White Paper
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iHydrant® Event Localization

This document explains how iHydrant's fully automated Event Localization technology dynamically processes incoming data, in close to real-time, to display heat maps which reveal the scope and magnitude of a pressure pulse (or water hammer) event and provide guidance for locating its likely source.

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Event Localization

Abstract:

Utilities experiencing water pressure issues within their distribution network may consider adding iHydrant fire hydrant pressure sensors with cellular reporting and near real-time alerts to improve their understanding of, and ability to respond to sudden and significant water pressure changes. This document explains how iHydrant's fully automated Event Localization technology dynamically processes incoming data, in close to real-time, to display Heat-Maps which reveal the scope and magnitude of a pressure pulse (or water hammer) event and provide guidance for locating its likely source.

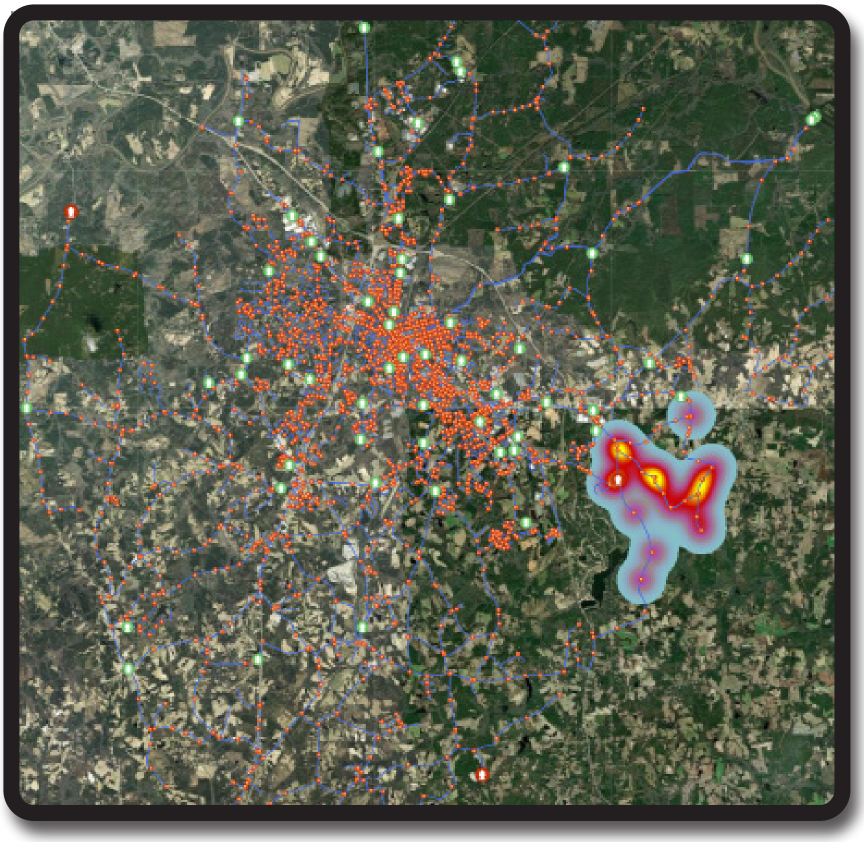
Introduction

Water utilities know that pressure pulses can have damaging effects on water distribution plumbing, both expanding any already present leaks and possibly causing pipes and joints to rupture, potentially resulting in extensive 3rd-party damage from escaping water.

Adding pressure sensing technology provides water utilities with the ability to dynamically monitor their piping network, but raises new questions:

1.) Can we understand the geographic scope and strength of impact of a pressure pulse / water hammer across the utility's water distribution network? And,
2.) Can we track the progression of a pressure pulse through a water distribution network as a guide to discovering its most likely source?

This paper explains how iHydrant's Event Localization Technology works to help answer these questions with Heat-Mapping displays in close to real-time.



