A Novel Integrated Modelling Approach to Design Cost-effective Agri-Environment Schemes to Prevent Water Pollution and Soil Erosion from Cropland

— A Case Study of Baishahe Watershed in Shanxi Province, China

Zhengzheng Hao

Coauthors: Dr. Astrid Sturm, Prof. Frank Wätzold

Outline

- Introduction
- Study region
- Methodology
- Results
- Discussion
- Conclusion

Introduction — background and motivation

- Intensive agricultural system has resulted in severe environmental risks, including soil erosion and water pollution in many regions (Evans *et al.*, 2019)

- A key policy instrument are agri-environment schemes (AES), payments to farmers to address environmental problems, have been widely applied in developed countries (Wunder & Wertz, 2009)

- Problems of AES include huge expense without adequate planning and design for cost-effective measures, like Sloping Land Conversion Programme in China (Li & Liu, 2010)

- To contribute the gap, a novel integrated modeling procedure can be a promising way to improve both:
  - Effectiveness of AES, with the intended environmental goals (reducing soil erosion and water pollution) being actually achieved
  - Cost-effectiveness of AES, with maximized environmental goals under certain budget, or minimized budget for given goals (Wätzold et al., 2016)

Introduction — objectives

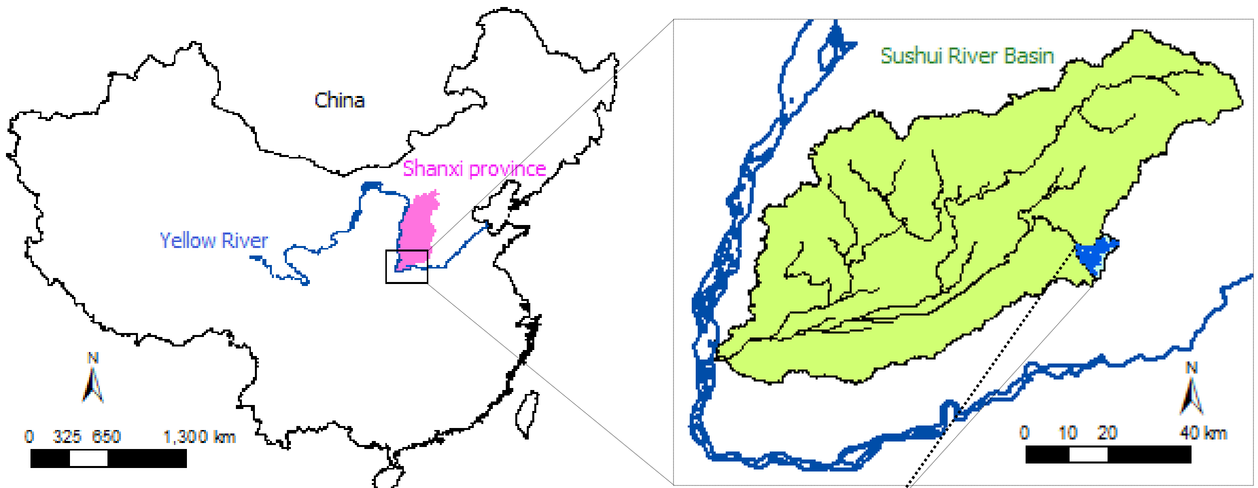
Aim:

- Develop a method for effective and cost-effective AES on cropland to reduce soil erosion and water pollution, through case study of Baishahe watershed in China

Specified objectives:

- Identify appropriate measures to prevent soil erosion (sediments), total nitrogen (N), total phosphorus (P) in the study region
- Consider heterogeneity, and quantify the mitigation impacts of each measure in each spatial unit using proper eco-hydrological model
- Consider same heterogeneity, and evaluate the costs incurred to farmers corresponding to each measure in each spatial unit
- Coordinate and cooperate the interdisciplinary works
- Simulation and optimization to get cost-effective AES

