Linking urbanization to the Biological Condition Gradient (BCG) using a Bayesian network approach

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Decreased infiltration/
Increased runoff

Contaminants
(human waste, pesticides, chemicals)

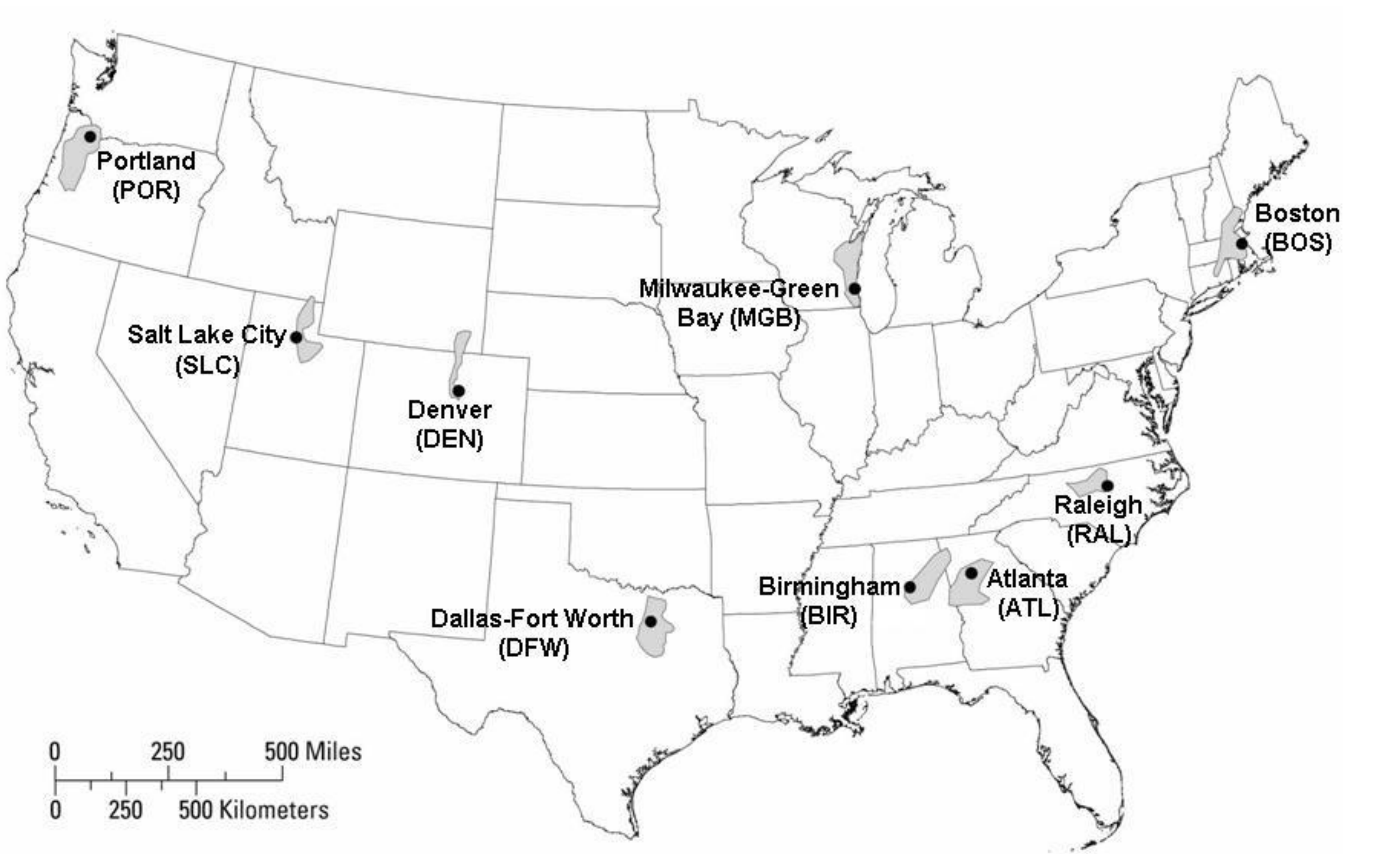
Sedimentation/Habitat disruption

Decreased canopy cover/
Destroyed riparian buffer

Channel incision/
Disconnected floodplain

Pictures: Woods Hole Research Center, USGS GA Water Science Center, Urban Creeks Council (CA), CDM Milwaukee

EUSE: Effect of Urbanization on Stream Ecosystems



USGS
science for a changing world

EUSE Study Design and Data Collection

- Regions selected to represent the effects of urbanization in parts of the country that differ in potential natural vegetation, temperature, precipitation, basin relief, elevation, and basin slope

- In each of nine regions, full suite of data collected for ~30 basins selected to represent gradient of urbanization

- Consistent measures of urban intensity, and sample-collection and processing methods across all ~270 basins total; incorporate different spatial scales

EUSE Variable Summary

Urban Intensity	Census	69 metrics
	Landcover	98 metrics
	Infrastructure	6 metrics
Physical	Hydrology	70 metrics
	Habitat	89 metrics
	Water temperature	33 metrics
	Climate	26 metrics
	Soils	25 metrics
	Topography	12 metrics
Chemical	Nutrients	52 metrics
	Pesticides	96 metrics
	SPMD Chemistry	29 metrics
Biological	Invertebrate response	194 metrics
	Algal response	414 metrics
	Fish response	196 metrics

Urbanization Modeling Dilemmas

- Address influences of **multiple stressors** acting simultaneously
- Incorporate **knowledge** of teams of subject matter experts and **data** into model construction
- Link effects of urbanization to **management endpoint**
- **Rank** management options incorporating science and uncertainty

Solution:
Bayesian Network Model

- Predict system of urbanization affecting biological condition using probabilistic nodes-and-arrows graphical interface

- Benefits:
  - **Decomposable** (parameterize conditionally independent subsets)
  - **Efficient** (calculate joint distribution, store a lot of information)
  - **Flexible** (relaxed assumptions, can model any structure)
  - **Updatable** (Bayes Theorem can combine expert and data info)
  - **Transparent** (many types of evaluation diagnostics)

- Ultimately, link to Biological Condition Gradient (BCG)
  → quantifiable management endpoint

The Biological Condition Gradient:
Standardized Biological Response to Increasing Levels of Stress

Levels of Biological Condition

Natural structural, functional, and taxonomic integrity is preserved.

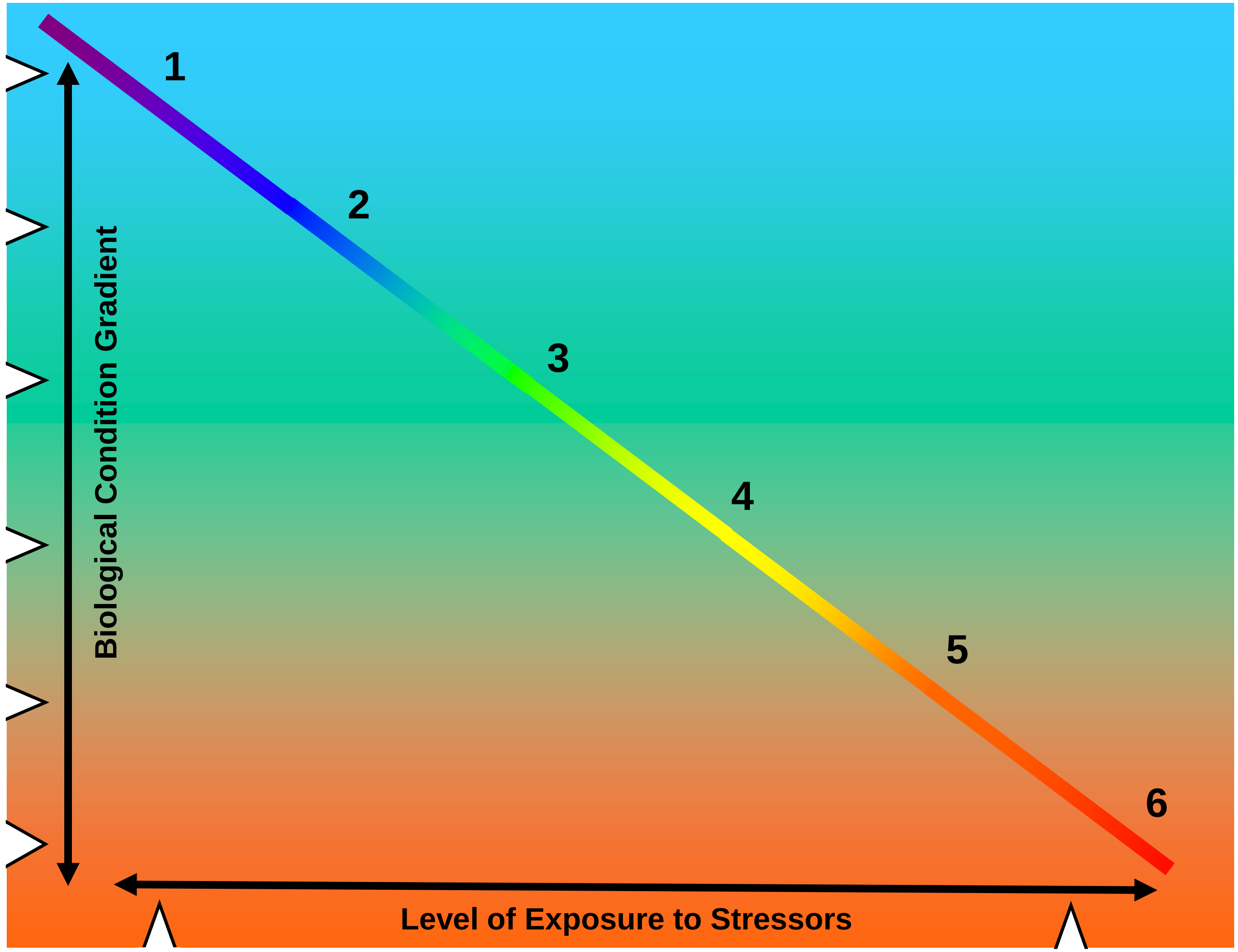
Structure & function similar to natural community with some additional taxa & biomass; ecosystem level functions are fully maintained.

