CSOnet: A Metropolitan Scale Wireless Sensor-Actuator Network

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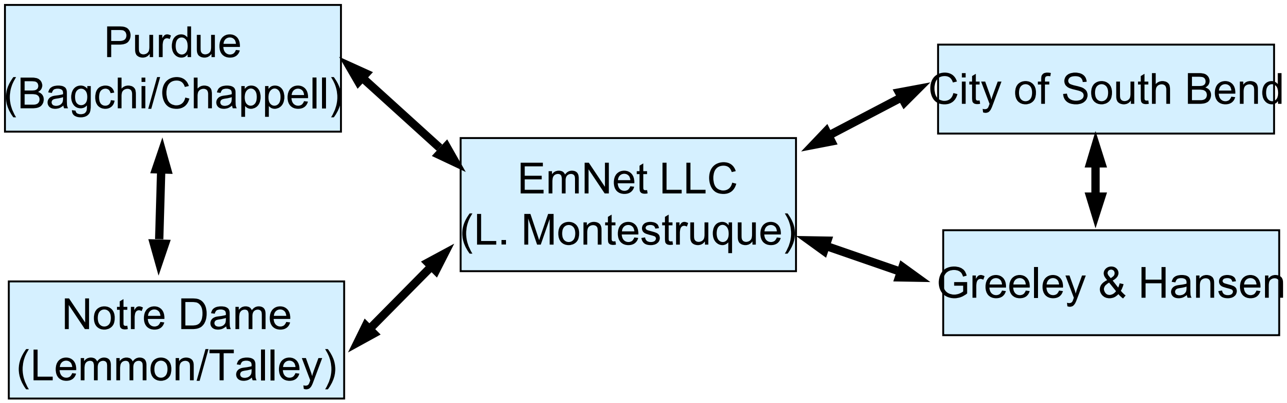
Outline

- Combined Sewer Overflow Problem
  - In-line Storage using CSOnet
- CSOnet System Hardware
- CSOnet Middleware
- Real-time Control Strategy
- Future Directions

CSOnet Project Background

- CSOnet concept: use of wireless sensor-actuator networks for distributed monitoring and control of combined sewer overflow (CSO) events.
- Concept originally created at Notre Dame (Lemmon/Talley)
    - Funded through the State of Indiana's 21st Century Technology Fund 1 million USD (2004-2006) - 1 million USD (2007-2009)
- Academic, private sector, and public sector partners



Purdue
(Bagchi/Chappell)

Notre Dame
(Lemmon/Talley)

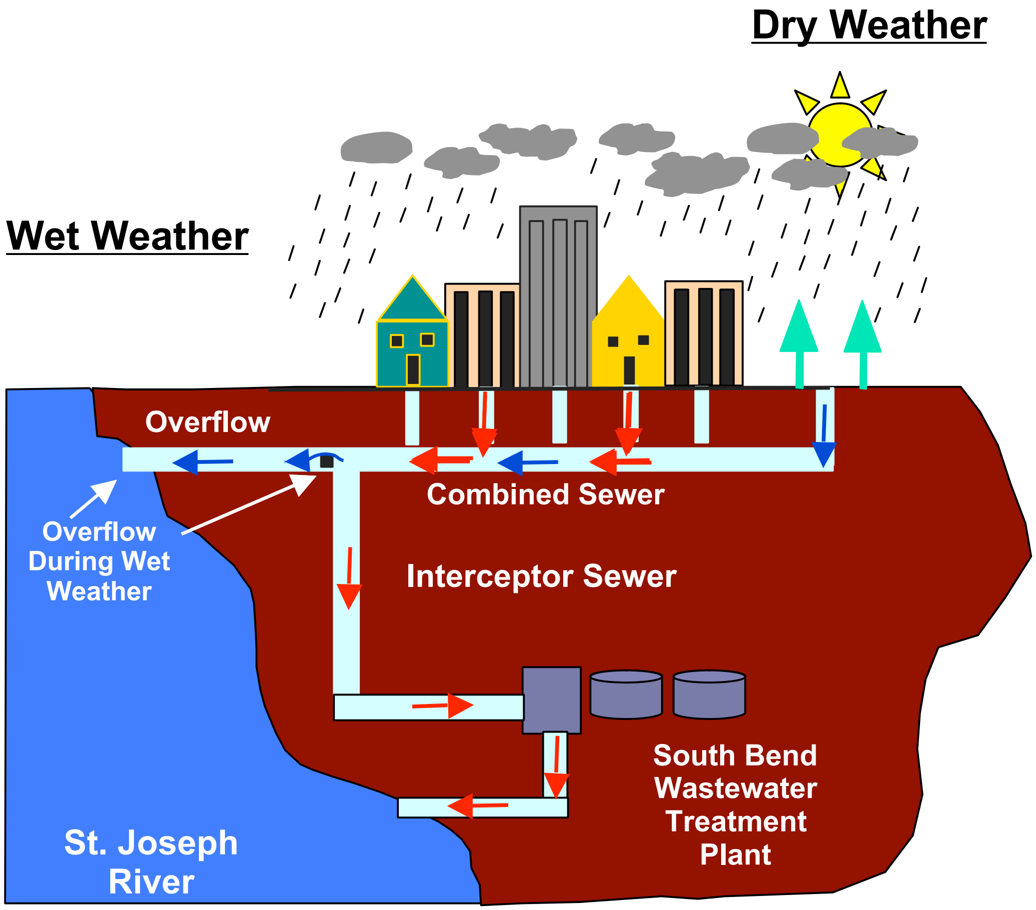
EmNet LLC
(L. Montestruque)

City of South Bend

Greeley & Hansen

- 150+ Sensor network monitoring 13,000 acres (summer 2008)
- Actuation component scheduled for completion in summer 2009

Combined Sewer Overflow Events



- **Combined sewer overflow (CSO)** events occur when a municipality dumps untreated water from combined storm and sanitary sewer flows into a river/stream.
- ***"Such 'exceedances' can pose risk to human health, threaten aquatic life and its habitat, and impair the use and enjoyment of the Nation's waterways."***

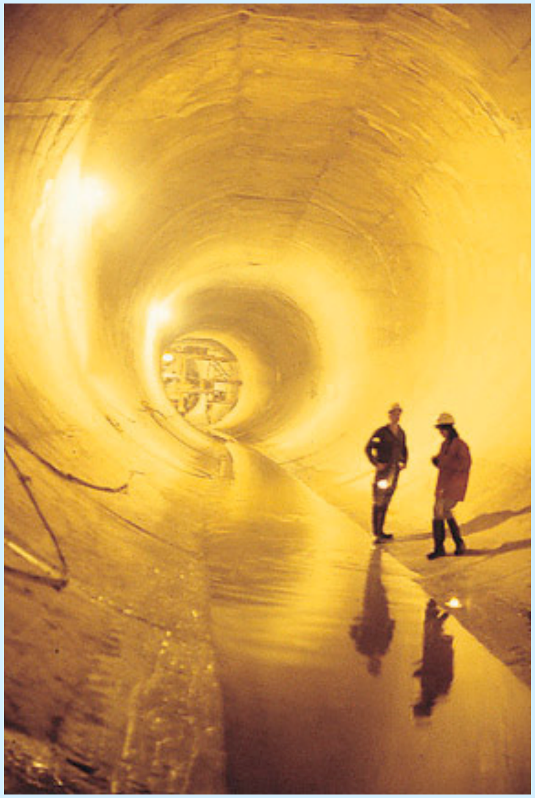
  EPA, "*Combined Sewer Overflow Control Policy,*" April 19, 1994. (www.epa.gov)
- EPA fines for CSO events
  - 1994 CSO Control Act
  - Fines are Significant
- Problem is Large-scale
  Over 772 cities nationwide

Solution Strategies

Sewer Separation

Expansion of WWTP

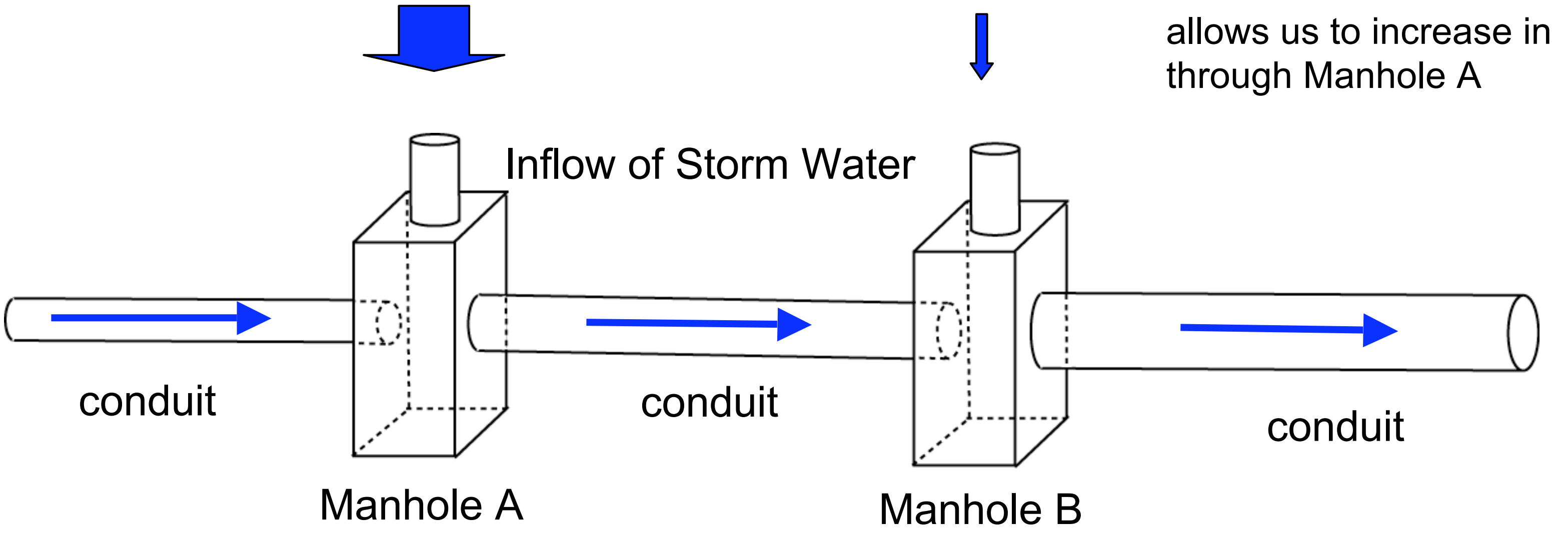
Off-line Storage Tunnels
Chicago's TARP project



These strategies all require significant investment in new infrastructure

In-line Storage

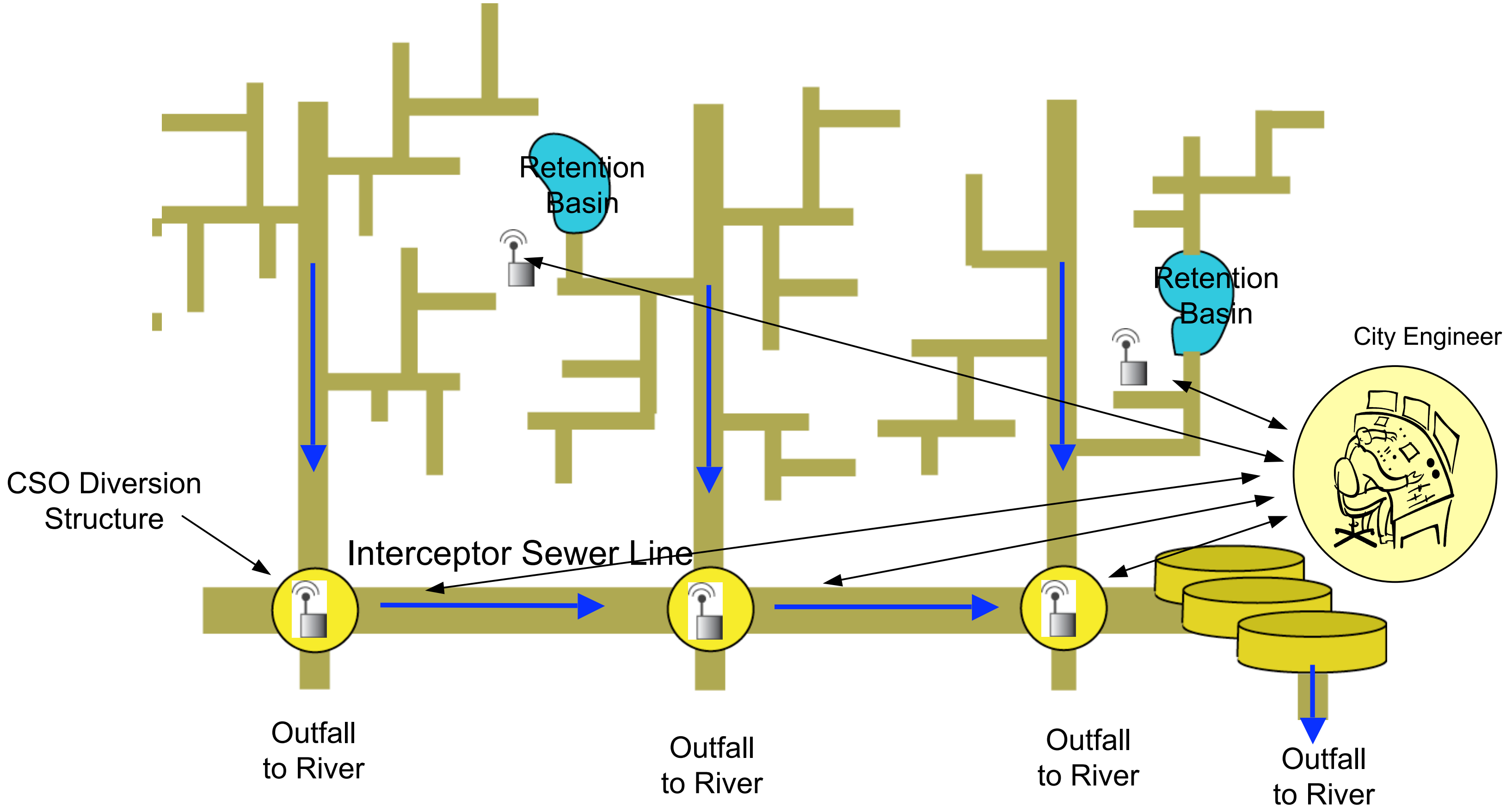
- Store excess water in unused parts of the system
- Reduces need for infrastructure enhancement
- Requires real-time monitoring and control of flows



