# Water-Quality Monitoring Network Optimization

## November 8, 2005

U.S. Department of the Interior
U.S. Geological Survey

# Presentation overview

- Part 1.  Data requirements
- Part 2.  Statistical methods
- Part 3.  Optimization method

Case study:  Great Smoky Mountains Water-Quality Monitoring Network (GRSM)

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# Why optimize?

- Must meet budget constraints
- Reallocation of funds to other monitoring efforts
- Determine if additional monitoring efforts are needed
- Reduce duplicated efforts
- Assessment of historical data

# What data are available?

- Land cover
- Soils
- Vegetation
- Geology
- Watershed characteristics
- Stream information
- Historical water-quality data (DLF)
- Biological monitoring data (DLF)
- Streamflow

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# GRSM Data

- Water Quality – pH, ANC, conductivity, nitrate, sulfate, chloride, sodium, and potassium
  - Quarterly grab samples
  - Period 1996-2001
- Watershed characteristics
  - Geology
  - Stream morphology
  - Vegetation
- Collocation information
  - Benthic study
  - Brook trout study
- Costs
  - Laboratory
  - Site access

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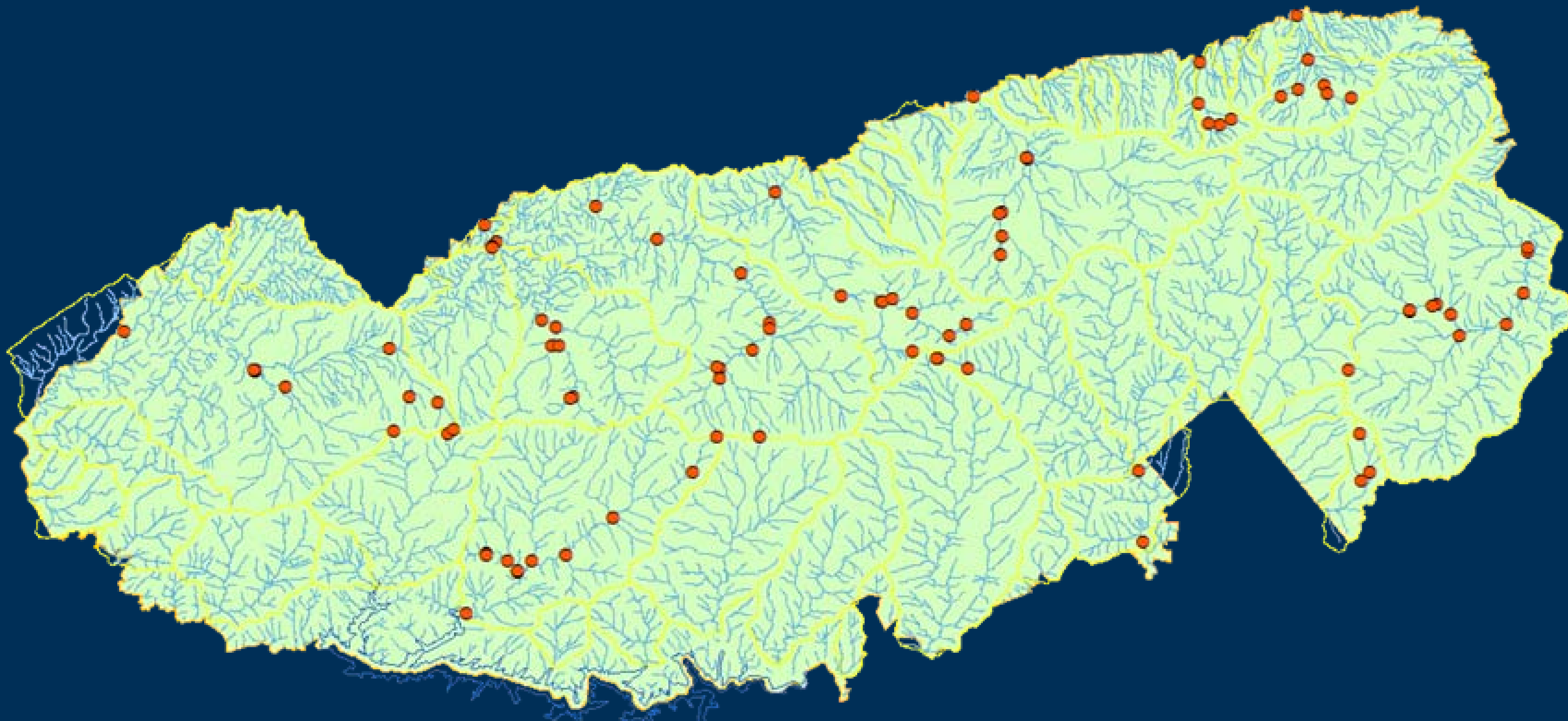
# Great Smoky Mountains Network



