Sectoral Applications Research Program (SARP)
Final Report

NOAA Award Number – NAOAR4310240

Time Period Addressed by this report – Final Report

Developing A Basin-Wide Framework for Drought Forecasting and Planning in the Chesapeake Bay Region

Principal Investigators

W. Josh Weiss, PhD, PE, D.WRE (Lead Investigator), Associate, Hazen and Sawyer, 1 South Street, Suite 1150, Baltimore, MD, 21202; 410-539-7681; jweiss@hazenandsawyer.com

Richard Palmer, PhD, PE (Co-PI), Professor and Head, Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 222 Marston Hall, 130 Natural Resources Road, Amherst, MA, 01003; 413-545-2508; palmer@ecs.umass.edu

John Balay, PH (Co-PI), Manager, Planning and Operations, Susquehanna River Basin Commission, 1721 N Front Street, Harrisburg, PA, 17102; 717-238-0423; jbalay@srbc.net

Clark Howells (Co-PI), Watershed Section Manager, Environmental Services Division, Bureau of Water and Wastewater, Department of Public Works, City of Baltimore, 18514 Prettyboy Dam Road, Parkton, MD, 21120; 410-396-1586; Clark.Howells@baltimorecity.gov

Project Team Members

William Becker, PhD, PE, BCEE (Institutional Representative), Vice President, Hazen and Sawyer, 498 Seventh Avenue, 11th Floor, New York, NY, 10018; 212-539-7000; wbecker@hazenandsawyer.com

Grantley Pyke, PE (QA/QC), Senior Associate, Hazen and Sawyer, 1 South Street, Suite 1150, Baltimore, MD, 21202; 410-539-7681; gpyke@hazenandsawyer.com

Kinsey Hoffman (Lead Modeler), Assistant Engineer, Hazen and Sawyer, 498 Seventh Avenue, 11th Floor, New York, NY, 10018; 212-539-7000; khoffman@hazenandsawyer.com

Kathryn Booras (Graduate Research Assistant), Department of Civil and Environmental Engineering, University of Massachusetts Amherst; Current: CDM Smith, 75 State Street, Suite 701, Boston, MA, 02109; 617-452-6000; kathryn.booras@gmail.com

Alexandra McIntyre (Graduate Research Assistant), Department of Civil and Environmental Engineering, University of Massachusetts Amherst; Current: Hazen and Sawyer, 9101 Southern Pine Boulevard, Suite 250, Charlotte, NC, 28273; amcintyre@hazenandsawyer.com

Benjamin Pratt, PE, CFM (Stakeholder Outreach), Susquehanna River Basin Commission, 1721 N Front Street, Harrisburg, PA, 17102; 717-238-0423; bpratt@srbc.net

Can Liu (Modeler), Susquehanna River Basin Commission, 1721 N Front Street, Harrisburg, PA, 17102; 717-238-0423; cliu@srbc.net

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Project Goal

This project was initiated to help bridge the gap between development of forecast and early warning products by NOAA and adoption and integration of such into water supply utility planning in the Chesapeake Bay region. The primary goal of this study was to develop a Drought Planning Tool (DPT) for the Susquehanna River Basin to inform stakeholder planning and drought coordination activities.

Geographical Location of Study

Susquehanna River Basin in the Chesapeake Bay watershed; case studies included City of Baltimore, MD; Capital Region Water, Harrisburg, PA; York Water Company, York, PA; and the City of Lancaster, PA

Partners

Peter Ahnert (Technical Advisor), Hydrologist in Charge; and Seann Reed; NOAA, National Weather Service, Middle Atlantic River Forecast Center (MARFC)

Kenan Ozekin, Water Research Foundation (WRF)

Decision-makers(s)/End User(s)

- Susquehanna River Basin Commission
- City of Baltimore, MD, Department of Public Works (DPW)
- Capital Region Water, Harrisburg, PA
- York Water Company, York, PA
- City of Lancaster, PA

Matching Funds/Leveraging

- Susquehanna River Basin Commission: $52,000 (in-kind labor)
- City of Baltimore DPW: Approx. 40 hours of staff time for two workshops, monthly project conference calls, and review of results
- CRW, YWC, Lancaster: Approx. 8 hours of staff time each for two workshops; various conference calls; and review of results

Research Objectives

The primary objectives of this project were to:

(1) Develop a quantitative Drought Planning Tool for the Susquehanna River Basin based on the OASIS system simulation model and drought forecast and early warning products from NOAA NIDIS, NWS, and other sources; and
(2) Evaluate the use of the Tool to support water utility drought planning and operations.