Reduced inflow to Manhole B allows us to increase inflow through Manhole A

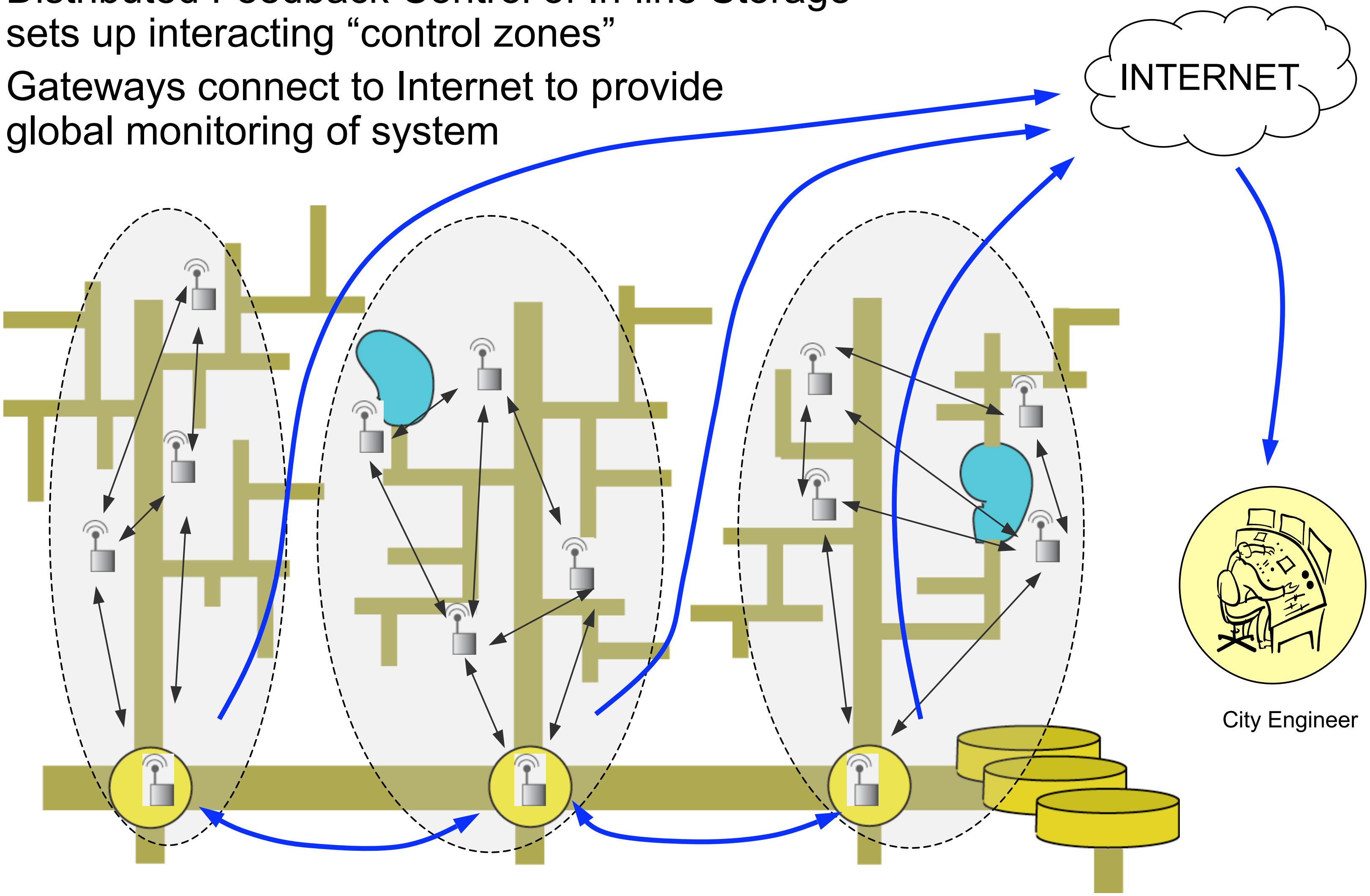
Centralized Model Predictive Control

- Pre-1974 combined sewer trunklines
- Interceptor Sewer to Wastewater Treatment Plant
- Monitoring and Control over SCADA network

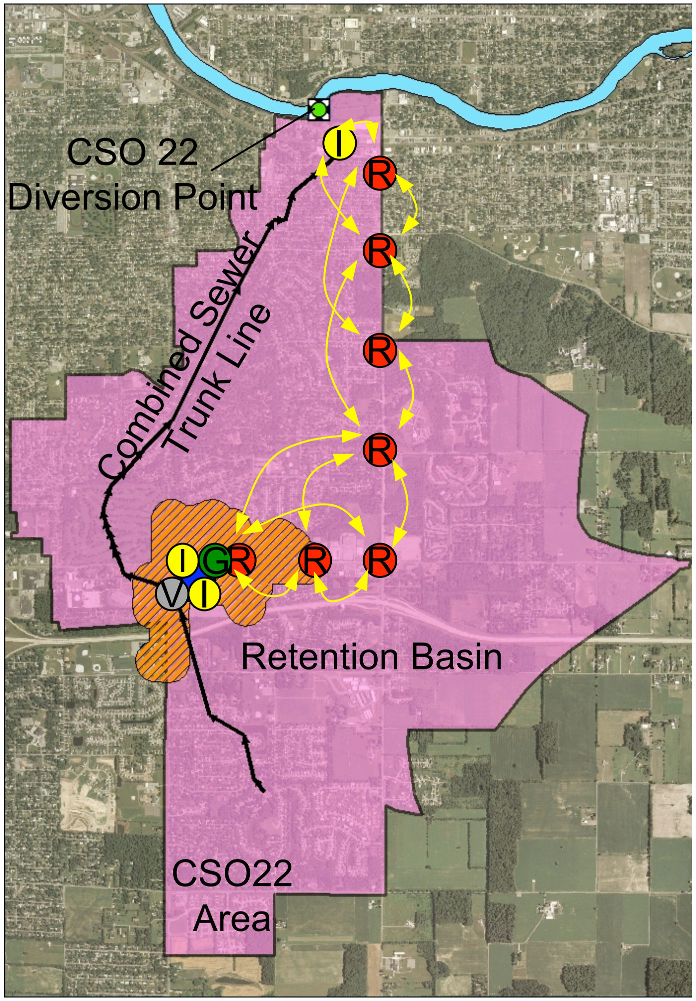


Distributed In-line Storage

- Distributed Feedback Control of In-line Storage sets up interacting "control zones"
- Gateways connect to Internet to provide global monitoring of system



Ireland/Miami Network (Summer 2005)



Prototype system controls retention basin based on flow measurements at CSO 22 diversion structure

- R 7 Relay Rnodes (radios)
- I 3 Instrumentation Inodes (sensors)
- G 1 Gateway Gnode connect to the internet
- V Automated valve
- Network is fully deployed and operational

First month of service the system prevented 2 million gallon CSO discharge

Continuous operation since summer 2005.

Slide provided by courtesy of EmNet LLC

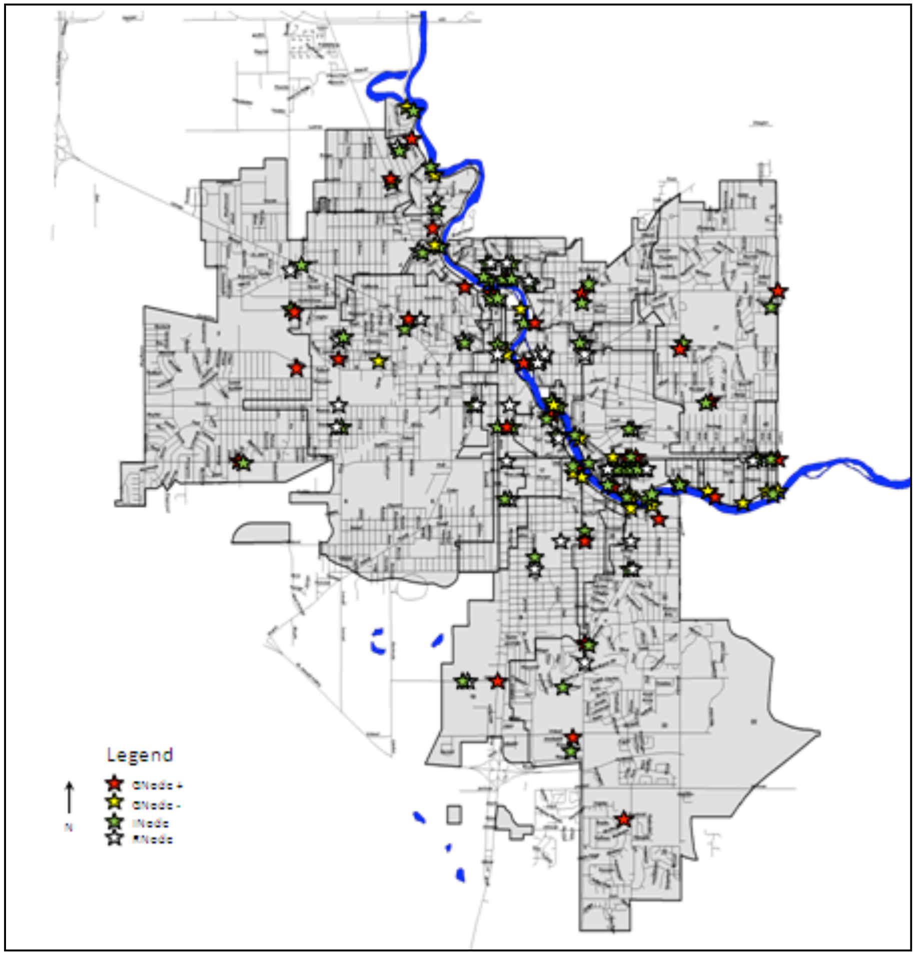
South Bend CSOnet

PHASE 1: (summer 2008)

- Monitor 36 outfalls, 27 interceptor locations, 42 trunkline locations, and 5 basins

PHASE 2: (summer 2009)

- Control at least 18 outfalls
- Control storage in retention basins
- Control remediation pumps wet weather discharges



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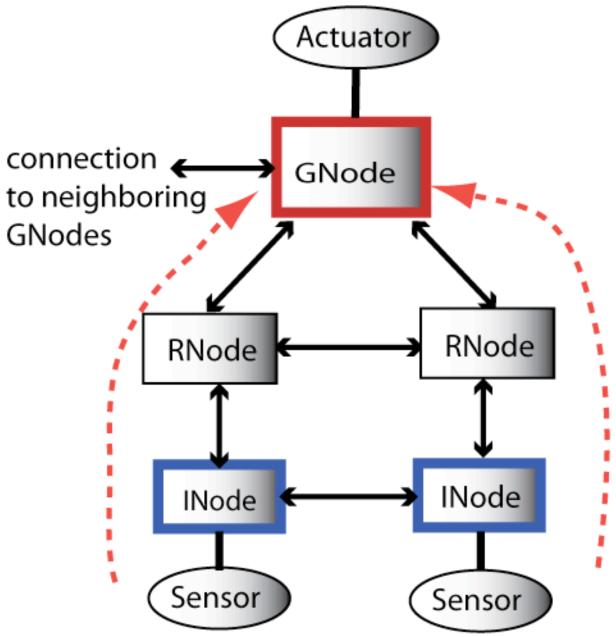
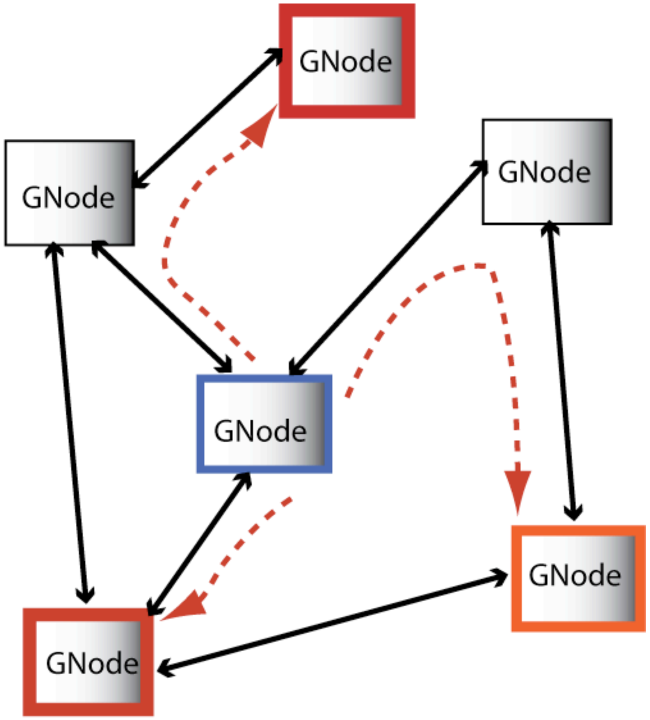
CSOnet Architecture

