A Multi-Criteria Decision Support System for Nonpoint Source Pollution Control

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Nonpoint Source (NPS) Pollution

- Any diffuse pollution sources that are not defined as point sources
  - Caused by rainfall or snowmelt moving over and through the ground
  - Runoff picks up/transport pollutants and deposits them in water bodies
  - Affects water bodies more during periods of high flow
  - Can accumulate high amount of pollutants in the water bodies
  - Usually controlled through prevention rather than treatment
Nonpoint Source (NPS) Pollution

- **Agricultural activities** are among the major sources of impairment in the United States and around the world.

- Control of agricultural NPS pollution is achievable through implementation of conservation practices, commonly known as **Best Management Practices (BMPs)**
  - Managerial: Source control
  - Structural: Delivery control
  - Vegetative: Both delivery and source control
Problem Statement

- How to determine the *type*, *size*, and *landscape position* of control measures?
**Problem Statement**

**NPS Pollution Control Implementation Strategies**

- **Field-by-Field**: Promoted by government agencies in the cost–share program
  - Might be effective at the field level
  - Does not guarantee maximum water quality benefits at the watershed scale

- **Watershed Scale**
  - Critical Source Area
  - Critical source areas contribute larger amounts of NPS pollutants
  - Is subjective, based on the experts recommendation
  - Important watershed processes and interactions are not incorporated
  - Monitoring long-term impact is infeasible

- Modeling
Problem Statement
NPS Pollution Control Implementation Strategies

Watershed Models
- To simulate complex hydrologic and water quality processes
- To estimate water quality benefits of NPS pollution control strategies

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## Problem Statement

**NPS Pollution Control Implementation Strategies**

### Watershed Models

- To simulate complex hydrologic and water quality processes
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\[4^{20} \approx 10^{12}\]
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$4^{20} \approx 10^{12}$

We need to use optimization algorithms
Problem Statement and Research Goals
Optimization of NPS Pollution Control Plans

**Objective**

To utilize an optimization framework to identify **types, sizes, and locations** of conservation practices for **maximum pollutants load reduction** at **minimum cost**.

Objectives are often conflicting and incommensurable.

Planning a NPS pollution control strategy is inherently a **multiobjective** problem.

Determines a set of **nondominated solutions** that comprise the “Pareto-optimal front”.

![Graph showing the Pareto-optimal front](image)
Problem Statement and Research Goals
Conservation Practices and Climate Change

- Significant shifts in climatic patterns are evident worldwide, including precipitation and temperature
- Will conservation benefits of practices be sustained?

Climate change will change

- diffusive transport of nonpoint source pollutants
- assimilative capacities of water bodies
- landscape position of critical areas

Primary Goal

- How coupling watershed models with regional climate projections can potentially provide answers to these questions?
Conceptual Framework

- Chance of Adoption
- Climate Change
- Land Use Change
- Optimal BMPs u/ Uncertain Conditions
- BMP Optimization

Introduction
Problem Statement
Framework
BMP Optimization
Climate Change

Optimization

Climate Change Spatial Downscaling Temporal Downscaling Impact Analysis

Technical Aspects
Decision Making
Agent-based MCD

Chance of Adoption
Land Use Change

Optimal BMPs u/ Uncertain Conditions
BMP Optimization

Conceptual Framework

Optimal BMPs u/ Uncertain Conditions

Conceptual Framework

Optimal BMPs u/ Uncertain Conditions

Conceptual Framework

Optimal BMPs u/ Uncertain Conditions
Conceptual Framework

Optimal BMPs under Uncertain Conditions

- Chance of Adoption
- Climate Change
- Land Use Change
- Baseline Model
- BMP Representation
- Best BMPs
- Optimization Algorithm
- Temporal Downscaling
- Spatial Downscaling
- Impact Analysis
- Decision Making Agent-based MCD
- Technical Aspects
- Chance of Adoption
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Optimal BMPs u/ Uncertain Conditions

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- Baseline Model
- BMP Optimization
- Best BMPs
- Decision Making
- Technical Aspects
- Agent-based
- MCDA
- Spatial Downscaling
- Temporal Downscaling
- Impact Analysis
- Optimization Algorithm
- Cost Est.
- Vegetation
- Managerial
- Structural
- BMP Representation
- NSGA-II
- SCE-UA
- DDS
- DREAM
Conceptual Framework

Optimal BMPs u/ Uncertain Conditions

Climate Change
- Temporal Down-scaling
- Spatial Down-scaling

Land Use Change

Impact Analysis

Chance of Adoption

BMP Optimization
- Baseline Model
- Calibration
- Sensitivity Analysis
- Behavioral Model
- Statistical Sound Eq.

BMP Representation
- Vegetation
- Managerial
- Structural
- Cost Est.

