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New optimization framework of watershed best management practice scenarios in a unit-boundary adaptive manner

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Outline

1. Background & study issue
2. Basic idea
3. Method design
4. Case study
5. Conclusions

1 Background & study issue

- ***Best Management Practices (BMPs)*** are effective practices for watershed management, e.g., controlling soil erosion.
- ***Spatial configuration of multiple BMPs*** for optimal environmental and economic effectiveness to support decision-making is ***a typical spatial optimization problem***, considering BMP ***types, locations, areas***, etc. (Gaddis et al., 2014; Srivastava et al., 2002).

Closing measures

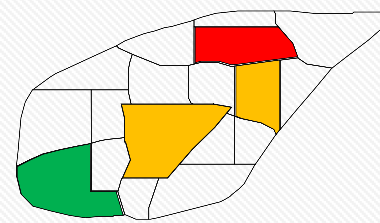
Contour hedgerow

Grass filter belt

Arbor-bush-herb mixed plantation

Contour terrace

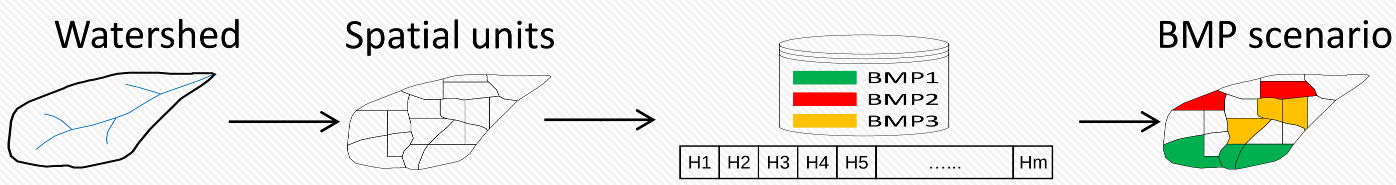
Riparian buffer



BMP scenario
(configuration of multiple BMPs for spatial units in a watershed)

Spatial optimization of BMP scenarios

- **Objectives that often potentially conflicting**
  - e.g., obtaining more environmental effectiveness with less economic investment
- **Geographic decision variables**
  - each spatial unit waiting for a decision (which type of BMP should be applied)
  - Decisions made for all spatial units constitute one BMP scenario

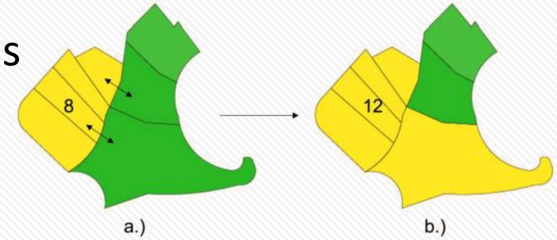


- **Constraining conditions**
  - Non-spatial constraints (e.g., lower bounds on environmental effectiveness)
  - Spatial constraints (e.g., BMPs A and B must not be closed to each other)

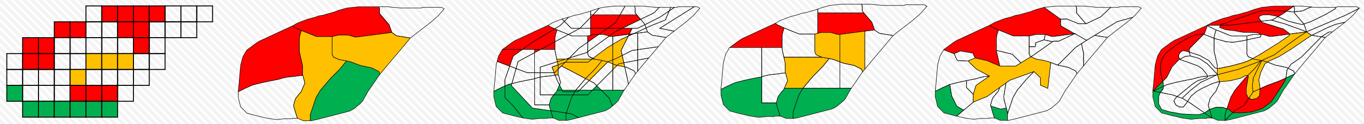
    Spatial constraints are ***closely related to the selected type of spatial unit*** (i.e., BMP configuration unit) and are vitally important in ***ensuring that the optimization and its solutions have meaningful geographical interpretations*** (Cova and Church, 2000; Qin et al., 2018; Yao et al., 2018; Zhu et al., 2019a).

Spatial constraints and their requirements on spatial units

- **Spatial relationships between BMPs and spatial locations**
  - ✓ e.g., ***suitable locations for specific BMPs*** (e.g., Kreig et al., 2019; Maringanti et al., 2011; Pennock, 2005; Qin et al., 2018)
  - ✓ **Different BMPs may require spatial units with different granularities**
- **Spatial relationships among adjacent BMPs**
  - ✓ e.g., ***compatibility*** (Ligmann-Zielinska et al., 2008), ***upstream-downstream relationships*** (Qin et al., 2018; Wu et al., 2018)
  - ✓ **Spatial units should inherently have adjacency relationships or spatial topology**
- **Spatial characteristics of spatial units**
  - ✓ **A basic idea**: ***applying BMPs to basic spatial units to form coarser BMP configuration units***, then ***adjusting and optimizing their boundaries*** based on domain specific knowledge (Brookes, 1997; Cao et al., 2011; Church et al., 2003; Liu et al., 2015).
  - ✓ **Basic spatial unit should be fine-grained** such as grid cells or enumerated tiny spatial areas (Fraley et al., 2010).



Existing types of BMP configuration units

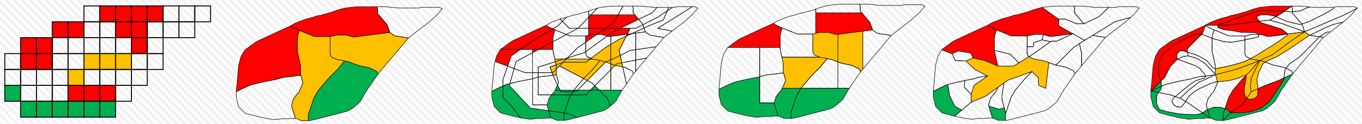


	Grid cells Gaddis et al., 2014	Subbasins Chichakly et al., 2013	Hydrologic response units (HRUs) Maringanti et al., 2011	Farms Kalcic et al., 2015	Hydrologically connected fields Wu et al., 2018	Slope position units Qin et al., 2018
Spatial relationships between BMPs and spatial locations	✓	✓	✓	✓	✓	✓
Spatial relationships among adjacent BMPs	✓	✓	✗	✓	✓	✓
Spatial characteristics of spatial units	✓	✗	✗	✗	✗	✗

- ***Extremely computational-intensive***
- **Only applicable for one BMP type in areas with a small count of grid cells**

- ***Once created, boundaries remain fixed during optimization***
- **Ignore an entire dimension of solution space constructed by boundary adjustment** (changes in the areas of BMPs), which may **render the spatial optimization less effective**

Existing types of BMP configuration units



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Spatial relationships between BMPs and spatial locations	✓	✓	✓	✓	✓	✓
Spatial relationships among adjacent BMPs	✓	✓	✗	✓	✓	✓
Spatial characteristics of spatial units	✓	✗	✗	✗	✗	?

