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

Hedeff Essaid[1,1], Aubrey Dugger[2,2], Jeni Keisman[3,3], Nancy Baker[4,4], Adam Benthem[3,3], Joel Blomquist[3,3], Katherine Calvin[5,5], Xingyuan Chen[5,5], Salme Cook[6,6], Galen Gorski[1,1], Andrew Hamilton[7,7], Liv Herdman[8,8], Abigail Jaye[2,2], Noah Knowles[3,3], P Milly[9,9], Diana Pedraza[1,1], Jason Pope[10,10], Andreas Prein[2,2], Patrick Reed[7,7], Gregory Rouze[11,11], Kevin Sampson[2,2], Ward Sanford[12,12], Gabriel Senay[13,13], Jared Smith[1,1], Terry Sohl[14,14], Charuleka Varadharajan[15,15], Chris Vernon[16,16], David Yates[2,2], and Jacob Zwart[1,1]

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[6]US Geological Survey Woods Hole Science Center
[7]Cornell University
[8]USGS New York Water Science Center
[9]USGS Water Mission Area
[10]USGS Virginia Water Science Center
[11]KBR
[12]United States Geological Survey (USGS)
[13]U.S. Geological Survey Earth Resources Observation and Science (EROS) Center
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Abstract

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. We are bringing together a community of scientists from the U.S. Geological Survey, National Center for Atmospheric Research, Department of Energy, and Cornell University to create an integrated human-hydro-terrestrial modeling framework, linking pre-existing models, that can explore and synthesize system response and vulnerability to drought in the Delaware River Basin (DRB). 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 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 Office

of the Delaware River Master administers provisions of the 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. The DRB weathered a major drought in the 1960s, but water resource managers do not know if current operations and water demands can be sustained during a future drought of comparable magnitude. The integrated human-hydro-terrestrial modeling framework will be used to identify water supply and ecosystem vulnerabilities to drought and will characterize system function and evolution during and after periods of drought stress. Models will be forced with consistent input data sets representing scenarios of past, present, and future conditions. The approaches used to unify and harmonize diverse data sets and open-source models will provide a roadmap for the broader community to replicate and extend to other water resource issues and regions.

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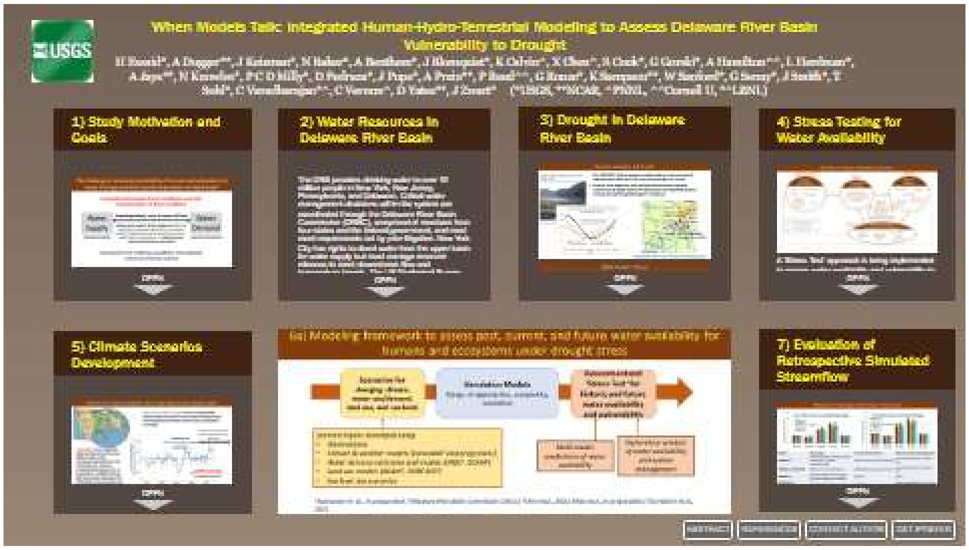

H Essaid*, A Dugger**, J Keisman*, N Baker*, A Benthem*, J Blomquist*, K Calvin^, X Chen^, S Cook*, G Gorski*, A Hamilton^^, L Herdman*, A Jaye**, N Knowles*, P C D Milly*, D Pedraza*, J Pope*, A Prein**, P Reed^^, G Rouze*, K Sampson**, W Sanford*, G Senay*, J Smith*, T Sohl*, C Varadharajan*^, C Vernon^,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

