# Optimal Monitoring Network Design in River Networks

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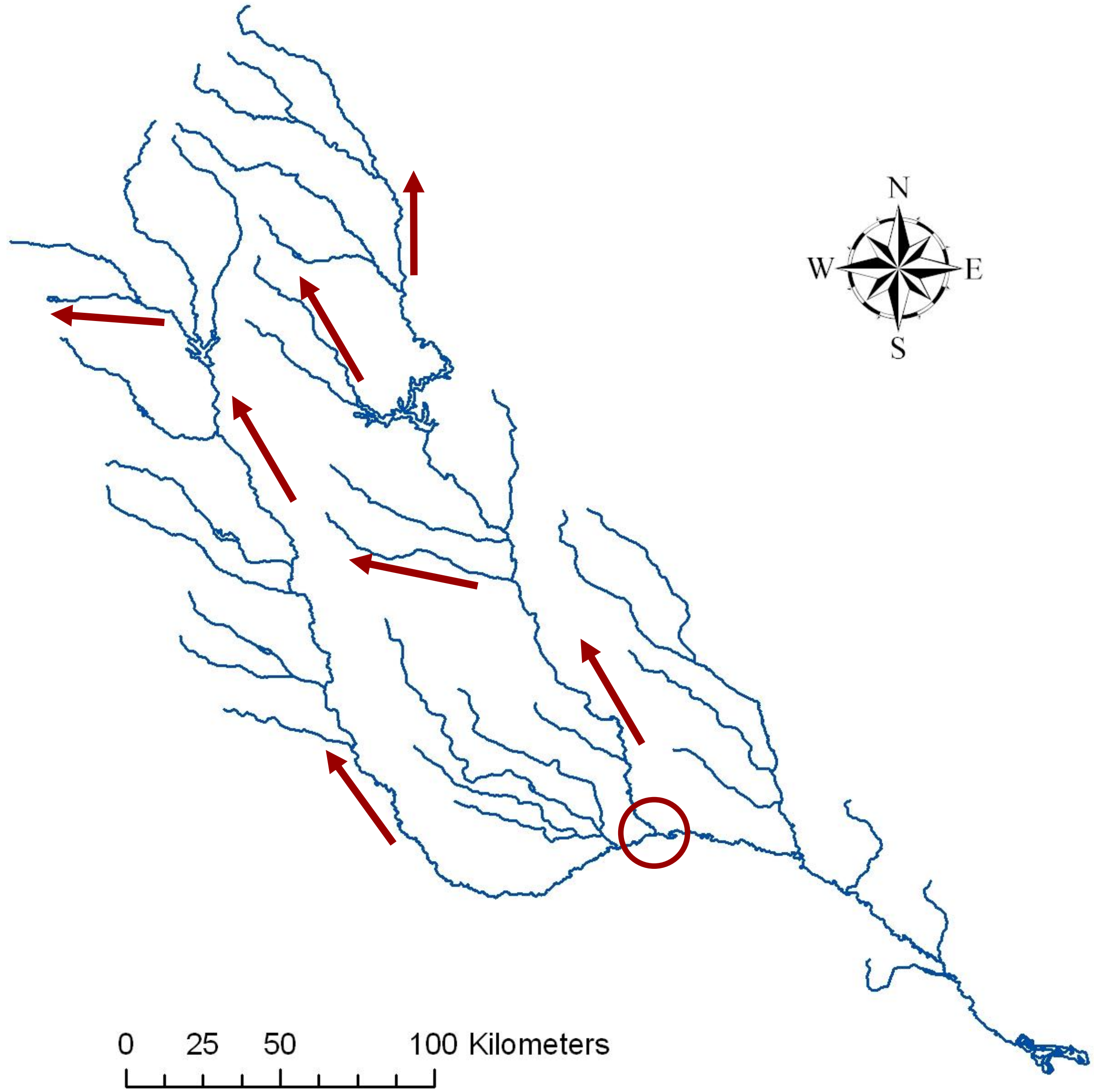
# Historical Problem Analyzed: Prospecting



# More Recently: Contaminant Monitoring Systems

- Provide sufficient and timely information on the quality of the river water to decision makers;

- Rapid identification of pollutant sources;

- Provide for immediate precautions after a deliberate or accidental spill.

# Design of Monitoring Systems:

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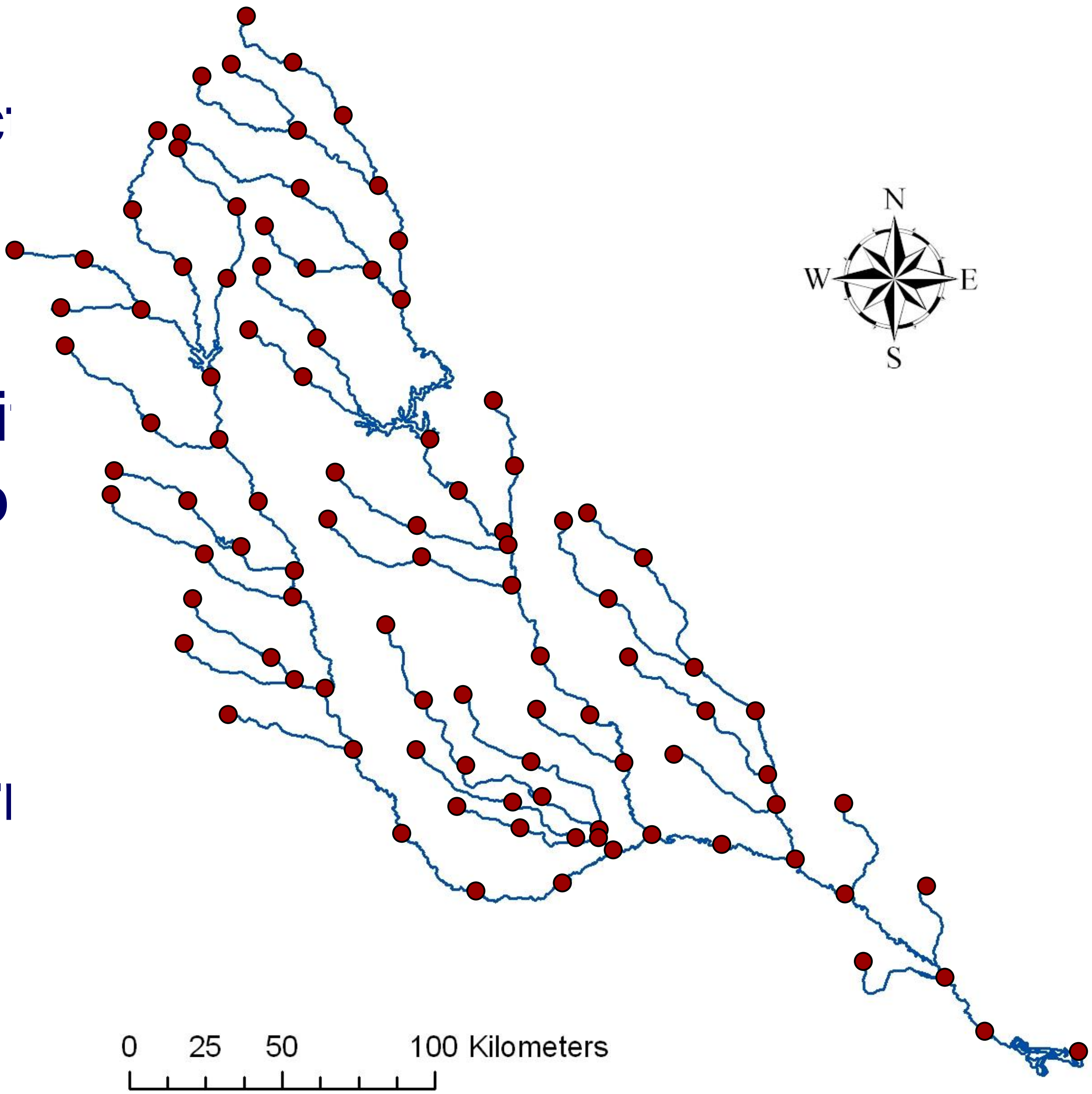
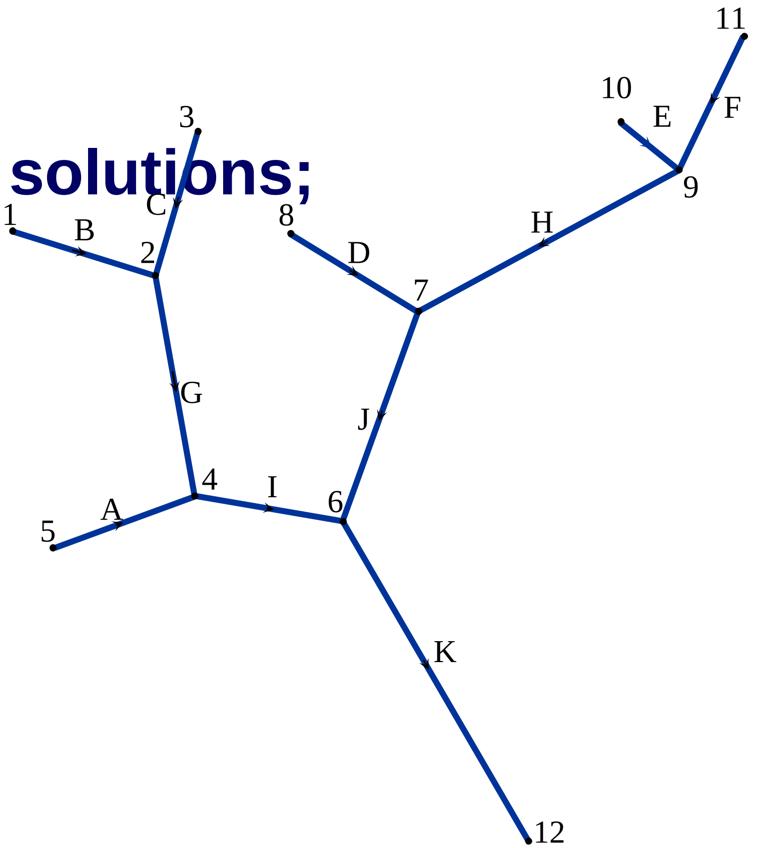
- Identi
  statio
- Deteri



# Previous studies:

## Based on:

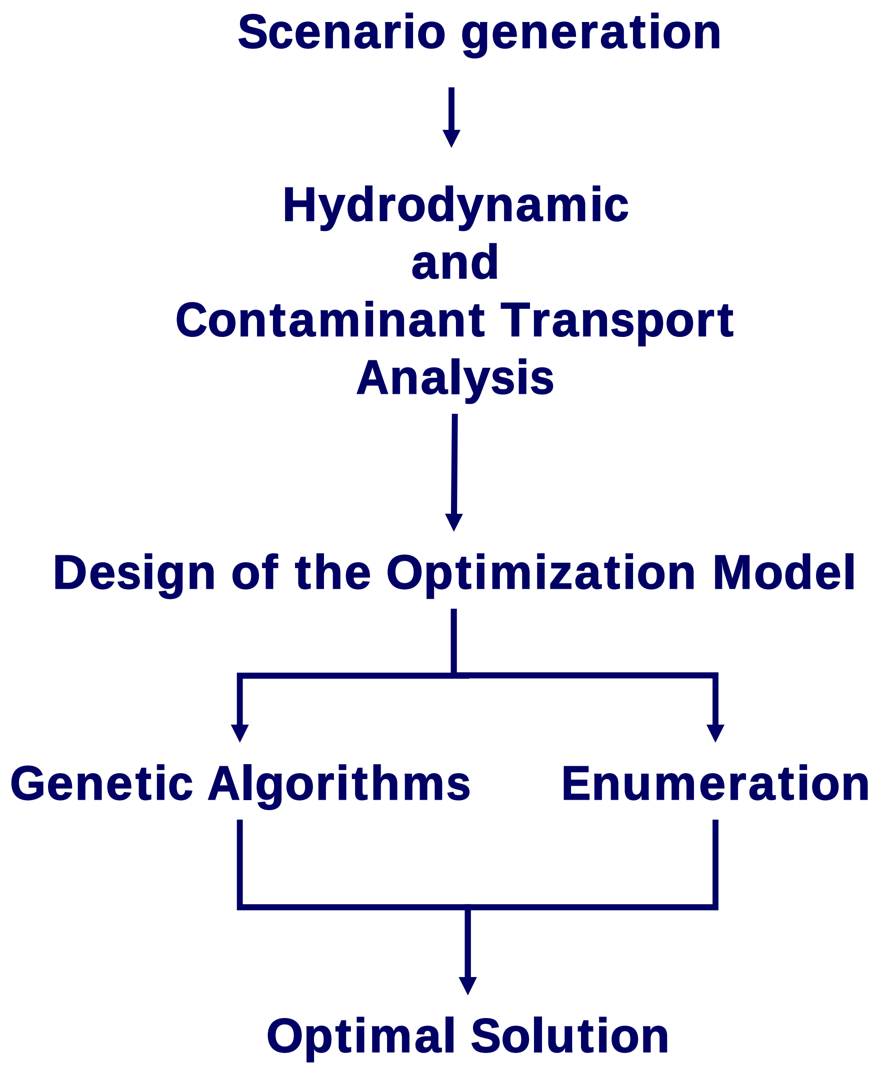
- **Steady state flow and transport solutions;**
- **Geometry of the river network (prospecting applications);**



