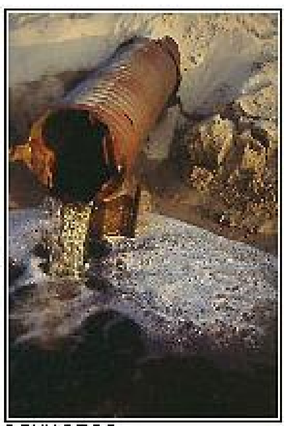
# Distributed Feedback Control of Combined Sewer Overflow Events using Embedded Sensor-Actuator Networks



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**CenSCIR Symposium - Carnegie-Mellon University - May 16, 2007.**

# Outline

- CSO problem
  - Distributed in-line storage
- Distributed Feedback Control System
  - Communication limitations
  - Interceptor Sewer application
- CSOnet System
  - System hardware
  - Current and future deployments



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# Status of National Wastewater Infrastructure

- "Both drinking water and wastewater declined from a D to a D- in the past four years. The nation's drinking water system faces a staggering public investment need to replace aging facilities, comply with safe drinking water regulations and meet future needs. Federal funding in 2005 remains at $850 million, less than 10 percent of the total national requirement. Aging wastewater systems discharge billions of gallons of untreated sewage into U.S. surface waters each year. The EPA estimates that the **nation must invest $390 billion over the next 20 years** to replace existing wastewater systems and build new ones to meet increasing demand."

**ASCE, 2005. US Infrastructure Report Card,**
**http://www.asce.org/reportcard/2005/index.cfm**

- Local Investment Levels
  - $250 Million over 20 years in South Bend Indiana (population: 100,000)
  - $2 BILLION over 20 years in Indianapolis Indiana (population: 800,000)



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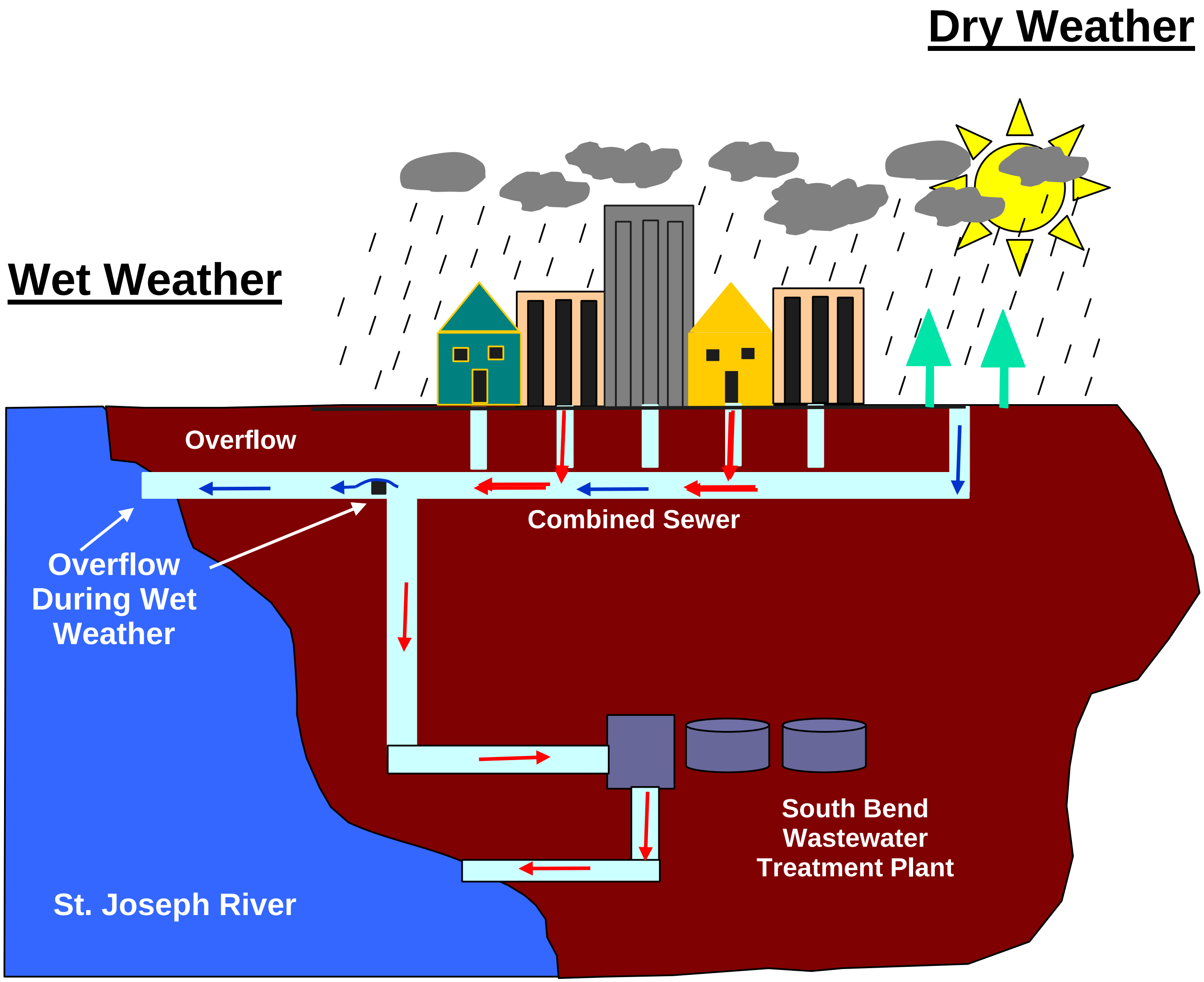
# Combined Sewer Overflow Events



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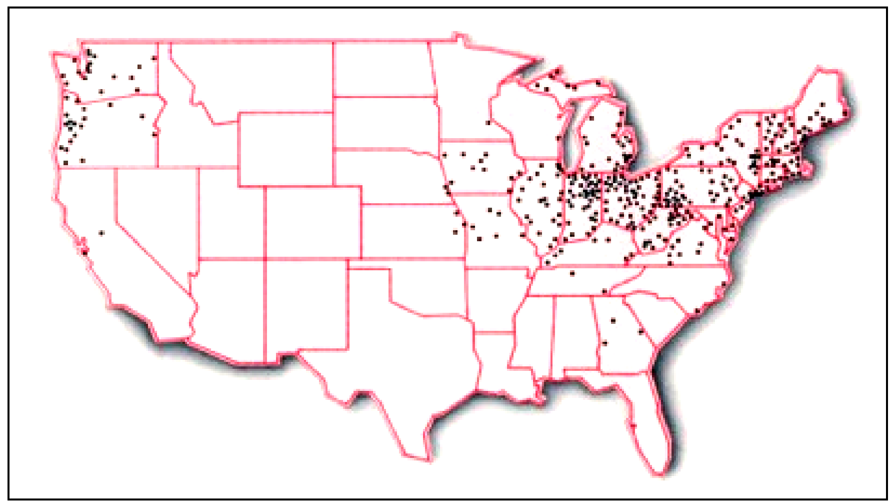
# Scope of the Problem

- **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 CSO Control Act of April 1994**
  - Short- and Long-term solutions
  - Large fines per CSO event per day
  - Hammond, IN pays $36 million
- Scope of the Problem
  - Over 772 cities nationwide
  - 105 cities in Indiana





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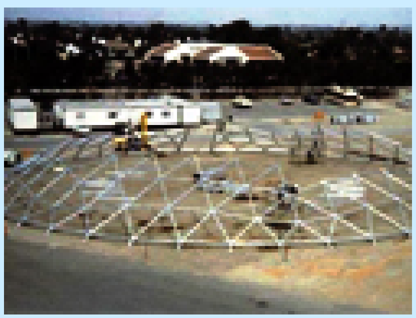
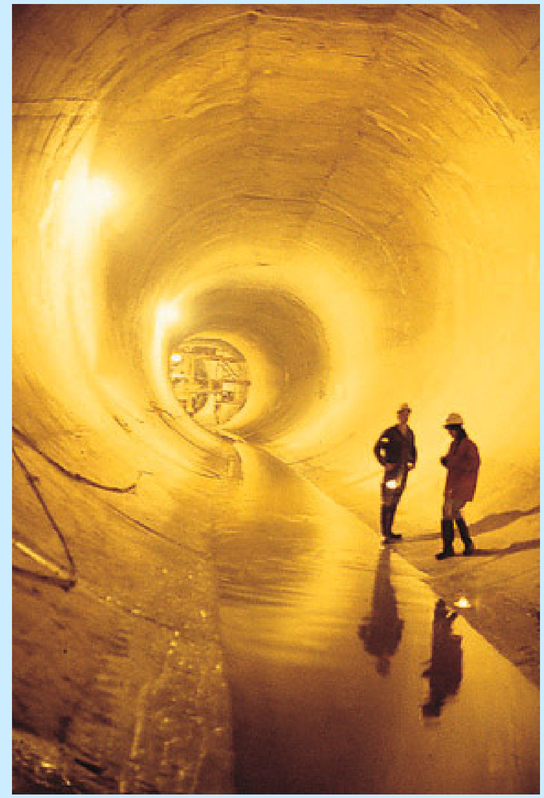
# Solution Strategies