- Hierarchical network
  - Unicasts in low level subnets, Multicasts over higher level
  - 3 types of Nodes - Gnode, Rnode, Inode

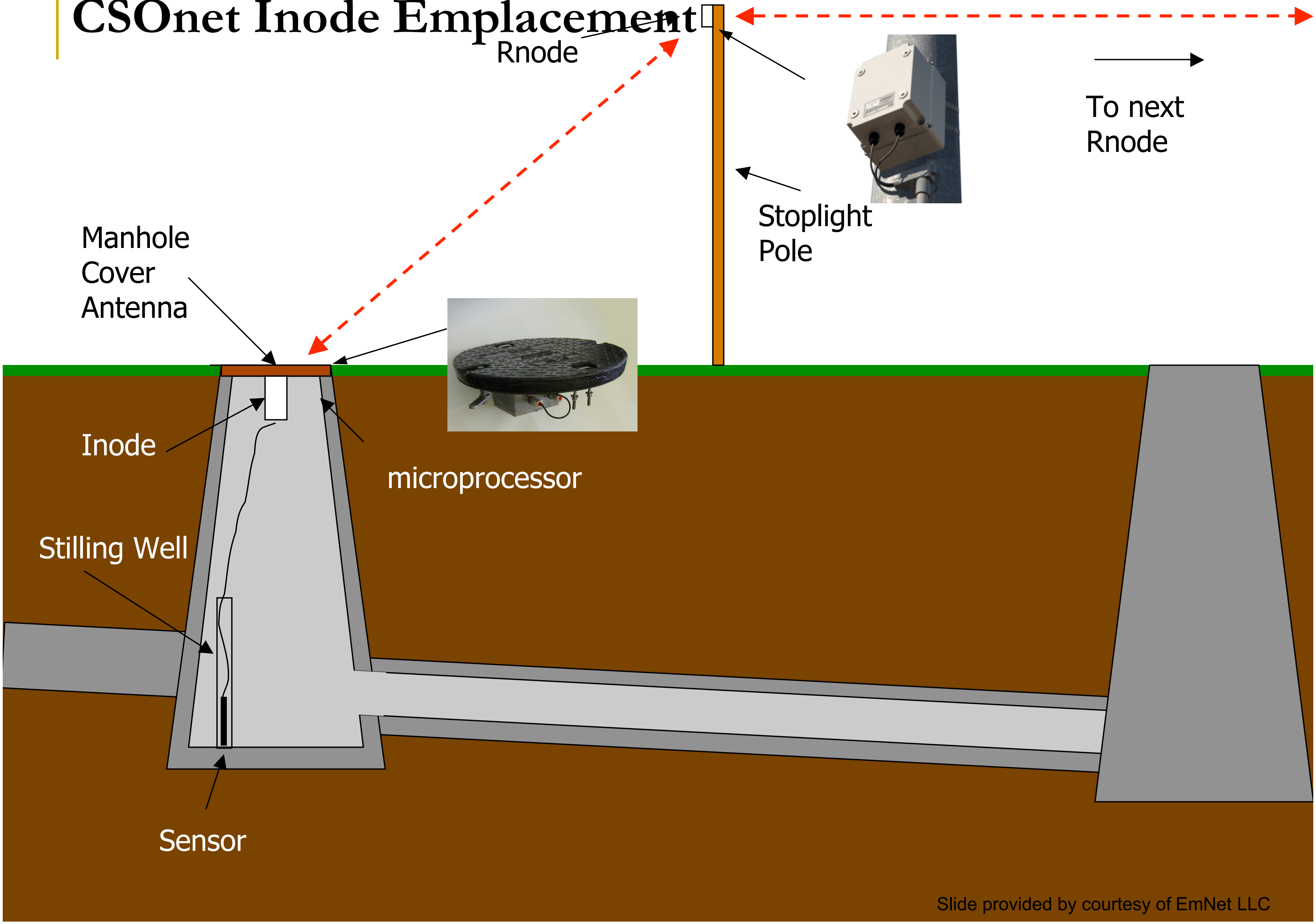


Mesh Radio Subnet
sensor data flows to GNode
which manages the actuator



GNodes broadcast their information
to neighboring GNodes.

CSOnet Inode Emplacement



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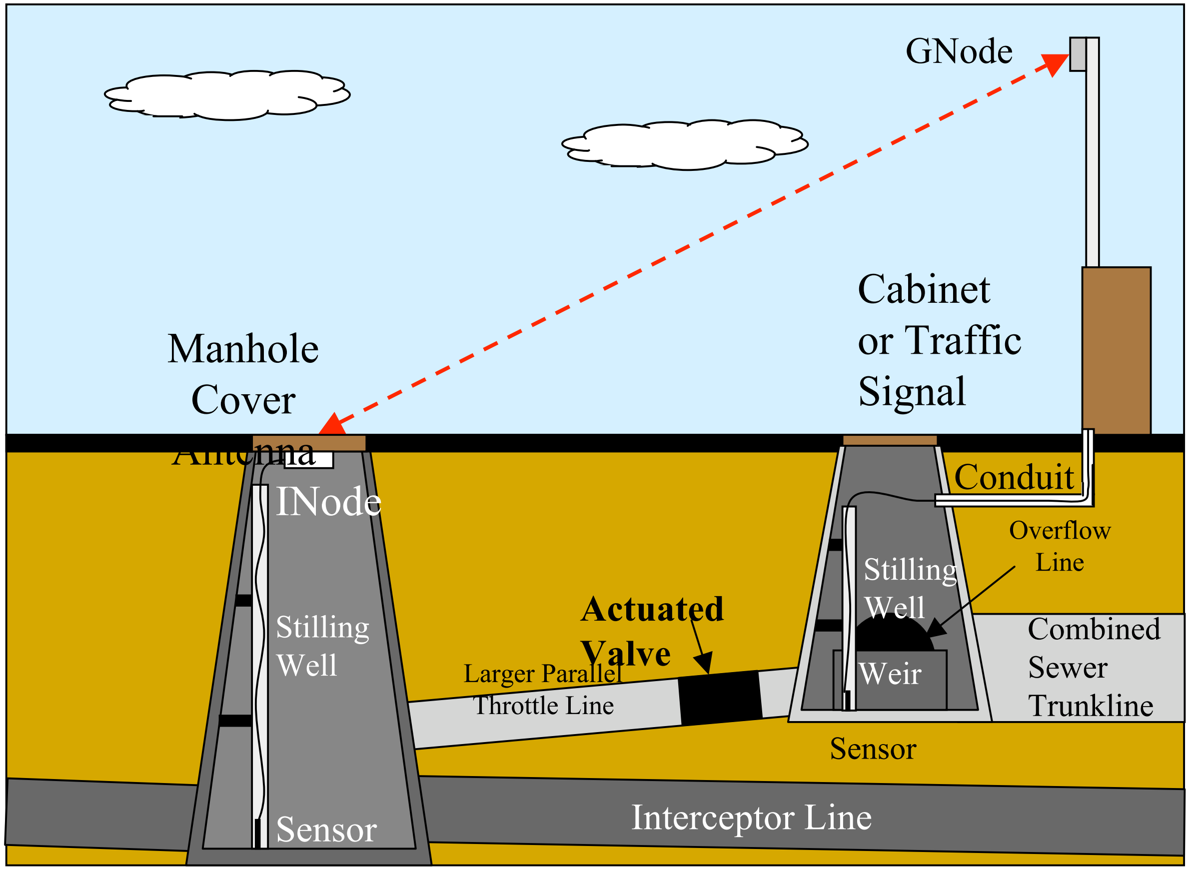
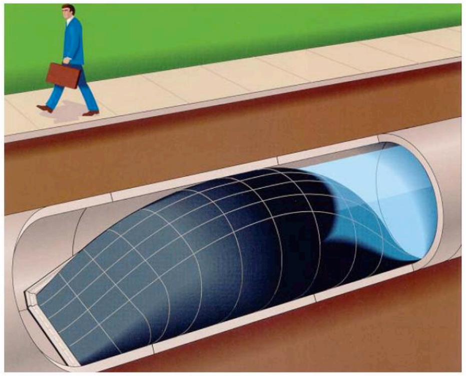
Actuators



Actuated Valve

Pneumatic Bladder



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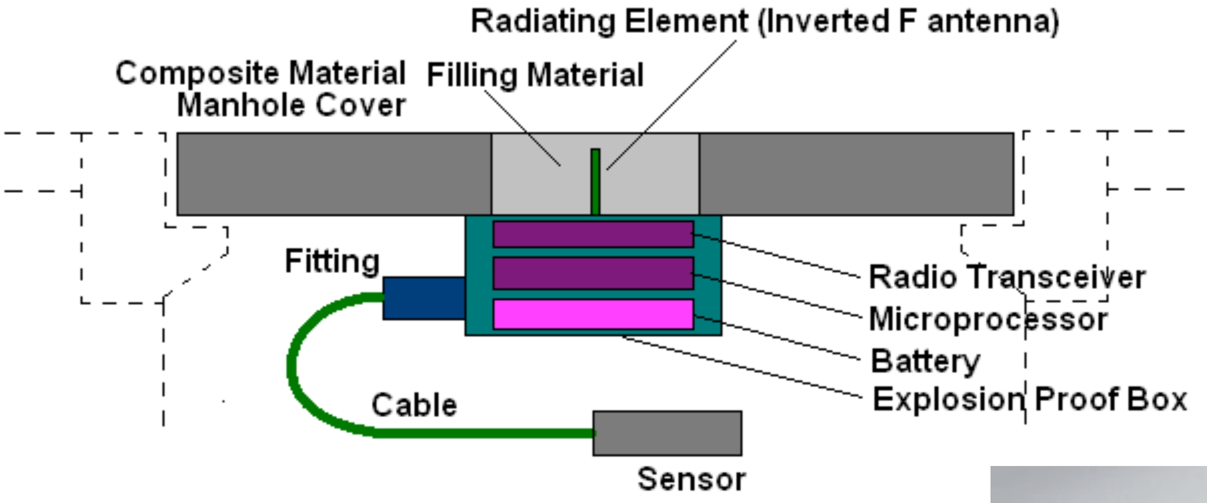
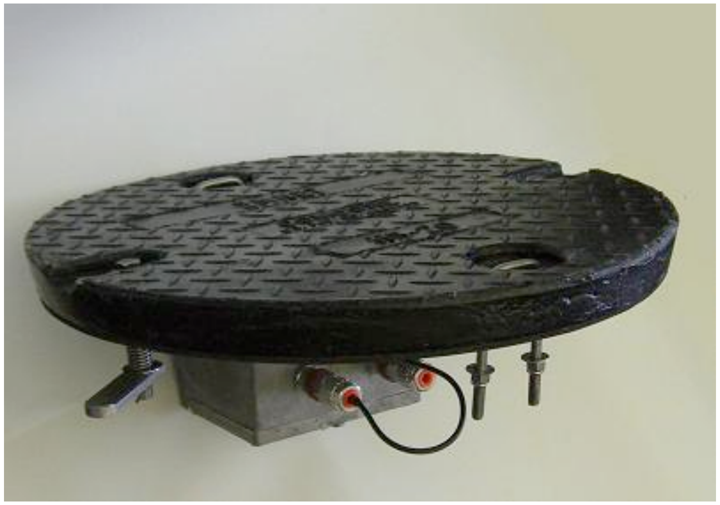
Composite Manhole Cover



- Manhole is extremely corrosive environment
- Initial prototypes "rusted" away with a few months

- Integration of processor, radio transceiver, and antenna into manhole cover
  - William Chappell - Purdue



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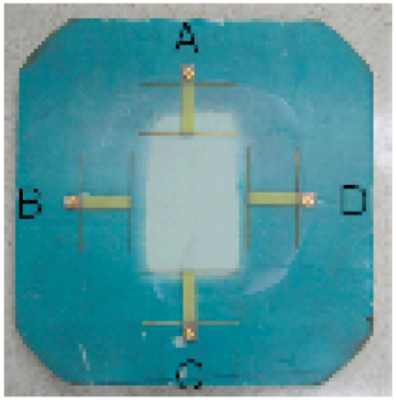
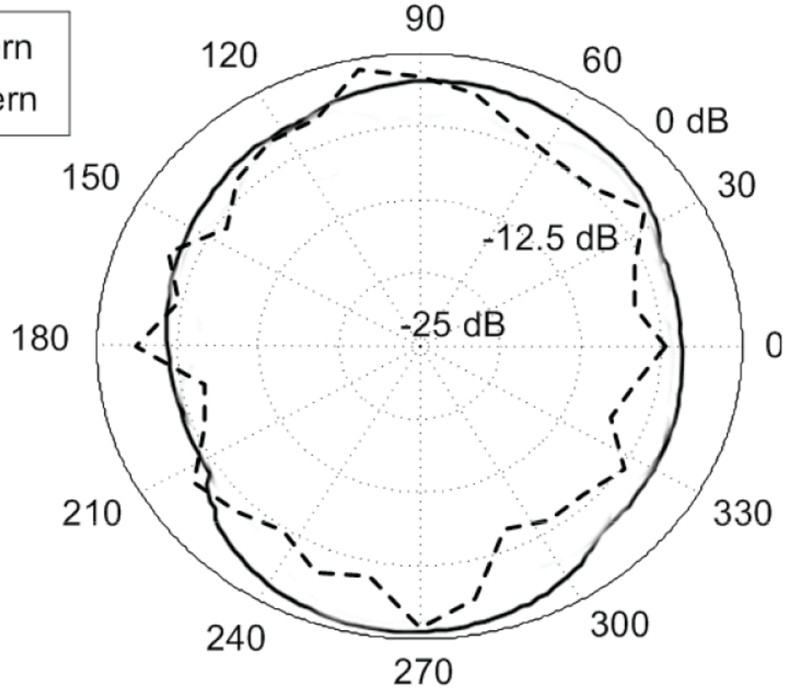
Intelligent Radio Antenna

