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Title: Development of Extended Period Pressure-Dependent Demand Water Distribution Models

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Development of Extended Period Pressure-Dependent Demand Water Distribution Models

Water supply and distribution systems are critical to sustaining life and economic activity throughout the world. In the United States, there are more than 53,000 potable water systems with nearly a million miles of pipe networks, which are publicly or privately owned. There are many threats that have the potential to result in service disruption to these systems, both human-caused and natural. For example, across the nation, water infrastructure assets have exceeded their expected design life, increasing the risk of failure. Failures in drinking-water infrastructure can result in water disruptions, impediments to emergency response, and damage to other types of essential infrastructure. In extreme situations caused by failing infrastructure or drought, low water pressure in systems may result in unsanitary conditions, increasing the likelihood of public health issues.

Network representations of water systems provide a means to evaluate system resilience to various failure mechanisms through modeling and simulation. Water distribution networks are represented through links and nodes that represent water system assets such as pipes, pumps, reservoirs, valves, and tanks. Table 1 provides a list of water distribution network model components.

Table 1. List of water distribution network model components

Component	Function
Junction	Non-physical component; model representation of a connection point between pipes, pumps, valves, tanks or reservoirs; location at which water demand is specified
Reservoirs	Representation of water supply source to which pipes connect
Tanks	Representation of storage facility to which pipes connect
Pipes	Representation of actual pipes
Pumps	Representation of actual pumps
Valves	Representation of actual valves

Los Alamos National Laboratory (LANL) has used modeling and simulation of water distribution systems for *N-1* contingency analyses to assess criticality of water system assets. Critical components considered in these analyses include pumps, tanks, and supply sources, in addition to critical pipes or aqueducts. A contingency represents the complete removal of the asset from system operation. For each contingency, an extended period simulation (EPS) is run using EPANET. An EPS simulates water system behavior over a time period, typically at least 24 hours. It assesses the ability of a system to respond and recover from asset disruption through distributed storage in tanks throughout the system. Contingencies of concern are identified as those in which some portion of the water system has unmet delivery requirements. A delivery requirement is defined as an aggregation of water demands within a service area, similar to an electric power demand. The metric used to identify areas of unmet delivery requirement in these studies is a pressure threshold of 15 pounds per square inch (psi). This pressure threshold is used because it is below the required pressure for fire protection. Any location in the model with pressure that drops below this threshold at any time during an EPS is considered to have unmet service requirements and is used to determine cascading consequences. The outage area for a contingency is the aggregation of all service areas with a pressure below the threshold at any time during the EPS.

Often when using hydraulic models such as EPANET to evaluate system performance under adverse conditions (e.g., contingencies), the simulation reveals negative pressures. Negative pressure results are usually an artifact of the numerical formulation of the network solver and do not actually exist in water distribution systems. Rather, negative or low pressures should be interpreted as locations in which the specified demand cannot be met.[1] Negative pressures arise because the formulations of the equations enforce demand satisfaction at the expense of energy. That is, demand at a junction is always constant and does not reduce drops in system pressure. This is commonly referred to as demand-driven analysis (DDA). A DDA analysis should be considered a conservative approach relative to the affect a disruption has on the ability to meet system demands. In reality, water demand is a function of system pressure.[2] When pressure drops below a reasonable threshold, the ability to supply water drops and therefore demand should be modified. A simulation that accounts for the pressure-demand relationship is commonly referred to as a pressure dependent demand (PDD) simulation. The objective of this capability development is to implement a PDD approach whereby LANL can more accurately represent system water delivery shortages in the event of asset disruption.

Method

There are several different approaches in the literature to solving network problems where demand is modeled as a function of the available pressure. The majority of the PDD methods presented require iterative approaches in which the network is modified manually and re-run until the pressures are adequate to meet demands. For example, Ang and Jowitt (2006) proposed an iterative approach in which the input model is progressively modified to include a set of artificial reservoirs at demand junctions with inadequate pressure.[3] In these cases, the demand at the node is removed and the flow into the artificial reservoir is determined by the available pressure. Similarly, Kanta and Brumbelow (2012) used an iterative approach to resolve low pressures.[4] However, instead of artificial reservoirs, they replaced the demand at the junction

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[1] Haestad 2003. "Advanced Water Distribution Modeling and Management." Haestad Press, Waterbury, CT.
[2] Haestad 2003. "Advanced Water Distribution Modeling and Management." Haestad Press, Waterbury, CT.
[3] Ang, W.K., Jowitt, P.W. (2006). "Solution for water distribution systems under pressure-deficient conditions." *Journal of Water Resources Planning and Management*, 132(3), 175-182.
[4] Kanta, L, Brumbelow, K. (2012). "Vulnerability, risk, and mitigation assessment of water distribution systems for insufficient fire flows." *Journal of Water Resources Planning and Management*, 139(6), 593-603.

with an emitter. An emitter in EPANET is a junction in which the delivered demand is a function of pressure, shown in Equation 1.

$$Q_{em}(i) = C_{em}(i)[p(i)]^{0.5} \qquad (1)$$

where $Q_{em}(i)$ is the delivered flow rate (gallons per minute (gpm)), $C_{em}(i)$ is an emitter discharge coefficient (gpm/psi$^{0.5}$), and $p(i)$ is the supplied pressure at the junction (psi).[5]

The Ang and Jowitt (2006) and the Kanta and Brumbelow (2012) approaches were designed for steady-state simulations, not extended period simulations. Using these approaches in an EPS would be extremely labor intensive, considering the iterative and manual nature of the methods. In a discussion letter responding to Ang and Jowitt (2006), the developer of EPANET, Lewis Rossman, proposed an equivalent method that does not require manual iterative procedures.[6] Rossman proposed minor code changes to the EPANET algorithm involving the implementation of status checks, similar to link status checks for pumps and valves already in the EPANET simulation environment. These status checks occur after every other iteration in the linear solve of demands and pressures. The advantage of this approach is that changes to the network can be made internal to the solution of the equations and does not require external modifications of the network. We implemented a similar approach for use in the LANL EPANET solver. The following sections describe this implementation and its performance relative to approaches in the literature.

