USING CRITICALITY ANALYSIS TO IDENTIFY IMPACT OF VALVE LOCATION

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Abstract

Identifying and quantifying the critical elements in a water distribution system has traditionally involved a great deal of judgment. With the coming of computerized hydraulic analysis, it became easier to "fail" a pipe in a distribution system to assess its impact on service. However, when a failure occurs in a real system, it does not remove a single pipe from a distribution system but rather a "segment" which can be isolated using valving. A segment will often include several nodes, portions of pipes, and other elements.

In this paper, the critical segments in a real system are identified based on existing valving. Then different rules for valve installation (e.g. N valves per junction, N-1 valves per junction) are used to add or remove isolating valves from the system and determine the performance of the system as a function of the density of valving

Keywords:
Water distribution, pipe network models, water valves, isolating valves, reliability, criticality, segments

INTRODUCTION

Portions of water distribution systems need to be taken out of service from time to time for maintenance and repairs. The fraction of the system that is taken out of service is limited by the placement of valves. The higher the density of isolating valves, the fewer customers who are put out of service and the smaller the impact on overall system operation. A tradeoff exists between the number of valves in a system (small impact of shutdowns) and cost.

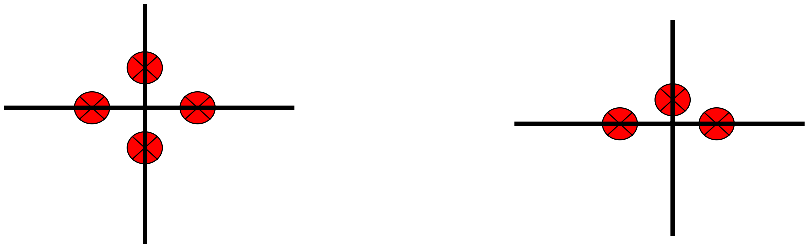
In general, valves are placed near the intersections of pipes. Only in long pipelines are vales placed very far from intersections. There are no regulations for the number of valves at any intersection. The Ten State Standards (GLUMB, 2003) give typical guidance for the placement of valves:

"Sufficient valves shall be provided on water mains so that inconvenience and sanitary hazards will be minimized during repairs. Valves should be located at not more than 500 foot (152 m) intervals in commercial districts and at not more than one block of 800 foot (244 m) intervals in other districts."

Various states and other agencies have similar but slightly modified rules such as California (2004) which states

"In general, valves on water mains of 12 inches (300 mm) and smaller diameter should be located such that water main lengths of not more than 1,000 feet (305 meters) can be isolated by valve closures."

The actual number and placement of valves is a judgment decision by the design engineer. The usual rule of thumb is to place at least N-1 valves at each intersection. For example, if there are four pipes leaving an intersection, then there should be at least three valves. In some cases, engineers may place N valves at an intersection for easier shutdowns. The difference between N-1 valves and N valves for some typical intersections is shown in Figure 1.



N valves at cross

N-1 valves at cross

N valves at T

N-1 valves at T

Figure 1. Alternative Valve Placement

DISTRIBUTION SYSTEM SEGMENTS

When valves are operated to isolate a portion of the distribution system, they do not isolate a single pipe link but a portion of the system which may correspond to a part of a single pipe or several pipes and their junctions. The smallest portion of a distribution system that can be isolated by operating valves is referred to a "distribution segment" (Walski, 1993). Systems are made up of a large number of distribution segments. Figure 2 shows a portion of a distribution system with three segments S-101, S-102 and S-103. Segment 102 is isolated using valves V-21 and V-22.

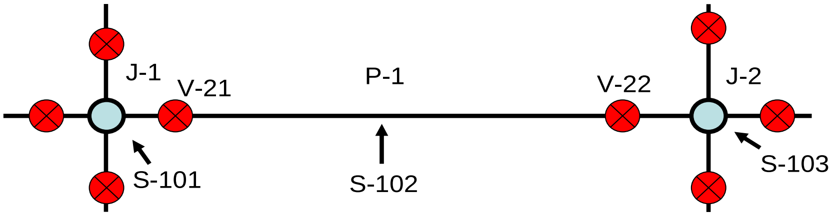


Figure 2. Distribution System Segments.