Evident changes in structure due to loss of some rare native taxa; shifts in relative abundance; ecosystem level functions fully maintained.

Moderate changes in structure due to replacement of some sensitive ubiquitous taxa by more tolerant taxa; ecosystem functions largely maintained.

Sensitive taxa markedly diminished; conspicuously unbalanced distribution of major taxonomic groups; ecosystem function shows reduced complexity & redundancy.

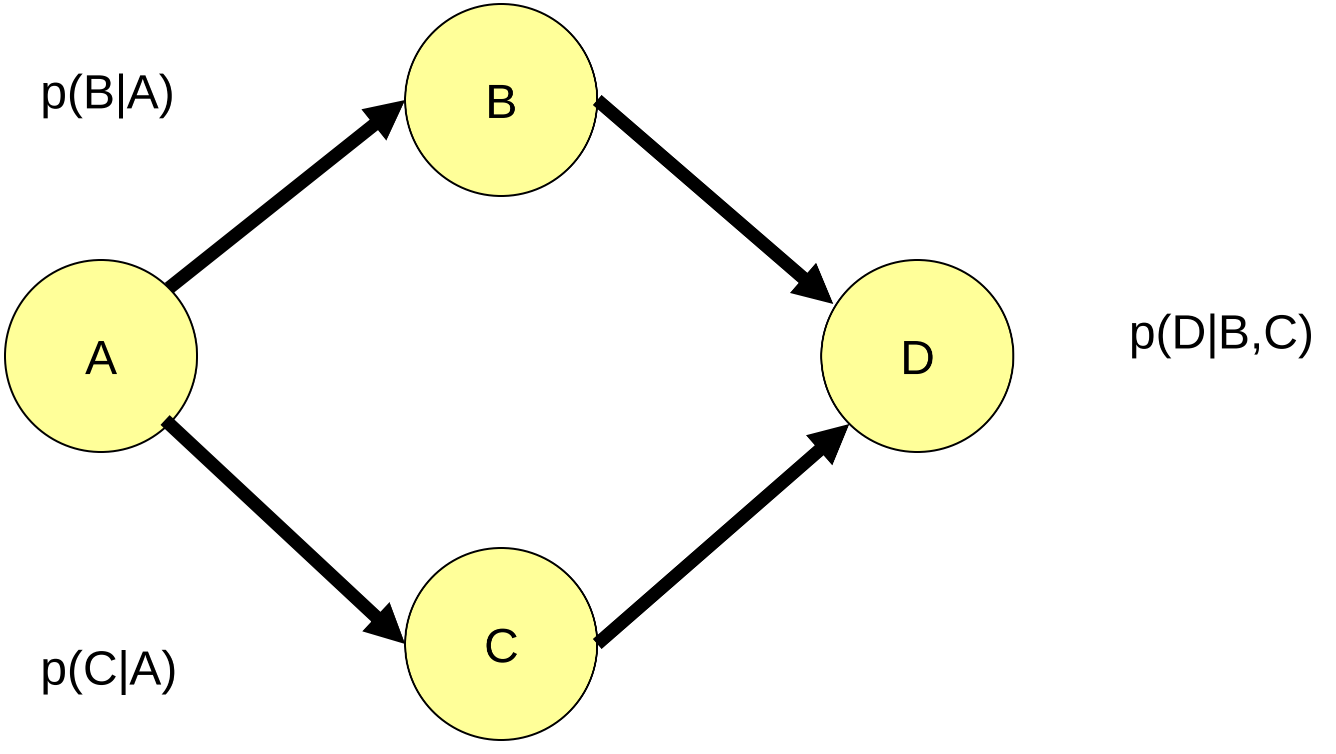
Extreme changes in structure and ecosystem function; wholesale changes in taxonomic composition; extreme alterations from normal densities.



Watershed, habitat, flow regime and water chemistry as naturally occurs.

Chemistry, habitat, and/or flow regime severely altered from natural conditions.

Bayesian network



p(A,B,C,D) =p(D|C,B)*p(C|A)*p(B|A)*p(A)

Bayes Theorem

expert prior

measured data

$$p(\theta|x) \propto p(\theta)p(x|\theta)$$

posterior

[ϴ is parameter; x is data]

Bayes Net modeling process:

1. Build the model - prior
2. Update the model - data
3. Evaluate the model - posterior

Prior model: Why Expert Knowledge?

- Expert judgment used implicitly in all model development; Need to acknowledge this and systematically, explicitly incorporate it into modeling process
- Focus on science and confirming or denying expected relationships (hypothesis approach)
- Integrated estimate of system uncertainties based on all information synthesized from career experience

EXPERTS

Biologists (Maine):

- Susan Davies, Maine DEP
- Dave Courtemanch, Maine DEP
- Tom Danielson, Maine DEP
- Susan Jackson, USEPA
- Jeroen Gerritsen, Tetra Tech Inc.
- Jim Coles, USGS
- Tom Cuffney, USGS

Water management (Massachusetts):

- Peter Weiskel, USGS
- Marilee Horn, USGS
- David Armstrong, USGS
- Chris Waldron, USGS
- Karen Beaulieu, USGS

Habitat scientists (Wisconsin):

- Faith Fitzpatrick, USGS
- Marie Peppler, USGS
- Barbara Scudder, USGS
- Amanda Bell, USGS