Pressure-Demand Relationship

A PDD implementation requires a definition of pressure-demand relationship. Wagner et al. (1988) and Kanta and Brumbelow (2012) described the pressure-demand relationship as shown in Equation 2.[7]

$$q(i) = \begin{cases} q_{des}(i) & p(i) \geq p_{ser}(i) \\ q_{des}(i)\left(\frac{(p(i) - p_{min}(i))}{(p_{ser}(i) - p_{min}(i))}\right)^{0.5} & p_{min}(i) \leq p(i) < p_{ser}(i) \\ 0 & p_{min}(i) > 0 \end{cases} \qquad (2)$$

where $q(i)$ is the actual flow at a junction (gpm), $q_{des}(i)$ is the desired flow at the junction, $p(i)$ is the simulated pressure at the junction (psi), $p_{ser}(i)$ is the pressure required to meet the desired flow (psi), and $p_{min}(i)$ is the minimum pressure at which any flow can be delivered at the junction

[5] Rossman (2000). "EPANET User Manual." U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. Cincinnati, OH.

[6] Rossman (2006). "Discussion of Solution for Water Distribution Systems under Pressure-Deficient Conditions by KWah Khim Ang and Paul W. Jowitt." *Journal of Water Resources Planning and Management*, 133,566-567.

[7] Wagner, J., Shamir, U., Marks, D. (1988). "Water Distribution Reliability: Simulation Methods." *Journal of Water Resources Planning and Management*, 114 (3), 276-294.

(psi). To be used as an emitter function in EPANET, the relationship needs to be in the form of equation 1. This can be accomplished by manipulating equation 2 and raising the pressure deficient junction elevation according to the relationship in equation 3.

$$z_{pdd}(i) = z(i) + \frac{p_{min}(i)}{\gamma} \qquad (3)$$

where $z_{pdd}(i)$ is the raised elevation of the emitter junction (ft), $z(i)$ is the original junction elevation, and γ is the specific weight of water (62.4 lb/ft^3).

The derived emitter coefficient is shown in Equation 4.

$$C_{em}(i) = \frac{q_{des}(i)}{(p_{ser}(i) - p_{min}(i))^{0.5}} \quad for\ p_{min}(i) \leq p(i) < p_{ser}(i) \qquad (4)$$

This derived emitter equation can be used to determine the flow rate at a node as a function of pressure. However, the selection of p_{min} and p_{des} is subjective and varies in the literature. Physically, as long as there is positive pressure water will flow. Therefore, 0 psi would theoretically be the minimum pressure. However, there is not a good consensus on which values are most appropriate. For example, Giustolisi et al. (2008) used 28 psi and 14 psi for p_{des} and p_{min}, respectively.[8] Kanta and Brumbelow (2012) used 35 psi and 20 psi for p_{des} and p_{min}, respectively. Later in this report, we will investigate the impact of using different values for p_{des} and p_{min}.

Modeling and Simulation Implementation

The EPANET software is open-source, implemented in the C programming language. LANL has previously used the open-source implementation to make modifications to the source code and recompile to a .dll for use in the water infrastructure simulation environment (WISE). The previously described pressure-demand relationship was also implemented in the EPANET software.

The PDD implementation began by following the suggestion of Rossman (2006), creating junction status checks similar to link checks already implemented in EPANET. These status checks occur on every other internal networks solve. The status check for junctions was implemented with a filter to include only junctions that have a demand associated with the location. If a demand was present, the pressure was checked against user-defined p_{min} and p_{des}. Based on the simulated pressure, the following determinations are made:

- For $p_{min} > p(i) < p_{des}$, the node status is Active (modeled as an emitter)
  - Raise elevation and junction i by p_{min}, according to Equation 3.

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[8] Giustolisi, R., Savic, D., Kapelin, Z. (2008). “Pressure-Driven Demand and Leakage Simulation for Water Distribution Networks.” *Journal of Hydraulic Engineering*, 134(5), 626-635.

- Define the emitter coefficient based on equation 4.
  - Remove existing base demand.
- For $p(i) \geq p_{des}$, the node status is Open (modeled as normal)
  - Reset the elevation to the original elevation at junction *i*.
  - Reset base demand to the original demand at junction *i*.
  - Set the emitter coefficient to zero, EPANET will ignore junction in emitter calculations.
- For $p(i) \leq p_{min}$, the node status Closed (No demand at the junction)
  - Reset the elevation to the original elevation at junction *i*.
  - Set base demand equal to zero
  - Set the emitter coefficient to zero, EPANET will ignore junction in emitter calculations.

Similar to link status checks, the junction status checks were initially called every other iteration during the network solve. During testing of the implementation, we found that this worked similarly as described by Rossman (2006) on simple networks with similar number of iterations to convergence and with similar simulation results. However, when we tested the implementation on real water distribution networks with thousands of junctions, the implementation had some challenges. The most significant challenge was the amount of time, in some cases, for the EPANET solver to reach convergence during a network solve. Upon investigation, we found that in some cases the junction status continued to oscillate between states. Therefore, we modified the implementation were made to make the implementation of the PDD solve more stable and efficient for use.