Segments present a problem for hydraulic models because segments do not correspond to pipe links. In fact, a segment will virtually never consist of an entire, single pipe link, but rather some collection of pieces of pipe links. Therefore, working with segments requires an entirely different topology than pipe network analysis. In addition, isolating valves are generally not treated as junction nodes in pipe models.

The WaterGEMS model (Bentley, 2006) addresses these issues by storing isolating valves elements at their correct locations along pipes but not using isolating valves as junction nodes. The isolating valves are used to create and store segment topology which is associated with any model file. The automatic generation of segments is the first step in the search for critical segments in a distribution system. Figure 3 shows segments in a portion of a typical distribution system.

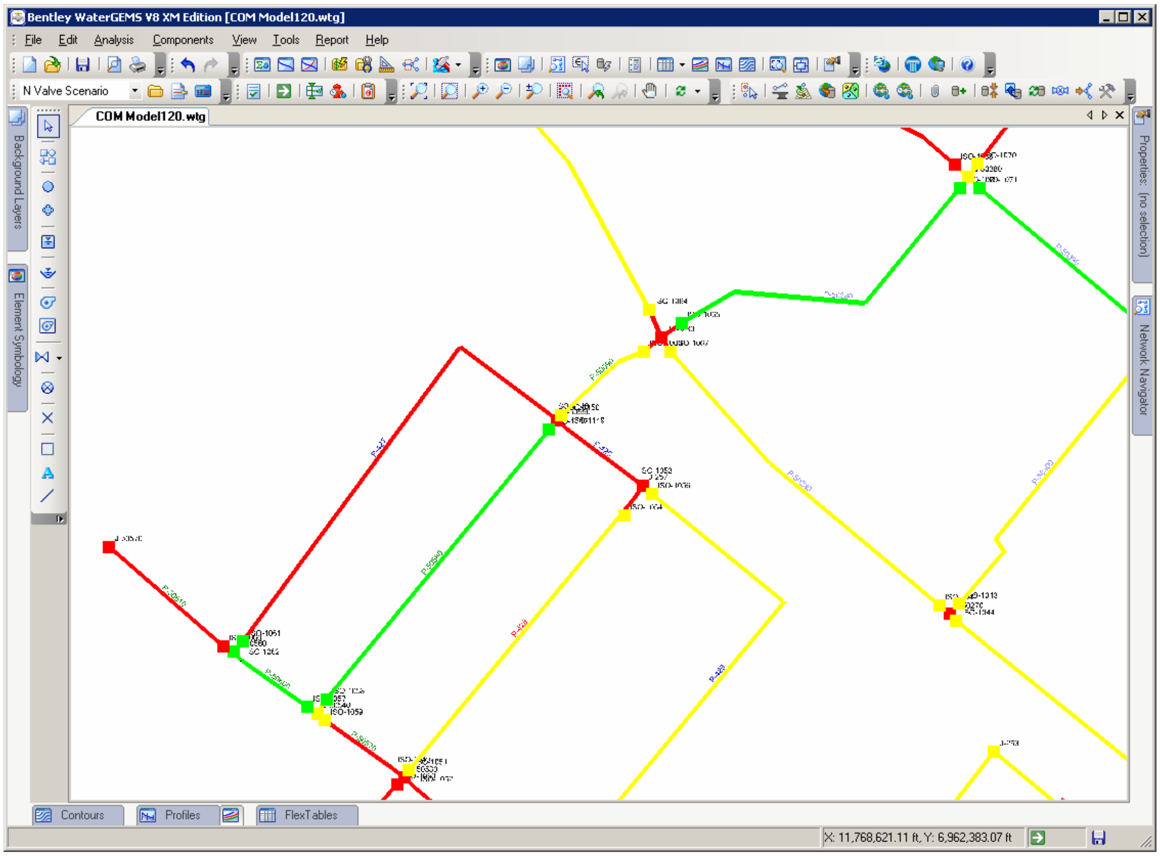


Figure 3. Illustration of distribution segments in a typical system

LITERATURE

Walski (1993) first proposed the use of distribution segments as the basic building block of assessing the reliability impacts of system outages. These ideas were further developed in subsequent papers Walski (1994), Goulter, et. al. (2000), and Walski (2002).

Jun et al. (2005) proposed a method for identifying distribution segments. WaterGEMS (Bentley Systems, 2006) contains a somewhat more efficient algorithm.

Other investigators on the topic of valving included Bouchart and Goulter (1991), Jowitt and Xu (1993), Yang et al. (1996) and Ozger and Mays (2004). In general, the subject of valve number and location has not received nearly the attention as other topics such as optimal pipe sizing, automated calibration or optimal control in the water distribution literature.

PROBLEM STATEMENT

In this study, the WaterGEMS (Bentley Systems, 2006) criticality and segmentation routines are used to evaluate the ability to isolate portions of the system and serve customers using different valve location guidelines. A real water distribution system is used. The effect of actual valve locations are compared with valves placed using the N-1 and N valve rules for valve placement using several indicators of system performance.

SYSTEM DESCRIPTION

The system used in this study is an actual, middle-sized system with a single, water treatment plant with three elevated storage tanks and one ground level pumped storage tank. The system contains 631,550 ft (192 km) of distribution mains. The model contains 1196 pipes and 961 junction nodes. The average flow was roughly 40 ML/day (10 MGD).