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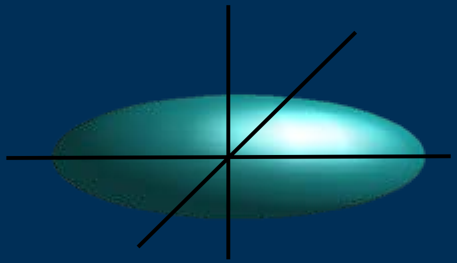
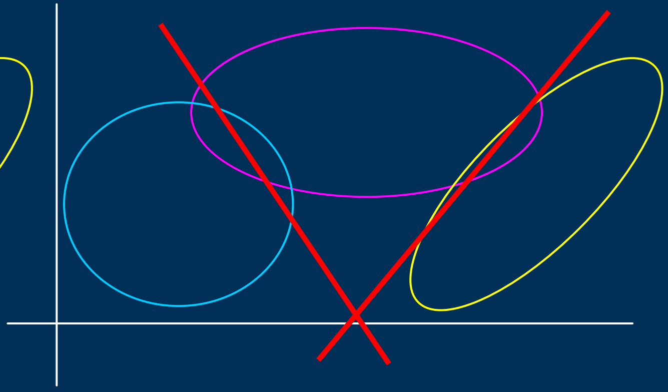
# The statistics toolbox

- Data screening (descriptive statistics)
- Principal components analysis (PCA)
- Cluster analysis (CA)
- Discriminant analysis (DA)
- Robust PCA

# Multivariate statistical methods

- **Principal components analysis – reduce the dimensionality of the data**
- **Cluster analysis – group similar sampling sites together then use cluster centroid distance as a measure of variability explained within each cluster**
- **Discriminant analysis – validation test for the clusters that were formed using cross-validation method**





# Optimization needs

- Mechanism for assigning benefits to sampling sites
- Objective function to score and compare different network designs
- Knowledge of any special circumstances that may need to be addressed in the benefit assignment or programming phase

# Special considerations (GRSM)

- Small clusters should remain intact – only clusters with large memberships should be targeted
- Ensure that all water-quality, geology, morphology, and vegetation clusters are represented in the final network

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# Determining costs and benefits (GRSM)

- Total network cost of $69,200
  - $19,200 per year for access and sampling time (640 man-hours X $30/man-hour)
  - $50,000 per year for laboratory, technical, administration, and overhead (approx. $602 per site/year)
- Total Benefit = 1.2 X $69,200 = $83,040
  - Basis:  Benefit should outweigh cost
  - Basis:  20 percent return is a modest expectation
  - $BENEFIT_{TOTAL} = \$83{,}040$
- Cost of p-sites:

$$COST_p = \sum_p LABCOST + \sum_p ACCESS$$

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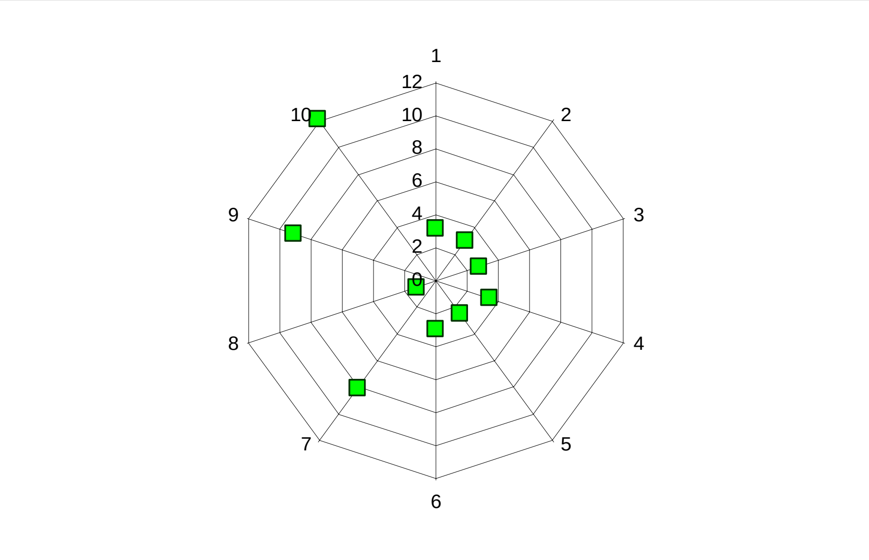
# Apportioning for site benefits (GRSM)