# Objectives:

- Determination of the optimal monitoring locations based on transient hydrodynamic and contaminant transport analysis;
- Comparison of the results of the proposed methodology with a recent study published in the literature;
- Purpose is to emphasize the effects of hydraulic and watershed characteristics on the optimal solution.
- Large scale application (Altamaha River System)

# Methodology:



## Hydrodynamics and Contaminant Transport:

- Use of a dynamic rainfall-runoff model for the simulation of runoff quantity and quality;
- Handle networks of unlimited network size;
- Use of a wide variety of standard and natural open channel geometries, and spatially variable hydraulic parameters;
- User defined external flows and water quality inputs.
- SWMM

# Performance Measures:

- **Average detection time**

$$\bar{t}(X) = \frac{1}{S}\sum_{i=1}^{S} t_i\left(\widehat{X}\right)$$

$$X = \left[x_1, x_2, \ldots, x_M\right]^T$$

$$t_i\left(\widehat{X}\right) = min\left\{d_i^1(X), d_i^2(X), \ldots, d_i^M(X)\right\} ; i = 1,2,3,\ldots,S$$

$d_i^m(X)$ : **detection time of the $m^{th}$ monitoring station for scenario $i$.**

$S$ : **total number of scenarios.**

$M$ : **total number of monitoring stations.**

$x_m$ : **index of the candidate junction for $m^{th}$ monitoring station.**

**Penalty : for a non-detected scenario,** $t_i\left(\widehat{X}\right) = Simulation\ time$ **.**

# Performance Measures:

- **Detection Likelihood**

$$R(X) = \frac{1}{S}\sum_{i=1}^{S}\left(\frac{1}{N_e}\sum_{k=1}^{N_e}\delta_k\left(\widehat{X}\right)\right)_i$$

$$\delta_k(X) = \begin{cases} 0 & \text{if } k^{th} \text{ contamination is not detected,} \\ 1 & \text{if } k^{th} \text{ contamination is detected.} \end{cases}$$

$N_e$ : **total number of contamination events within a scenario.**

# Optimization Model:

$$f_1 = \underset{X}{Minimize}\left\{\overline{t}\left(\widehat{X}\right)\right\}$$

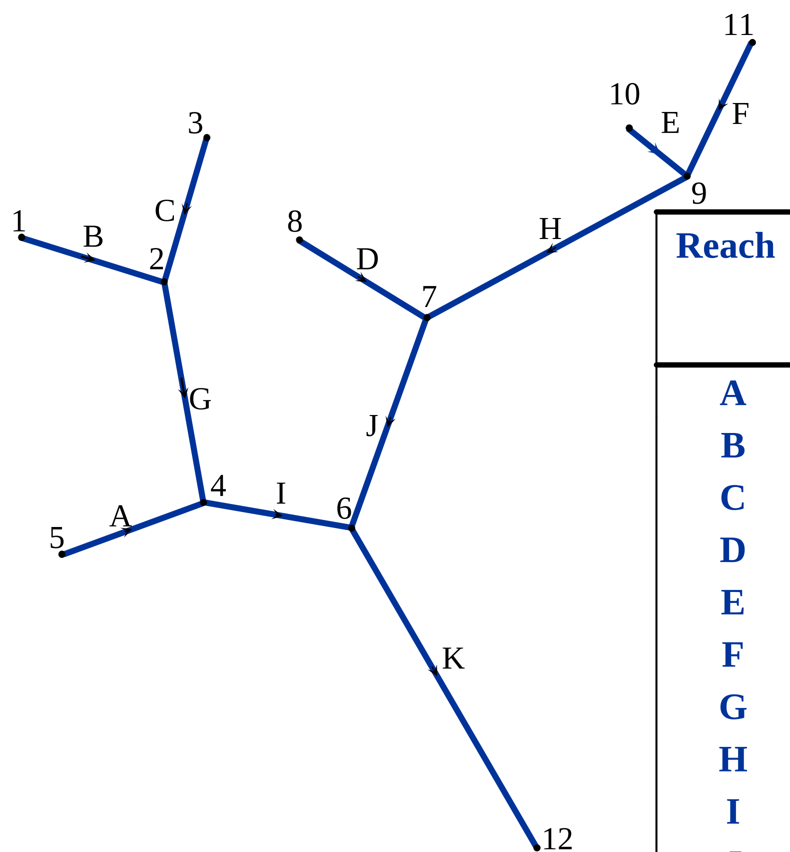
$$f_2 = \underset{X}{Maximize}\left\{R\left(\widehat{X}\right)\right\}$$

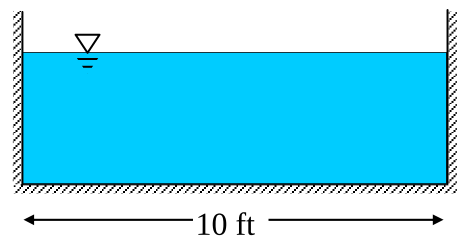
$$s.t.\ M = M_o$$

$M_o$ **: total number of monitoring sites.**

# Application:

## Hypothetical River Network




| Reach | Length (ft) | Flow rate ($ft^3/s$) | Depth (ft) | Width (ft) | Channel slope | Manning's n |
|---|---|---|---|---|---|---|
| A | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| B | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| C | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| D | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| E | 1000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| F | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| G | 3000 | 20 | 2.08 | 10 | 0.0001 | 0.02 |
| H | 4000 | 20 | 2.08 | 10 | 0.0001 | 0.02 |
| I | 2000 | 30 | 2.75 | 10 | 0.0001 | 0.02 |
| J | 3000 | 30 | 2.75 | 10 | 0.0001 | 0.02 |
| K | 5000 | 60 | 4.53 | 10 | 0.0001 | 0.02 |

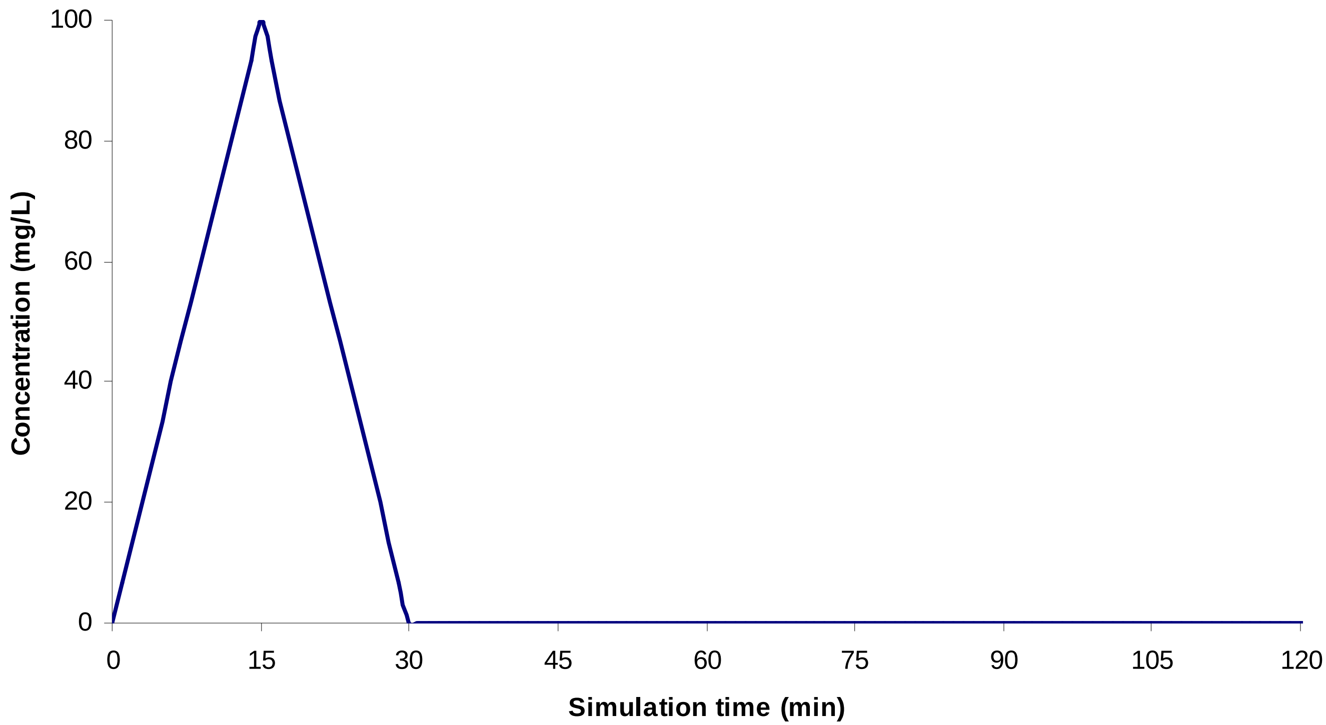
Three monitoring stations at junctions:

$$\binom{12}{3} = 220$$ possible placements

# Application:

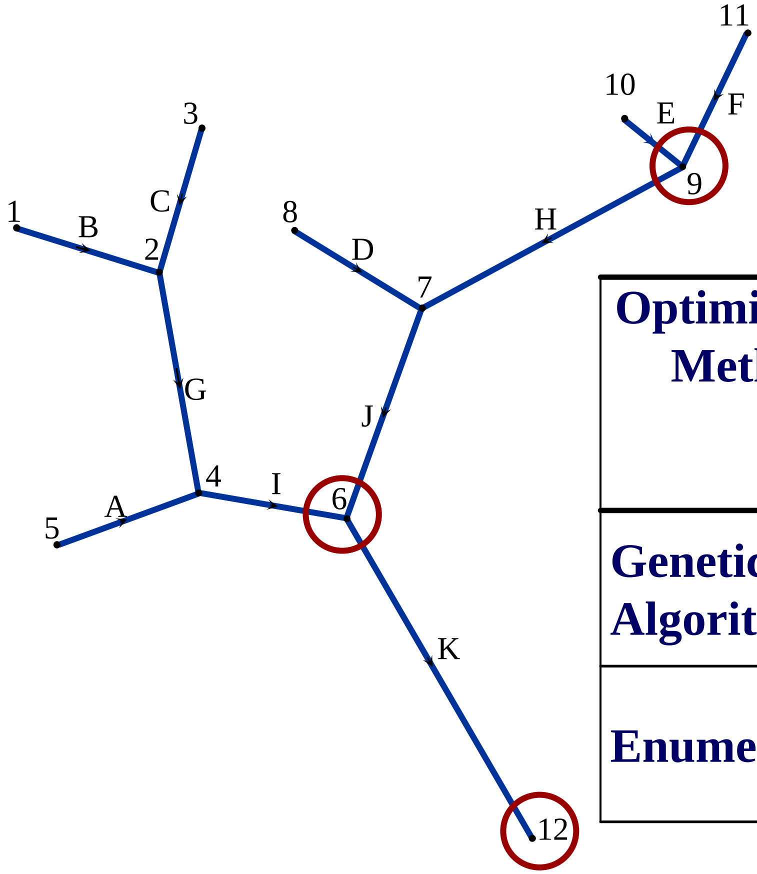
## Case 1 Scenario: Single contamination at any junction

- **Total number of scenarios, *S* =12;**
- **Simulation time: 4 days;**
- **Contamination occurs at the beginning of simulation.**