The actual system has 1234 isolating valves. With N valves per intersection, the system would have 1730 valves and with N-1 valves per intersection, it would have 1208. The actual system valving is much closer to the N-1 layout than the N-valve layout.

The source and water treatment plant is located roughly 6 kilometers (4 miles) away from the main portion of the distribution system and is served through a 600 mm (24 in.) transmission main. All of the distribution storage is located downstream of this transmission main.

The model used is an actual WaterGEMS model for which additional detail was added based on AutoCAD maps of the distribution system. Valve location for the “actual” scenario was taken from the AutoCAD maps.

The N-valve system was developed by inserting isolating valves into the model such that each intersection had N valves. The N-1 system was created by inserting valves when fewer than N-1 existed, which was seldom the case, and deleting the valve closest to the source when there were N valves at an intersection.

EVALUATION OF VALVING ALTERNATIVES

The WaterGEMS segmentation analysis was used to automatically generate segments in the distribution system once isolation valve data were supplied. As expected, the system with N-valves per intersection contained more and smaller segments than the system with N-1 valves per intersection.

There is no single indicator of the value of isolating valves in a distribution system. For this paper, several different indicators of the effect of isolating valves on system performance were used. They are summarized in Table 1 below and are explained in the following paragraphs.

Table 1. Comparison of performance of alternative valving

Property	**N-1**	**Actual**	**N**
No. of segments	936	931	1458
Average segment length, m	206	207	132
Max. No. of valves/segment	6	11	5
Segment > 4 valves	7	28	2
Average No. of valves/segment	2.37	2.55	2.58
Average system shortfall, %	0.4	0.4	0.2

The length of a segment is an important indicator of the maintainability of the system because it gives an indication of the likelihood that any segment will have an outage and the possible number of customers on any segment. The N-valve system had significantly smaller segments than the N-1 and Actual system.

The maximum number of valves per segment and number of segments requiring more than 4 valves to achieve a shutdown demonstrate the benefit of the N-valve system. While these indicators are not so much indicators of system performance as much as they are indicators of the worst areas of the system, they do show that the N valve system is much less likely to have serious problems in achieving a shutdown, whether it is routine or emergency.