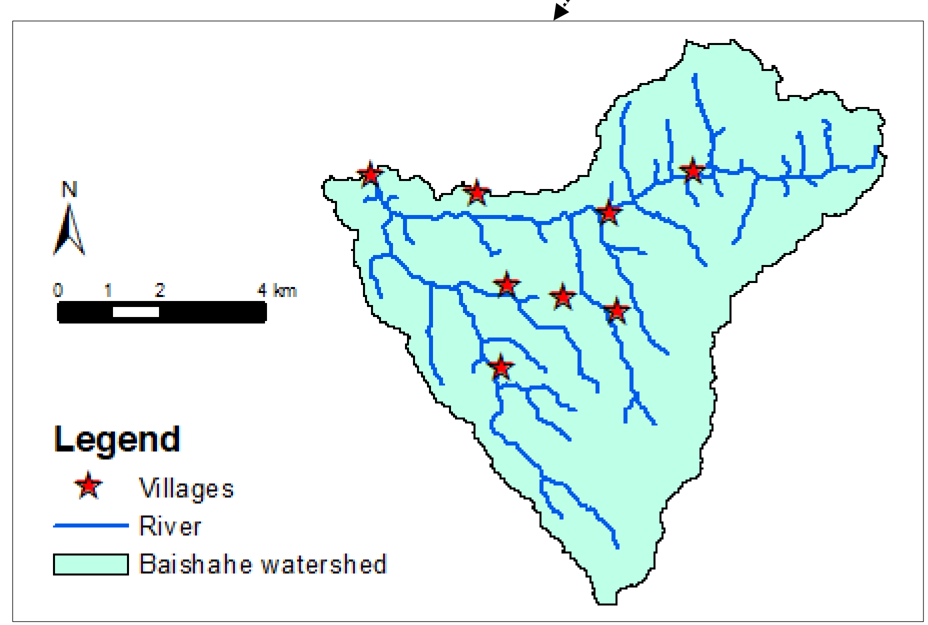
Study region



Baishahe watershed

Area:	56 km^2
Going through:	Eight villages
Main activities:	Small holder crop-livestock systems
Land-cover:	Woodland, grassland, arable land
Main crops:	Winter wheat, corn

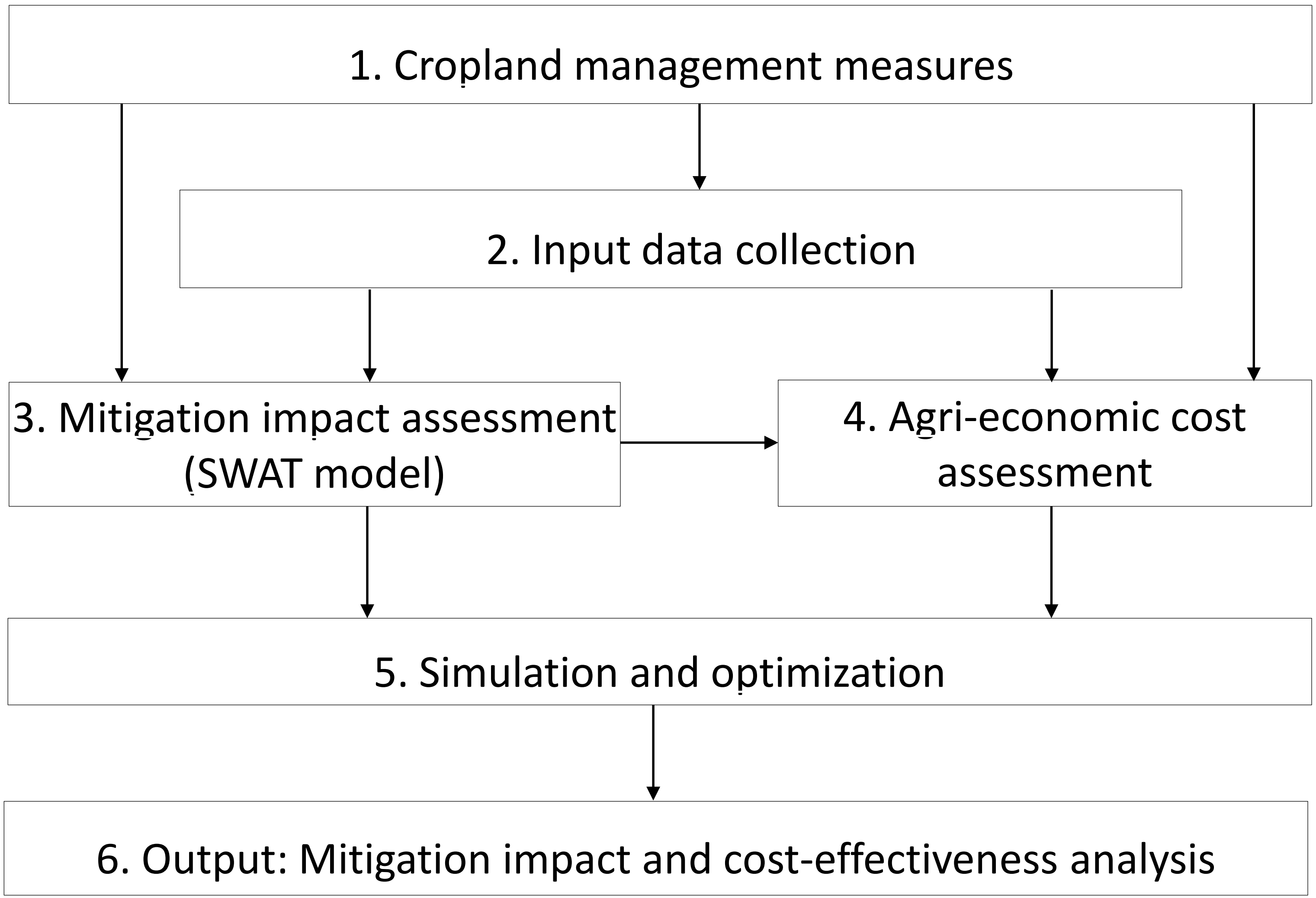
(Source: Material from Water Conservancy Bureau and Environment Protection Agency in Xia county.)



(Source: Own results with ArcGIS, with data source of RESDC, 2015.)

Methodology — framework

Design AES: contract of five years (2018~2022), considering spatial heterogeneity



(Source: Modified based on Wätzold et al., 2016.)