To increase the stability of the PDD solution, we changed the frequency of junction status checks to occur only once—after a DDA reaches convergence. In this manner, the steady-state solution is assumed to be determined, from which the demands are modified according to the PDD rules. After which, a new steady state solve is run for the time step. This process continues for a time step until there are no status changes at junctions or until a user-defined maximum number of PDD iterations are reached. Additionally, we changed the first PDD iteration to allow only a status change to Active for any $p(i)$ below p_{des}. Subsequent iterations were allowed to change only the Active junctions to either Open or Closed. These changes significantly enhanced the efficiency of the solution, generally reaching convergence within two or three PDD iterations. Figure 1 shows the PDD process as implemented; the with shaded processes indicate new additions to the EPANET code.

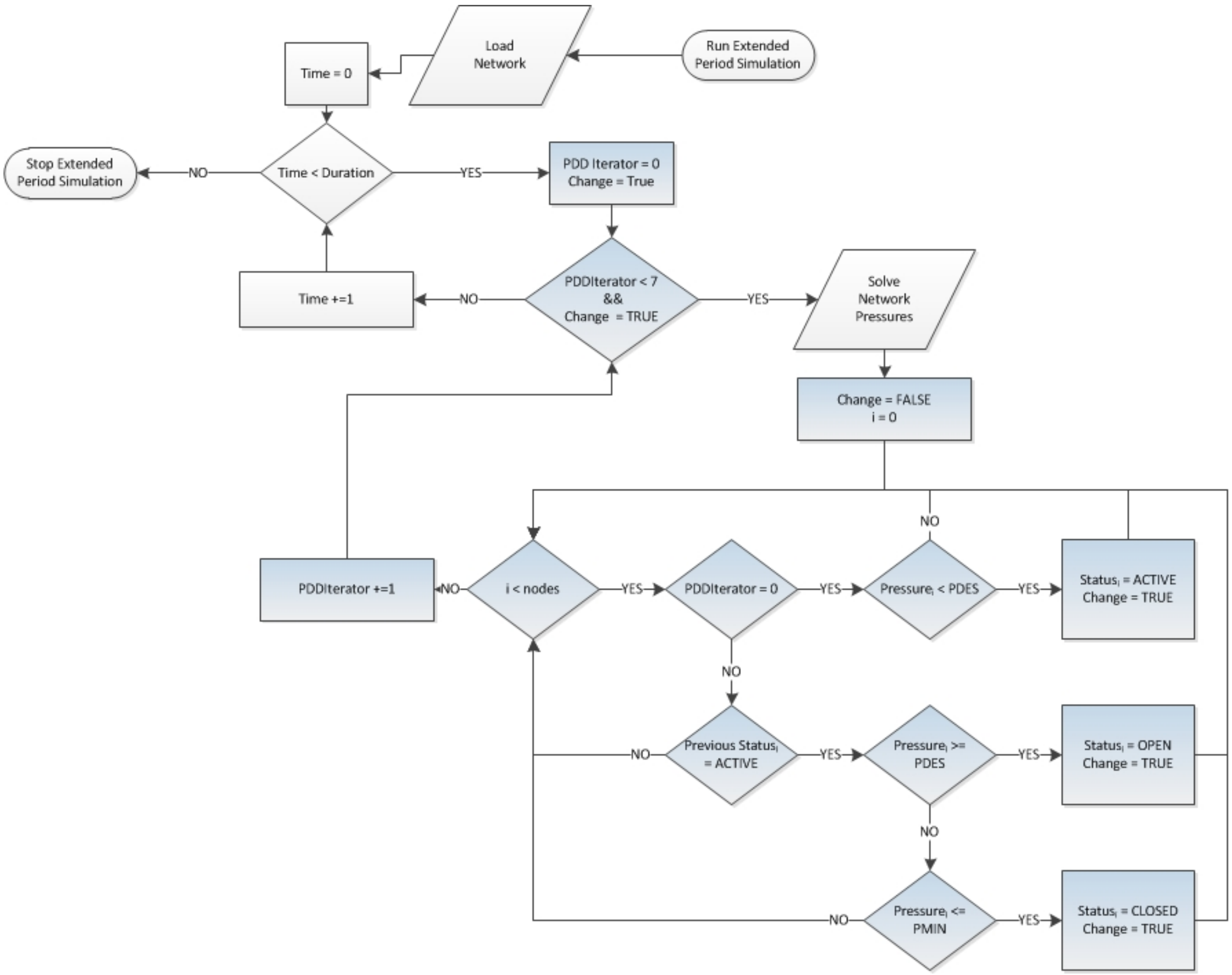

Figure 1. PDD implementation in the EPANET source code.

We implemented the previously described PDD solution in the EPANET source code and compiled a new .dll to use within WISE. Figure 2 shows the WISE interface.

