Modeling disruption and dynamic response of water networks

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August 19, 2016

Threat to water networks

- The main threats to water infrastructure systems can be classified in three different scenarios of attack: physical, cyber, and chemical and biological.
- Each scenario is unique and requires different vulnerability assessments and protection and mitigation efforts.

- Many observers believe that physical events that destroy or disrupt water systems are more likely to occur than contamination events because explosive materials are readily available and require a lower level of expertise for deployment compared to the development and deployment of contaminants.
- An intentional physical attack on a well-selected set of critical components can result in catastrophic disruption of water service.

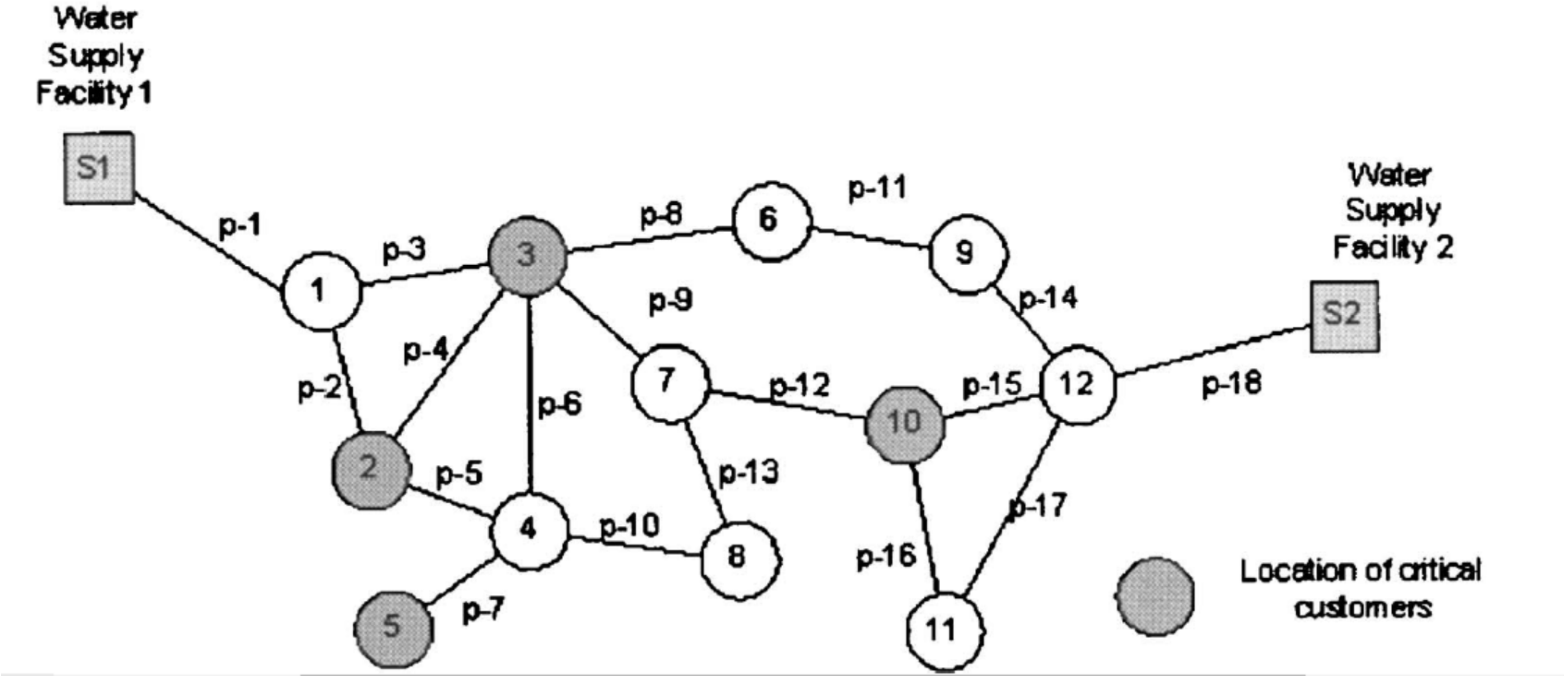
Consequences

- Three different indices are introduced and used to assess the consequences of an intentional physical attack:
  - 1) the degree of water supply disruption to major critical infrastructure facilities,
  - 2) economic loss, and
  - 3) the number of people suffering water outage.