USGS

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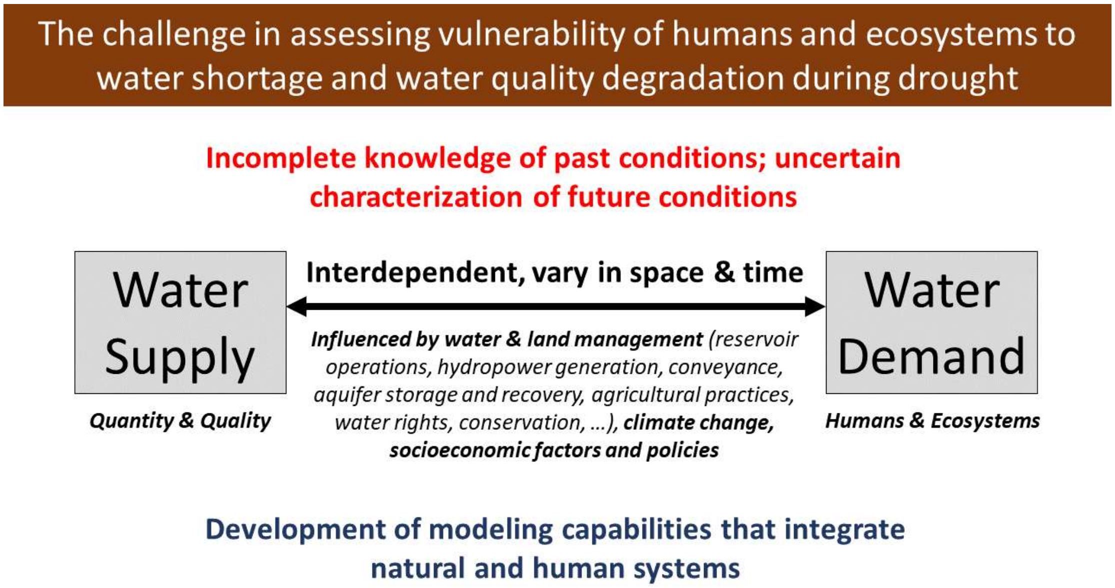
Frontiers in Hydrology

1) STUDY MOTIVATION AND GOALS



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:

1. The ability of existing retrospective models (2000-2016) to reproduce past observed water resource conditions

2. The ability of existing models to reproduce water resource conditions during the 1960s drought of record

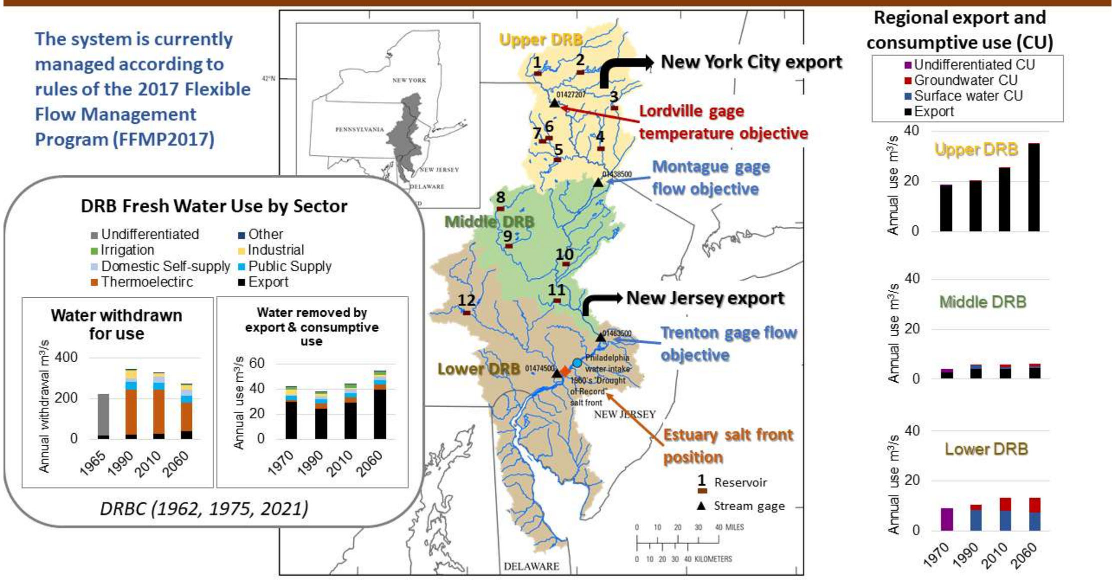
3. Predict the impacts of a 1960s-like drought occurring today under current water management, land use land cover (LULC), and water demand conditions