Sewer Separation


Expansion of WWTP



Off-line Storage Tunnels
Chicago's TARP project



These strategies all require significant investment in new infrastructure



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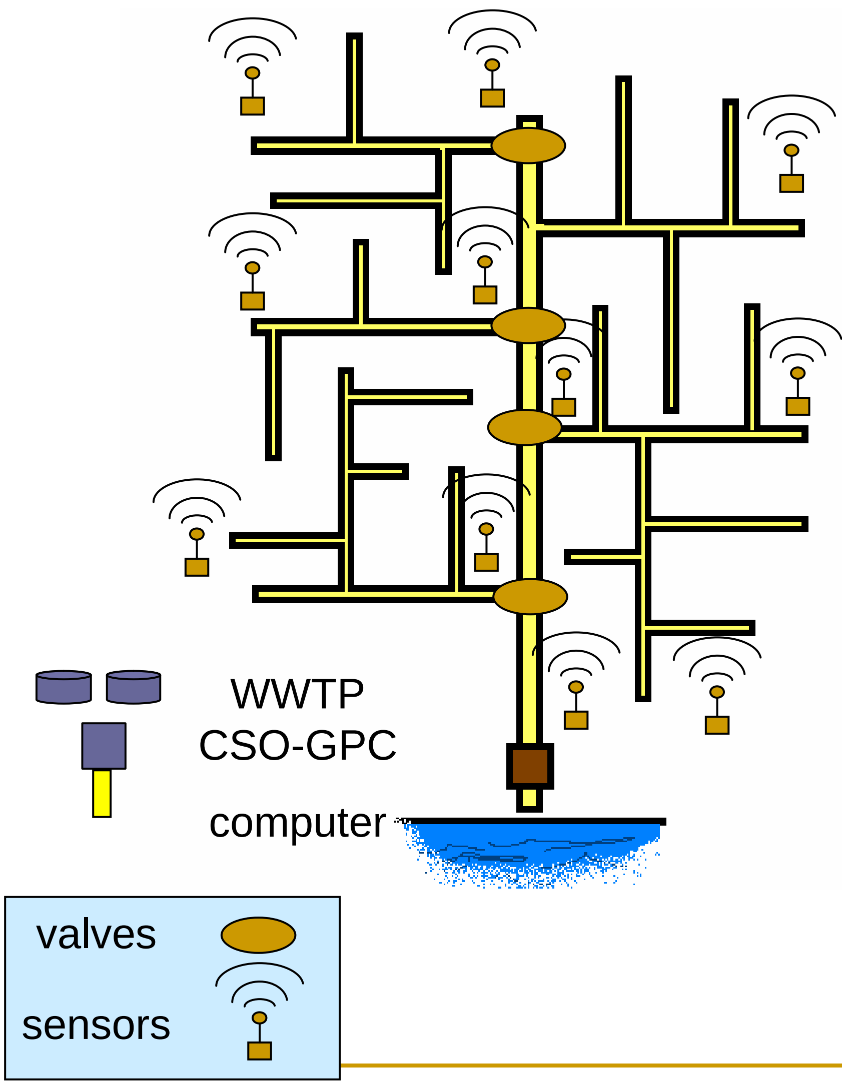
# Centralized In-line Storage




- Take advantage of under utilized capacity of existing sewer infrastructure.
- Hold storm water in large sewer lines and basins until storm has passed, then release water for treatment at WWTP.
- Requires real-time monitoring and control in which **centralized computer** at WWTP gathers information from all sensors and then outputs data back out to all actuators.
- Requires significant investment in SCADA communication infrastructure
- Requires highly detailed SWMM model of city sewer system
- Scales poorly with city size (BPR-CSO)



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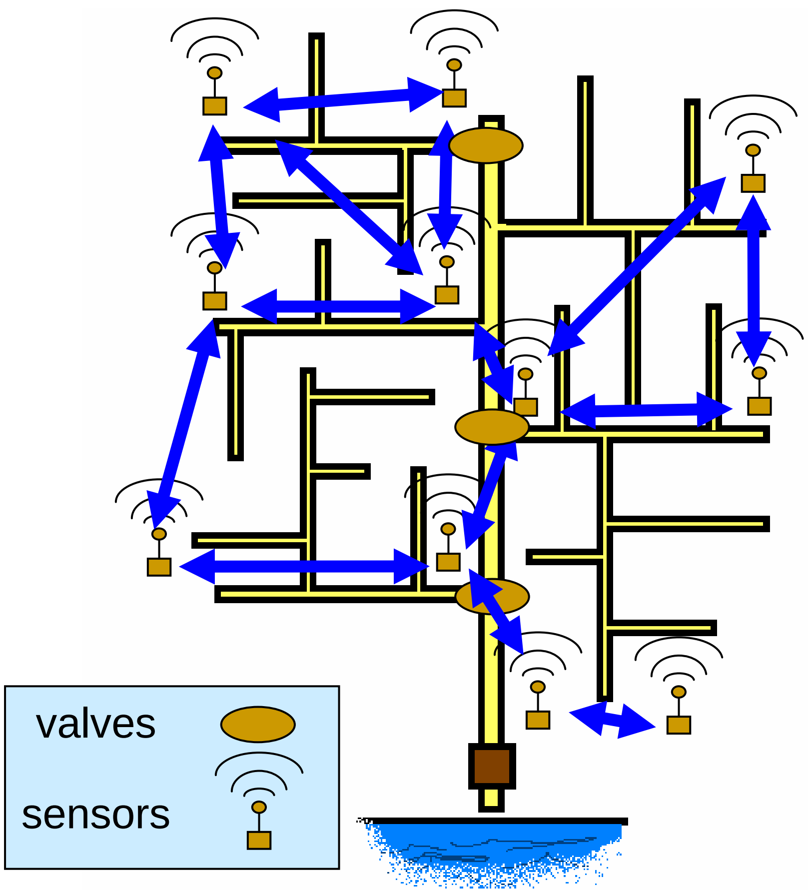
# Distributed In-line Storage




- **Multi-hop Mesh Networks:** Rather than using a SCADA network connecting to a central location, we use a multi-hop wireless network interconnecting sensors and valves
- **Distributed Control:** The control decisions are made locally at each valve in the system. These decisions mainly require nearest neighbor information.
- **Scalable Cost:** Recent prototype deployments (EmNet LLC) in South Bend suggest that deployment costs scale linearly with city size.
- **Fault Tolerance:** Takes greater advantage of feedback so our control decisions can handle greater model uncertainty and faults.



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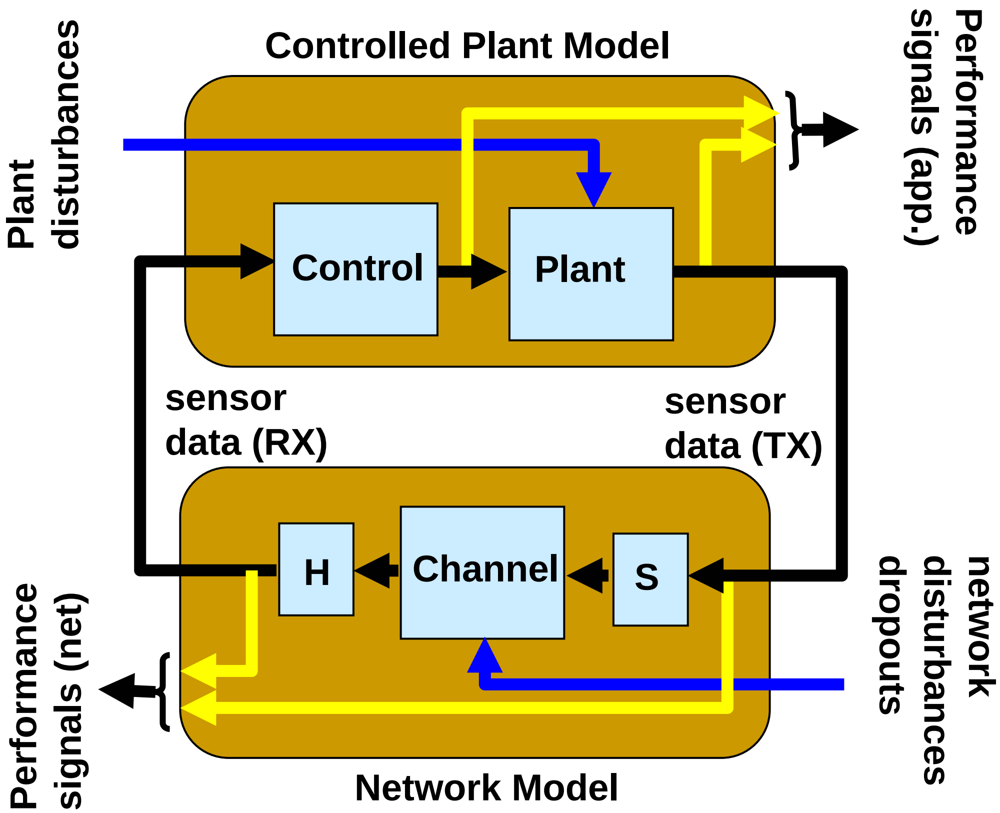
# Feedback Control over Sensor Actuator Networks




- **Controlled Plant Model**:
  - set of "controlled" differential equations.
  - plant disturbances: storm water
- **Network Model:**
  - Transmitted (TX) sensor data is sampled (S), sent over channel, and reconstructed using a zero order hold (H).
  - network disturbances: dropped packets
- **Performance:**
  - **Application:** Minimize an integrated measure of the app's performance signal (state + control)
  - **Network:** Minimize an integrated measure of Received (RX) sensor data's distortion.