- ***Determined once the drainage network been extracted***
- **Cannot not be changed during watershed modeling and BMP scenario optimization**

- ***Rely on existing boundaries of landuse and soil types, etc.***
- **Difficult to adjust boundaries dynamically in an easy and reasonable way**

- **Basic landform units along hillslopes**

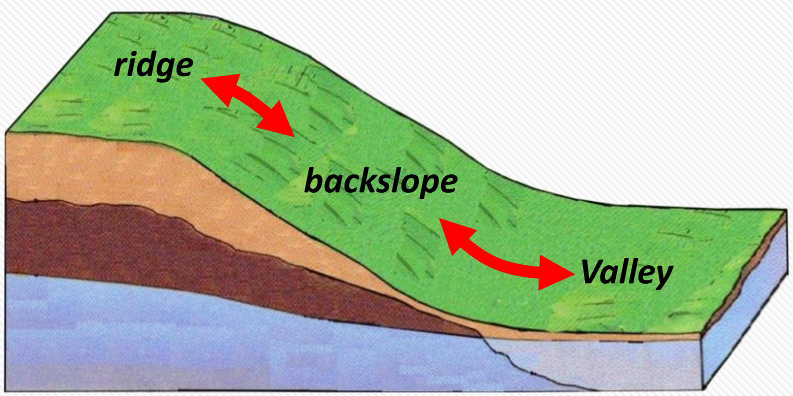
Study issue

How to **reasonably adjust boundaries of slope position units**, and hence ***enlarge the search space*** of the optimization of BMP scenarios to ***make the optimization more effective***?

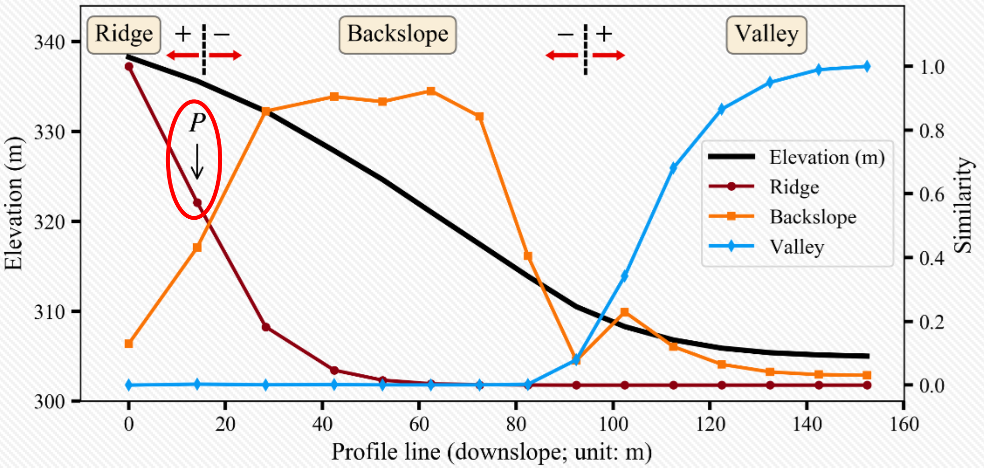
2 Basic idea

Slope positions (e.g., ridge [or summit], backslope, and valley)

- ***Spatial transition*** between slope positions ***is often gradual***
- Can ***be quantified by fuzzy slope positions*** (MacMillan et al., 2000; Qin et al., 2009): similarities to all slope position types
- Transitional areas between two successive slope positions along a hillslope ***maybe reasonably classified as either one type because of both low similarities***