4. 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

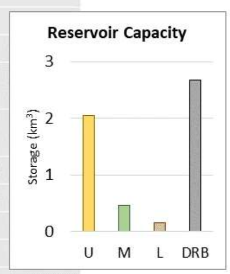
2) WATER RESOURCES IN DELAWARE RIVER BASIN

Water resource management with past and projected future water use



Reservoirs in the Delaware River Basin

Map no.	Reservoir (dam name if different from reservoir)	Year dam completed	DRB Region (State)	Storage Capacity km³	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 (HE - 21.6 M, R)
5	**Wallenpaupak (Wilsonville)**	1926	U (PA)	0.33	Public Utility: (HE - 44.0 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 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

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.

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).

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1654038346/agu/7B-76-B2-C6-E8-0A-87-A8-41-C8-45-E1-61-9B-C9-CD/Video/SleckmanLULC_Media1_c9g6wv.mp4

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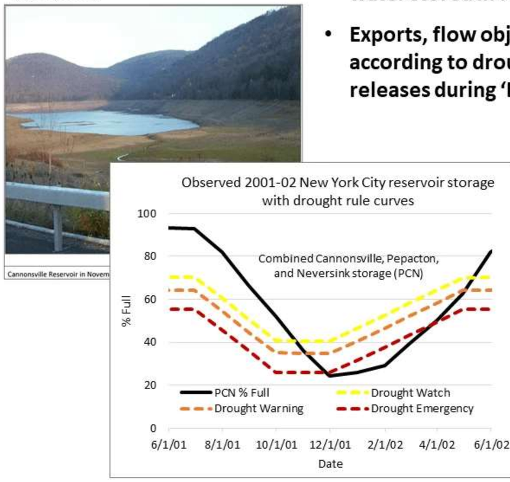
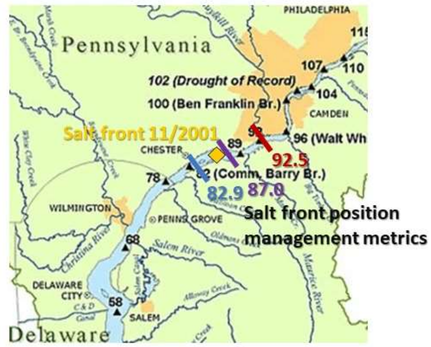
3) DROUGHT IN DELAWARE RIVER BASIN

Reservoir operations and drought

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



- **The FFMP2017 defines drought conditions based on 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**

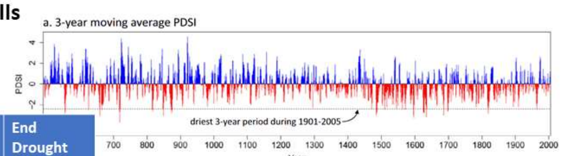


[Delaware River Basin Commission | River Mileage System]

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**



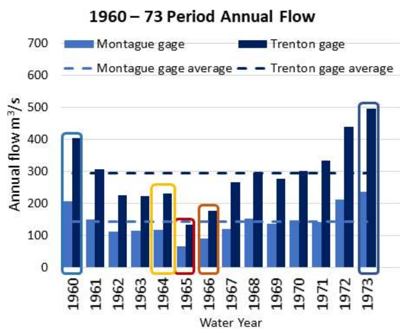
McCabe and Wolock (2020)

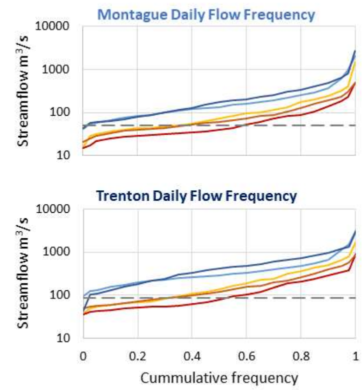
DRBC (2019)

