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Using slope positions as spatial configuration units for optimizing watershed best management practices

Cheng-Zhi QIN, Liang-Jun ZHU, Hui-Ran GAO, A-Xing ZHU,
Jun-Zhi LIU, Hui WU

*(State Key Laboratory of Resources and Environment Information System,
Institute of Geographic Sciences & Natural Resources Research,
Chinese Academy of Sciences)*

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Contents

1. Background

- Watershed **Beneficial (/Best) Management Practices** (**BMPs**)
  - to control soil erosion, reduce nonpoint source pollution, and protect the ecological environment of a watershed (Gitau et al. 2004; Turpin et al. 2005; Arabi et al. 2006; Panagopoulos et al. 2012)
- BMP scenarios
  - Different BMP scenarios for a watershed have different environmental effectiveness and net cost.


Closing measures

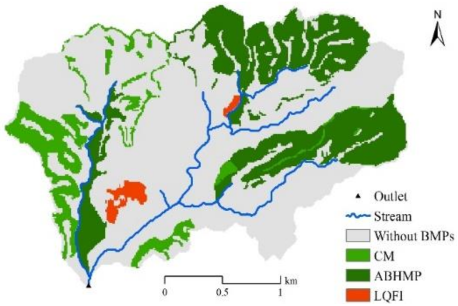

Contour hedgerow


Grass filter belt


Arbor-bush-herb mixed plantation


Terrace

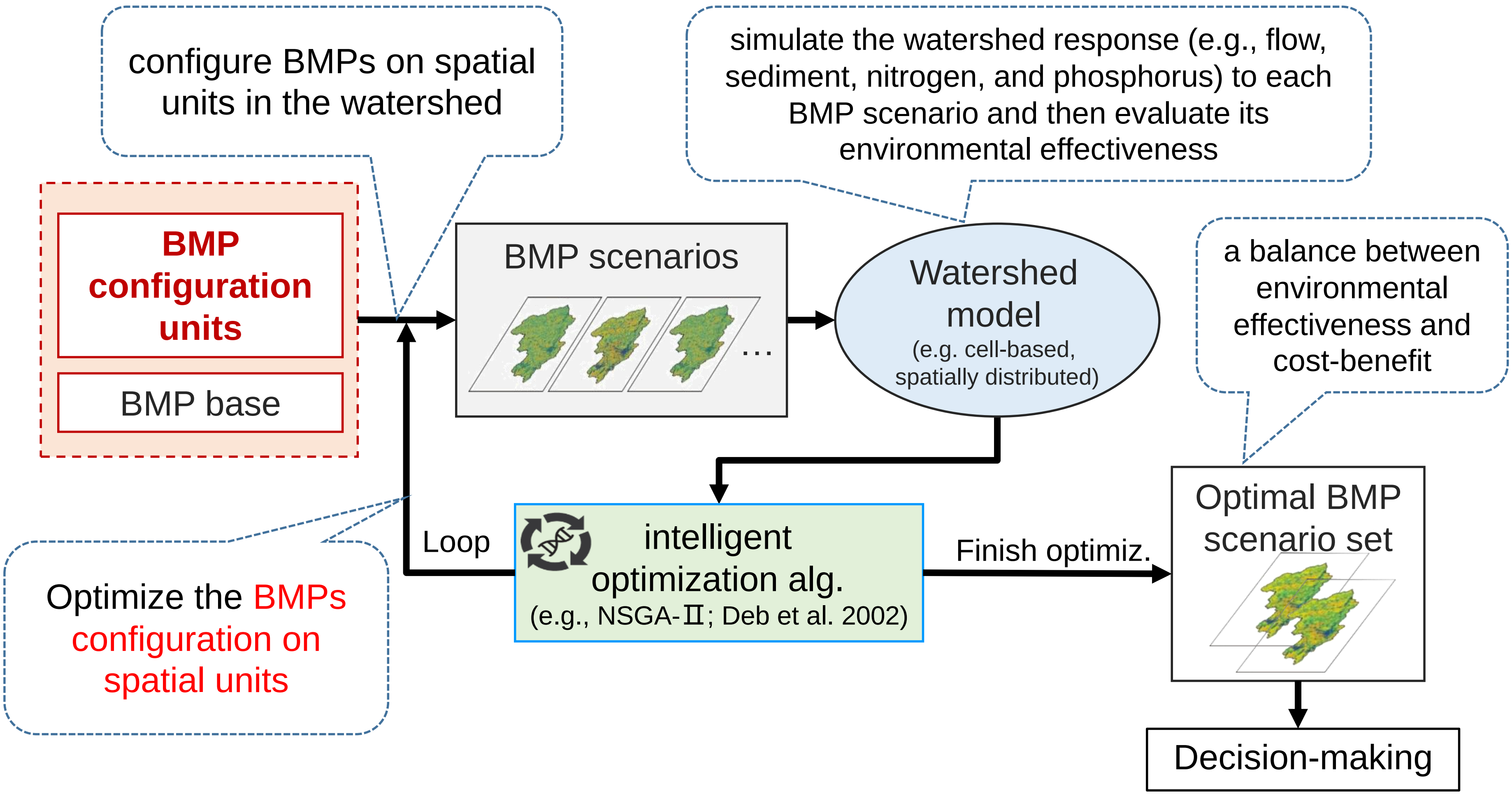

Riparian buffer



BMP scenario
(i.e., configuration of BMPs for spatial units in watershed)

How to plan optimal BMP scenarios for watershed management?

- Spatial optimization based on watershed modeling coupled with intelligent optimization algorithms



BMP configuration units commonly used in existing studies

Too general for spatially-explicit BMP configurations

One HRU may occupy several parts on a hillslope. HRUs are not internally linked (Arnold et al. 2010; Bieger et al. 2016).
Impact of spatial relationships between BMPs on HRUs cannot be effectively assessed.

Often delineated according to **land ownership, current landuse**, or soil type boundaries.
Weak spatial relationships between fields/farms related to hillslope processes.

sub-basins (Chang et al. 2007; Chichakly et al. 2013)	hydrologic response units (HRUs) (Maringanti et al. 2011)	fields (Srivastava et al. 2002)	farms (Gitau et al. 2004; Wu et al. 2017)

Current BMP configuration units cannot well represent the spatial relationships between BMPs and different parts on hillslope according to hillslope processes.
The performance of spatial optimization of watershed BMPs will be impacted.

Research issue in this study

New spatial configuration units for optimizing watershed BMPs ?

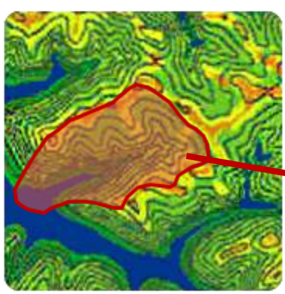
- which can effectively represent the spatial relationships between BMPs and different parts on hillslope according to hillslope processes.