- **Sites ranked using distance from centroid**
- **Ranks are then summed across categories - one score for each** $\Psi_i = \omega_1 W_i + \omega_2 G_i + \omega_3 M_i + \omega_4 V_i + \omega_5 C_i$
- **All scores are then summed for apportionment total,** $\Psi_{TOTAL}$

$$BENEFIT_i = \frac{\Psi_i}{\Psi_{TOTAL}} \times BENEFIT_{TOTAL}$$

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# Optimization using simulated annealing

- Heuristic method based on the thermodynamics of heating a body to a temperature so that all bonds have been broken between molecules
- Controlled cooling is then applied so that the molecules can arrange themselves to a minimal energy state
- Simulated annealing escapes local minima/maxima
- Maximize the objective function

$$NETBENEFIT_p = \sum_p BENEFIT - \sum_p COST$$

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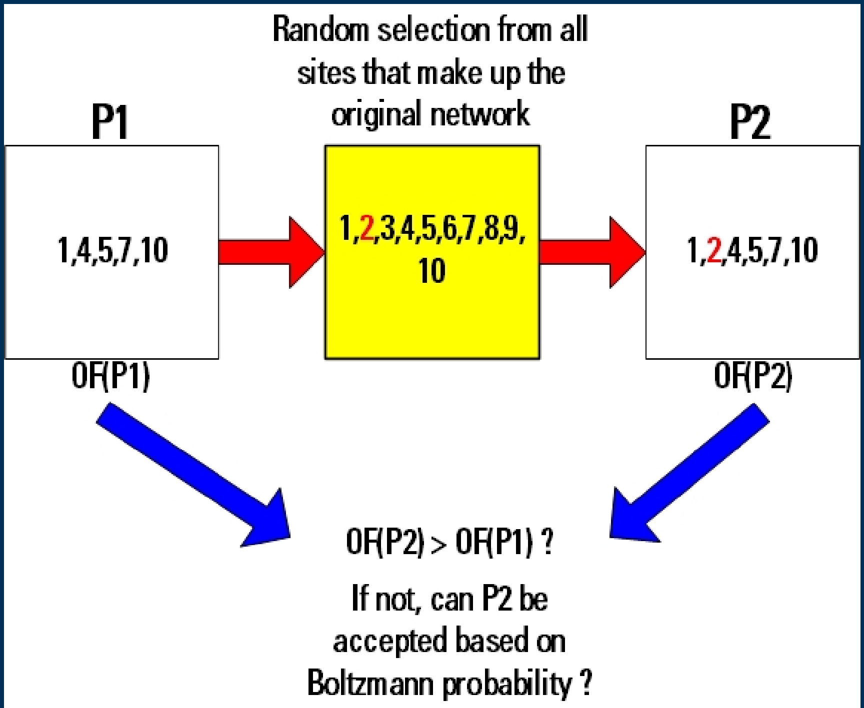
# Basics of Simulated Annealing

- Start with a network (P1)
- Randomly choose one site from all sites in the network
  - If in the P1 network, test OF for removal (P2)
  - If out of the P1 network, test OF for addition (P2)
- If OF(P2) < OF(P1), can P2 still be accepted using the Boltzmann probability?
  - As temp gets lower it becomes harder for a network to be accepted using the Boltzmann probability
- Continues until the termination loop is satisfied