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			

Streamflow during the 1960s Drought-of-Record

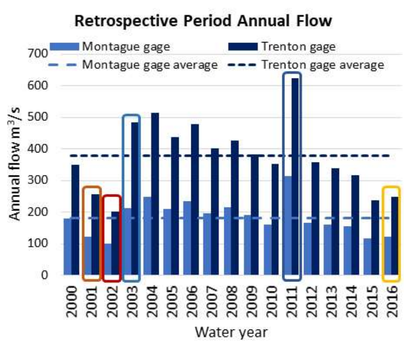
During the drought emergency of WY1965 flow fell below the non-drought flow objective at Montague (49.6 m^3/s) 56% of the year, and at Trenton (85.0 m^3/s) 52% of the year

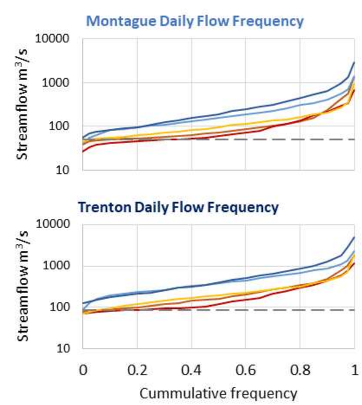




Streamflow and drought during the 2000-16 retrospective period

During the drought emergency of WY2002 flow fell below the non-drought flow objective at Montague (49.6 m^3/s) 31% of the year, and at Trenton (85.0 m^3/s) 14% of the year





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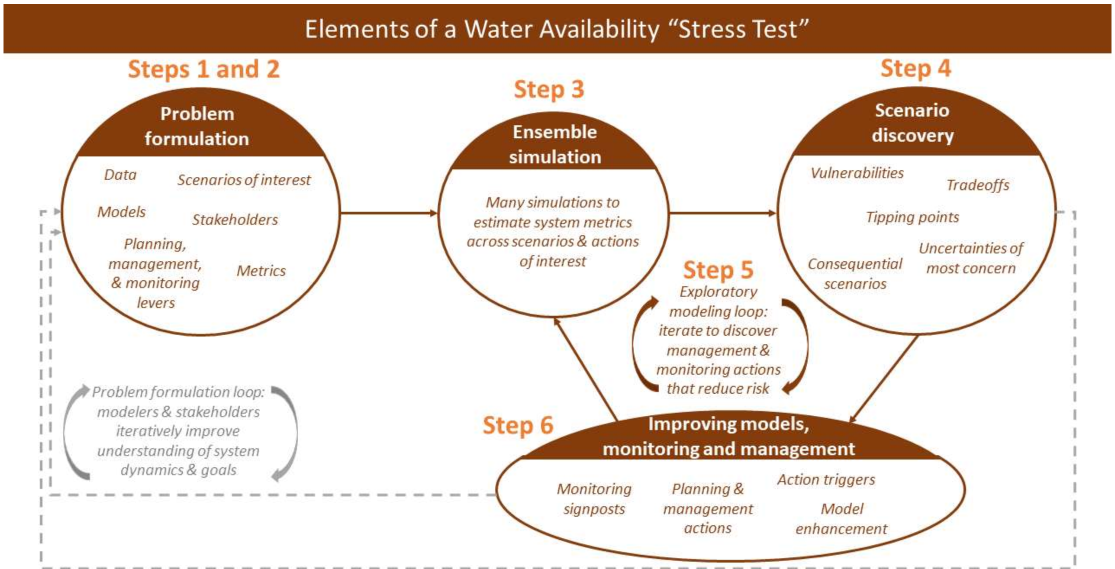
4) STRESS TESTING FOR WATER AVAILABILITY