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# Capacity Limits in Multi-hop Networks

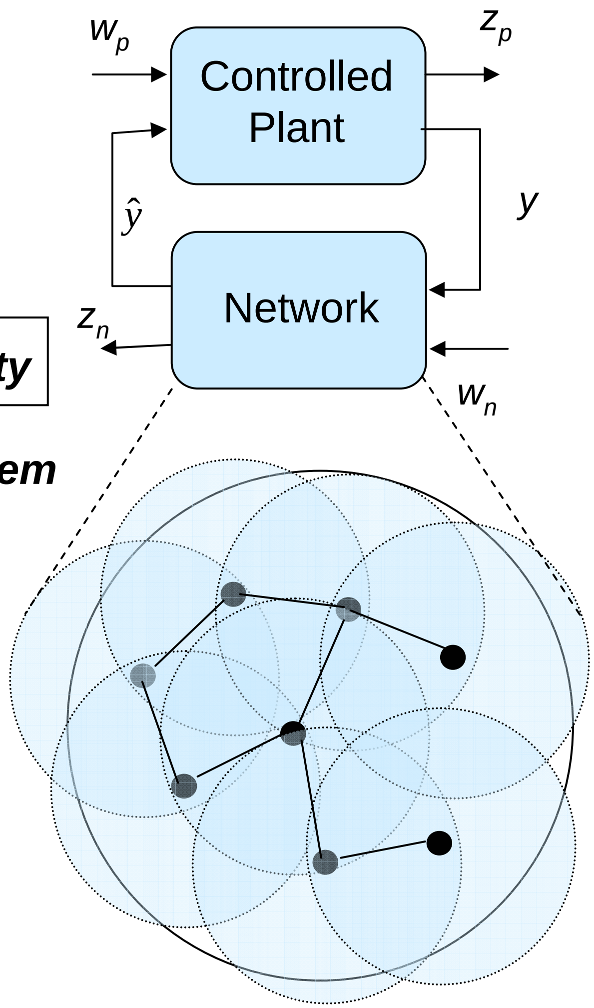
- **Disk Model**
  Two nodes can reliably exchange packets if and only if they lie within a disk of radius $\Delta$ of each other

- **Transport Capacity** ***$C=O(W\sqrt{n})$***
  *$W$ = TX rate of each node (bit/sec)*
  *$n$ = number of network nodes*

***Single node throughput vanishes as n goes to infinity***

- ***Impact of Limited Network Capacity on Control System Performance***
  - *Stability under Finite Rate Quantized Feedback*
  - *Stability / Performance under Randomly dropped feedback.*
  - *Relation between network connectivity and packet delay*
  - *Control oriented "Distortion-Rate" functions*

- ***Avoid Throughput Limits by:***
  - *Send "Information" rather than raw "Data" (coding)*
  - *Send packets over shorter distance (networked apps).*



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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**

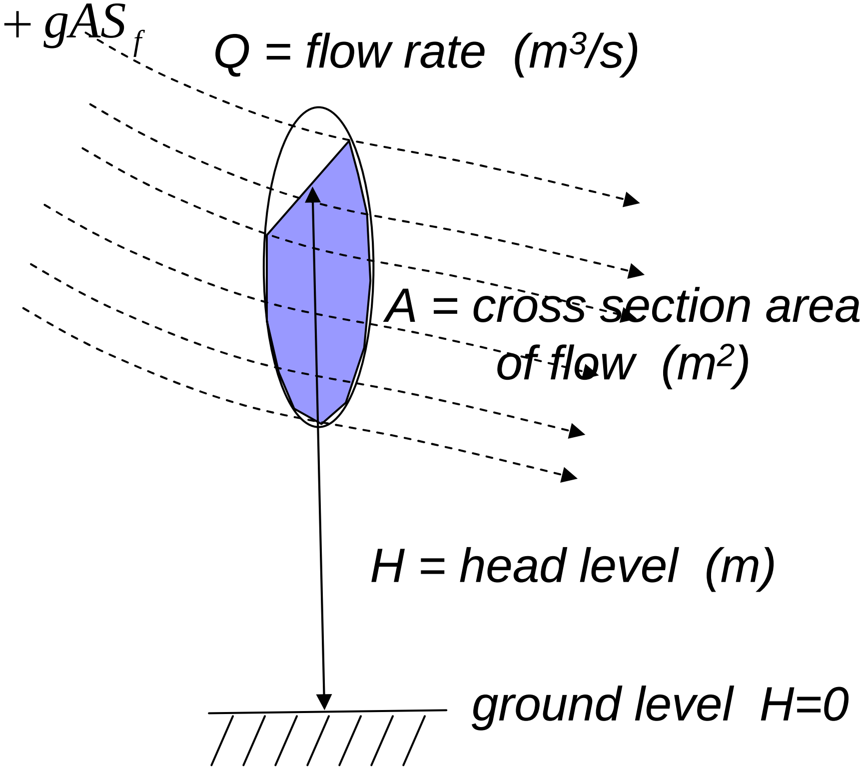
$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

- **Manning's equation**

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

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

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



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# Simplified Wave Model

- **Slowly varying flow rate**

$$\frac{\partial H}{\partial x} = \frac{H_d - H_u}{L} \quad , \quad \frac{\partial A}{\partial x} = \frac{A_d - A_u}{L}$$

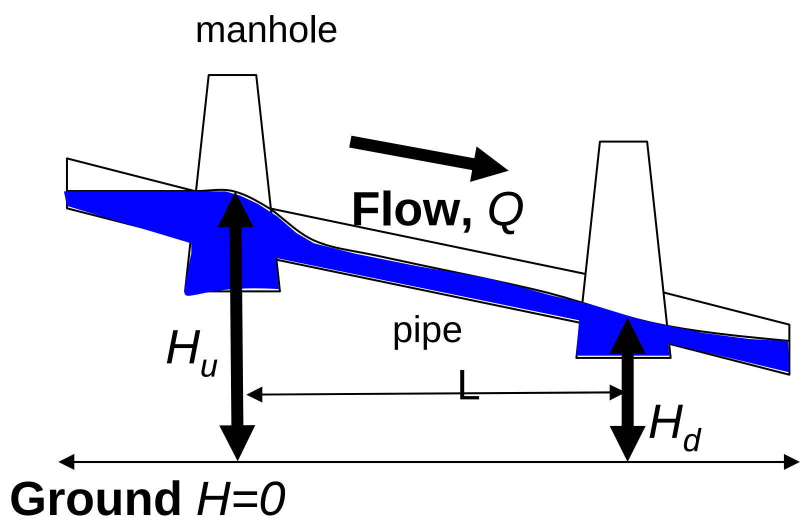
- **Flow Resistance Equation (momentum equation)**

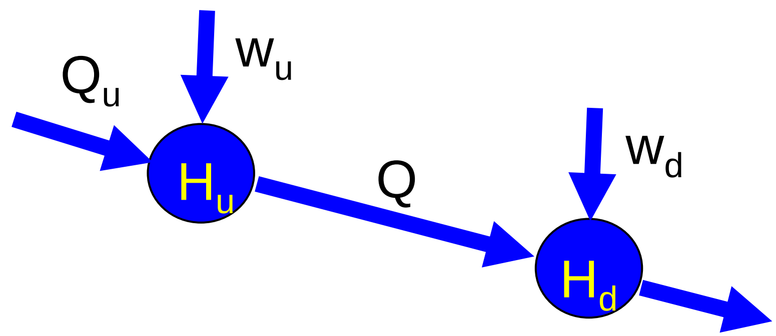
$$H_u - H_d = kQ^2$$

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

- Continuity Equation

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



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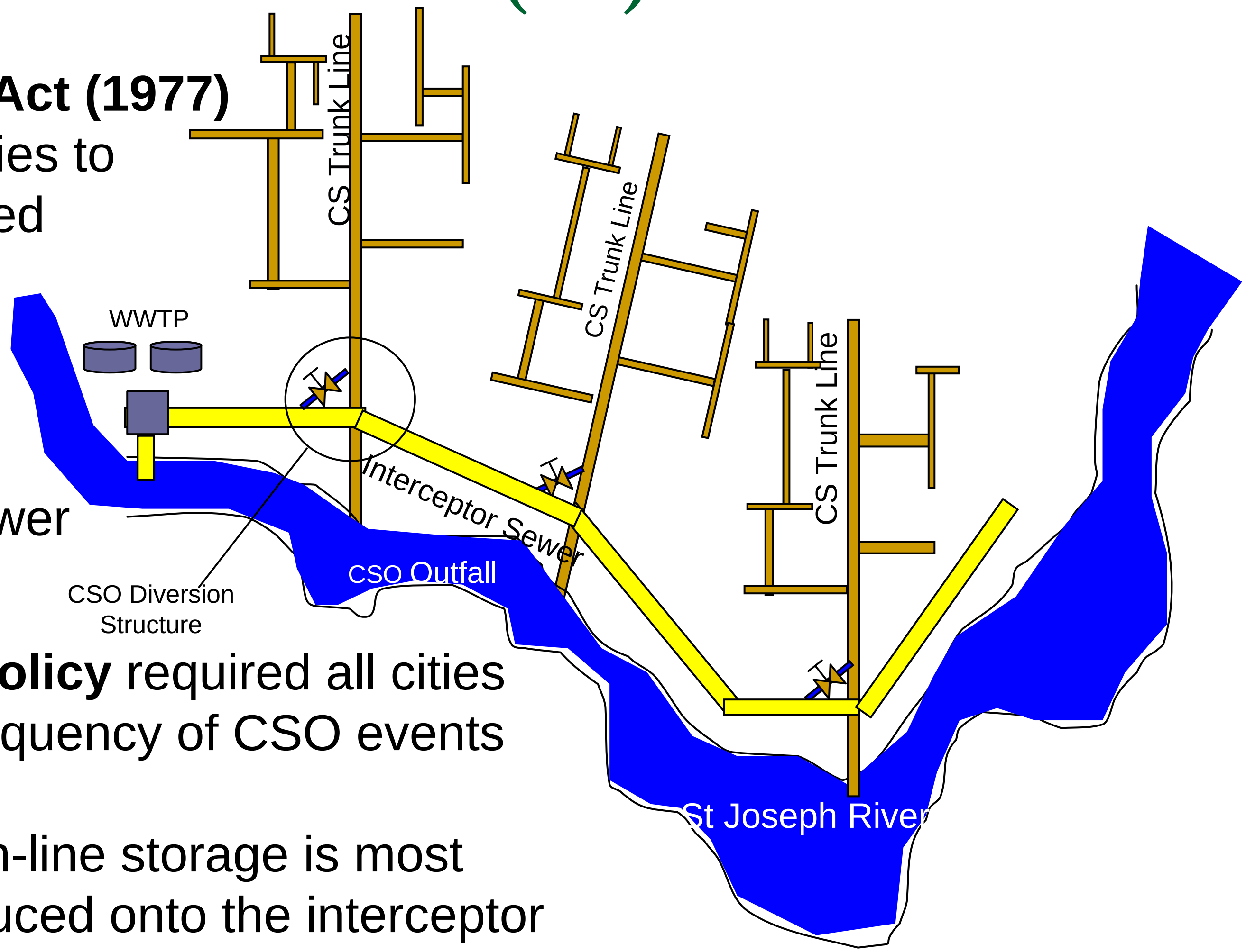
# Interceptor Sewer Model (SB)