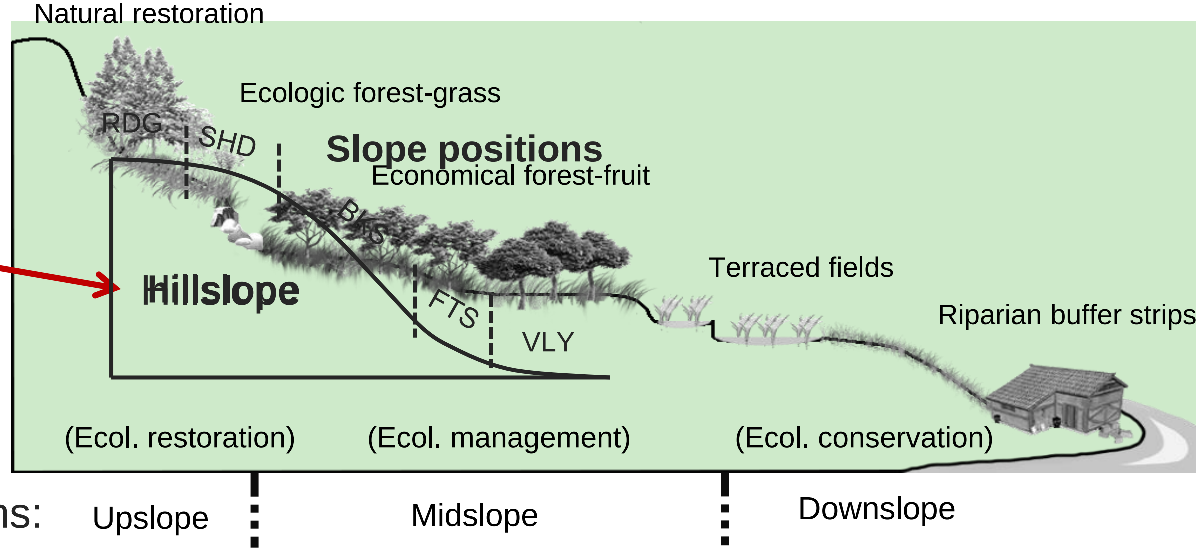
2. Basic idea

Slope positions (e.g., ridge, backslope, and valley) **as BMP configuration units**

- basic landform units and topographically connected units along hillslope;
- homogeneous functional units (from the perspective of physical geography, such as geomorphic, soil, and hydrologic conditions), which affect hillslope-scale processes (e.g., surface runoff and soil erosion; Mudgal et al. 2010) and hence affect the effectiveness of BMPs (Bosch et al. 2012; Hernandez-Santana et al. 2013).
- Characteristics of both BMPs and slope positions should be considered during BMPs configuration (Berry et al. 2005; Goddard 2005; Pennock 2005; Mudgal et al. 2010).

Sub-watershed

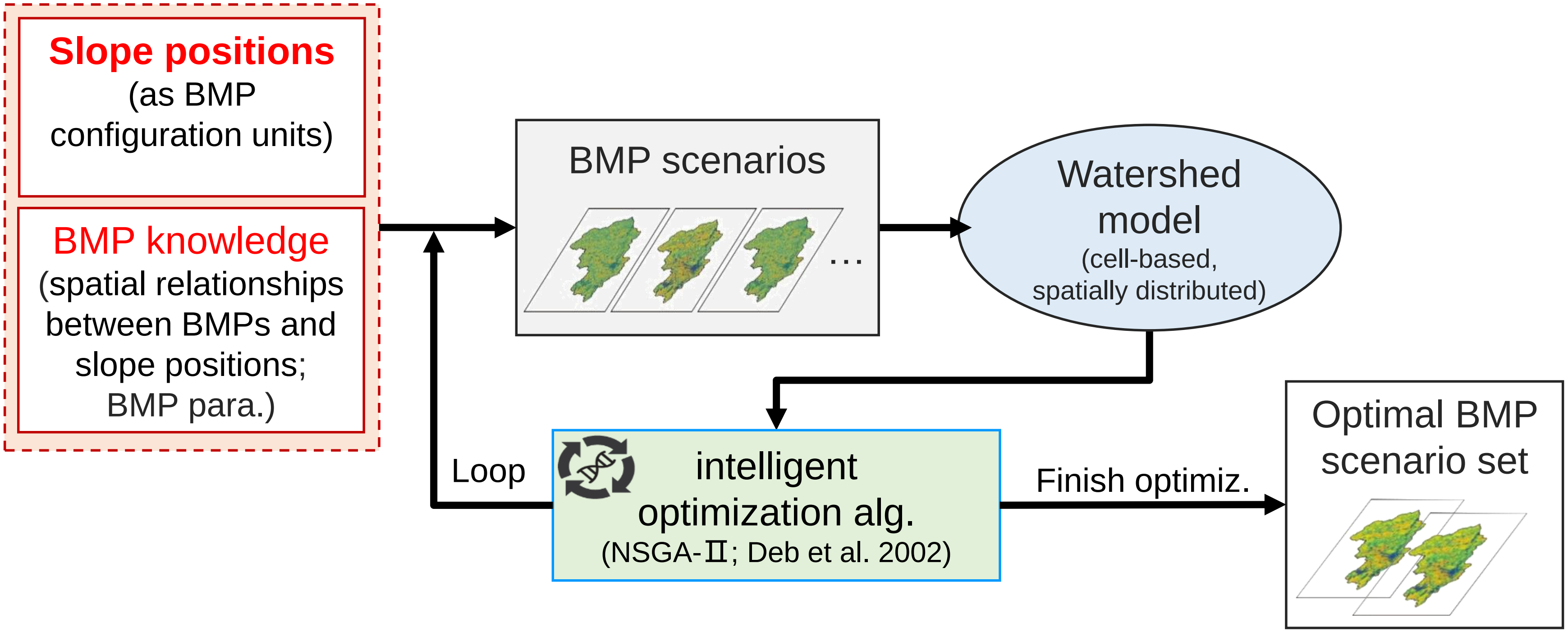




Slope positions:

e.g., practical management experiences of soil and water conservation in SE China (an integrated management scheme adapted from Cai et al. (2012))

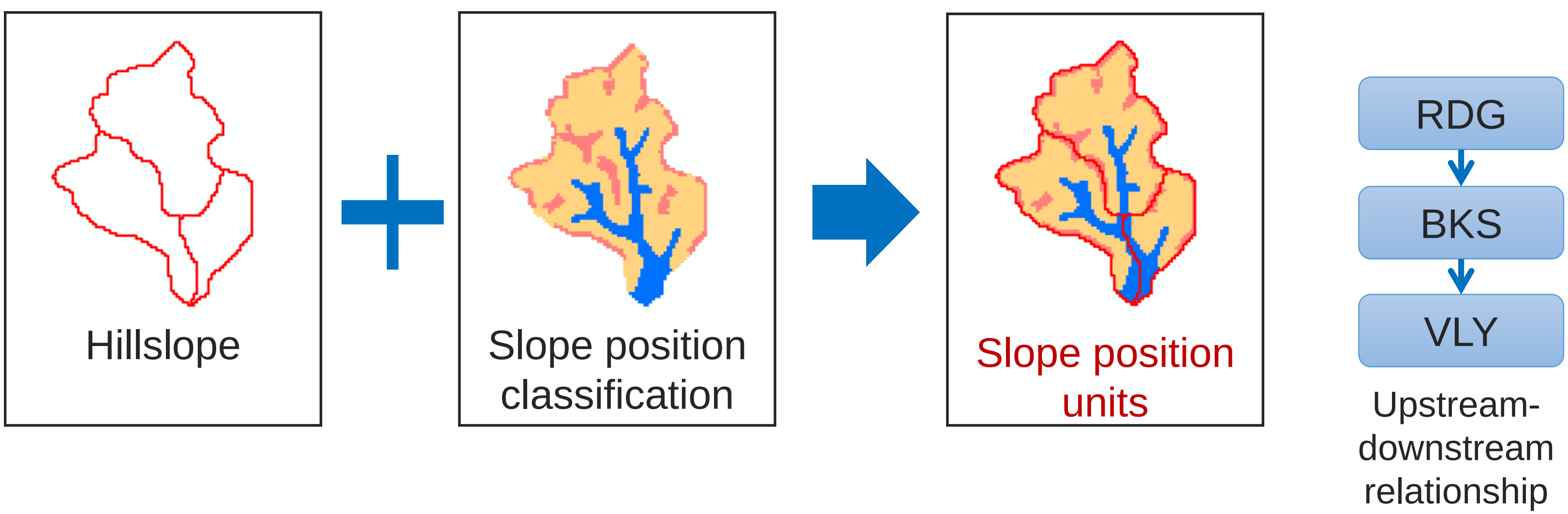
3. An approach to spatial optimization of watershed BMPs based on slope position units



- Key issues in design of the proposed approach:
  1) delineate slope positions for an area;
  2) formalize & use the knowledge of the spatial relationships between BMPs and slope positions.