Additional objectives that were addressed during this project include:

(1) Develop a set of methodologies for near- and medium-term predictions of drought likelihood;
(2) Identify key climate and other drought index parameters of importance for the Chesapeake Bay Region; and
(3) Develop practical guidance for NOAA drought products and a framework for implementation of similar planning tools in other basins.

Research Approach and Methodology

The Drought Planning Tool consists of a system simulation model (OASIS, HydroLogics, Inc.); time series of climatological/meteorological drought indices and forecasts; model code for water supply drought operations[1]; and a post-processing dashboard for evaluation of tradeoffs among cost, water supply reliability, and other performance metrics of interest for alternative drought scenarios. Following integration of time series and operations logic, drought indices and operational alternatives were evaluated for four water supply utility case studies: City of Baltimore, MD; Capital Region Water, Harrisburg, PA; York Water Company, York, PA; and the City of Lancaster, PA.

The Susquehanna River Basin Commission (SRBC) maintains an OASIS model of the entire Susquehanna River Basin. This model was updated in 2016 to extend the hydrologic record from 1930-2014 and update input data and operating rules. OASIS is a mass balance model that simulates the routing of water through a water resources system, represented as a series of nodes (e.g., reservoirs, demands) and arcs (e.g., streams, aqueducts). A coding language specific to water resources (Operations Control Language, or OCL) allows users to program complex or system-wide rules. SRBC has used the OASIS model to develop and test management alternatives for the operation of the Conowingo Pond, a multi-purpose reservoir near the mouth of the Susquehanna River with important hydroelectric, water supply, recreation, and environmental objectives.

For this project, historical time series of climatological and meteorological indices were imported to the OASIS model. These included commonly used indicators of drought: cumulative precipitation and streamflow; Palmer Drought Severity Index (PDSI); Palmer Hydrological Drought Index (PHDI); Palmer Modified Drought Index (PMDI); and Standardized Precipitation Index (SPI). Cumulative precipitation and streamflow time series included the last 6 months of precipitation and the last 3 and 12 months of streamflow. Historical time series values for the simulation period (1930-2014) were generated from OASIS model input time series (streamflow and precipitation) and converted to a volume for each day of the time series (aggregated over past n-day horizon). Monthly historical time series values for PDSI, PHDI, PMDI, and SPI for the simulation period were retrieved from the U.S. Drought Portal and imported into the OASIS simulation model.

Three kinds of streamflow forecast time series were developed for the DPT to inform drought operations: non-conditional (or “climatology”), conditional (or “statistical”), and preliminary/experimental NWS Hydrologic Ensemble Forecast Service (HEFS) forecasts. These forecast types are probabilistic forecasts, rather than deterministic (single value), meaning the forecast is an ensemble made up of multiple separate forecasts, called traces or ensemble

[1] Water supply operations logic was developed for case study utilities; this code serves as a template for development of similar code for other stakeholders.

members. Each trace has an equally likely chance of occurring and typically extends for up to one year into the future.

Both non-conditional and statistical “reforecasts” were generated for every time step of the long-term simulation period. A reforecast is the forecast ensemble that would have been available at a previous point in time. These reforecasts were generated using R, a language and environment for statistical computing. Statistical forecasts were constructed using the Hirsch autoregressive, lag 1 (AR-1) method; monthly streamflow ensembles were obtained by conditioning each trace with the previous month’s observed flow and adding a random component derived from historic streamflow records. Ensemble traces were disaggregated to a daily time step using historic ratios of daily to monthly streamflow.

HEFS reforecasts were provided by the Mid-Atlantic River Forecast Center (MARFC) for a roughly 10-year period (2001-2010). To enable testing of realistic, forecast-based operating rules, ensembles were summarized by horizon and percentile to produce a single streamflow volume on each day of the simulation period. Selected horizons for the DPT included seven, 30, 60, and 90 days. Selected percentiles included the 5th, 10th, 25th, and 50th percentiles, emphasizing the dry end of the distribution to support drought prediction. For each simulation day, daily forecast volumes within each forecast trace were accumulated to the length of the selected horizon; percentiles were calculated across the ensemble traces, resulting in a single forecast volume for each percentile and horizon.