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 • Climate (long-term) & weather (short-term) • LULC change **Water demand** • Municipal & industrial • Irrigation • Energy (thermal cooling, hydroelectric, fracking) • Ecosystems **Model uncertainty** • Structural, parametric • Data, assumption, & scale mismatches across model chain Changing regulations & policy Sea level rise & impact on salt front Ecosystem health & needs	**Reservoir operations** • Total volume of releases • Timing of releases **Infrastructure & BMPs** • Reservoirs, water treatment facilities, fixing leaky pipes, green stormwater infrastructure **Monitoring & action triggers** Water transfers & banking agreements • Water purchase option contracts • Drought mitigation banking Insurance • Parametric contracts with payments triggered by drought	**Physical/hydrologic systems** • GCMs, WRF-NoahMP, NWM, NHM, MODFLOW, ... **Water management** • WEAP/Pywr, GCAM, Fore-SCE, power systems **Institutions, regulations, social history** • ODRM, DRBC, community groups, activists **Water quality** • Temperature, salinity, habitat Financial models • Revenues, financial risk management, affordability & equity	**Sectors** • Drinking water supply, agriculture, ecosystems, electricity **Type of metric** • 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** • Upstream & downstream • In-basin & out-of-basin • Large municipalities small rural users

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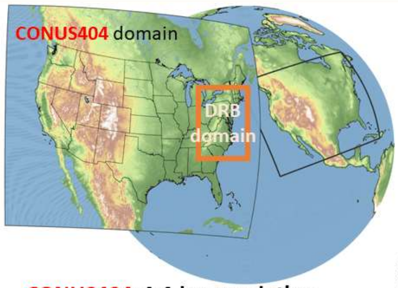
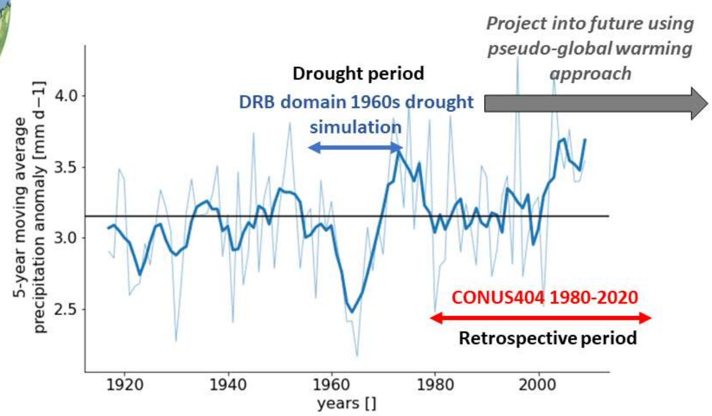
5) CLIMATE SCENARIOS DEVELOPMENT