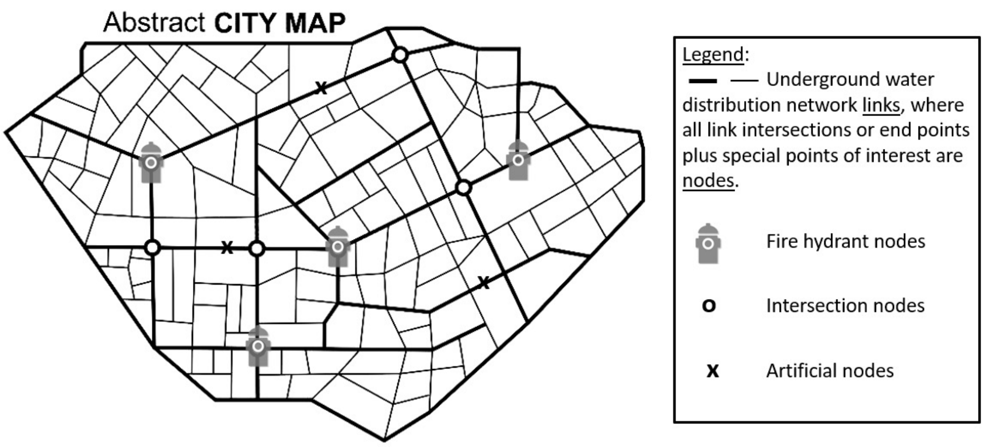
Time-Based Model

Before activating iHydrant's Heat Mapping option, a specially adapted version of the utility's infrastructure model must be created, as imported from a series of utility-provided data files. These (typically GeoJSON geospatially formatted) files will describe the utility's water distribution network, with particular emphasis on pipe properties:

a.) Pipe materials (e.g., ductile iron, cast iron, PVC, reinforced concrete, etc.) and

b.) Other known pipe characteristics such as:
- length of pipe segment,
- inside pipe diameter,
- pipe wall thickness, and
- pipe material composition.

Like many Hydraulic Data Models, iHydrant uses a mathematical graph theory approach where the utility's water distribution network is viewed as a collection of pipe segments called "links" which intersect or terminate at endpoints called "nodes." There may also be special points of interest which include possible sources for a pressure pulse (or water hammer), such as perhaps a pump, valve or an industrial tap along a pipe. As the Event Localization process is explained further, the reader will recognize the importance of including in the uploaded utility GIS (Geographic / Geospatial Information System) data files any such likely sources of pressure pulses as artificial network nodes.



The links and nodes, typically hydrant and valve locations, will be uploaded from the utility GIS data files to create an iHydrant time-based model.

Pipe Celerity

Velocity of a Pressure Pulse

iHydrant's Event Localization technology depends on expectations of how much time it should take for a pressure pulse to travel from one node location to another via various links on the graph. Therefore, a critical first step is to estimate the "transit time" for a pressure pulse to pass through each pipe link in the water distribution network.

iHydrant's time-based model uses the uploaded utility pipe properties to calculate a "celerity factor", meaning how fast an energy (or pressure or sound) pulse should travel through a pipe segment with those pipe properties. This calculation of energy wave Velocity follows Hampson's (2014) formulation for pipe celerity, which is:

$$c = \sqrt{\frac{K/\rho}{1+(K/E)(D/e)}}$$

Where:

- c is the speed of sound in the pipe (km/s)
- K is Bulk Modulus of the fluid (water)
- E is Young's modulus of elasticity for the pipe material (see Appendix)
- D is the inside diameter of the pipe
- e is the pipe wall thickness
- p is the density of the fluid (water)

That "c" or celerity is the Velocity in the (transit) Time = Distance (i.e. pipe link length) / Velocity calculation for determining the transit time per link between nodes for each link in the model. These celerity factors have been predefined for all known types of pipe and additional celerity factors are calculated by a 3rd-party when an unrecognized type of pipe is encountered. By dividing the length of each pipe link (the Distance) by that celerity (the Velocity), we can calculate the expected Time required for a pressure pulse or water hammer to travel through that pipe link.

Transit Time Matrix

Because pressure pulses may travel along multiple water distribution pathways between their source and any sensor locations, the same pulse event may arrive at the same sensor location more than once, at slightly different times and intensities, depending on possible multiple pathways taken. This adds to the complexity of identifying the same event across multiple sensors and emphasizes the importance of knowing pipe specifics.

