Toward a decision-support system for managing Lake Champlain’s water quality under uncertain climatic and societal change

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Vermont EPSCoR

PTAC Stakeholder Meeting

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Presentation overview

- Share motivations for a **decision-support system** (DSS) for achieving water quality resilience to nutrient loading in Lake Champlain
  - Introduce a simplified optimization model for identifying **strategic investment and policy portfolios (SIPPs)** from a **basin planner's perspective**
  - Discuss challenges with representing multiple stakeholders and uncertainty
- Encourage feedback and ideas, but keep in mind data and model limitations
- Small group "problem formulation" activity at the end

Motivating questions

- Will the 2016 TMDL make the lake's water quality resilient to nutrient loading during extreme events?
  - Under current conditions?
  - In the future?
- What other actions might be necessary?
- How can our DSS identify strategies that are cost-effective and robust to future uncertainty?
- How can we use our DSS in conjunction with stakeholder expertise?

Scenario A:

- High emission climate
- More frequent and intense extreme events
- Centralized governance network
- High economic growth rate

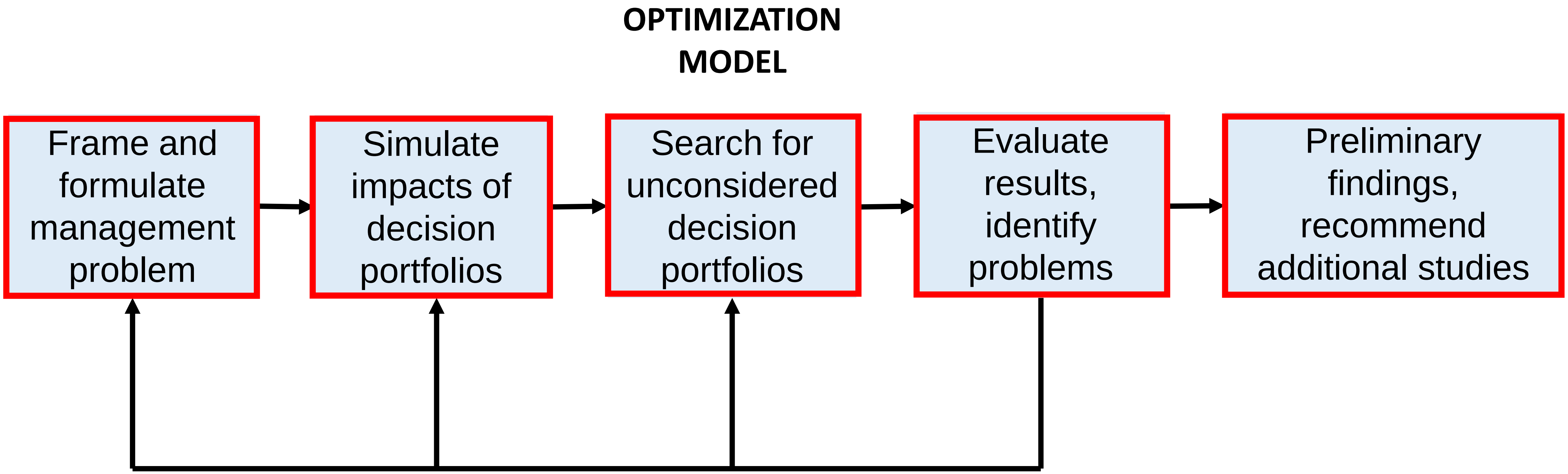
Scenario B:

- Low emission climate
- No change in the frequency and intensity of extreme events
- Decentralized governance
- Low economic growth rate

Our proposed decision-support system (DSS)

- Managing for harmful algal blooms (HABs)
    - Requires knowledge of lake conditions and extreme hydro-meteorological events
- Contains an optimization model, which can identify previously unconsidered portfolios
    - Aims to minimize HABs and their impacts to society and ecosystems
    - Aims to minimize the costs of reducing these impacts
- Contains mechanisms for incorporating stakeholder feedback into iterative model development

Decision-support system schematic



OPTIMIZATION MODEL

Frame and formulate management problem

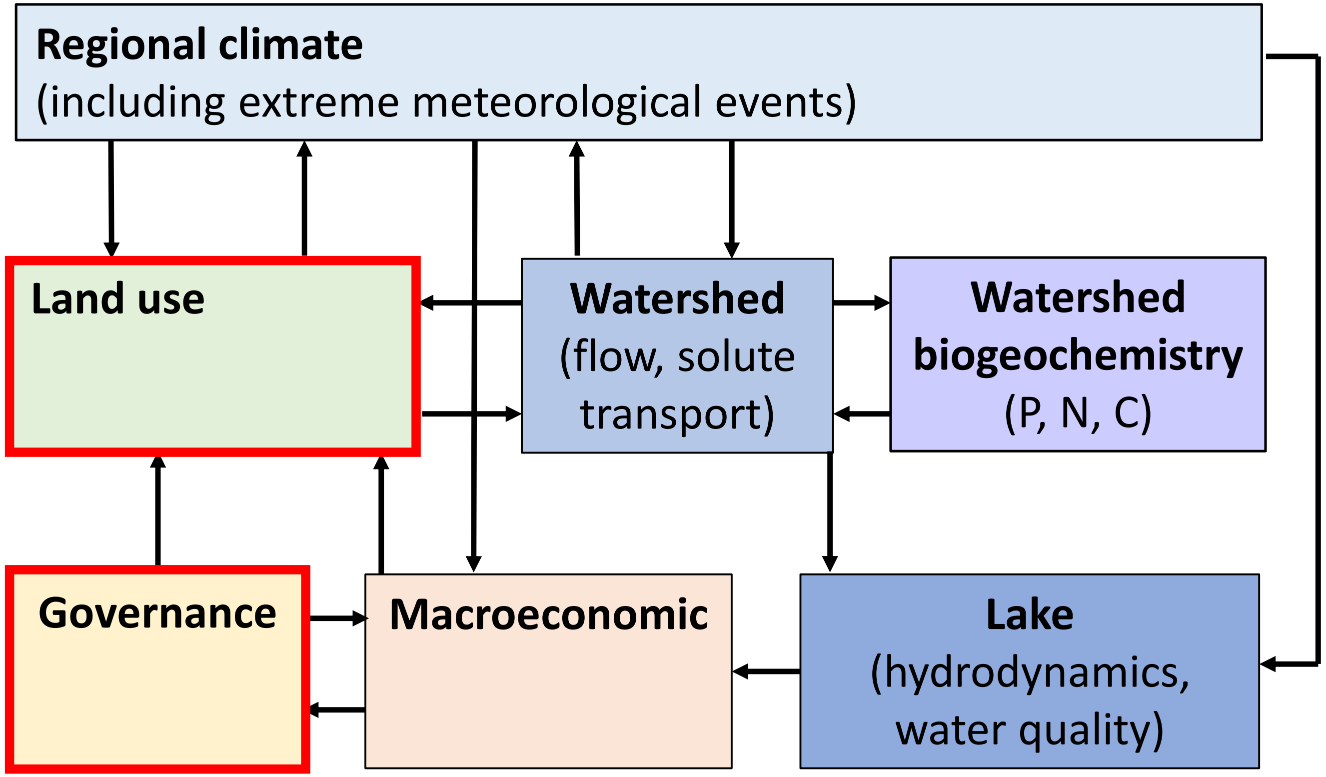
Simulate impacts of decision portfolios

Search for unconsidered decision portfolios

Evaluate results, identify problems

Preliminary findings, recommend additional studies

BREE Integrated Assessment Models



Regional climate
(including extreme meteorological events)

Land use

Watershed
(flow, solute transport)

Watershed biogeochemistry
(P, N, C)

Governance

Macroeconomic

Lake
(hydrodynamics, water quality)