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

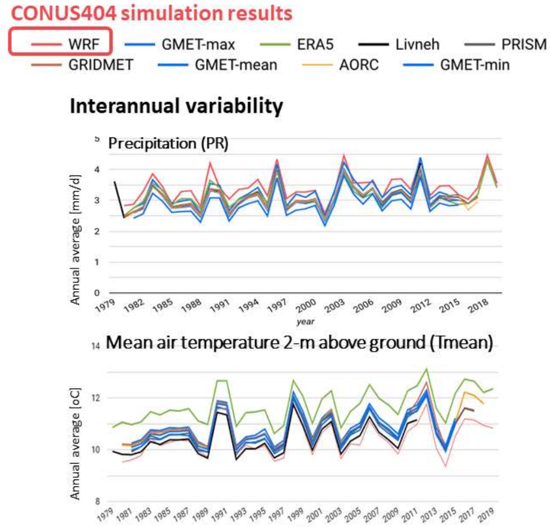
Evaluation data sets

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

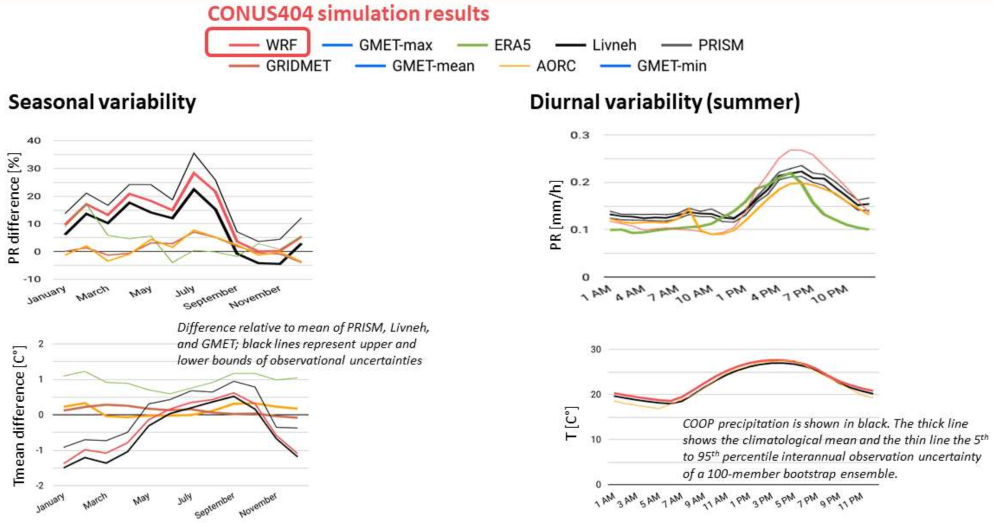
CONUS404 Mid-Atlantic Region Bias

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

CONUS404 simulation results



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



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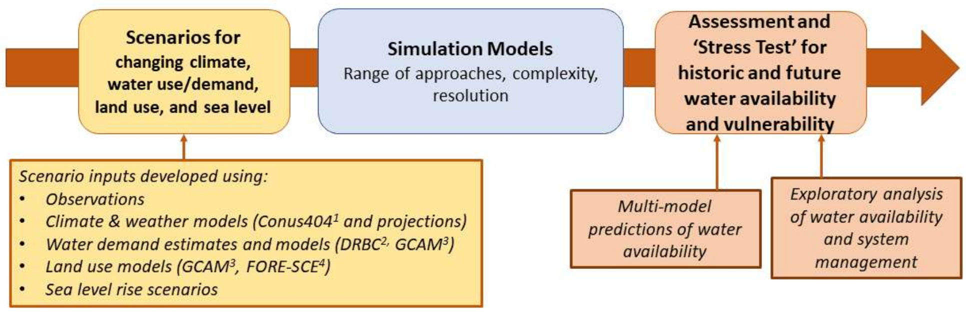
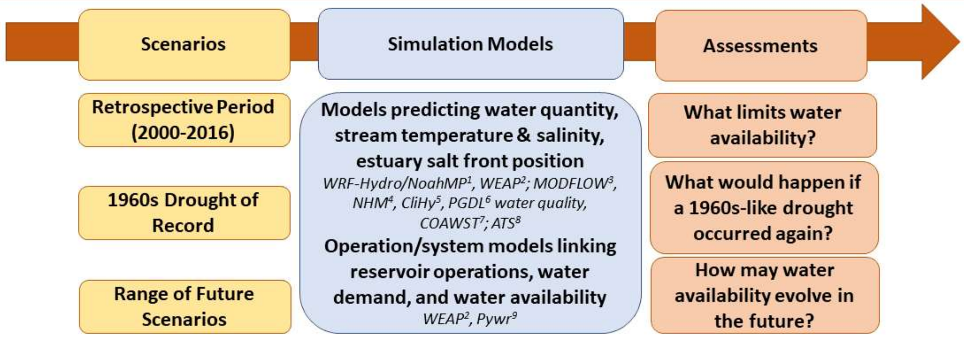
6a) Modeling framework to assess past, current, and future water availability for humans and ecosystems under drought stress



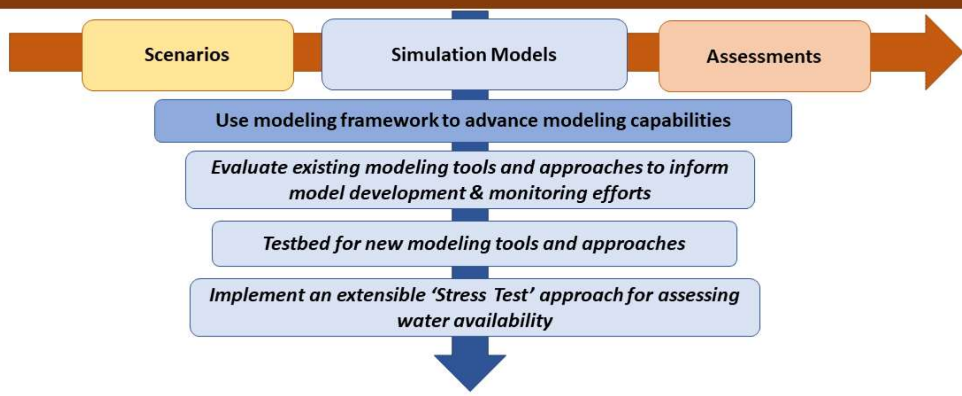
[1]Rasmussen et al., in preparation; [2]Delaware River Basin Commission (2021); [3]Chen et al., 2020; Khan et al., in preparation; [4]Dornbierer et al., 2021