# Application:

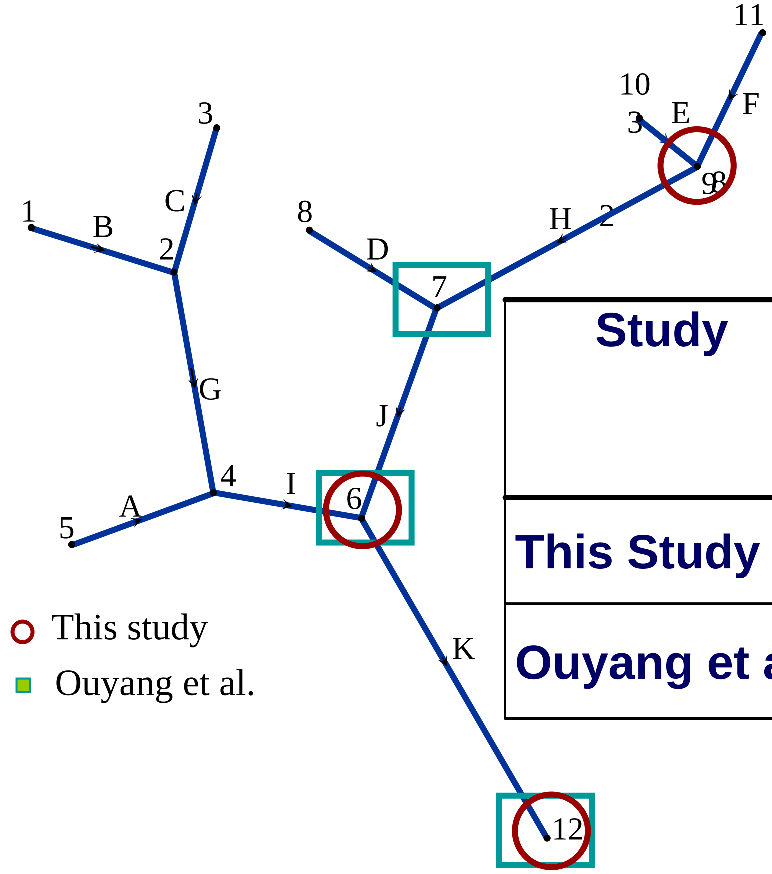
## Case 1: Results




| Optimization Method | Optimum Sensor Locations | Average Detection Time (min) | Reliability (%) |
|---|---|---|---|
| Genetic Algorithm | 6 – 9 – 12 | 63.75 | 100 |
| Enumeration | 6 – 9 – 12 | 63.75 | 100 |

# Application:

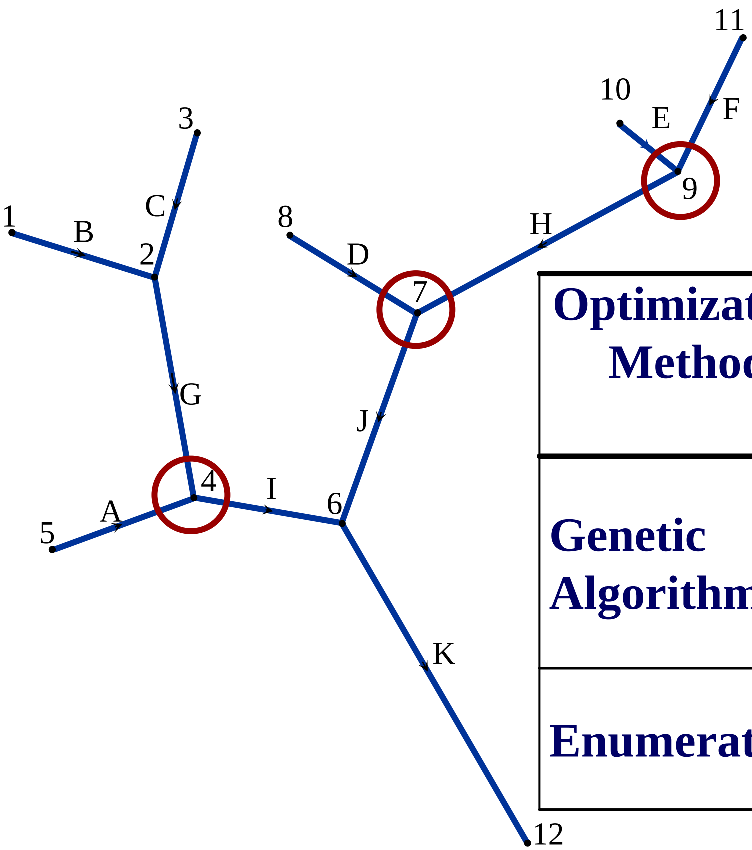
## Comparison for Case 1 with Ouyang et al.




| Study | Optimum Sensor Locations | Average Detection Time (min) | Reliability (%) |
|---|---|---|---|
| This Study | 6 – 9 – 12 | 63.75 | 100 |
| Ouyang et al. | 6 – 7 – 12 | 72.50 | 100 |

# Application: (an inferior solution)

## Case 1: Results




| Optimization Method | Optimum Sensor Locations | Average Detection Time (min) | Reliability (%) |
|---|---|---|---|
| **Genetic Algorithm** | **4 – 7 – 9** | **1000** | **83** |
| **Enumeration** | **4 – 7 – 9** | **1000** | **83** |

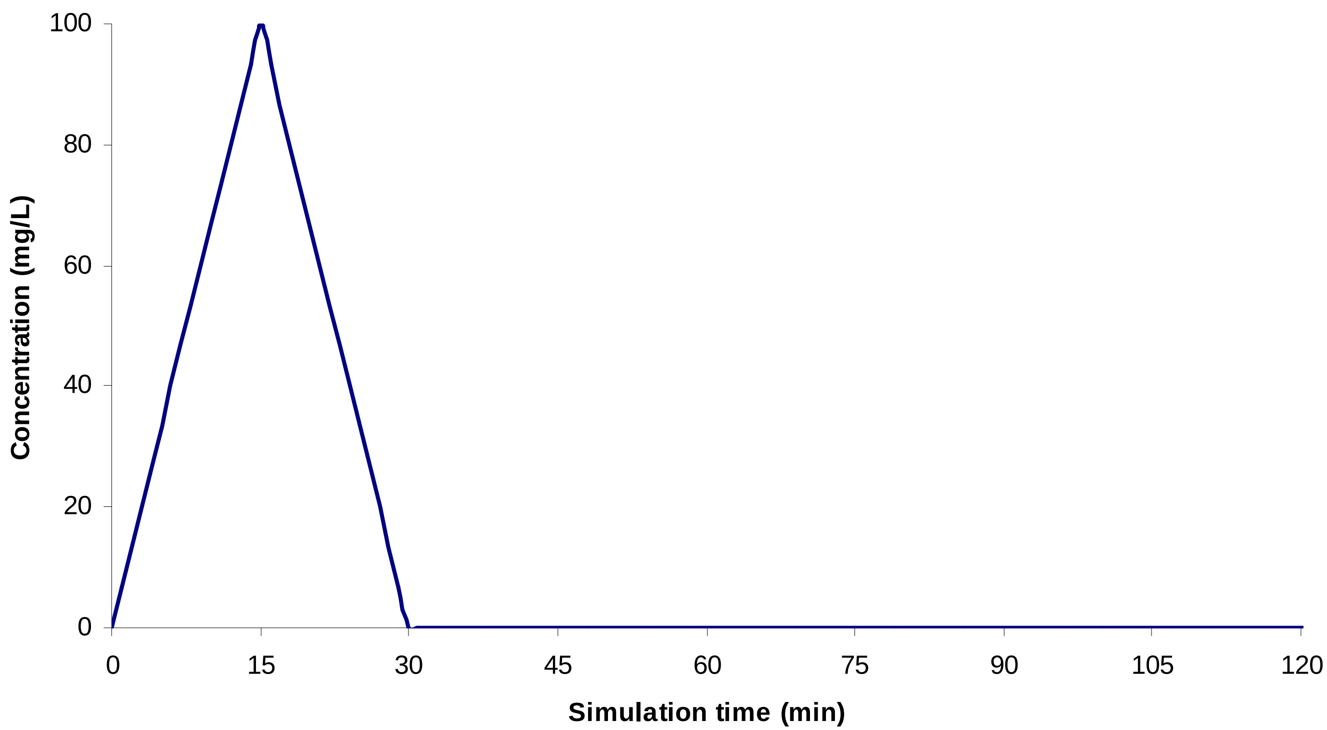
# Application:

## Case 2: Two simultaneous spills at distinct junctions

- **Total number of scenarios;**

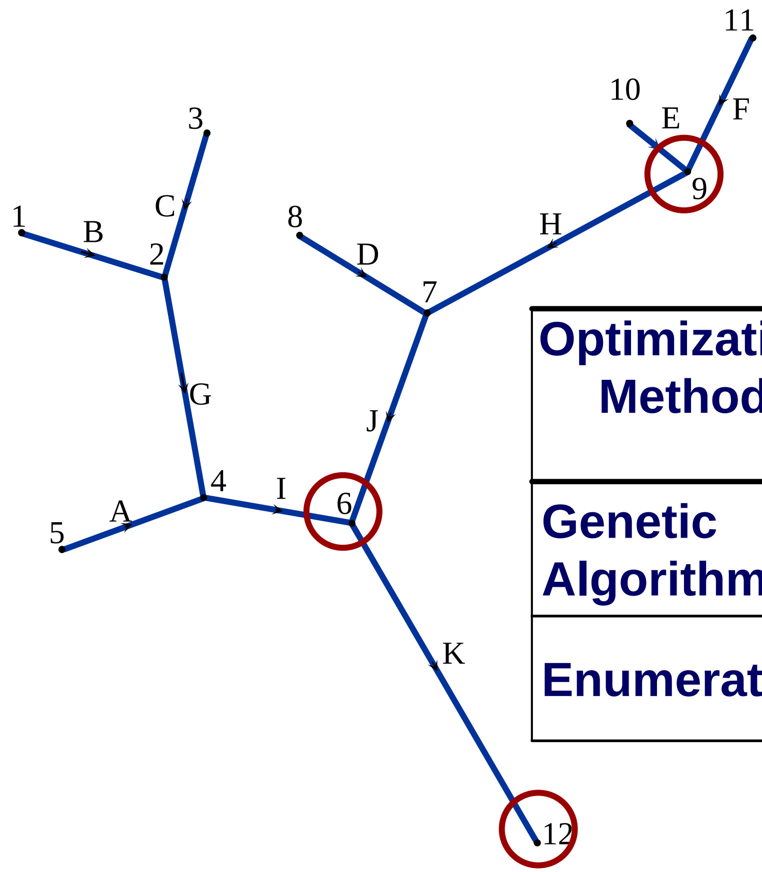
$$S = \binom{12}{2} = 66$$

- **Simulation time: 4 days;**
- **Contamination occurs at the beginning of simulation.**



# Application:

## Case 2: Results




| Optimization Method | Optimum Sensor Locations | Average Detection Time (min) | Reliability (%) |
|---|---|---|---|
| Genetic Algorithm | 6 – 9 – 12 | 37.73 | 100 |
| Enumeration | 6 – 9 – 12 | 37.73 | 100 |

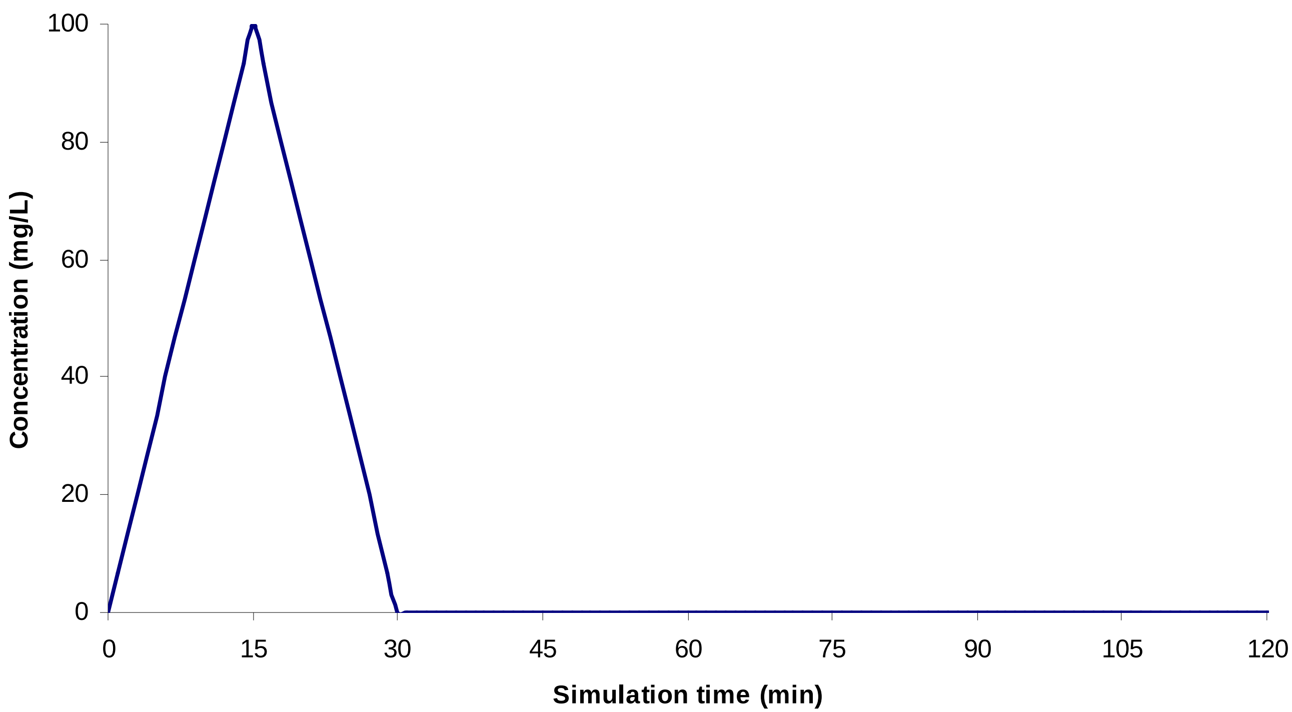
# Application:

## Case 3: Two spills with a 15 min time lag

- **Total number of scenarios;**

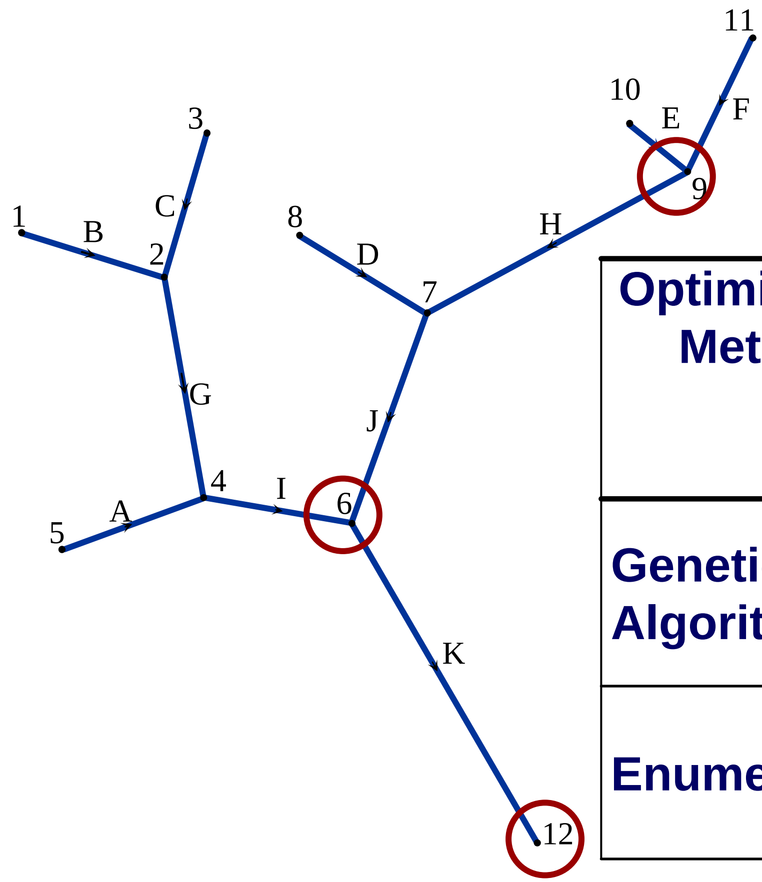
$$S = 2\binom{12}{2} = 132$$

- **Simulation time: 4 days;**
- **First spill occurs at the beginning of simulation.**



# Application:

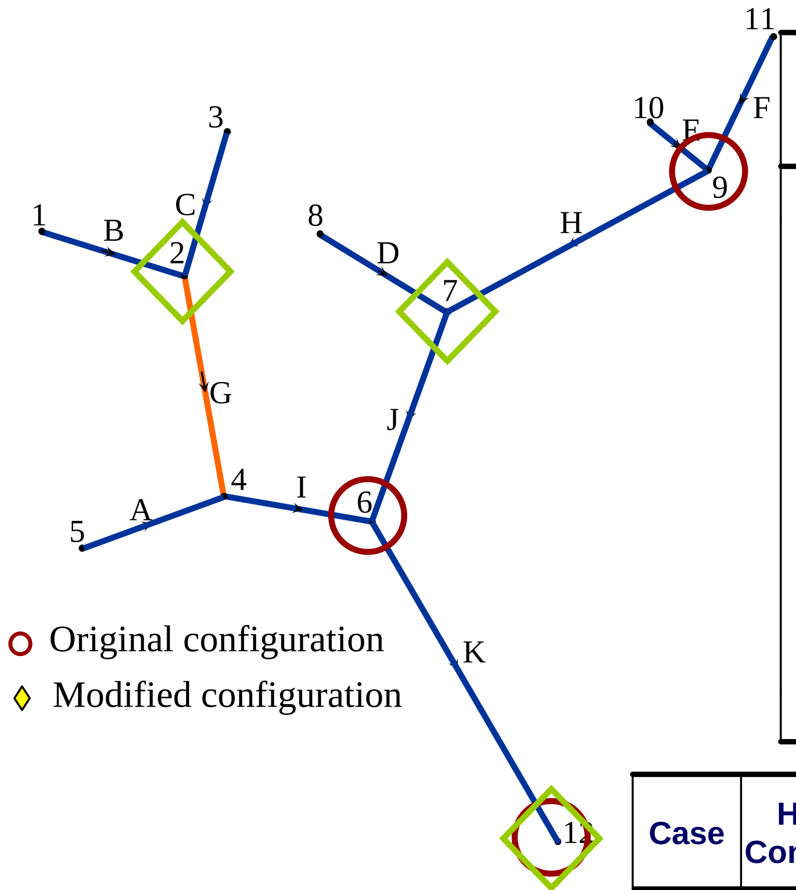
## Case 3: Results




| Optimization Method | Optimum Sensor Locations | Average Detection Time (min) | Reliability (%) |
|---|---|---|---|
| Genetic Algorithm | 6 – 9 – 12 | 44.55 | 100 |
| Enumeration | 6 – 9 – 12 | 44.55 | 100 |

# Application:

## Emphasis on hydraulic characteristics

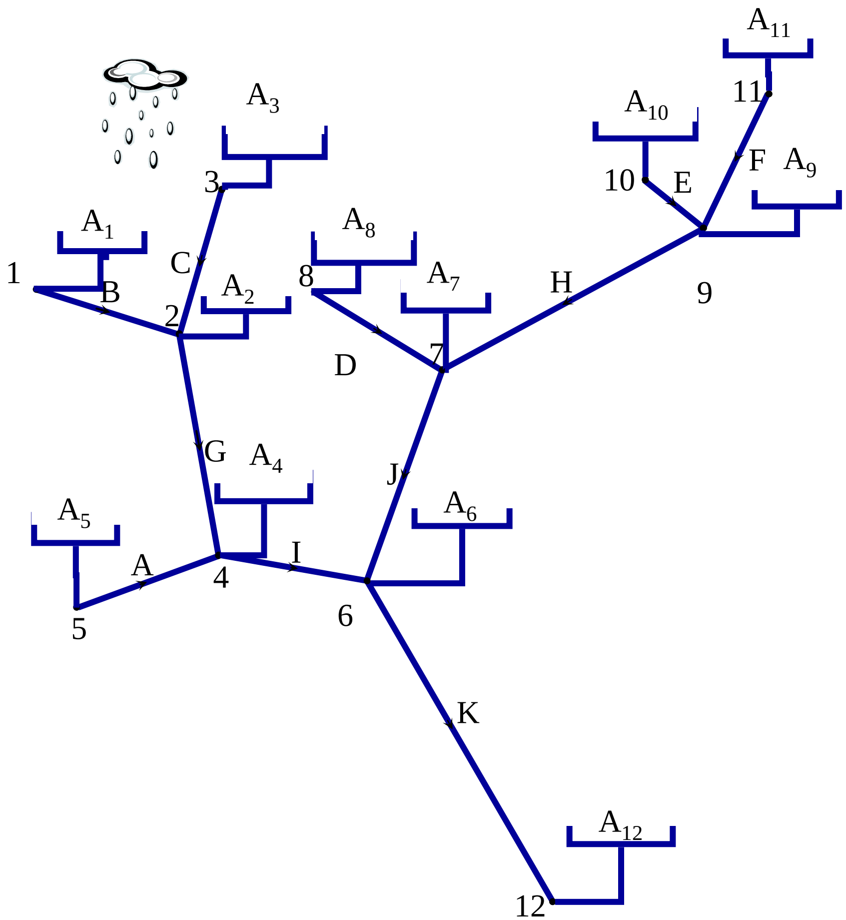



| Reach | Length (ft) | Flow Rate ($ft^3/s$) | Depth (ft) | Width (ft) | Channel Slope | Manning n |
|---|---|---|---|---|---|---|
| A | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| B | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| C | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| D | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| E | 1000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| F | 2000 | 10 | 1.31 | 10 | 0.0001 | 0.02 |
| G | 3000 | 20 | 3.96 | 10 | 0.0001 | 0.05 |
| H | 4000 | 20 | 2.08 | 10 | 0.0001 | 0.02 |
| I | 2000 | 30 | 2.75 | 10 | 0.0001 | 0.02 |
| J | 3000 | 30 | 2.75 | 10 | 0.0001 | 0.02 |
| K | 5000 | 60 | 4.53 | 10 | 0.0001 | 0.02 |

| Case | Hydraulic Configuration | Optimum Sensor Locations | Average Detection Time (min) | Reliability (%) |
|---|---|---|---|---|
| 1 | Original<br>Modified | 6 – 9 – 12<br>2 – 7 – 12 | 63.75<br>70.00 | 100<br>100 |
| 2 | Original<br>Modified | 6 – 9 – 12<br>2 – 9 – 12 | 37.73<br>39.32 | 100<br>100 |
| 3 | Original<br>Modified | 6 – 9 – 12<br>2 – 9 – 12 | 44.55<br>46.14 | 100<br>100 |

# Application:

## Emphasis on watershed characteristics

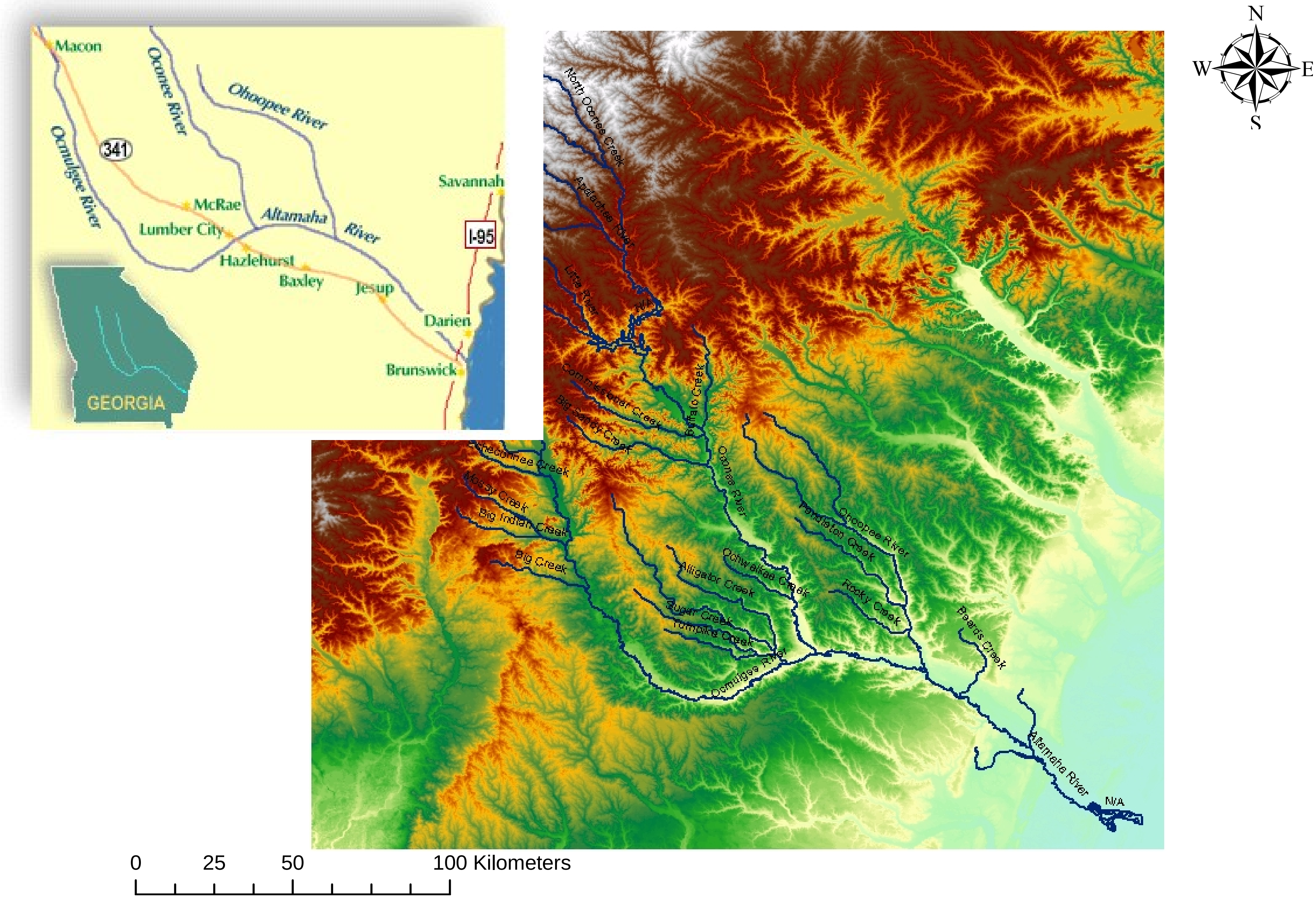



| Catchments | Connected Junction | Area (ac) |
|---|---|---|
| $A_1$ | 1 | 1 |
| $A_2$ | 2 | 2 |
| $A_3$ | 3 | 1 |
| $A_4$ | 4 | 2.5 |
| $A_5$ | 5 | 1 |
| $A_6$ | 6 | 2.5 |
| $A_7$ | 7 | 3 |
| $A_8$ | 8 | 1 |
| $A_9$ | 9 | 1.5 |
| $A_{10}$ | 10 | 0.5 |
| $A_{11}$ | 11 | 1 |
| $A_{12}$ | 12 | 2.5 |