Initial screening of drought indices, forecasts, and operating rules was conducted using a simulation model of just the City of Baltimore’s water supply system, referred to as the Drought Action Response Tool (DART). DART was developed using STELLA®, an object-oriented modeling platform, in close collaboration with staff from Baltimore DPW. Results of these screening analyses were used to guide parameter and input selection for the DPT and inform operating rule development for the water supply case studies.[2]

Full case study evaluations of drought indices and operations were conducted using the DPT. Simulations were conducted first using baseline operating rules to compare drought indices. Indices that provided the best performance were used to trigger alternative operating scenarios, which were developed for each case study based on system characteristics (e.g., sources, infrastructure) and guided by workshop discussions with utility planning and operations staff. Performance metrics included measures of supply reliability (e.g., minimum and average annual reservoir storage); estimated incremental operating cost (e.g., treatment, lost revenue due to use restrictions, pumping); and frequency of triggering drought status. Simulation results were analyzed using a custom post-processing dashboard, built using the Microsoft PowerBI software platform.

[2] Further detail on these analyses is provided by Booras et al. (2017) and McIntyre et al. (2017); see list of completed, peer and non-peer reviewed publications.

Accomplishments - Research Findings

For each case study, two sets of DPT simulations were carried out: (1) one set to compare responses of drought indices and reforecasts to dry periods and severe droughts within the historical simulation period under baseline (current) water supply operations; and (2) one set to compare alternative operating strategies, triggered by a subset of drought indices and reforecasts. Performance of runs was viewed as a tradeoff between metrics of supply reliability through dry periods and the cost associated with use of secondary supplies or use restrictions.

The first set of simulations revealed a strong linear relationship between reliability and cost: when secondary supply was used more frequently, reliability metrics showed an improvement over the baseline run but costs increased. For the City of Baltimore and Capital Region Water case studies, most indicators improved long-term reliability, but resulted in increased annual operating costs. For the York Water Company case study, none of the indicators improved long-term reliability, and most indicators demonstrated a reduced annual operating cost. Indicators that resulted in long-term reliability and cost metrics closest to the baseline run were SPI indices at 6- and 12-month horizons at the -1/-2/-3 thresholds and streamflow forecast-based indices. The key takeaway from all case studies is that new indicators alone (under existing drought contingency plans) are not better able to identify the right time to initiate secondary supplies than the existing base runs that use storage-based triggers.

The second set of simulations contained model runs tailored to each case study. These runs included: combinations of indicators to trigger actions under existing drought contingency plans; use of demand cutbacks or restrictions to improve reliability; and changes to existing operating rules at the onset of drought conditions.

For the Baltimore case study, a combined forecast- and storage-based operating trigger for initiating pumping from the secondary supply performed the best in terms of balancing reliability and cost objectives. This strategy initiated three stages of pumping from the Susquehanna River (secondary supply) based on Days of Supply Remaining (DSR) and total reservoir storage thresholds. This combined-index strategy helped eliminate “false positives,” when forecasts anticipated dry conditions but they had not yet impacted system storage, as well as the periods of drought recovery when system storage remained low but forecasts showed natural refill, indicating that pumping from the more costly secondary supply could be terminated.

An alternate strategy tested for Baltimore was to operate the secondary supply such that total system storage is as close to full as possible on July 1st, using streamflow forecasts and DSR to initiate pumping whenever projected June storage is predicted to be less than 75%. This strategy altered the timing, but not magnitude, of pumping from the secondary supply in a way that could be beneficial to both the City of Baltimore (by maintaining or decreasing costs of operating the secondary supply) and other Lower Susquehanna River users (by avoiding pumping during the lowest-streamflow periods).

A third finding from the Baltimore case study was that performance of alternate triggers and operating policies was highly dependent on the assumed demand level. When annual average demand was increased by 33-50%, secondary supply usage was increased by about 400%, and alternate indicators did not initiate secondary supply usage far enough in advance of rapidly declining primary supply storage levels. This finding demonstrated that current operating rules in low-flow periods are typically tuned to demand levels, and that as demand changes, alternate drought indicators must be selected with appropriate lead times to protect system reliability through drought periods.

