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Modifications to Sandia's MDT and WNTR tools for ERMA

Energy Resilience for Mission Assurance

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Acronyms and Abbreviations

CDF – Cumulative Distribution Function

DBT – Design Basis Threat

DLL – Dynamic Link Library

DOD – Department of Defense

DOE – Department of Energy

ERMA – Energy Resilience for Mission Assurance

ESTCP - Environmental Security Technology Certification Program

GIS – Geographic Information Systemsc

I/O – Input/Output

JSON – JavaScript Object Notation

MDT – Microgrid Design Toolkit

MPH – Miles per Hour

MSC –Microgrid Sizing Capability

PDF – Probability Density Function

PRM –Microgrid Performance and Reliability Model

SCADA – Supervisory Control and Data Acquisition

TMO – Technology Management Optimization

USACE – U.S. Army Corps of Engineers

WNTR – Water Network Tool for Resilience

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1.0 Background

ERMA is leveraging Sandia's Microgrid Design Toolkit (MDT) [1] and adding significant new features to it. Development of the MDT was primarily funded by the Department of Energy, Office of Electricity Microgrid Program with some significant support coming from the U.S. Marine Corps. The MDT is a software program that runs on a Microsoft Windows PC. It is an amalgamation of several other software capabilities developed at Sandia and subsequently specialized for the purpose of microgrid design. The software capabilities include the Technology Management Optimization (TMO) application for optimal trade-space exploration, the Microgrid Performance and Reliability Model (PRM) for simulation of microgrid operations, and the Microgrid Sizing Capability (MSC) for preliminary sizing studies of distributed energy resources in a microgrid.

The MDT is a decision support software tool for microgrid designers in the early stages of the design process. The software employs powerful search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user defined objectives such as cost, performance, and reliability.

Using the MDT, a designer can:

- Effectively search through large design spaces for efficient alternatives
- Investigate the simultaneous impacts of several design decisions
- Have defensible, quantitative evidence for decisions
- Gain a quantitative understanding of the tradeoff relationships between design objectives (cost and performance for example)
- Gain a quantitative understanding of the trade-offs associated with alternate design (technological) decisions

The MDT and its underlying technologies have been used on several programs and by several agencies to help design and assess microgrids.

While the MDT is still in active development, stable releases are periodically released through the DOE Office of Electricity. Currently, version 1.3 is available for public release from the DOE Microgrid Portfolio of Activities webpage[1]. Version 1.3 does not contain the upgrades built as part of the ERMA project, detailed in the MDT Upgrades section below which are scheduled for release as part of version 1.4.

ERMA is also leveraging the Water Network Tool for Resilience (WNTR) [2], which is developed by Sandia National Laboratories in partnership with the U.S. Environmental Protection Agency. WNTR is designed to simulate and analyze resilience of water distribution systems, subject to a wide range of disruptive events. The software is an open-source Python package which includes capabilities to 1) generate and modify water network models, 2) define component level fragility curves, 3) model

[1] https://www.energy.gov/oe/microgrid-portfolio-activities

disruptive events such as power outages, earthquakes, fires, pipe breaks, and contamination incidents, 4) model response and repair strategies, 5) evaluate resilience using a wide range of metrics, and 6) analyze results and generate graphics. The software builds on existing hydraulic and water quality simulation capabilities in EPANET [3] [4].

WNTR has been used in a wide range of infrastructure resilience analysis including hurricane preparedness in the U.S. Virgin Islands [5] and earthquake preparedness in California [6] [7]. Additionally, the software is used by a growing external user community for a wide range of applications, including leak detection and cyber security (e.g., [8] [9]). The software is also being used by the United States Army Corps of Engineers (USACE) in an Environmental Security Technology Certification Program (ESTCP) to evaluate the impact of water disruptions on mission assurance in Fort Bragg [10]. The software is available through the U.S. Environmental Protection Agency GitHub website at https://github.com/USEPA/WNTR. Further information is available at https://wntr.readthedocs.io.