$2000\ ft \rightarrow 1\ ac$

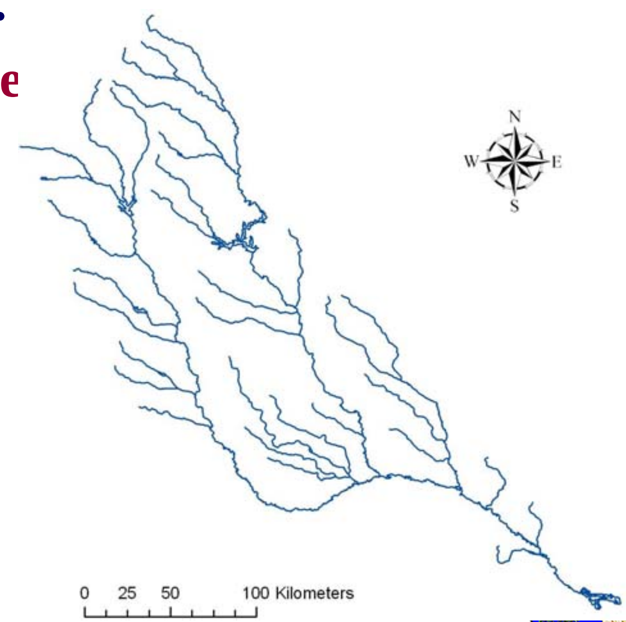
Rainfall intensities : 1, 2 and 3 in/hour
Rainfall duration : 1 hour
Rain Concentration: 10 mg/L
Simulation time : 10 hours

# Altamaha River Basin Application:

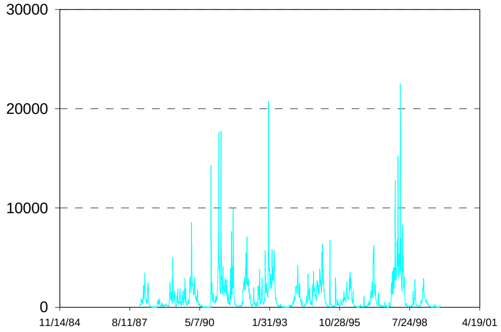


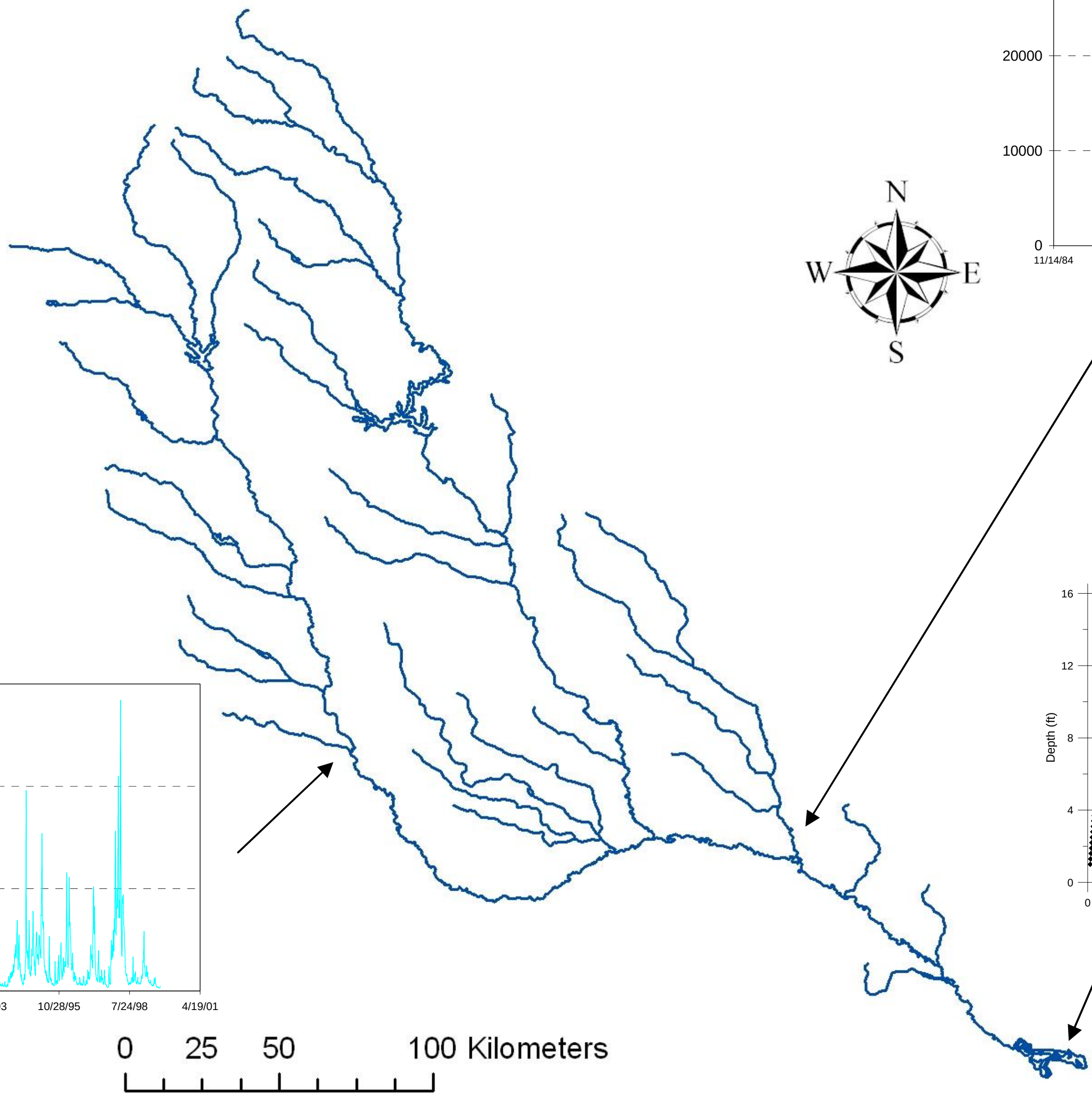
# Altamaha River Network (Assumptions):

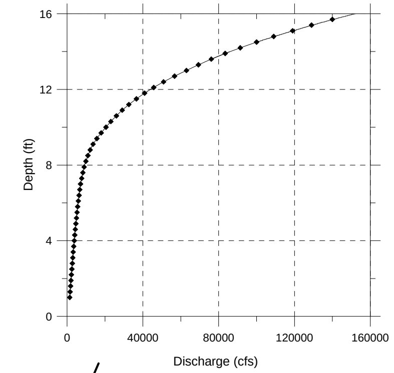
- **Trapezoidal Channels throughout river network;**
  - **GIS and USGS based channel geometry data can be included.**
- **Constant slope for each river reach;**
  - **GIS and USGS based channel geometry data can be included also other spatially variable parameters can be introduced.**
- **Transient contaminant transport with fate and dilution effects ;**
  - **Unsteady rainfall events can be analyzed as demonstrated.**
- **Single contamination scenarios are considered.**
  - **Multiple contaminant sources can be conside**