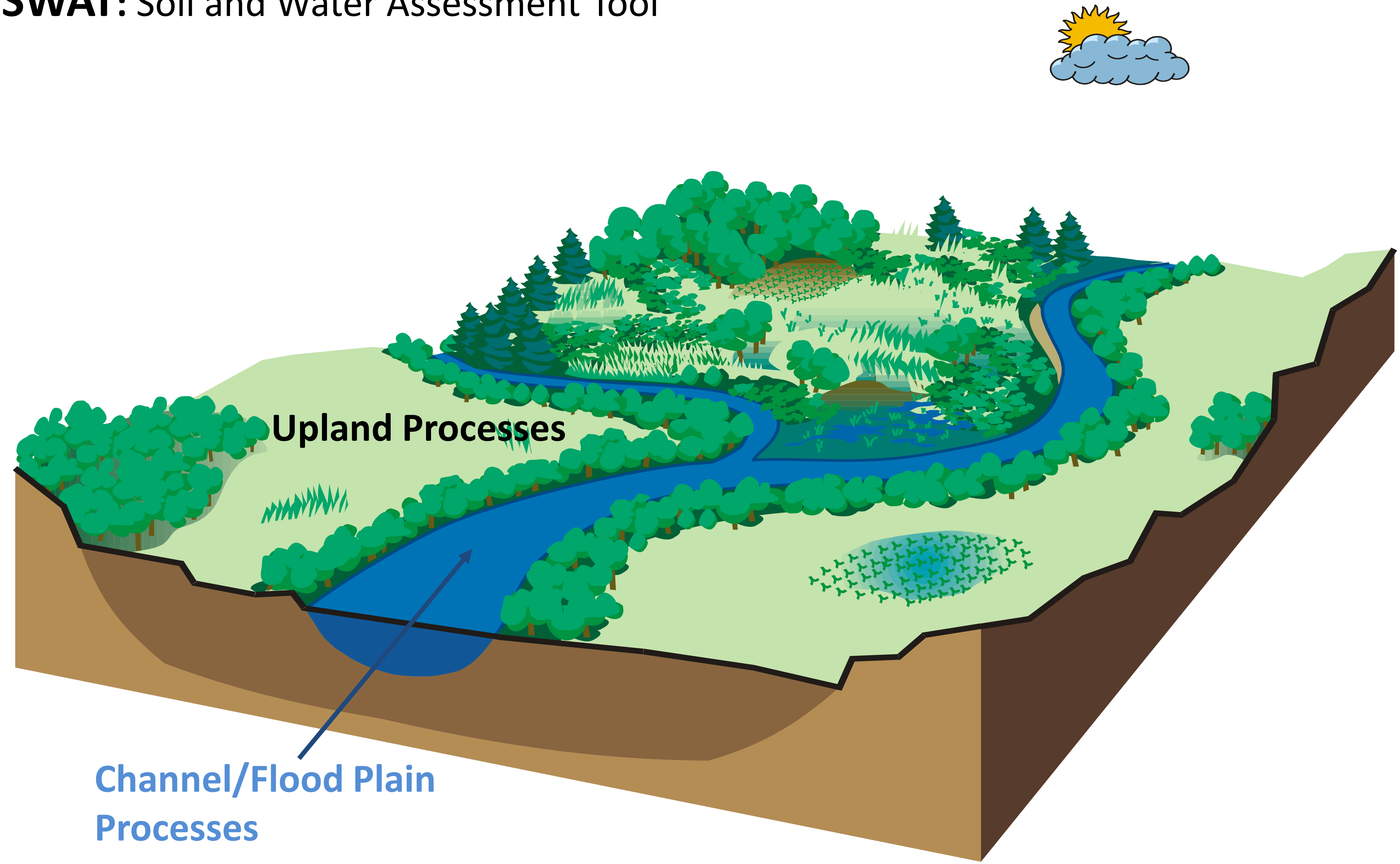
Measure identification — selected measures

type	measures	code
structural measures	vegetative filter strip: 5 meters	M1
	vegetative filter strip: 10 meters	M2
	vegetative filter strip: 15 meters	M3
tillage activities	no-till	M4
nutrient management	chemical fertilizer: 25%↓	M5
	chemical fertilizer: 40%↓	M6
	chemical fertilizer: 50%↓ + swine manure 1000kg/ha	M7
	chemical fertilizer: 50%↓ + sheep manure 1000kg/ha	M8
crop planting	cover crop: Soybean	M9
	cover crop: Corn	M10
compounded	chemical fertilizer: 25%↓ + no till	M11
	chemical fertilizer: 40%↓ + no till	M12

(Source: USDA-NRCS, n.d., and materials from the Agricultural Bureau in Xia county.)