2.0 MDT & WNTR Upgrades

As a result of the ERMA project, the capabilities of MDT and WNTR were combined to create a platform for integrated water-power infrastructure design and resilience assessment. This required significant upgrades to both WNTR and MDT. A user of the MDT can now model the dependence of power load for water pumps and water treatment on the ability to meet water load throughout the water distribution system. Many, but not all, the upgrades to the two packages were made specifically for the purpose of integration.

2.1 MDT Upgrades

As indicated some upgrades made to the tools were not done to support the integration of the two. The following two sections detail capability upgrades to the MDT that do not have to do with integration with WNTR.

2.1.1 Fragility

The concept of fragility as used in the MDT has roots in seismic analysis where it is used to provide a prediction of potential damage during an earthquake [11]. In that domain, a fragility curve describes the probability of reaching or exceeding a specific damage state under earthquake excitation. By extension, in the MDT, a fragility curve describes the probability of a component reaching failure in response to a specific hazard imposed at a given intensity. Examples might include the probability of a transformer failing due to a flooding level of 17 feet above sea level or the likelihood of a conductor failing as a result of wind speeds reaching 135 MPH.

The MDT already required a user to define one or more design basis threats (DBTs). The concept of a DBT was extended to include the notion of hazards. An example might be a DBT of “Cat 4 Hurricane” with hazards including high winds and flooding. Each hazard is assigned an intensity probability density function (PDF). As the MDT will simulate many occurrences of a DBT, each onset of a DBT will cause a random draw from each Hazard PDF to determine the intensity for that occurrence. Subsequently, each component with a registered fragility to a hazard has a failure PDF and corresponding cumulative distribution function (CDF) defined in terms of hazard intensity. The hazard intensity is plugged into that failure CDF and a value in the range of 0-1 results; 0 meaning will not fail and 1 meaning will definitely fail. A random number is drawn and compared to that value. If the random number exceeds the value, then the component is taken out of service. If not, the component remains functional. This new feature applies to both power system components and water system components.

2.1.1.1 Example – Cat 4 Hurricane with Winds & Flooding

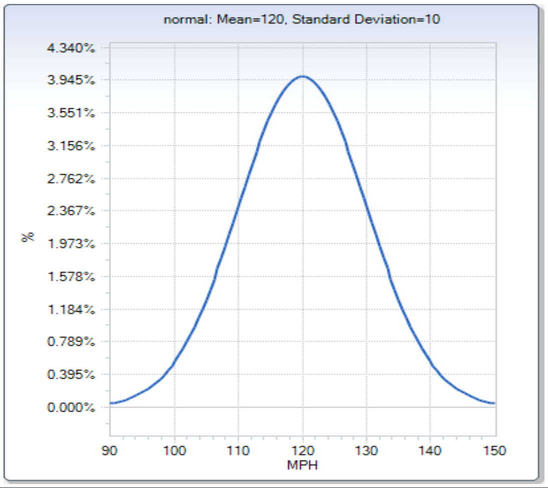

Figure 1: **Hazard:** High Winds: Intensity determined from a Normal Distribution with mean 120 and a standard deviation of 10 miles per hour.

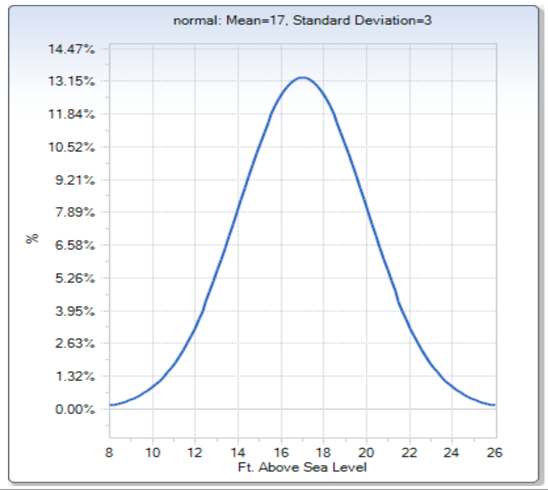

Figure 2: **Hazard:** Flooding: Intensity determined from a Normal Distribution with mean 17 and standard deviation of 3 feet above sea level.