- Municipal deployments must cope with fading effects due to multipath interference.
- Intelligent switching between multiple antennae



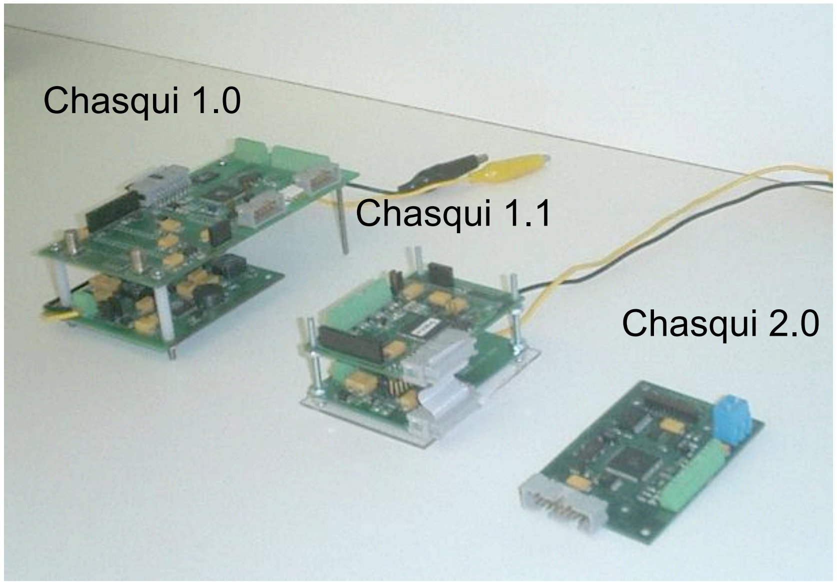
Yagi-Uda Antennae
with angular diversity

Intelligent Manhole Cover with Angular Diversity

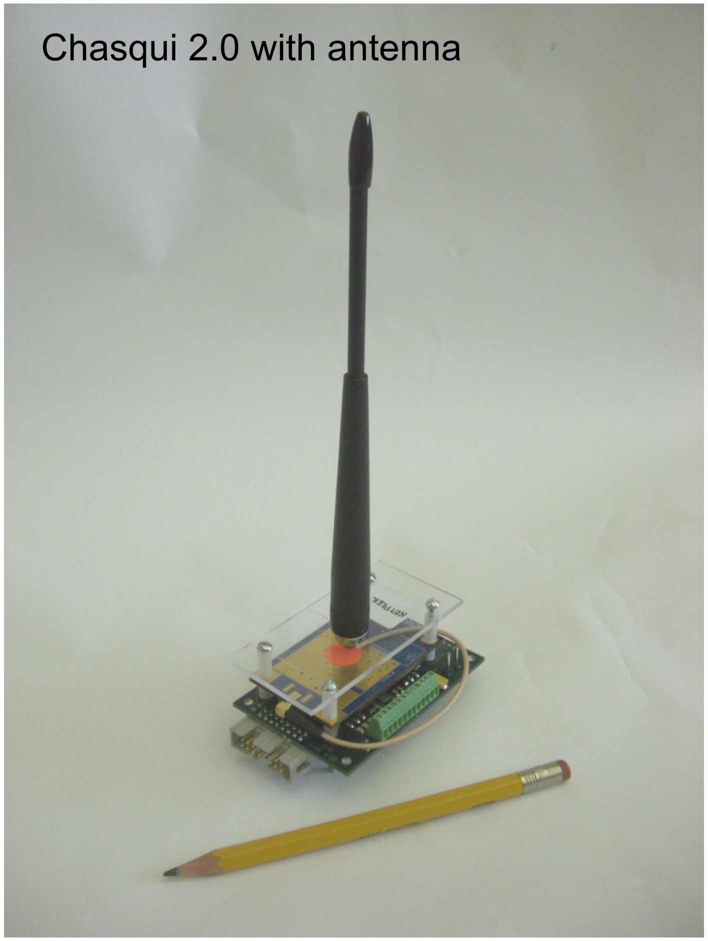


Chasqui Module

- Inode and Rnode are based on the Chasqui Module



- Based on UCB Mica2 Module
- MaxStream Radio (115 kbps/900 MHz)
- Rugged Sensor-Actuator I/F
- Precision Real-time Clock (2ppm drift)
- TinyOS Compatible



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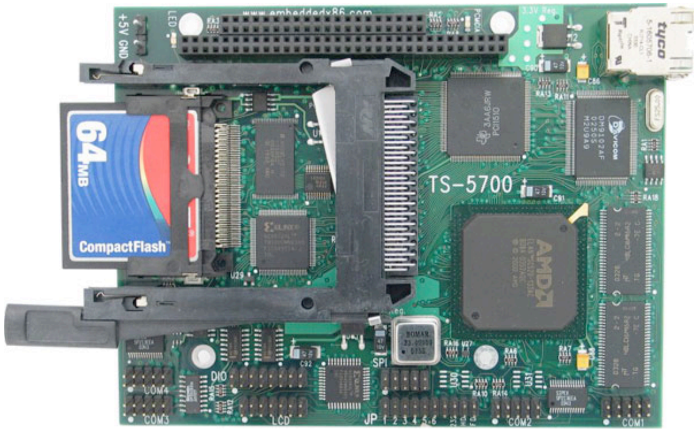
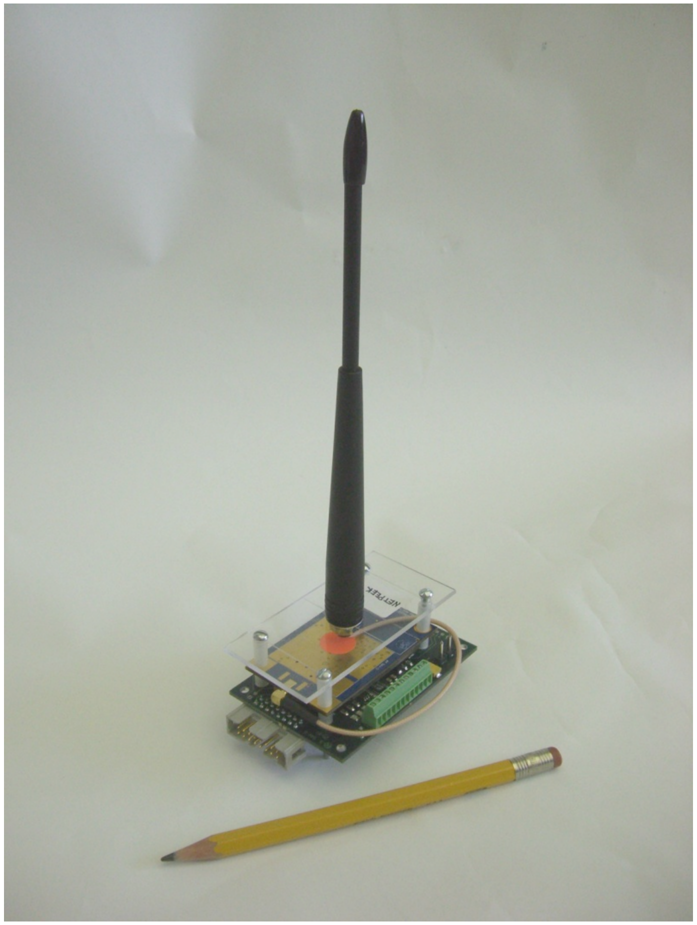
GNode

- Gateway Node consists of
  - Single Board Computer (SBC) xx86
    - compact Linux
  - Chasqui Node (radio - actuator interface)
  - Cellular connectivity to Internet.



Single Board Computer



Chasqui Module

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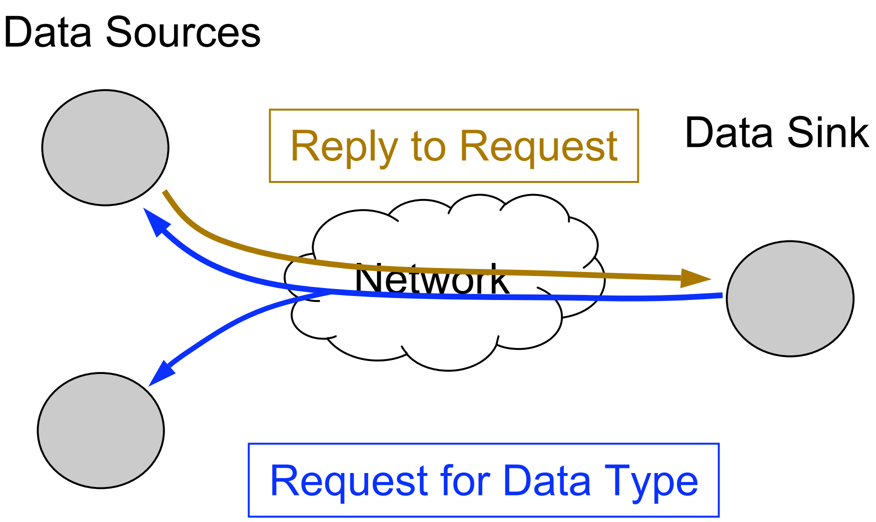
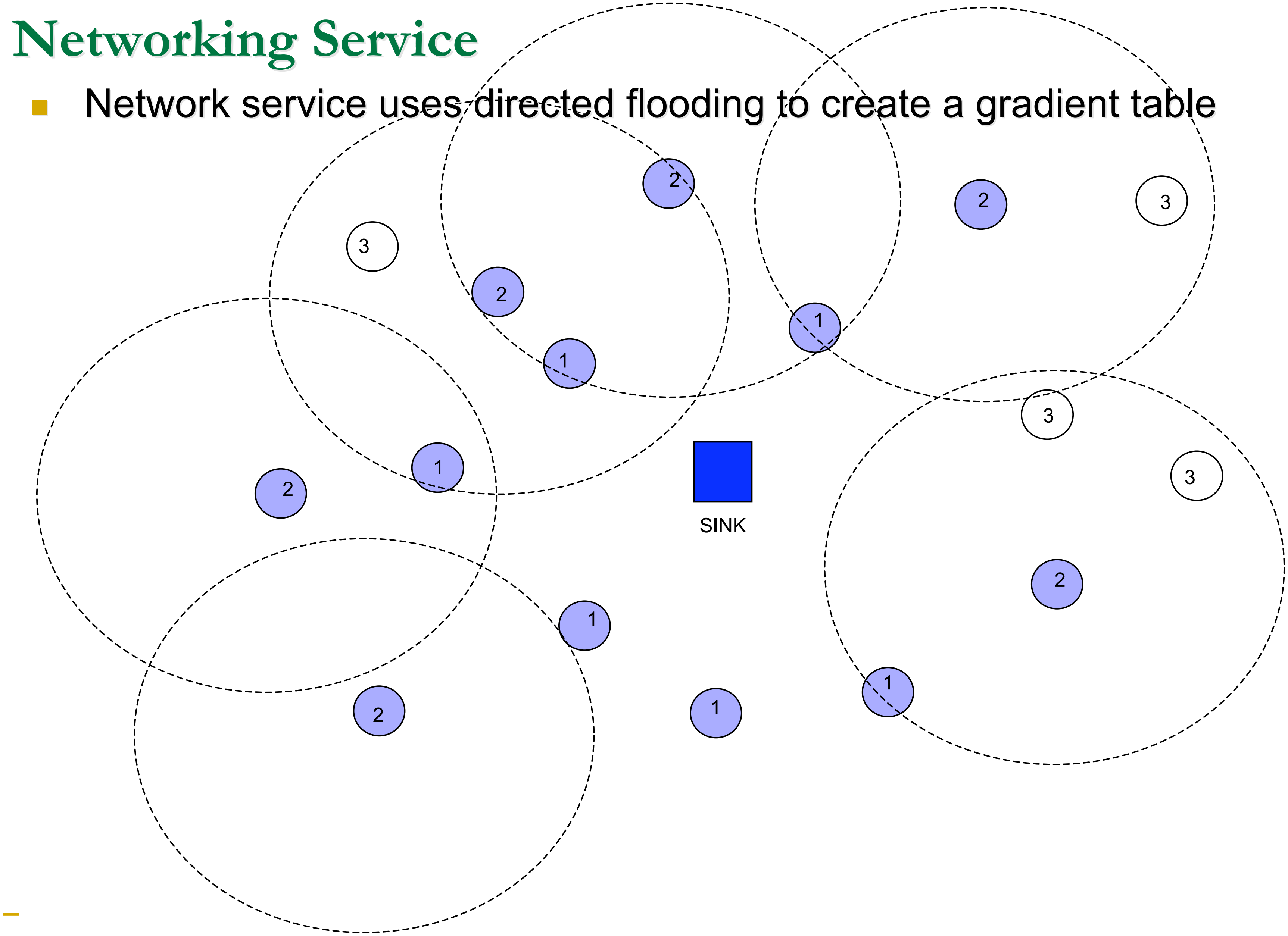
Middleware for Mesh Radio Networks

- Middleware maintains an network abstraction that can be easily used by application software
  - Time-slotted publish-subscribe network abstraction
- Middleware services
  - Clock Synchronization
  - Networking Service
  - Routing Service
  - Power Management Service
  - Reprogramming Service
- Programmed using TinyOS