1) Delineation of slope position units

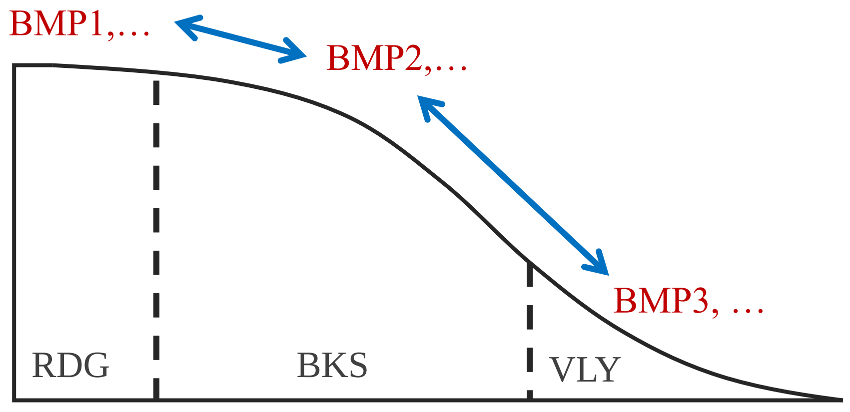
- Three types of slope positions (i.e., ridge, backslope, and valley) (Arnold et al. 2010)
- Derive slope position units through digital terrain analysis (Qin et al. 2009; Zhu et al. 2018)
- Maintain a hierarchical structure of spatial units, i.e., sub-basin, hillslope, & slope position



https://github.com/lreis2415/AutoFuzSlpPos

2) Formalize the knowledge of the spatial relationships between BMPs and slope positions

- Knowledge of the spatial relationships between the BMPs and slope positions can be formalized as two types of rules:

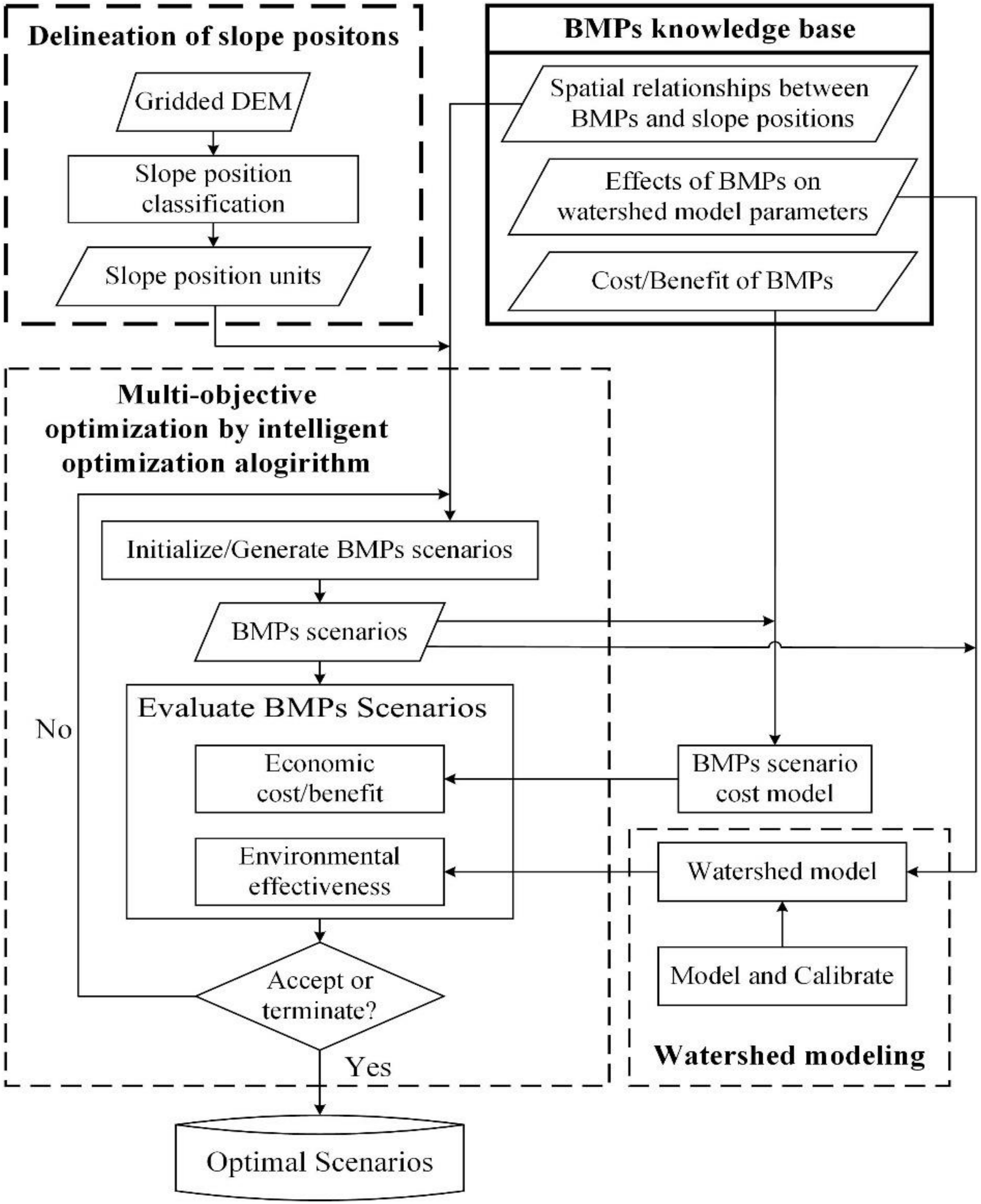


(1) suitable BMPs for each type of slope position;

(2) spatial constraint among BMPs on different types of slope position along the hillslope from upstream to downstream