- **Clean Water Act (1977)** requires all cities to treat discharged sewage.

  This led to installation of interceptor sewer and WWTP.




- **1994 CSO policy** required all cities to reduce frequency of CSO events

  Distributed in-line storage is most easily introduced onto the interceptor sewer, with control being at the CSO diversion structures



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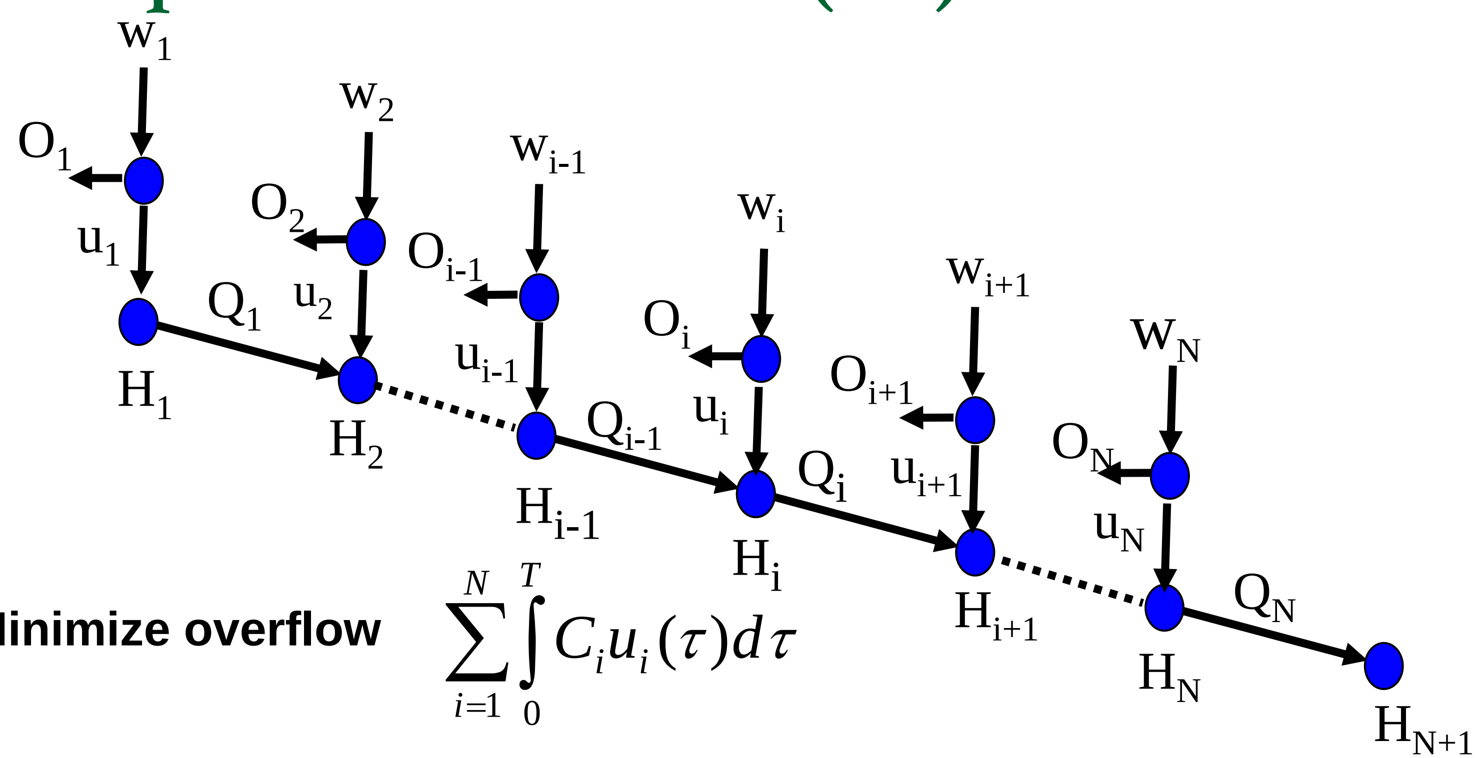
# Interceptor Sewer Model (SB)




- **Minimize overflow** $$\sum_{i=1}^{N}\int_0^T C_i u_i(\tau)\,d\tau$$
- **Dynamics**
$$\alpha_i(\tau)\dot{H}_i = u_i(\tau) + Q_{i-1}(\tau) - Q_i(\tau)$$
$$0 = H_i(\tau) - H_{i-1}(\tau) - k_i(\tau)Q_i^2(\tau)$$
- **Safety**
$$0 \le u_i(\tau) \le w_i(\tau), \qquad \sum_{i=1}^{N} u_i(\tau) \le \overline{Q}$$
$$H_i(\tau) \le \overline{H}_i$$



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# Pointwise Optimization Problem

$$\max_{u[k]} \sum_{i=1}^{N} C_i u_i[k]$$

Suboptimal pointwise solution maximizes diverted flow at a given time instant *k*.

$$\text{subject to:} \quad 0 \le u_i[k] \le w_i[k], \quad \sum_{i=1}^{N} u_i[k] \le \overline{Q}$$

$$H_i[k+1] \le \overline{H}_i$$

$$Q_{i-1}[k] - Q_i[k] + u_i[k] \le \frac{a_i}{T}\left(H_i[k+1] - H_i[k]\right)$$

The pointwise solution has a max-min form:

$$u_i^*[k] = \max\left(\min\left(\overline{U}_i[k], w_i[k]\right), 0\right)$$

$$\text{where} \quad \overline{U}_i[k] = \frac{a_i}{T}\left(\overline{H}_i - H_i[k]\right) + Q_i[k] - Q_{i-1}[k]$$



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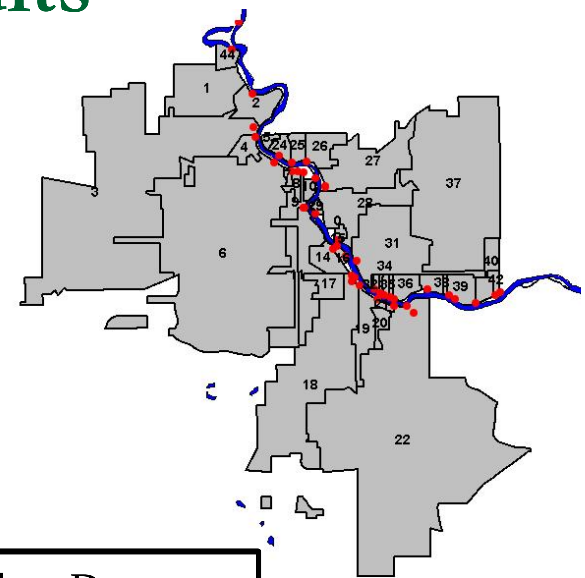
# Pointwise Optimal Control Results



1. Two Week Storm (80%) (0.485” of rain in 11 hrs)
2. One Month Storm (90%) (0.799” of rain in 13 hrs)
3. One Year Storm (99%) (2.046” of rain in 19 hrs)

| 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



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# RHC Controller (no active flooding constraints)

**THEOREM:**

Let u* maximize the objective

$$\sum_{i=1}^{N} \int_{t_n}^{t_n+T_n} C_i u_i(\tau) d\tau$$

Subject to constraints

$$a_i \frac{dH_i}{dt} = u_i + Q_{i-1} - Q_i$$

$$0 = H_i - H_{i+1} - k_i Q_i^2$$

$$0 \le u_i \le w_i, \quad \overline{H}_i \ge H_i, \quad \overline{Q} \ge \sum u_j$$

and **assume no “flooding” constraints are active over the horizon $T_n$ .**

Then the optimal control solves the linear program

$$\begin{aligned} &\text{maximize} \quad \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{C}_{\mathrm{i}} u_i(\tau) \\ &\text{subject to} \quad u(\tau) \in U_\tau = \text{admissible controls} \end{aligned}$$