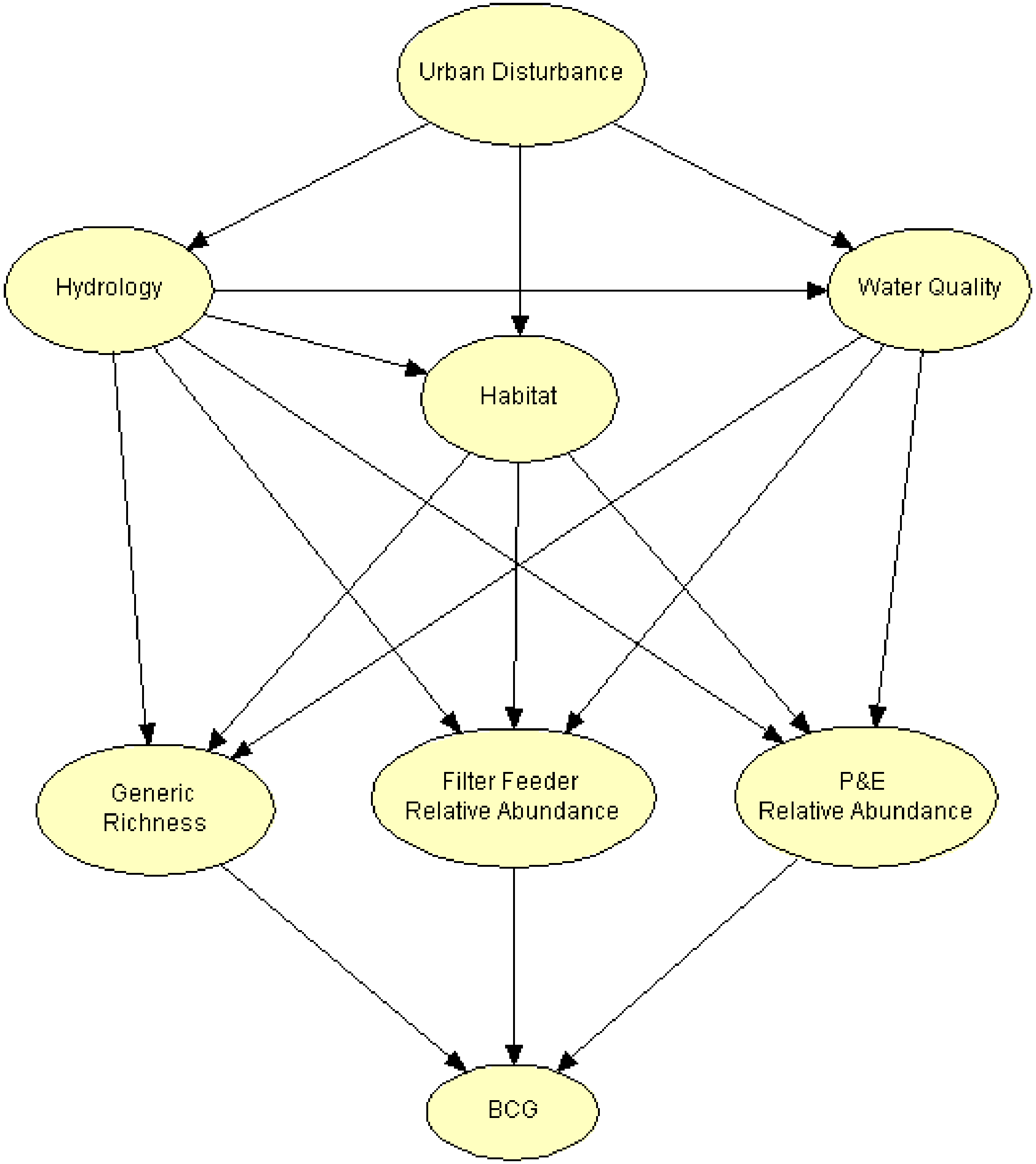
Urban planners/managers (Baltimore):

- Paul Sturm, Center for Watershed Protection
- Bill Stack, City of Baltimore, Department of Public Works, Water Quality Management Service
- Kernell G. Ries, USGS
- Ronald Bowen, Anne Arundal County, Maryland, Department of Public Works
- Janis Markusic, Anne Arundal County, Maryland, Department of Public Works
- Christopher Victoria, Anne Arundal County, Maryland, Department of Public Works
- Joe MacDonald, American Planning Association
- Karen Cappiella, Center for Watershed Protection
- Hala Flores, Anne Arundal County, Maryland, Department of Public Works
- James Gerhart, USGS

Expert Elicitation

- Develop model structure
  - Describe chain of events that link urbanization to aquatic invertebrate communities
  - Graphically represent using nodes and arrows
- Develop conditional probability tables
  - Quantify relationships between parent and child nodes
  - Quantify uncertainty in those relationships