By applying Dijkstra's shortest path (graph theory) algorithm, iHydrant's time-based model determines the shortest accumulated transit time pathway between each pair of nodes, such that a matrix is created showing the minimum or fastest transit time required for a pressure transient to travel the shortest path links between any two nodes in the graph.

Such a Transit Time Matrix could be likened to an old-fashioned highway driving paper map (see image below), where the distance between any two cities is shown as a diagonal half-matrix, as shown by the mileage intersection of a "from" row entry for one city and a column "to" entry for the other city. The full matrix is only required if the distance is different depending on your direction of travel (not customary for driving maps).

In this case, our matrix measures Transit Times, not Distances as with the driving maps.

	Atlanta	Boston	Chicago	Dallas	Denver	Houston	Las Vegas	Los Angeles	Miami	New Orleans	New York	Phoenix	San Francisco	Seattle	Washington
Atlanta		1095	715	805	1437	844	1920	2230	675	499	884	1832	2537	2730	657
Boston	1095		983	1815	1991	1886	2500	3036	1539	1541	213	2664	3179	3043	44
Chicago	715	983		931	1050	1092	1500	2112	1390	947	840	1729	2212	2052	695
Dallas	805	1815	931		801	242	1150	1425	1332	504	1604	1027	1765	2122	1372
Denver	1437	1991	1050	801		1032	885	1174	2094	1305	1780	836	1266	1373	1635
Houston	844	1886	1092	242	1032		1525	1556	1237	365	1675	1158	1958	2348	1443
Las Vegas	1920	2500	1500	1150	885	1525		289	2640	1805	2486	294	573	1188	2568
Los Angeles	2230	3036	2112	1425	1174	1556	289		2757	1921	2825	398	403	1150	2680
Miami	675	1539	1390	1332	2094	1237	2640	2757		892	1328	2359	3097	3389	1101
New Orleans	499	1541	947	504	1305	365	1805	1921	892		1330	1523	2269	2626	1098
New York	884	213	840	1604	1780	1675	2486	2825	1328	1330		2442	3036	2900	229
Phoenix	1832	2664	1729	1027	836	1158	294	398	2359	1523	2442		800	1482	2278
San Francisco	2537	3179	2212	1765	1266	1958	573	403	3097	2269	3036	800		817	2864
Seattle	2730	3043	2052	2122	1373	2348	1188	1150	3389	2626	2900	1482	817		2755
Washington D.C.	657	440	695	1372	1635	1443	2568	2680	1101	1098	229	2278	2864	2755	

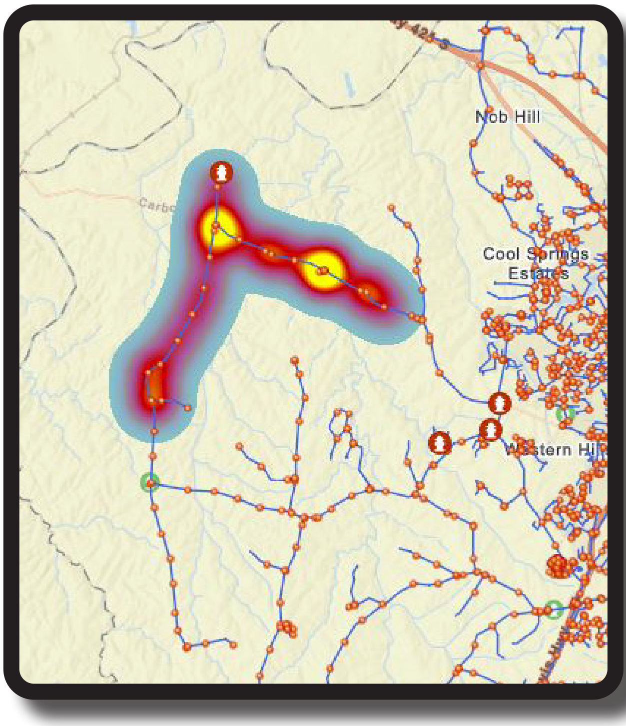
More complete and accurate content in the utility's GIS asset files, for creating this Transit Time Matrix, will improve the accuracy of the Event Localization algorithm, as described on subsequent pages.