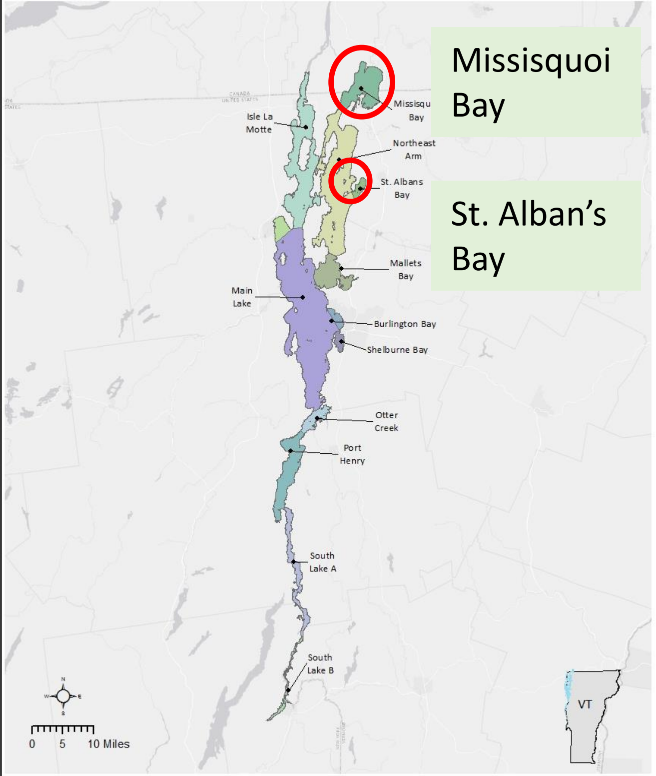
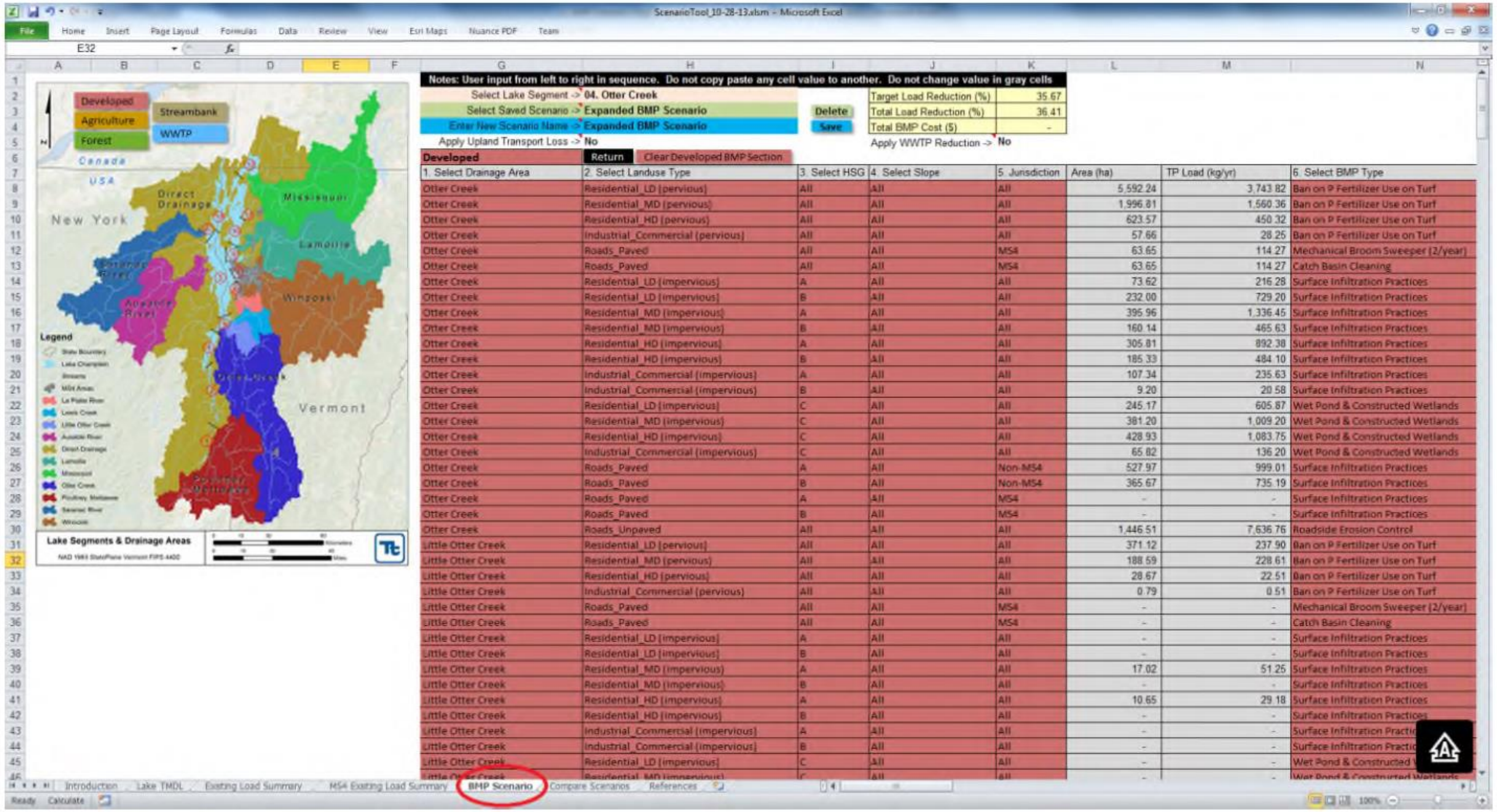


Figure 1: Lake Champlain Segments Subject to Vermont Phosphorus TMDLs. (LCBP 2012).

Data Source: ESRI, TetraTech.

Map Tracker ID: 10397.

Complementing existing decision-support systems



Notes: User input from left to right in sequence. Do not copy paste any cell value to another. Do not change value in gray cells

Select Lake Segment -> **04. Otter Creek**
Select Saved Scenario -> **Expanded BMP Scenario**
Enter New Scenario Name -> **Expanded BMP Scenario**
Apply Upland Transport Loss -> **No**

Delete
Save

Target Load Reduction (%)	35.67
Total Load Reduction (%)	36.41
Total BMP Cost ($)	-

Apply WWTP Reduction -> **No**

Developed Return Clear Developed BMP Section

1. Select Drainage Area	2. Select Landuse Type	3. Select HSG	4. Select Slope	5. Jurisdiction	Area (ha)	TP Load (kg/yr)	6. Select BMP Type
Otter Creek	Residential_LD (pervious)	All	All	All	5,592.24	3,743.82	Ban on P Fertilizer Use on Turf
Otter Creek	Residential_MD (pervious)	All	All	All	1,996.81	1,560.36	Ban on P Fertilizer Use on Turf
Otter Creek	Residential_HD (pervious)	All	All	All	623.57	450.32	Ban on P Fertilizer Use on Turf
Otter Creek	Industrial_Commercial (pervious)	All	All	All	57.66	28.25	Ban on P Fertilizer Use on Turf
Otter Creek	Roads_Paved	All	All	MS4	63.65	114.27	Mechanical Broom Sweeper (2/year)
Otter Creek	Roads_Paved	All	All	MS4	63.65	114.27	Catch Basin Cleaning
Otter Creek	Residential_LD (impervious)	A	All	All	73.62	216.28	Surface Infiltration Practices
Otter Creek	Residential_LD (impervious)	B	All	All	232.00	729.20	Surface Infiltration Practices
Otter Creek	Residential_MD (impervious)	A	All	All	395.96	1,336.45	Surface Infiltration Practices
Otter Creek	Residential_MD (impervious)	B	All	All	160.14	465.63	Surface Infiltration Practices
Otter Creek	Residential_HD (impervious)	A	All	All	305.81	892.38	Surface Infiltration Practices
Otter Creek	Residential_HD (impervious)	B	All	All	185.33	484.10	Surface Infiltration Practices
Otter Creek	Industrial_Commercial (impervious)	A	All	All	107.34	235.63	Surface Infiltration Practices
Otter Creek	Industrial_Commercial (impervious)	B	All	All	9.20	20.58	Surface Infiltration Practices
Otter Creek	Residential_LD (impervious)	C	All	All	245.17	605.87	Wet Pond & Constructed Wetlands
Otter Creek	Residential_MD (impervious)	C	All	All	381.20	1,009.20	Wet Pond & Constructed Wetlands
Otter Creek	Residential_HD (impervious)	C	All	All	428.93	1,083.75	Wet Pond & Constructed Wetlands
Otter Creek	Industrial_Commercial (impervious)	C	All	All	65.82	136.20	Wet Pond & Constructed Wetlands
Otter Creek	Roads_Paved	A	All	Non-MS4	527.97	999.01	Surface Infiltration Practices
Otter Creek	Roads_Paved	B	All	Non-MS4	365.67	735.19	Surface Infiltration Practices
Otter Creek	Roads_Paved	A	All	MS4	-	-	Surface Infiltration Practices
Otter Creek	Roads_Paved	B	All	MS4	-	-	Surface Infiltration Practices
Otter Creek	Roads_Unpaved	All	All	All	1,446.51	7,636.76	Roadside Erosion Control
Little Otter Creek	Residential_LD (pervious)	All	All	All	371.12	237.90	Ban on P Fertilizer Use on Turf
Little Otter Creek	Residential_MD (pervious)	All	All	All	188.59	228.61	Ban on P Fertilizer Use on Turf
Little Otter Creek	Residential_HD (pervious)	All	All	All	28.67	22.51	Ban on P Fertilizer Use on Turf
Little Otter Creek	Industrial_Commercial (pervious)	All	All	All	0.79	0.51	Ban on P Fertilizer Use on Turf
Little Otter Creek	Roads_Paved	All	All	MS4	-	-	Mechanical Broom Sweeper (2/year)
Little Otter Creek	Roads_Paved	All	All	MS4	-	-	Catch Basin Cleaning
Little Otter Creek	Residential_LD (impervious)	A	All	All	-	-	Surface Infiltration Practices
Little Otter Creek	Residential_LD (impervious)	B	All	All	-	-	Surface Infiltration Practices
Little Otter Creek	Residential_MD (impervious)	A	All	All	17.02	51.25	Surface Infiltration Practices
Little Otter Creek	Residential_MD (impervious)	B	All	All	-	-	Surface Infiltration Practices
Little Otter Creek	Residential_HD (impervious)	A	All	All	10.65	29.18	Surface Infiltration Practices
Little Otter Creek	Residential_HD (impervious)	B	All	All	-	-	Surface Infiltration Practices
Little Otter Creek	Industrial_Commercial (impervious)	A	All	All	-	-	Surface Infiltration Practi
Little Otter Creek	Industrial_Commercial (impervious)	B	All	All	-	-	Surface Infiltration Practi
Little Otter Creek	Residential_LD (impervious)	C	All	All	-	-	Wet Pond & Constructed

Clean Water Roadmap Tool

Lake Champlain Water Quality Management “Action Arenas”

ACTION ARENA	DESCRIPTION
Agricultural T	Actors involved in agricultural technical assistance provision meet regularly to coordinate actions around achieving common water quality goals. Agricultural TA working groups are loosely coordinated and meet episodically.
	ivers. Priority is given to lical pattern, usually
Lake Champl	rtunities for Action” the LCB.
Total Max	ected (2013-2015) the State The Environmental ıture are responsible for
	zed to local municipalities. advice to local town
Municipal S	ltants, the municipal and technical assistance
Roadway St	ws with a goal of mitigating
G	romulgation of green reen infrastructure projects

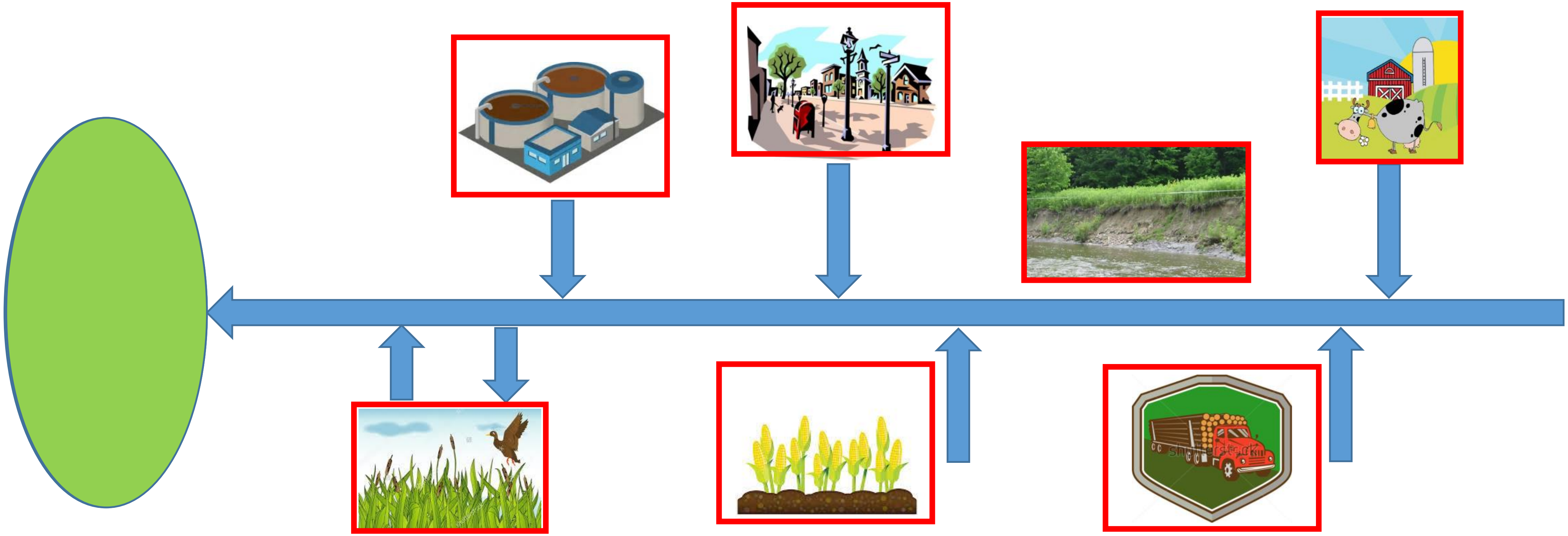
- Actors participate in tactical basin planning meetings to develop water quality management plans for specific watershed and rivers.