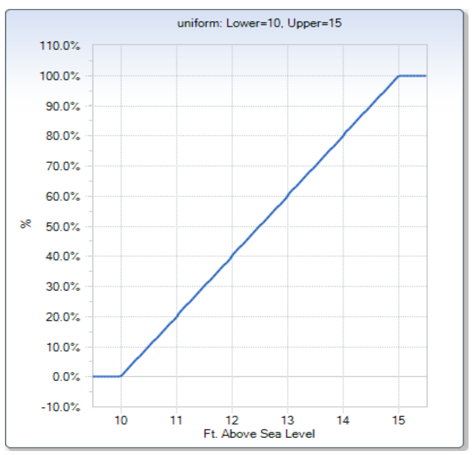

Figure 3: **Component:** Diesel Generator (DG) – Fragility to flooding defined by a failure PDF that is a Uniform distribution with a lower bound of 10 and an upper bound of 15 feet above sea level. Shown is the cumulative distribution function.

At the onset of any DBT, a random number is drawn from each of the hazard intensity distributions. For example, assume that this hurricane occurrence carries with it top wind speeds of 124 MPH and peak flood levels of 14 feet above sea level. Looking at Figure 3, reading off the cumulative probability for 14 feet above sea level, you get a value of 80%. This means that at 14 feet above sea level, there is an 80% chance of the diesel generator failing. The simulator will draw another random number in the range [0, 1] and compare that value to 0.8. If the value is <= 0.8, the generator is taken out of service. If it is >0.8, the generator remains in service. This process is repeated for each simulated DBT.

2.1.2 Missions

The primary purpose of ERMA is to bring mission assurance directly into the analysis of defense critical infrastructure. The thesis is that by calculating metrics directly relating to missions, resilience planning and evaluation can be more relevant to military decision makers than if we only continue to report on standard resilience metrics such as ability to maintain critical load service during disruptions.

To support this objective, a new set of constructs for mission representation and metrics have been built into the MDT. The constructs mirror very closely the hierarchical relationship designed as part of ERMA that relates infrastructure to assets, assets to mission functions (or tasks), and mission functions to missions.

In this context, we consider an asset to be anything that consumes infrastructure products (electricity, water, information, etc.) and in turn provides a service critical to a mission. For power system modeling, an asset is characterized as an electrical load on the grid. For water system modeling, an asset is characterized by a water load on the water distribution network. Consider the following diagram.