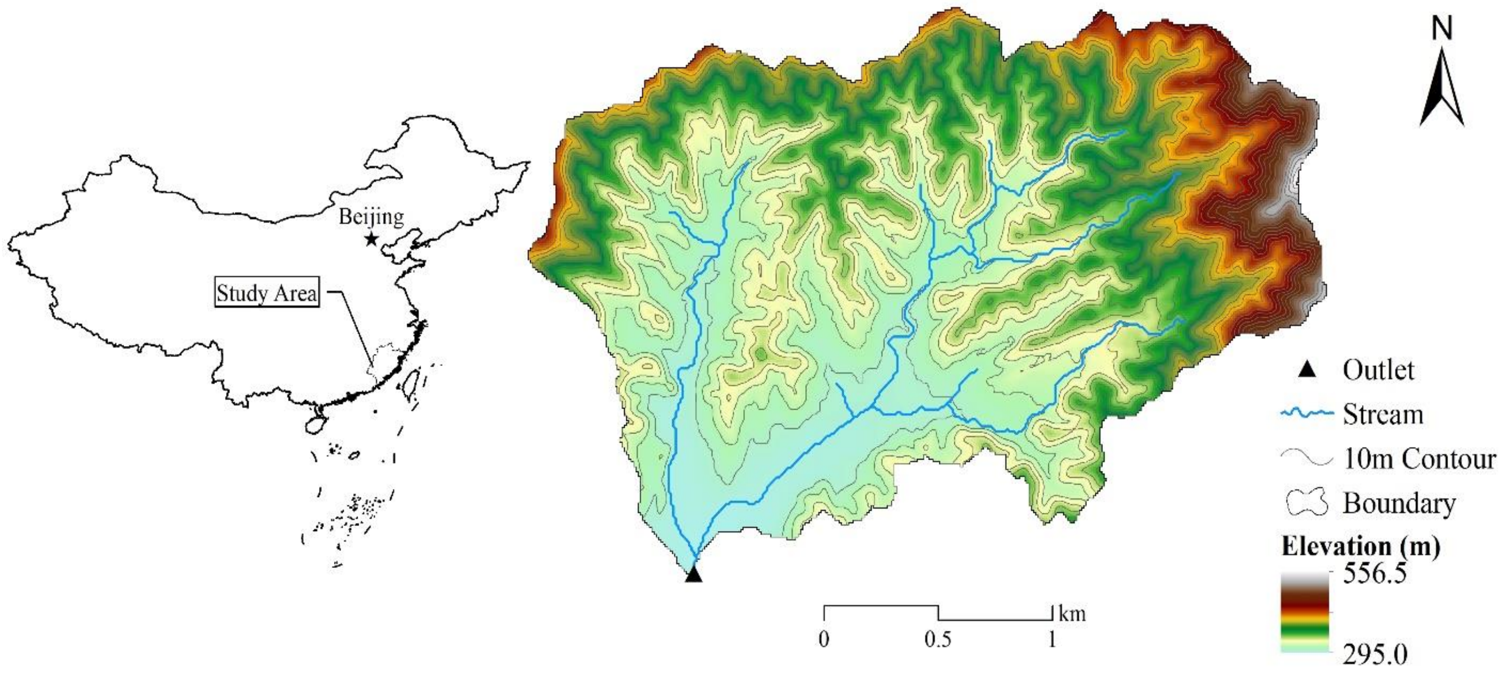
- **local experience → rule**

Framework of the proposed approach



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

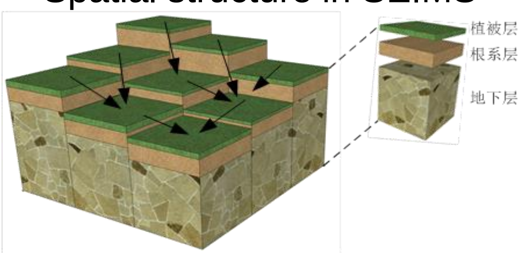
- Study area: Youwuzhen watershed (~5.39 km^2), Fujian province, China
  - in the upstream of the Ting river, **the typical red-soil hilly region in southeastern China**
  - Terrain: low hills with steep slopes (elevation: 295.0m~556.5m; average slope: 16.8°), broad alluvial valleys;
  - Climate: under a mid-subtropical monsoon moist climate. Annual average temperature: 18.3 ℃; annual average precipitation: 1697.0 mm, while intense short-duration thunderstorm events from March to August contribute about three quarters of annual precipitation (Chen et al. 2013);
  - Main landuse types: forest, paddy field, orchard, with an area ratio of 59.8%, 20.6%, 12.8%, respectively;
  - suffers from severe soil erosion.



2) Watershed processes modeling

- SEIMS (Spatially Explicit Integrated Modeling System) (Liu et al. 2014, 2016)
  - A cell-based, parallel-computing watershed processes simulation framework;
  - flexible for coupling various watershed processes modules;
  - can simulate long-term watershed processes (e.g., hydrology, soil erosion, and plant growth).

Spatial structure in SEIMS



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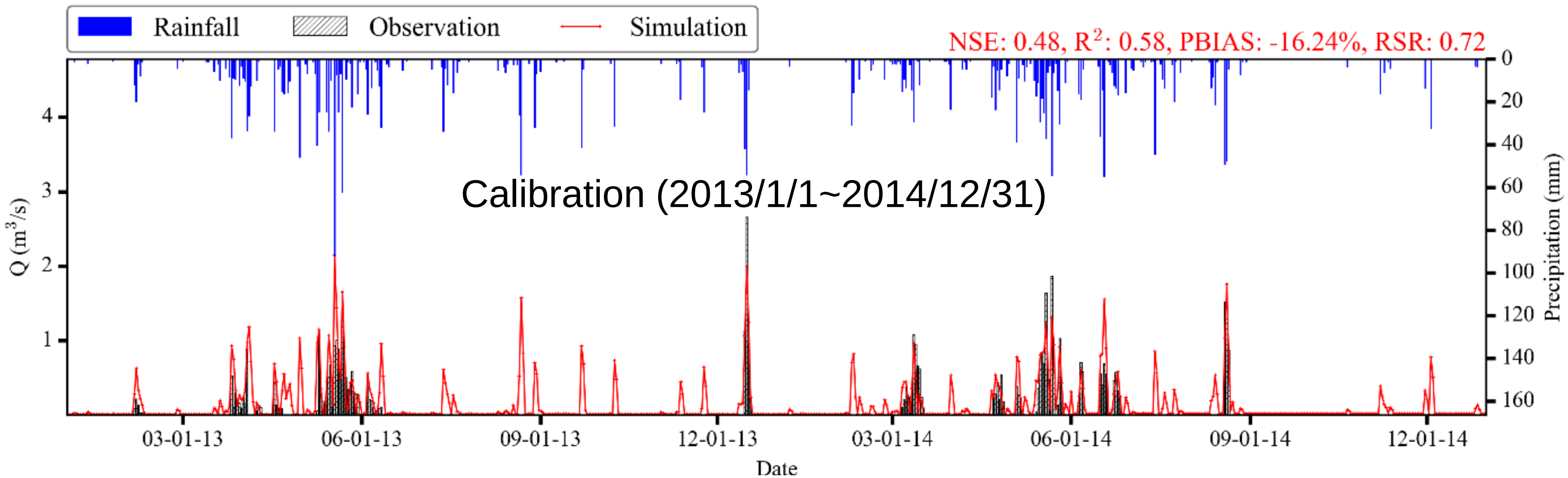
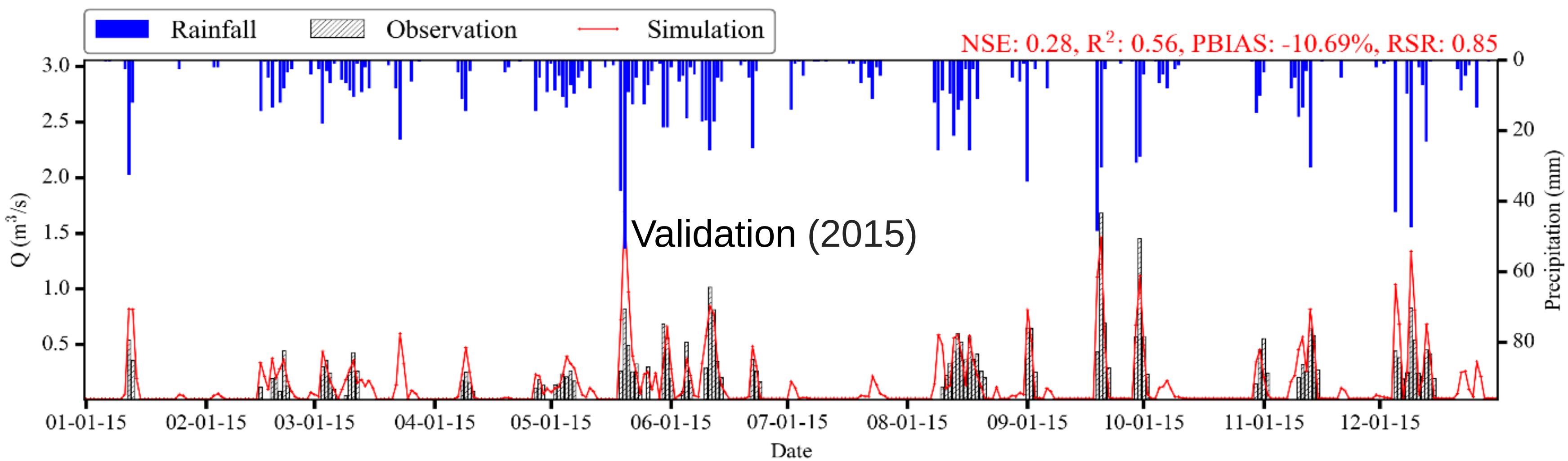
Processes	method/algorithm
interception	maximum canopy storage method (Aston 1979)
depression storage	empirical equation (Linsley et al. 1975)
Surface runoff and infiltration	a modified coefficient method in WetSpa (Liu 2004)
potential evapotranspiration	Priestley-Taylor equation (Priestley & Taylor 1972)
percolation process	method in SWAT (Neitsch et al. 2011)
Interflow	Darcy's Law and the kinematic approximation
groundwater flow	a linear reservoir method (Liu 2004)
overland flow routing	a diffusive transport approach (Liu et al. 2003)
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
DEM	**10 m**
landuse	10 m (Chen et al. 2013)
soil	1:50,000 (Chen et al. 2013)
meteorological data & precipitation	**Daily**