- Priority is given to projects with higher return on investments relative to water quality.

- Tactical basin planning meetings take place on a cyclical pattern, usually producing annual plans for the management of water quality across a geographic (watershed) region.

Identifying strategic investment and policy portfolios from a ***basin planner's*** perspective

Which portfolios provide the most "bang for the basin planner's buck"?



Writing prompt

- **WHOSE DECISIONS MATTER MOST?**

- Whose decision heuristics matter most in this system? Whose objectives and perceptions of constraints matter most?

Simplified basin planner problem for water quality management in bays of Lake Champlain

GOAL(S)/ OBJECTIVE(S)

What is the basin planner trying to achieve? How is their performance measured?

CONSTRAINTS

What might limit their ability to achieve these objective(s)?

DECISIONS

What are the decisions that can be made to achieve these objective(s)?

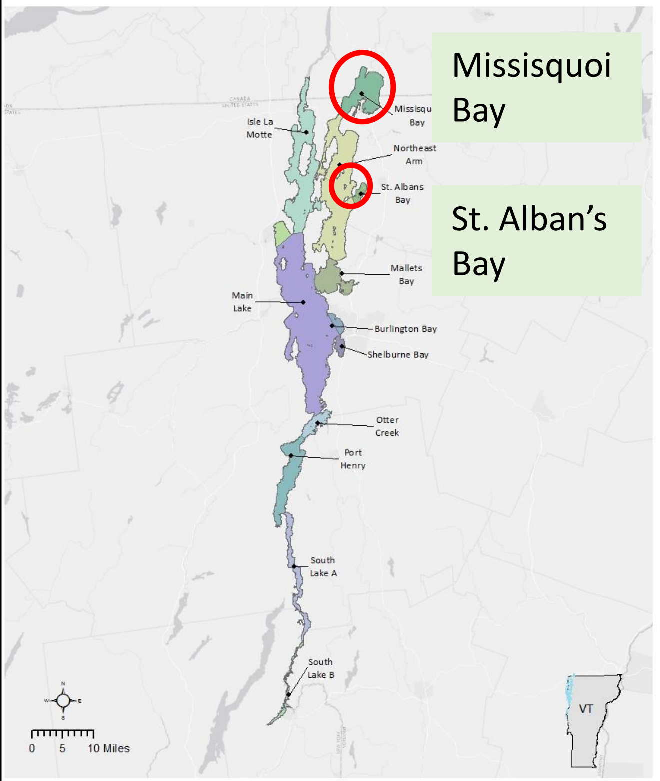


Figure 1: Lake Champlain Segments Subject to Vermont Phosphorus TMDLs. (LCBP 2012).

Data Source: ESRI, TetraTech.

EPA

Map Tracker ID: 10397.

Performance metrics for goals and objectives

- One objective is to minimize economic impact of reducing HABs
- Which performance metrics should we use to assess the impacts of decisions on HABs?
- Consider types of:
    - Water quality indicators
    - Economic impacts
    - Non-economic impacts

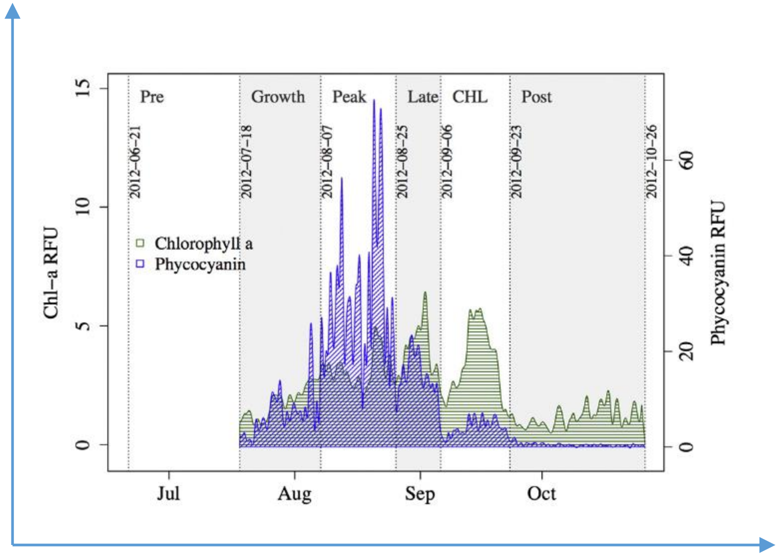
Possible harmful algal bloom indicators

Impact	Indicators	Performance metrics
Overall bloom severity	Chlorophyll *a*	Peak hourly concentration Duration over impact thresholds Trophic state index
Drinking water treatment	Cyanotoxins	Concentrations
Recreation and tourism	Chlorophyll *a* Water clarity	See above for chlorophyll *a* *Secchi* depth (SD), TSI
Property values	Chlorophyll *a* Water clarity	See above for chlorophyll *a* Secchi depth (SD), TSI
Ecosystem	Dissolved oxygen	Min concentration Min saturation percentage

HAB indicators which reflect WQ resilience

“the ability of a soil, river or lake to maintain or to recover similar water quality as prior to the [extreme] event”

INTENSITY (e.g. chlorophyll *a* conc.)



DURATION (days)

Figure from Isles *et al*. (2015)

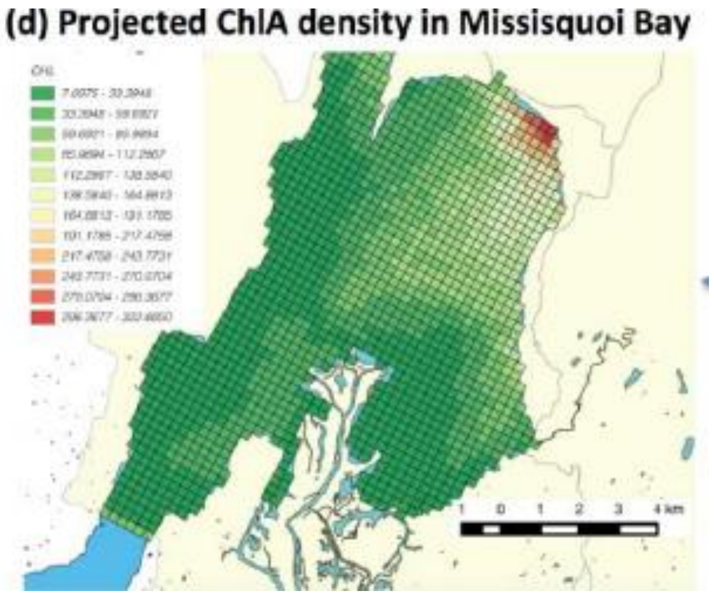


Figure based on Zia et al. (2016)

Can water quality impacts be monetized?

Impact	**Indicators**	**Performance Metrics**
Drinking water treatment	Cyanotoxins	Additional drinking water treatment costs (part of macroeconomic model)
Recreation and tourism	Chlorophyll *a* Water clarity (SD) TSI	Equations relating recreation and tourism economy metrics to water quality indicators
Property values	Chlorophyll *a* Water clarity (SD) TSI	Equations relating property values to water quality indicators
Ecosystem	Various	Recreational losses can be monetized Ecosystem service valuations possible Intrinsic values more difficult

MEA ecosystems services valuation framework

- ***Provisioning*** services are goods an ecosystem provides
- ***Regulating*** services consider role of ecosystem in regulation of ecological processes
- ***Cultural*** services recognize non-material values to humans
- ***Supporting*** services include plant production, nutrient cycling

digital.vpr.net

123RF.com

Valuing regulating ecosystem services in watersheds

Discussion Prompt

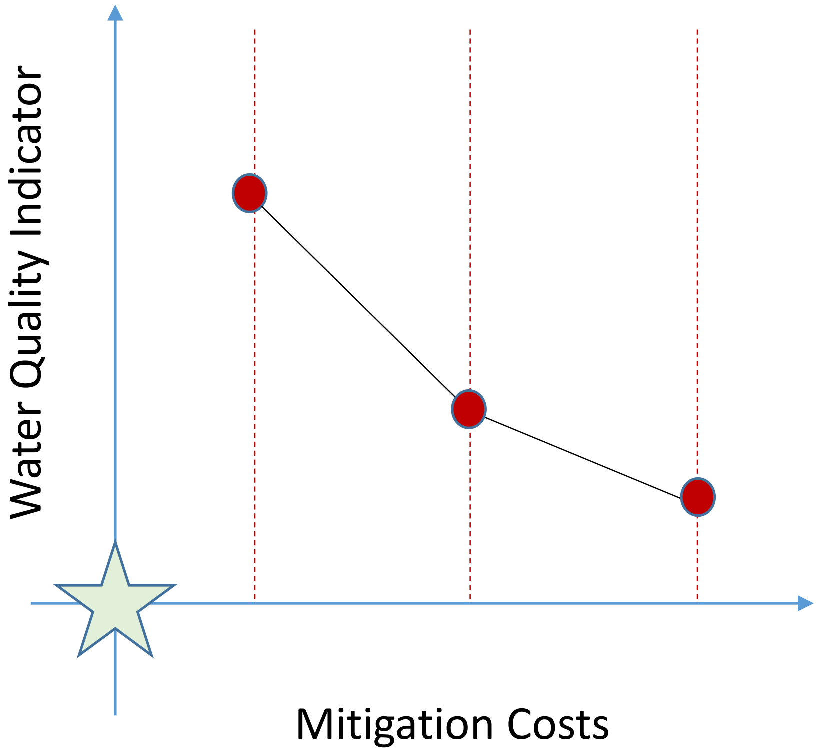
- What performance metrics should we use to assess the impacts of strategic investment and policy portfolios (SIPPs) on HABs?