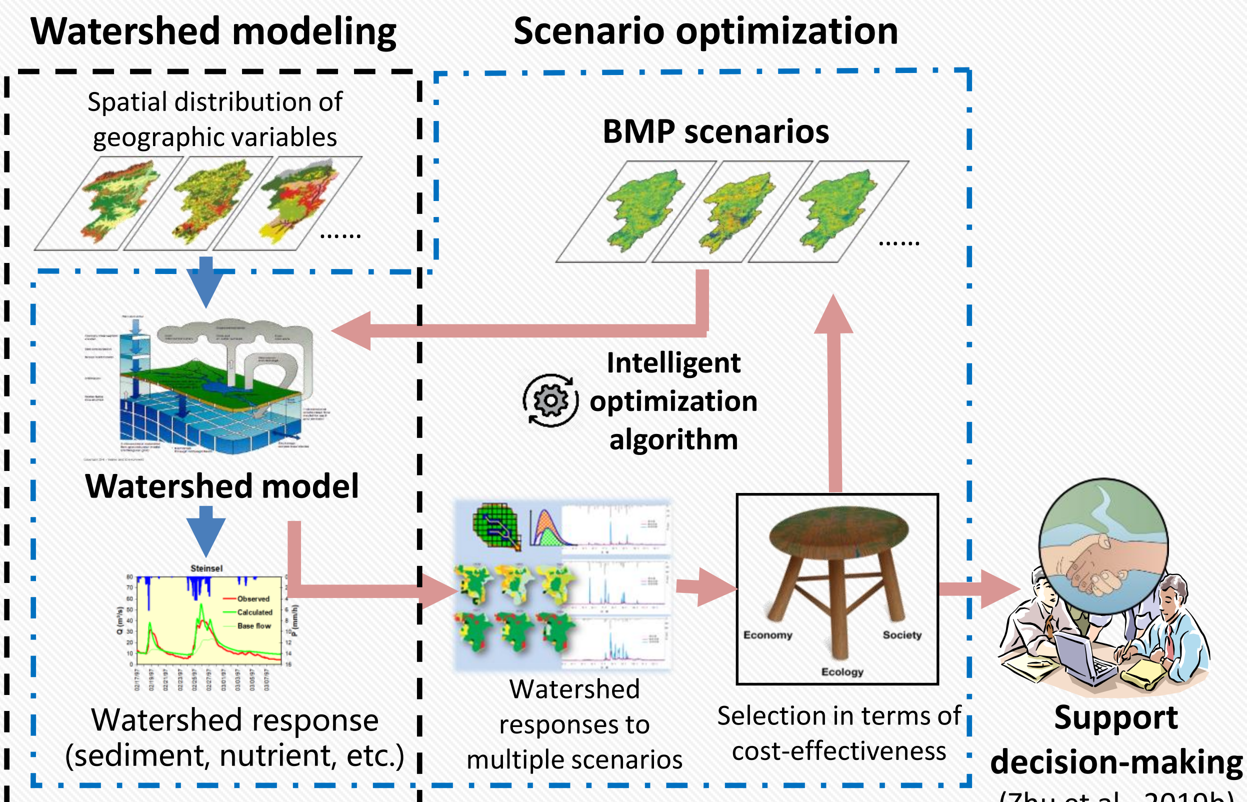
Gradation of slope positions in reality



Boundary adjustments of slope position units

3 Method design

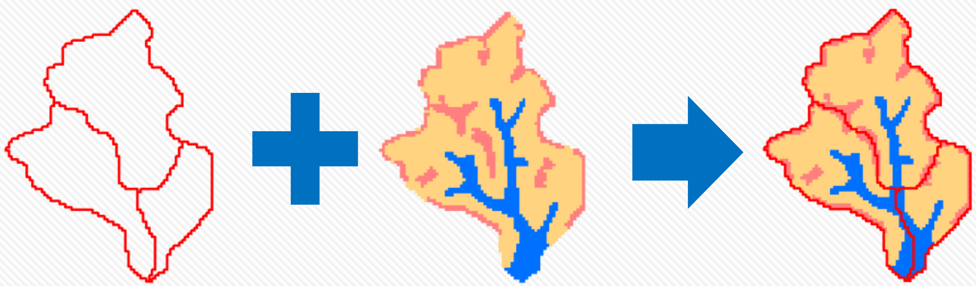
- Dynamic threshold method of adjusting boundaries of slope position units
- New optimization framework of BMP scenario based on the boundary-adaptive slope position units

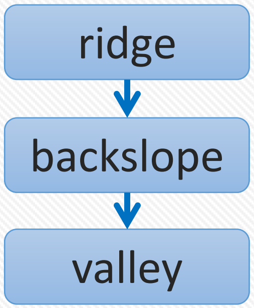


(Zhu et al., 2019b)

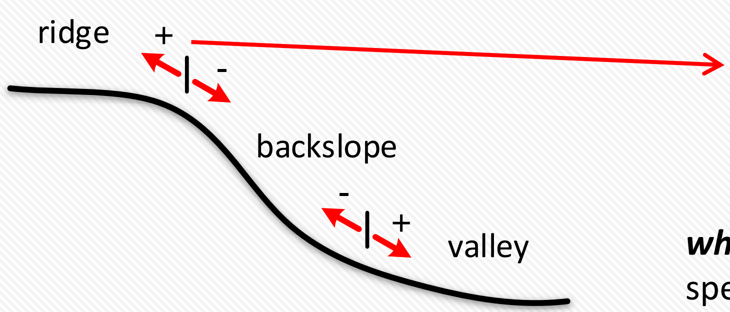
Dynamic threshold method of adjusting boundaries of slope position units

- **Boundary-fixed slope position units** (taking three types of slope positions as an example)
  - A group of slope position units are defined within one hillslope unit
  - Maximum similarity principle is applied (Qin et al., 2009, 2018)





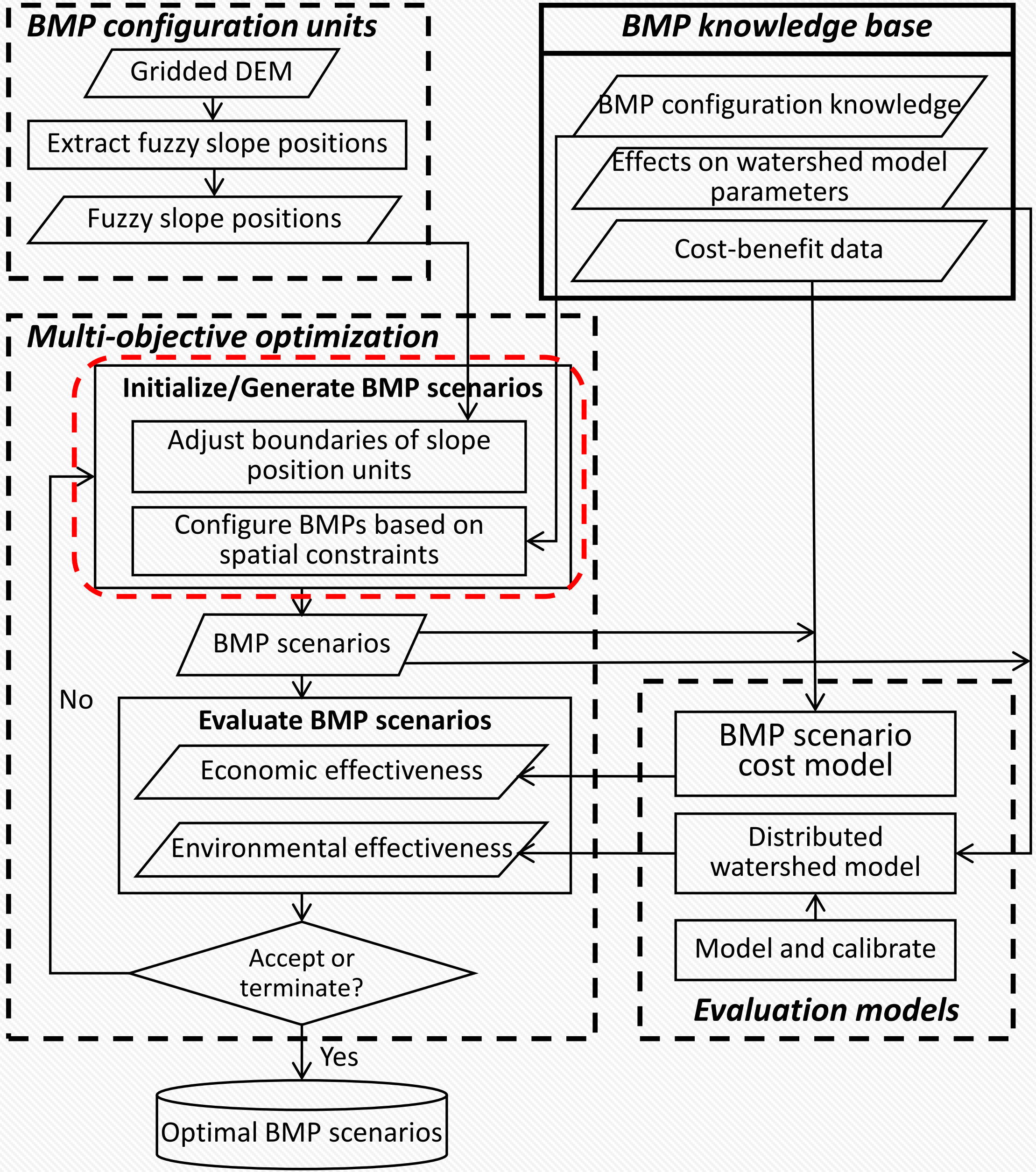
- **Dynamic threshold method based on fuzzy slope positions**
  - Two thresholds with plus/minus signs are designed for each hillslope
  - E.g., the threshold for the boundary of backslope-to-ridge:
    - ***positive → expansion from backslope to ridge***



$$\begin{cases} S_{\text{valley}} < S_{\text{backslope}} < S_{\text{ridge}} \\ S_{\text{ridge}} - S_{\text{backslope}} < |t| \\ S_{\text{backslope}} - S_{\text{valley}} > |t| \end{cases}$$

where *S* represents fuzzy slope positions and *t* is the threshold specified for the expansion from backslope to ridge.