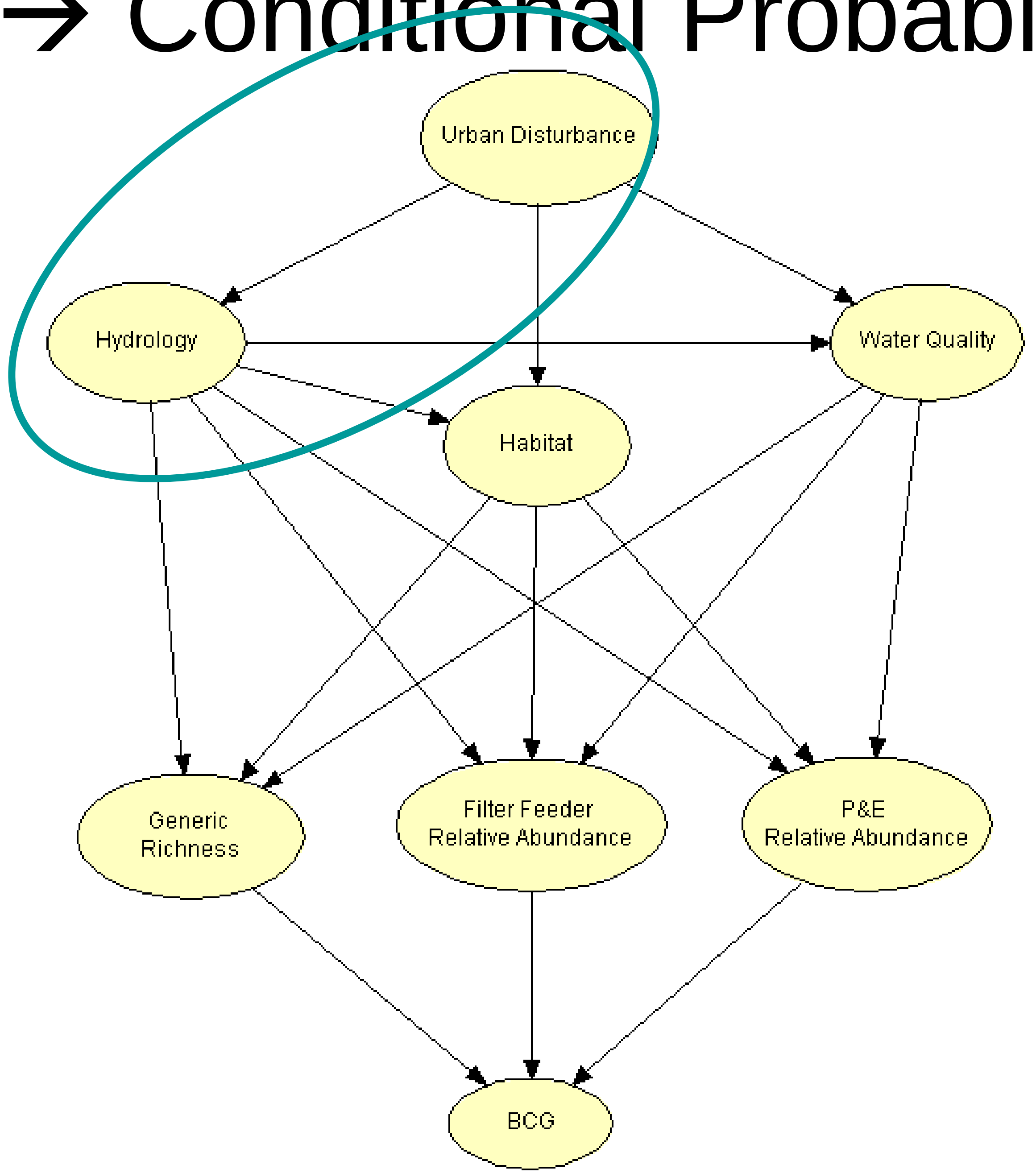
Elicit→ Model structure



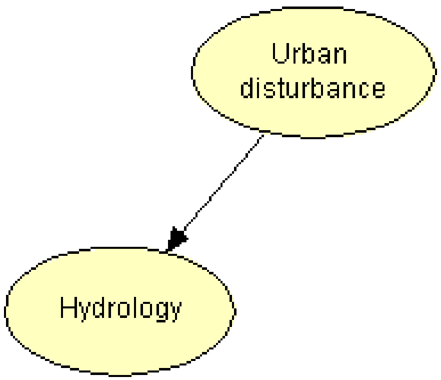
Elicit→ Variables and bins

<table>
<tr><th rowspan="2">Node</th><th rowspan="2">Variable: units</th><th colspan="6">Discrete Categories</th></tr>
<tr><th colspan="2">low</th><th colspan="2">medium</th><th colspan="2">high</th></tr>
<tr><td>Urban disturbance</td><td>Urban land cover: percent urban land cover in basin area</td><td colspan="2">0-7%</td><td colspan="2">>7-31%</td><td colspan="2">>31-100%</td></tr>
<tr><td>Hydrology</td><td>Flashiness: rises greater than seven times the annual median rise</td><td colspan="2">0</td><td colspan="2">1-3</td><td colspan="2">4 +</td></tr>
<tr><td>Habitat</td><td>Substrate: dominant (>50% of transects) substrate type</td><td colspan="3">fine
(sand and smaller)</td><td colspan="3">coarse
(gravel and larger)</td></tr>
<tr><td>Water quality</td><td>Conductivity: at low base flow, µsiemens per centimeter at 25^{O}C</td><td colspan="2">0-139</td><td colspan="2">>139-269</td><td colspan="2">>269</td></tr>
<tr><td>Generic richness</td><td>Generic richness: total number of genera</td><td colspan="2">0-14</td><td colspan="2">15-37</td><td colspan="2">38 +</td></tr>
<tr><td>Filter feeder relative abundance</td><td>Filter feeder relative abundance: percent of total abundance that are filter feeders</td><td colspan="2">0-30%</td><td colspan="2">>30-60%</td><td colspan="2">>60-100%</td></tr>
<tr><td>P&E relative abundance</td><td>P&E relative abundance: percent of total abundance that are Plecoptera or Ephemeroptera</td><td colspan="2">0-5%</td><td colspan="2">>5-20%</td><td colspan="2">>20-100%</td></tr>
<tr><td>BCG</td><td>Biological Condition Gradient: discrete scale of 1 (best) to 6 (worst)</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
</table>

Elicit→ Conditional Probabilities



Elicit→ Conditional Probability Tables (CPTs)



Assume 100 streams in the northeast US have the following characteristics,
and all other features are randomly distributed
as if you were taking a random sample of streams…

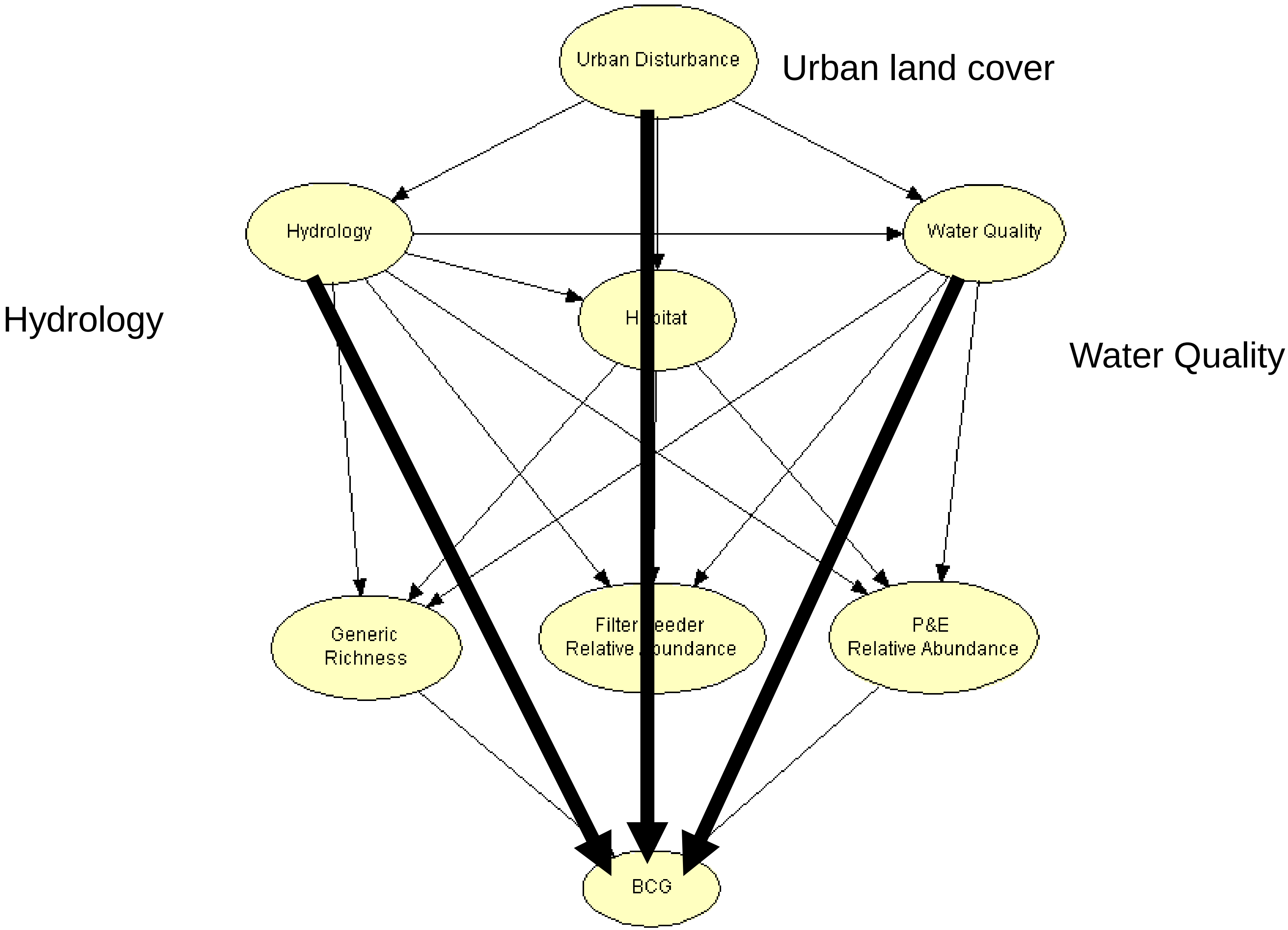
Given: How would you distribute 100 streams?

Urban disturbance: Percent urban land cover	Hydrology: Flashiness greater than 7 times the annual median rise		
Low (0–7 %)	Low (0 rises)	Medium (1-3 rises)	High (4+ rises)
	20	70	10

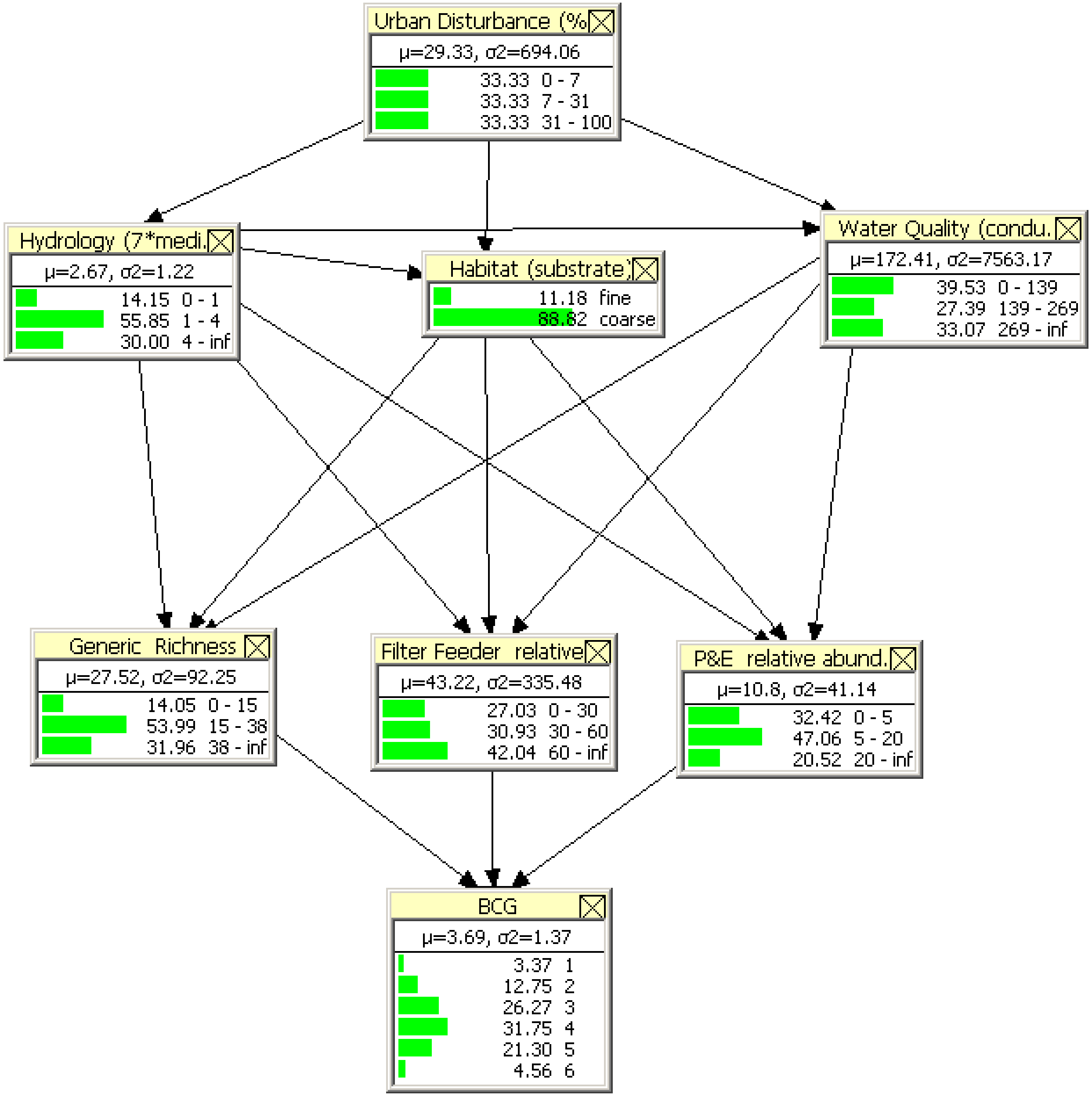
Elicit→ Conditional Probability Tables (CPTs)