- Consider types of:
  - Water quality indicators
  - Economic impacts
  - Non-economic impacts
  - Ecosystem services

- Can you think of any metrics we have not mentioned yet?

Identifying multi-objective tradeoffs with constraints

- Can recommend best water quality outcome for a given budget
- Tradeoffs inform final decision, do not dictate them!
- Choice depends on stakeholder values
- Can also examine economic and non-economic impacts of poor water quality



Toward a lake management problem formulation

	Tradeoff between mitigation costs and HAB severity	Tradeoff between mitigation costs and HAB impacts	Regional economic performance
GOALS/ OBJECTIVES	• Min mitigation costs • Min HAB severity indicator(s)	• Min mitigation costs • Min economic impacts • Min non-monetizable impacts (e.g. cultural values)	• Maximize regional economic performance • Minimize economic volatility • Minimize non-monetary impacts (e.g. cultural values)
KEY CONSTRAINTS	• Budget • TP TMDL • Other water quality constraints (e.g. DO)	• Budget • TP TMDL • Other water quality constraints (e.g. DO)	• Budget • TP TMDL • Other water quality constraints (e.g. DO)

Secondary benefits of water quality mitigation

- Must consider benefits for other watershed stressors
- For instance, riparian buffers may improve flood resilience
- Can include these in our cost framework

Adjusted mitigation costs = Mitigation costs - Secondary benefits

- Or add them as additional objectives

WATERSHED STRESSORS:

- Nutrient Loading
- Flow alteration
- Channel erosion
- Encroachment
- Land erosion
- Pathogens
- Thermal stress
- Acidity
- Invasive Species
- Toxins

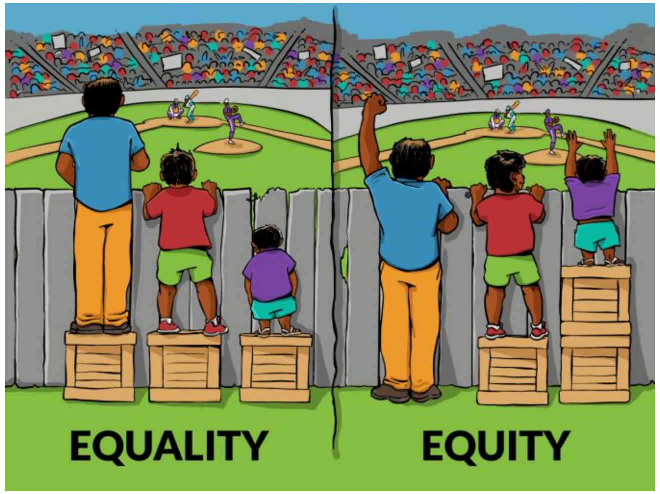
Missisquoi and Lamoille Tactical Basin Plan (2016)

Some possible additional constraints

INFRASTRUCTURE DESIGN	An agricultural BMP cannot be built on developed land
BUDGETARY	A state agency can only fund agricultural programs with a total budget of $25M
REGULATORY	Total phosphorus annual load cannot be exceeded. Must account for margin of safety.
BEHAVIORAL	Farmers who are financially stressed are more likely to sell or abandon their farmland
FAIRNESS	All regulations must be applied uniformly to different stakeholder groups

Evaluating impacts across stakeholders

- Must evaluate fairness of decisions to different stakeholders
- In some cases, uniform application of policies to everyone is best (equality)
- In other cases, disadvantaged stakeholders may need extra assistance (equity)
- DSSs can ensure either equality or equity by constraining basin planner decisions



Strategic investment & policy portfolios (SIPPs)

- Focus on reducing pollution from:
    - Agricultural land
    - Developed (urban) land
    - Forests
    - Streambanks
    - Roads
    - Point sources (WWTPs)
- Must be able to model significant impacts
- Includes traditional BMPs and innovative practices
- Can also include policies and programs
- Can take uncertain performance into account

agriculture.vermont.gov

http://plan.lcbp.org

Hypothetical long-term implementation

	2020	2030	2040	2050	2060	2070	2080	2090
Dairy Farmers								
Strategy 1	X	X	X	X	X	X	X	X
Strategy 2					X	X	X	X
Corn Farmers								
Strategy 1	X	X	X	X	X	X	X	X
Strategy 2					X	X	X	X
Urban Residents								
Strategy 1	X	X	X	X	X	X	X	X
Strategy 2					X	X	X	X

A simplified basin planner problem statement

OBJECTIVES

- Minimize mitigation costs
- Minimize economic impacts
- Minimize non-monetizable impacts (e.g. cultural)

CONSTRAINTS

- Mitigation Costs $\leq$ Budgets
- Annual TP load $\leq$ TMDL – Margin of Safety
- Stakeholder equality/equity constraints
- Legal and regulatory constraints (e.g. Act 64)

DECISIONS

- BMPs and other innovative practices
- Policies and programmatic interventions

A few hypothetical stakeholder objectives

Profit-maximizing farmer

OBJECTIVES

- Max short-term profits

CONSTRAINTS

- Water quality regulations
- Budgets

Ecologically conscious farmer

OBJECTIVES

- Max long-term profits
- Min HAB contribution

CONSTRAINTS

- Water quality regulations
- Budgets

Profit-maximizing tourism company

OBJECTIVES

- Max short-term profits

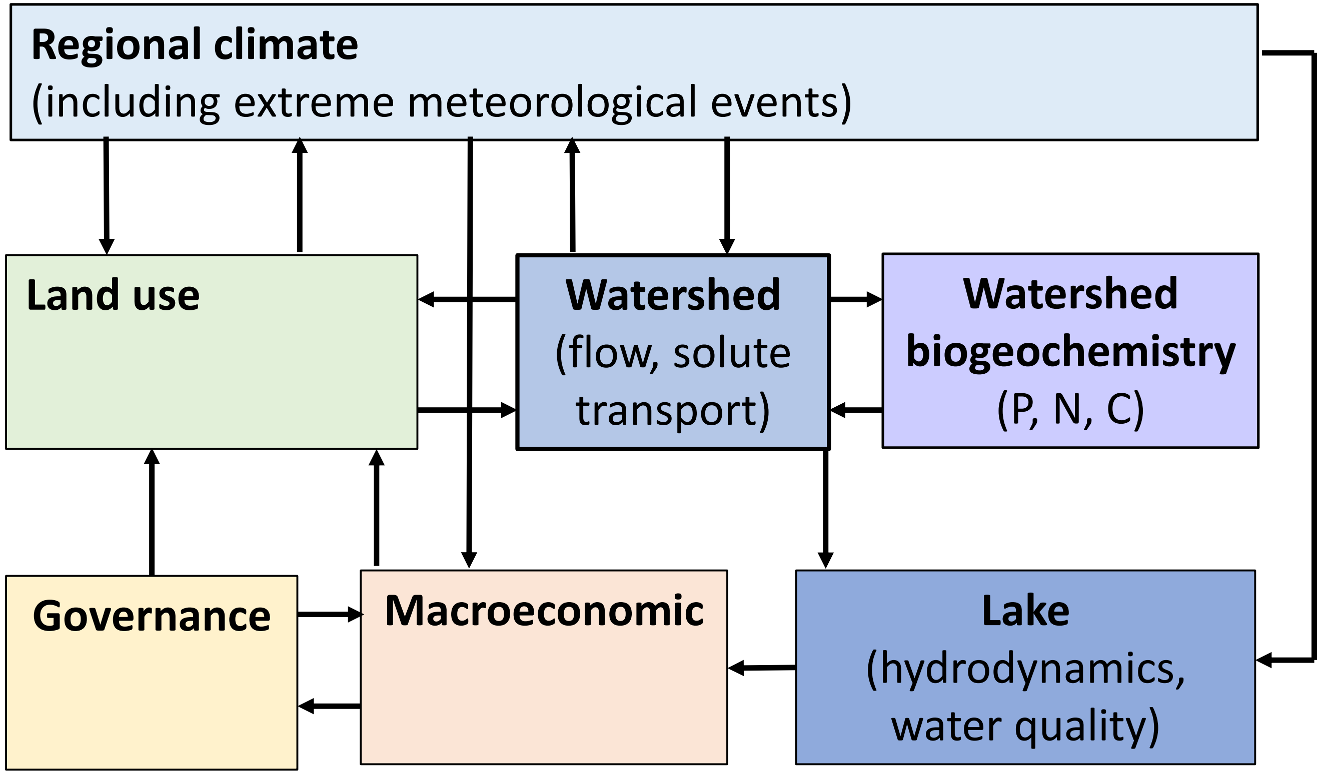
CONSTRAINTS

- HABs
- Water quality regulations
- Budgets

Uncertainty analysis objectives

- Parameter sensitivity analysis during model calibration and validation
    - Can also integrate parameter uncertainty into optimization model
- Generate future scenarios using Monte Carlo simulations
    - Objectively generate diverse sets of climate, land use and governance scenarios
- Propagation of errors through model cascades
- Selection of a set of climate models that represent plausible range of future
    - Will consider ability to reproduce historical observations conditions
- Model land-use change due to socioeconomic and governance changes

Uncertainty in present system



- Which parts of the model contribute the most uncertainty to HAB estimates?

- How might the structures of each IAM sub-model not represent the real-world accurately?

- Which links between models are difficult to represent?