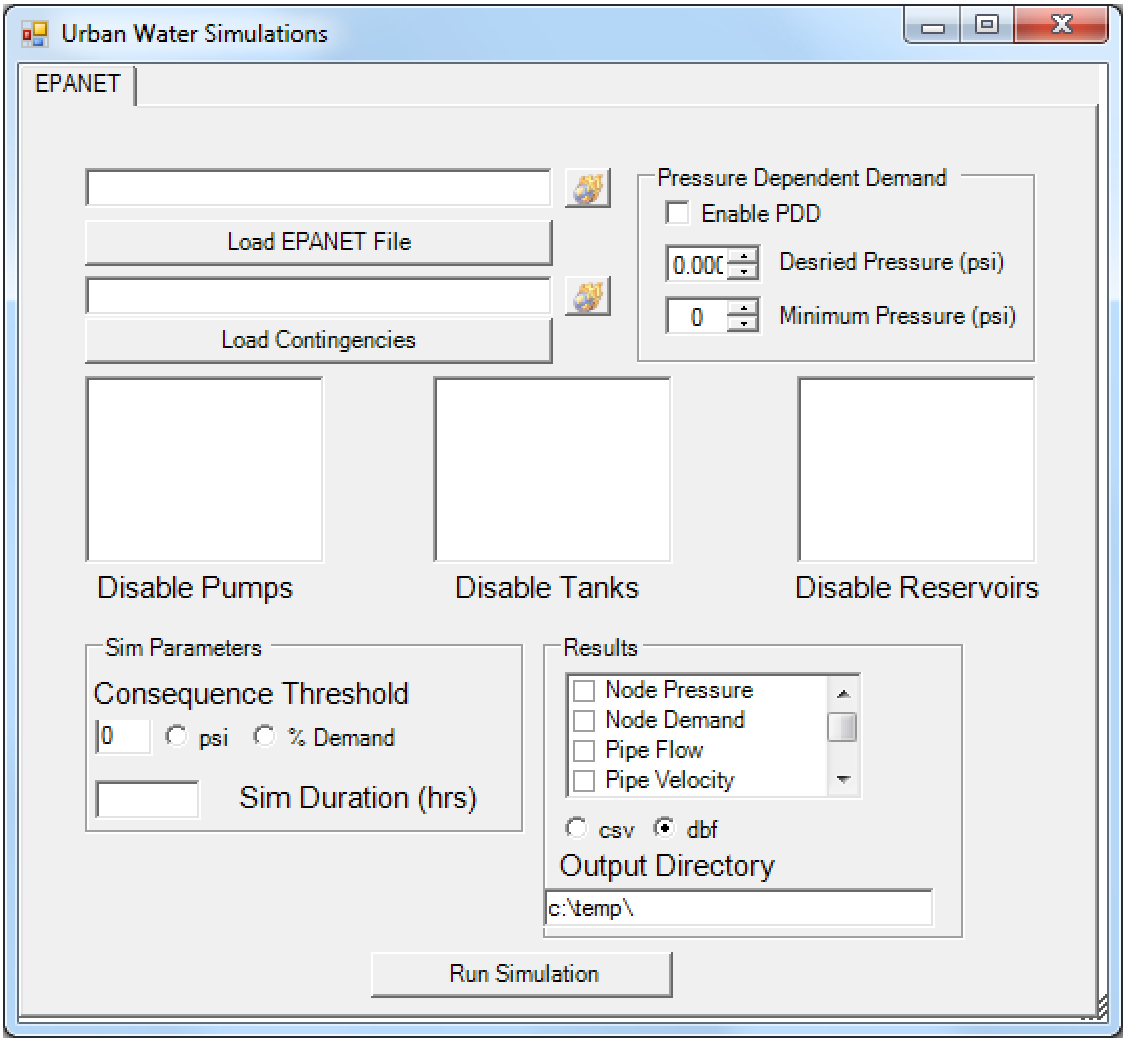

Figure 2. WISE interface for urban water simulations.

The WISE interface provides users with the option to use the original EPANET solution or the modified PDD solution. In addition, the p_{des} and p_{min} parameters are user-defined within this interface.

Verification and Validation

Ang and Jowitt (2006) provided benchmarks for PDD solutions in their paper. These were also verified by Rossman (2007). This section describes two of these benchmarks and the performance of the PDD solver as implemented by LANL.

Single Reservoir

The first benchmark is a simple network with eight pipes, six junctions, and one reservoir, as shown in Figure 3.

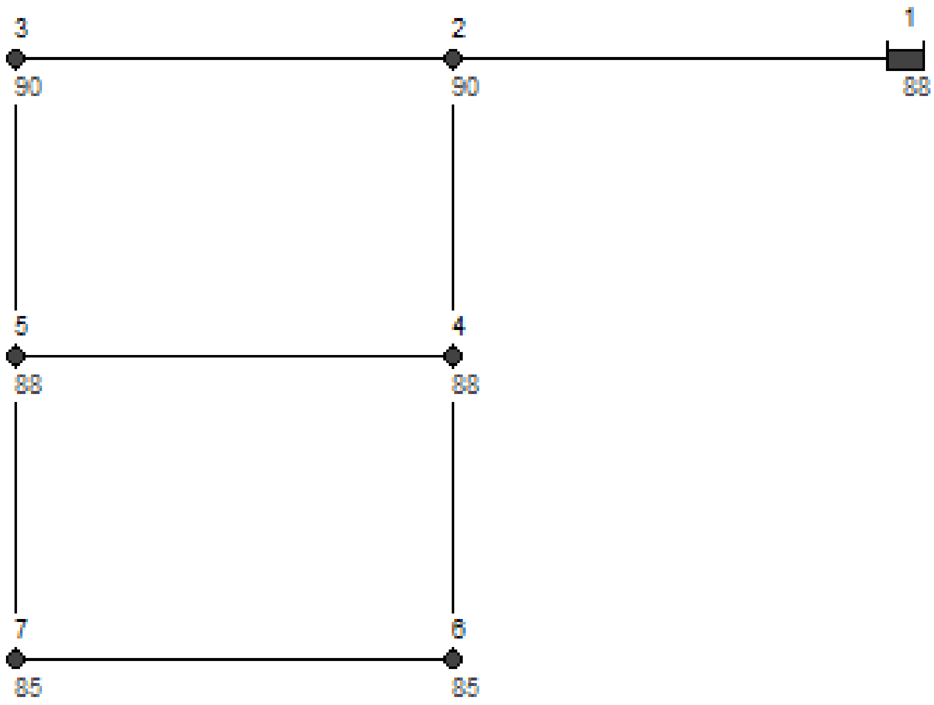

Figure 3. Single Reservoir PDD comparison with Ang & Jowitt (2006)