Response

- In principle, the operational response strategy minimizes water supply disruption at critical infrastructure facilities, economic losses as a result of the disruption, and the number of people affected by the water outage.
- The strategy involves the selection of a set of nodes to which the utility manager chooses not to supply water in order to get adequate water supply to more critical nodes.

- Hydraulic constraints:
  - conservation of mass at each junction node
  - conservation of energy for each pipe
  - minimum pressure requirement


Water Supply Facility 1
S1
Water Supply Facility 2
S2
p-1
p-2
p-3
p-4
p-5
p-6
p-7
p-8
p-9
p-10
p-11
p-12
p-13
p-14
p-15
p-16
p-17
p-18
1
2
3
4
5
6
7
8
9
10
11
12
Location of critical customers

Monitoring system

- In a SCADA (Supervisory Control and Data Acquisition) system, information about the current state of the network received, in terms of
  - water volumes in reservoirs,
  - status of pumps and valves,
  - latest demand readings,
  - pressure and/or how readings at selected points.

Detection and localization of bursts

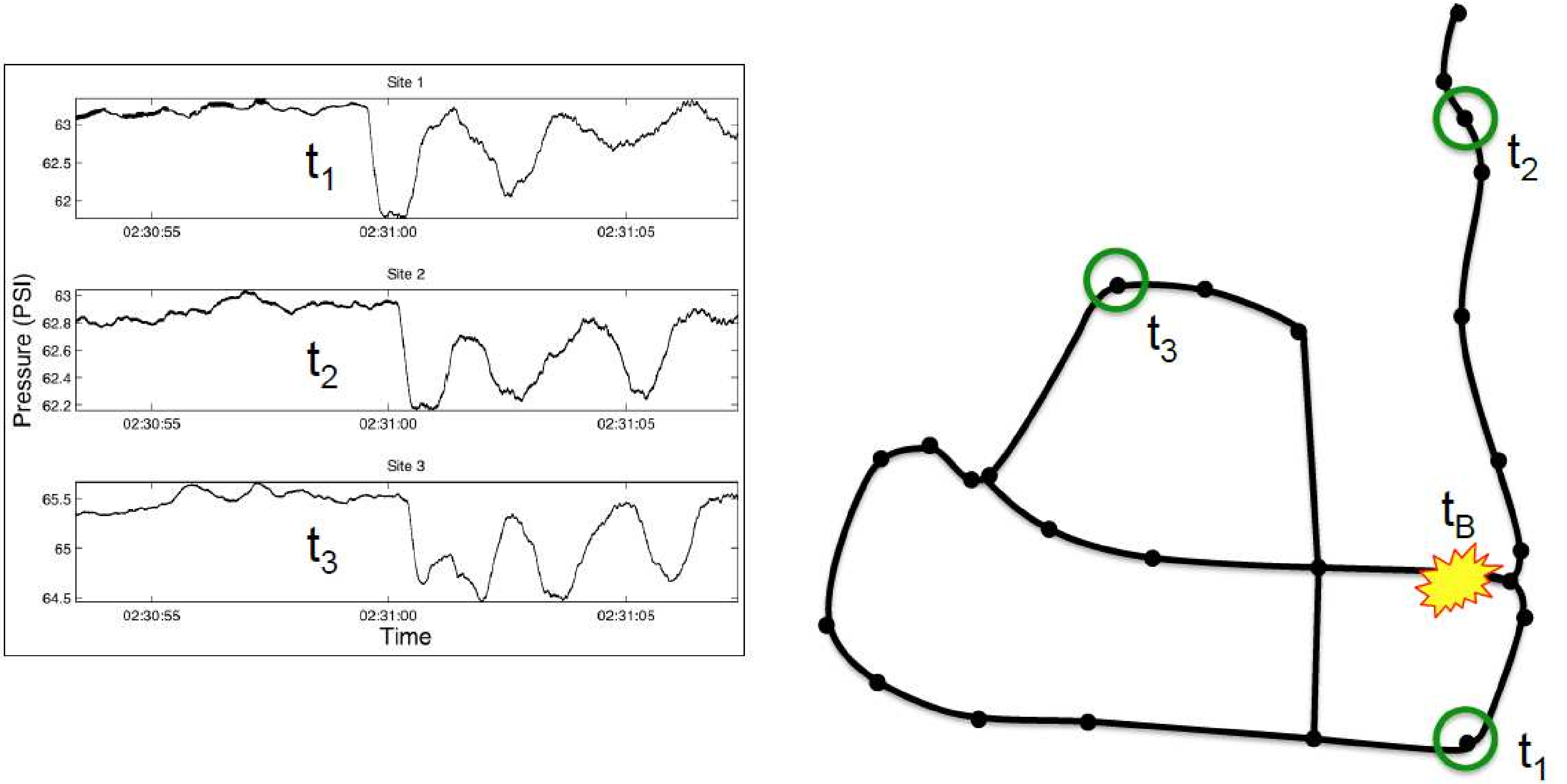
- Many events in a water distribution system, such as bursts, leaks or valve operations can be detected as pressure transients.