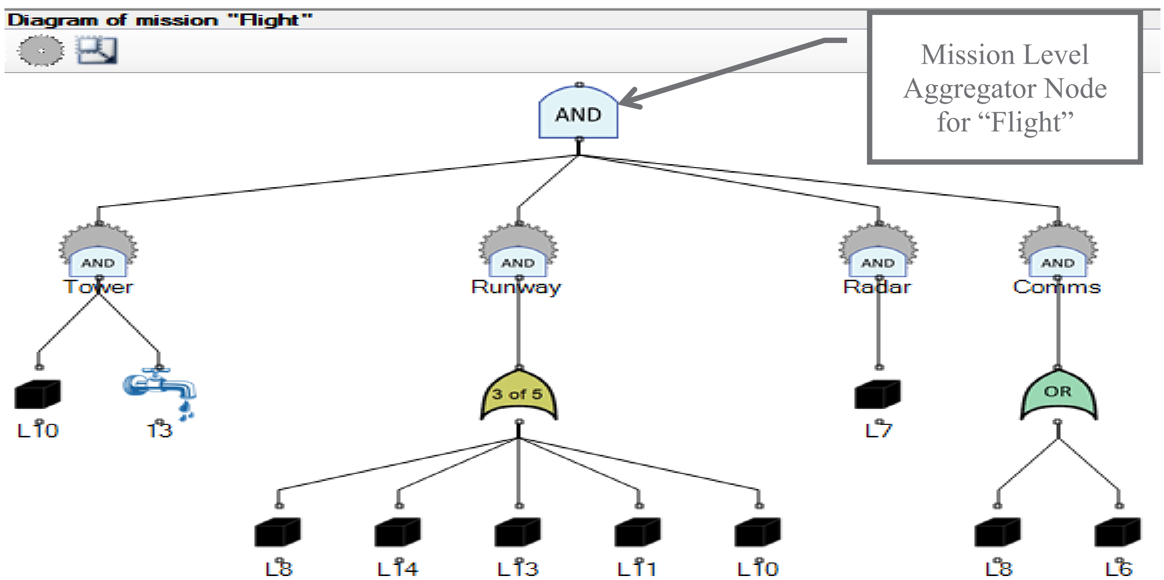

Figure 4: Notional mission diagram for a "Flight" mission with 4 functions feeding it (Tower, Runway, Radar, and Comms).

In this figure, a "Flight" mission is fed by 4 mission functions. Tower, Runway, Radar, and Comms. Those mission functions are in turn supported or supplied by electrical loads (L10, L8, L14, etc.) and a water load (13). Note that these loads can be arranged arbitrarily using and, or, and m-of-n junctions. An m-of-n node is shown under the Runway function indicating that only 3 of the 5 runways must be operational for the runway function to be operational. The Flight mission overall is only operational if each of the 4 functions below it are operational.

In the MDT, this construct can be evaluated at any time to determine, based on which loads are being served and which are not, which missions are available and which are not. Integrating that status over time provides the result for the Mission Availability metric. Other metrics, such as maximum mission outage duration, can similarly be tracked or calculated.

While these constructs are interesting and provide the framework from which to calculate mission metrics based on infrastructure service, there is another aspect of the impacts that having this information in the simulation. It primarily relates to how the simulation decides to drop loads when power is short and to reconnect them when power is sufficient to do so. Prior to having this information, loads were dropped based on their tier category (critical uninterruptible, critical interruptible, priority, etc.) and size. Now, a new set of logic exists that attempts to capture the full impact on mission operability given a prospective load drop. For example, the simulation now knows that dropping L10 or L7 will cause loss of the flight mission. It also knows that if all runway loads are being served, that dropping one 1 or 2 of them will not cause a loss of mission. There may be multiple missions that depend on the same loads and functions. Therefore, the ranking of impacts for any possible load drop must take that into account and must respect the priority of the missions as well.

Finally, loss of mission is not the only consideration. Even if a mission is not lost because of a drop, it may be made more fragile. For example, dropping a second runway will not cause the Flight mission to go down, but it will bring it closer to coming down by reducing the number of droppable loads to 1 (either L8 or L6 from comms). Dropping any other load will result in mission loss. This fragility is also characterized for all missions and used in the comparison when deciding which load to drop.
Adding loads back in when power becomes available uses similar logic but in the other direction.
Mission metrics, such as mission availability, have been added into the MDT to be configured and optimized alongside other metrics for system design.

2.1.3 Integration with WNTR

To support the power-water co-simulation, substantial upgrades to the MDT graphical user interface (GUI) and underlying simulation have been made. The MDT was already a drag-n-drop interface to visually create electrical distribution grids and configure them. With the ERMA upgrades, the MDT interface has been extended to allow the drag-n-drop configuration of a water distribution system as well. Consider Figure 5 below.