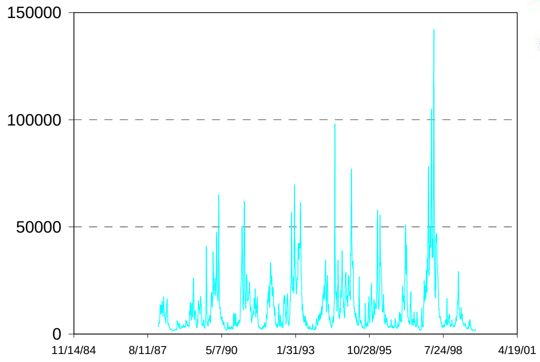


# Flow Calibration:

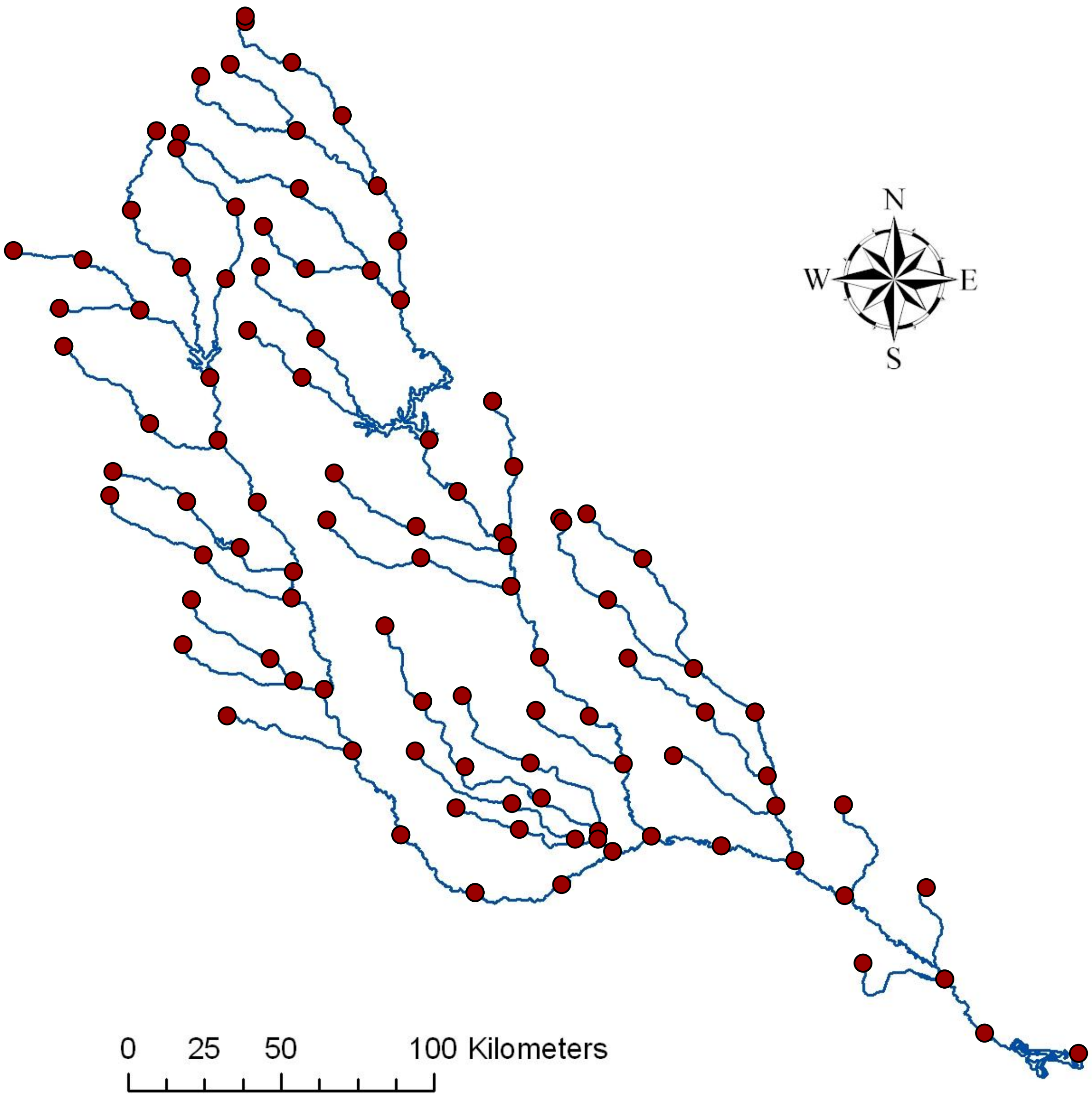


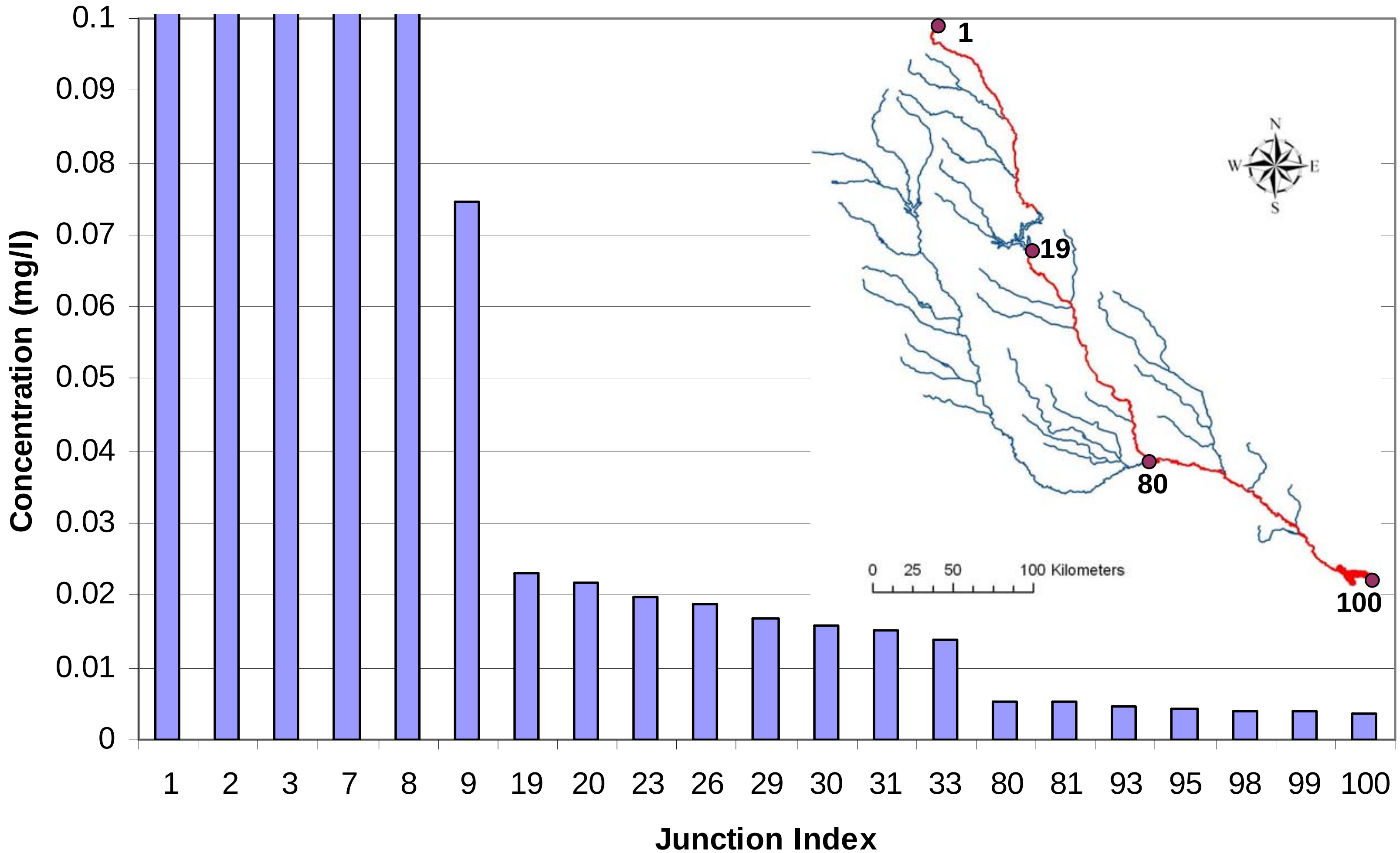



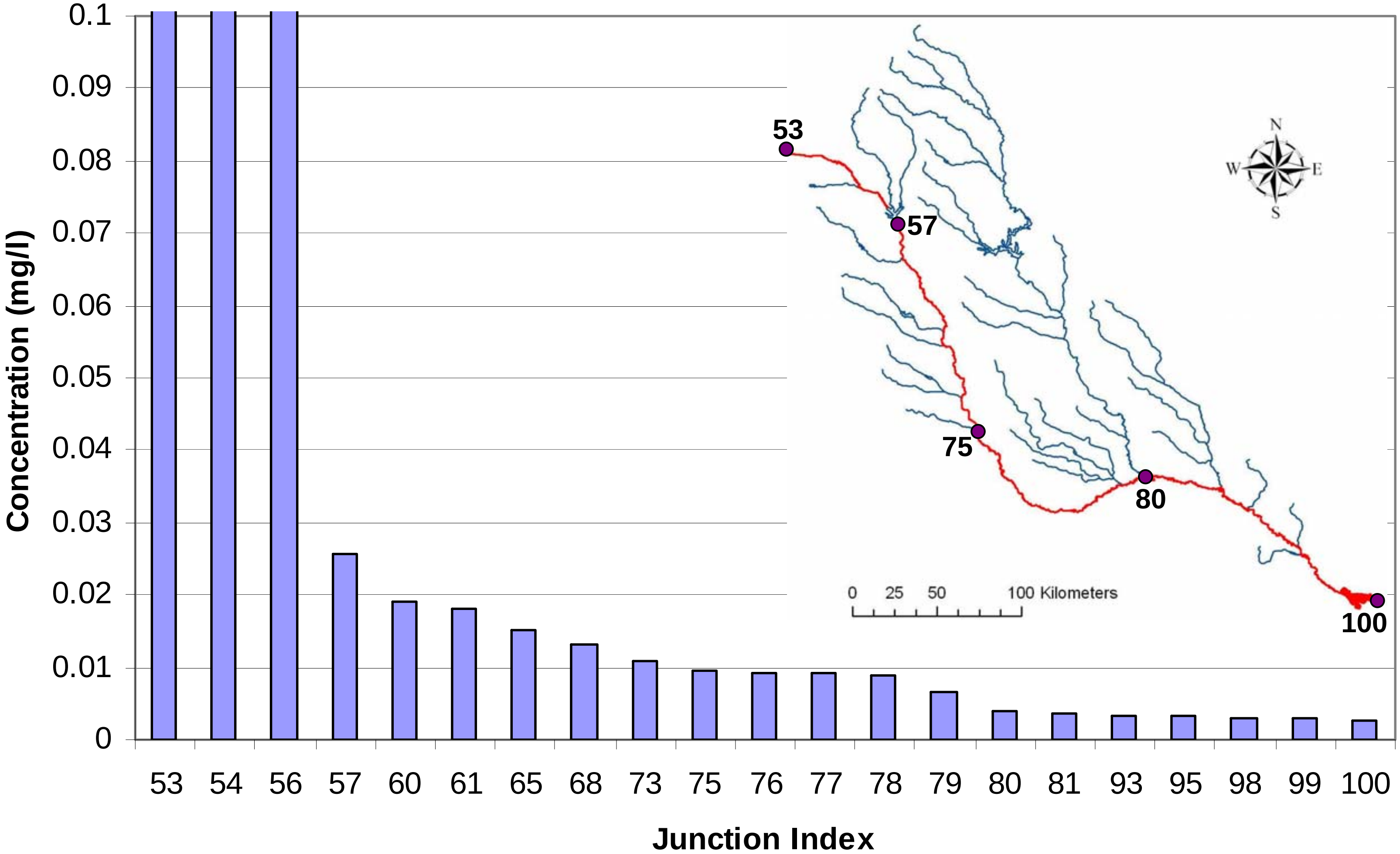
# Altamaha River Network (Scenarios):



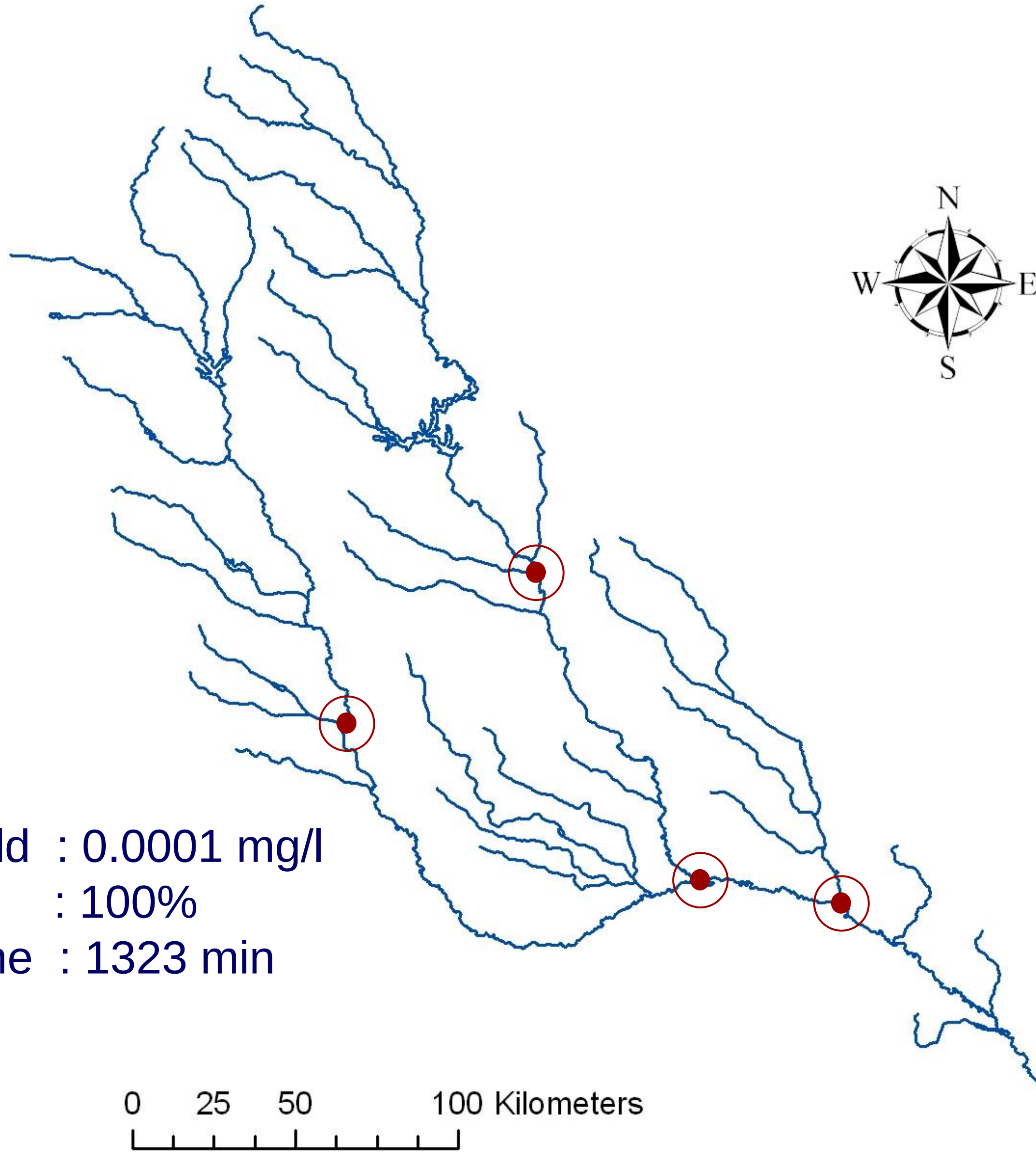
# Altamaha River Network (Breakthrough Curves-1):