BMP scenario optimization approach based on boundary-adaptive slope position units

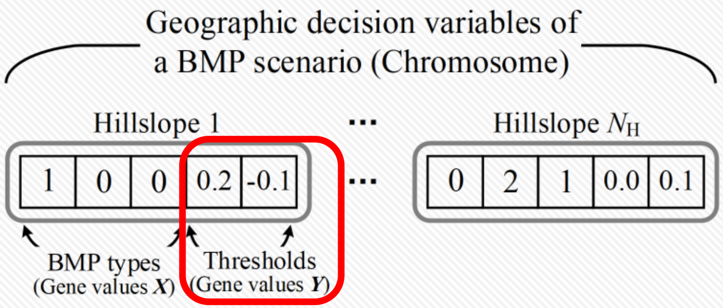


- **A widely used optimization framework was adopted and improved** (Arabi et al., 2006; Maringanti et al., 2011; Qin et al., 2018)
  - Delineation of BMP configuration units
  - BMP knowledge base
  - Evaluation models
  - Multi-objective optimization process
  - ✓ **Extension of geographic decision variables**
  - ✓ **Definition of spatial constraints**

BMP scenario optimization approach based on boundary-adaptive slope position units

➢ Extension of geographic decision variables

- BMP types configured on each unit
- ***Two adjustment thresholds are added for each hillslope***



➢ Definition of BMP scenario optimization problem

- A generalized expression: $\min\left[-F\left(X,Y\right)\wedge G\left(X,Y\right)\right]$

Subject to:

$$X_i = f\,(\text{topography}, \text{land-use}, \text{soil}, \ldots)$$

Relationships between BMPs and spatial locations

$$h(X_i, X_{i+1}, \ldots, X_{i+N_P-1})\ ,\ \text{e.g.,}\ \begin{cases} X_{i,m_1} + X_{i+1,m_2} \le 1 \\ X_i = 0,\ \text{if}\ X_{i+1} = m \\ e(X_{i+1}) \ge e(X_i) \end{cases}$$

Spatial relationships among adjacent BMPs, e.g., up-down relations

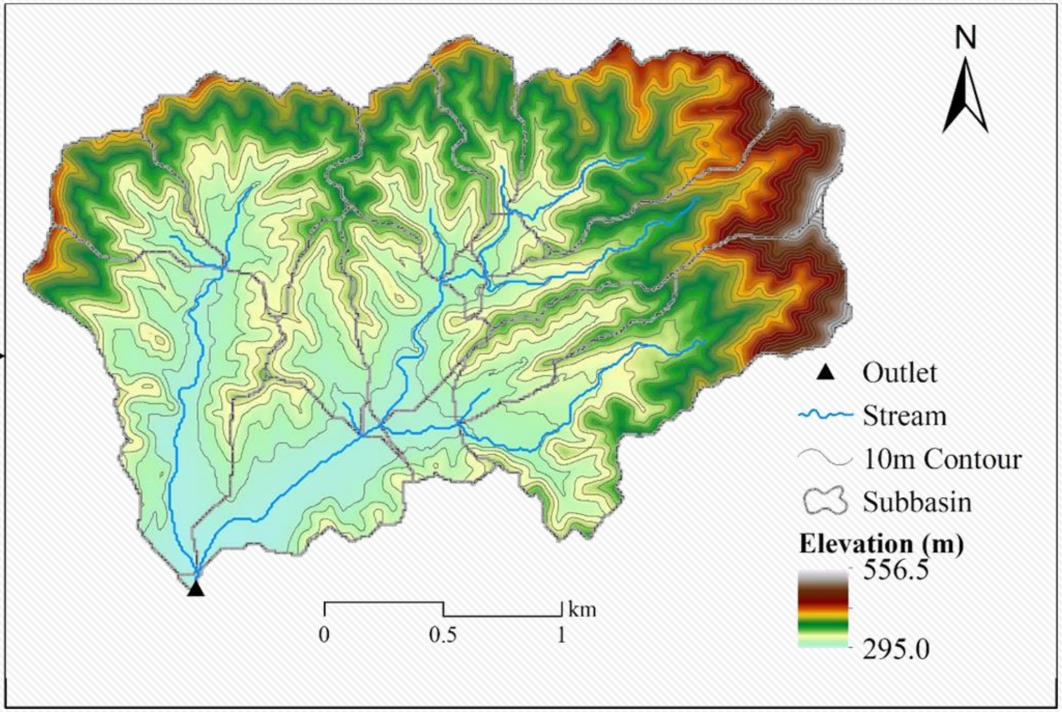
$$Y_j = \begin{cases} t, & X_i \ge 0 \text{ and/or } X_{i+1} \ge 0 \\ 0, & \text{otherwise} \end{cases} ,\ \forall i = j - N_P$$

Occurrence condition of boundary adjustment

where *F* and *G* are objective functions on env. Effectiveness and eco. cost, respectively; X_i denotes the configuration of BMP on the *i*th slope position units and Y_j denotes the *j*th adjustment threshold; $X_{i,m} = 1$ means BMP *m* is configured on X_i.

4 Case study: optimization of BMP scenarios for mitigating soil erosion

- **1) Study area**: Youwuzhen watershed (~5.39 km^2), Fujian province, China
  - ***Location***: in the upstream of Ting river, **the typical red-soil hilly region in southeastern China**
  - ***Terrain***: low hills with steep slopes (average slope: 16.8°), broad alluvial valleys
  - ***Climate***: under a mid-subtropical monsoon moist climate
  - ***Landuse***: primarily, forest (59.8%), paddy field (20.6%), and orchard (12.8%)
  - ***Soil***: red soil (dominant type, infertile, acidic, nutrient-deficient, poor in organic matter, low capacity for holding and supplying water) and paddy soil.



2) BMP knowledge base of the Youwuzhen watershed

➢ **Four representative BMPs in the study area are considered** (Chen et al. 2017; Qin et al., 2018)

BMP	Photo	Brief description
Closing measures (CM)		Closing the ridge area and/or upslope positions from human disturbance (e.g., ban on felling tree and grazing) to facilitate afforestation.
Arbor-bush-herb mixed plantation (ABHMP)		Planting trees (e.g., *Schima superba* and *Liquidambar formosana*), bushes (e.g., *Lespedeza bicolor*), and herbs (e.g., *Paspalum wettsteinii*) in level trenches with compound fertilizer on hillslopes.
Low-quality forest improvement (LQFI)		Improving the infertile forest located in the upslope and steep backslope positions by applying compound fertilizer to the hole with a size of 40 × 40 × 40 cm in the uphill position of crown projection.
Orchard improvement (OI)		Improving orchards on the middle and down slope positions under better water and fertilizer conditions by constructing level terraces, drainage ditches, storage ditches, irrigation facilities and roads, planting economic fruit, and interplanting grasses and Fabaceae (*Leguminosae*) plants.