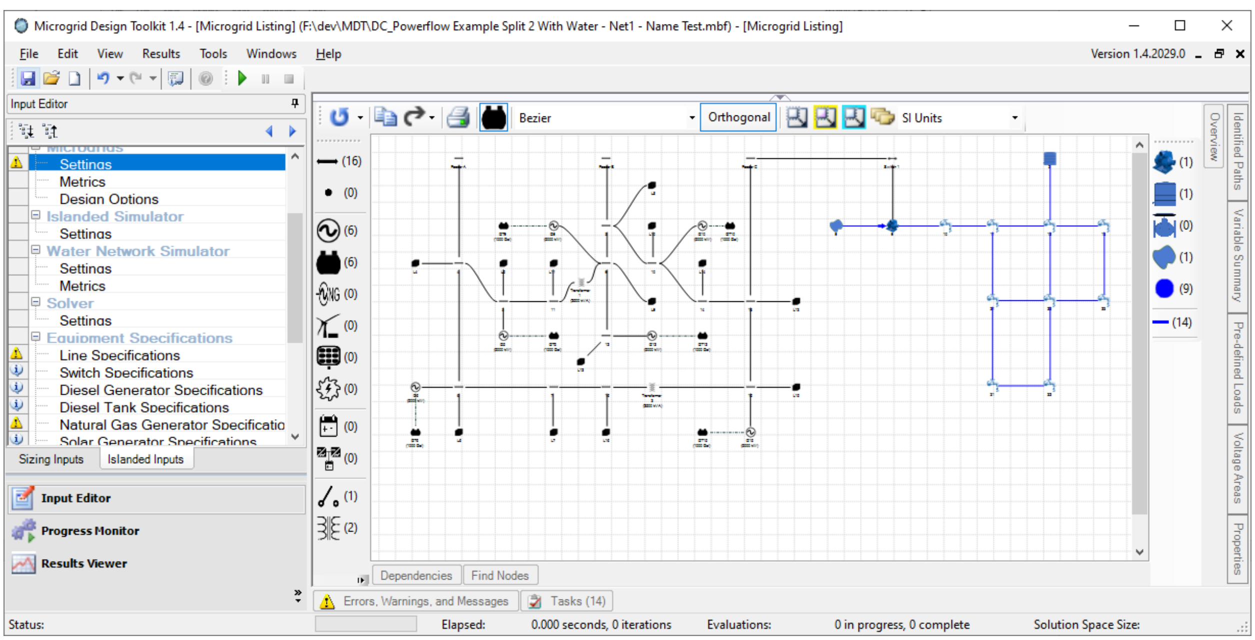

Figure 5: The MDT User Interface with both an electrical (black) and water distribution system (blue).

Figure 6 below is a zoomed in view of the connection between the water and power networks. One can see that water pump “9” is connected to “Feeder C” through “Switch 1”.

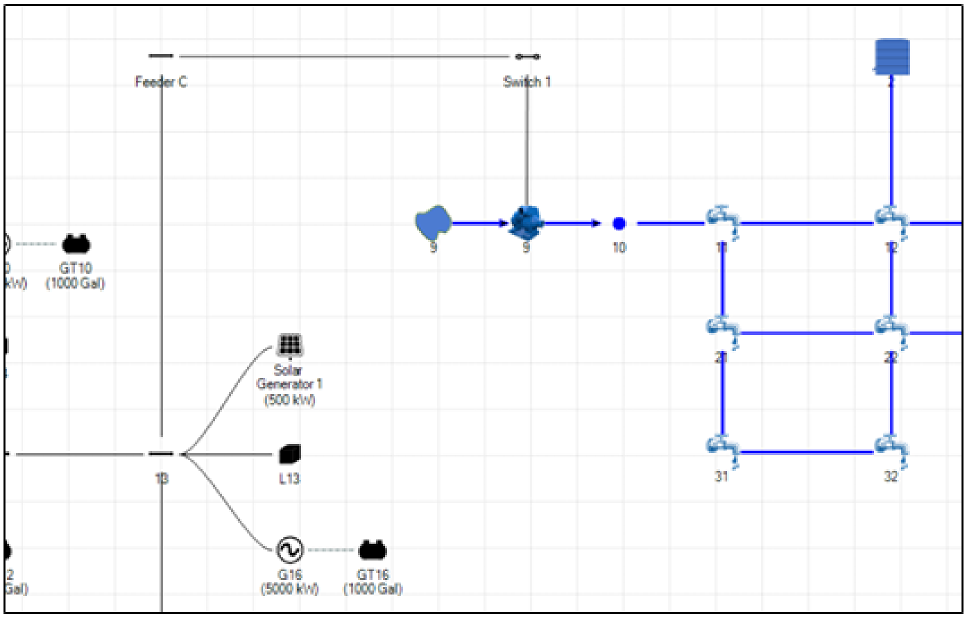

Figure 6: Diagram of a power system (left) connected to a water system (right) demonstrating that pump "9" requires electricity.