https://github.com/lreis2415/SEIMS

Simulated flow discharge (m^3/s) at the watershed outlet

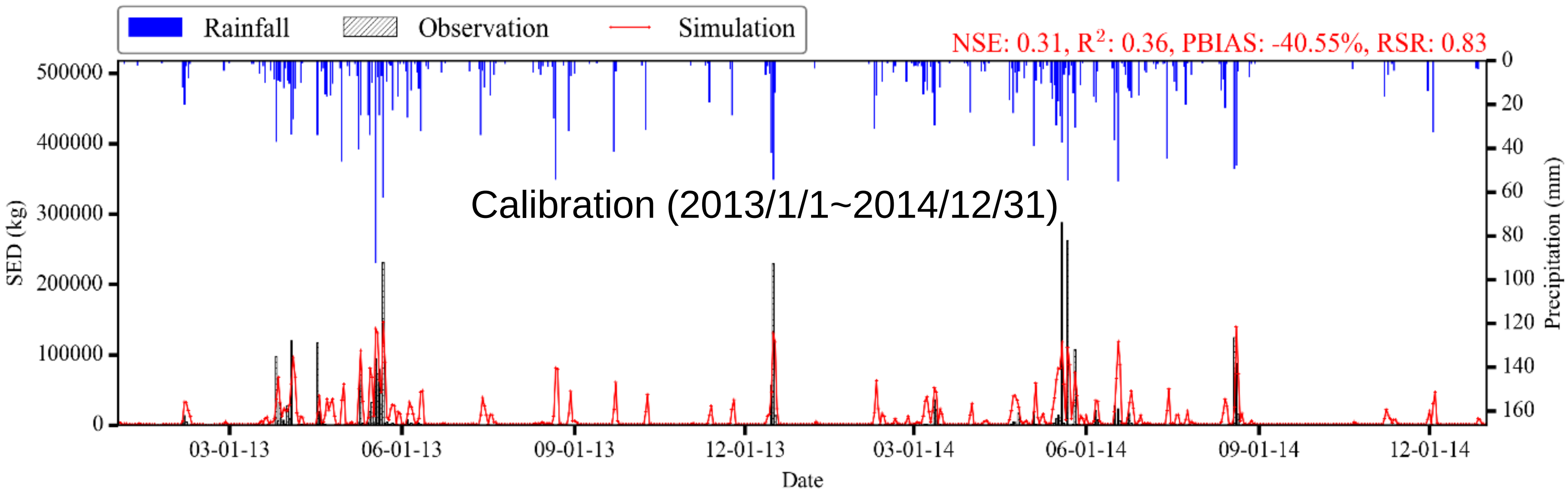


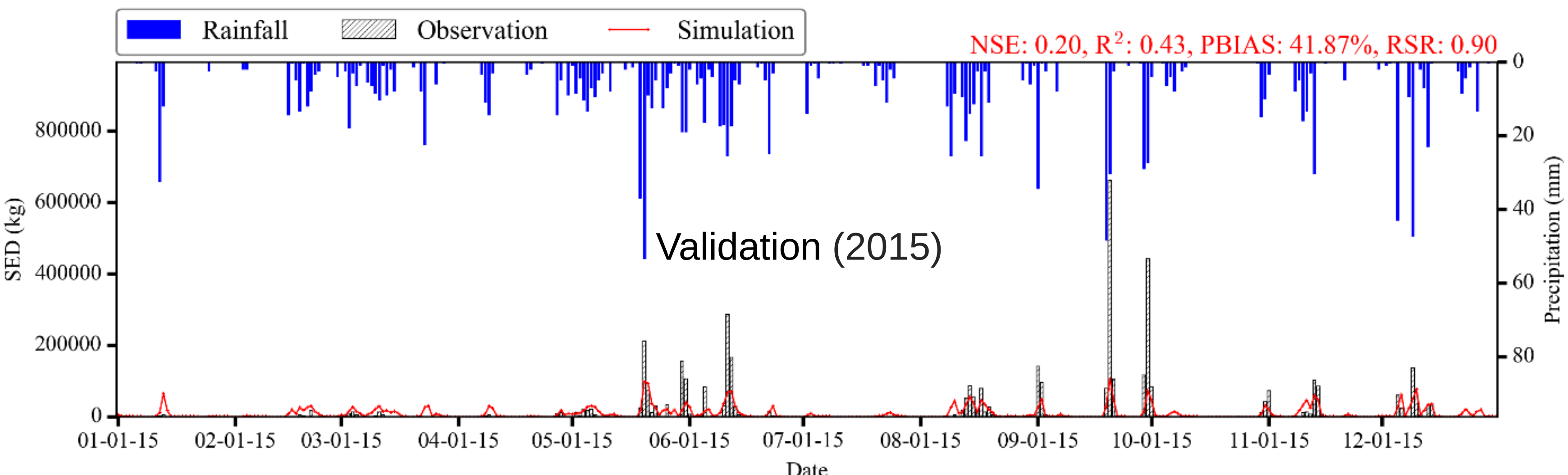


- The periodic monitoring flow and sediment discharge data at the watershed outlet from 2013 to 2015 were provided by the Soil and Water Conservation Bureau of Changting county.