- Slow leaks, valve and other maintenance operations typically result in transients that can be detected over a time scale of minutes or hours. Conversely, pipe burst events result in pressure transients that must be detected over time-scales from milliseconds to seconds.

- Pipe burst events result in a sudden change in the flow through the pipe producing a pressure transient which propagates along the pipeline.
- This pressure pulse travels in both directions away from the burst origin at the speed of sound in water (wave speed of the pipe). Pipe junctions and endpoints in the physical network reflect the pulse, and its speed is altered by the pipe material and diameter as it travels through the network. The transient is also attenuated by friction in the pipes, causing dispersion that reduces the slope or steepness of the transient wavefront.

- In order to detect and localize instantaneous burst events (and hence, give a starting point to accurately locate the leak), it is advantageous to use pressure measurements.
- When several detection time estimates of burst events arrive in quick succession from several different nodes, it can be assumed they relate to the same event.
- Consequently, these observations can be fused to provide an estimate of the burst location within a defined search space.

- Travel time is determined by dividing the known pipe length by the wave speed. In order to localize an event using the graph, the burst transient must be detected at two or more measurement points.
- The detection times from each node represent the times that the transient arrived at the node (the *time-of-arrival*).
- The problem is to find the vertex that is the most likely location of the burst, given multiple time-of-arrival estimates from sensor nodes within the network.



A simplified visualisation of a pipe network as a graph showing detection times ($_1$, $_2$, $_3$) at sensor nodes and the burst location ($_B$). Pressure traces with transients are shown for context.

- Assume the burst event occurs at time ! and is detected at nodes and at times and $_{k}$ respectively. The travel times from the burst location to the measurement points (- $_{B}$) and ($_{k}$ − $_{B}$) cannot be determined, however the difference between the arrival times ($_{j}$ − $_{k}$) is known. It is also possible to calculate the shortest travel time $_{jk}$ between any two vertices and in the graph, e.g., using Dijkstra’s algorithm.