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# RHC Control under active flooding constraints

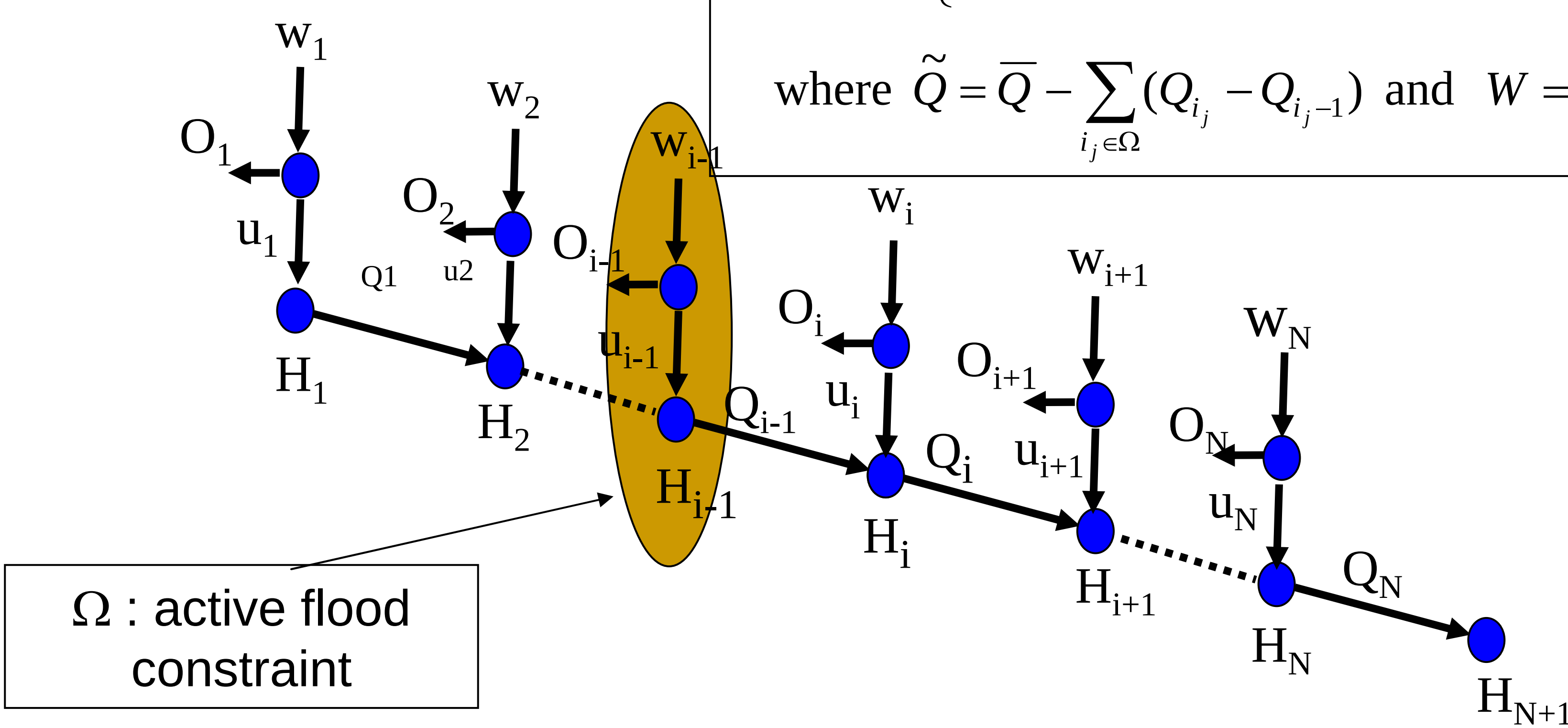
**CASE 1:** node $i_j$ is in $\Omega$

$$u_{i_j} = Q_{i_j} - Q_{i_j-1}$$

**CASE 2:** node $i_j$ is NOT in $\Omega$

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

$$\text{where } \tilde{Q} = \overline{Q} - \sum_{i_j \in \Omega} (Q_{i_j} - Q_{i_j-1}) \text{ and } W = \sum_{i_k \notin \Omega, k=1}^{j-1} u_{i_k}$$



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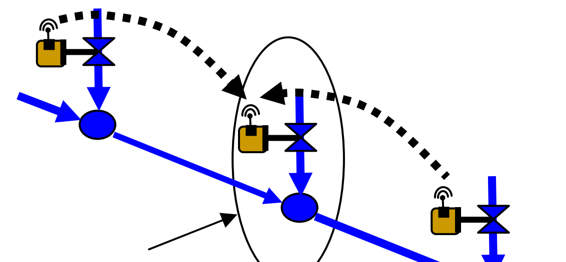
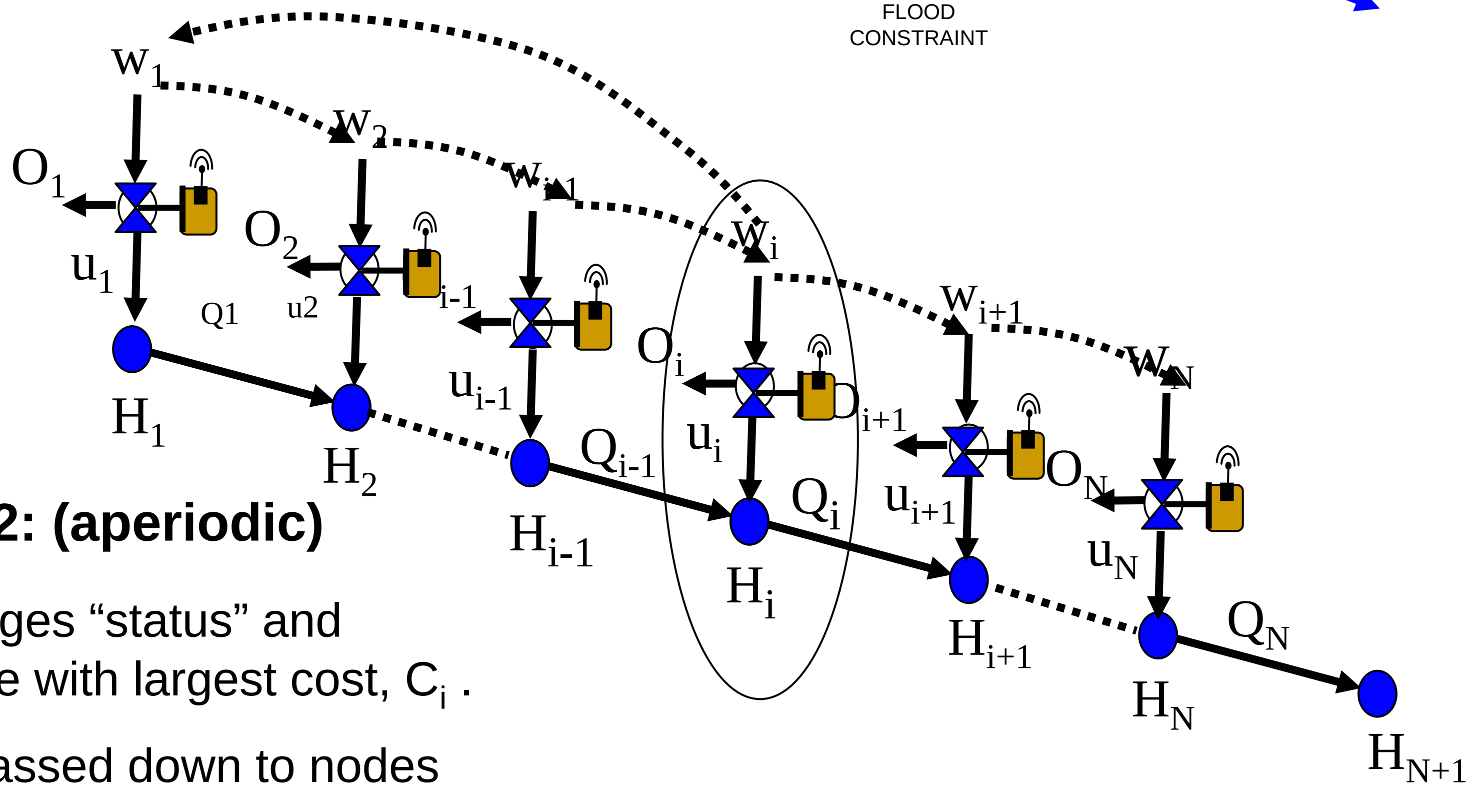
# Network Traffic

**Traffic Class 1: (periodic)**

requested by nodes in Ω

(flood constraints active)




**Traffic Class 2: (aperiodic)**

Node changes "status" and signals node with largest cost, $C_i$ .

Message passed down to nodes with lower costs.