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

Simulated sediment export (kg) at the watershed outlet

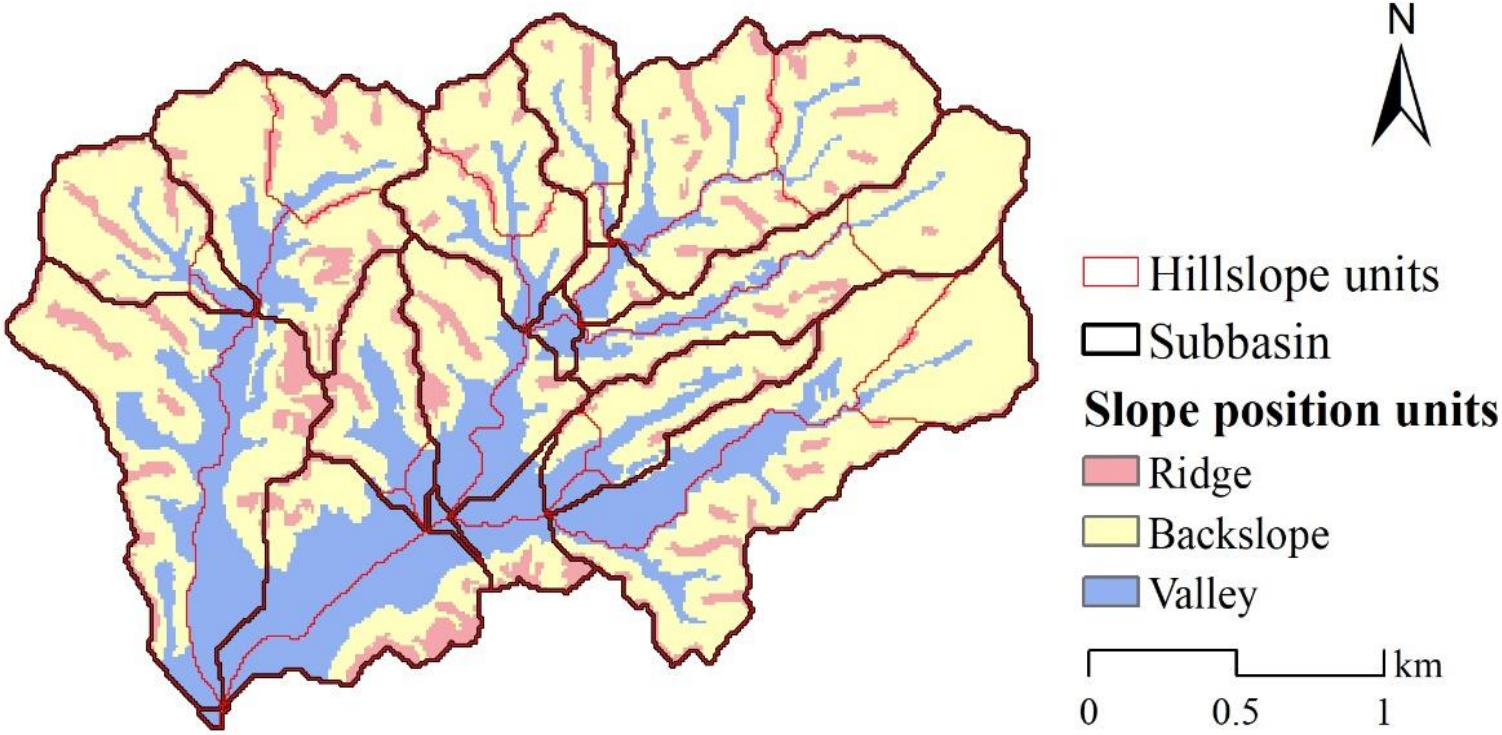




NSE: Nash-Sutcliffe efficiency
PBIAS: percent bias
RSR: root mean square error-standard deviation ratio

3) Delineation of slope position units

- 17 sub-basins, 35 hillslopes, and 105 slope position units delineated in the study area



4) BMPs & knowledge considered in this study

- Four BMPs in study area

(Chen et al. 2013; Chen et al. 2017)

BMP	Brief description	Effective. grade
Closing measures (CM)	Facilitate afforestation from human disturbance (e.g., tree felling and grazing). **Suitable for the ridge area and upslope positions** that suffer low or moderate soil erosion.	**3**
Arbor-bush-herb mixed plantation (ABHMP)	Planting trees (e.g., Schima superba and Liquidambar formosana), bushes (e.g., Lespedeza bicolor), and herbs (e.g., Paspalurn wettsteinii) in level trenches with compound fertilizer in positions with high-to-violent soil and water losses. **Suitable for all slope positions**.	**5**
Low-quality forest improvement (LQFI)	Improving the infertile forest by applying compound fertilizer to every hole (40 cm × 40 cm × 40 cm) in the uphill position of crown projection. Suitable for the moderate or serious eroded land in **the upslope and steep backslope positions**.	**4**
Orchard improvement (OI)	Constructing level terraces, drainage ditches, storage ditches, irrigation facilities and roads, planting economic fruit, and interplanting grasses and Fabaceae (Leguminosae) plants in orchards on the **middle and down slope positions** under better water and fertilizer conditions.	**4**

(**effectiveness grade (1~5):** higher grade means better effectiveness of mitigating soil erosion)

- The spatial relationships between BMPs and slope positions along the hillslope from upstream to downstream: local experience (Chen et al. 2013) → rule
  - Rule: The effectiveness grade of the BMP placed on the backslope should be greater than or equal to that of the BMP placed on the ridge of the same hillslope.

    e.g., effectiveness order of BMP sequences for ridge and backslope of a hillslope: ABHMP-ABHMP, CM-ABHMP, CM-CM

    e.g., ABHMP-CM will be ignored because the effectiveness grade of CM (i.e., 3) is less than that of ABHMP (i.e., 5)

Environmental effects and cost-benefit of BMPs in study area

- **Environmental effects of BMPs** on major soil properties and USLE factors after 8 years of implementation, according to the sample data in Changting county.
  - presented in watershed model by relative alterations of major parameters related to hydrologic and soil erosion processes (Wu et al. 2017)

(Chen et al. 2013; Fujian Soil and Water Conservation Monitoring Station 2010)

BMP	OM*	BD	PORO†	SOL_K	USLE_K‡	USLE_P‡
CM	1.22	0.98	1.02	0.81	1.01	0.90
ABHMP	1.45	0.93	1.07	1.81	0.82	0.50
LQFI	1.05	0.87	1.13	1.71	0.81	0.50
OI	2.05	0.96	1.03	1.63	0.88	0.75

Notes: Values in table are relative changes (i.e., multiply) corresponding to the original properties.
OM = Organic matter, BD = Bulk density, PORO = Total porosity, SOL_K = Soil hydraulic conductivity.
* The effect on organic matter is the same as on soil organic carbon.
† The effect on total porosity is the same as on field capacity, wilting point, etc.
‡ USLE_K and USLE_P are soil erodibility factor and conservation practice factor in USLE model, respectively.

- **Cost-benefit for each BMP**

(unit: 10,000 RMBY/km^2; Wang 2008)

BMP	Implementation cost	Annual maintenance cost	Annual benefit
Closing measures (CM)	15.5	1.5	2.0
Arbor-bush-herb mixed plantation (ABHMP)	87.5	1.5	6.9
Low-quality forest improvement (LQFI)	45.5	1.5	3.9
Orchard improvement (OI)	420	20	60.3

5) Multi-objective optimization by intelligent optimization algorithm

- Optimization objectives in this study:

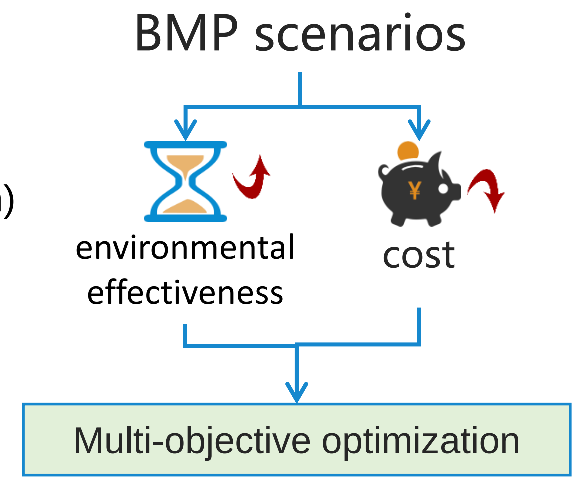
(1) maximizing the reduction rate of soil erosion

- compare with a baseline scenario (scenario for model calibration)