The junction elevations are shown in Figure 3; they range from 85 to 90 meters. The demand at all junctions is 25 liters per second (LPS), with the exception of junction 7 which has an additional 50 LPS for fire flow. The pipes are 350 millimeters (mm) for pipe 1, 300 mm for pipes 2 and 3, 250 mm for pipes 4 and 5, and 200 mm for pipes 6, 7, and 8. The length for all pipes is 1000 meters, and the roughness coefficient is 130. Network simulations were run with varying water levels at the reservoir, from 86 m to 117.56 m. Table 4 shows the PDD simulation results from the LANL implementation.

Table 2. PDD simulation results for the single reservoir benchmark

Reservoir Level (m)	Node 2 (LPS)	Node 3 (LPS)	Node 4 (LPS)	Node 5 (LPS)	Node 6 (LPS)	Node 7 (LPS)	Total Delivered (LPS)
86	0.0	0.0	0.0	0.0	10.1	10.5	20.6
88	0.0	0.0	0.0	0.0	18.2	19.1	37.3
90	0.0	0.0	9.9	0.0	22.3	23.6	55.8
92	0.0	0.0	25.0	9.3	23.0	23.2	80.5
94	25.0	0.0	25.0	15.0	22.8	23.7	111.5
96	25.0	7.2	25.0	24.5	24.5	23.2	129.4
98	25.0	21.4	25.0	25.0	25.0	24.9	146.4
100	25.0	25.0	25.0	25.0	25.0	30.7	155.7
117.56	25.0	25.0	25.0	25.0	25.0	75.0	200.0

The network is insufficient to meet the fire flow demands for lower reservoir water surface elevations. As the water level increases, more of the required demand is delivered. Table 5 shows the percent difference between the LANL simulation results and the results obtained by Ang and Jowitt (2006) for each simulation.

Table 3. Percent difference in delivered demand between the LANL PDD solve and Ang and Jowitt (2006).

Reservoir Level (m)	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Total Delivered
86	0.0	0.0	0.0	0.0	-2.2	3.9	0.8
88	0.0	0.0	0.0	0.0	-2.2	3.8	0.8
90	0.0	0.0	0.7	0.0	-2.2	3.8	0.8
92	0.0	0.0	0.0	2.5	0.2	1.5	0.8
94	0.0	0.0	0.0	2.4	-1.9	3.7	0.7
96	0.0	2.6	0.0	1.4	0.5	1.4	0.7
98	0.0	2.1	0.0	0.0	0.0	2.3	0.7
100	0.0	0.0	0.0	0.0	0.0	2.5	0.5
117.56	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The percent difference between the Ang and Jowitt (2006) and the LANL PDD simulations are small. In general, the LANL PDD delivered demands are slightly higher, with the exception of Node 6. Both models predicted the same nodes to be completely without water in all cases.

Pipe 4 Failure

The second benchmark uses the network layout from the single reservoir problem, with the exception that pipe 4 is removed to represent a failure, and there is not a fire flow at Node 7. Figure 4 shows the network layout.

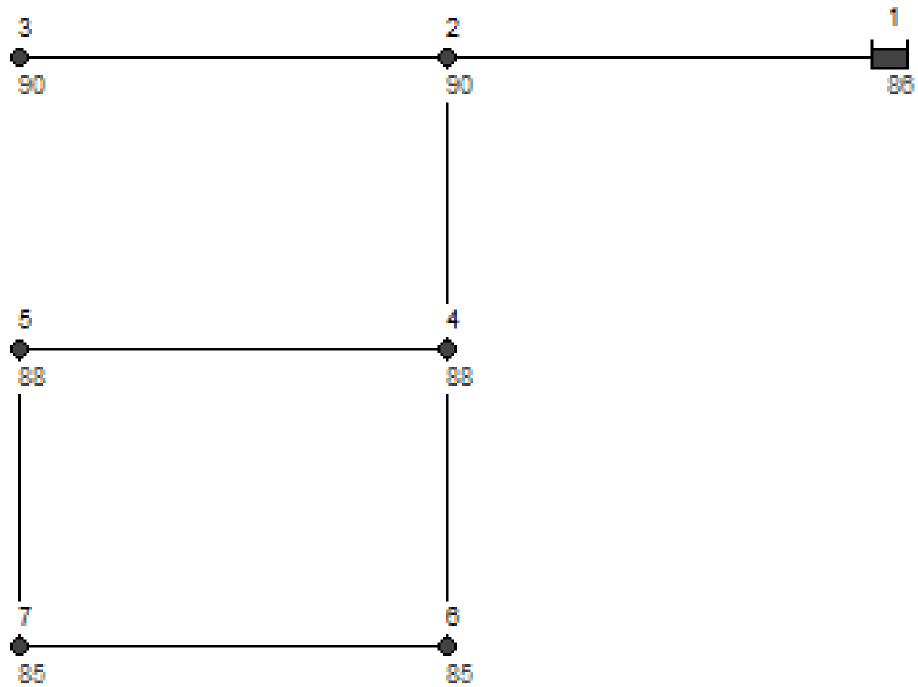

Figure 4. Single Reservoir, Pipe 4 failure PDD comparison with Ang & Jowitt (2006)

Similar to the single reservoir problem, the network was solved using a range of reservoir water surface elevations and the results are shown in Table 7.