Given this linkage, the MDT simulation will not only operate both the electrical and water (via WNTR) networks and compute metrics for both, but will facilitate communication between the two indicating power service to the pump and failures and repairs of components. WNTR will react to power losses and failures by taking components in and out of service. This will impact the behavior of the water network and the resulting performance which will communicated back to the MDT.

With this new capability, co-simulation and subsequently, co-optimization of power and water networks can be achieved.

2.2 WNTR Upgrades

WNTR upgrades fall into 5 main categories as described below. This includes model export, PRM wrapper, hydraulic simulation, mission related metrics, and geospatial capabilities.

2.2.1 JSON model export

One of the core data requirements for the use of WNTR is a water network model. This includes the physical properties and layout of the pipes, valves, tanks, pumps, and reservoirs in the systems along with the network operations (controls) and demands (water loads). The model is often stored in a file format that is well established within the EPANET user community, known as an EPANET INP file. While WNTR includes a parser for this text file, more robust methods were needed to integrate WNTR with external tools like MDT. For this reason, one of the first upgrades to WNTR for the ERMA project was to enable the export the water network model to an easier-to-parse JSON-formatted file. Creating a standard export format in JSON allowed a simple command-line script to be written that MDT could call that would read in an EPANET INP file and output a JSON file that the MDT code could then easily parse.

2.2.2 PRM wrapper

The PRM acts as the communication layer between MDT and WNTR. The PRM creates model objects that correspond to both MDT and WNTR objects which then pass attributes and settings from the user

GUI to the WNTR hydraulic simulator once the MDT is executed. MDT, through the PRM, configures the WNTR water network model, passes information to WNTR to advance through a "blue sky" period (when no DBT is active) or to account for a DBT when power resources might be limited. The PRM then receives evaluations regarding water availability and power needs. A new Python module was written to encapsulate this functionality and keep the MDT specific functions outside the wider, public release of WNTR.

2.2.3 Hydraulic simulation

Hydraulic simulation in WNTR solves a set of differential equations that specify mass balance at nodes and headloss in pipes. Typical use of WNTR includes a set of operational controls (which define pump, tank and valve behavior) and a predefined simulation duration. Integration with MDT required several updates to the to the hydraulic simulator. This includes the following:

1) Power prioritization: While most water network models include standard controls that define when pumps operate and require power, the integration with MDT requires prioritization between the water and power model, such that power settings set by MDT override water network controls. This forces the pump to stay off even when other system rules would want to turn on the pump. Results from an example power outage analysis are shown in Figure 7. The example includes a power outage that overrides normal operations for 20 hours. Water service availability is reported as a function of time and location.

2) Stop conditions: MDT integration requires the ability to stop the WNTR hydraulic simulations when power needs on the water distribution system change. For this reason, the hydraulic simulator was modified to accept "stop conditions" that are evaluated every timestep to see if the simulation should continue. In the integration with MDT, stop conditions are set to check if a pump status has changed (turned from on to off or off to on). When this occurs, the simulation ends early and the PRM is notified that the simulation was not able to advance fully because of a change in power load. This information is used by PRM to evaluate power needs across the power-water system.

3) Efficient stepwise simulation: Because stop conditions need to be evaluated at every timestep, efficient use of the EPANET library was required to avoid undue file I/O and data storage. WNTR typically creates a new EPANET instance and EPANET INP file for each simulation. While this uses a pure C-library to read, run, and write output to avoid Python loops, MDT requires potentially thousands of calls to WNTR for a single simulation and the overhead was unacceptably high. As a result, a new, stepwise simulator was written for WNTR that used EPANET in an iterative manner. While this still requires the use of Python loops, the timing proved significantly better than using the I/O intensive original method. The new stepwise simulation provides the ability to advance for an arbitrary length of time, to use the new stop conditions, and to make inter-report step calls to get instantaneous readings from specified nodes and links that are otherwise lost in the more formatted EPANET output post-simulation.