Pressure Events

iHydrant pressure sensors are continuously monitoring water pressure readings in milliseconds. An alerting event occurs when those pressure readings exceed either their normal upper or lower boundary values for multiple sequential readings. That same alerting event may be observed by multiple iHydrant sensors at different locations in the water distribution network.

Event Localization is activated when a pressure event is determined to be the same event reported from a minimum of three or more sensors (or iHydrants) at different locations meeting the alerting criteria within a short time window. Based on the pre-calculated time model of the utility's infrastructure, heat maps can display the affected areas on the dashboard. The value of this visualization that occurs minutes after the event, can help a utility find the source of the issue such as a non-surfacing main failure when time is critical.

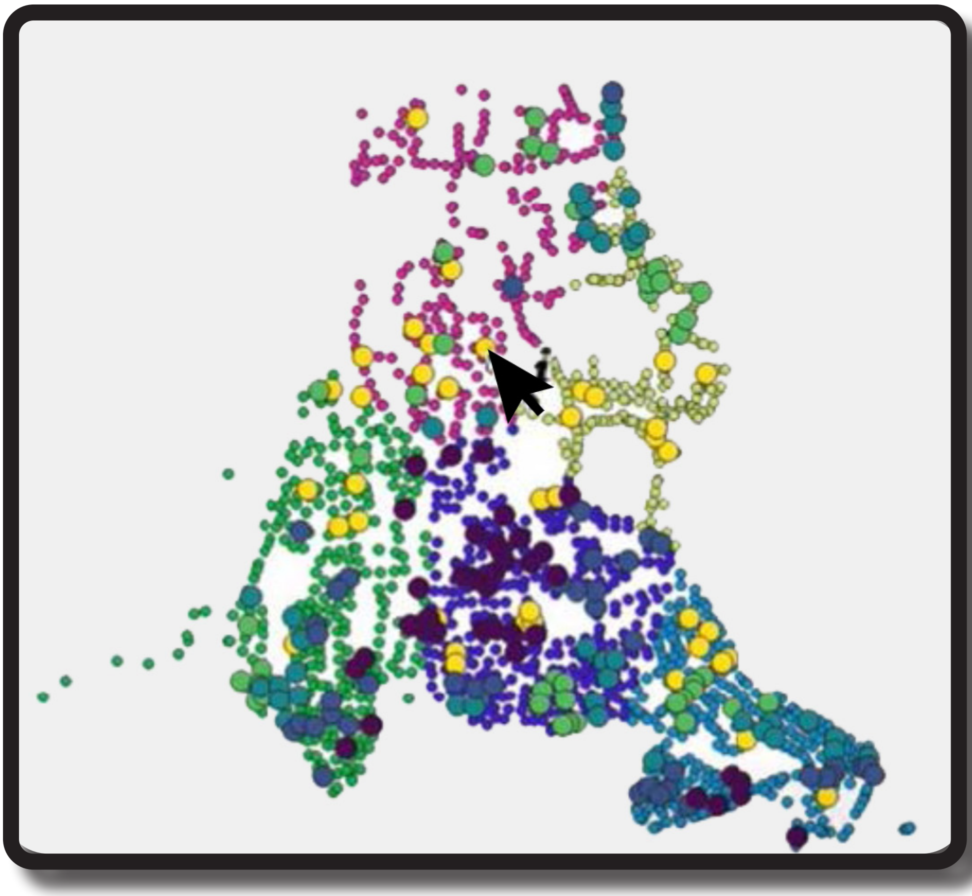
Since iHydrants can track transient waves which can travel very quickly, by observing the alerting event timestamps at different locations, it's possible to determine the chronological sequence in which the sensors first detected the event and therefore it is possible to back-track that event in time to determine both its direction of travel and its most likely origin.



Propagation Study

To maximize the possibility of detecting an alerting event, we need to determine where to place sensors to increase the likelihood of capturing an event when it occurs. Such a study can also be broken down into regions which can help with deployment strategies focusing on problem areas.

Using the same GIS asset layers that are required for creating the time-based model, a simulation will select a random number of sources (valves) to use as possible points of origin for future alerting events. A weighted error average is calculated for which hydrant nodes appeared more frequently in detecting the alerting event and ranked accordingly. This study uses the Event Localization algorithm discussed next.