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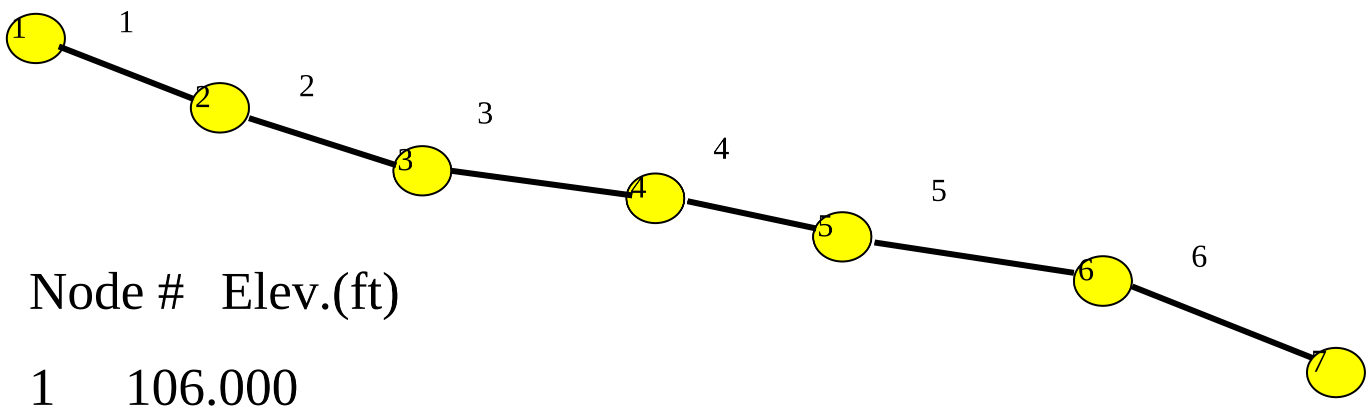
# Simplified 7-node Interceptor Sewer




| Node # | Elev.(ft) |
|---|---|
| 1 | 106.000 |
| 2 | 2103.000 |
| 3 | 100.000 |
| 4 | 98.608 |
| 5 | 98.257 |
| 6 | 97.581 |
| 7 | 95.813 |

| Link | Diam(ft) | Length(ft) | Slope |
|---|---|---|---|
| 1 | 2.5 | 700 | .004 |
| 2 | 3.5 | 1000 | .0030 |
| 3 | 4.5 | 580 | .0024 |
| 4 | 5 | 530 | .0007 |
| 5 | 6 | 690 | .001 |
| 6 | 6.5 | 520 | .0034 |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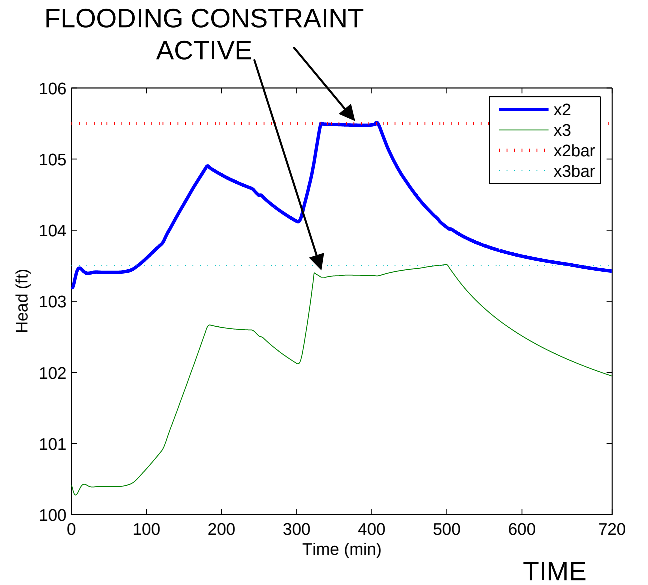
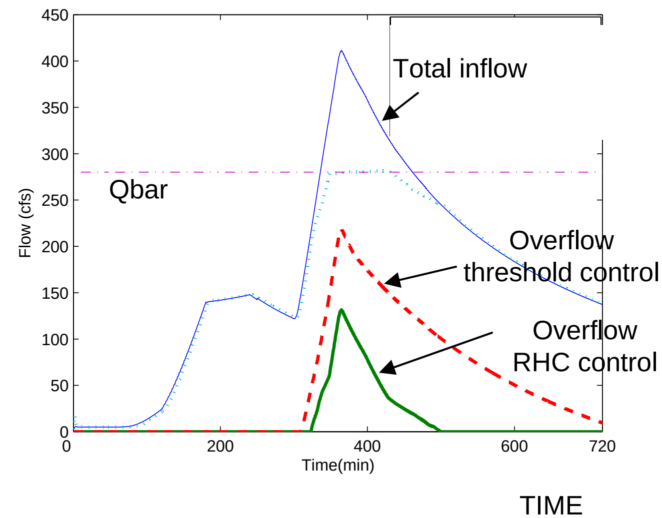
# Results

- Fixed Threshold Strategy
- Pointwise Controller
- RHC Optimal Controller




| | Overflow |
|---|---|
| threshold | 2.6 million ($ft^3$) |
| pointwise | 0.58 million ($ft^3$) |
| RHC | 0.54 million ($ft^3$) |



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# CSOnet - 21st Century Fund Project

- **Project Objective:**
  - **Develop Wireless sensor-actuator networks to monitor and control the frequency of CSO events.**
- **Sponsored by Indiana's 21st Century Technology Fund**
  - **Initial Project (2004-2006) developed and deployed CSOnet prototype**
  - **Follow-on Project (2007-2009) will expand original prototype to a metropolitan scale covering the entire City of South Bend**
- **Project Partners**
  - **University of Notre Dame, Purdue University, EmNet LLC, Greeley and Hansen, and the City of South Bend.**
- **Accomplishments to Date**
  - **Development of CSOnet sensor network components.**
  - **Integration into a working system that was deployed in summer 2005.**
  - **Prototype's continuous operation as part of city infrastructure.**
  - **In first month of service, CSOnet prevent a 2 million gallon CSO discharge at a cost that was half of a comparable SCADA network implementation.**


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# CSOnet System Components

**INode:** sensor measurements, battery powered, can be placed in manhole.

**RNode:** in charge of forwarding INode messages to other nodes, battery or solar powered. Current range: 1,000-2,500 ft, depending on line of sight clarity.

**GNode:** can connect to ethernet based network or cellular network, access to wireless network, controls structures.



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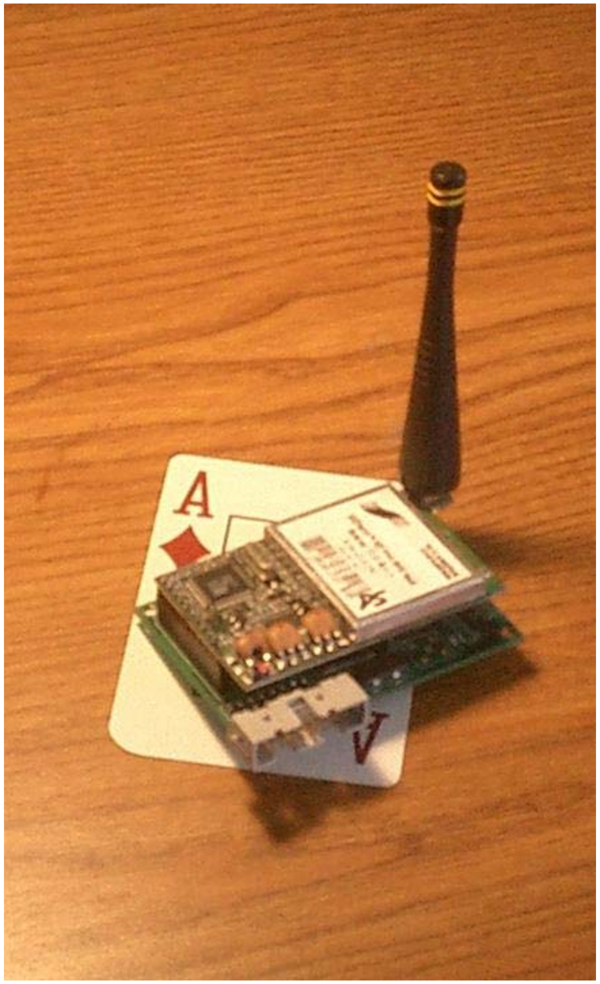
# Wireless Platform (EmNet LLC)



**Heart of the system is a wireless sensor network platform based on U.C. Berkeley's Mica2.**

- Wireless Platform: Chasqui Node
- ATmega128 processor
- Berkeley's TinyOS compatible
- 100mW 900 MHz FHSS radio
- Standard industrial sensor interface
- 6V power supply