Table 4. Pipe 4 failure PDD simulation results

Reservoir Level (m)	Node 2 (LPS)	Node 3 (LPS)	Node 4 (LPS)	Node 5 (LPS)	Node 6 (LPS)	Node 7 (LPS)	Total Delivered (LPS)
86	0.0	0.0	0.0	0.0	9.7	8.4	18.0
88	0.0	0.0	0.0	0.0	17.5	15.1	32.7
90	0.0	0.0	0.9	0.0	22.9	19.8	43.6
92	25.0	1.7	11.1	0.0	22.9	19.8	80.4
94	25.0	24.4	17.4	0.0	22.9	19.8	109.5
96	25.0	25.0	25.0	0.0	24.6	21.2	120.8
98	25.0	25.0	25.0	3.2	25.0	25.0	128.2
100	25.0	25.0	25.0	11.1	25.0	25.0	136.1
117.56	25.0	25.0	25.0	25.0	25.0	25.0	150.0

The network is insufficient to meet the demands during a pipe failure for lower reservoir water surface elevations. As the water level increases, more of the required demand is delivered. Table

8 shows the percent difference between the LANL simulation results and the results obtained by Ang and Jowitt (2006) for each simulation.

Table 5. Percent difference in delivered demand between the LANL PDD solve and Ang and Jowitt (2006) for the Pipe 4 failure benchmark.

Reservoir Level (m)	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Total Delivered
86	0.0	0.0	0.0	0.0	0.6	1.0	0.8
88	0.0	0.0	0.0	0.0	0.6	1.0	0.8
90	0.0	0.0	0.2	0.0	0.6	1.1	0.8
92	0.0	12.8	0.8	0.0	0.6	1.1	0.8
94	0.0	1.2	1.0	0.0	0.8	0.9	0.8
96	0.0	0.0	0.0	0.0	1.2	1.3	0.5
98	0.0	0.0	0.0	24.4	0.0	0.0	0.5
100	0.0	0.0	0.0	6.6	0.0	0.0	0.5
117.56	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The percent differences between the Ang and Jowitt (2006) and the LANL PDD are small. The exception is Node 3 at an elevation of 92 m, and Node 5 at an elevation of 98 m. In these cases, the demand delivered is small and slight differences between the models have a large relative difference. In reality, the demand delivered between the models is within 0.5 LPS in both cases. In general, the LANL PDD delivered demands are slightly higher. Both models predicted the same nodes to be completely without water in all cases.

Verification Summary

LANL used published benchmarks by Ang and Jowitt (2006) to verify the implementation of the PDD solve in EPANET. The benchmark used a single reservoir network for two scenarios: fire flow and a pipe failure. In both cases, the LANL PDD solver had similar delivered demands as Ang and Jowitt (2006), as shown in Figure 5.