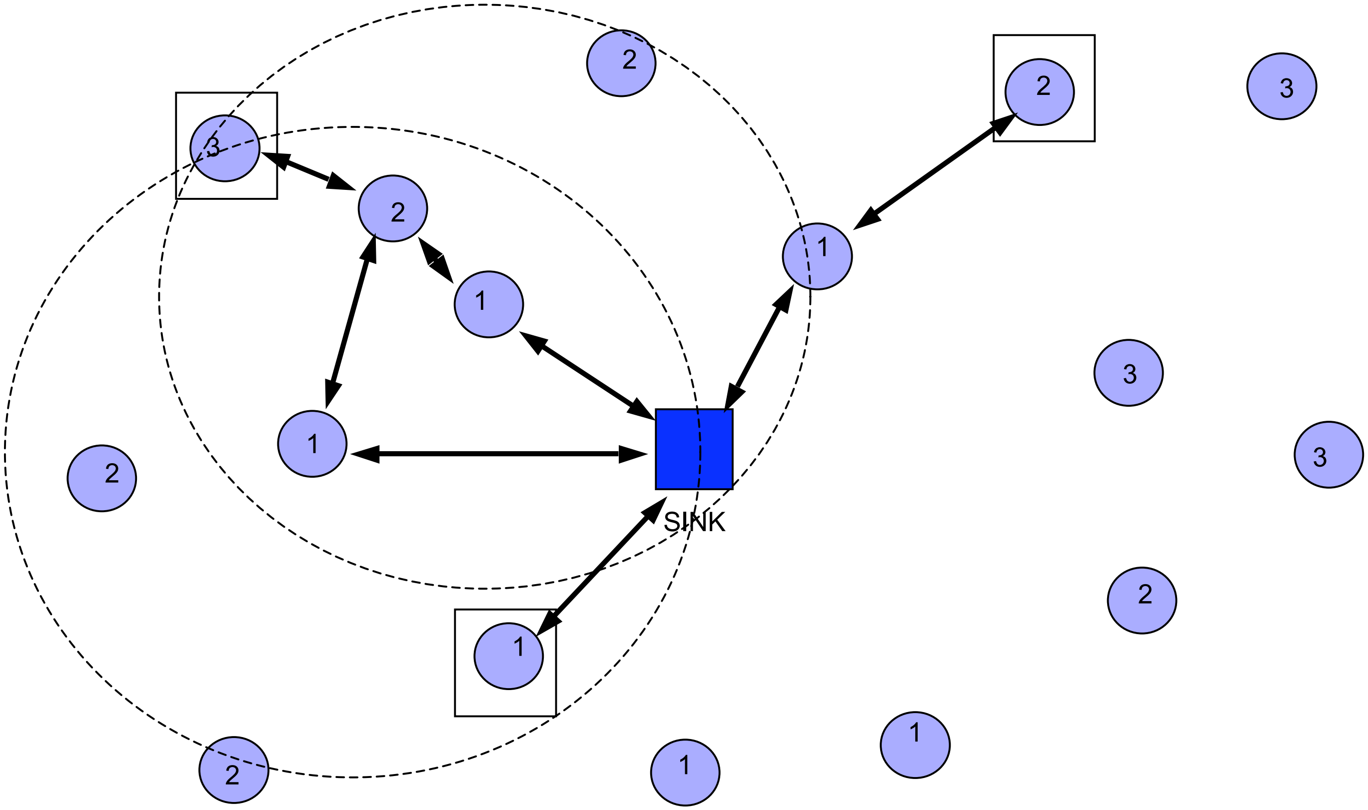
Networking Service

- Network service uses directed flooding to create a gradient table



Stateless Gradient-based Routing

- Broadcast to all upgradient nodes



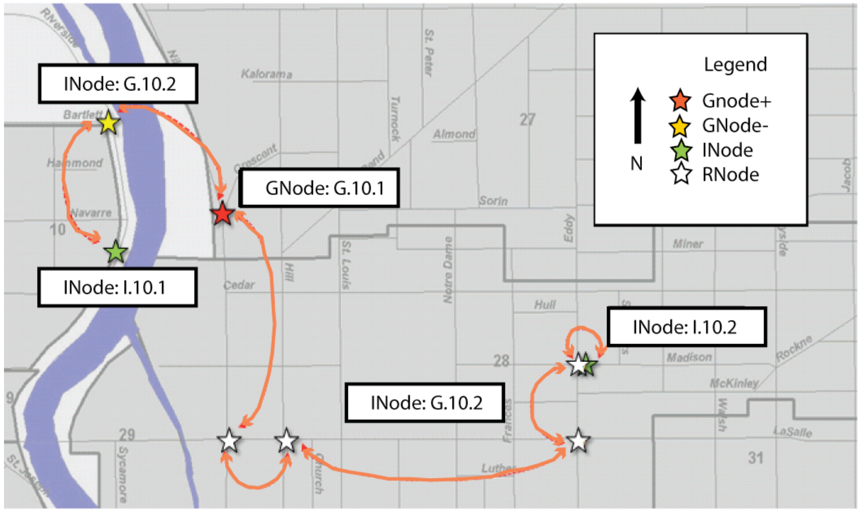
Congestion Issues

- CSOnet has two types of subnets
  - large diameter with few sensors
  - small diameter with many sensors
- Small diameter networks can have congestion problems unless the data received at the gateway is buffered

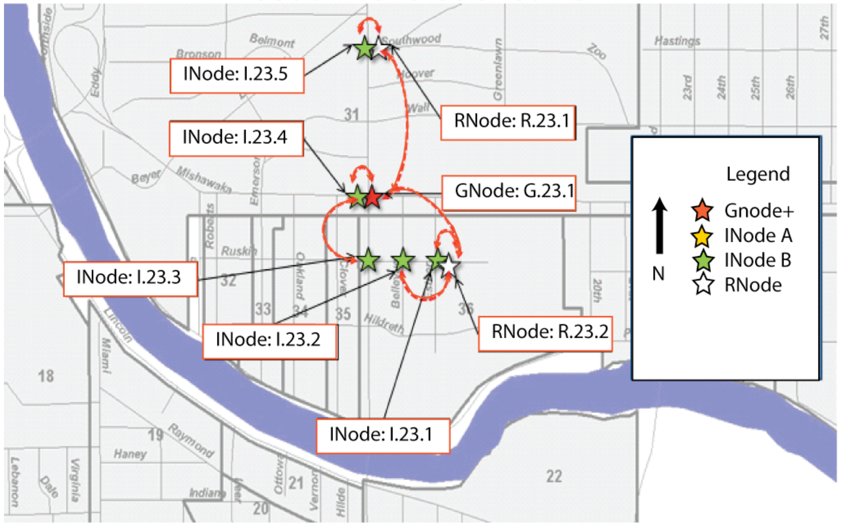
Subnet 23 Throughput Results

Node	Throughput no buffering	Throughput with buffering
G.23.1	100%	100%
I.23.1	46%	89%
I.23.2	56%	91%
I.23.3	77%	93%
I.23.4	91%	100%
I.23.5	75%	85%

South Bend Subnet 10

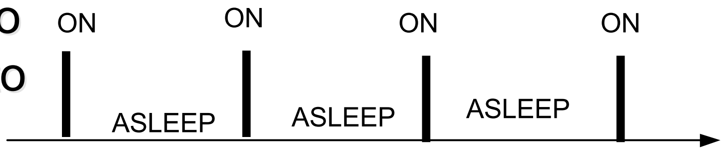


South Bend Subnet 23

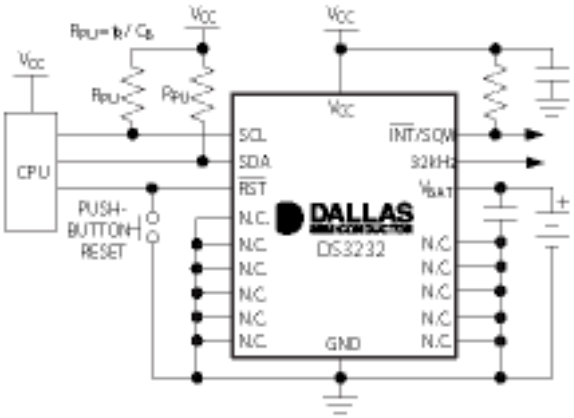


Power Management

- Management of system duty cycle
  - 2 percent duty cycle - 5 minute period
  - During sleep cycle, microprocessor put into deep sleep mode. External timer is used to wake the system back up

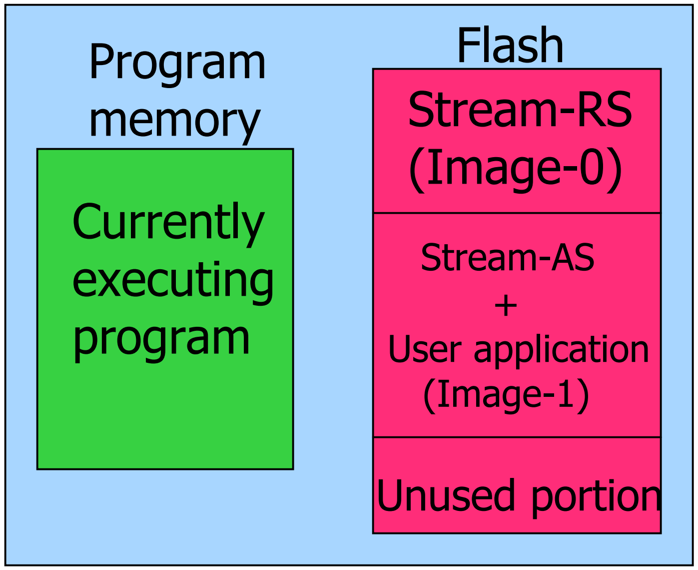


- Requires tight "clock" synchronization
  - Chasqui uses Dallas DS3231 RTC with 2 ppm drift.
  - Resync network clocks every six hours
- Chasqui service lifetime
  - 2 years between service
  - 3.6 volt - 19 amp-hour lithium source
  - Currently more cost effective to replace batteries than to use renewable power systems such as solar.



Wireless Reprogramming

- “Stream” Reprogramming protocol developed by Dr Saurabh Bagchi (Purdue)
- Less overhead than Deluge
- Stream segments the program image into Stream-RS (Stream Reprogramming Support) and Stream-AS (Stream Application Support)
- Stream-RS
  - Core reprogramming component
  - Preinstalled, before deployment, in all nodes
- Stream-AS
  - A small subset of reprogramming component that is attached to the user application
  - Instead of wirelessly transferring through the network user application plus the entire reprogramming component, Stream transfers Stream-AS plus the user application



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Complete Dynamic Wave Model

- Momentum Equation

$$0 = gA\frac{\partial H}{\partial x} + \frac{\partial Q}{\partial t} - \sigma\frac{Q}{A}\left(2\frac{\partial A}{\partial t} + \frac{Q}{A}\frac{\partial A}{\partial x}\right) + gAS_f$$

- Continuity Equation

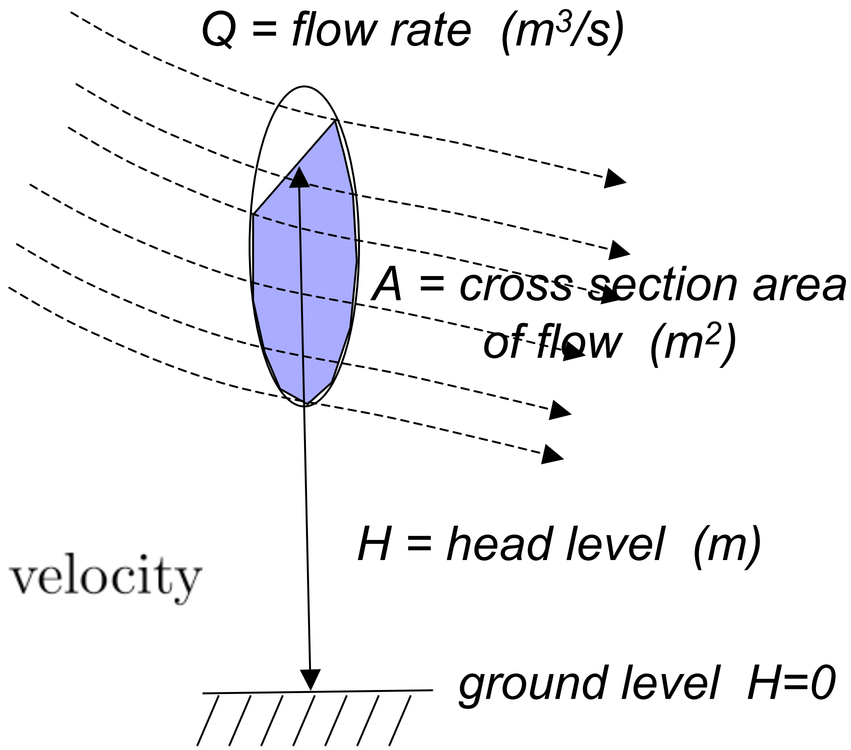
$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

- Manning's equation

$$S_f = \frac{(n/1.49)^2}{AR^{4/3}}Q|V|$$

$$\text{where } V = \frac{Q}{A} = \text{flow velocity}$$

$$R = \text{pipe radius}$$



Simplified Wave Model

- Flow Resistance Equation (momentum equation)

