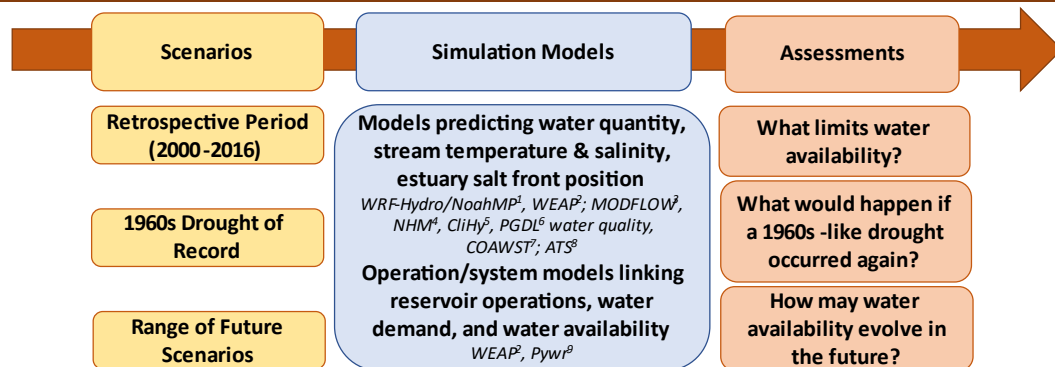
6) Modeling Framework (slide show box of iPoster)

6a) Modeling framework to assess past, current, and future water availability for humans and ecosystems under drought stress



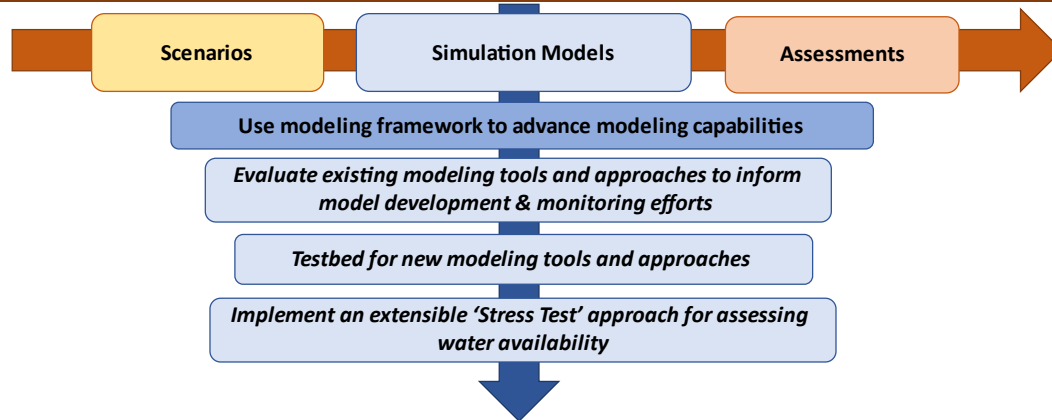
¹Rasmussen et al., in preparation; ²Delaware River Basin Commission (2021); ³Chen et al., 2020; Khan et al., in preparation; ⁴Dornbierer et al., 2021

6b) Scenarios considered, models used, and assessment questions



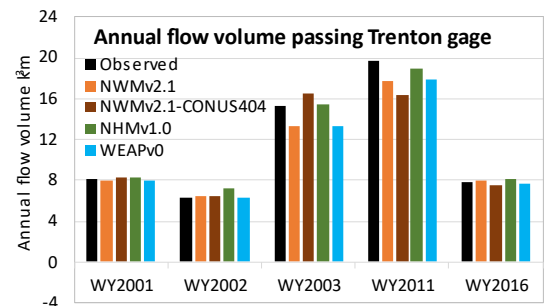
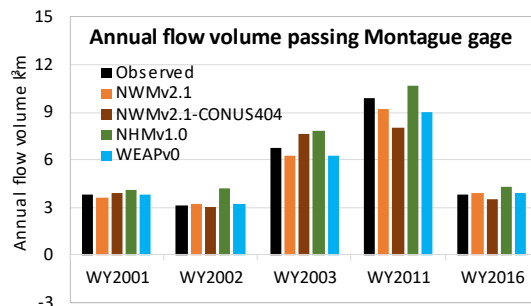
¹Gochis et al., 2020; ²Yates et al., 2005; ³Langevin et al., 2017; ⁴Regan et al., 2018; ⁵Milly and Dunne, 2020; ⁶Jia et al., 2021; ⁷Warner et al., 2010; ⁸Coon et al., 2019; ⁹Tomlinson et al., 2020