For the Capital Region Water (CRW) case study, most alternative operating strategies resulted in more pumping from secondary supply than the current baseline run. Similar to the Baltimore case study, the CRW case study showed that combined forecast and storage-based indicators helped increase supply reliability at a relatively low additional cost while mitigating some of the pumping “false positives.” The alternate operating strategies also demonstrated that the case study’s primary supply reservoir is very responsive to low inflows (rapid reservoir drawdown) and to secondary supply pumping or large inflows (reservoir recovery) because it is a small reservoir relative to daily demand. Current storage triggers for secondary supply pumping are very low (about 12% usable storage). Findings from this evaluation suggest that intermediate trigger(s) and/or earlier blending of primary and secondary supplies should be considered.

The York Water Company (YWC) supply system is different than the Baltimore and CRW systems in that a river source is the utility’s primary supply, reservoir storage is the secondary supply, and the Susquehanna River is used to refill the secondary supply reservoirs when they are substantially drawn down. Accordingly, index-based triggers did not generally help improve reliability due to a temporal misalignment of indices/forecasts and reservoir drawdown. For example, since the reservoirs are the secondary supply, they could be completely full when forecasts indicate an approaching dry period; there would be no reason to trigger refill of the reservoirs from the Susquehanna River under this scenario. This suggests that drought indices are more relevant for operation of reservoir supply systems than run-of-river systems.

An area of improvement for the YWC case study was observed during recovery from dry periods. Combined forecast and storage-based triggers were successful at reducing the amount of pumping required to refill the secondary reservoirs, thereby reducing the operating cost. While this results in a slight decrease in reliability, as measured by reservoir storage, such a decrease may be acceptable if forecasts indicate that the reservoirs are likely to recover by natural inflows.

A third finding from the YWC case study was that demand cutbacks could almost entirely alleviate the need for pumping from the Susquehanna River to refill secondary supply reservoirs. Note that demand cutbacks are a last resort for this utility due to the associated loss in revenues, so this alternate operating strategy is not practical. This observation supports the finding from the Baltimore case study that performance of alternate indices and strategies are highly dependent on total demand levels.

Accomplishments - Outreach and Communication Activities

This project included extensive outreach efforts, including project-specific and Basin-wide stakeholder workshops, numerous conference presentations, and a planned nationwide webinar to be facilitated by WRF (under development). Collectively, the outreach activities described below met three key objectives:

- Raise awareness of the Drought Planning Tool within the Basin stakeholder community;
- Raise awareness of NOAA early warning drought and forecast products within the Chesapeake Bay region; and
- Solicit peer review and guidance on DPT applications from the broader research and water resources communities.

Two sets of workshops were conducted for the project case studies, one set with staff from the City of Baltimore's Department of Public Works and a second set with case study participants from the Lower Susquehanna River Basin. Initial project workshops were conducted in the first half of the project during design of the case study analyses. These workshops focused on introducing the project and the Drought Planning Tool; discussing drought indices and forecasts; reviewing baseline operating policies; and soliciting input from utility staff on potential alternatives to evaluate. These workshops were followed by informal phone calls with utility staff to discuss follow up questions. A second set of workshops was held near the end of the project to review case study results and solicit input on any additional refinements or alternatives to evaluate.

In addition to the case study workshops, the project team conducted outreach via several local and regional stakeholder groups, including: the Baltimore Metropolitan Council's Reservoir Watershed Management Program; the Lower Susquehanna River Source Water Protection Partnership; the Maryland Water Monitoring Council; the Conowingo Pond Management Workgroup; and the Pennsylvania Section of the American Water Works Association. This outreach focused on briefing regional stakeholders on NOAA drought products and development of the DPT.

Finally, project members gave presentations on this project at several national conferences, including: the 2016 American Water Resources Association Annual Conference (Orlando, FL); the 2016 World Environmental & Water Resources Congress (West Palm Beach, FL); the 2017 American Water Works Association Annual Conference and Exhibition (Philadelphia, PA); the 2017 AWRA Summer Specialty Conference on Climate Change Solutions: Collaborative Science, Policy, and Planning for Sustainable Water Management (Tysons, VA); and the 2017 Interstate Council on Water Policy Annual Meeting (Baltimore, MD). In January 2018, Dr. Weiss will draw upon results from this project during his participation on a panel discussion at the 28th Annual Meeting of the American Meteorological Society (Austin, TX), entitled "Decision Making by Water Utilities: Using Climate/Weather Information in Short and Long-Term Planning."