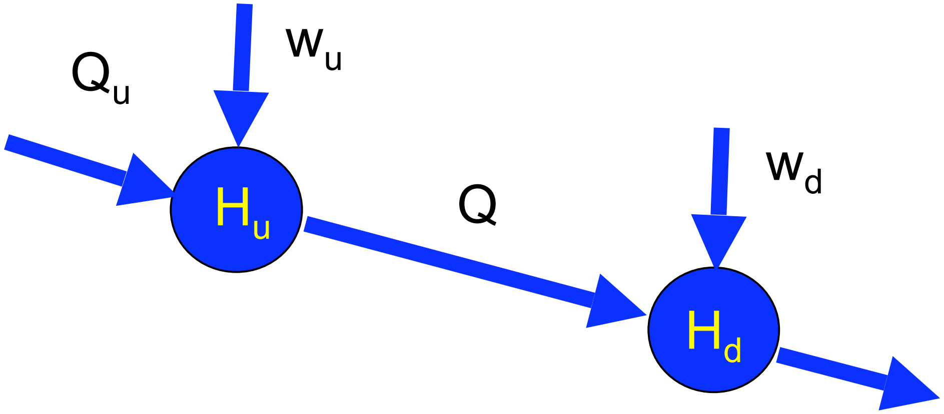
$$kQ^2 = H_u - H_d$$

$$\text{where } k = \frac{L(n/1.49)^2}{A^2 R^{4/3}} - \frac{\sigma}{gA^3}(A_d - A_u)R$$

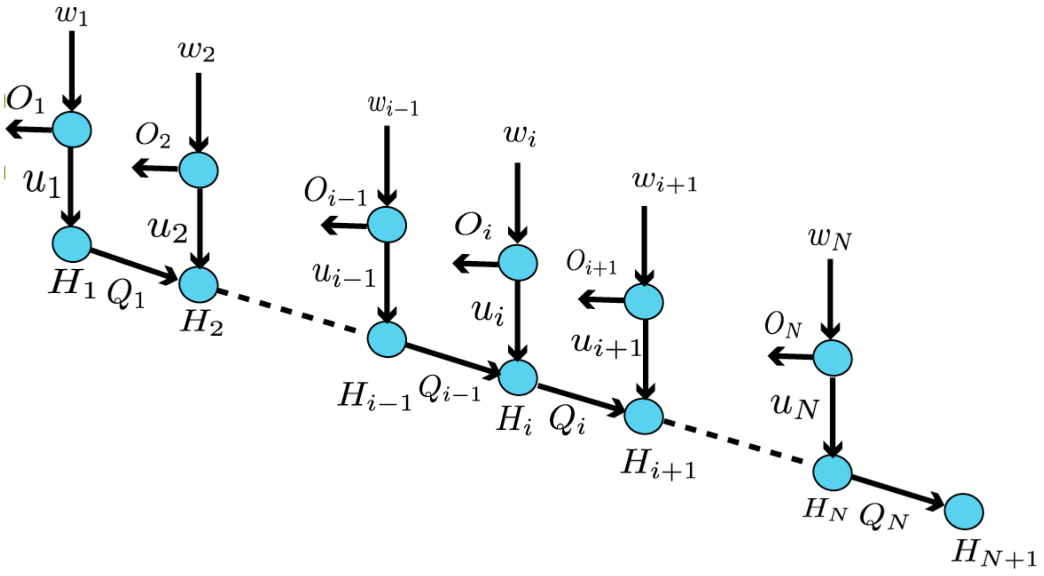
- Simplified Continuity Equation

$$a_i \frac{\partial H_i}{\partial t} = \sum Q_{\text{in}} - \sum Q_{\text{out}} + w_i$$

Where a_i = water surface area



Distributed Real-time Control



- Model Variables
  - w_i = storm inflow
  - O_i = overflow
  - u_i = diverted flow
  - H_i = water height (head)
  - Q_I = pipe flow rate

Optimal Control Problem

$$
\begin{array}{ll}
\max_{u_i} & \sum_{i=1}^{N} \int_0^T C_i u_i(t)\,dt \\
\text{subject to} & \dot{H}_i = u_i + Q_{i-1} - Q_i \\
 & 0 = H_i - H_{i+1} k_i Q_i^2 \\
 & 0 \leq u_i \leq w_i \\
 & \overline{H}_i \geq H_i \\
 & \overline{Q} \geq \sum_j u_j
\end{array}
$$

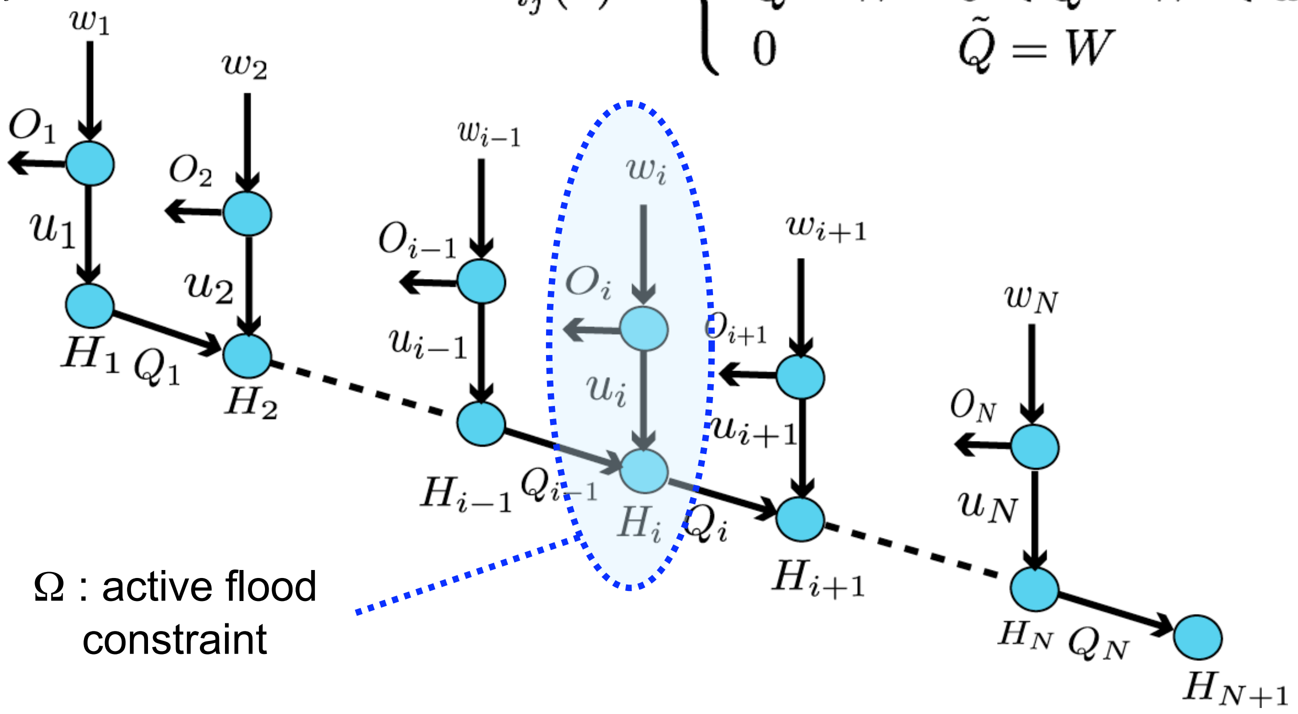
- Maximize “diverted flow”
- Subject to:
  - Conservation of Mass
  - Conservation of Momentum
  - Admissible control
  - No flooding
  - WWTP capacity limit

Supervisory Control Strategy

Control Selection Algorithm

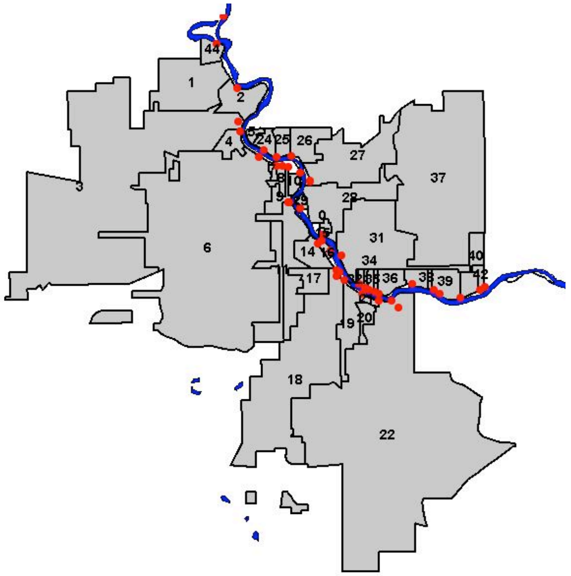
- Assume costs are ordered as $C_{i_{j+1}} < C_{i_j}$
- If node i_j is flooded $u_{i_j} = Q_{i_j} - Q_{i_j-1}$
- If node i_j is not flooded then

$$u_{i_j}(\tau) = \begin{cases} w_{i_j} & \tilde{Q} - W \geq w_{i_j} \\ \tilde{Q} - W & 0 < \tilde{Q} - W < w_{i_j} \\ 0 & \tilde{Q} = W \end{cases}$$



Ω : active flood constraint

Supervisory Control Results



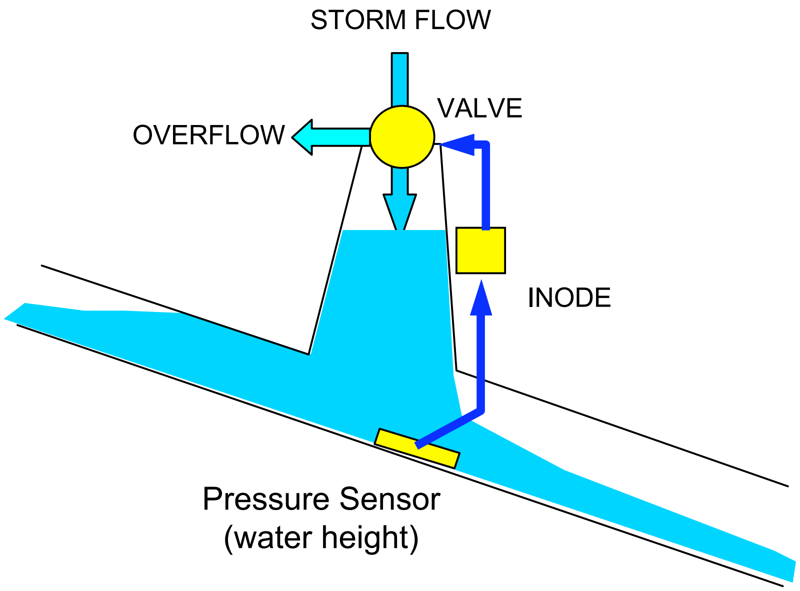
- "Optimal" Supervisory Control Strategy
  - Open valves until "flooding" constraint is active
  - Then reduce diverted inflow to prevent violation of flooding constraint

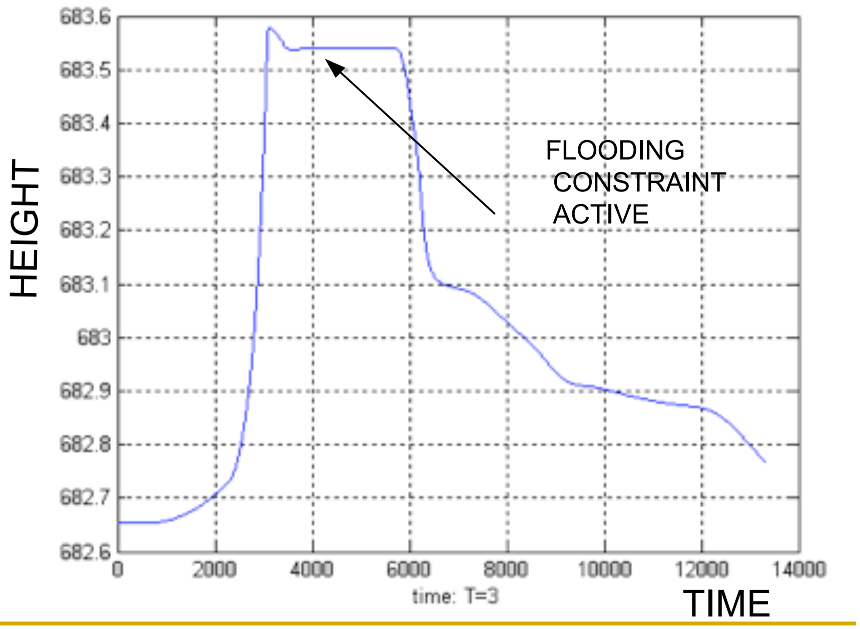
Storm	Existing System Overflow (ft3 x 10^6)	Controlled System Overflow (ft3 x 10^6)	Overflow Volume Decrease (ft3 x 10^6)	Overflow Decrease (%)
Storm 1	1.50	1.10	0.40	**27%**
Storm 2	3.46	2.68	0.78	**23%**
Storm 3	13.6	9.45	4.15	**31%**