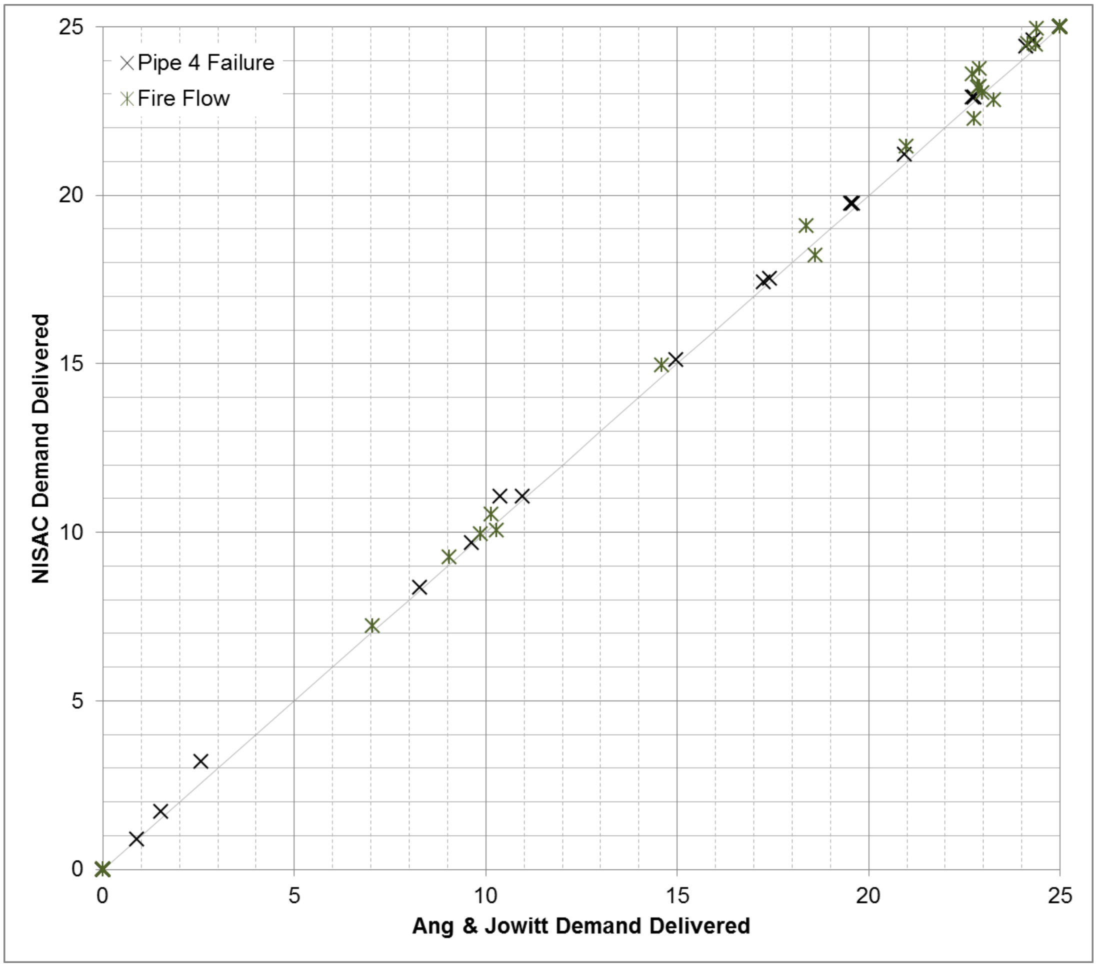

Figure 5. Summation of the PDD benchmark simulations.

Case Study

Using the PDD network solver as described previously, a case study was conducted to evaluate the sensitivity of the p_{des} and p_{min} relative to outage area in terms of population impacted. To accomplish this task, LANL used a large water distribution network consisting of tens of thousands of nodes and links. To create a scenario in which there would be insufficient pressure to meet required demands, one of two main supply sources to the network was eliminated through a ruptured pipe. A range of pressure thresholds were selected to create 11 scenarios, as shown in Table 9.

Table 6. Pressure thresholds for sensitivity analysis.

Scenario	Desired Pressure (psi)	Minimum Pressure (psi)
1	0	0
2	10	0
3	20	0
4	30	0
5	40	0
6	20	10
7	30	10
8	40	10
9	30	20
10	40	20
11	40	30

The pressure thresholds ranged from 0 psi to 40 psi. These values cover the ranges found in the literature for PDD pressure thresholds. We ran each scenario using the specified thresholds and evaluated a 24-hour EPS. For each hour, the percent demand delivered relative to the required demand was recorded at each junction. For each junction, the minimum percent demand was determined at any time during the EPS. We use the minimum percent demand delivered at any hour during the simulation in the outage area and consequence estimation. In addition to the 11 PDD scenarios, we ran a DDA simulation for comparison purposes. The simulation results are shown in Figure 6. In addition, Figure 6 shows the elevation profile for the distribution system. This was included only as reference to indicate areas of higher elevation. It would be expected that areas of higher elevation would be most affected during a pipe failure. As expected, the areas of high elevation correspond to areas where demand is not fully met.