Accomplishments - Measuring Impact on Decision-Making

This project was initiated to address a critical need for water resources planning in the Chesapeake Bay Region, and more specifically in the Susquehanna River Basin. NOAA NWS and RFC products have become increasingly quantitative and detailed; however, water planners in the Region have been slow to adopt these data sources to inform drought planning and operations. Further, much of the drought planning in the Region is done in silos, with various divisions based on state and local requirements, industry (e.g. supply, agriculture, power), and individual objectives. The Drought Planning Tool developed under this project addresses these needs in two critical ways.

First, the use of SRBC's OASIS system model as the DPT platform provides a quantitative, simulation-based tool to evaluate alternative drought policies across multiple scales. With the DPT, alternative planning or operations scenarios for individual entities are simulated within the context of the overall Basin; thus, impacts and benefits outside of that entity can be easily quantified. Further, this ensures that planning scenarios analyzed by different stakeholders are conducted in a consistent manner, using the same inputs and assumptions, to provide apples-to-apples comparisons. These aspects of the DPT will greatly enhance drought coordination and stakeholder decision-making activities in the Basin.

Second, the DPT is a platform for integrating NOAA drought products into planning activities in a quantitative manner. Existing use of drought indices and forecasts to inform drought policy in the Basin was largely limited to qualitative consideration of these products in determining current drought status. Inclusion of these products in the DPT enables evaluation of alternative drought mitigation policies triggered by index and forecast-informed measures of weather and Basin conditions. This approach will help stakeholders emphasize proactive and "no regrets" policies for which performance can be predicted in a quantitative manner through DPT simulations.

The case studies conducted during this project serve as demonstrations of a framework to use the DPT to develop and test drought index and forecast-based operating policies and quantify the benefits and impacts of such, at various scales. In each case, these analyses provided the four water supply participants with valuable information on the utility of NOAA drought index and forecast products and alternative drought mitigation strategies. Importantly, the main objective of the case studies was not to identify an "optimized" set of operating rules for each water supply utility but rather to show tradeoffs between cost and drought reliability while demonstrating a tool and framework for those utilities to continue to test and adopt their own alternative operating strategies and drought plans.

For Baltimore DPW, this improvement in planning capabilities has already borne fruit in the context of the City's application for increased allocation from the Susquehanna River during low flow periods. Negotiations between the City and SRBC are being guided by DPT simulations and innovative strategies are being considered, such as offsetting consumptive use mitigation fees with forecast-informed operations. As these negotiations continue, they will serve as a valuable test case for the DPT in facilitating multi-party and multi-objective coordination in the Basin. Future planning is underway to extend the DPT from planning to operational implementation, in which real-time simulations, fed by current system status, drought indices, and NWS forecasts, could be used to support drought coordination activities.

Accomplishments - Deliverables produced

- Susquehanna River Basin Drought Planning Tool (delivered to SRBC)
- Drought Planning Tool Post-Processing Dashboard (delivered to SRBC)
- NOAA SARP Final Report (this document)
- Drought Planning Tool Case Study Report (in progress; to be delivered to SRBC and case study participants upon completion)

Significant Deviations from Proposed Workplan

This project deviated from the proposed workplan in two major aspects. First, the original intent of a second case study (in addition to the Baltimore case study) was to address basin-scale drought planning, with aspects related to water utility operations, hydropower operations, environmental objectives, and interstate coordination. After meeting with SRBC staff and other stakeholders, it was clear that such a wide-ranging effort would be a logistical challenge to undertake. The project team decided that the second case study would instead focus just on water utility planning and operations within the lower portion of the Susquehanna River Basin as a surrogate for larger scale (i.e. more than one stakeholder) use of the DPT. This case study was facilitated by SRBC staff via an existing stakeholder workgroup, the Lower Susquehanna River Source Water Protection Partnership (SWPP), through which the three water supply utility volunteers were selected. Second, the project team originally envisioned a set of Basin-wide workshops that would support design and execution of the DPT analyses. Instead, we opted for smaller, case study focused workshops, including two with staff from the City of Baltimore and two with the SWPP case study participants. These workshops, supplemented by several larger workshops associated with existing stakeholder workgroups, enabled detailed discussions on operational and planning needs for water utility cases studies.