Given: How would you distribute 100 streams?

Urban disturbance: Percent urban land cover	Hydrology: Flashiness greater than 7 times the annual median rise		
	Low (0 rises)	Medium (1-3 rises)	High (4+ rises)
Low (0–7 %)	20	70	10
Medium (>7-31 %)	15	55	30
High (>31-100%)	10	40	50


Urban Disturbance
Urban land cover
Hydrology
Water Quality
Hydrology
Water Quality
Generic Richness
P&E Relative Abundance
BCG

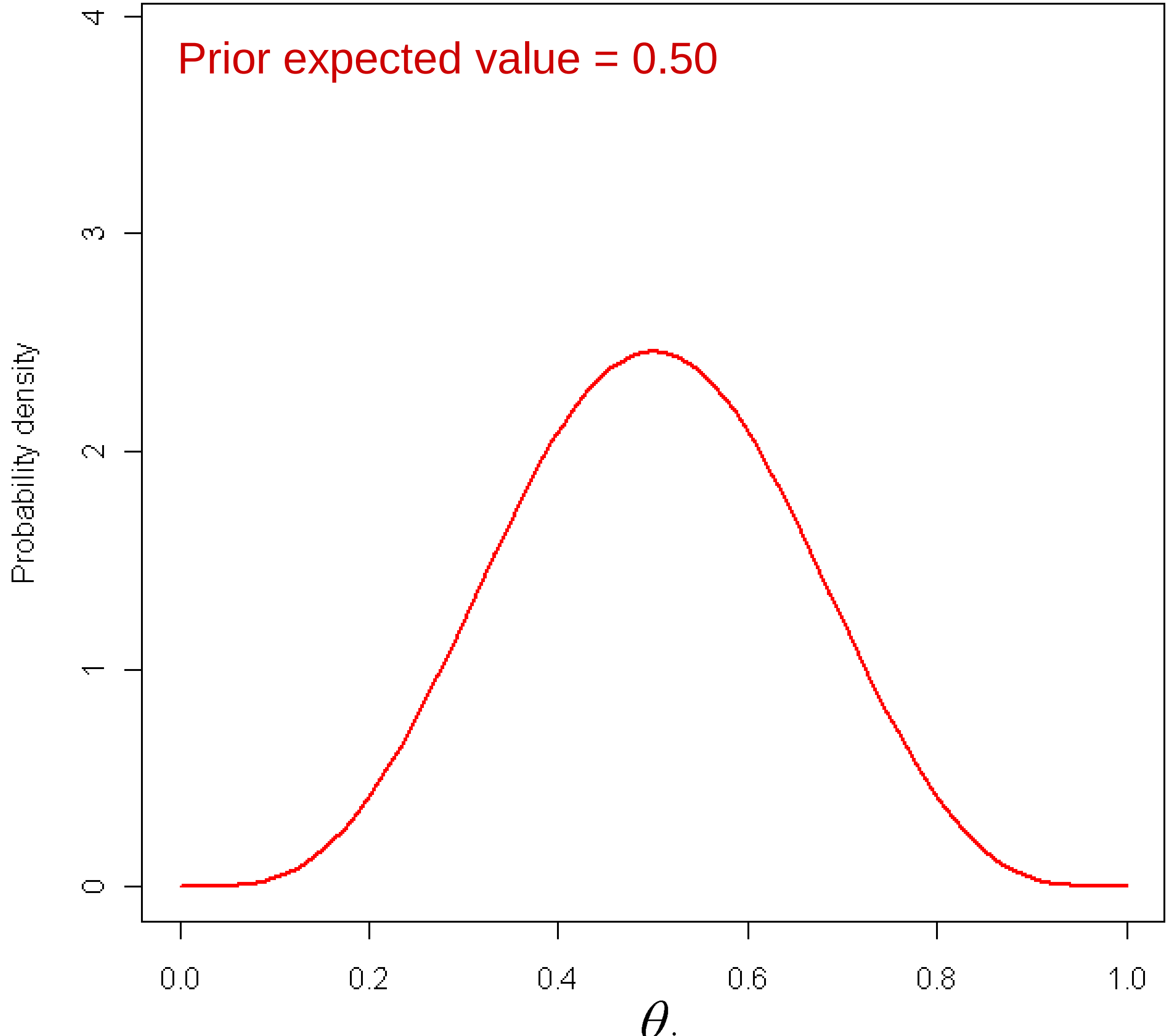
Bayesian network benefits



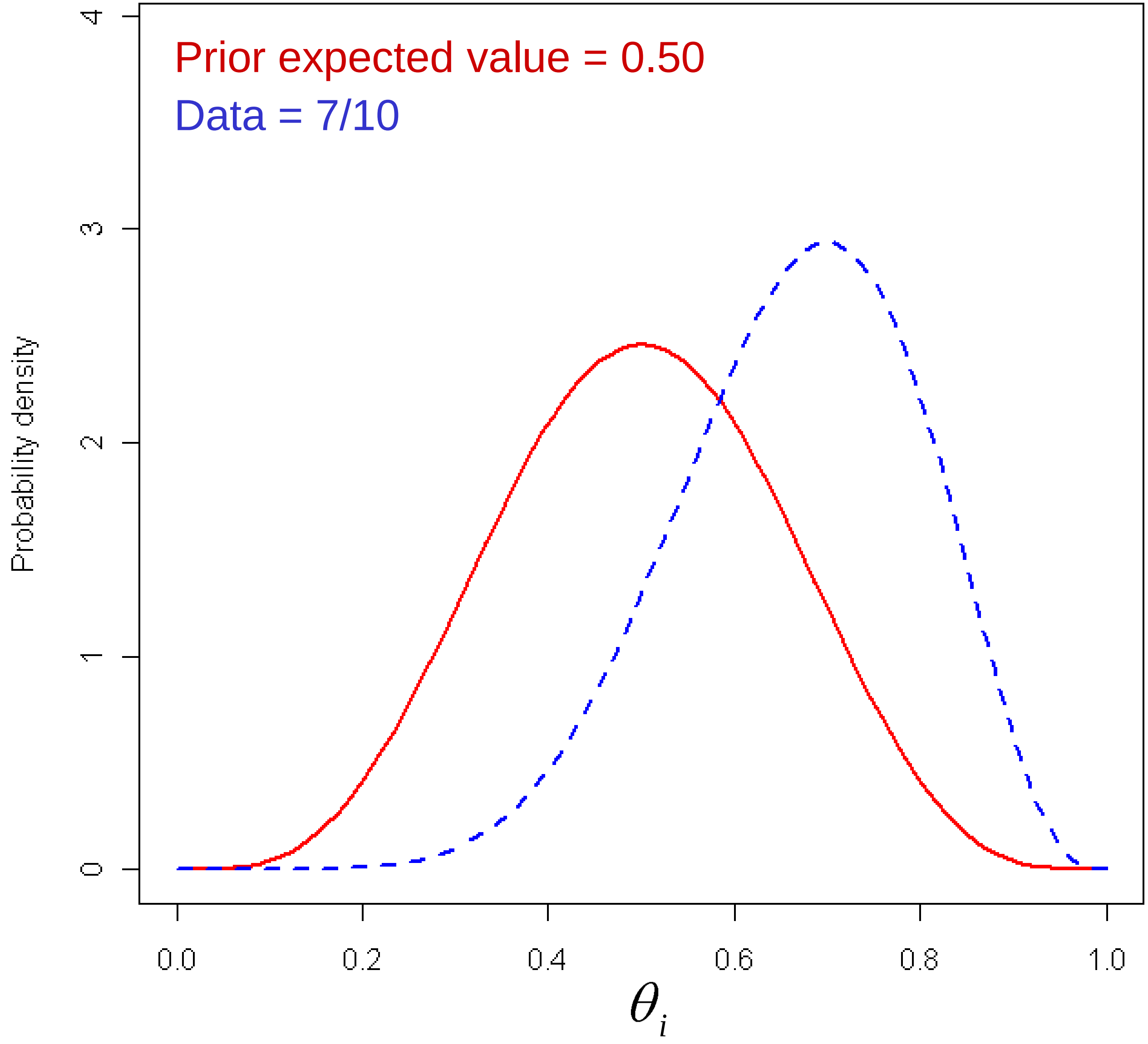
Bayes Net modeling process:

1. Build the model - prior
2. Update the model - data
3. Evaluate the model - posterior

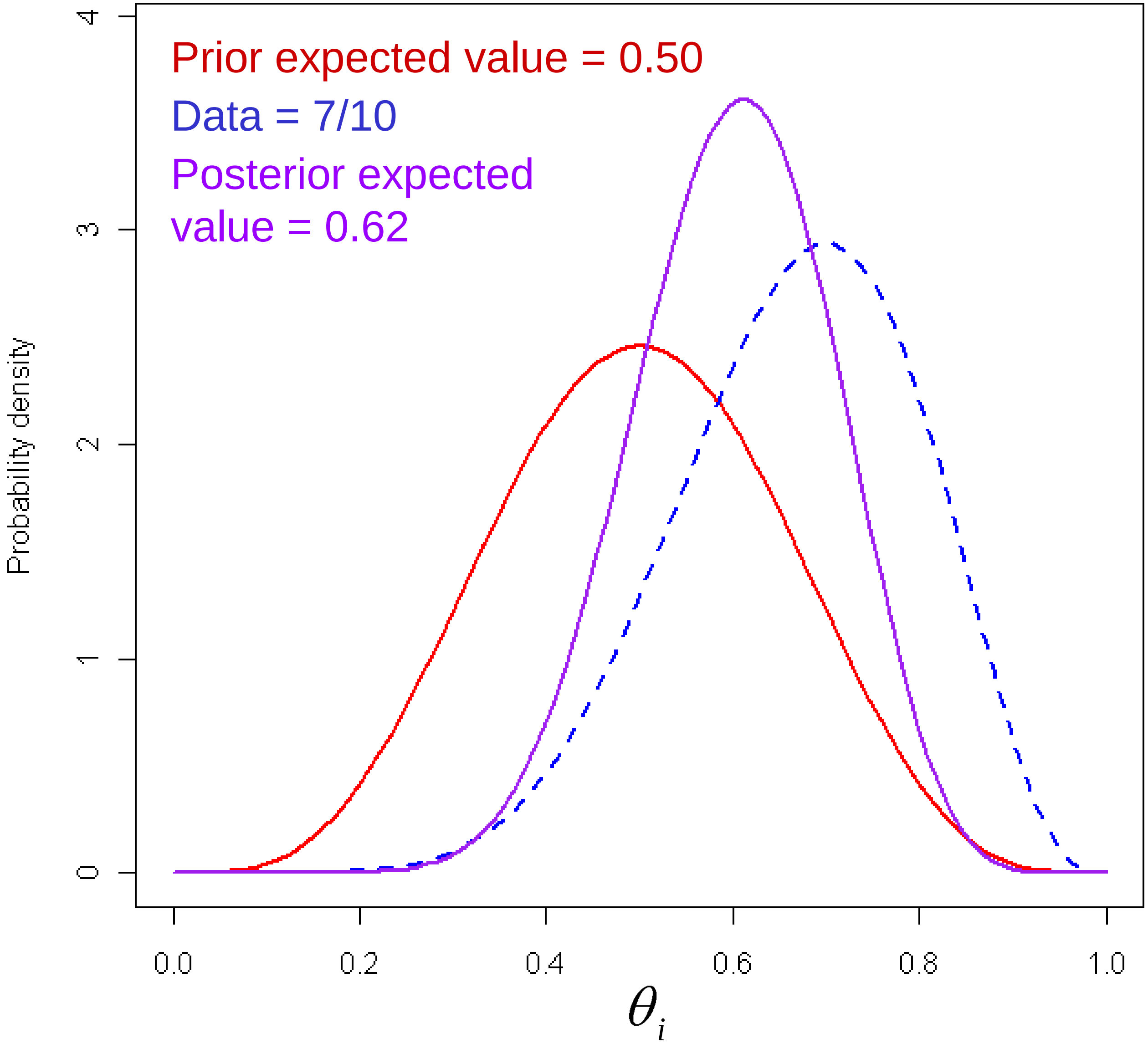
Bayesian updating



Bayesian updating



Bayesian updating



Measured data

Node	Variable	Site 1	Site 2	. . .	Site 30
Urban disturbance	percent urban land cover in basin	27	15	. . .	68
Hydrology	rises greater than 7 times the median rise	3	1	. . .	11
Habitat	dominant substrate type	fines	coarse	. . .	fines
Water quality	conductivity at low base flow	353	143	. . .	515
Generic richness	number of genera	22	35	. . .	19
Filter feeder relative abundance	percent of total abundance that are filter feeders	86.39	61.39	. . .	81.91
P&E relative abundance	percent of total abundance that are Plecoptera or Ephemeroptera	1	9.76	. . .	0
BCG	tier from 1 (best) through 6 (worst)	5	3	. . .	6

PRIOR

Urban disturbance: Percent urban land cover	Hydrology: Flashiness greater than 7 times the annual median rise		
Low (0–7 %)	Low (0 rises)	Medium (1-3 rises)	High (4+ rises)
	0.20	0.70	0.10

DATA

Urban disturbance: Percent urban land cover	Hydrology: Flashiness greater than 7 times the annual median rise		
Low (0–7 %)	Low (0 rises)	Medium (1-3 rises)	High (4+ rises)
	1/10	8/10	1/10

POSTERIOR

Urban disturbance: Percent urban land cover	Hydrology: Flashiness greater than 7 times the annual median rise		
Low (0–7 %)	Low (0 rises)	Medium (1-3 rises)	High (4+ rises)
	0.15	0.75	0.10

Bayes Net modeling process:

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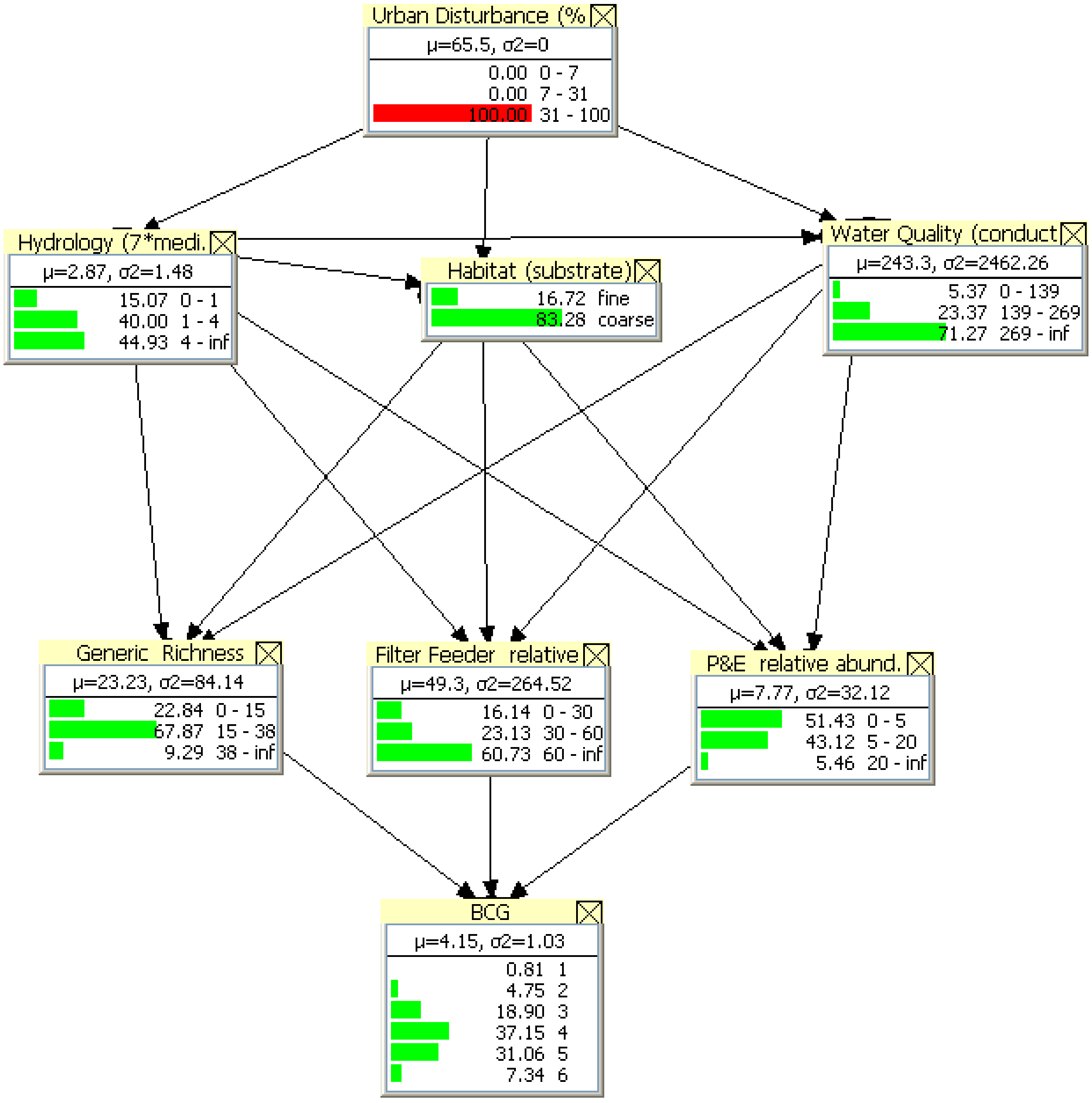
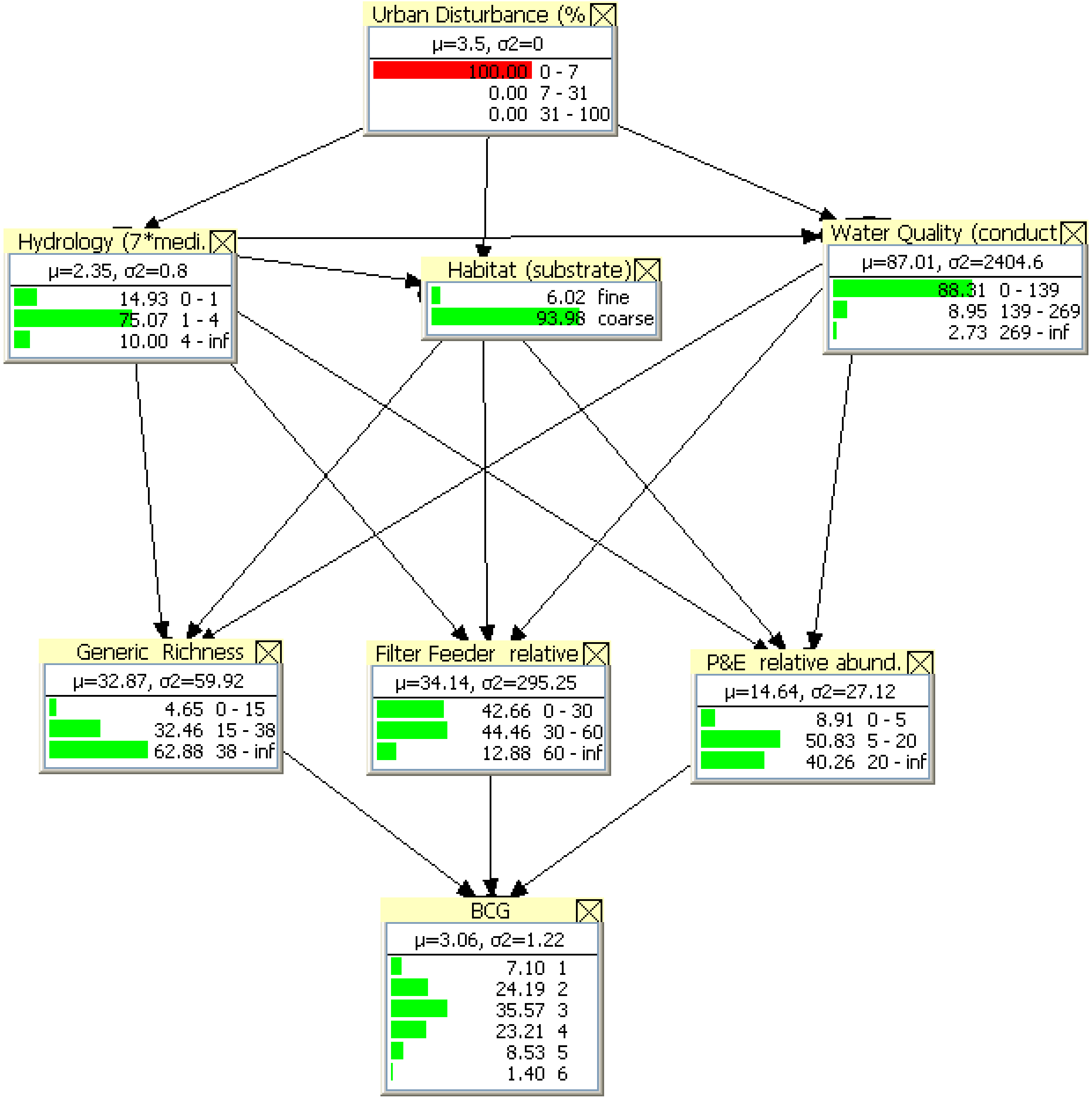
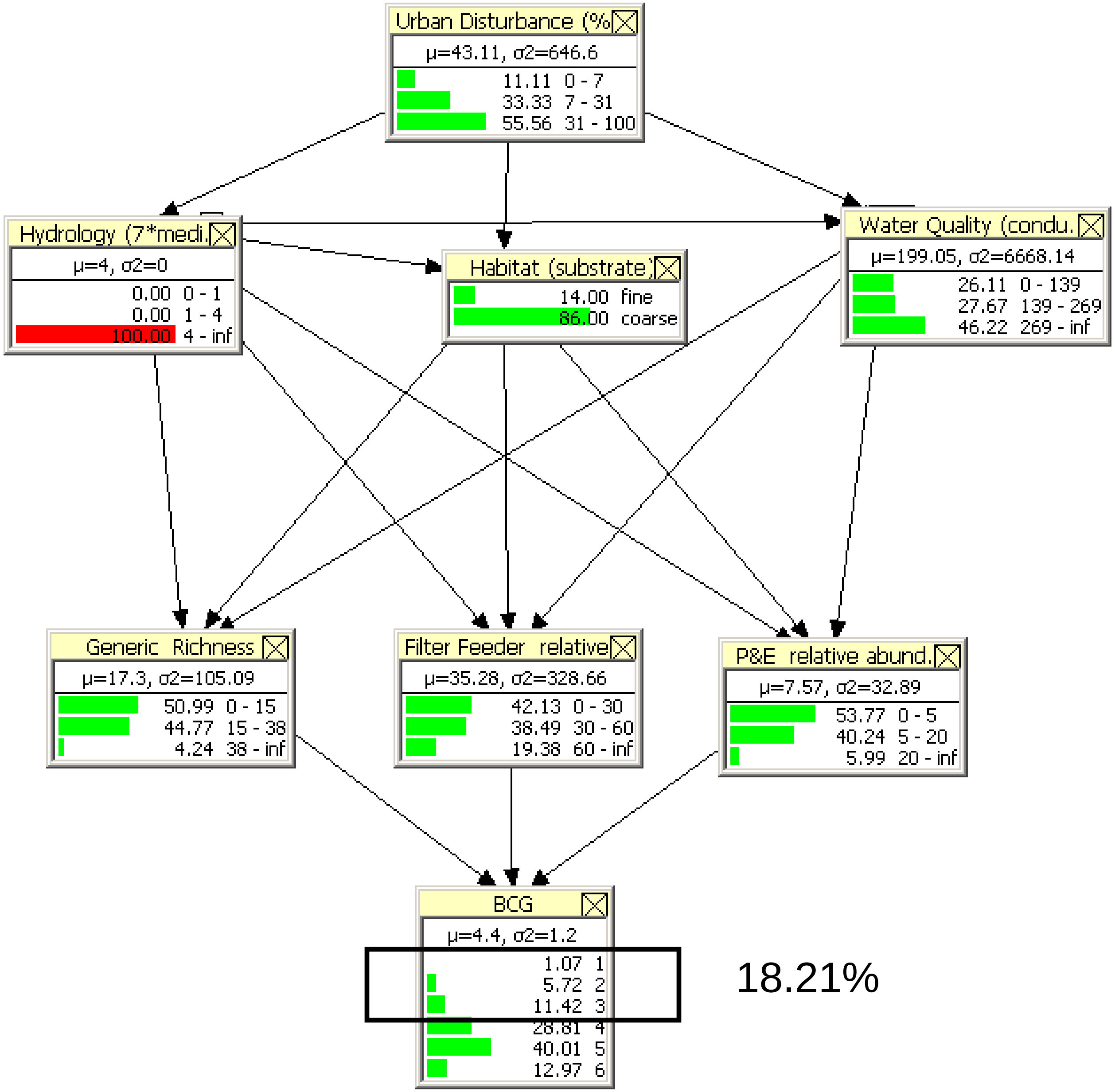
Posterior predictive: high urban