Mitigation impact simulation — SWAT model

SWAT: Soil and Water Assessment Tool



Mitigation impact simulation — SWAT model

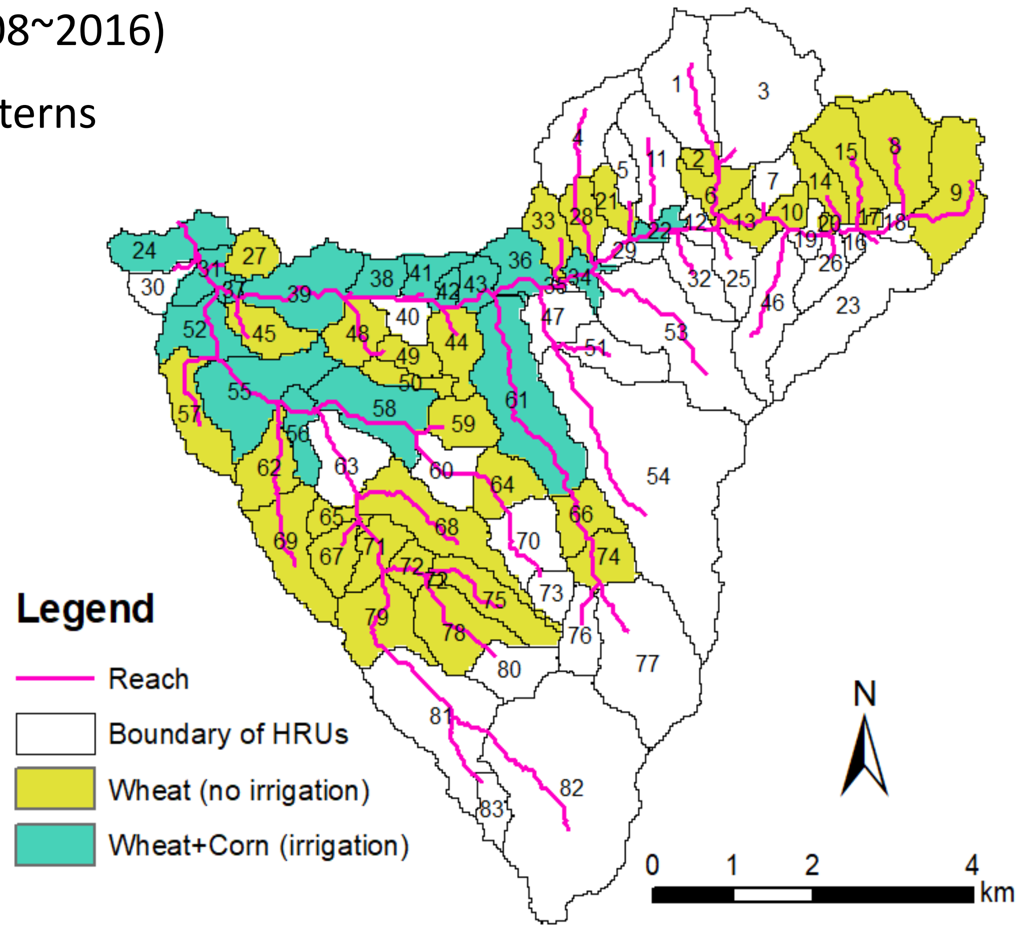
Model setup
- DEM — digital elevation model
- Soil data
- Land use data
- Weather data (2008~2016)
- Local cropping patterns