Optimization Algorithm
- NSGA-II
- SCE-UA
- DDS
- DREAM

Decision Making
- Technical Aspects
- MCDA
- Agent-based

Spatio-Temporal Down-scaling

Impact Analysis

Change of Adoption

Optimal BMPs u/ Uncertain Conditions
Conceptual Framework

Optimal BMPs under Uncertain Conditions

- Climate Change
  - Temporal Downscaling
  - Spatial Downscaling
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- Chance of Adoption
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Baseline Model
- BMP Representation
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- Optimization Algorithm
- Best BMPs
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  - Agent-based

Technical Aspects
- Sensitivity Analysis
  - Calibration
  - Statistical Soundness
- Eq.

Decision Making
- Cost Est.
- Vegetation
- Management

Spatial Downscaling
- Impact Analysis
- Temporal Downscaling

Decision Making
- Agent-based
- Technical Aspects

Climate Change
- Downscaling
  - Impact Analysis
  - Temporal Downscaling

Decision Making
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Climate Change
- Downscaling
  - Impact Analysis
  - Temporal Downscaling
Physically-based & distributed parameters
Long-term, continuous, & daily time-steps
Simulates flow, sediment, erosion, nutrients, pesticides, and bacteria
Subdivides watersheds into sub-watersheds and then HRUs
Introduction

Problem Statement

Framework

BMP Optimization

Climate Change

Framework

BMP Tool

Conservation Plan

Economic Component

Fitness Function

MCDA

Near Optimal Solution

Enviro.

Economic

Technical

Social

BMP ranking

IPCC SRES

Avg. Monthly Temperature & Precipitation

Max Tmp

Min Tmp

Climate Downscaling

Daily Climate Data

Pcp

Optimization

Mating

Selection

Mutation

Terminate?

Optimal Solution

NO

Yes

Crossover

Factors

pdf

GSA Method

Sample

Sensitivity Analysis

Selected Factors

Factors pdf

SA

Simulation

HRU

Streams

Subbasin

Hydrology and Water Quality

Hydrology and Water Quality

Eagle Creek Watershed (ECW)

Area = 25,000 (ha)
52% row crops
27% pasture
12% urban
9% forest

35 Subbasins
446 HRUs
1 Streamflow Gauge
9 Water Quality Gauge

Physically-based & distributed parameters
Long-term, continuous, & daily time-steps
Simulates flow, sediment, erosion, nutrients, pesticides, and bacteria
Subdivides watersheds into sub-watersheds and then HRUs
Simulation
HRU
Streams
Subbasin
Hydrology and Water Quality

Optimal Solution

Calibration

Parameters

Optimizer

Objective Function

Terminate?

Optimal Solution

Selected Factors

Factors

pdf

GSA Method

Sample

Sensitivity Analysis

Selected Factors

Calibration

Parameters

Optimizer

Objective Function

Terminate?

Optimal Solution

Selected Factors

Factors

pdf

GSA Method

Sample

Sensitivity Analysis

Selected Factors

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A Mixed Discrete-Continuous Multiobjective Genetic Algorithm for Targeted Implementation of Nonpoint Source Pollution Control Practices

Primary Goal
To present an integrated simulation-optimization framework to identify a set of optimal types, sizes, and locations of NPS pollution control practices at the watershed scale.

1 Ahmadi et al. (2013), A mixed discrete-continuous variable multiobjective genetic algorithm for targeted implementation of nonpoint source pollution control practices. Water Resources Research, 49(12), 8344-8356.
## NPS Pollution Control Plans Optimization

### Novelty of this research

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|          | binary | binary | discrete | continuous |

Discrete-Continuous variables are referred to as **Mixed-Chromosome** in evolutionary algorithm.

We used modified Nondominated Sorting Genetic Algorithm II (NSGA-II)
Problem Setup

Conservation Practices:

<table>
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<tr>
<th>BMP</th>
<th>Parameter</th>
<th>Binary</th>
<th>Mixed</th>
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<tr>
<td>Fertilizer Management</td>
<td>Rate Reduction (%)</td>
<td>20</td>
<td>0-30 (Continuous)</td>
</tr>
<tr>
<td>Grassed Waterways</td>
<td>Width (m)</td>
<td>15</td>
<td>10, 15, 25 (Discrete)</td>
</tr>
<tr>
<td>Grade Stabilization</td>
<td>Height (m)</td>
<td>1.2</td>
<td>1.2 (Binary)</td>
</tr>
<tr>
<td>Tillage/Residue Mgt.</td>
<td>Type</td>
<td>Conservation</td>
<td>Conventional</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Conservation No-till (Discrete)</td>
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Objectives:

- Maximize pollutant load reduction: $\Delta L_z = \left( L_{z, base} - L_{z, BMP} \right)/L_{z, base} \times %100$
  - Atrazine
  - Nitrate
- Minimize cost: Implementation + Operation & Management + Offsite (crop production loss)

Application of NSGA-II (population = 108, parallel nodes = 12)
Results

Mixed-variable optimization resulted in

- up to 20-25% higher efficiency in reduction of pollutants load
- up to 40% lower cost for the same level of load reduction
- less solutions with negative impact on pollutants load
Results