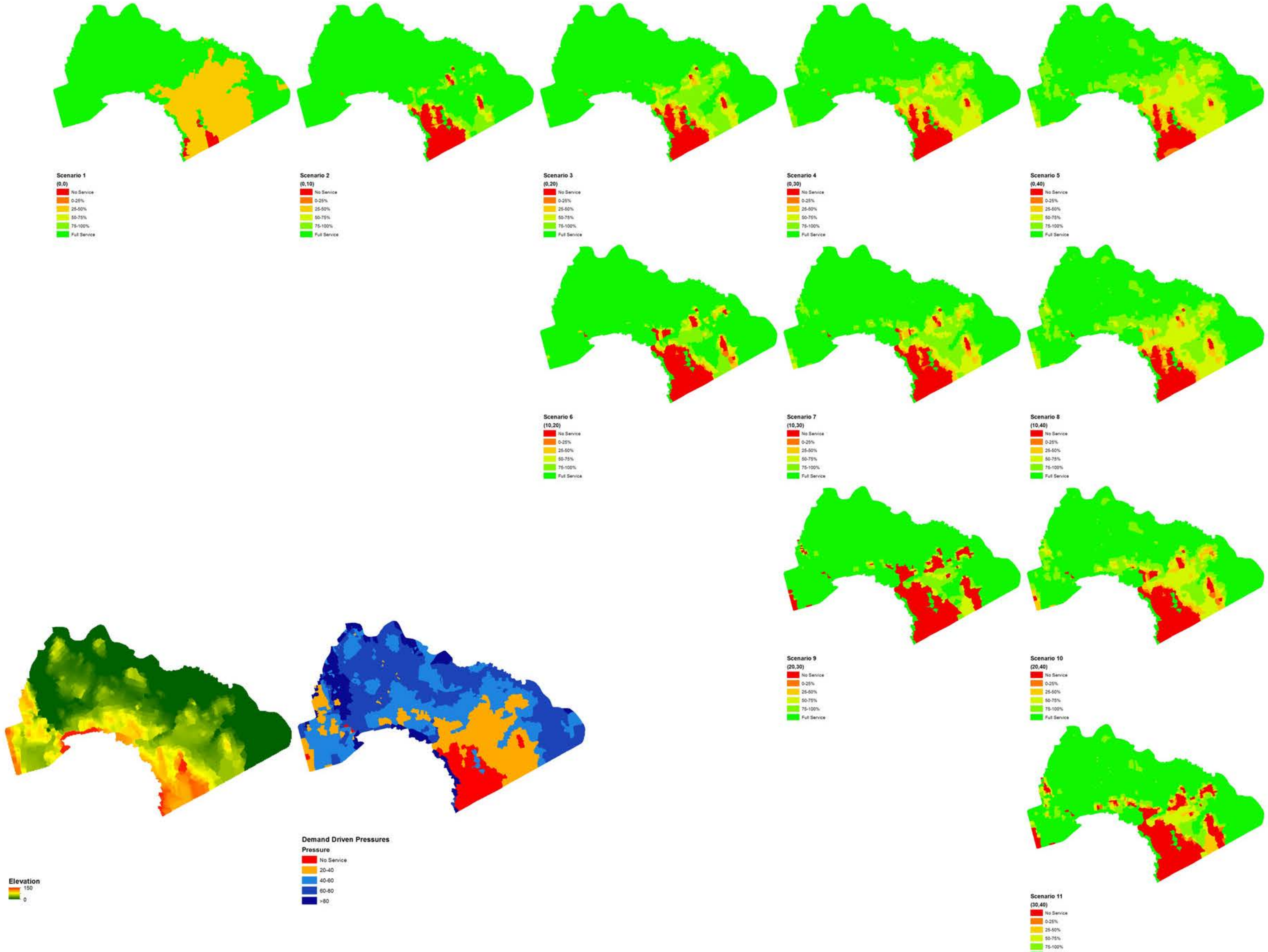

Figure 6. PDD simulation results for a large system. Elevation and a DDA simulation are shown at the lower left.

In general terms, the areas with insufficient pressure in the DDA simulation are similar to areas where the PDD identified delivery shortages. The following are some general, perhaps obvious, observations from the PDD simulation:

- As p_{des} increases and the difference between p_{des} and p_{min} increases, the number of junctions with unmet delivery requirements increases. This is an expected outcome because a higher p_{des} begins decreasing demands sooner. In addition, the wider range p_{des} and p_{min} allows more partial deliveries rather than completely eliminating the delivery.
- As p_{min} decreases (moving from top to bottom in Figure 6), areas that were partially served become areas of no service.

We also considered the population impacts for each of the simulations. In the water distribution network, each junction with demand corresponds to a service area. The service area is a geospatial representation of an area that receives water from the junction. Each service area has an estimate of the population within the geographical unit, in addition to economic activity and other critical infrastructure. For each simulation, we tallied the population impacted by pressure deficiency and demand reduction. These results are shown in Table 10 and Table 11 for the DDA and the PDD simulations, respectively. The DDA thresholds shown in Table 10 were selected based on the values used for p_{des}. In a DDA simulation, these thresholds could also potentially be used in consequence analysis, although LANL typically uses 15-20 psi.

In almost all cases, the number of people with less than 100% of the required demand in the PDD scenarios is less than the population affected for any of the thresholds used in the DDA simulation. This occurs because as demands begin to reduce in the higher elevations first, there is more supply available to other areas where the pressure may be marginal. That is, by reducing the flow to some customers, areas of low pressure are minimized. The lowest number of impacted population occurred in Scenario 2. This scenario had a required pressure of 10 psi for full demand delivery and did not completely shut off the delivery until 0 psi. The total population with less than 100 percent demand in this scenario was just under 16,000 people. PDD Scenario 5 had the most population impacts. This scenario had a required pressure of 40 psi, and did not cut off flow to customers until 0 psi. In general, we observed that the higher the required pressure threshold is and the larger the difference in required and minimum pressures, the more people will be affected by reduced demand deliveries.

Table 7.Population impacts for demand driven solve

Pressure Threshold (psi)	Population Impacted
< 40	153,362
< 30	132,782
< 20	119,600
< 10	99,173
<= 0	60,149

Table 8. Population impacts for each scenario in the pressure dependent solve

	Population Impacted by Scenario										
Percent Demand Met	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11
100	232,516	266,441	250,621	235,016	204,313	258,342	240,796	218,037	248,636	224,032	231,644
75-100	0	9,278	18,422	28,429	52,171	8,750	23,157	36,747	13,426	28,438	17,332
50-75	57,557	5,265	11,720	17,121	24,420	7,539	13,396	22,435	3,417	16,417	11,465
25-50	0	1,009	2,219	3,509	3,906	3,220	3,798	5,063	0	8,673	3,847
0-25	0	424	747	722	855	467	787	1,303	0	1,840	2,405
0	760	8,416	7,105	6,036	5,167	12,515	8,900	7,248	25,354	11,434	24,141
Less than 100	57,557	15,976	33,108	49,781	81,354	19,976	41,137	65,548	16,843	55,368	59,189

Conclusion

LANL has implemented a PDD solver within its water infrastructure simulation environment. We have evaluated this implementation against benchmarks available in the literature and it has shown to perform well against these benchmarks. In addition, the implementation is effective in modeling pressure dependent demands in large network systems, similar to those that LANL uses in resilience studies. The PDD implementation does have some dependence on the selected thresholds for required and minimum pressure.

Further research should focus on the relationship between pressure and demand. This relationship has physical basis, but it also has an element of human behavior involved. Demands are an estimate based on metered usage. As the pressure drops, there is a physical element involved in the ability to deliver water to a location. However, as pressure drops, some of the demand may completely stop or be reduced dramatically. For example, if a person perceives lower pressures some normal practices may be reduced. These include turning off lawn sprinklers or perhaps not showering because of insufficient pressure. These behaviors should also be considered when determining the proper relationship between demand and pressure in low-pressure conditions. There are some potential methods in which this may be determined. For example, water utilities generally keep records on pipe failures or other service disruptions. These data, in conjunction with other system data such as tank levels or observations of water meters, could be used more effectively to estimate the relationship.

It is expected that this development will be used extensively in future water system resilience studies, in addition to fast-response analyses where network data is available. This capability provides a more realistic, less conservative representation of system behavior during adverse conditions.

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