Plausible future scenarios

Scenario A:

- High-emission climate scenario
- More frequent and intense extreme events
- Centralized governance network
- High economic growth rate

Scenario B:

- Low-emission climate scenario
- No change in the frequency and intensity of extreme events
- Decentralized governance network
- Low economic growth rate

- Subjective scenarios reflecting stakeholder concerns and narratives are also possible

Previous climate and land-use change models

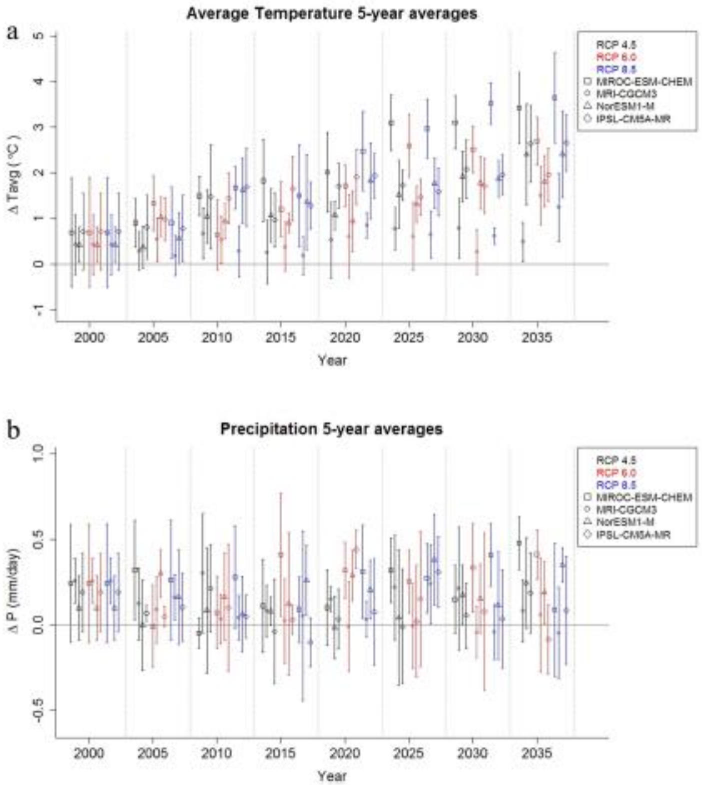


Figure 2. (a) Four GCM projections for three RCP scenarios of temperature change in the Missisquoi watershed (baseline = 1970–1999). (b) Four GCM projections for three RCP scenarios of precipitation change in the Missisquoi watershed (baseline = 1970–1999).

Zia *et al*. (2016)

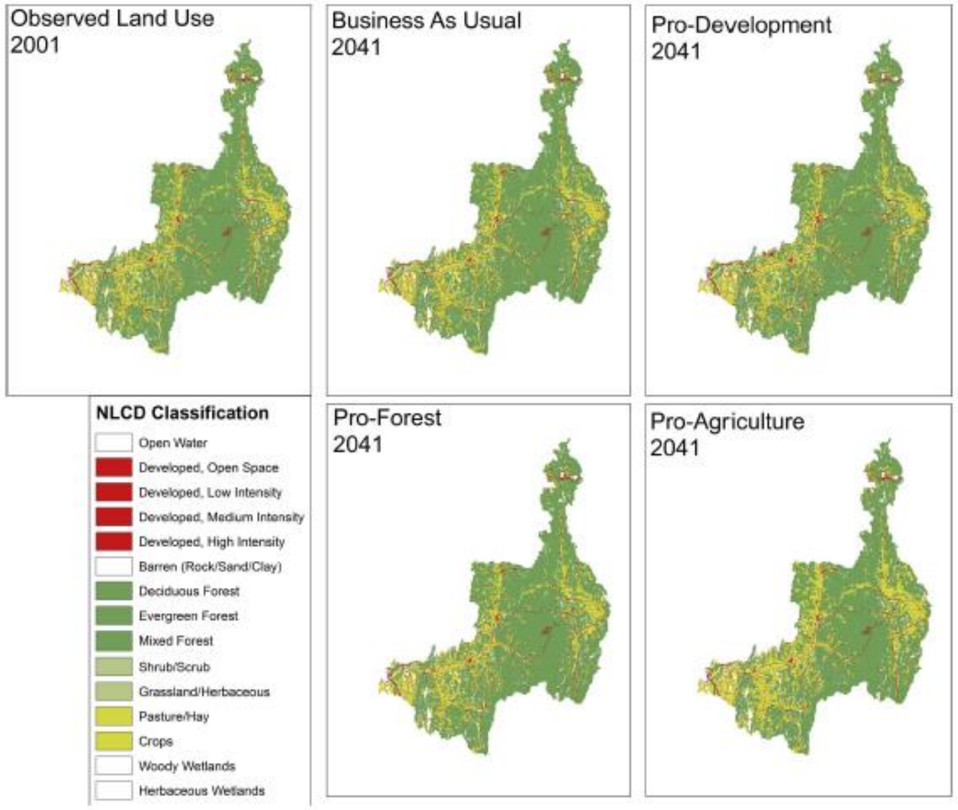


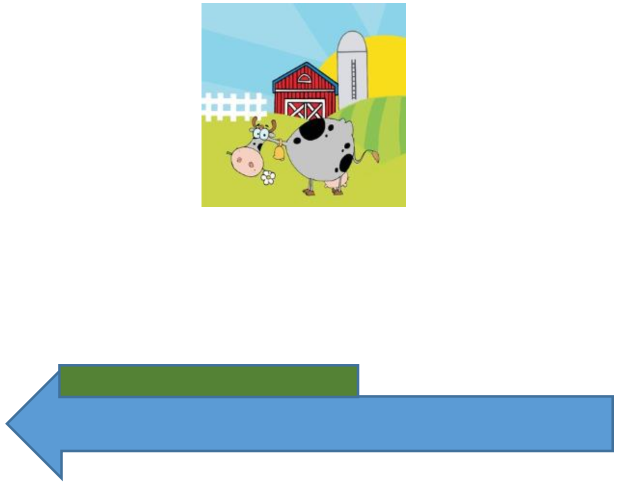
Figure 3. Land-use classifications produced by the LULCC model for four economic and policy scenarios for the final simulation year (2041), also showing initial land-cover at start of simulation.

Zia *et al*. (2016)

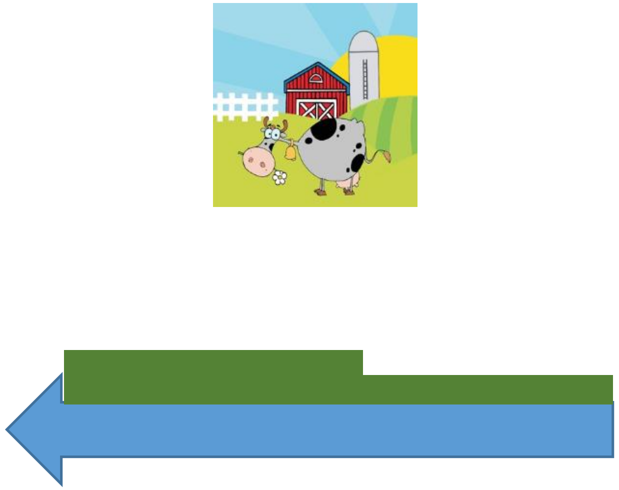
Strategies robust to future uncertainty

PLANNING FOR SCENARIO A
(MAJOR CHANGE)

PLANNING FOR SCENARIO B
(NO SUBSTANTIAL CHANGE)



ROBUST PLANNING ACROSS
SCENARIOS

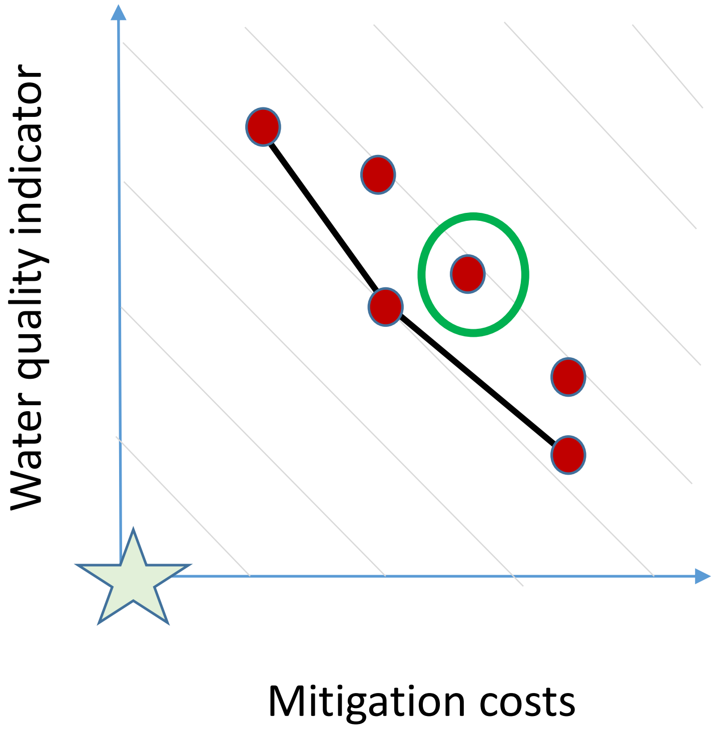


Uncertainty in values

- In some cases, stakeholders might have different views of a problem and disparate goals/objectives
- In other cases, stakeholders might agree on a set of goals/objectives but might want to assign them different priorities
- Stakeholder values may also affect choices for decisions, constraints, and parameters
- Values may change over time, especially with governance transitions

Generating near-optimal solutions

- "Optimal" might imply absolute best solution
- Models do not represent real-world perfectly
- "Near-optimal" solutions may be preferred
- Can reveal wide range of feasible strategies
- Screening-level analysis also encourages iterative model development



Writing exercise: problem formulation

- ***PERSPECTIVES OF THE LAKE MANAGEMENT PROBLEM***
- ***Formulate the problem from the perspective of one the stakeholders listed on your sheet or choose one of your own.***

Thank you!