↓

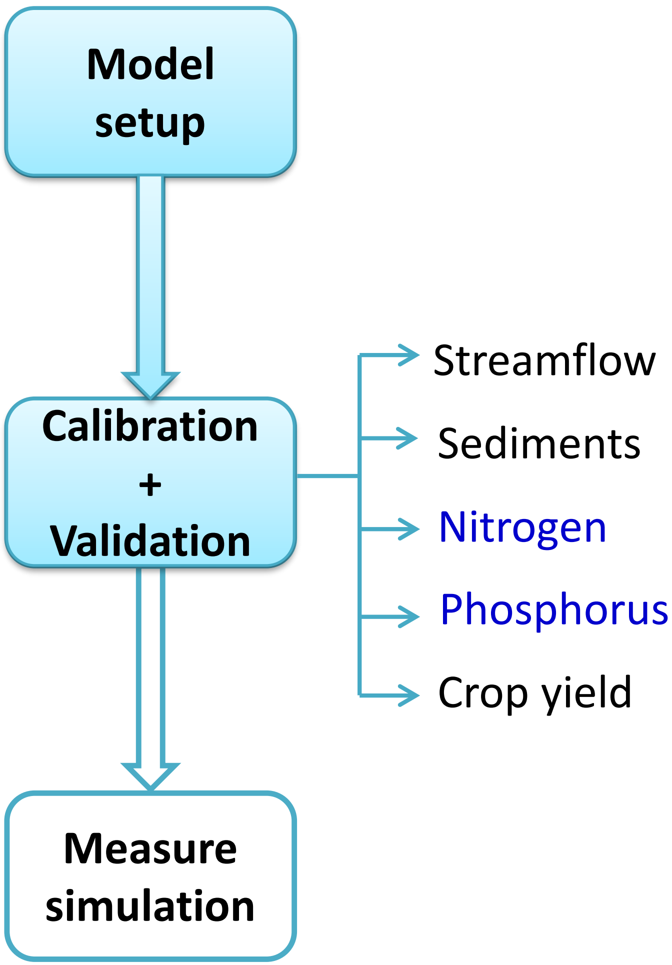
Calibration + Validation

↓

Measure simulation



Mitigation impact simulation — SWAT model



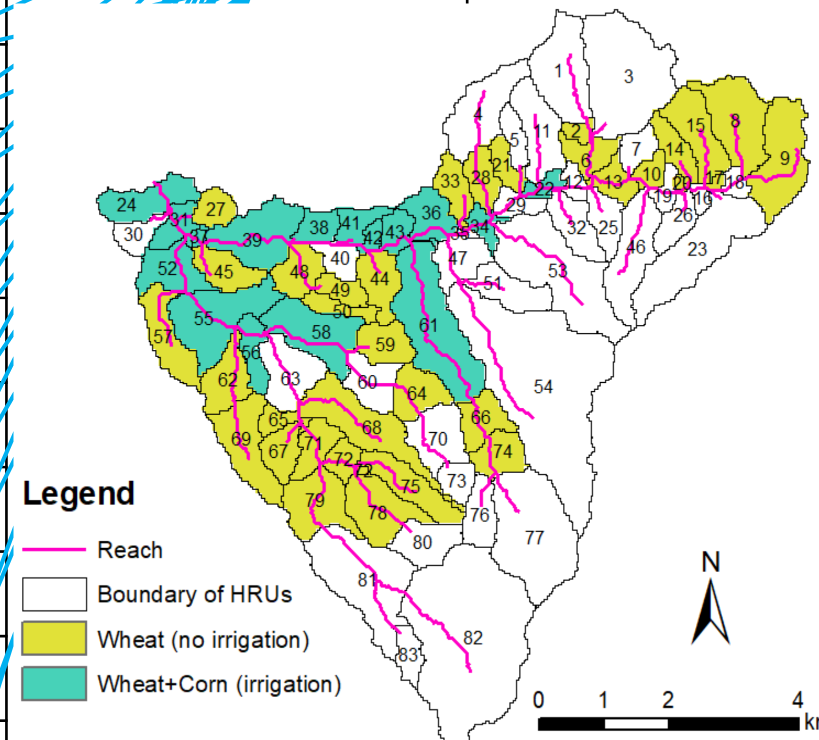
Mitigation impact simulation — SWAT model