List of completed, peer and non-peer reviewed publications, white papers, or reports

Two students at the University of Massachusetts Amherst, Kathryn Booras and Alexandra McIntyre, completed their Master’s theses related to this project.

The following manuscript has been revised and accepted for publication in the ASCE Journal of Water Resources Planning and Management:

Booras, K., McIntyre, A.R., Weiss, W.J., Howells, C., and Palmer, R.N. (2017). "Drought Management using Aggregate Drought Indices: A Case Study of the City of Baltimore Water Supply". *Journal of the Water Resources Planning and Management*. In press.

A second manuscript is in preparation and will be submitted to the same journal, titled “Analyzing Streamflow Forecasts in the Context of System Performance: A Case Study of the City of Baltimore Water Supply”.

We have been invited to submit a paper to the *Journal of the American Water Resources Association* as part of the featured collection entitled, “Climate Change Solutions”. The manuscript will be submitted by the deadline of March 9, 2018. Tentative authors and title are:

Weiss, Hoffman, Pratt, Balay, Palmer, Howells. “Quantitative Drought Planning in the Northeastern US: the Susquehanna River Basin Drought Planning Tool.”

List website addresses relevant to the project for further information (if available)

N/A

List of presentations/seminars, photos, or other visuals related to project

The following attachments comprise project planning, coordination, and review activities (project meetings and case study workshops):

- *2015-03-27 NOAA SRB Drought Planning Tool Kickoff.pdf* – Slides from project kickoff meeting
- *SRBC_2015_04_29_v2.pptx* – Slides from NOAA MARFC briefing to the project team
- *2015-10-23 Baltimore Drought Workshop – Introduction.pptx* – Slides from initial briefing to Baltimore DPW staff
- *2016-03-14 Baltimore Workshop with Director Chow – Full.pptx* – Slides from project briefing for Baltimore DPW Director Chow
- *2016-05-19 Lower Susquehanna Case Study Workshop.pptx* – Slides from first workshop with Lower Susquehanna River SWPP case study participants
- *Follow-up Call with York Water 2016-08-31.pdf* – Slides used during follow-up call with York Water Company
- *2017-05-03 Lower Susquehanna Case Study Workshop 2.pptx* – Slides from second workshop with Lower Susquehanna River SWPP case study participants
- *2017-07-27 Baltimore Case Study Meeting 2 - Background Material.pdf* – Background material provided to City of Baltimore staff and managers prior to second case study workshop
- *2017-07-27 Baltimore Case Study Meeting 2.pptx* – Slides from final Baltimore case study workshop to review results with James Price, Acting Bureau Head, Water and Wastewater

The following attachments comprise project outreach activities (conferences and meetings):

- *2015-06-30 NOAA SRB Drought Planning Tool Lower Susquehanna DWP.pptx* – Slides from presentation to the Lower Susquehanna River SWPP
- *2015-11-13 Maryland Water Monitoring Council* – Slides from presentation at the Maryland Water Monitoring Council 2015 annual meeting
- *2016-06-30 Conowingo Pond Management Workgroup.pptx* – Slides from presentation to the 2016 annual meeting of the Conowingo Pond Management Workgroup
- *2016-11-03 PA AWWA NOAA-SRBC Overview.pptx* – Slides from presentation at the 2016 Pennsylvania Section American Water Works Association (AWWA) meeting
- *2016-11-13 AWRA Weiss Towards a Basin-Wide Drought Planning Tool in the Susquehanna River Basin.pptx* – Slides from presentation at the 2016 American Water Resources Association (AWRA) Annual Conference (Orlando, FL)
- *2017 AWWA ACE Drought Weiss.pptx* – Slides from presentation at the 2017 AWWA Annual Conference (Philadelphia, PA)
- *2017-06-22 Conowingo Pond Management Workgroup.pptx* – Slides from presentation to the 2017 annual meeting of the Conowingo Pond Management Workgroup (project update)
- *2017 AWRA Drought Weiss.pptx* – Slides from presentation at the 2017 AWRA Summer Specialty Conference on Climate Change Solutions: Collaborative Science, Policy, and Planning for Sustainable Water Management (Tysons, VA)