2) BMP knowledge base of the Youwuzhen watershed

➢ **Two categories of BMP knowledge base** (Qin et al., 2018; Zhu et al., 2019a):

- BMP configuration knowledge for initializing/generating scenarios
- Environmental effectiveness and cost-benefit data for evaluating BMP scenarios

<table>
<tr><th colspan="2" rowspan="2">Purpose</th><th rowspan="2">Item</th><th colspan="4">Value</th></tr>
<tr><th>CM</th><th>ABHMP</th><th>LQFI</th><th>OI</th></tr>
<tr><td colspan="2" rowspan="2">Initializing/Generating BMP scenarios</td><td>Suitable locations</td><td>forest, ridge and backslope</td><td>forest and orchard, all positions</td><td>forest, backslope</td><td>forest and orchard, valley</td></tr>
<tr><td>Effectiveness grade to represent spatial relationships of BMPs along the hillslope</td><td>3</td><td>5</td><td>4</td><td>4</td></tr>
<tr><td rowspan="9">Evaluating BMP scenarios</td><td rowspan="6">Environmental effectiveness by watershed model [1]</td><td>OM</td><td>1.22</td><td>1.45</td><td>1.05</td><td>2.05</td></tr>
<tr><td>BD</td><td>0.98</td><td>0.93</td><td>0.87</td><td>0.96</td></tr>
<tr><td>PORO</td><td>1.02</td><td>1.07</td><td>1.13</td><td>1.03</td></tr>
<tr><td>SOL_K</td><td>0.81</td><td>1.81</td><td>1.71</td><td>1.63</td></tr>
<tr><td>USLE_K</td><td>1.01</td><td>0.82</td><td>1.71</td><td>1.63</td></tr>
<tr><td>USLE_P</td><td>0.9</td><td>0.5</td><td>0.5</td><td>0.75</td></tr>
<tr><td rowspan="3">Economic effectiveness by cost model</td><td>Initial (￥10,000/km^2)</td><td>15.5</td><td>87.5</td><td>45.5</td><td>420</td></tr>
<tr><td>Maintain (￥10,000/year·km^2)</td><td>1.5</td><td>1.5</td><td>1.5</td><td>20</td></tr>
<tr><td>Benefit (￥10,000/year·km^2)</td><td>2</td><td>6.9</td><td>3.9</td><td>60.3</td></tr>
</table>

Notes: [1] Effects of BMPs on watershed modeling include soil property parameters. Values for these items represent relative changes (i.e., multiplying) to the original property values. In addition, some model parameters that have the same value as the present ones are not listed, e.g., the effect on soil organic carbon is the same as on OM.

OM: organic matter, BD: bulk density, PORO: total porosity, SOL_K: soil hydraulic conductivity, USLE_K: soil erodibility factor, USLE_P: conservation practice factor

3) Watershed modeling

- **SEIMS (Spatially Explicit Integrated Modeling System)** (Liu et al. 2014, 2016; Zhu et al., 2019c)
  - **A cell-based, modular, and parallelized** watershed modeling framework;
  - **Flexible and extensible** to couple various watershed processes modules and BMP models;
  - **Module library** contains hydrology, soil erosion, nutrient cycling, and plant growth processes for long-term and storm-event simulations.
- **Calibration and validation** (Zhu et al., 2019a)
  - Warm period: 2012, calibration: 2014-2015, validation: 2013, simulation timestep: **Daily**
  - **Morris screening** for sensitive parameters
  - **Auto-calibration** based on NSGA-II

Processes	Modeling method/algorithm
Interception	maximum canopy storage method (Aston 1979)
Potential evapotranspiration	Penman-Monteith equation (SWAT; Allen et al., 1989)
Surface runoff & infiltration	A modified coefficient method in WetSpa (Liu 2004)
Depression storage	Empirical equation (Linsley et al. 1975)
percolation process	Method in SWAT (Neitsch et al. 2011)
Interflow	Darcy's Law and the kinematic approximation (Liu 2004)
overland flow routing	A diffusive transport approach (Liu et al. 2003)
groundwater flow	A linear reservoir method (Liu 2004)
channel flow routing	Muskingum method (Cunge 1969)
Sediment yield caused by water erosion	MUSLE (Williams 1975)
sediment routing in stream channels	A simplified Bagnold stream power equation (Williams 1980)
Plant growth process	Adapted from SWAT model (Williams 1995)

Data	Resolution
Basic spatial data (DEM, landuse, soil)	**10 m**
Meteorological data & precipitation	**Daily**, 2012-2015
Observation (streamflow & sediment at outlet)	**Daily**, 2012-2015

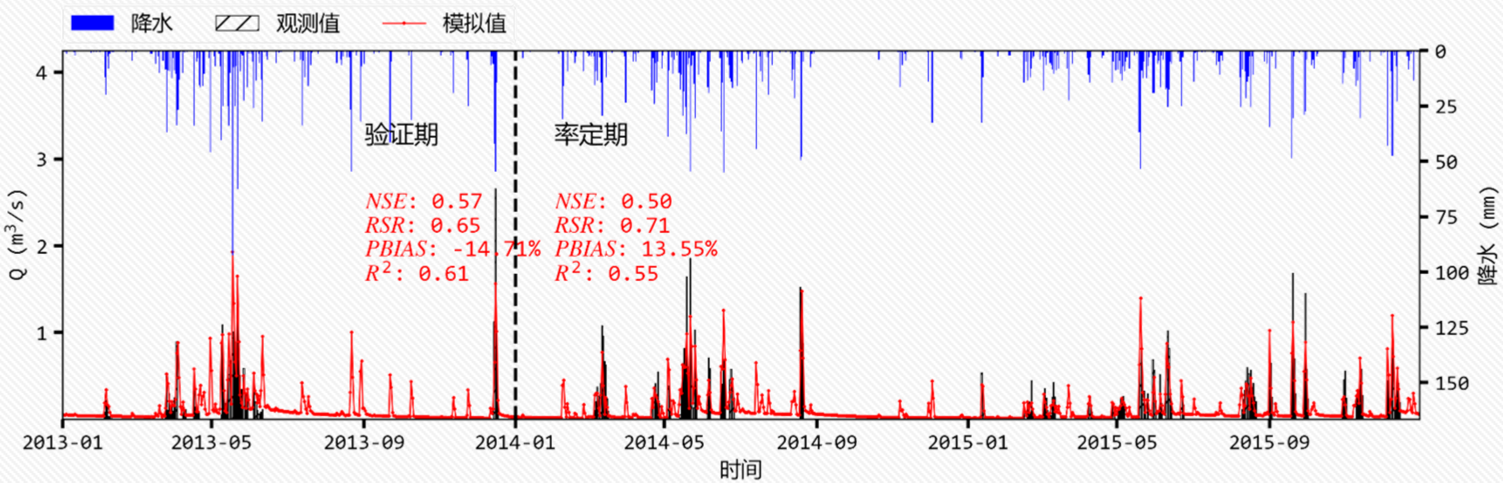
Source code: https://github.com/lreis2415/SEIMS