# Altamaha River Network (Breakthrough Curves-2):

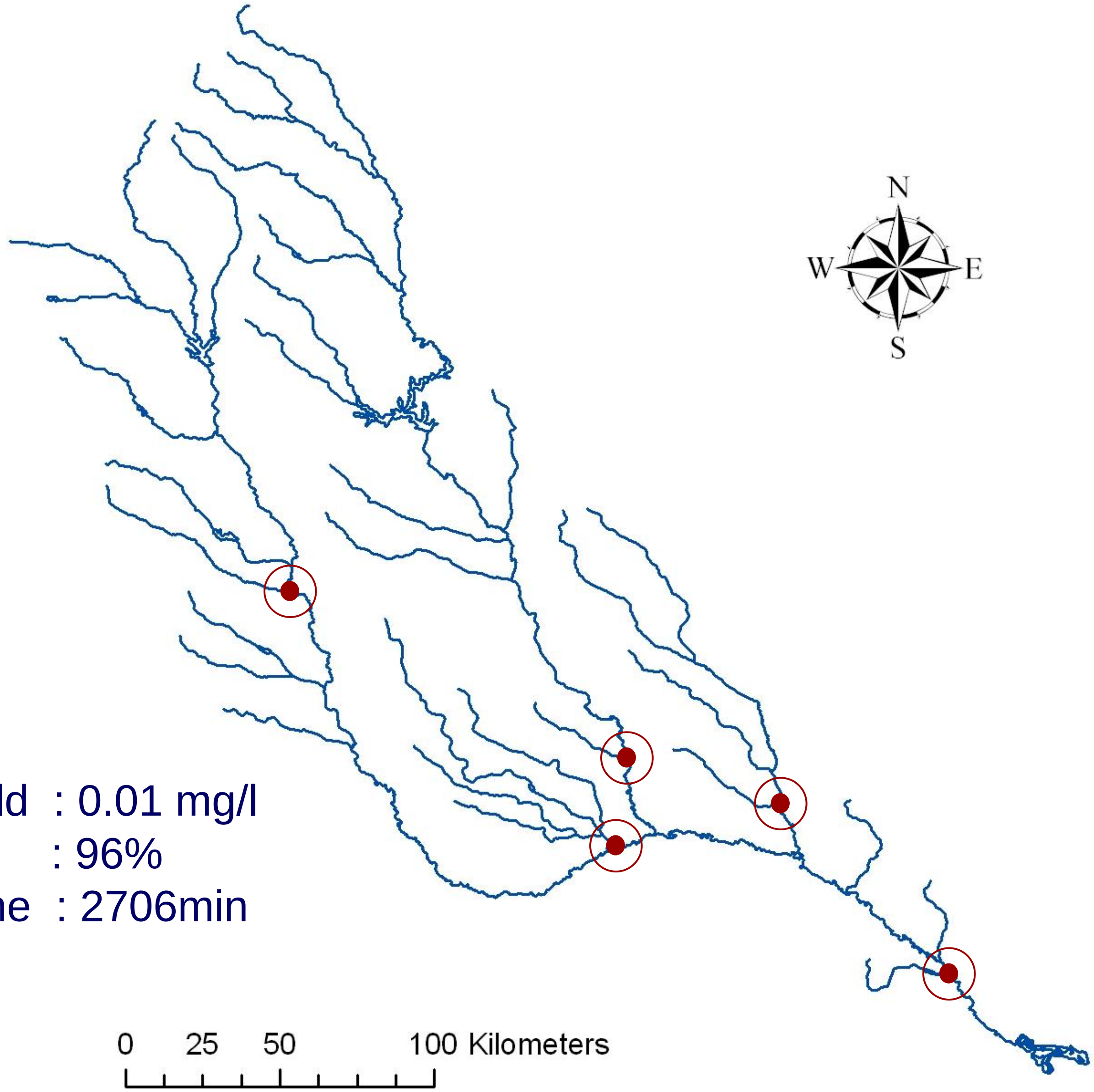


# Altamaha River Network (5 Sensor Solution):



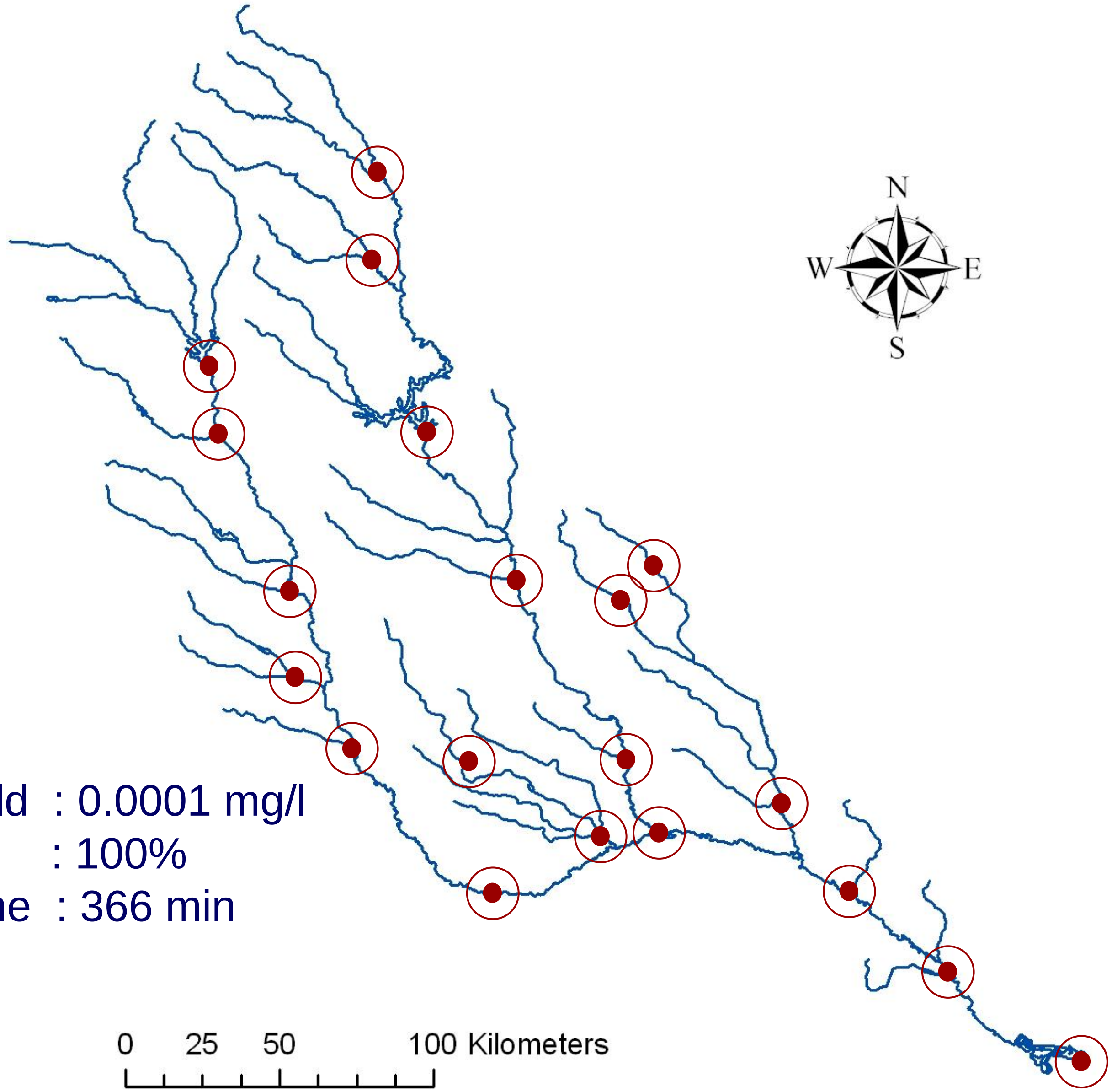

Detection threshold : 0.0001 mg/l
Reliability : 100%
Ave. Detection time : 1323 min

# Altamaha River Network (5 Sensor Solution):



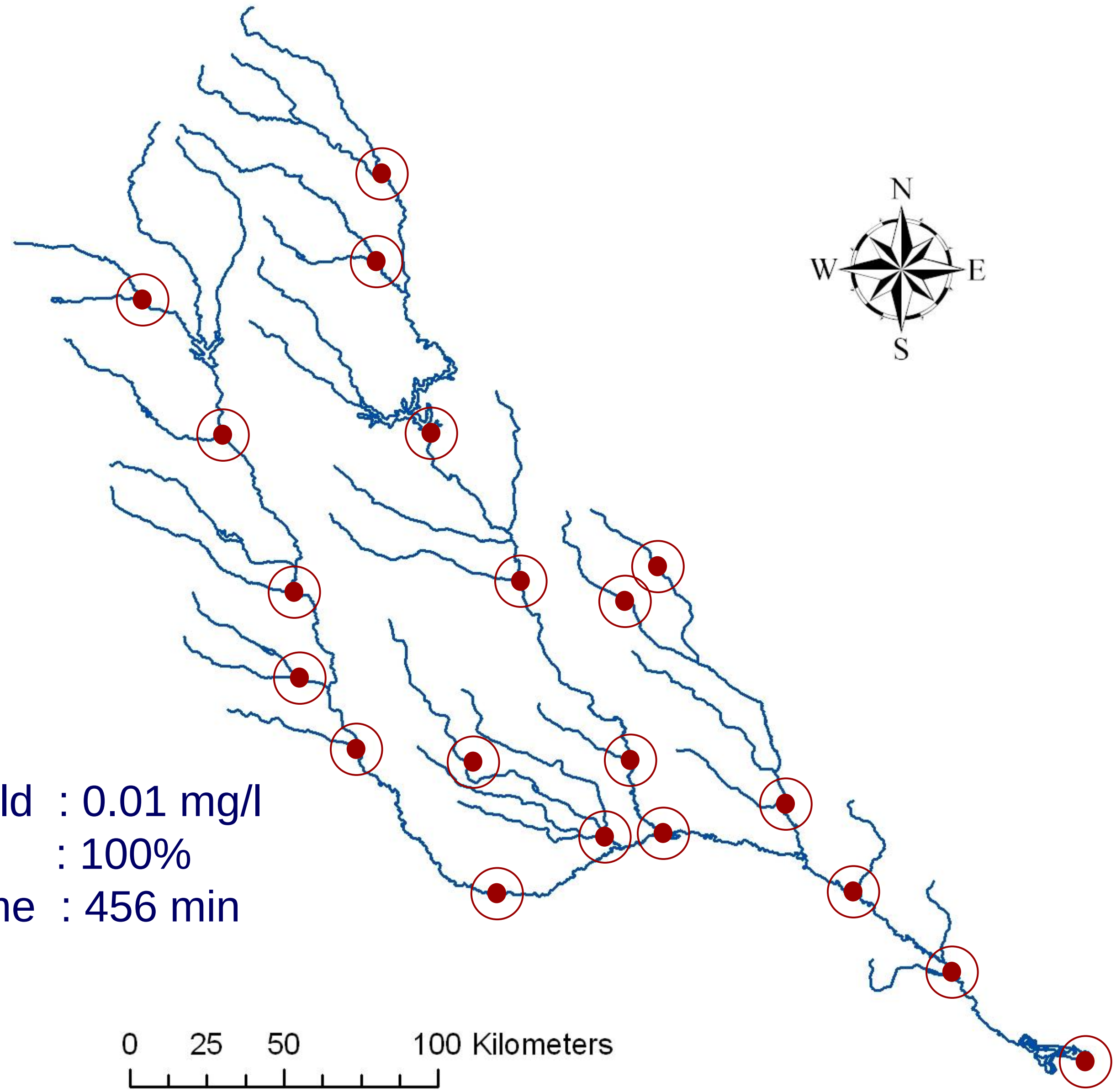

Detection threshold : 0.01 mg/l
Reliability : 96%
Ave. Detection time : 2706min

# Altamaha River Network (20 Sensor Solution):



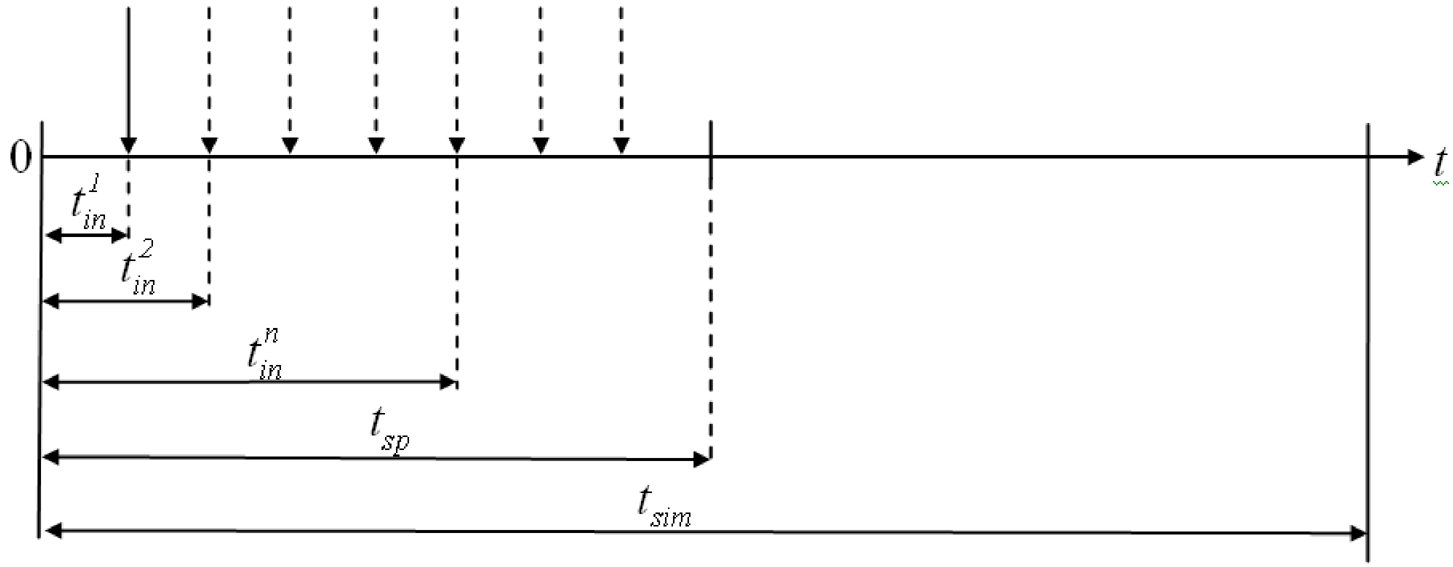

Detection threshold : 0.0001 mg/l
Reliability : 100%
Ave. Detection time : 366 min

# Altamaha River Network (20 Sensor Solution):




Detection threshold : 0.01 mg/l
Reliability : 100%
Ave. Detection time : 456 min

# Altamaha River Network (Pareto Front Analysis)




$$t_{dl}^{n} = t_{sim} - t_{in}^{n}$$

(max travel time 8 days)