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



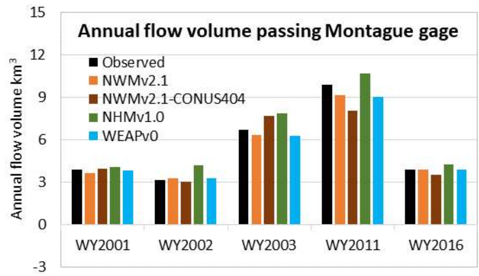
[1]Gochis et al., 2020; [2]Yates et al., 2005; [3]Langevin et al., 2017; [4]Regan et al., 2018; ; [5]Milly and Dunne, 2020; [6]Jia et al., 2021; [7]Warner et al., 2010; [8]Coon et al., 2019; [9]Tomlinson et al., 2020

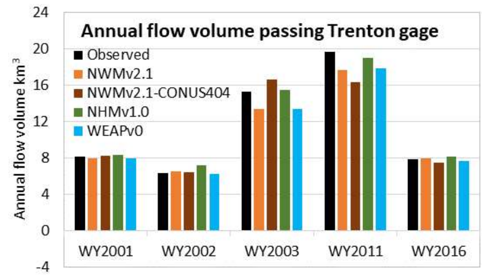
6c) Using the modeling framework to advance modeling capabilities



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)[2]	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

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

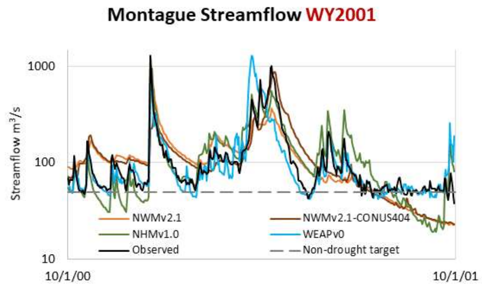
The prediction of annual streamflow volume at the Montague and Trenton stream gages is similar to observed flow volume for all models. Model values are closer to observed values during dry years compared to wet years. In wet years, model response and climate data set representation of large storms influence 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.

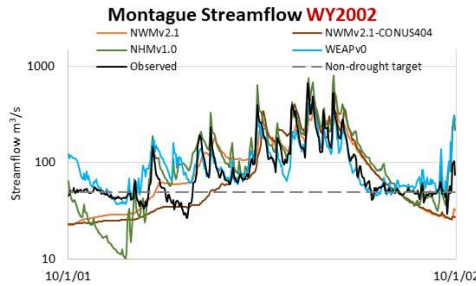
Model performance at low flows is important for addressing drought and reservoir management in DRB. The WY2001 and WY2002 Montague hydrographs and flow frequency plots (second figure below) indicate that the WEAPv0 model reproduces observed low flows and occurrence frequency better than the other models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

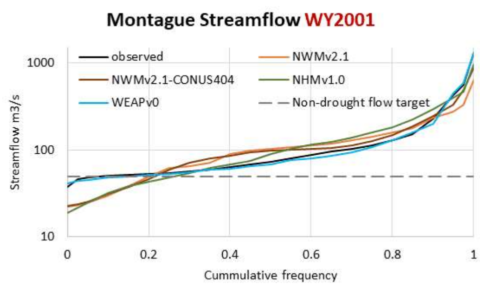
Retrospective hydrologic model results – Streamflow

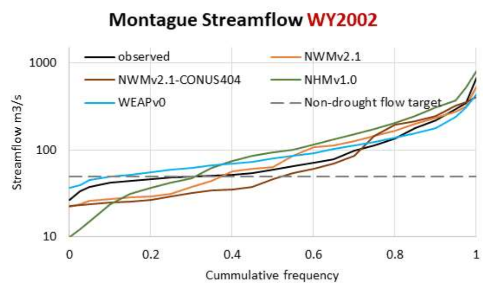




Model	Montague gage streamflow Nash Sutcliffe Efficiency (NSE)						Trenton gage streamflow NSE					
Water Year (dry/wet)	2001	2002	2003	2011	2016	Mean	2001	2002	2003	2011	2016	Mean
NWMv2.1	0.51	0.58	0.56	0.61	0.32	**0.51**	0.58	0.86	0.50	0.84	0.56	**0.67**
NWMv2.1-CONUS404	0.60	0.53	-0.02	0.27	0.13	**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





	Annual frequency of streamflow below non-drought flow objective											
	Montague gage						Trenton gage					
Water Year (dry/wet)	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.