Table A. Scenario A—Moving Uniform Rainfall

Pressure-based Feedback

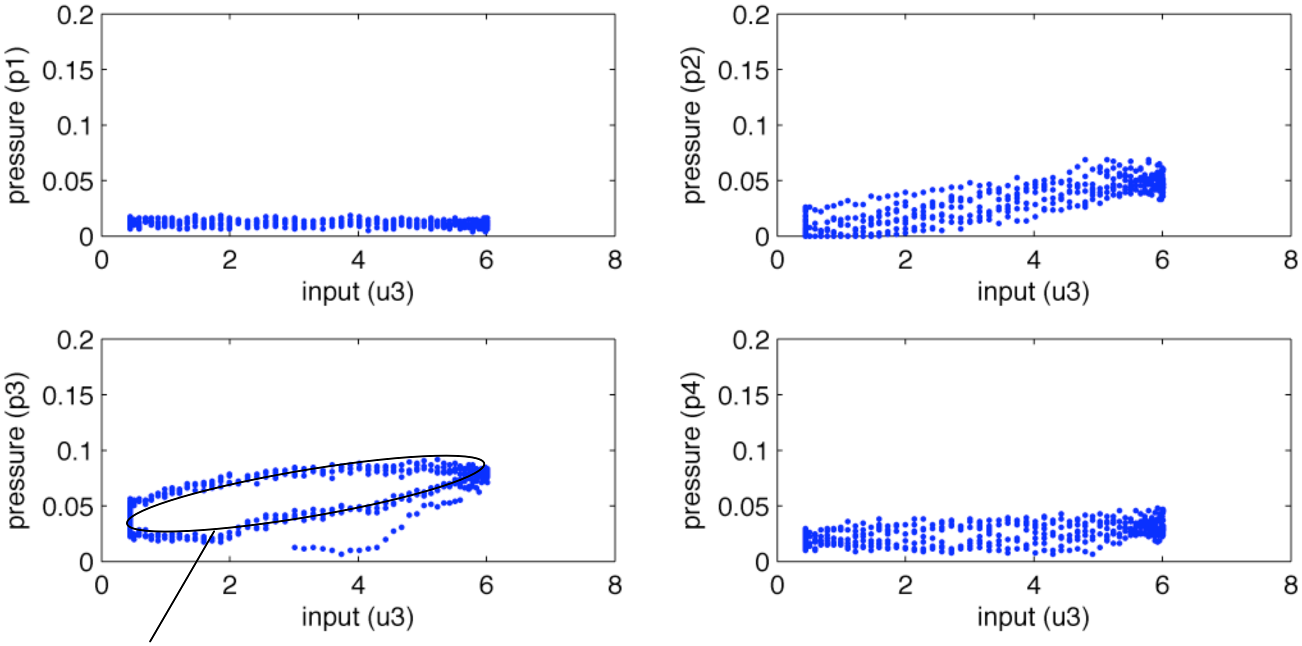
- Actual system only has “pressure” (head) measurements
- Decentralized Pressure-based Controller used to enforce flooding constraint.
- Model of Head Level Dynamics
- Limitation: the diverted flow must be positive





Input-Output Behavior of Node

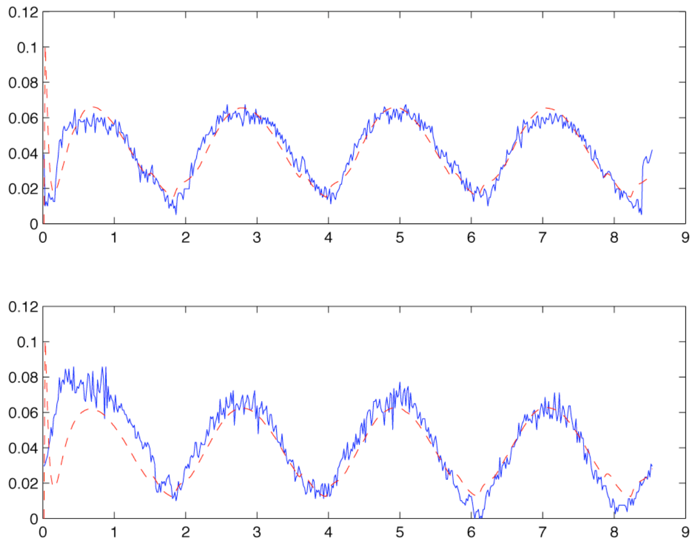
- Testbed Experiments showed that “head” level dynamics had at least 3 state variables
  - Head level, downstream flow rate, water stored in upstream link



Ellipsoidal shape of response implies additional energy storage

Head Model Identification

- Drive interceptor line with a “persistently exciting” input signal
- Gather input/output data for a “design” set and a “test” set.
- Use “design” data set and Matlab’s SysID toolbox to identify a state-based model
- Test that model against the “test” data set.



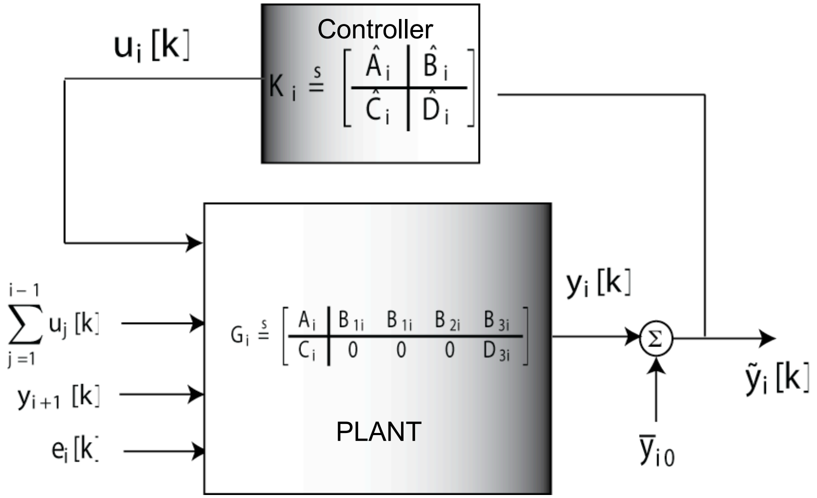
SB Interceptor Line Node 8 Model

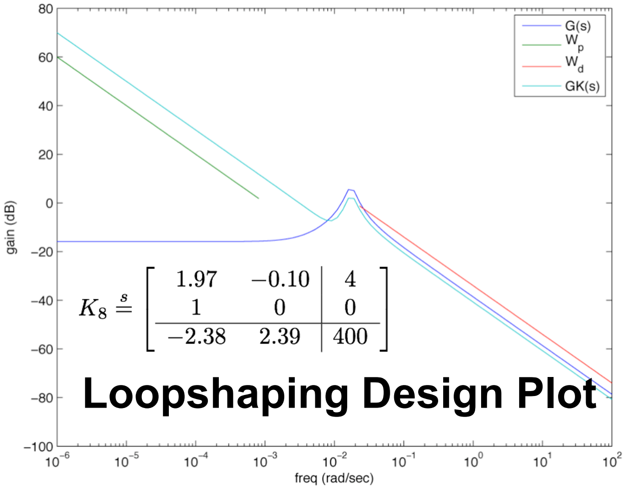
$$G_8 \overset{s}{=} \left[\begin{array}{cc|ccc} 0.9899 & 0.002 & 0.012 & 0.114 & 0.002 \\ -0.048 & 1.004 & 0.046 & 0.453 & 0.385 \\ \hline 0.063 & -0.0001 & 0 & 0 & 0 \end{array}\right]$$

Pressure-based Controller Design

- Disturbance rejection problem
- Loopshaping Design
  - Often yields PID-type control
- State-based controller

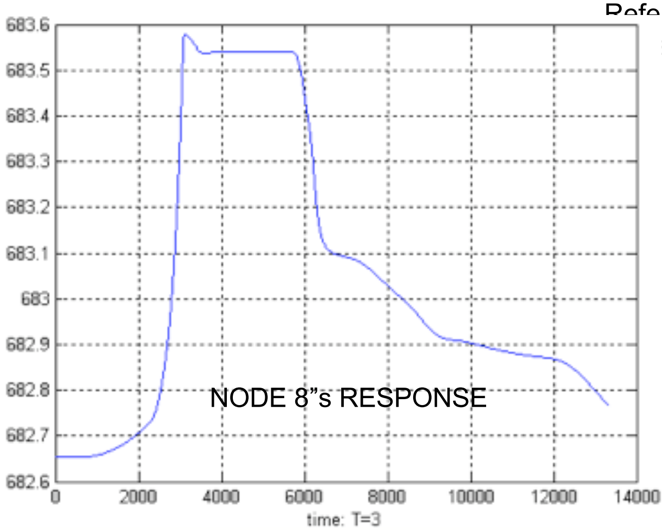
$$K_i \overset{s}{=} \left[\begin{array}{c|c} \hat{A}_i & \hat{B}_i \\ \hline \hat{C}_i & \hat{D}_i \end{array}\right]$$



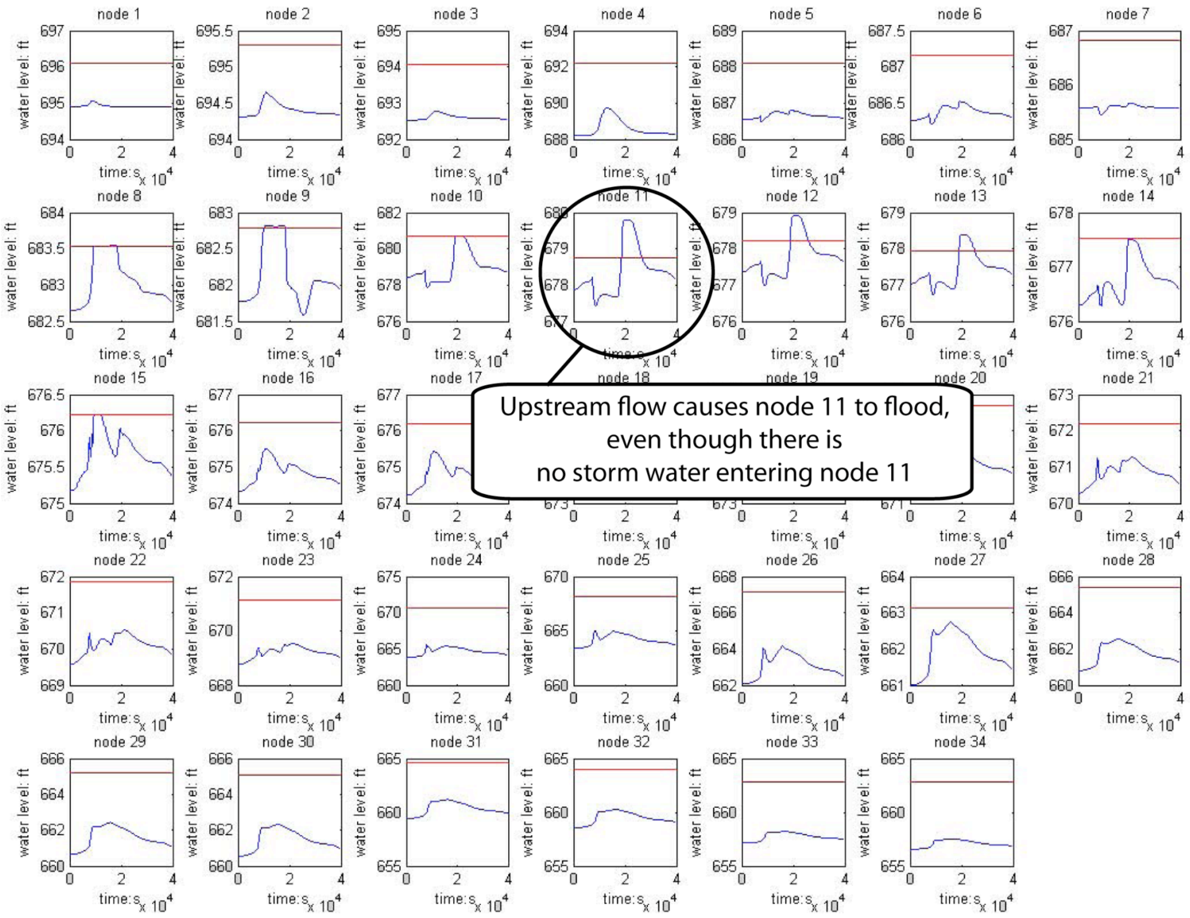


$$K_8 \overset{s}{=} \left[\begin{array}{cc|c} 1.97 & -0.10 & 4 \\ 1 & 0 & 0 \\ \hline -2.38 & 2.39 & 400 \end{array}\right]$$

Loopshaping Design Plot



Flooding under Supervisory Control

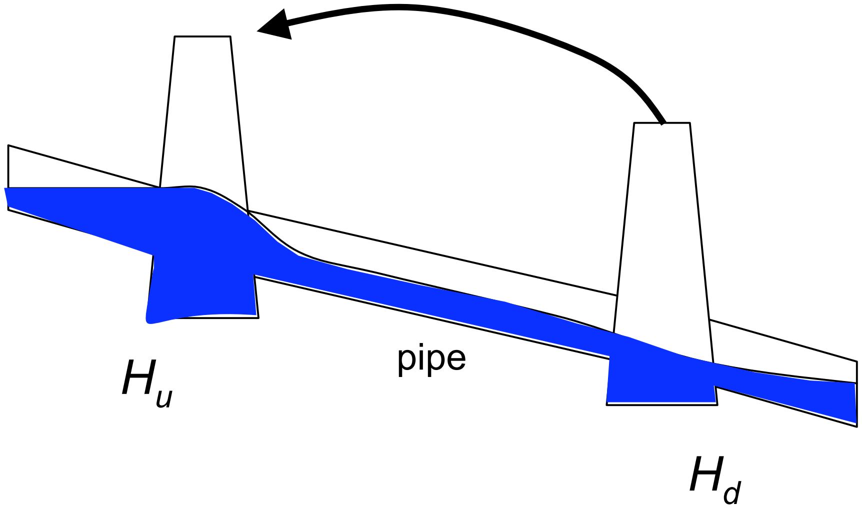


Upstream flow causes node 11 to flood, even though there is no storm water entering node 11