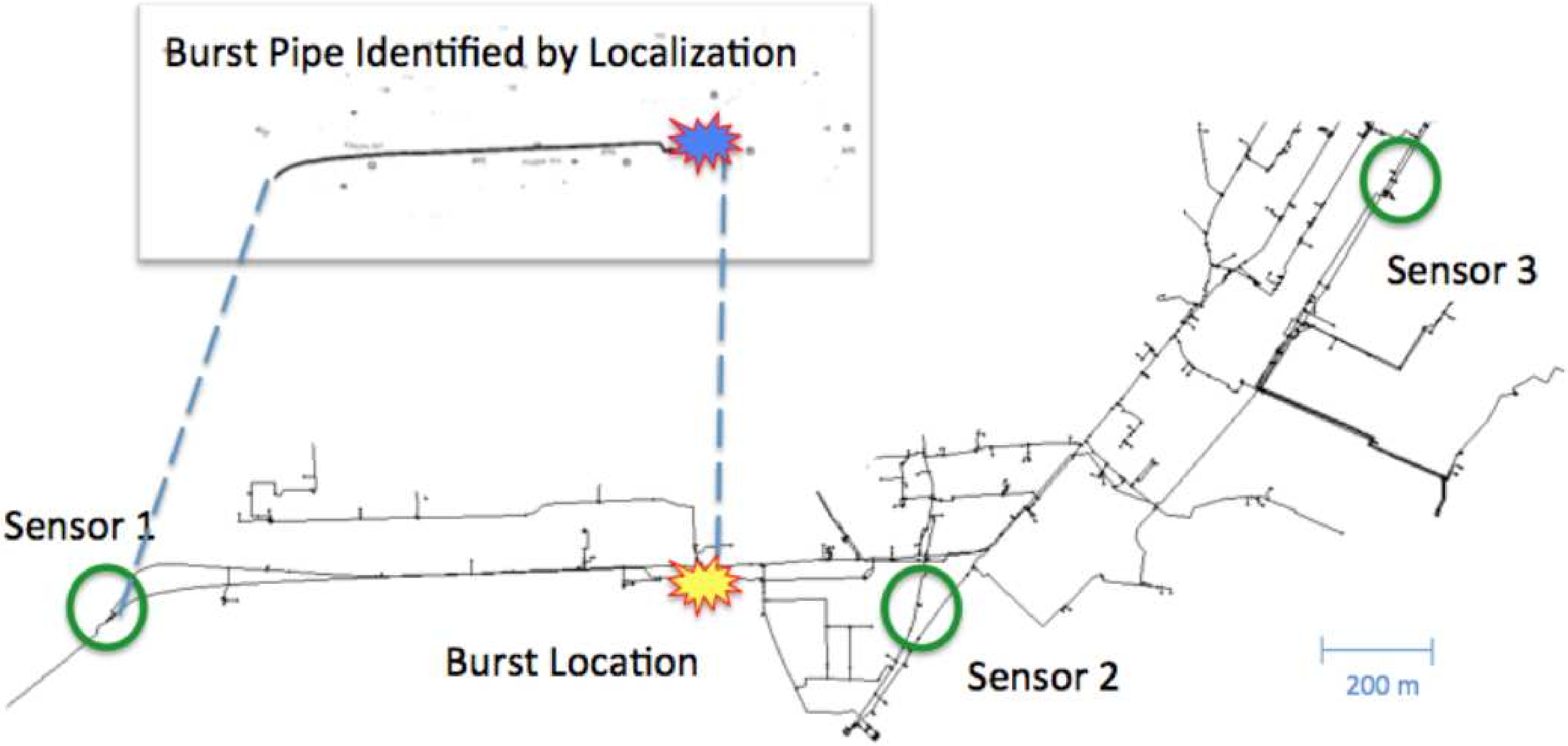
- So, if the burst occurs at vertex , where = 1… (= the number of vertices in the graph), it follows that:

$$(\ _j - \ _k) - (\ _{ij} - \ _{ik}) = 0$$

- However, due to timing, measurement and other errors, the left-hand side of the equation is unlikely to be zero. The most likely burst location is determined by minimizing the following metric over the search space:

$$S_i = \sum_{\substack{j,k\in S_B \\ j\neq k}} \left|(t_j - t_k) - (\tau_{ij} - \tau_{ik})\right|$$

- This metric combines the detection times from all the nodes that detected the event in the set $_{B}$. In practice, the search space can be artificially limited as required, for example by providing a bound on the maximum distance a pressure transient is expected to travel in a network of a given complexity.
- The most likely burst location is always quantized to the nearest junction, and this may not be the actual best match for the observed time of arrivals at each sensor node. Therefore, a second refinement step can be applied, where a local search is performed around the most likely vertex, by adding extra ‘virtual’ vertices in around it at fixed intervals along the edge (pipe). This allows accurate arrival times to provide accurate position estimates.


Burst Pipe Identified by Localization
Sensor 3
Sensor 1
Burst Location
Sensor 2
200 m