Posterior predictive: low urban

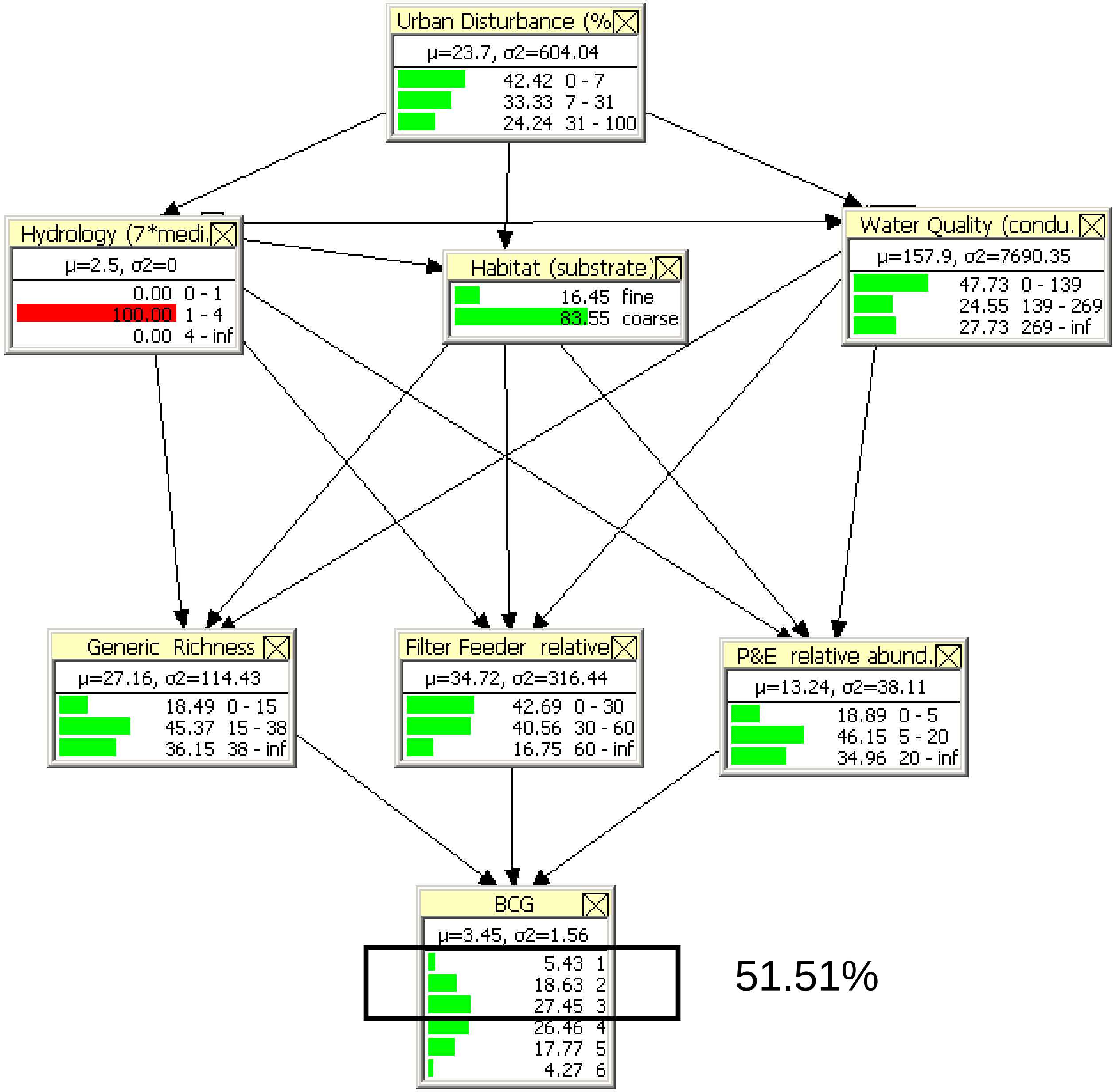


Sensitivity analysis: Decreasing flashiness from high….



18.21%

… to medium,



…increases likelihood of BCG Tier 3 or better from 18% to 52%.

	Possible stream condition improvements increases likelihood of achieving BCG Tiers by:		
	Flashiness high to medium	Substrate fine to coarse	Conductivity high to medium
BCG Tier 1	1.07% → 5.43% Δ = 4.36%	0.83% → 4.33% Δ = 3.50%	0.65% → 2.87% Δ = 2.22%
BCG Tier >2 (i.e., 1 & 2)	6.79% → 24.06% Δ = 17.27%	5.56% → 19.57% Δ = 14.01%	4.57% → 13.95% Δ = 9.38%
BCG Tier >3 (i.e., 1, 2, & 3)	18.21% → 51.51% **Δ = 33.30%**	14.06% → 45.00% Δ = 30.94%	16.63% → 37.03% Δ = 20.40%

Decreasing flashiness one bin has greater effect on BCG Tier attainment likelihood than managing substrate or conductivity

Northeast Bayesian Network Model

Conclusions:

- Can use this model to rank likelihood of attaining desired management endpoint given different management actions (in this case, managing flashiness more likely to improve BCG than managing substrate or conductivity)

- Model supports EUSE urbanization regression work but does so in more integrated, comprehensive framework

- Shows BCG can be modeled from small set of invert metrics, in terms of probability of attaining each BCG Tier

- Major contributions to literature: (1) Parameterization of BCG relative to urban stressors and (2) Introduce new framework for urbanization management modeling

Northeast Bayesian Network Model

Benefits of new framework:

- Increase conceptualization of environmental and ecological processes (network of relationships between variables)
- Able to analyze entire system together (acknowledge that biological response driven by many factors)
- Interactive end product; easy for users to understand without necessarily being bogged down with complex mathematics
- Flexible modeling construct; can incorporate a variety of possible management actions and predict effects probabilistically
- Enormous potential for use in environmental management decision making


Thank you!
Questions?
U.S. Department of the Interior
U.S. Geological Survey