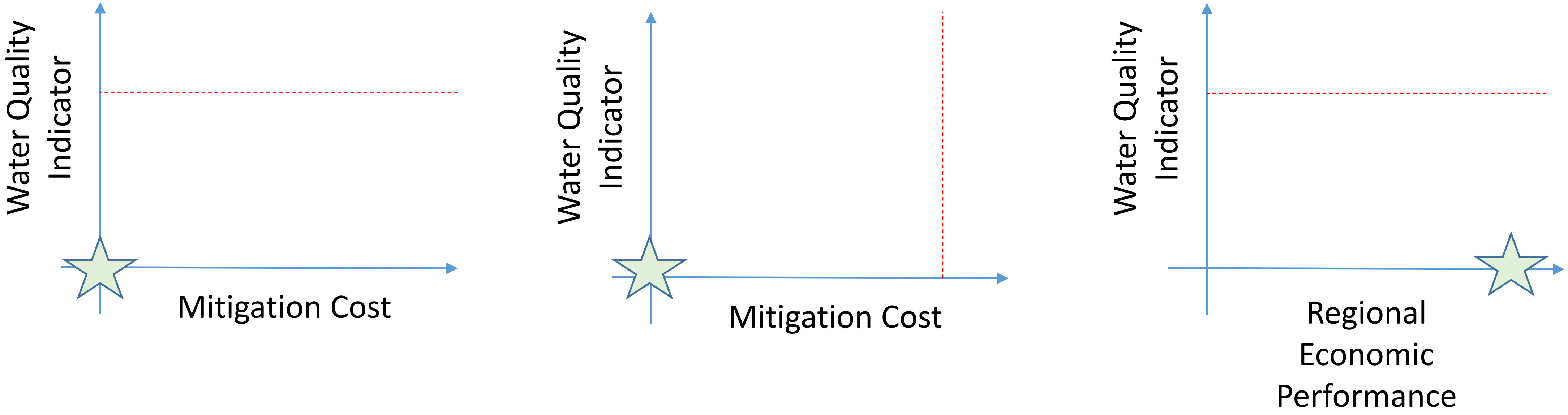
Acknowledgements:

This work is funded by the National Science Foundation via Vermont EPSCoR
Grant Nos. EPS-1101317 and EPS-1556770

QUESTION SLIDES

Jointly defining objectives and constraints

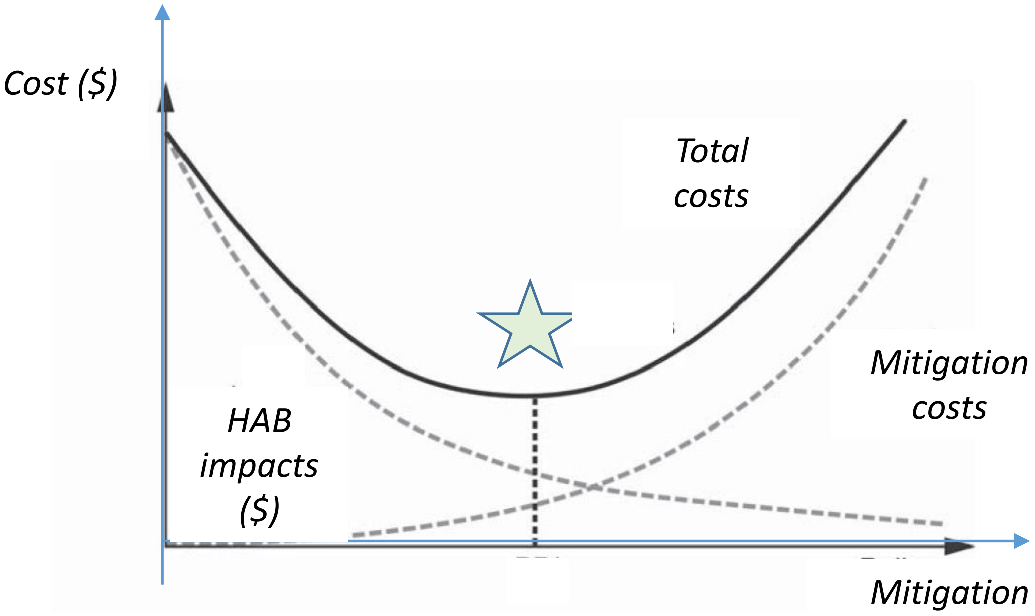
- What is the basin planner trying to achieve?
- What might limit it?



Option B: Minimize mitigation costs and expected impacts

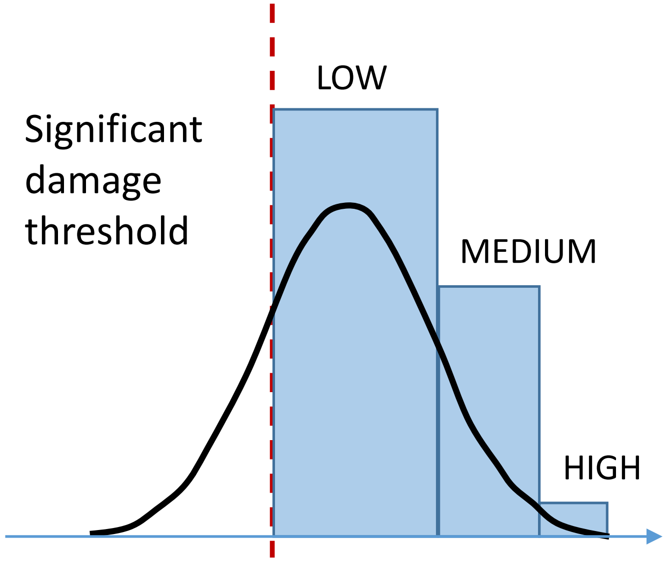
Total costs = Mitigation costs + Expected impact costs

- Expected impact costs are a measure of risk
- Must consider likelihood of blooms of different severity
- Associate blooms of a given severity with impacts



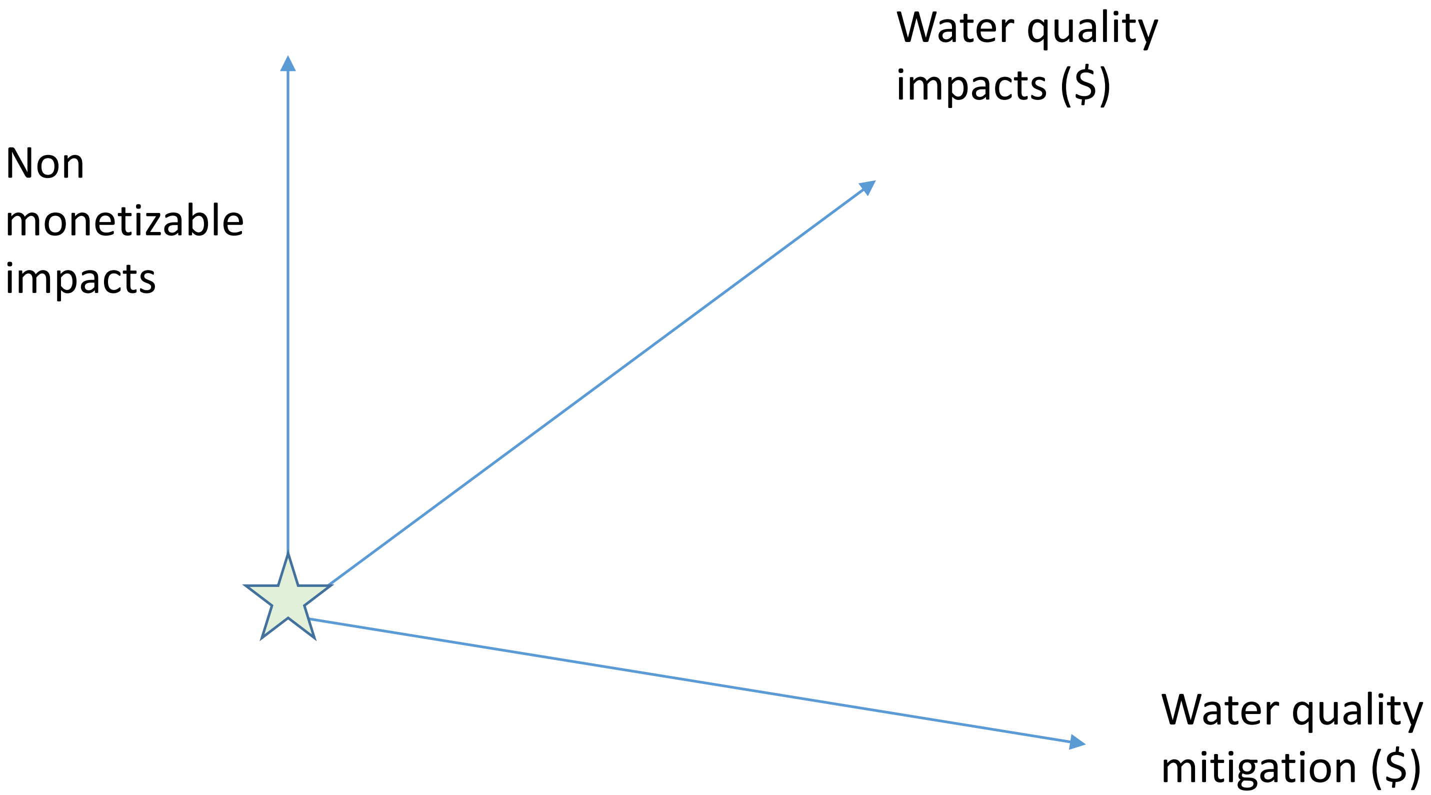
Estimating risk of water quality impacts