Event Localization Algorithm

The Event Localization algorithm uses a Monte Carlo simulation technique, named after the famous casino in Monaco, but which is a widely accepted computational method for obtaining a high-probability, best-case solution to a complex problem where it's not possible or not practical to formulate all the relationships between the variables involved.

With Monte Carlo simulations, we propose a possible solution with one set of values for the variables (like "rolling the dice") and then again with another set of values, and repeatedly with possibly hundreds or thousands of combination sets (called iterations) of variable values. For each combination / iteration we calculate an outcome, and the "winning" iteration is the set of variable values which produces the "best" (i.e. lowest error factor) outcome, as explained further below.

Also, because the Monte Carlo approach is statistical (not formulaic), the process provides a confidence factor as to how good that "best" answer is expected to be, such as perhaps 96% certain that this is the best possible solution, based on the limitations of the model.

The Event Localization algorithm starts by creating a short-list of all (at least a minimum of three) iHydrant sensors which recorded any pressure pulse events during the narrowly defined timeframe which the algorithm has determined to be a likely "same event."

Event Localization Algorithm

To identify the most likely source of the pressure event, the Event Localization algorithm studies many “what if it started here?” simulation iterations to determine how likely each possible node was as a source (or nearby the source) of the pressure event, as shown in the Error Factor Matrix described below. And it measures that likelihood in reverse by examining the Error Factor for how “wrong” each guess (i.e., iteration) is. Then the guess with the lowest Average Error Factor (i.e., “least wrong”) is presumed to be the most likely correct guess as to the node closest to the source of the pressure event.

These Error Factors are calculated by comparing the actual time differentials between when each hydrant of a specific pairing saw a “same event” versus the predicted time differential between those two hydrants, as calculated earlier in the Transit Time Matrix.

For example, if the water distribution network has 1,000 nodes (i.e., pipe intersections, valves, hydrants, etc.), then the Error Factor Matrix must have 1,000 rows, with each row representing a node or point from which the event might have originated.

And, if 4 sensors observed that same event, there will be (4*3)/2= 6 pairings of sensors to be studied. So, 6 sensor pairings times those 1,000 nodes creates a 6,000 entry Error Factor Matrix, which will require 6,000 simulation iterations to complete, one iteration for each entry in the matrix.

For each node in the water distribution network, the simulation examines each pairing of sensors and asks, “If the event started at this node”:

1.)What’s the “predicted time difference” for this same event to reach these two sensors, as defined in the Transit Time Matrix?
2.) What was the “actual time difference” between when these two sensors observed this same event?
3.) The variance (as an absolute value) between the “predicted time difference” and the “actual time difference” is saved as the Error Factor Matrix entry for that node row and that sensor pairing column.

Event Localization Algorithm

If these two iHydrant sensors were observing the same event and if the Transit Time Matrix was a perfect forecast of reality, then this Error Factor should be zero.

Once all the hydrant pairing (column) situations have been simulated for a node (row) and their respective Error Factors have been calculated, the Error Factors for that row are averaged to create a Node Average Error Factor for that node / row.

After all rows have been simulated and fully calculated, the rows are sorted by Node Average Error Factor from lowest value to highest, where the lowest Node Average Error Factors are presumed to be the most likely situations where multiple sensors saw the same event and that the event likely originated at or nearby that row's node.

A predefined Average Error Limit is used as a limiting filter, such that rows with an excessive Average Error Factor are discarded as not being the same event, such that only rows with a low Average Error Factor proceed to Heat Mapping visualization.