Model setup → **Calibration + Validation** → **Measure simulation**

Measures (12 ones)
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12

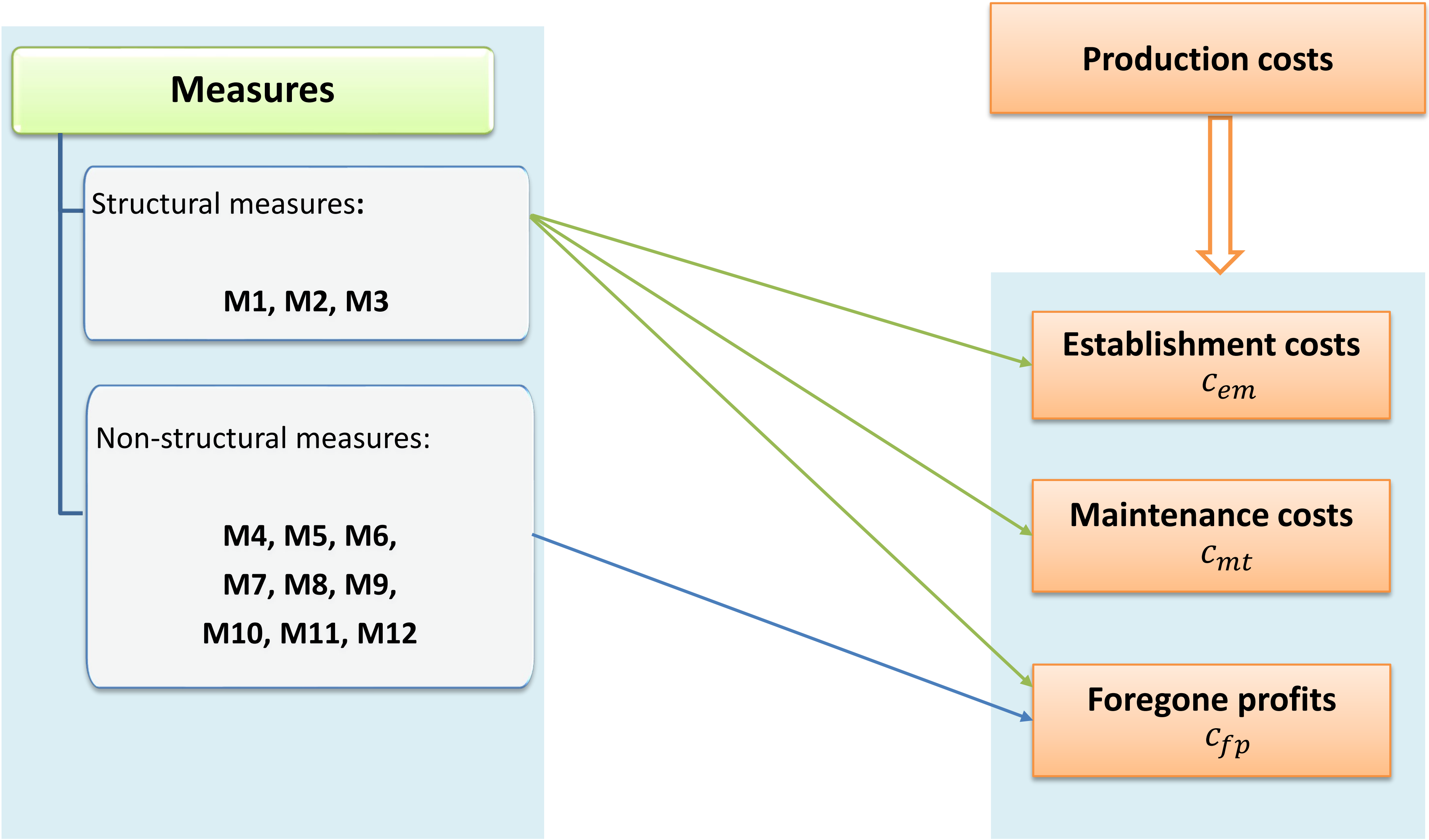
HRUs (50 ones)
2
6
78
79

- Sediments
- Nitrogen
- Phosphorus



(Source: Own results from SWAT.)

Cost assessment — cost categories



(Source: Based on Mettepenningen et al., 2017.)

Cost assessment — formula development

Formula development

Measures

Structural measures:

M1, M2, M3

Non-structural measures:

M4, M5, M6,

M7, M8, M9,

M10, M11, M12

Average annual costs

$$c_a = c_{em} \cdot \frac{r \cdot (1+r)^4}{(1+r)^5 - 1} + c_{mt} + c_{fp}$$

c_a: Average annual costs
c_e: Establishment costs
r: Discounting rate
n: Number of years of AES life
c_{mt}: Maintenance costs
c_{fp}: Foregone profits

$$c_a = c_{fp}$$

c_a: Average annual costs
c_{fp}: Foregone profits

(Source: Based on Boardman et al. 2017.)

Cost assessment — formula development

Formula development

Cost calculation regarding each category

$$c_{em}^{h,m} = c_v^{h,m} \cdot a_s^{h,m}$$

$$c_{mt}^{h,m} = rm \cdot c_{em}^{h,m} + N \cdot c_c^{h,m} \cdot a_s^{h,m}$$

$$c_{fp}^{h,m} = \begin{cases} \left[\left(r_{y,ref}^{h} - r_y^{h,m}\right) - \left(c_{v,ref}^{h} - c_v^{h,m}\right)\right] \cdot a_s^{h,m}, m : structural\ measures \\ \left[\left(r_{y,ref}^{h} - r_y^{h,m}\right) - \left(c_{v,ref}^{h} - c_v^{h,m}\right)\right] \cdot A^h, m : non - structural\ measures \end{cases}$$

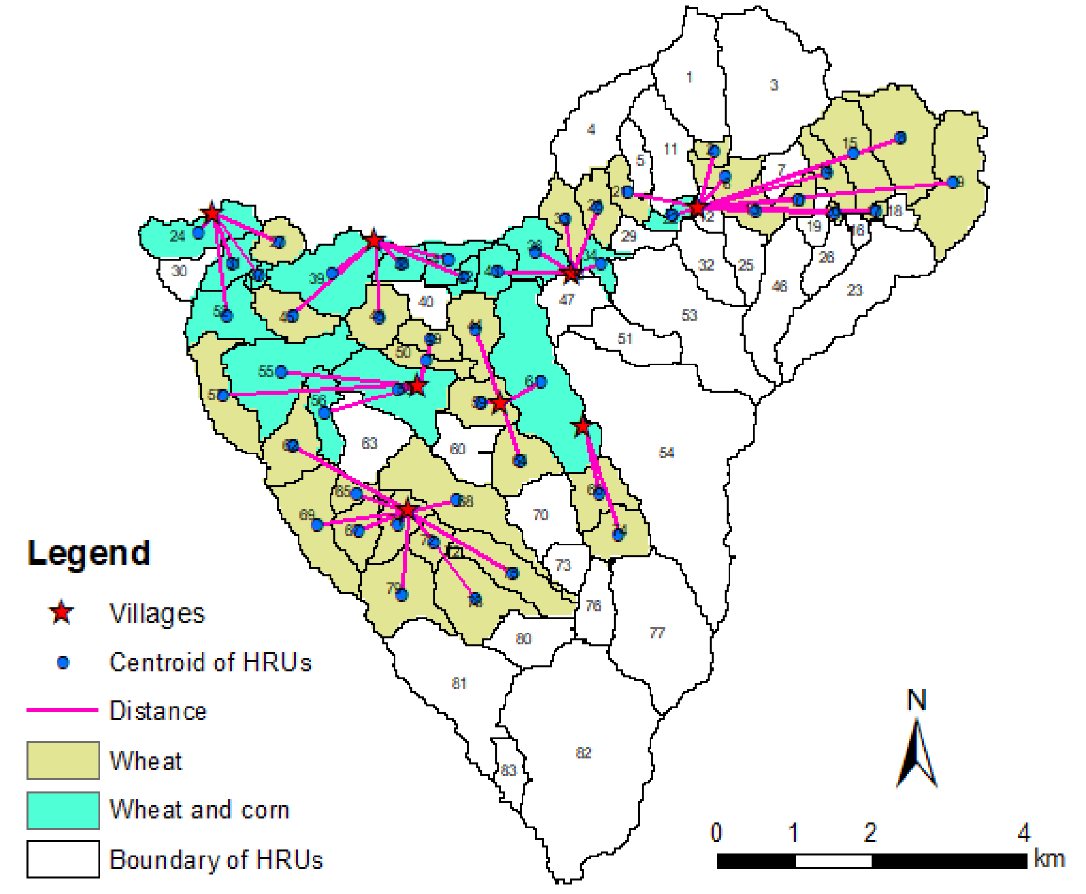
$c_v^{h,m}$: Total variable costs needed for a measure m implementation in a HRU h
$a_s^{h,m}$: Area of structural measures being applied
$rm \cdot c_{em}^{h,m}$: General maintenance cost of structural measures, with rm being the ratio of maintenance to establishment cost
$N \cdot c_c^{h,m} \cdot a_s^{h,m}$: Cost for mowing the filter strip, with $c_c^{h,m}$ being the unit cost per cut and N being the number of cuts per year
$r_{y,ref}^{h}$ and $r_y^{h,m}$: Changed yield revenue under business as usual (BAU) and a measure
$c_{v,ref}^{h}$ and $c_v^{h,m}$: Changed total variable costs under BAU and a measure
A^h: Area of the whole HRU where non-structural measures are applied