Model performance of the SEIMS-based Youwuzhen model

One optimal calibration solution was selected as *the baseline scenario*

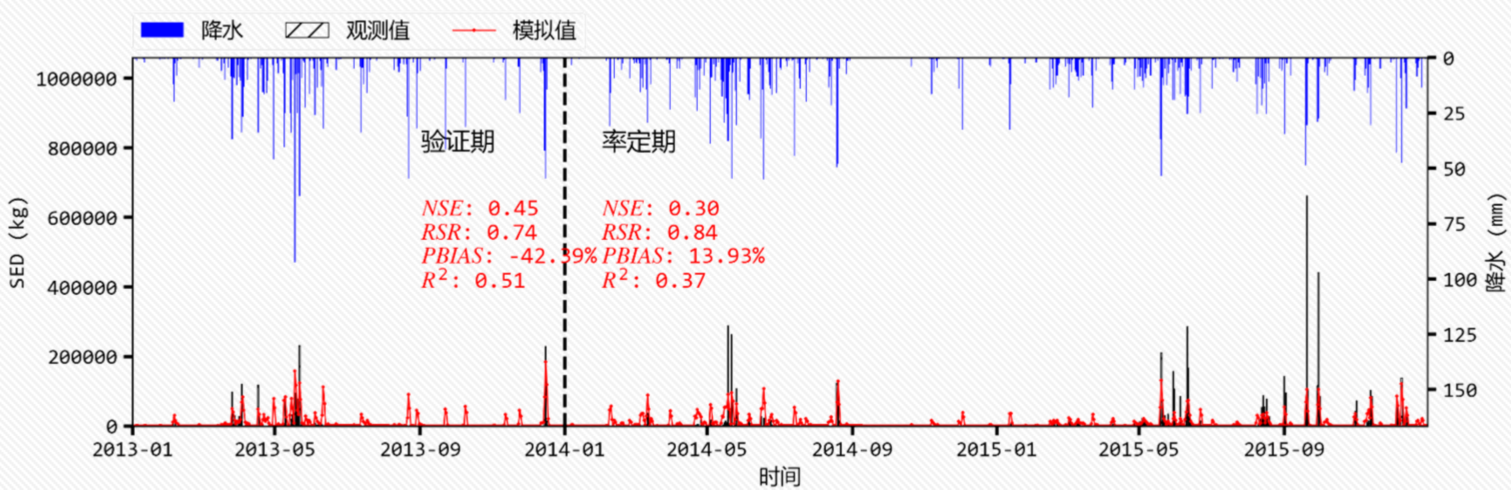
Streamflow

m³/s



Sediment

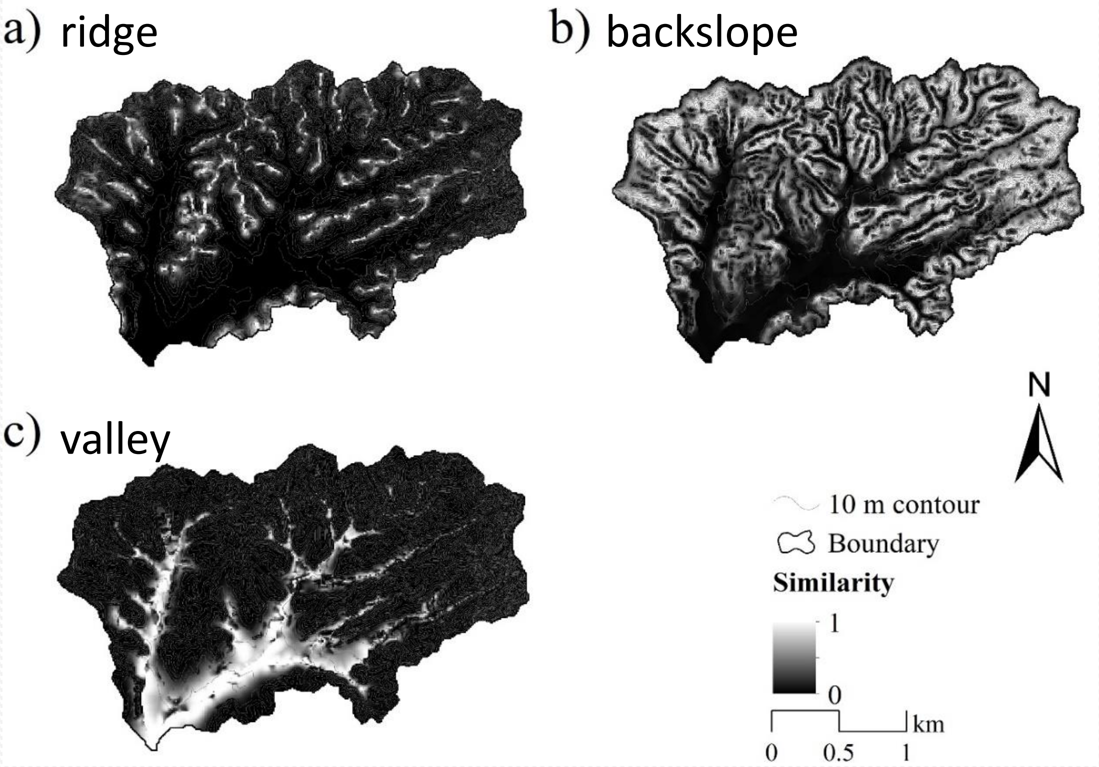
kg



NSE: Nash-Sutcliffe efficiency
PBIAS: percent bias
RSR: root mean square error-standard deviation ratio

4) Deriving fuzzy slope positions

- ***To compared with the boundary-fixed slope position unit approach*** used by Qin et al. (2018) and Zhu et al. (2019a), the same ***three types of slope positions*** were adopted, i.e., ridge, backslope, and valley.
- ***Extracted by the prototype-based fuzzy inferencing method*** (Qin et al., 2009; Zhu et al., 2018).