116 vs. 6378 Generations
12,500 vs. 690,000 Runs
Results

116 vs. 6378 Generations
12,500 vs. 690,000 Runs
Hybridization

- hybridization with gradient-based local search method
  
The GA-based optimization methods guarantee “convergence” but not “optimality”
- hybridization of decision variable

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<td>10</td>
<td>15</td>
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Ahmadi et al. (2014), Application of Multicriteria Decision Analysis with A Priori Knowledge to Identify Optimal Nonpoint Source Pollution Control Plans. J. of Water Resources Planning and Management, 04014054
Hybridization

- hybridization with gradient-based local search method
  The GA-based optimization methods guarantee “convergence" but not “optimality"
- hybridization of decision variable

The Hybrid method terminated in 66 generations after the binary optimization solutions were identified

Hybrid algorithm was nearly 35 times faster than the Mixed-variable NSGA-II

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1 Ahmadi et al. (2014), Application of Multicriteria Decision Analysis with A Priori Knowledge to Identify Optimal Nonpoint Source Pollution Control Plans. J. of Water Resources Planning and Management, 04014054
Motivation for Next Step
Impact of climate change on diffuse nutrient fluxes at the watershed scale

Impacts of Climate Change
Effective design and implementation of watershed plans require characterization of changes in fluxes of water, sediment, and chemicals in response to climate change

Primary Goal
To assess the potential impacts of the changing climate on pollutant fluxes at the watershed scale over the 21st century

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Climate Downscaling

112 Bias-Correction Spatial Disaggregation (BCSD) climate projections
16 GCMs covering 3 emissions path scenarios (A2, A1b, and B2)

Global Circulation Models (GCM) Outputs

Spatial Downscaling
Bias Correction

Meteorological Station

Temporal Downscaling
resampling and scaling/incrementing

Monthly Mean Precipitation
Monthly Mean Temperature

Daily Precipitation
Minimum Daily Temperature
Maximum Daily Temperature

1950 2010 2015 2034 2045 2064 2080 2100
Results
Temperature and Precipitation

- Maximum Temperature (°C)
- Minimum Temperature (°C)
- Annual Precipitation (mm)
Results
Temperature and Precipitation

- Maximum Temperature (°C)
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Results
Temperature and Precipitation

![Graphs showing temperature and precipitation trends over time.](image-url)
Results
Temperature and Precipitation

- Maximum Temperature (°C)
- Minimum Temperature (°C)
- Annual Precipitation (mm)
Results

Temperature and Precipitation
Results
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![Temperature Graph](image1)
![Precipitation Graph](image2)
Results
Temperature and Precipitation

[Graphs showing temperature and precipitation trends over time]
Results
Temperature and Precipitation
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- Maximum Temperature (°C)
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- Annual Precipitation (mm)
Results
Temperature and Precipitation

[Graphs showing temperature and precipitation trends over years from 2010 to 2100]
Results
Temperature and Precipitation
Results
Temperature and Precipitation

1. Maximum Temperature (°C)
2. Minimum Temperature (°C)
3. Annual Precipitation (mm)
Results
Temperature and Precipitation

![Graphs showing temperature and precipitation trends over years.](image)
Results
Temperature and Precipitation

[Graphs showing temperature and precipitation trends for different scenarios (SRES A2, SRES A1B, SRES B1).]
Results
Temperature and Precipitation
Results
Temperature and Precipitation

![Graphs showing temperature and precipitation trends over time.](image-url)
Results
Temperature and Precipitation
Results
Temperature and Precipitation
Results
Temperature and Precipitation
Results
Changes in Temperature and Precipitation

- Mid- and Late-century temperature projections were significantly higher than early century projections.
- Median precipitation for late-century emission pathway ensembles increased by 4, 7, and 10% for B1, A1B, and A2 scenarios, respectively.
Results

Changes in Streamflow and Sediment

- Small upward trends in median annual streamflow and sediment yields were observed
- Changes between emission pathways were not significant
Results

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Results
Changes in TN and TP Loads

- Changes in total nitrogen (TN) and total phosphorus (TP) between emission pathway ensembles for a given assessment period were not statistically significant.
Results

Changes in Dissolved N and P Loads

- Dissolved nutrient loads showed a significant increase between early- and late-century periods.
- The warmer, wetter conditions predicted tend to increase decomposition of organic matter and mineralization of nitrogen and phosphorus.

![Graphs showing changes in dissolved P and NO3 loads over different emission scenarios.](image-url)
Conclusion

- Mixed–variable optimization provided more realistic alternatives and higher flexibility to the decision makers.
- Proportion of dissolved (nitrate and soluble phosphorus) to total nutrients generally increased from the early-century to the late-century periods.
- Performance of BMP plans under different climatic projections will alter substantially; however, the optimal types and locations of BMPs remained relatively unchanged (not discussed here).