$t_{in}^{n}$ : $n^{th}$ selected time of injection. $n = 1,2,3,...$

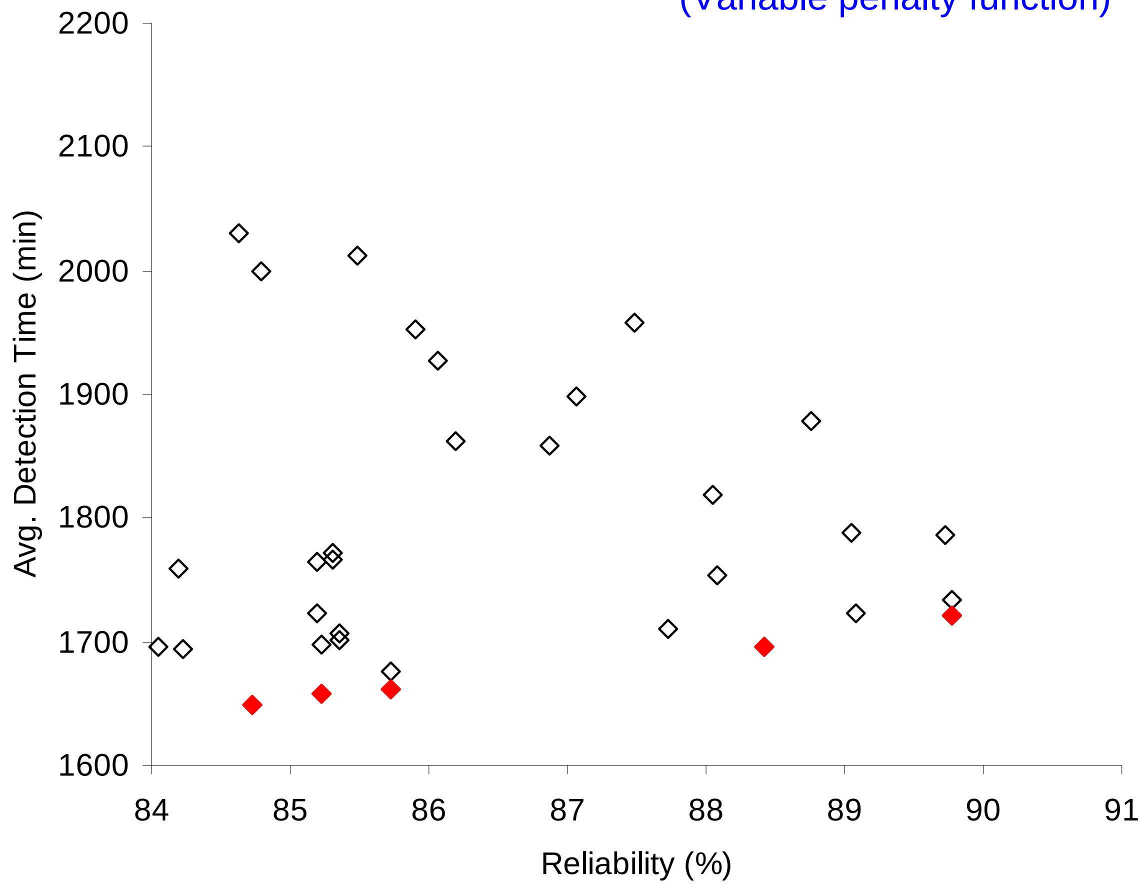
$t_{sp}$ : Time period for possible spills to occur (2 days).

$t_{sim}$ : Simulation time (4 days).

$t_{dl}^{n}$ : Detection time limit for the scenarios with $n^{th}$ selected time of injection and penalty for non-detected contaminations within this set.

# Altamaha River Network (Pareto Front Analysis)

Number of sensors : 5
Detection threshold : 0.01 mg/l
Number of nodes spill may occur : 100
Number of scenarios : 4800
(Variable penalty function)



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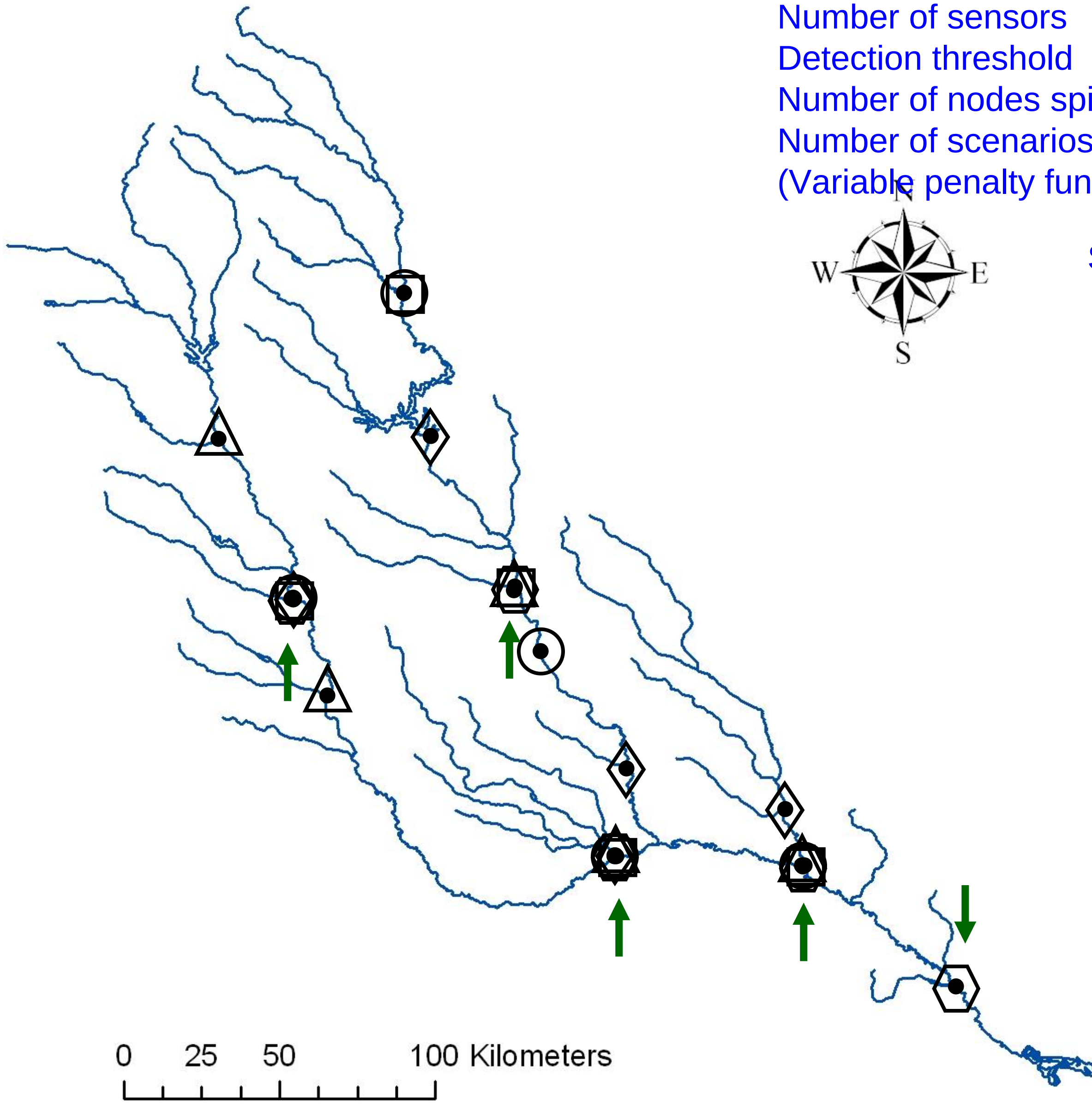
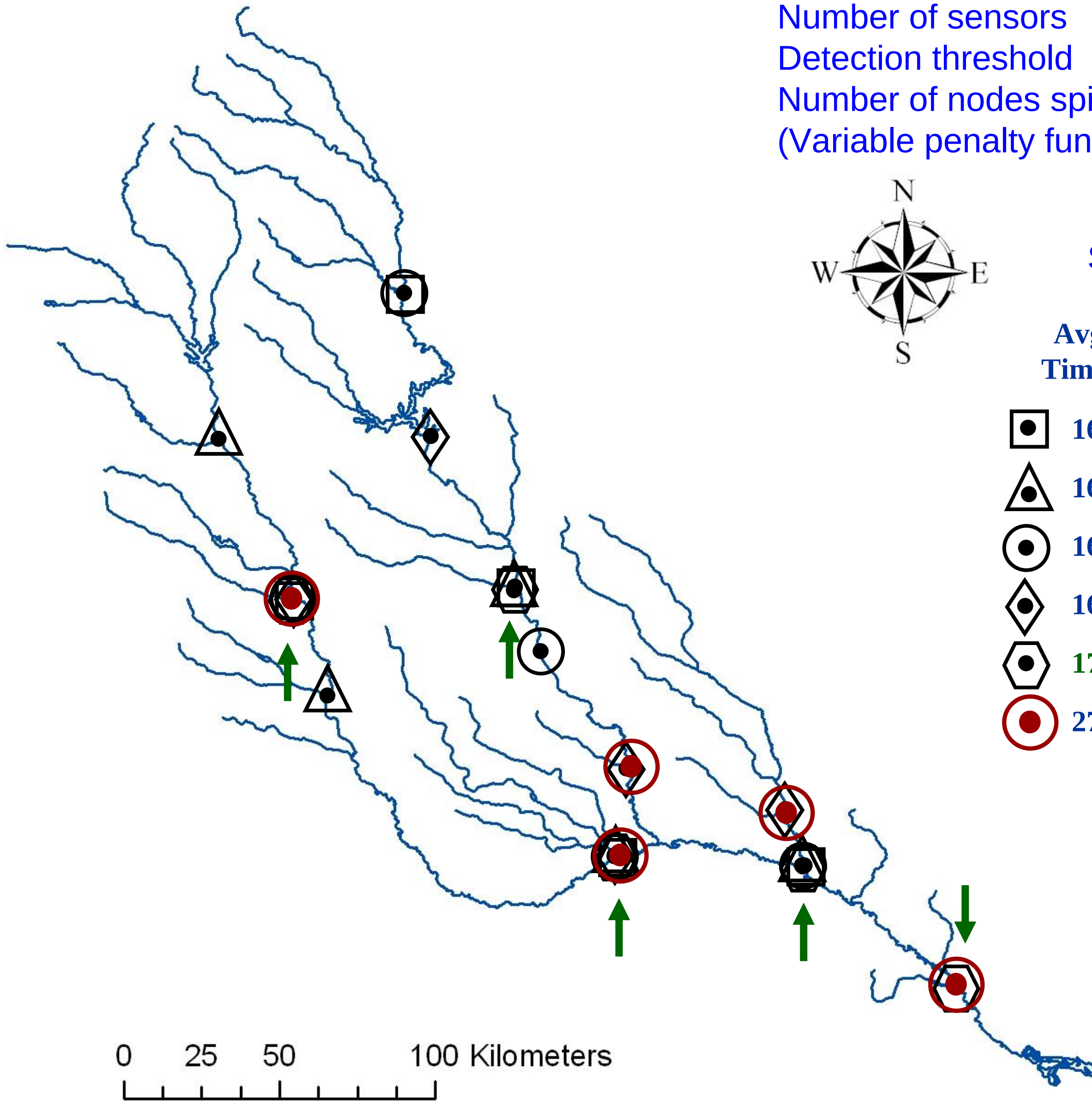



Solutions on the Pareto Front

| | Avg. Det. Time (min) | Reliability (%) |
|---|---|---|
| ⊡ | 1648.8 | 84.7 |
| △ | 1658.6 | 85.2 |
| ⊙ | 1662.0 | 85.7 |
| ◇ | 1696.0 | 88.4 |
| ⬡ | 1720.4 | 89.8 |

# Altamaha River Network (Pareto Front Analysis)




Number of sensors : 5
Detection threshold : 0.01 mg/l
Number of nodes spill may occur :100
(Variable penalty function)

Solutions on the Pareto Front

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|---|---|---|---|
| ⊡ | 1648.8 | 84.7 | 4800 |
| △ | 1658.6 | 85.2 | 4800 |
| ⊙ | 1662.0 | 85.7 | 4800 |
| ◇ | 1696.0 | 88.4 | 4800 |
| ⬡ | 1720.4 | 89.8 | 4800 |
| ⊙ | 2705.9 | 96 | 100 |

# Conclusions:

- **Hydrodynamic and watershed characteristics have important impacts on transport of contaminants through a river network which effect the optimal monitoring locations selected.**

- **Optimal monitoring locations highly depend on these factors rather than the geometry of the river system.**

- **If the objective of the monitoring system is to detect contamination in a shorter time, dynamic transport simulation is a crucial step in design.**

- **Representation of the scenarios considered is important.**

***Thank you…***