(2) minimizing the net cost of BMPs

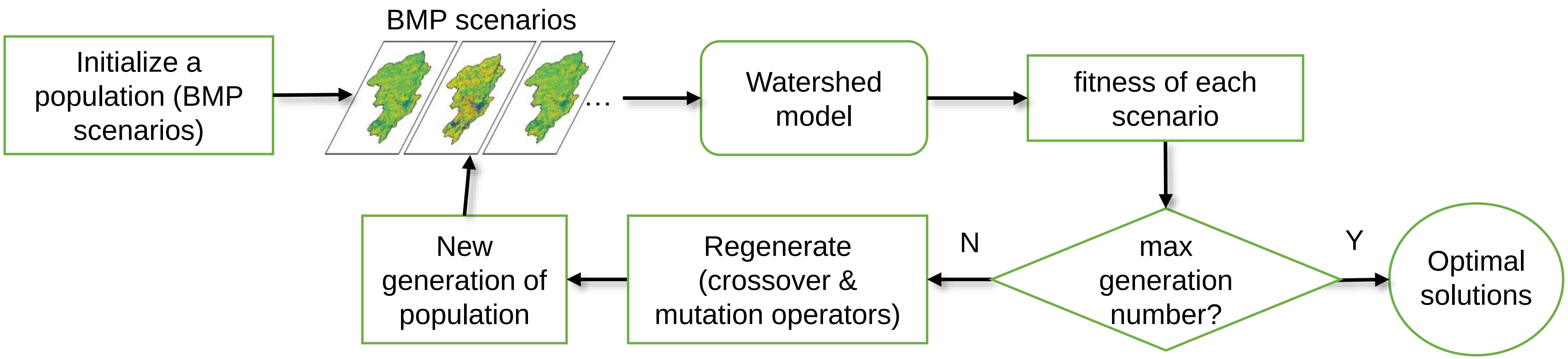
$$g(X)=\sum_{i=1}^{n} A(x_i)\times\left\{\left[C(x_i)+yr\times\left(M(x_i)-B(x_i)\right)\right]\right\}$$

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.



NSGA-II (Non-dominated Sorting Genetic Algorithms II; Deb et al., 2002)

- Creation of BMP scenario obeys the rules of spatial relationships between BMPs and slope positions.
- a BMP scenario: an individual of a population, which is represented as a chromosome with genes as variables (i.e., BMP configuration units with selected BMP type or without BMP).



6) Experimental design

The proposed approach vs. “the random approach”

- The random approach: the traditional approach to spatial BMPs optimization which initializes and generates individuals (BMP scenarios) by randomly selecting and allocating BMPs on configuration units.
- with same settings
  - ✓ Watershed model
  - ✓ BMP configuration units (i.e., slope position units in this study)
  - ✓ BMP parameter-settings in watershed model
  - ✓ NSGA-II: initial population size: 60; selection rate: 0.8; maximum generation number: 100; crossover probability: 0.75; mutation probability: 0.15
- Difference: The proposed approach used rules of the spatial relationships between BMPs and slope positions during spatial BMPs optimization.

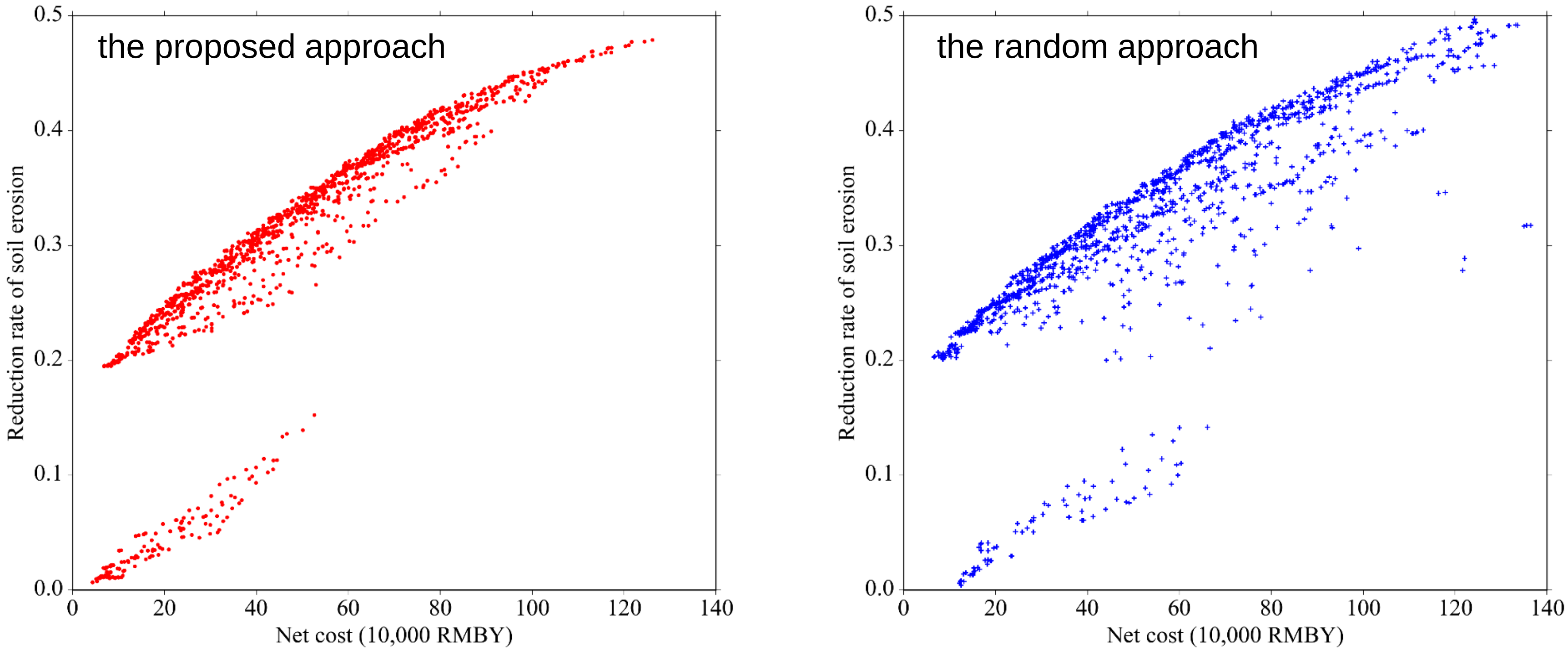
Evaluate the quality of near Pareto optimal solutions

(1) From a mathematical perspective: convergence and diversity of near Pareto optimal solutions derived from all generations,

(2) From a geographical perspective: the rationality of the spatial configurations of BMP scenarios selected from the near Pareto optimal solutions

7) Results and Discussion

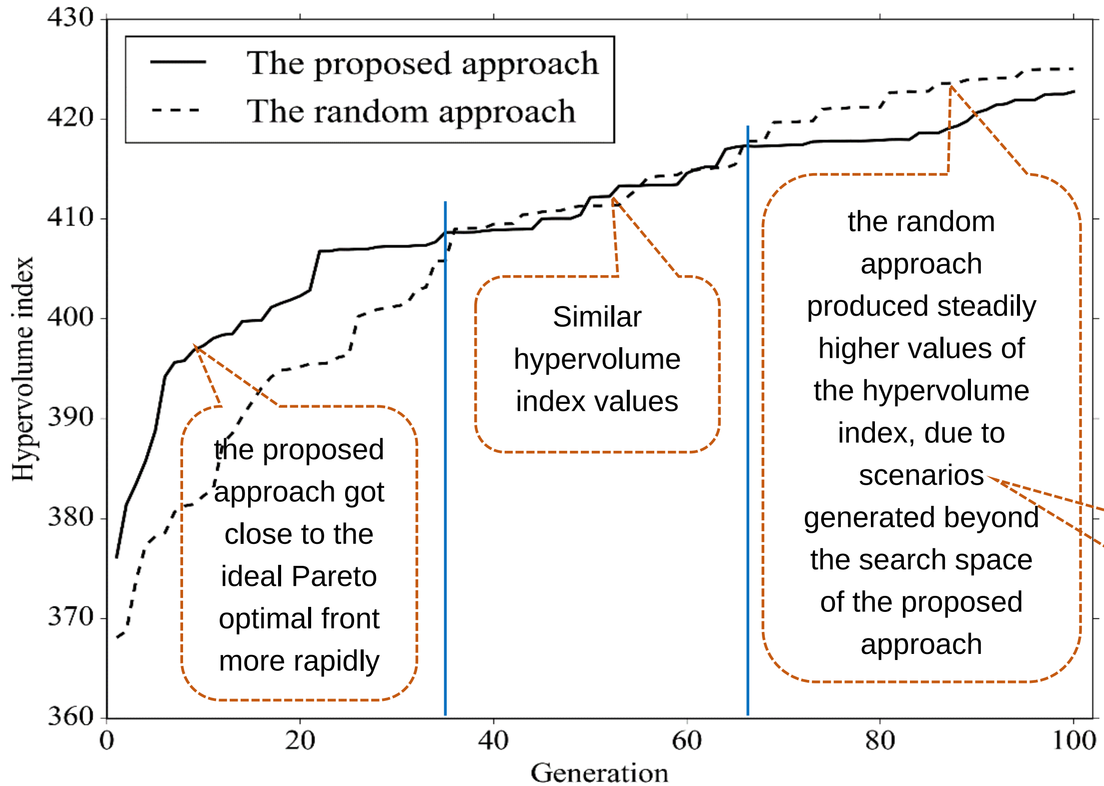
Near Pareto optimal solutions derived from all generations