4) Timestep adjustments: The power system model in MDT and the water system model in WNTR operate on very different timesteps. For example, while it is not unusual to recompute power balance every second, water balance calculations generally occur on a 15-minute timestep. Furthermore, EPANET has a timestep lower bound of 1 second. Any simulation less than or equal to 1 second is a steady state simulation in WNTR. In addition to the timestep limitations, MDT requires simulation for very long durations, hundreds or thousands of years, which also runs into EPANET limitations. For this reason, time, and timing, have been the most difficult elements of the integration between MDT and WNTR. While the power model in MDT can perform calculations very quickly for any arbitrary time, WNTR, and water models in general, require a full hydraulic simulation which is time dependent. This means that to simulate 5 seconds ahead, 5 minutes ahead, or 5 years ahead results in significantly different computational costs in WNTR.

There have been several attempts to find ways to get around this. First, the MDT-WNTR integration includes an option to approximate long durations of time by simulating only the last day. This is only recommended during blue sky periods where power resources are not limited. Second, during simulation of a DBT where MDT may advance for fractions of a second, WNTR will only advance when a minimum of 2 seconds (the minimum for a transient simulation) is requested by MDT. In the interim, WNTR will return the last time's results when dealing with sub-2-second requests, and move forward at a variable pace when larger steps were requested by the MDT. This is only possible due to the creation of the stepwise simulator, where WNTR can now change hydraulic step size dynamically during the simulation.

5) <u>Thread-safe simulation</u>: Another upgrade to WNTR was to ensure that the newer, thread-safe API for EPANET was fully enabled. As WNTR was originally written for EPANET 2.0.12 [3], which was not thread safe, it had been using the same functions to call EPANET 2.2 [4]. While these functions are conveniently available for upgrade without modification of the underlying DLL access code, they were still non-thread-safe calls to what should be a thread-safe library. This modification allows MDT to call WNTR in a multithreaded way without needing the overhead of a thick multi-process call that would restart a new Python instance.

6. <u>Real-time simulation</u>: While the MDT-WNTR integration uses the tightly coupled stepwise simulation described above, an additional simulation mode was added to WNTR to support loosely coupled simulation. This mode of operation has been demonstrated with cyber-security applications where WNTR provides the real-world results of certain sensors or controllers being changed. WNTR runs in a loop, continuously, providing "real time" status of the system and advancing automatically according to the wall clock. All user intervention – i.e., changes to pump/valve/pipe settings – must come from some external, SCADA-like system simulator, not from internal WNTR controls (which are removed from the model on startup). Communication to/from the network happen automatically every timestep and results must be collected by an external process.

2.2.4 Mission related metrics

WNTR includes the ability to define multiple demands (water loads) per junction. In this context, a junction can represent an individual building or an aggregate collection of buildings/water users. Each water demand is defined as a timeseries and can be associated with water for a particular use or mission. For example, a junction can include water demand to support personnel and water demand to support fire fighting capacity. In WNTR, each demand can be assigned a category and priority such that the ability to meet water needs can be mapped to missions. When considering water (or power) limited scenarios, demands with high priority can now take precedence over lower priority demands.

2.2.5 Geospatial capabilities

WNTR has also been updated to integrate diverse geospatial datasets into resilience analysis. These capabilities become increasingly important when integrating water distribution network models with site specific hazard, facility, and mission information for case studies. These capabilities allow the user to 1) generate a water distribution network model from a utility asset database, 2) integrate diverse geospatial datasets into the analysis including hazard maps and census data, and 3) export the network model and simulation results for visualization and additional post-processing within Geographic Information Systems (GIS) compatible software platforms. As part of this update, WNTR can now read and write GeoJSON formatted files.