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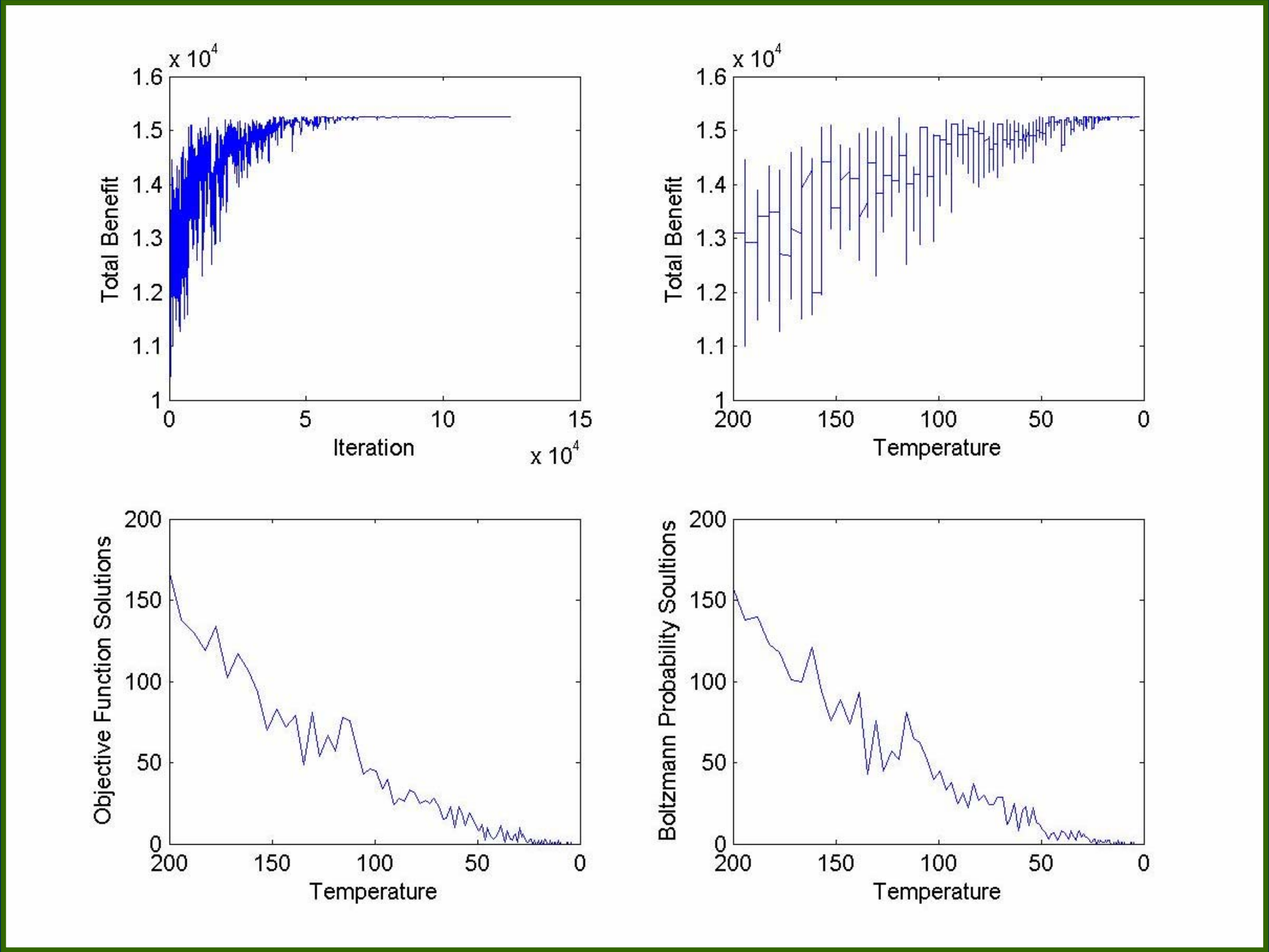
# Objective function tracking

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# Network optimization

**Simulated annealing program written for two cases**

- **First case (SA1) – Simulated annealing is performed on the network to determine the overall optimum network configuration**
- **Second case (SA2) – user-specified number (n) of sites desired in the final network. The optimized network will contain exactly n-sites**
  - **Provides a validation for SA1 results**
  - **Provides a logical format for considering other sampling sites to be retained or discontinued**