Some insights into the nature of system problems can be gained by examining the largest segments that are not transmission mains. Figure 4 shows the largest distribution segment in terms of valves required for shutdown. While the total number of valves in the segment is 11, only 9 are required for a shutdown because 2 feed a small loop that is tied into this segment in two places. The segment consists of over 1236 m (4,045 ft) of 200 mm (8 in.) pipe that was most likely a transmission main in an undeveloped area when first installed. As the system filled in taps were made on it but no new valves were installed on this main.

The small loop attached to that segment is an example of an “outage segment”, a segment that loses service when an upstream segment is shut down. Outage segments are common in branched (tree-like) systems but one does not expect to see them in a highly looped system such as this one. However, there are 99 outage segments in the Actual system. Most are fairly obvious tree branches, but some like this, one have multiple feeds. However, the multiple feeds come off the same upstream segment.

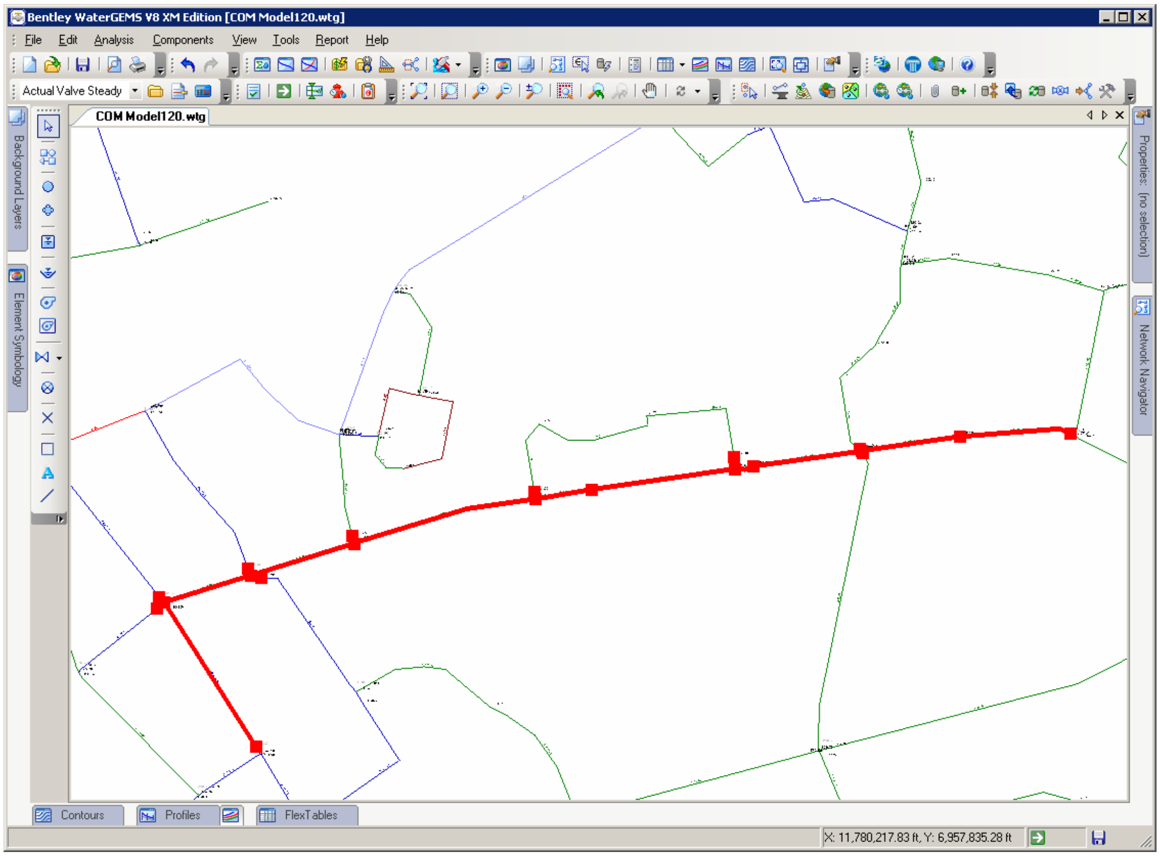


Figure 4. Segment with large number of isolating valves

Correcting the issues caused by a shortage of valves in a large segment involves shutting down the segment and installing additional valves. This will cause customers to be without water service and demonstrates that it is better to install more valves when the system is newly installed rather than minimize valves only to have to install more expensive valves (because of the extra cost of excavation, shutdown and repaving) later, while inconveniencing a larger number of customers.

The above analyses were based simply on connectivity and valve location without taking into account the hydraulics of the system. In criticality analysis, the hydraulics impacts of the outages are taken into account. There are three possible responses of demands to an outage

1. No (or virtually no) impact,
2. Zero flow supplied because they are in outage segment,
3. Reduction in flow supplied because of drop in pressure.

The first two impacts can be determined quickly with no real need to use a pipe network model except to establish connectivity. The third effect is somewhat more problematic in that it requires the establishment of a relationship between pressure and flow supplied. This relationship is called a pressure dependent demand (PDD) function and can be based on an orifice equation because water leaves a distribution system by way of orifices. Most models are fixed demand models and cannot account for the impact of pressure on flow supplied. Modeling PDD is described in Wu, Wang and Walski (2006). The PDD function used in this study is given by

$$Q = 0 \qquad \text{if } P < 0$$

$$Q = Q_{ref}\sqrt{P/P_{ref}} \qquad \text{if } 0 < P < P_{ref}$$