List of Media Coverage

N/A

For Final Report please include

See attached file: *2017-10-31 NA14OAR4310240 Final Report Project Slides.pptx*

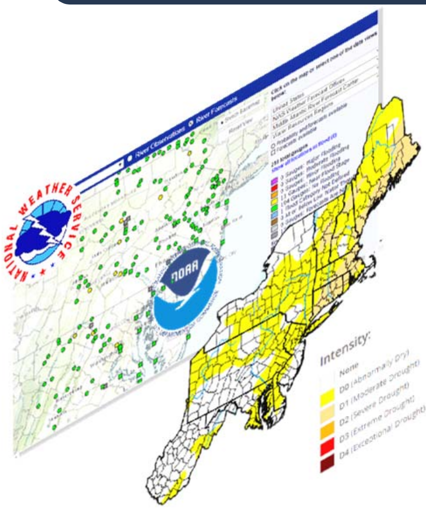
Developing a Basin-Wide Framework for Drought Forecasting and Planning in the Chesapeake Bay Region

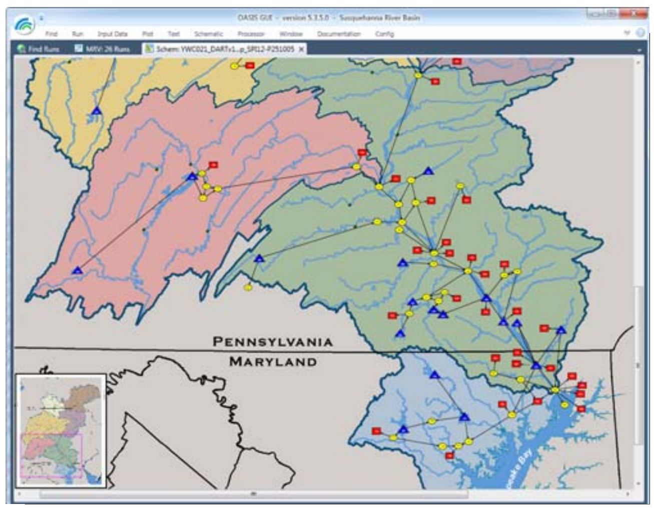
Submitted 10/31/2017

Hazen | SRBC Susquehanna River Basin Commission NY ▪ PA ▪ MD ▪ USA | UMass Amherst | Baltimore City DPW Department of Public Works

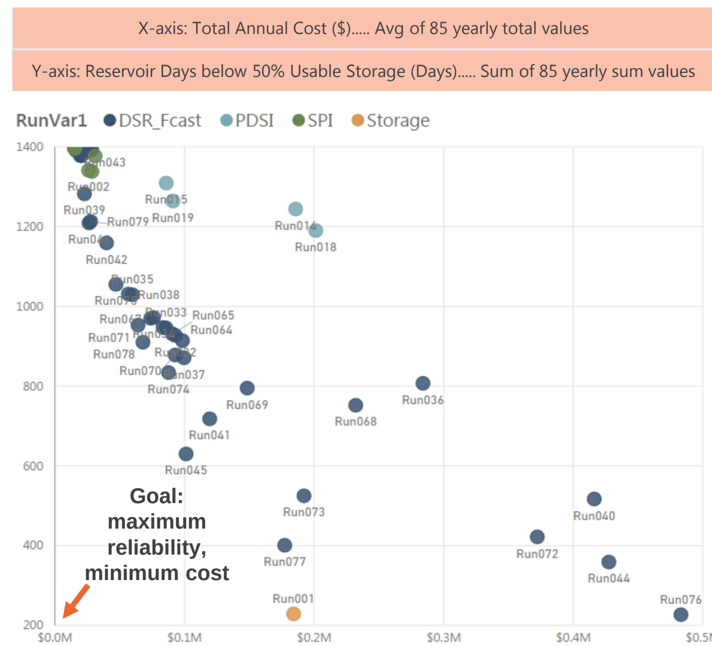
NOAA SARP 2014 Award NAOAR4310240

Implemented quantitative drought indices and forecasts in SRBC OASIS, a water supply system simulation model





Evaluated quantitative tradeoffs between key performance metrics for a range of alternatives



Facilitated interactive stakeholder workshops to communicate results and elicit feedback