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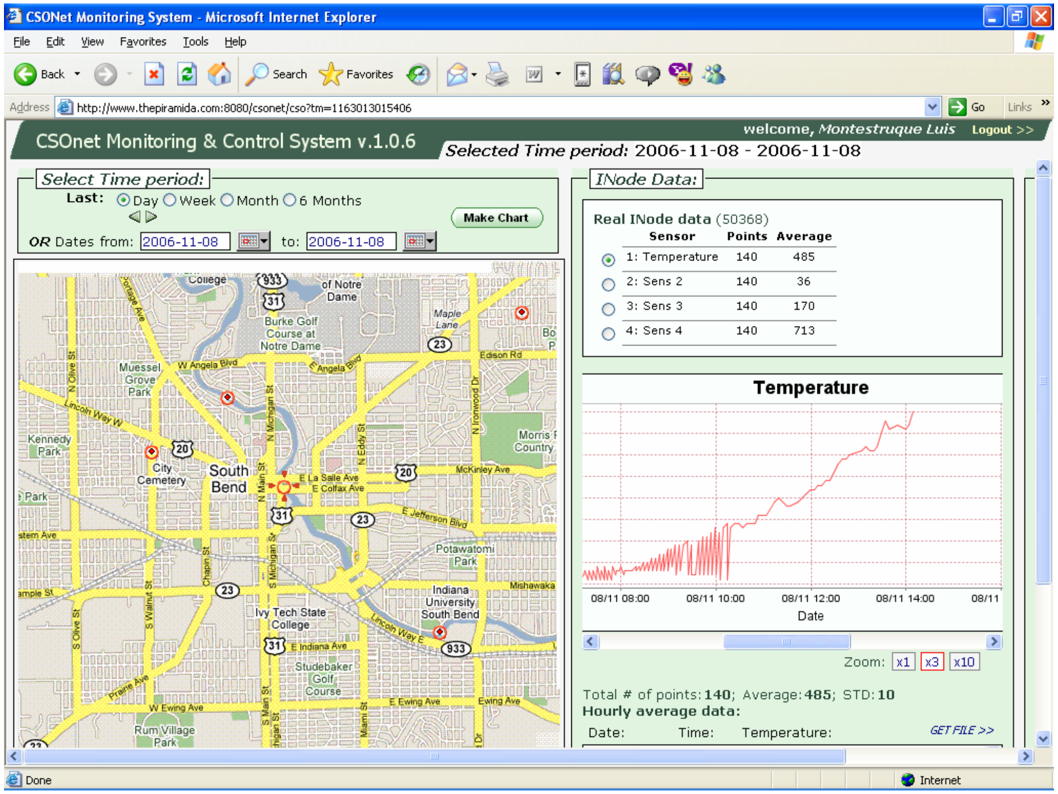
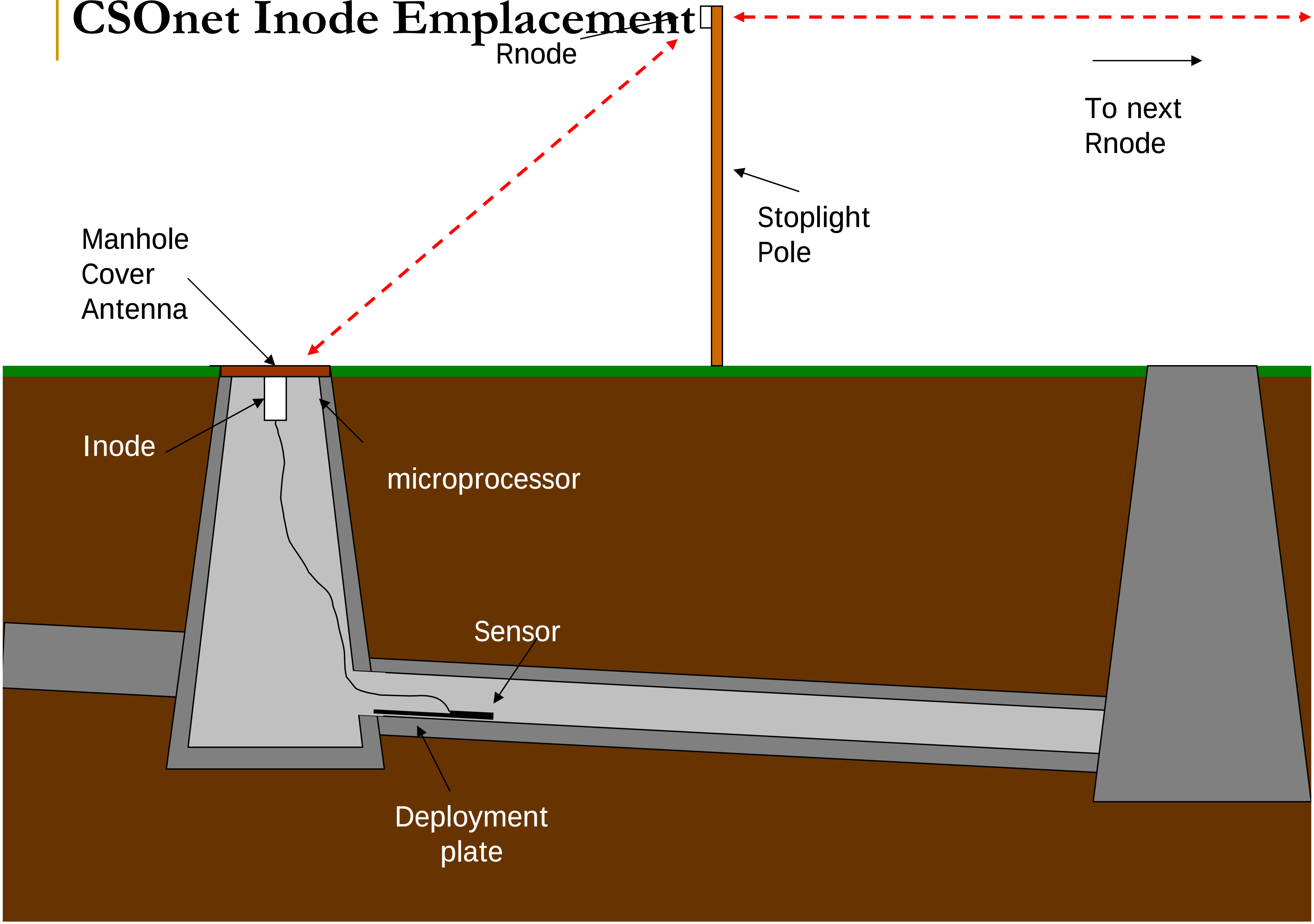
# CSOnet Data Delivery (EmNet LLC)



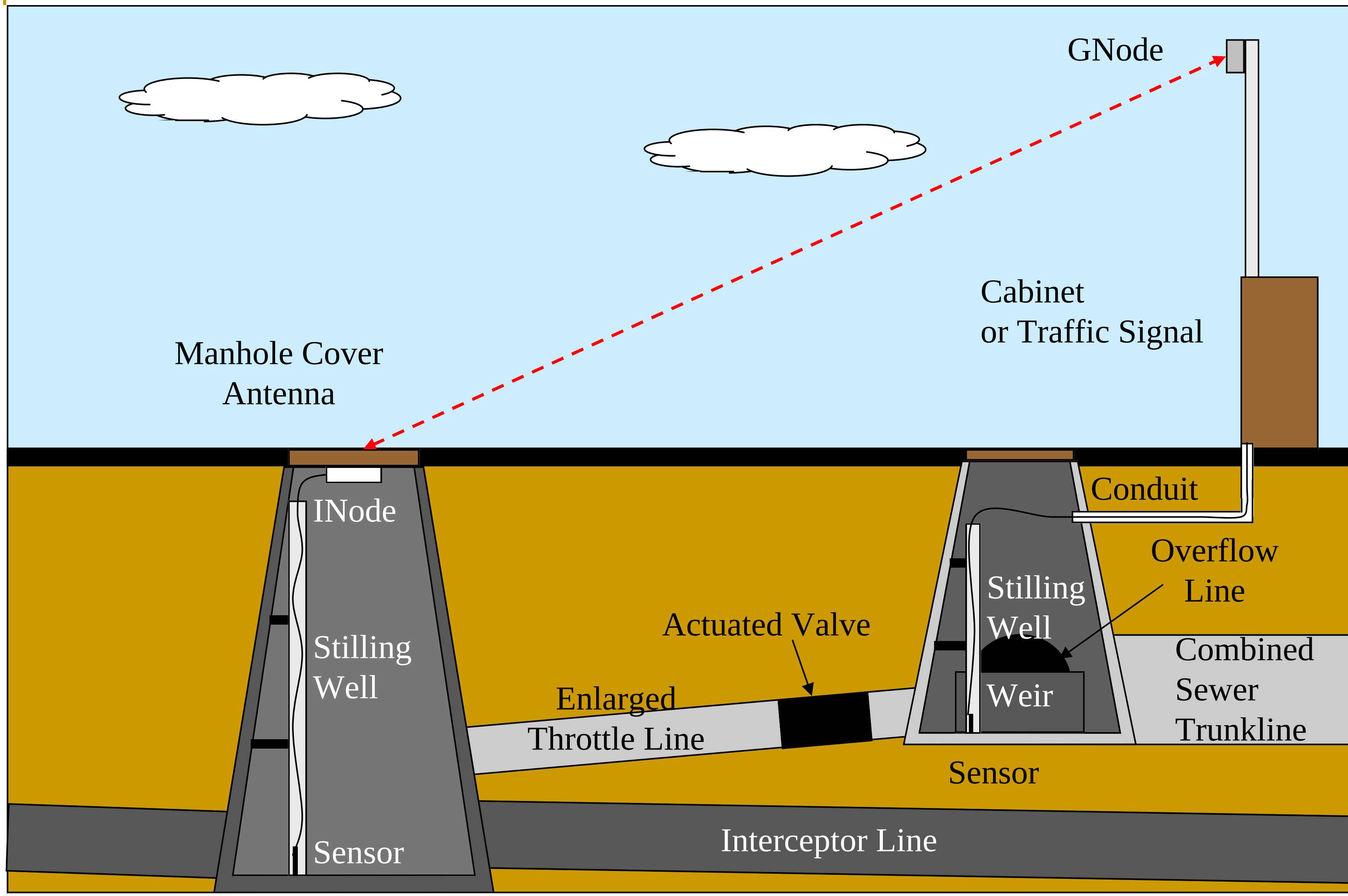

Chasqui Nodes convey sensor data over wireless mesh network to Gnodes that forward data to EmNet Database Server.