6c) Using the modeling framework to advance modeling capabilities



7) Evaluation of Retrospective Simulated Streamflow

Retrospective hydrologic model results- Flow volume



Model	Description	Climate driver data set	Water operations/management
NWMv2.1 ¹	Calibrated National Water Model configuration of WRF-Hydro/NoahMP	NOAA Analysis of Record (AORC)	Level pool reservoir, no water use
NWMv2.1-CONUS404	NWMv2.1 (no recalibration)	CONUS404 (no bias correction) ³	Level pool reservoir, no water use
NHMv1.0 ⁴	Calibrated National Hydrologic Model configuration of PRMS	Daymet	None
WEAPv0 ⁵ (in development)	Hydrologic operations model	gridMET	Water supply/demand including reservoir operations

¹National Weather Service, 2022;²National Weather Service, 2021;³Rasmussen et al., in preparation;⁴Regan et al., 2018;⁵Yates et al., 2005

The National Water Model (NWMv2.1), National Water Model with CONUS404 climate and no recalibration (NWMv2.1-CONUS404), and the National Hydrologic Model (NHMv1.0) are hydrologic models that primarily represent natural streamflow and do not include water demand and use. Reservoirs are not included in NHMv1.0 and are represented using the simple level pool approach in NWMv2.1 and NWMv2.1-CONUS404. The Water Evaluation and Planning

hydrologic and operations model (WEAPv0, ongoing development) is currently the only DRB hydrologic model that includes reservoir operations linked with water demand and use. Furthermore, the four models are currently each driven by a different climate driver data set. Thus, we expect differences in model performance and streamflow estimates.

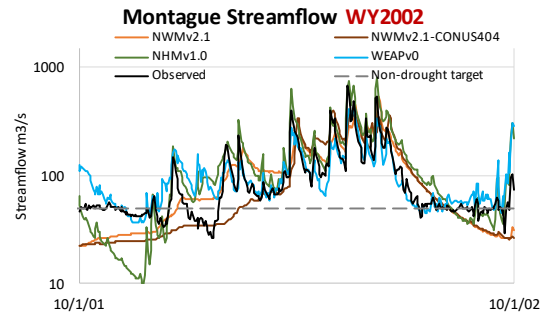
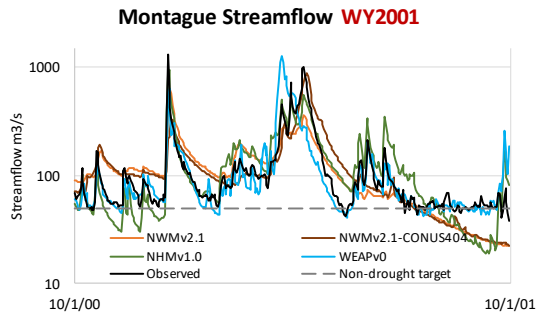
The predictions of annual streamflow volume at the Montague and Trenton stream gages is similar to observed flow volume for all models. Model values are closer to observed values during dry years compared to wet years. In wet years, model response and climate data set representation of large storms influence the results. The Nash Sutcliffe Efficiency (NSE) was used as a simple metric for overall correspondence between observed and simulated streamflow (see first figure below). Model fits were better at the Trenton gage than the Montague gage possibly because reservoir influences diminish downstream. Overall, the NHMv1.0 has the best fit as measured by NSE, however, Montague hydrographs for dry years WY2001 and WY2002 demonstrate that there are no consistent patterns in the performance of the models for flows greater than the non-drought flow target. Differences in NWMv2.1 and NWMv2.1-CONUS404 streamflow reflect differences in the Analysis of Record Climate (AORC) and CONUS404 climate data sets.