5) Multi-objective optimization of BMP scenarios based on boundary-adaptive slope position units

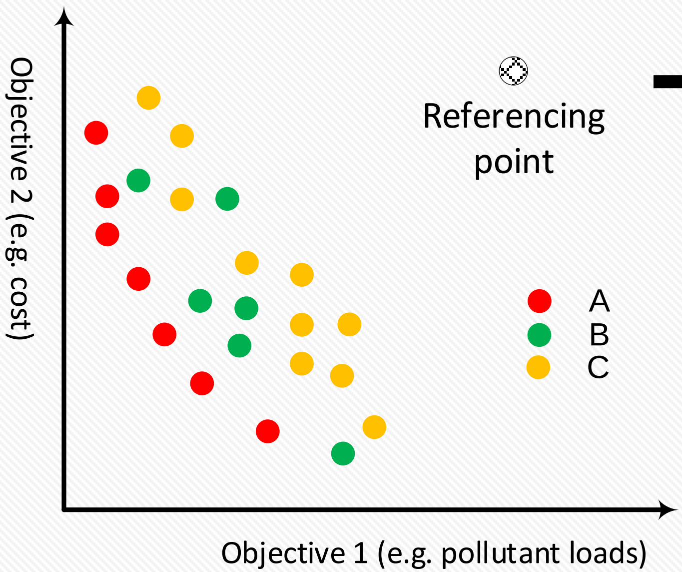
- **Optimization objectives in this study**:
  - Maximizing the reduction rate of soil erosion (compared with baseline scenario)
  - Minimizing the net cost of BMP scenario: $g(X)=\sum_{i=1}^{n} A(x_i)\times\{[C(x_i)+yr\times(M(x_i)-B(x_i))]\}$

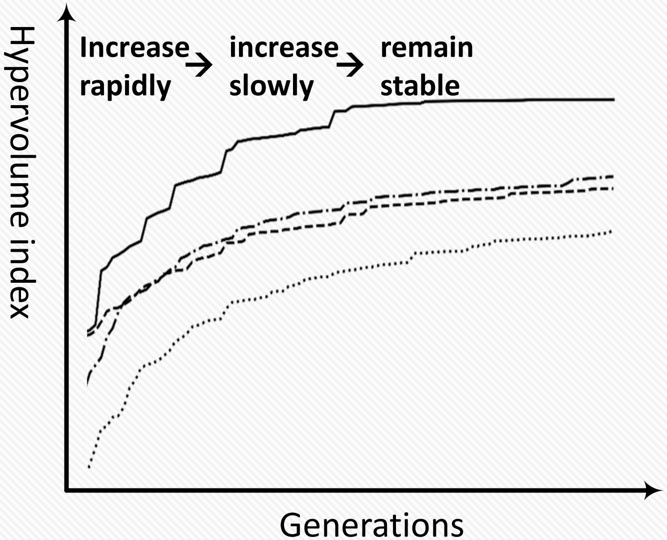
where $A(x_i)$ is the area covered by the BMP; $C(x_i)$, $M(x_i)$, and $B(x_i)$ are unit costs for initial implementation, annual maintenance, and annual benefit, respectively.

- **Experimental design: boundary-adaptive units vs. boundary-fixed units**
  - ***Exp1***: Optimization based on boundary-adaptive slope position units (**ADAPTDUNIT**)
  - ***Exp2***: Optimization based on boundary-fixed slope position units (**FIXEDUNIT**)
  - ***Exp3***: Taking the near-optimal Pareto solution of ***Exp2*** as the initialization population, and applying the proposed dynamic threshold method during the following optimization (**FIXEDUNIT+DYN**)
  - ***Parameter settings for multi-objective optimization (NSGA-II algorithm)***:
    - ✓ Initial population size: 480; crossover probability: 0.8; mutation probability: 0.1
    - ✓ Maximum generation number: 50 (100 for FIXEDUNIT)
    - ✓ **Eight discrete threshold values for boundary adjustment**: ±0.2, ±0.15, ±0.1, ±0.05

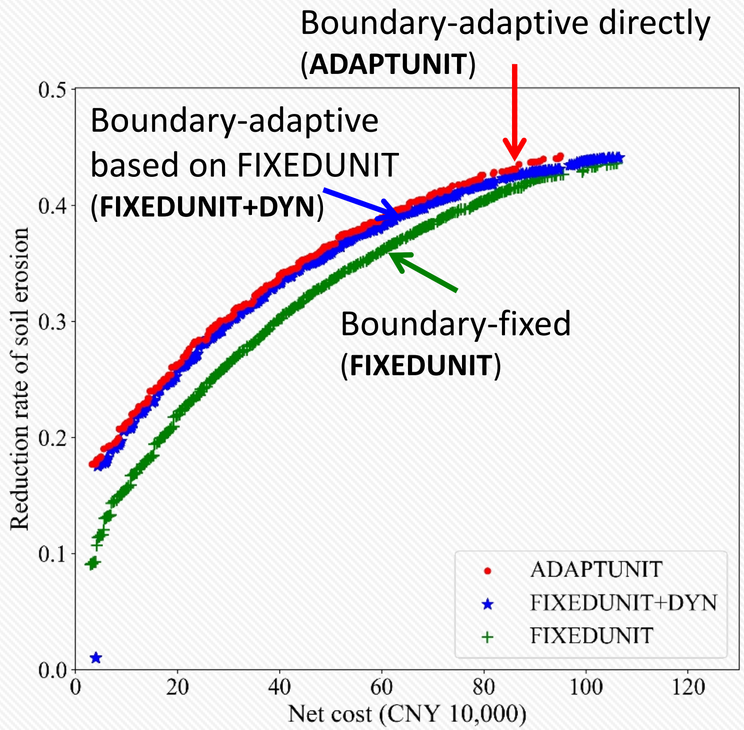
Evaluation method

- **Cost-effectiveness of near-optimal Pareto solutions**
  - Scatter plot, ***the more non-dominated solutions, the better cost-effectiveness*** (Deb et al., 2002)
  - Hypervolume, quantitative quality index considering convergence and diversity (Zitzler and Thiele, 1999), ***the higher index value, the better quality*** (Zitzler et al., 2003)
- **Optimization efficiency**
  - Changes of hypervolume indexes between generations as a qualitative estimator: ***the faster to reach stable, the better optimization efficiency*** (Zhu et al., 2019a)