(Source: Based on Mewes et al., 2015 and Maringanti et al., 2011.)

Cost assessment — Data source

Data sources

- Questionnaire
- SWAT model
  - Crop yield
  - Area
  - Distance
- Internet search



(Source: Own results from SWAT.)

Simulation and optimization

Simulation:

Mimicking farmers' behavior of measure selection, depending on the payment and cost of each measure in each HRU

Assumption: Farmers are profit-maximizers

$$NB^{h,m} = p^m - c_a^{h,m} / A^h$$

$NB^{h,m}$: Net economic benefits farmers earned from measure m implementation in HRU h

p^m: Payment of measure m per unit area

A^h: Area of a HRU h

Optimization:

Identifying a set of measures and related payments, which induces farmers to select measures in a way that the resulting land use pattern of an AES generates the maximum total mitigation impact for a given budget level (Method: simulated annealing)

$E_{AES} = \sum_h E_{m,h}$ → max, subject to $SP_{AES} = \sum_h p^m \cdot A^h \leq B_0$

E_{AES}: Total mitigation impact of an AES

$E_{m,h}$: Mitigation impact of m in h

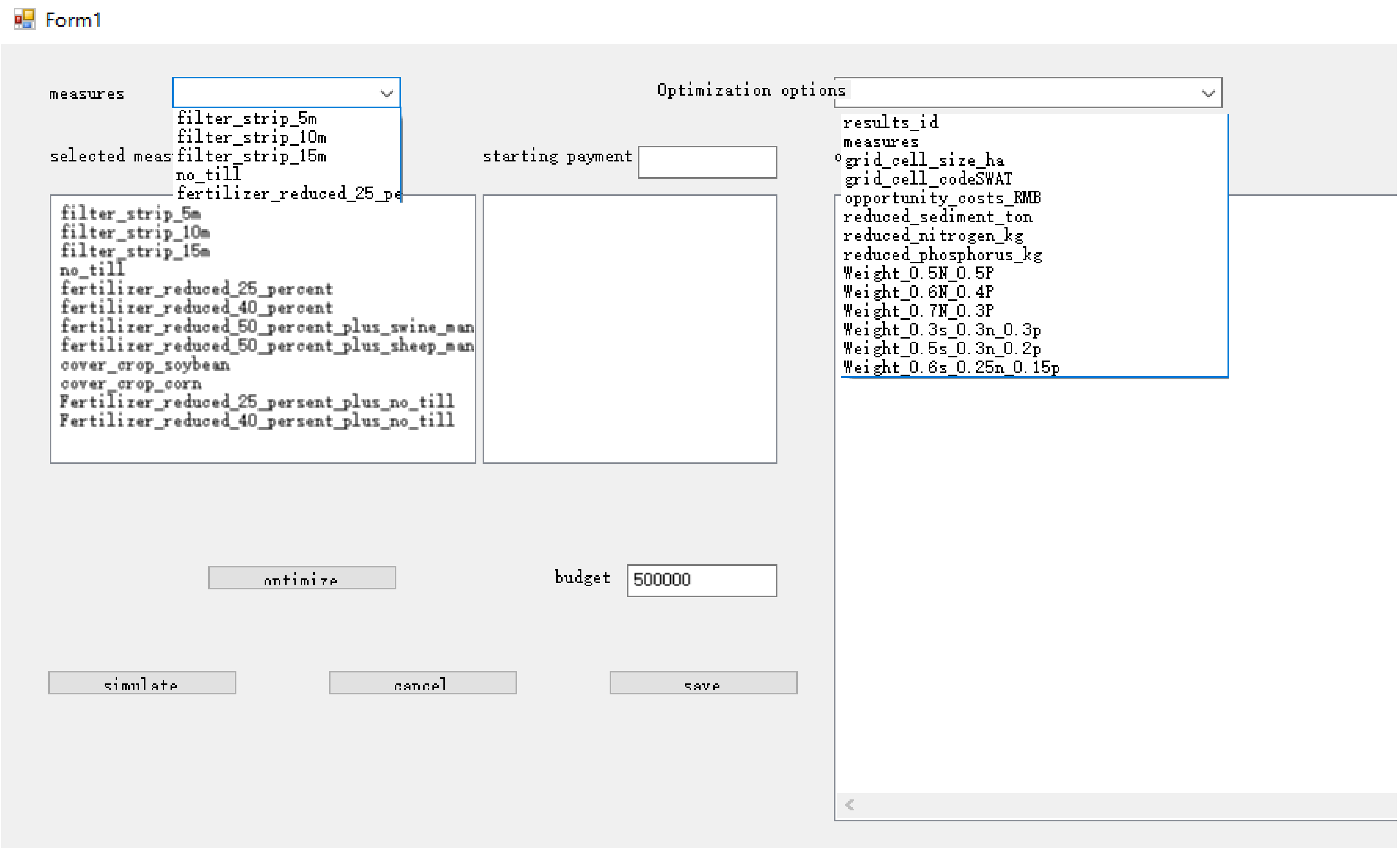
m and h: The measures and HRUs being selected in an AES