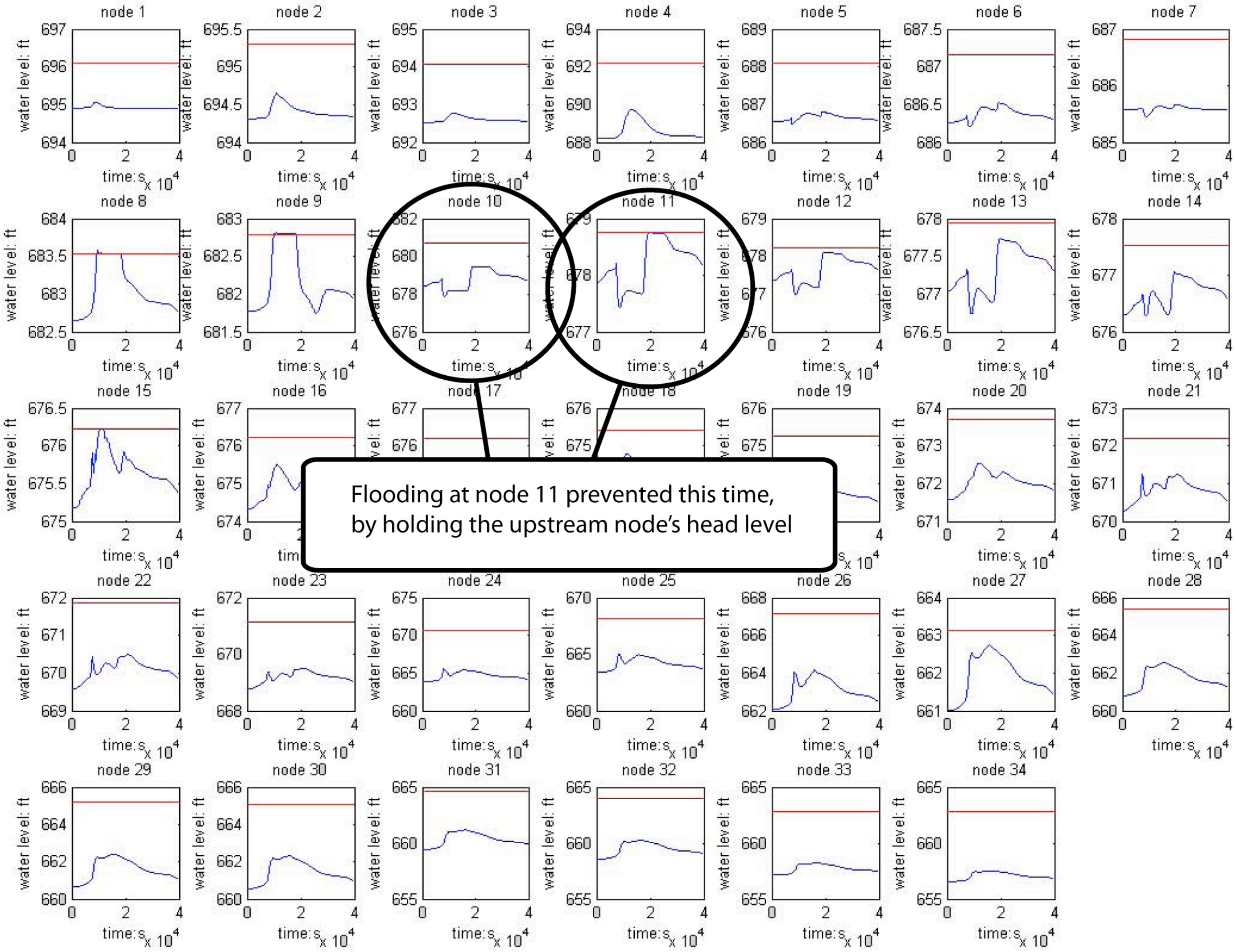
- Supervisory strategy is only "necessary" for optimality
- This strategy can lead to localized flooding in a flooded node loses "control authority"

Flood Prevention

- Flooding may occur if node loses “control authority”
- Flood Prevention Protocol
  - If node *i* is about to flood and has no remaining control authority THEN request upstream node to “hold” at its current head level.



Simulation Results - Head Levels



Flooding at node 11 prevented this time, by holding the upstream node's head level

Simulation Results - Total Overflows (ft^3)

	Passive Threshold	Supervisory Control	Decentralized Control	Percent Change
STORM C	405980	123750	152490	60%
STORM D	1206900	770430	883560	26%
STORM E	2682800	2050200	2141200	20%
STORM G	9280600	8068800	8413400	9%

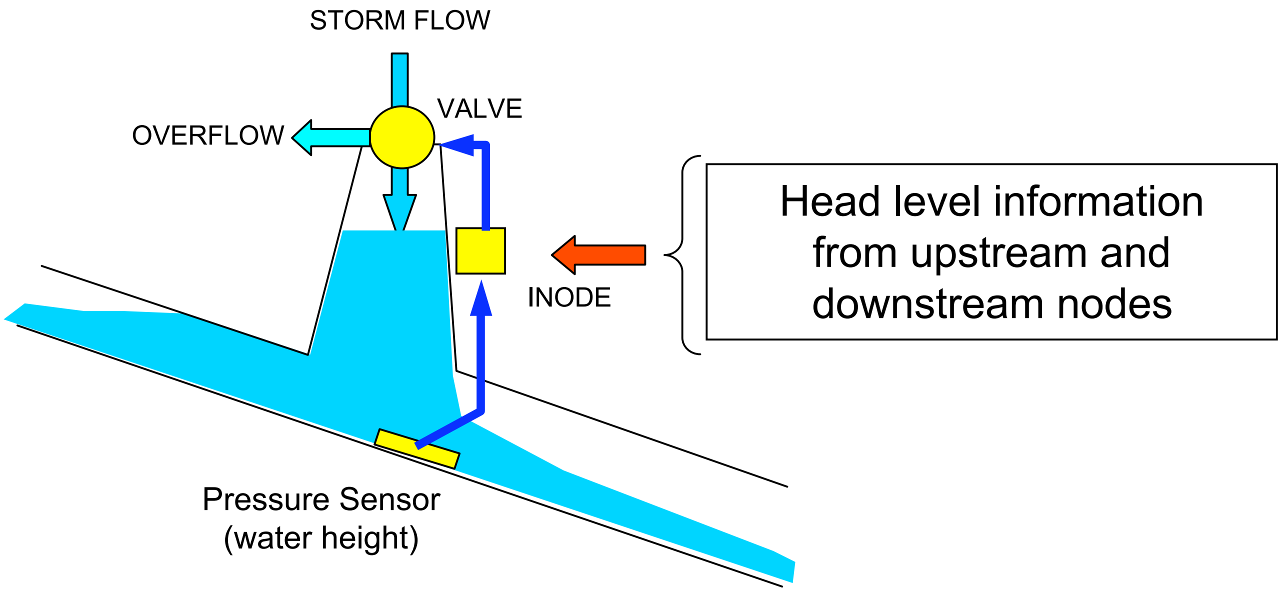
- 10-60 percent reduction in total overflow

Outline

- Combined Sewer Overflow Problem
  - In-line Storage using CSOnet
- CSOnet System Hardware
- CSOnet Middleware
- Real-time Control Strategy
- Future Directions

Moving toward Distributed Local Control

- CSOnet's controller
  - High-level supervisor to enforce optimality
  - Low-level decentralized controllers to enforce safety (no flooding)
  - We could do better with "distributed" local controls

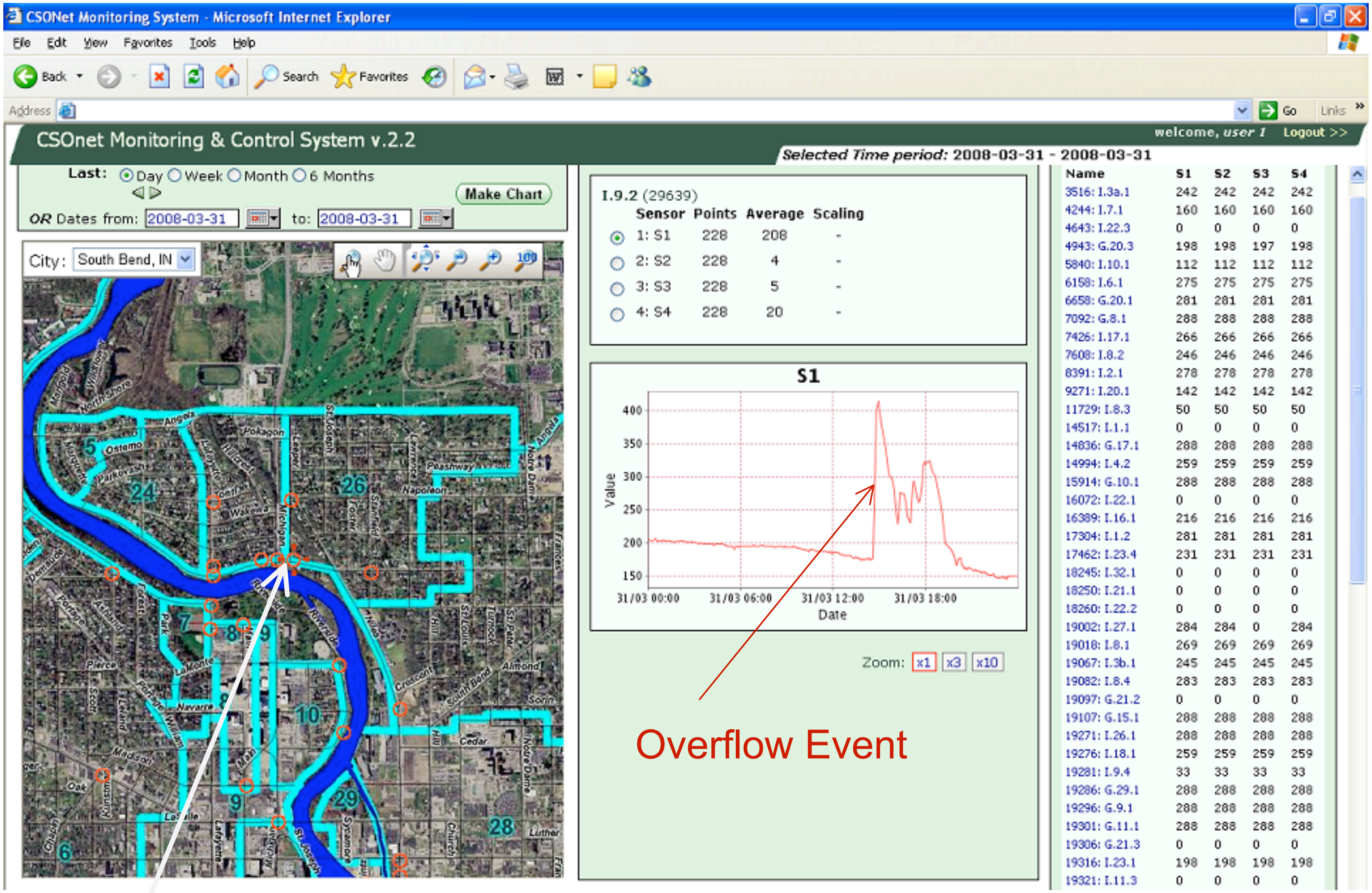


Head level information from upstream and downstream nodes

Need for Real-time Middleware

- Distributed control requires hard/firm real-time message delivery
- It may be possible to develop real-time middleware services in isolation, but real-time guarantees are quickly lost as additional services are added.
- The lack of composable middleware services capable of providing end-to-end hard/firm real-time guarantees limits is an obstacle to the use of low-level distributed control.
- Future work is moving in this direction
- Additional CSOnet Developments
  - Deployment of Actuation in South Bend System (summer 2009)
  - Two additional Indiana cities are installing CSOnet
- Monitoring and Control of Civil Infrastructure
  - Bridge monitoring
  - Leak detection in water distribution networks

CSOnet Website



Selected Time period: 2008-03-31 - 2008-03-31

Last: ● Day ○ Week ○ Month ○ 6 Months

OR Dates from: 2008-03-31 to: 2008-03-31

City: South Bend, IN

I.9.2 (29639)

	Sensor	Points	Average	Scaling
●	1: S1	228	208	-
○	2: S2	228	4	-
○	3: S3	228	5	-
○	4: S4	228	20	-

Name	S1	S2	S3	S4
3516: I.3a.1	242	242	242	242
4244: I.7.1	160	160	160	160
4643: I.22.3	0	0	0	0
4943: G.20.3	198	198	197	198
5840: I.10.1	112	112	112	112
6158: I.6.1	275	275	275	275
6658: G.20.1	281	281	281	281
7092: G.8.1	288	288	288	288
7426: I.17.1	266	266	266	266
7608: I.8.2	246	246	246	246
8391: I.2.1	278	278	278	278
9271: I.20.1	142	142	142	142
11729: I.8.3	50	50	50	50
14517: I.1.1	0	0	0	0
14836: G.17.1	288	288	288	288
14994: I.4.2	259	259	259	259
15914: G.10.1	288	288	288	288
16072: I.22.1	0	0	0	0
16389: I.16.1	216	216	216	216
17304: I.1.2	281	281	281	281
17462: I.23.4	231	231	231	231
18245: I.32.1	0	0	0	0
18250: I.21.1	0	0	0	0
18260: I.22.2	0	0	0	0
19002: I.27.1	284	284	0	284
19018: I.8.1	269	269	269	269
19067: I.3b.1	245	245	245	245
19082: I.8.4	283	283	283	283
19097: G.21.2	0	0	0	0
19107: G.15.1	288	288	288	288
19271: I.26.1	288	288	288	288
19276: I.18.1	259	259	259	259
19281: I.9.4	33	33	33	33
19286: G.29.1	288	288	288	288
19296: G.9.1	288	288	288	288
19301: G.11.1	288	288	288	288
19306: G.21.3	0	0	0	0
19316: I.23.1	198	198	198	198
19321: I.11.3	0	0	0	0

Overflow Event

Sensor Location

Slide provided by courtesy of EmNet LLC