MODEL BLOOM SEVERITY PROBABILITIES

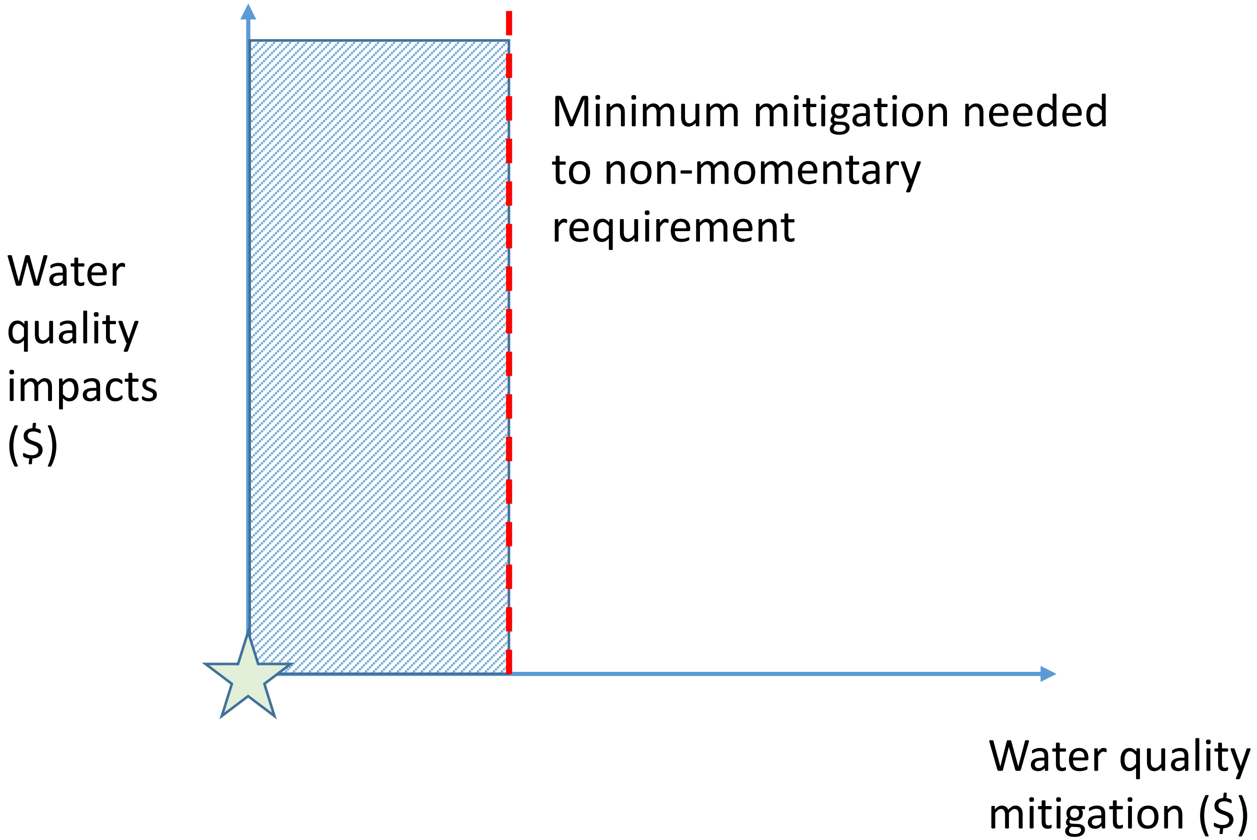


Bloom “severity”

Option C: Add non-monetizable impacts as additional objectives



Option D: Incorporate non-monetary objectives as constraints



Minimum mitigation needed to non-momentary requirement

Water quality impacts ($)

Water quality mitigation ($)

Agricultural structural strategies (BMPs)

WATERCOURSE PROTECTION

- Grassed waterways
- Riparian buffers
- Field ditch buffers
- Fencing
- Barnyard runoff management

SOIL AMEMDMENTS (FERTILIZER & MANURE)

- Manure injection
- Manure-spreading setbacks
- Reduced P manure
- Precision manure application
- Rapid incorporation of manure and fertilizer
- Fertilizer application based on routine soil testing

CROPPING PRACTICES

- Cover crops
- Conservation tillage
- Changes in crop rotation
- Crop to hay
- Strip crop

Some developed land (urban) BMPs

- Traditional BMPs
  - Decentralized detention/retention ponds
  - Infiltration basins
  - Sediment traps

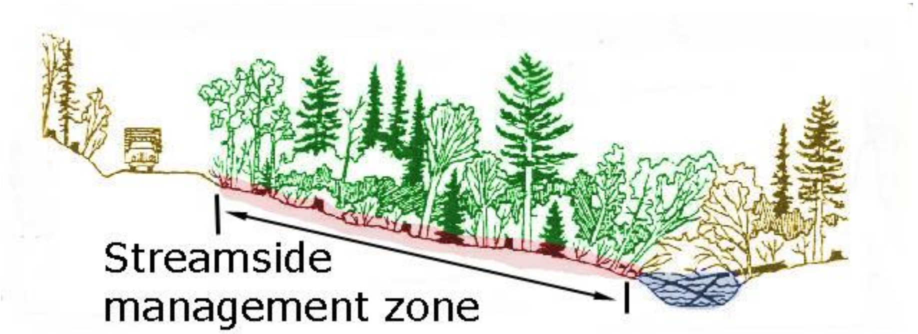
- Green BMPs
  - Bioretention systems
  - Constructed wetlands
  - Vegetated/grass swales

- Land cover management
  - Reduce extent of impervious area
  - Reduce connectivity of impervious area

Can include significant cumulative impacts of distributed stormwater infrastructure

Strategies for other types of land use

- Forests
  - Logging BMPs
- Roads
  - Erosion control
  - Culverts and ditches
  - Storm sewers and pipes
- Streambanks
  - Bank stability restoration



http://www2.dnr.cornell.edu

https://www.nrcs.usda.gov

Role of optimization modeling

- Optimization model will complement existing TMDL decision-making tools

- Simulation models ask “*What would happen if we did this?*”

- Optimization models ask “*What should we do if this happens?”*

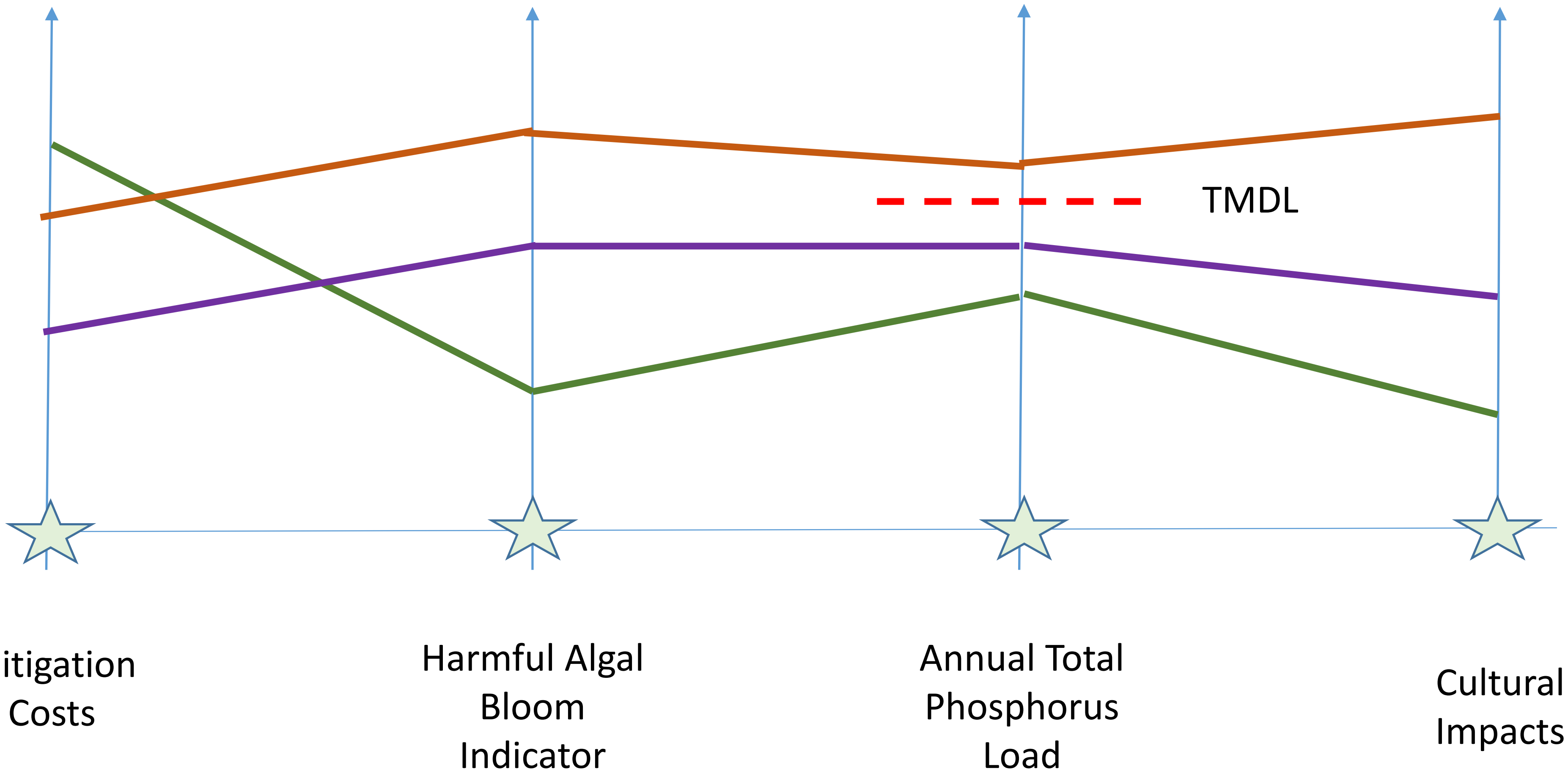
  - Optimization algorithms expedite search for “best” performing decisions according to defined objectives

  - However, we will use near-optimal solutions algorithm to reveal “close to optimal” solutions that may be preferable to model optima