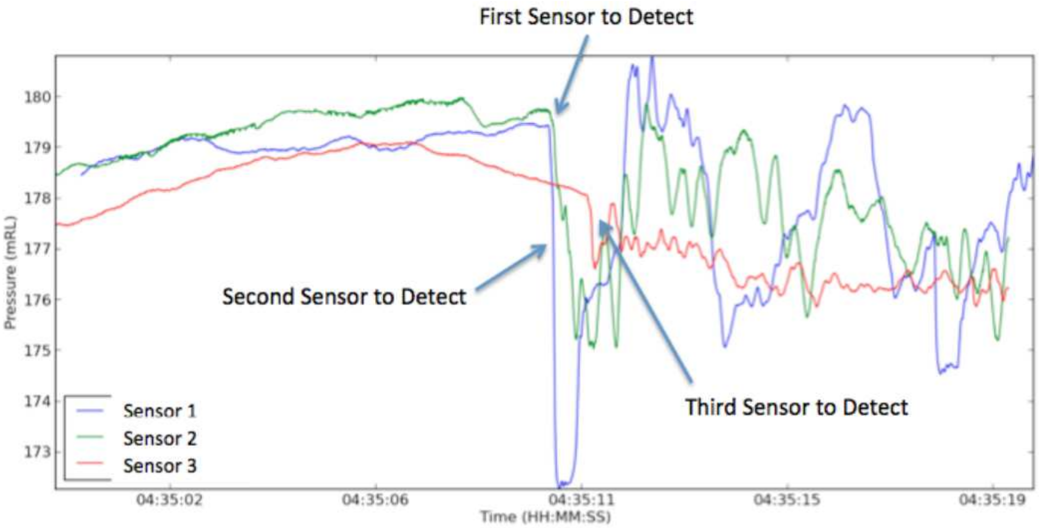
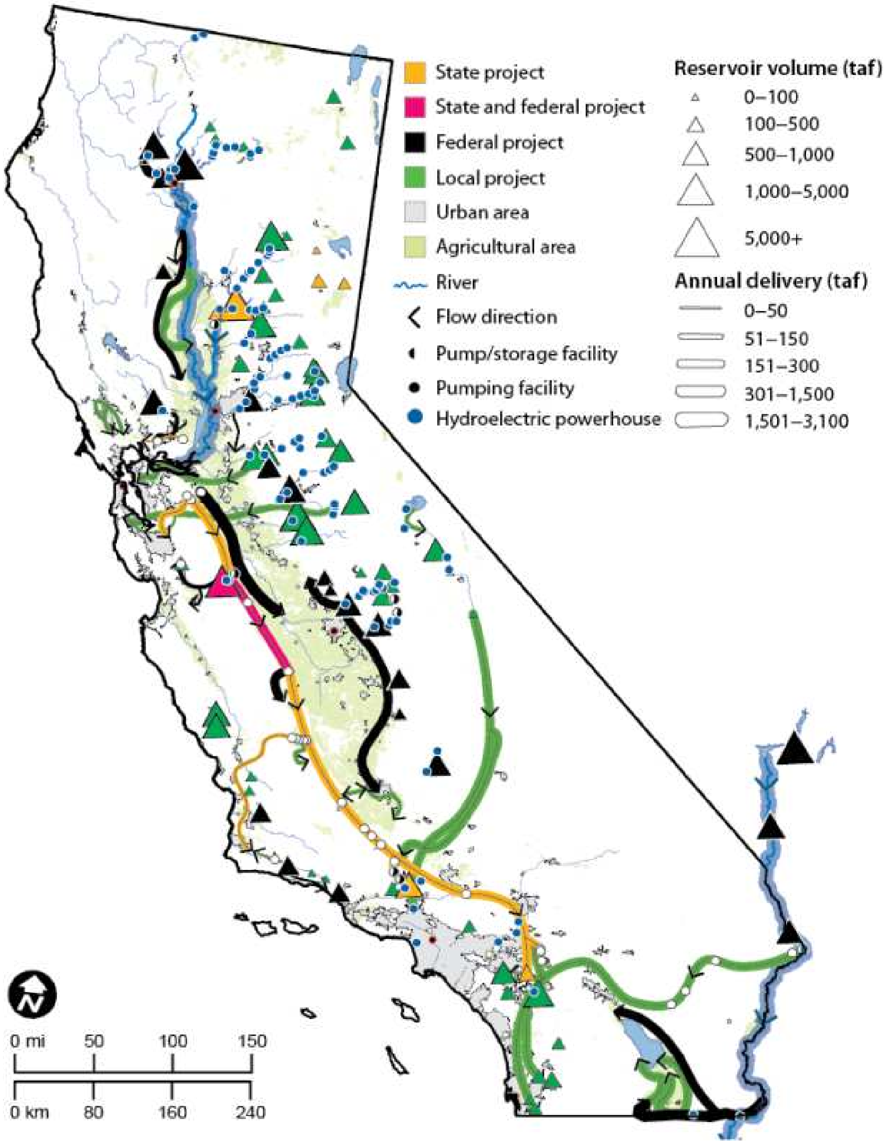
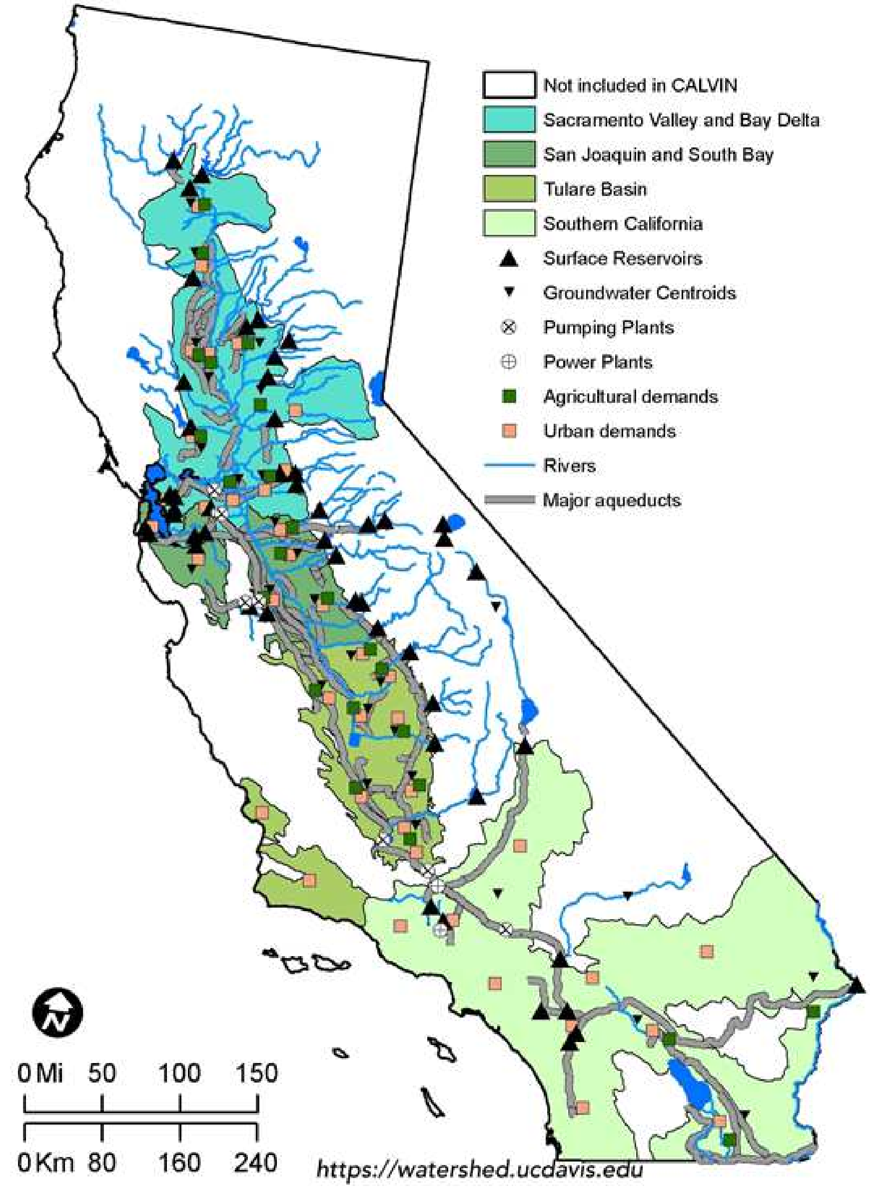


Table 1 – Time Difference of Arrival (TDOA) Estimates for Burst Event

TDOA	Sensor 1	Sensor 2	Sensor 3
Sensor 1: 4:35:10.398 am	0	0.110	-0.743
Sensor 2: 4:35:10.508 am	-0.110	0	-0.635
Sensor 3: 4:35:11.141 am	0.743	0.635	0





https://californiawaterblog.com/2012/02/09/insights-for-california-water-policy-from-computer-modeling/
https://californiawaterblog.com/2012/11/30/getting-through-the-dry-times/

U.S. Bureau of Reclamation's

Central Valley Project

California, USA