- •Web based access
- •Secure login
- •Graphical interface
- •Open Architecture
- •Tomcat server
- •Java scripts
- •MySQL database

# CSOnet Inode Emplacement



# CSOnet Actuator Deployment



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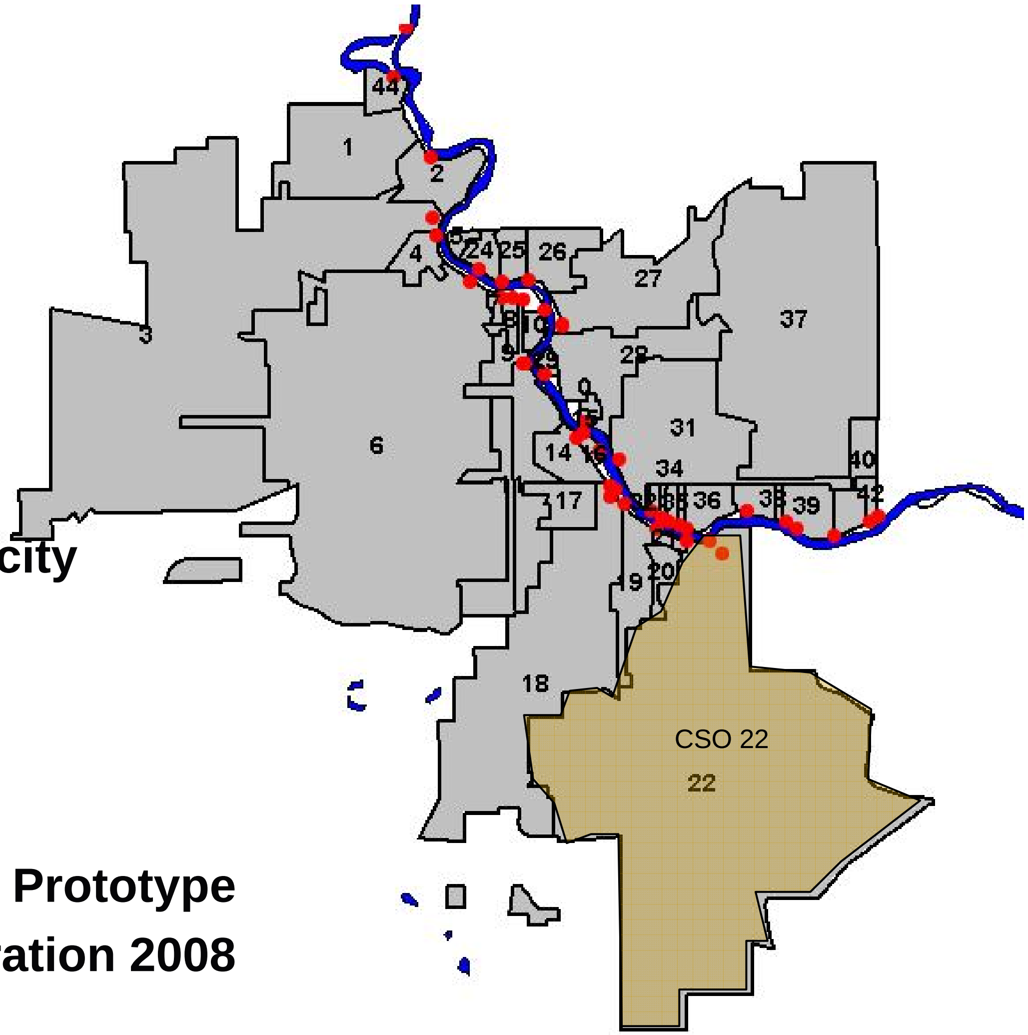
# South Bend Indiana Combined Sewer

**South Bend Indiana Combined Sewer System**

- **36 CSO outfalls (marked by )**
- **13,100 acres**
- **70 MGD WWTP Capacity**

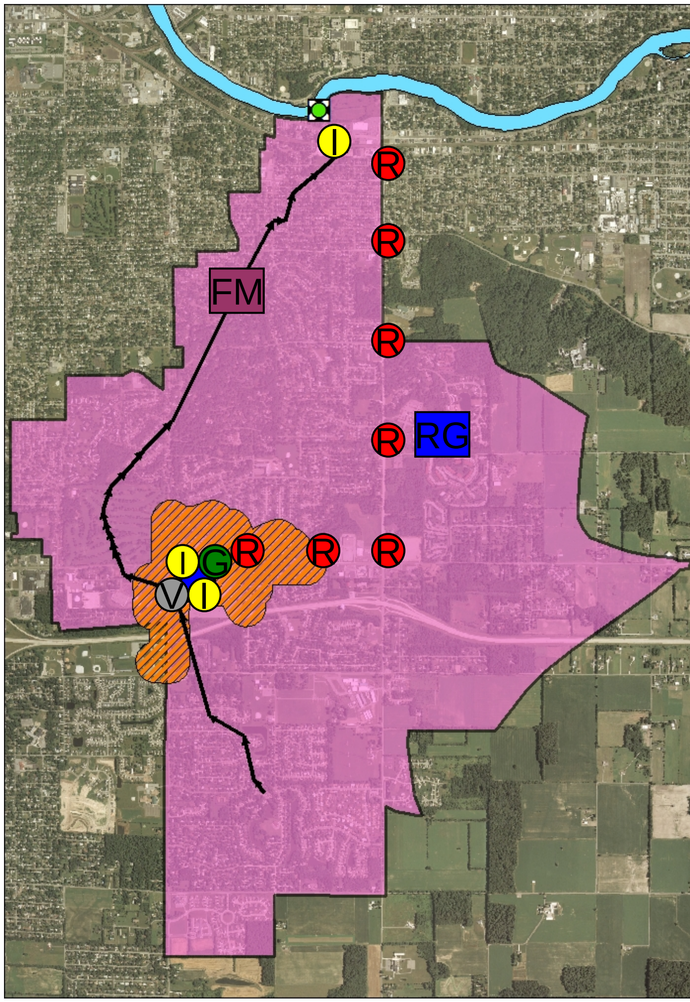



**Indiana 21st CTF Project**

Notre Dame, Purdue,
EmNet LLC, South Bend

- **Summer 2005 CSOnet Prototype**
- **Metro-scale Demonstration 2008**

# Ireland/Miami Network (Summer 2005)




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

- 7 Rnodes (radios)
- 3 Inodes (sensors)
- 1 Gnode that controls an automated valve at the basin
- Gnode is also able to connect to the internet
- Network is fully deployed and operational
- Flow Meter in the trunk sewer
- Rain gauge

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

Continuous operation since summer 2005.



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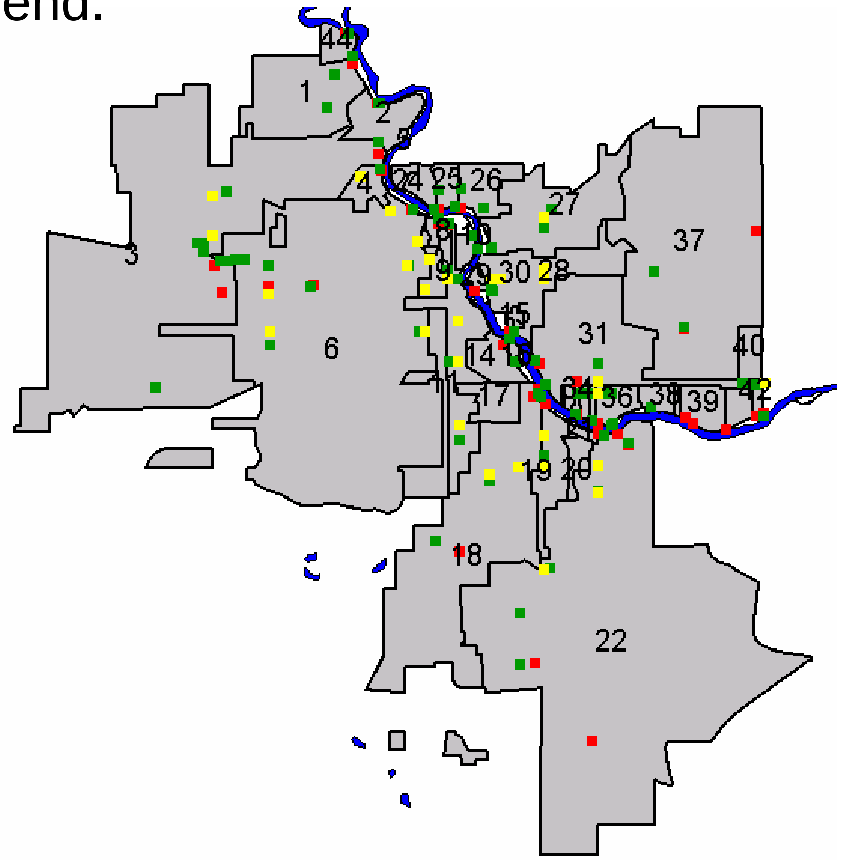
# South Bend Interceptor Sewer Project

Follow-on will extend 2005 prototype to the entire interceptor sewer in South Bend.




PHASE 1:

- Monitor 36 outfalls, 26 interceptor locations, 42 trunkline and river crossing locations, and 5 basins
- Control at least 2 additional basins

PHASE 2:

- Control at least 18 outfalls
- Control remediation pumps wet weather discharges



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# Summary

- CSO problem is an issue of national scope and importance
- Distributed feedback control provides a cost effective and scalable method for implementing in-line storage strategies.
- Optimal feedback control algorithms are distributed in nature and appear to fit within the capacity limits of multi-hop mesh communication networks.
- Current real-life deployments have validated the system hardware and middleware.
- Future deployments will extend this work to a metropolitan scale. Success at this level opens the way for deployment on a national scale.



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