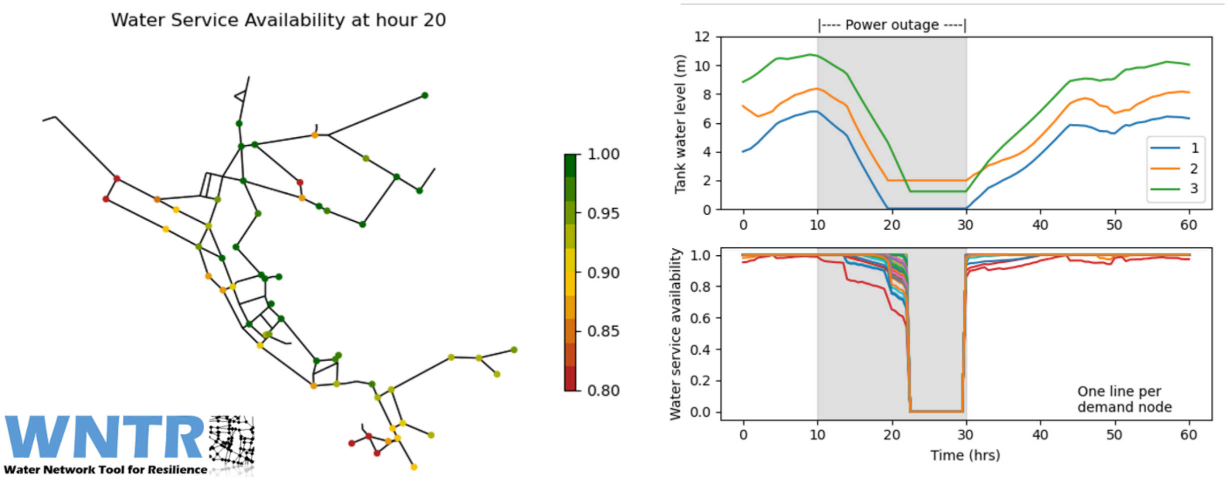

Figure 7. Example WNTR analysis using a small water network model (59 demand nodes, 2 pumps, 3 tanks, and 2 water sources) with a 20-hour power outage starting at hour 10. Results include water service availability and storage capacity as a function of time, showing drastic reduction of water availability due to power cuts.

3.0 Integration with Other Models

As detailed, the MDT and WNTR have been tightly integrated. For the purposes of ERMA, no other tight integrations with MDT or WNTR will be completed. The outputs generated will be used in the larger process of computing overall mission metrics that consider not only power and water, but also gas, communications, and buildings. Those will be loose integrations and the final calculations will be done outside of the MDT and WNTR.

4.0 Future Opportunities

Beyond ERMA, the Sandia team is using WNTR to quantify resilience of water-power infrastructure systems in Puerto Rico, the U.S. Virgin Islands, along with several other cities in the U.S. While the capabilities in WNTR have been demonstrated on utility-scale systems, additional capabilities are needed to fully integrate design, response, adaptation, mitigation, and intervention strategies into the resilience framework. The development team is currently working on evaluation and optimization methods to improve this capability. The integration of WNTR with MDT is an important step in this direction. Furthermore, the team is working on expanding the drinking water focus of WNTR to include additional critical water infrastructure, including wastewater, stormwater, water treatment, and source water.

Given that the data requirements for water resilience analysis are often not available for utility-scale assessment, the team is also working on methods to generate and calibrate water infrastructure models from diverse data sets. Current research is funded by the U.S. Environmental Protection Agency, Department of Energy, and Laboratory Directed Research and Development.

The new capabilities of MDT will be very useful beyond ERMA. Fragility analysis complements the existing wearout failure simulation of components to allow modelers to express the dangers to infrastructure inherent to specific threats. The mission modeling and assessment will be valuable to future DOD related resilience work but also has applicability to civilian infrastructure. When one recognizes the corollary between the provision of mission service and the provision of community services (emergency medical, pharmacy, fire suppression, food, shelter, etc.), then it becomes clear that this capability will enhance the MDT's ability to account those services when designing power and water distribution systems.

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