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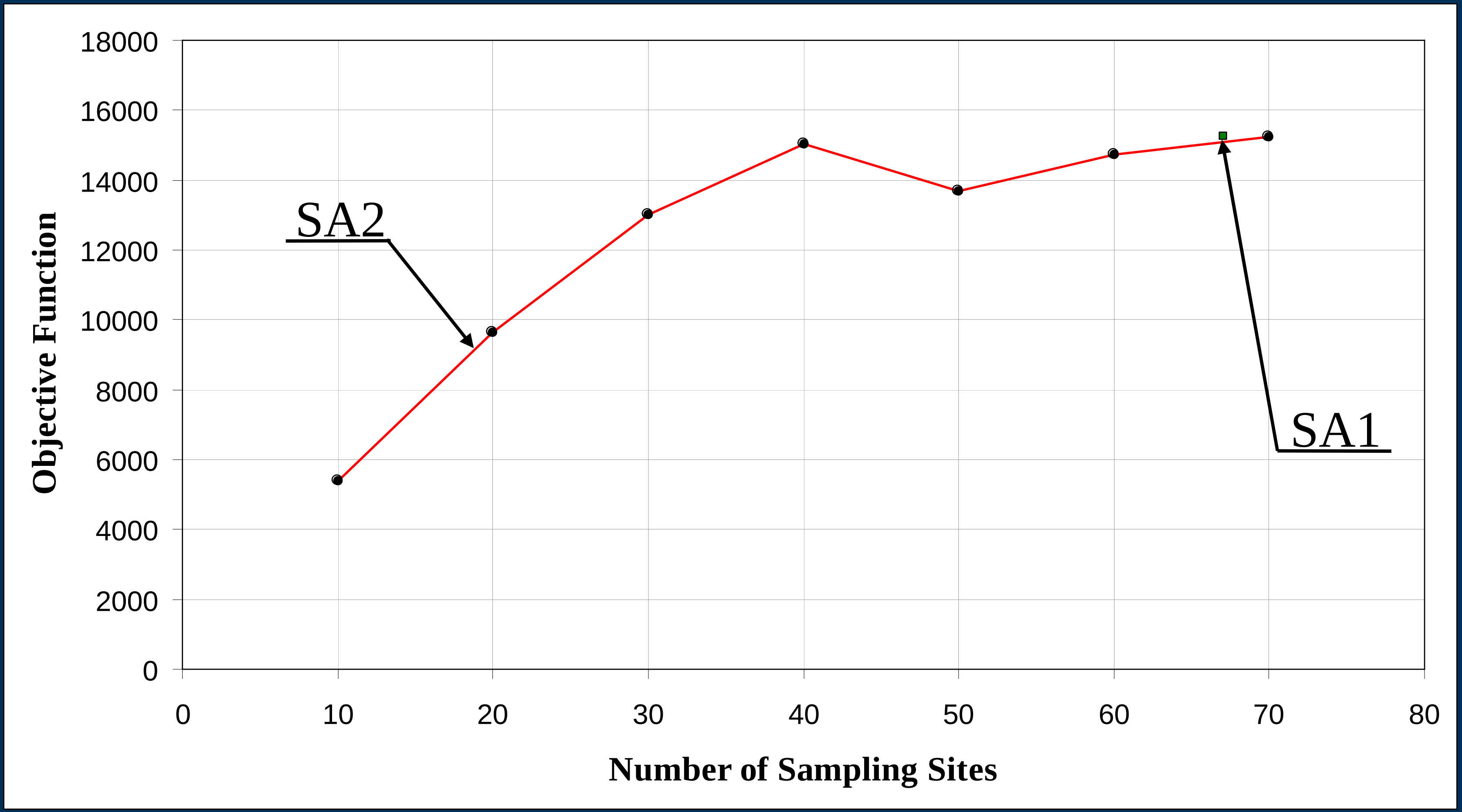
# SA2 results – *n* best sites