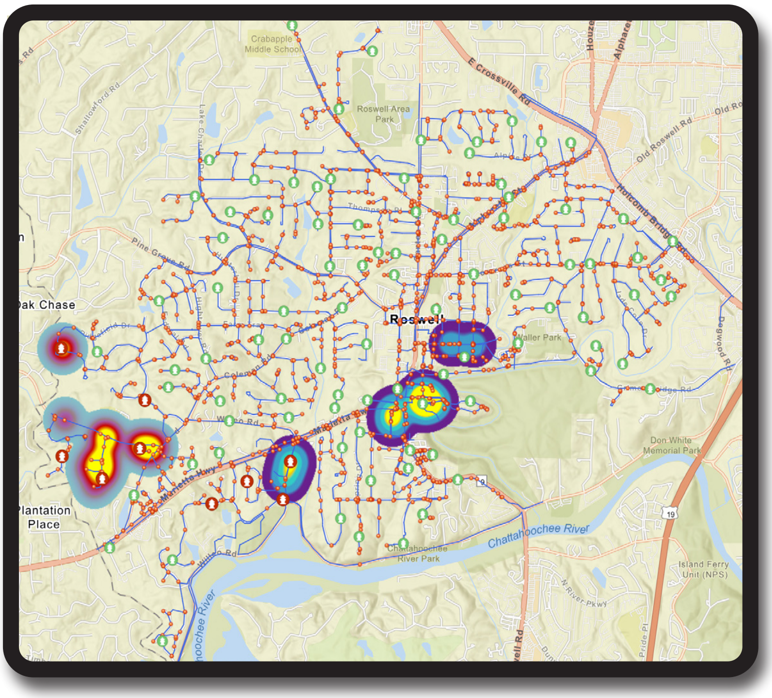
Heat Mapping

Using the “same event” probability output from the Event Localization service, the Heat Mapping display:

a.) Overlays that hydraulic topology on top of an ESRI™ geographic map.
b.) Superimposes varying sizes of balloon shapes around the iHydrants which reported this event to visualize the geographic scope of sensor locations reporting this event.
c.) Applies graduated color symbology within those balloons to visualize the intensity of the event at individual locations within those balloon-shaped geographies.

The color scale for the Heat Map can be found on the Legend, with yellow being a high probability that the event occurred in that location and where blue is a lower probability.

As you zoom in and out on the map, the resolution of the Heat Map will change in resolution to help you determine the most likely location of the event. The hydrant icons shown in red are the iHydrants that detected the event. Green hydrants are neighboring iHydrants that did not detect the event. You can see these details on the zoomed in map shown below.



Since the iHydrant Event Localization service is continually running in the background to dynamically process all iHydrant pressure events as soon as they're reported, the time gap between event occurrences and heat mapping is close to real-time as those pressure events are occurring. This close to real-time Heat-Mapping capability provides utilities with the awareness and information needed to immediately assess the magnitude and scope of a pressure event and the likelihood of any associated damage with consequential costs and complications.

Summary

This document explained the inner mechanisms used by iHydrant's Event Localization technology and algorithms, and Heat Mapping visualization to identify and display, in close to real-time:

1.) That a same pressure pulse / water hammer event has occurred, as reported by three or more iHydrant pressure sensors.
2.) The geographic scope which has been affected by this pressure pulse event.
3.) The likely source of this pressure pulse, as suggested by its highest intensity iHydrant sensor as shown on the map, and more precisely by the lowest Error Factor node / row in the Error Factor Matrix.

Given the damage and expense caused by pressure pulses / water hammers in water distribution systems, this is extremely useful information, especially in close to real-time, for better understanding:

1.) That damage may have occurred, and the geographic scope of any such damage.
2.) The likely relationship between the intensity of the pressure pulse and any observed consequences.
3.) The likely sources and causes of such pressure pulses, such that actions can be taken to reduce their intensity or impact for future occurrences.

Authors:
Sneha Borra, iHydrant's VP of Operations and inventor on iHydrant's Event Localization patent application which includes Heat Mapping concepts; and,
Brian Morrow, iHydrant's VP of Administration and lead inventor on many of iHydrant's earliest patents.

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Appendix: Assumptions and Sources for Young’s Modulus of Elasticity

Pipe type	Young’s Modulus Assumption	Source
PVC	4	https://www.engineersedge.com/manufacturing_spec/properties_of_metals_strength.htm"
Ductile Iron	166	https://www.ductile.org/didata/Section3/3part1.htm#Modulus%20of%20Elasticity
Steel	200	https://www.engineeringtoolbox.com/young-modulus-d_417.html
Cast Iron	92.2	https://www.engineeringtoolbox.com/young-modulus-d_773.html
Copper	110	https://www.engineeringtoolbox.com/young-modulus-d_773.html
Brass	100	https://www.engineeringtoolbox.com/young-modulus-d_417.html"
Unknown	PVC assumed	