- The proposed approach shows a better convergence and a similar diversity in the Pareto optimal front, compared with the random approach.
- By considering the relationships between BMPs and slope positions, the proposed approach can reduce the search space of optimal solutions (or, higher computational efficiency)
  - The calibrated SEIMS model was executed to evaluate 1476 BMP scenarios for the proposed approach and 1523 BMP scenarios for the random approach.

Near Pareto optimal solutions under different generations

- **Change of the hypervolume index with generations**: a quantitative comparison of the quality of near Pareto optimal solutions considering both convergence and diversity (Zitzler et al. 2003)
  - hypervolume index (Zitzler & Thiele 1999): measures the volume (or area) of objective space covered by a set of near Pareto optimal solutions.
  - A higher hypervolume index indicates a better quality of solutions, from a mathematical perspective.



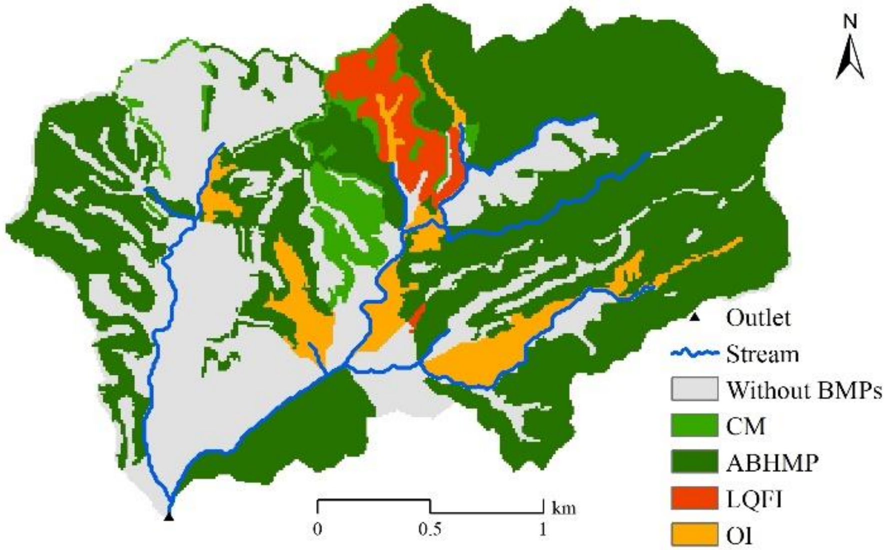
✓ The proposed approach can effectively use the rules of spatial relationships between BMPs and slope positions to achieve better solutions during optimization.

Are these scenarios practical in terms of spatial configurations of BMPs?

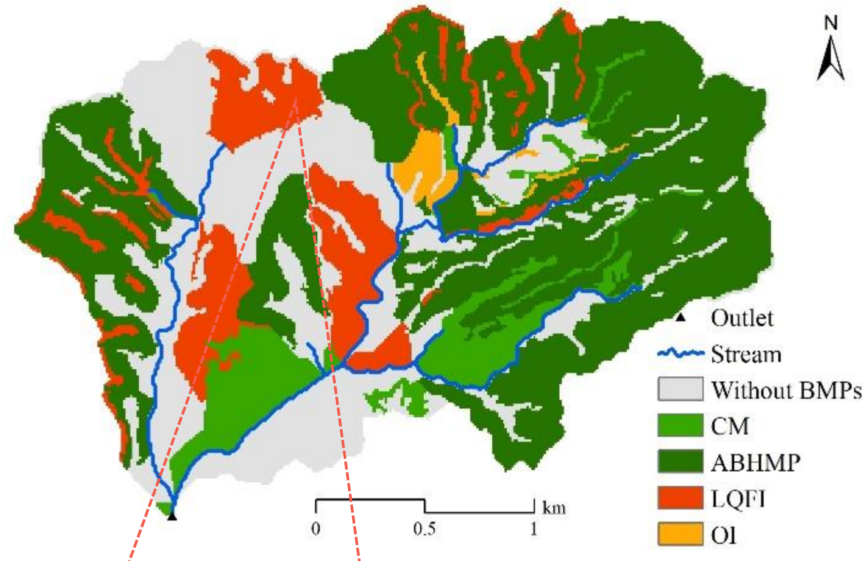
* The reference point for calculating the hypervolume index is (300, -1), i.e., the economic benefit being 300 million RMBY and the reduction rate of soil erosion being -1.

BMP scenarios selected from the near Pareto optimal solutions of the last (100th) generation

the proposed approach
(47.7% reduction rate of soil erosion and 1.22 million RMBY net cost)



the random approach
(47.9% reduction rate of soil erosion and 1.15 million RMBY net cost)



match the relationships between BMPs and slope positions

unreasonable for practical engineering
e.g., allocating Orchard improvement (OI) on ridges, and Closing measures (CM) on valleys

- The proposed approach can derive more practicable optimal BMP scenarios than the random approach.
  - From the mathematical view, the random method generates a more optimal solution (lower net cost of the scenario) than the proposed approach.
  - The spatial BMP configuration of the scenario from the random approach shows several inappropriate allocations which violate the relationships between BMPs and slope positions (impractical for watershed management).

4. Summary

- Slope positions as BMP configuration units for optimizing watershed BMPs
- An approach to spatial optimization of watershed BMPs based on slope position units
  - The spatial relationships between BMPs and slope positions can be explicitly considered in spatial BMPs optimization.
  - Experimental results show that the proposed approach is effective and efficient at proposing practicable BMP scenarios.
- The proposed approach can be combined with
  - other watershed models (e.g., SWAT+; Bieger et al. 2016),
  - other intelligent optimization algorithms (e.g., SPEA2; Zitzler et al. 2001),
  - other slope positions systems (Qin et al. 2009; Zhu et al. 2018),
  - other BMPs available for different study areas.

Thank You for Your Attention !

Qin C-Z, Gao H-R, Zhu L-J*, Zhu A-X, Liu J-Z, Wu H. Spatial optimization of watershed best management practices based on slope position units. ***Journal of Soil and Water Conservation***, accepted.

Zhu L-J, Zhu A-X, Qin C-Z*, Liu J-Z. Automatic approach to deriving fuzzy slope positions. ***Geomorphology***, 2018, 304: 173-183.

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秦承志 (QIN Cheng-Zhi)

Email: qincz@lreis.ac.cn

Webpage: http://people.ucas.ac.cn/~qincz?language=en