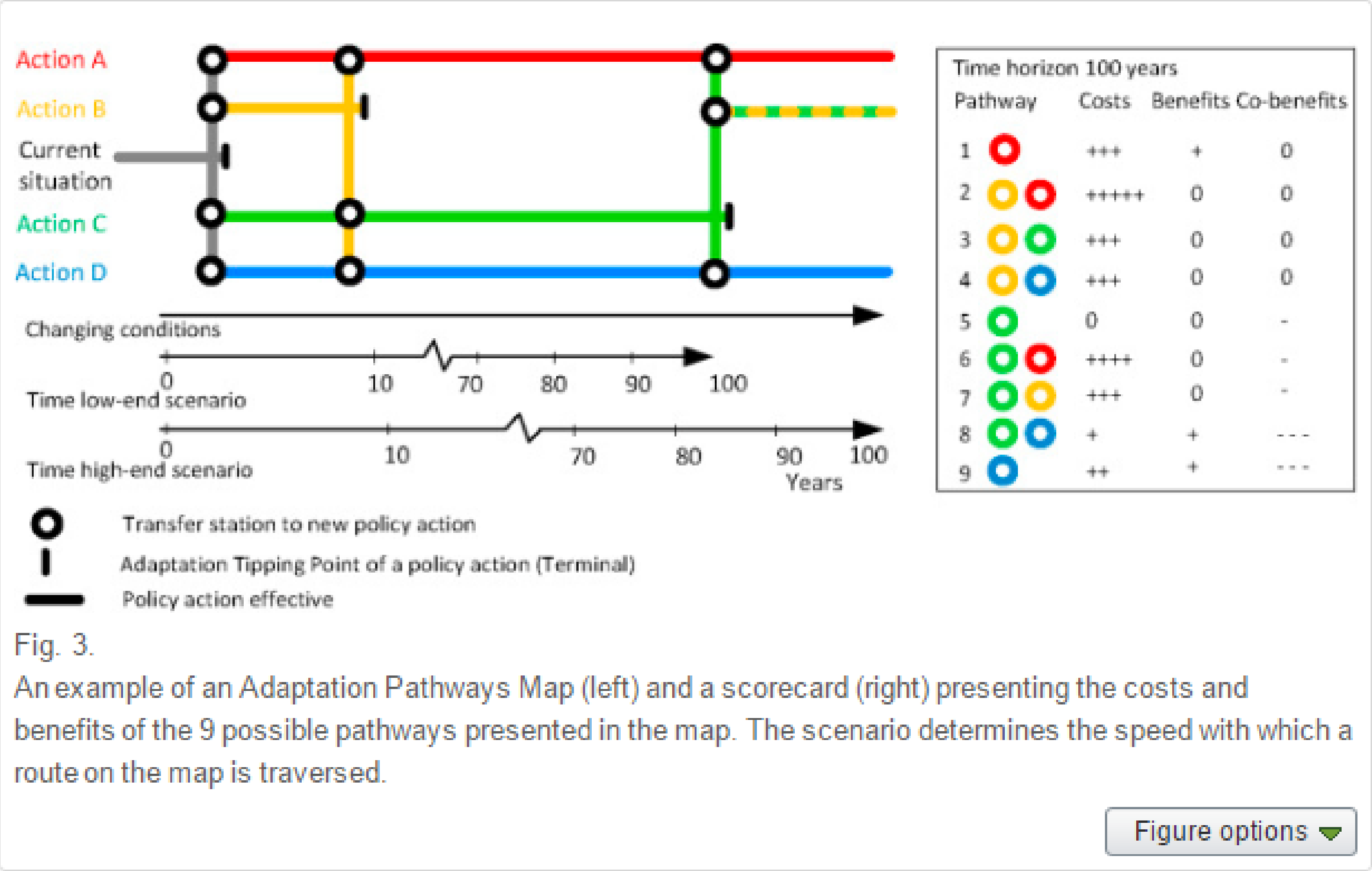
Managing loads of total bioavailable phosphorus

- TMDL dictates reduction of annual total phosphorus (TP) load entering lake
- Potentially ***bioavailable*** phosphorus is most important for HABs
  - Dissolved phosphorus (DP) is bioavailable
  - Some particulate phosphorous (PP) is potentially bioavailable
- In Lake Champlain, research is beginning to show:
  - DP controls blooms in deeper segments
  - PP is more critical in shallow bays subject to more internal loading
- Practices designed to reduce PP load may increase DP loads
- Total bioavailable phosphorus (TBAP) reflects this bioavailability

Hypothetical multi-objective analysis



Dynamic adaptive policy pathways



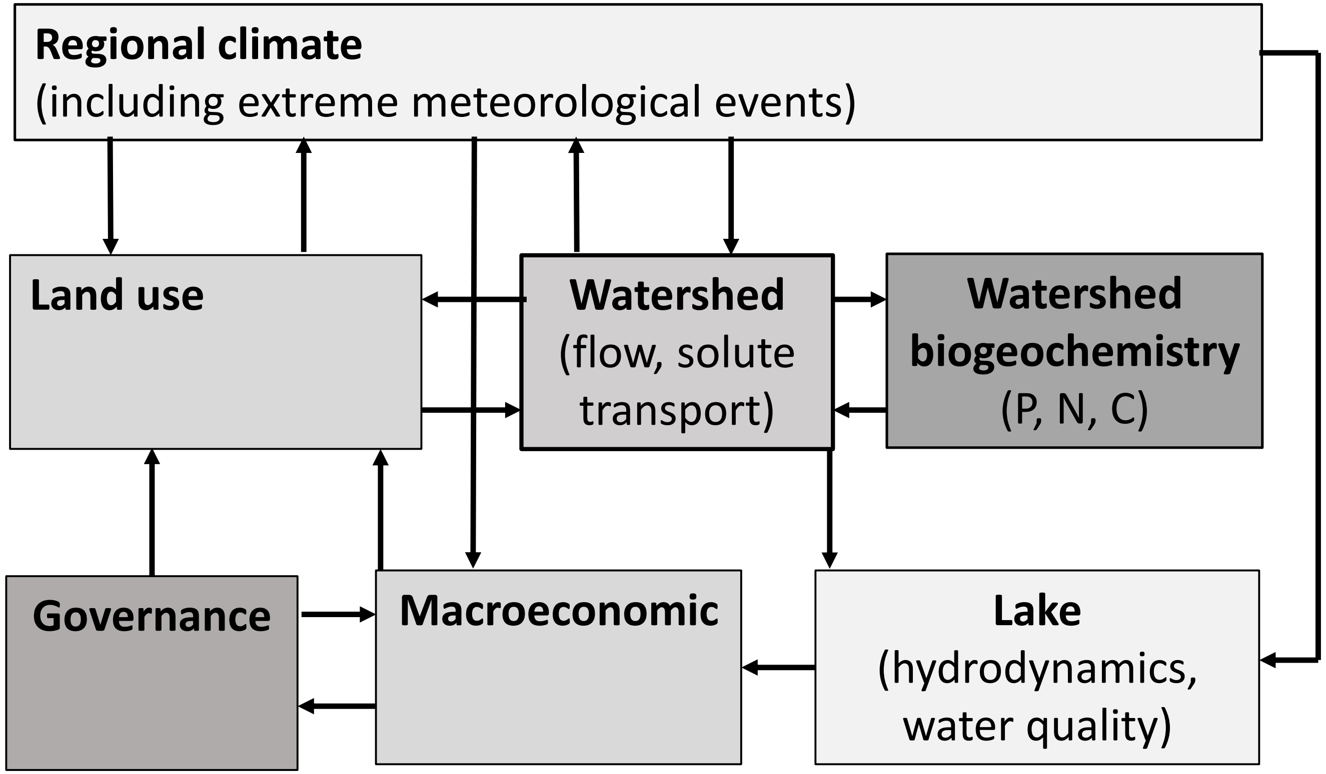
Time horizon 100 years

Pathway		Costs	Benefits	Co-benefits
1	🔴	+++	+	0
2	🟡 🔴	+++++	0	0
3	🟡 🟢	+++	0	0
4	🟡 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟡	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Fig. 3.

An example of an Adaptation Pathways Map (left) and a scorecard (right) presenting the costs and benefits of the 9 possible pathways presented in the map. The scenario determines the speed with which a route on the map is traversed.

Kwakkel *et al*. (2016)



Regional climate
(including extreme meteorological events)

Land use

Watershed
(flow, solute transport)

Watershed biogeochemistry
(P, N, C)

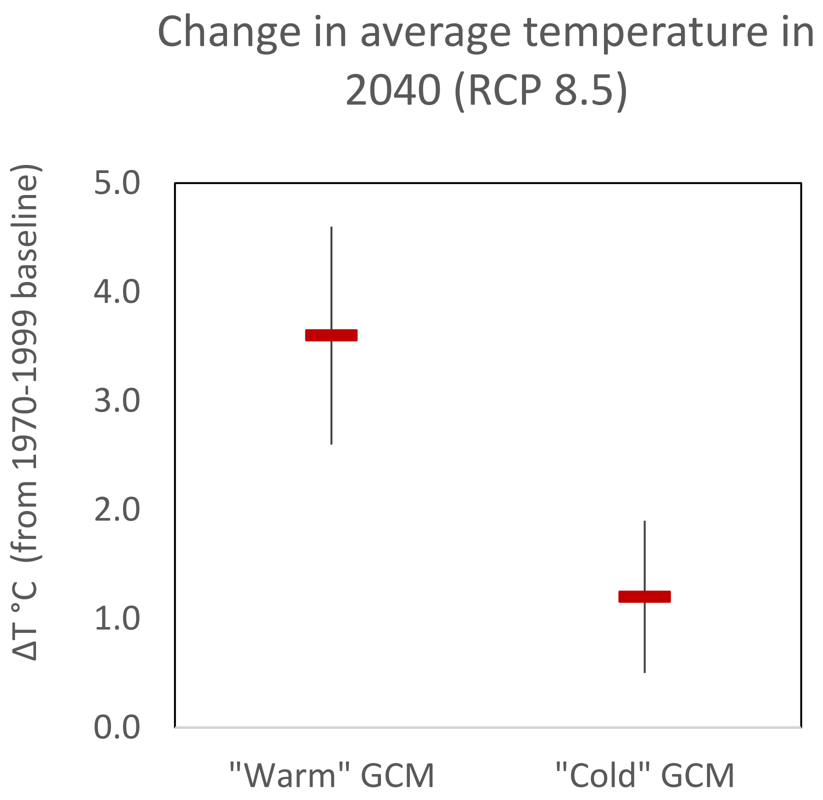
Governance

Macroeconomic

Lake
(hydrodynamics, water quality)

Addressing future uncertainty

- Must consider within- and between-scenario uncertainty
- Within-scenario uncertainty indicates range for a given scenario
- Assigning scenarios probabilities is more challenging
- Will consider scenario probabilities based on their ability to reproduce historical data
- Will pool data from different scenarios to characterize between-model uncertainty



Incorporating parameter uncertainty

- Phosphorus removal efficiency depends on:
  - Design parameters (width, vegetation)
  - Site conditions (soil, slope)
  - Runoff type (snowmelt, convective storm)

- Removal efficiency often highly uncertain
  - Riparian buffer efficiency can range from less than 0% to greater than 90%
  - Can compute range for different site characteristics

- Stochastic optimization:
  - Takes into account uncertainty of inputs and parameters when recommending decisions

SINGLE PARAMETER VALUE

$$\varepsilon_{RB} = 0.54$$

PARAMETER 95% CONFIDENCE INTERVAL

$$\varepsilon_{RB} = (0.196, 0.712)$$

Conditional upon favorable site conditions