ABSTRACT

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

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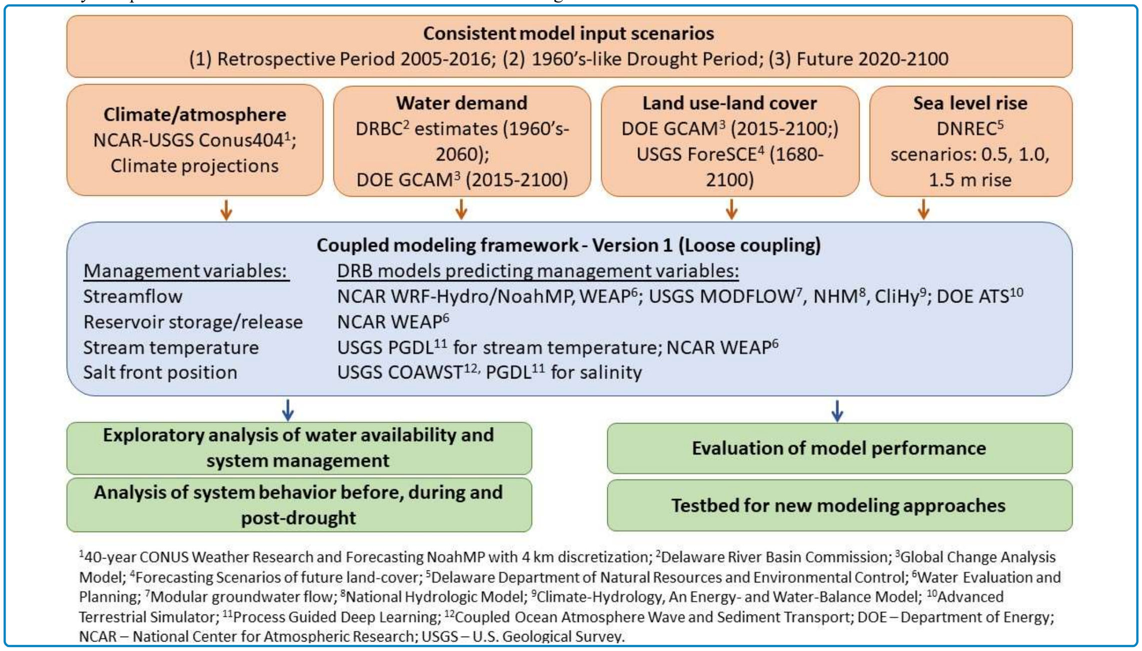
Holistic approaches are needed to investigate the capacity of current water resource operations and infrastructure to sustain water supply and critical ecosystem health under projected drought conditions. Drought vulnerability is complex, dynamic, and challenging to assess, requiring simultaneous consideration of changing water demand, use and management, hydrologic system response, and water quality. We are bringing together a community of scientists from the U.S. Geological Survey, National Center for Atmospheric Research, Department of Energy, and Cornell University to create an integrated human-hydro-terrestrial modeling framework, linking pre-existing models, that can explore and synthesize system response and vulnerability to drought in the Delaware River Basin (DRB). 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 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 Office of the Delaware River Master administers provisions of the 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. The DRB weathered a major drought in the 1960s, but water resource managers do not know if current operations and water demands can be sustained during a future drought of comparable magnitude. The integrated human-hydro-terrestrial modeling framework will be used to identify water supply and ecosystem vulnerabilities to drought and will characterize system function and evolution during and after periods of drought stress. Models will be forced with consistent input data sets representing scenarios of past, present, and future conditions. The approaches used to unify and harmonize diverse data sets and open-source models will provide a roadmap for the broader

community to replicate and extend to other water resource issues and regions.



(https://agu.confex.com/data/abstract/agu/hydrology22/7/8/Paper_1033787_abstract_945434_0.jpg)

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