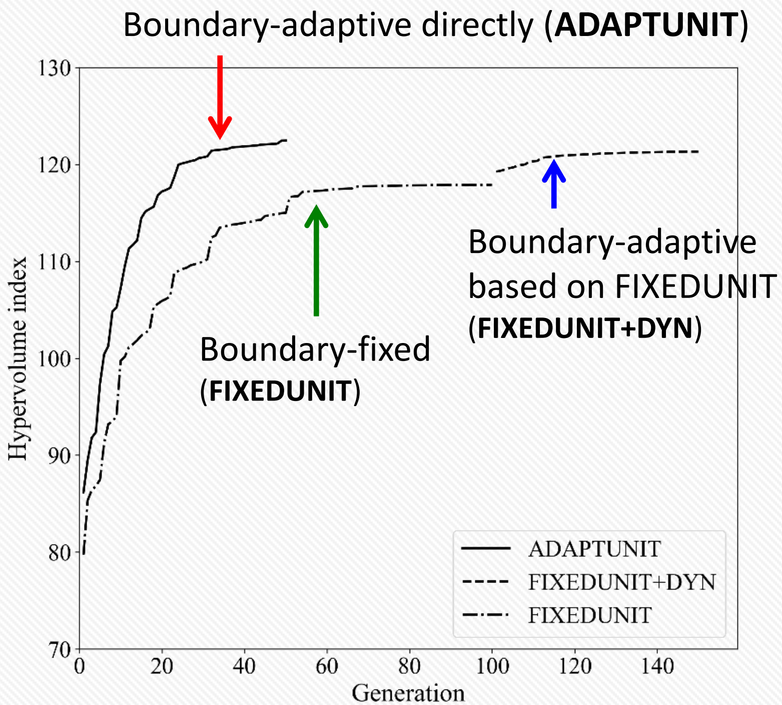




6) Results: Near-optimal Pareto solutions and hypervolume index



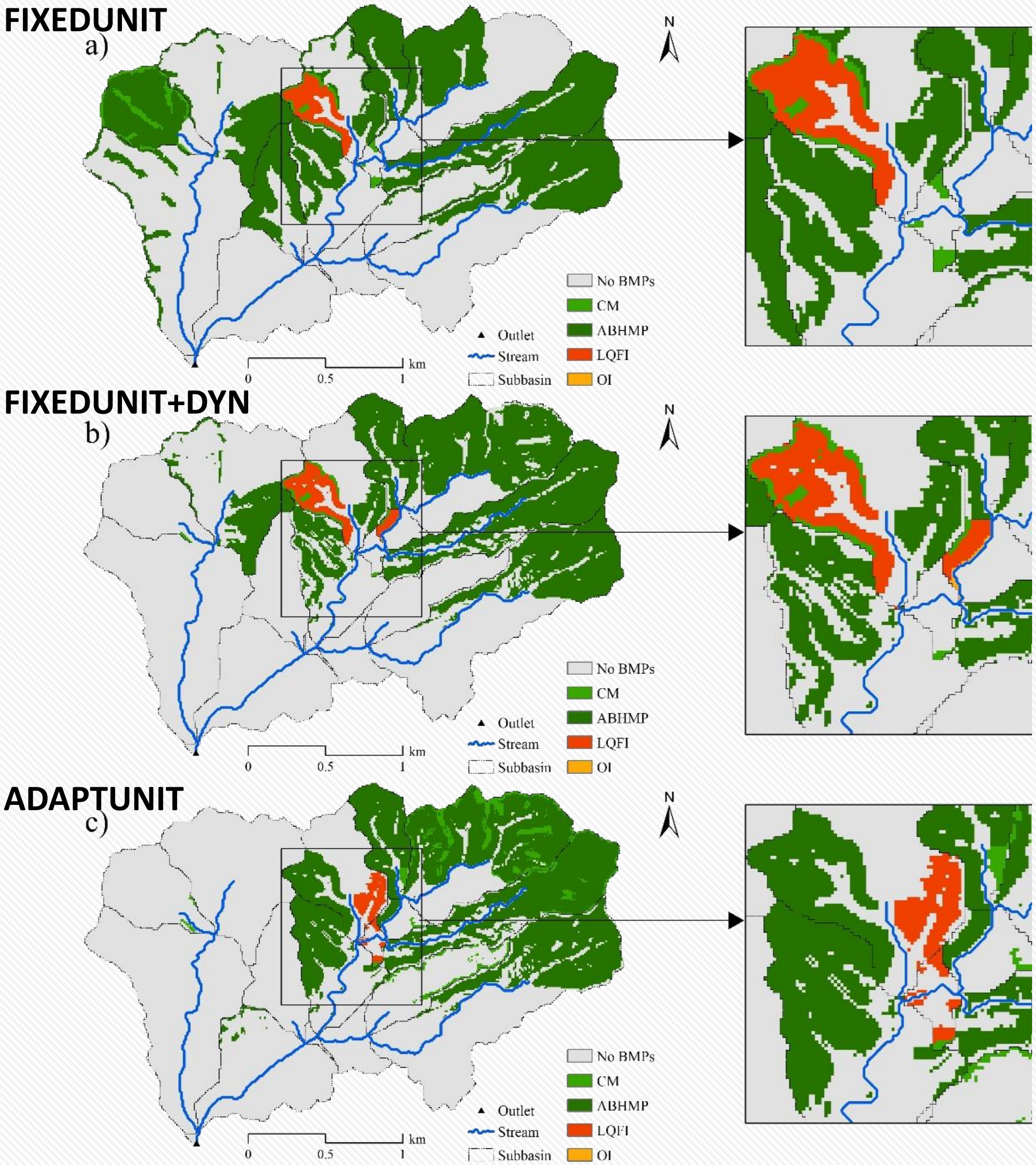
Near-optimal Pareto solutions for the 50th and 100th generations



Hyervolume index changes with generations

- ✓ **ADAPTUNIT performed the best!**
- ✓ The proposed optimization approach can ***significantly enlarge the search space*** and ***obtain optimal BMP scenarios with better cost-effectiveness and higher optimization efficiency*** than that with boundary-fixed units.

6) Results: spatial distribution of optimized BMP scenarios



- ✓ Compared with **FIXEDUNIT**, BMP scenarios based on ***boundary-adaptive units showed more fragmented or even mosaic spatial distribution***.
- ✓ With more hillslopes underwent boundary adjustments, ***utilizing boundary adjustment from the initialization of optimization produce better BMP scenarios*** (i.e., ADAPUNIT beats FIXEDUNIT+DYN).

5 Conclusions

- A novel idea of **adjusting boundaries of BMP configuration units** during the spatial optimization of BMP scenarios
- **New optimization framework of BMP scenarios in a unit-boundary adaptive manner**
  - Techniques adopted in the case study can be easily replaced by those with similar functionalities for ***boundary-adaptive units***, ***watershed modeling***, ***multi-objective optimization process***, etc.
- In a broader sense, this study exemplifies the potential for ***transforming qualitative, vague, and empirical geographical knowledge into quantitative, explicit, and automated geospatial algorithms*** to effectively solve environmental management problems.

Thanks for your attention!

Citation:

Zhu, L-J, Qin, C-Z*, and Zhu, A-X. **2020**. Spatial optimization of watershed best management practice scenarios based on boundary-adaptive configuration units. ***Progress in Physical Geography: Earth and Environment***, doi:10.1177/0309133320939002.

Software:

SEIMS (Spatially Explicit Integrated Modeling System): *https://github.com/lreis2415/SEIMS*

AutoFuzSlpPos(Automated Fuzzy Slope Position): *https://github.com/lreis2415/AutoFuzSlpPos*

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