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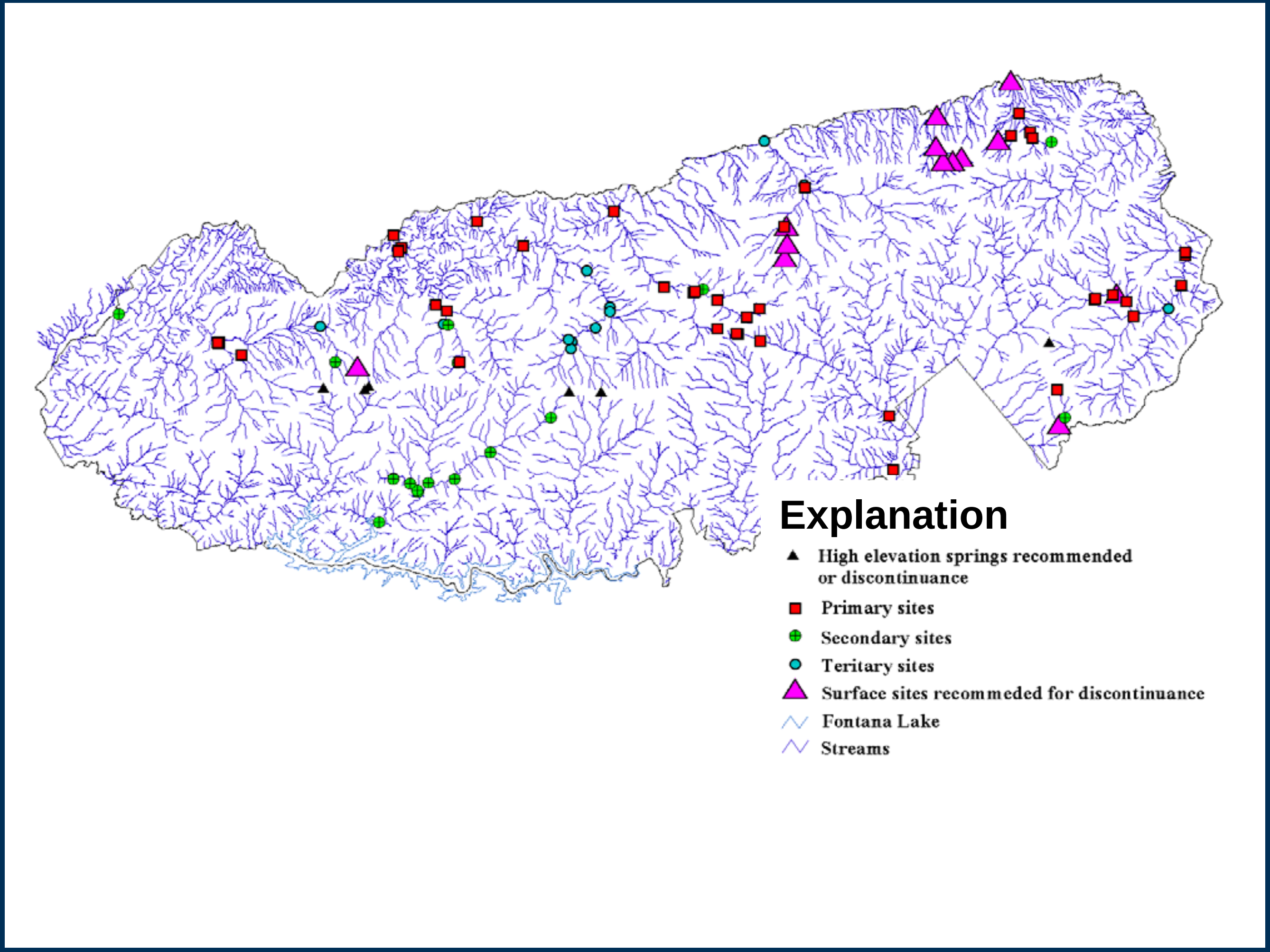
# Redesigned Network (GRSM)

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# Sensitivity analysis

- Vary weighting factors
- Test individual categories
- Vary the cost multiplier for benefits

# Temporal assessment

- Resampling of data at different sampling frequencies
- Compare trends at different sampling frequencies to the trend from the original high-frequency data (MIN)
  - Boxplot analysis
  - Mann-Kendall test for trend
  - Time series regression
- Identify frequency where dependency becomes an issue using the autocorrelation function (MAX)
- Confidence level to reliably detect a trend within a certain number of years

# ArcMap Tool Application