SP_{AES}: Summed payments of an AES

m and h: The measures and HRUs being selected in an AES

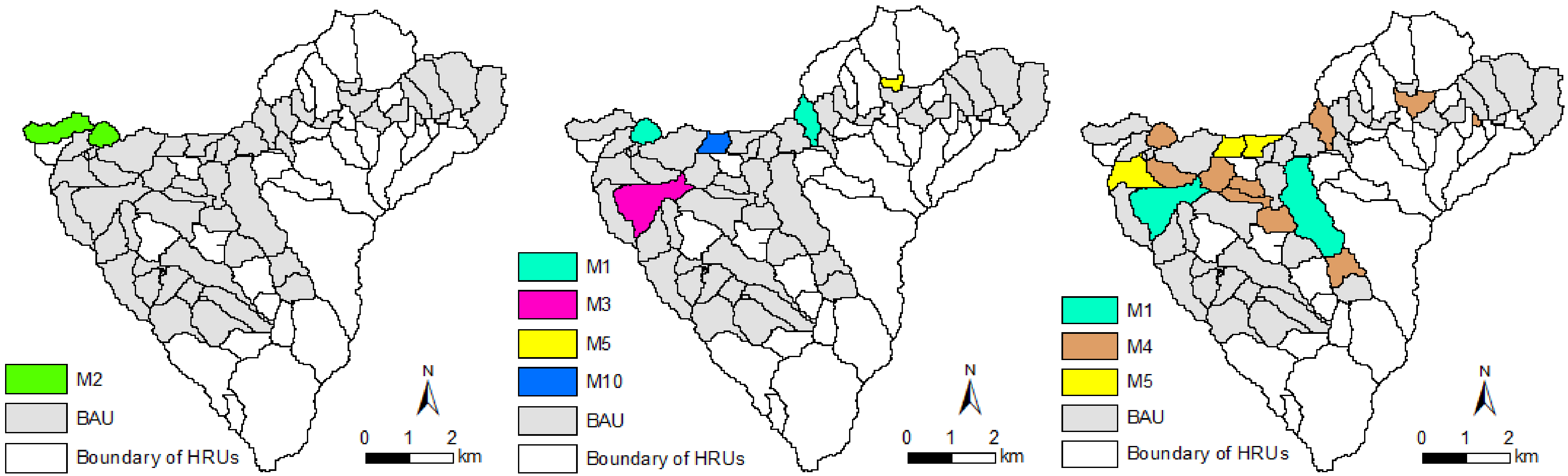
B_0: Budget level of an AES

Optimization modelling procedure



Demonstration — AES design

Mitigation target: Sediment
Measure offered: 12 measures



$B_0 = 100000$ (RMB)	$B_0 = 300000$ (RMB)	$B_0 = 500000$ (RMB)
$p^{M2} = 1204$ (RMB/ha)	$p^{M1} = 543$ (RMB/ha) $p^{M3} = 930$ (RMB/ha) $p^{M5} = 1703$ (RMB/ha) $p^{M10} = 4533$ (RMB/ha)	$p^{M1} = 115$ (RMB/ha) $p^{M4} = 1225$ (RMB/ha) $p^{M5} = 263$ (RMB/ha)
$E_{AES} = 369.3$ (ton) (4.2% mitigation to BAU)	$E_{AES} = 595.5$ (ton) (6.8% mitigation to BAU)	$E_{AES} = 1395.5$ (ton) (15.9% mitigation to BAU)

(Source: Own results. Exchange rate: 1 Euro = 7.8 RMB.)

Discussion and conclusion

- Data limitation (SWAT model; cost assessment)
- Cost components of measures (transaction costs; uncertainty costs)
- Assumptions (HRUs are farms)

- Developing a novel generic method
- Considering spatial heterogeneity for both mitigation impacts and costs at the same heterogeneous level
- Designing the cost-effective measures allocation from perspective of AES design instead of top-down planning
- Building an interdisciplinary research
- Applying high technical and quantified research

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