Model performance at low flows is important for addressing drought and reservoir management in DRB. The WY2001 and WY2002 Montague hydrographs and flow frequency plots (second figure below) indicate that the WEAPv0 model reproduces observed low flows and occurrence frequency better than the other models because it simulates reservoir releases.

Evaluation of machine learning and hydrodynamic model predictions of the estuary salt front position are being presented in a poster by Gorski et al. (poster 435-157).

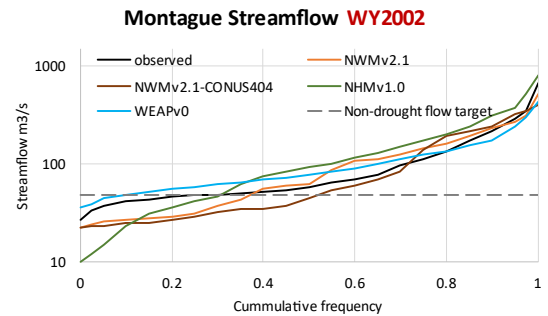
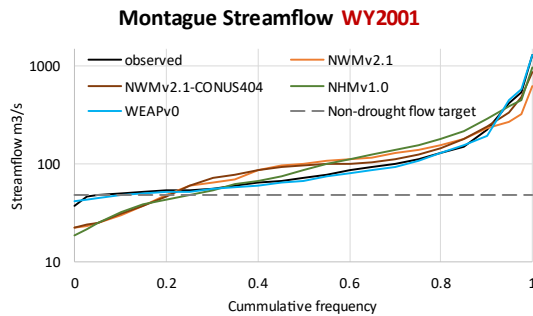
Model evaluation is ongoing and will include other water budget components and stream temperature. The models will subsequently be used to simulate the 1960s drought using the DRB drought climate simulation and results will be evaluated. The models will then be used to explore future scenarios in a 'Stress Testing' framework to assess potential water availability and vulnerability to drought.

Retrospective hydrologic model results- Streamflow



Model	Montague gage streamflow Nash Sutcliffe Efficiency (NSE)						Trenton gage streamflow NSE					
Water Year (dry/wet)	2001	2002	2003	2011	2016	Mean	2001	2002	2003	2011	2016	Mean
NWMv2.1	0.51	0.58	0.56	0.61	0.32	0.51	0.58	0.86	0.50	0.84	0.56	0.67
NWMv2.1-CONUS404	0.60	0.53	-0.02	0.27	0.13	0.30	0.59	0.85	0.01	0.69	0.35	0.50
NHMv1.0	0.76	0.56	0.70	0.76	0.77	0.71	0.85	0.94	0.83	0.91	0.87	0.88
WEAPv0	0.08	0.70	0.31	0.60	0.56	0.45	0.60	0.87	0.43	0.85	0.68	0.69
Mean	0.56	0.55	0.41	0.56	0.42	0.50	0.61	0.87	0.45	0.79	0.59	0.66

Retrospective hydrologic model results- Streamflow frequency distribution



Water Year (dry/wet)	Annual frequency of streamflow below non-drought flow objective											
	Montague gage						Trenton gage					
	2001	2002	2003	2011	2016	Mean	2001	2002	2003	2011	2016	Mean
Observed	0.07	0.30	0.01	0.00	0.03	0.08	0.01	0.14	0.00	0.00	0.05	0.04
NWMv2.1	0.20	0.37	0.03	0.00	0.26	0.17	0.08	0.18	0.03	0.00	0.15	0.09
NWMv2.1-CONUS404	0.22	0.51	0.04	0.03	0.24	0.21	0.06	0.43	0.04	0.00	0.14	0.13
NHMv1.0	0.27	0.31	0.00	0.01	0.08	0.13	0.09	0.16	0.00	0.00	0.00	0.05
WEAPv0	0.04	0.10	0.00	0.00	0.00	0.03	0.03	0.08	0.00	0.00	0.01	0.02
Model mean	0.18	0.32	0.02	0.01	0.14	0.14	0.06	0.21	0.02	0.00	0.07	0.07

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

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