$$Q = Q_{ref} \qquad \text{if } P > P_{ref}$$

Where Q = flow supplied
Q_{ref} = demand with no pressure shortfall
P = actual pressure
P_{ref} = pressure above which all demand is met

For this study, a reference pressure of 28 m (40 psi) was used as a reference pressure, which means that as long as the pressure exceeded 28 m, all demands were met; when pressure dropped below 28 m, the flow supplied dropped below flow demanded according to the above equation.

When each segment is taken out of service, the flow supplied by the system may be reduced below the flow demanded. The indicator used in this study is the percent system demand shortfall. Table 1 shows that the average shortfall for N-valving was 0.2% while for the N-1 and Actual systems it was 0.4% This is a result of fewer customers losing service for any individual outage when the segments are smaller.

There appeared to be very little reduction in flow supplied to nodes that are not completely cut off from the source. This is due to the fact that this system, like most systems in developed countries, has a great deal of redundancy and excess capacity in reserve for fire flows. Removing a segment does not significantly impact downstream pressure because of this, especially when there are multiple sources (tanks) as in this system.

The criticality analysis described above was for steady state hydraulics. If an extended period simulation (EPS) run was used as the basis for the criticality analysis, it showed that the system worked well (as shown in the steady state runs) as long as the tanks did not run dry. If the transmission main connecting the treatment plant and the main portion of the distribution system was out of service for a sufficiently long time, the system would completely fail, as one would suspect

While it's clear that N valves per intersection results in a more reliable system than one with N-1 valves, it's not possible to clearly quantify the benefits of using N valves per intersection as opposed to N-1 valves. This is not a shortcoming of the software but rather an indication of the difficulty of clearly defining valid measures of system reliability. The tradeoff between costs of valve installation and costs of not providing service need to be weighed to obtain a good indicator of the benefits of more dense valving.

SUMMARY

This work quantified the impacts of using N-valves per intersection as opposed to N-1 valves using several indicators and contrasted these cases with the valving from a real system. It is difficult however to determine if the benefits of additional valving exceed the cost. For practical design and operation purposes, it is not so important to identify overall rules for valve operation as it is to identify locations in a specific system where valving is inadequate and ensure that the problem is corrected there.

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