Using SWAT and an optimization algorithm for quantifying ecosystem services and trade-offs in large river basins – Challenges and potential solutions

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Session G2: Environmental Applications

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HELMHOLTZ
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RESEARCH – UFZ

Overall modelling objective:

Exploring the capacity of landscapes for providing different ecosystem services (and depicting their trade-offs)

provisioning service

Food

regulating service

Water (quality)

Trade-offs

Fuel / Bioenergy

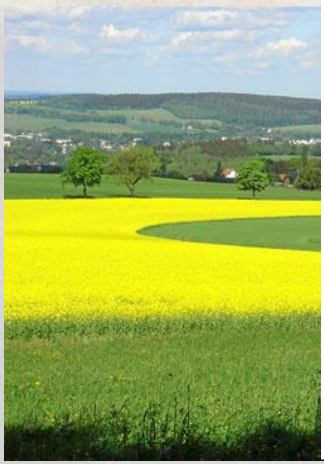
provisioning service

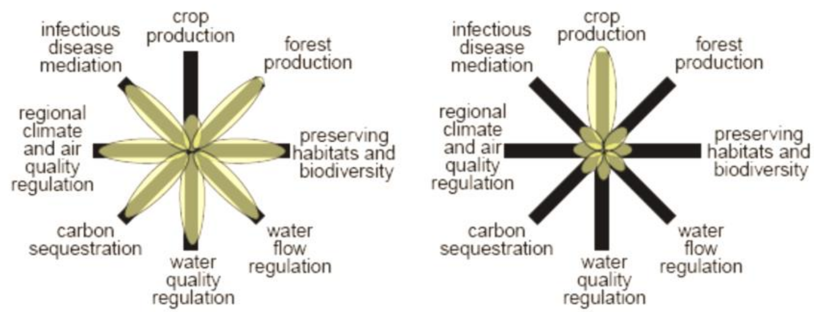
Water (quantity)

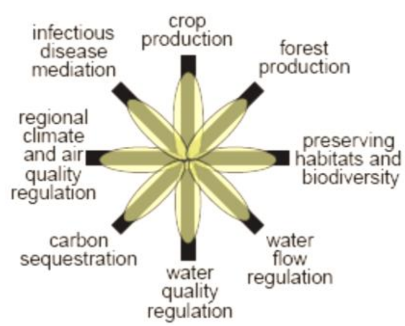
provisioning service

Overall modelling objective:

Exploring the capacity of landscapes for providing different ecosyste







Foley et al. (2005), Science 309: 570-573

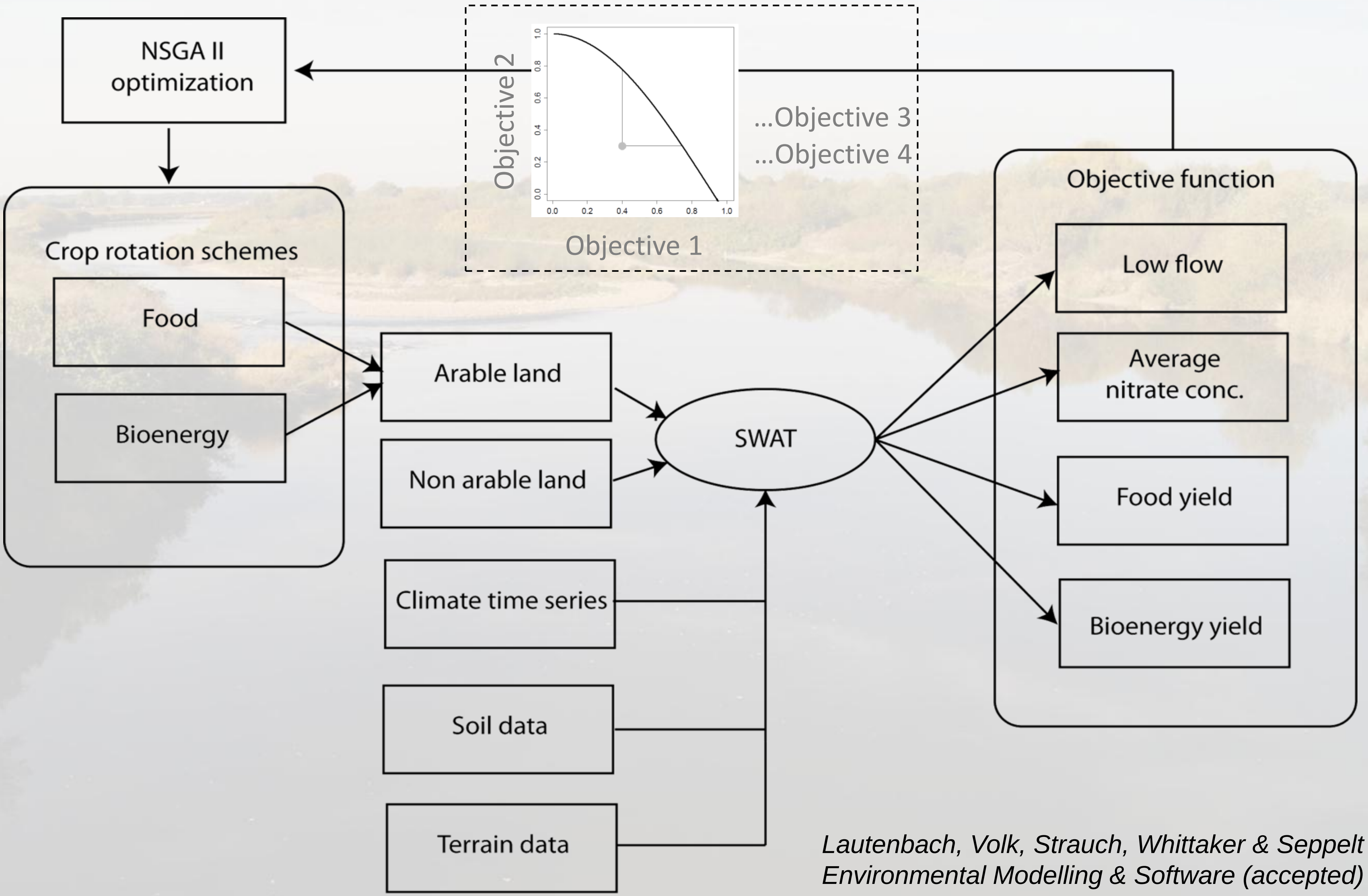
Fuel / Bioenergy

provisioning service

Water (quantity)

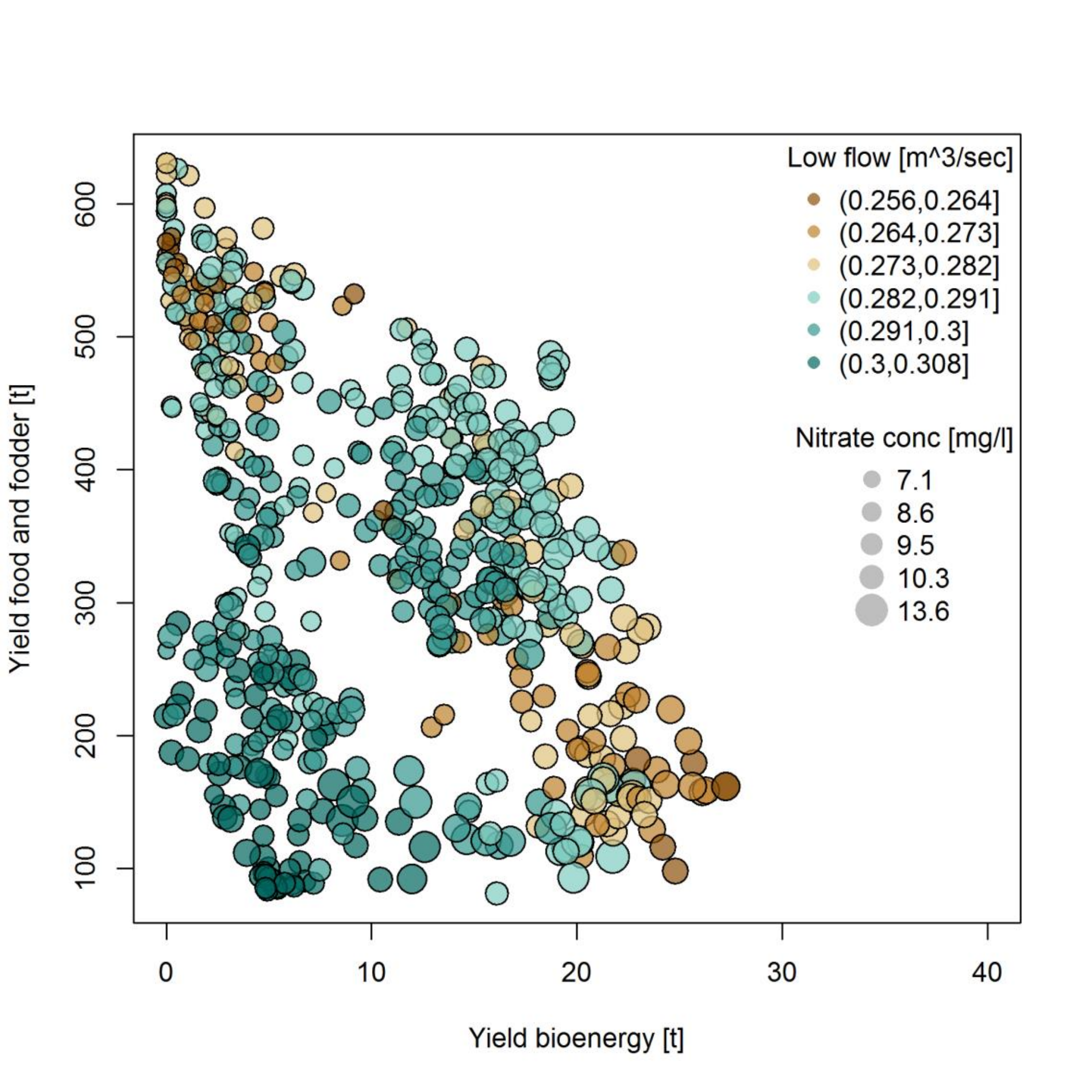
provisioning service

Method: Watershed modeling within an optimization framework



Lautenbach, Volk, Strauch, Whittaker & Seppelt (2013): Environmental Modelling & Software (accepted)

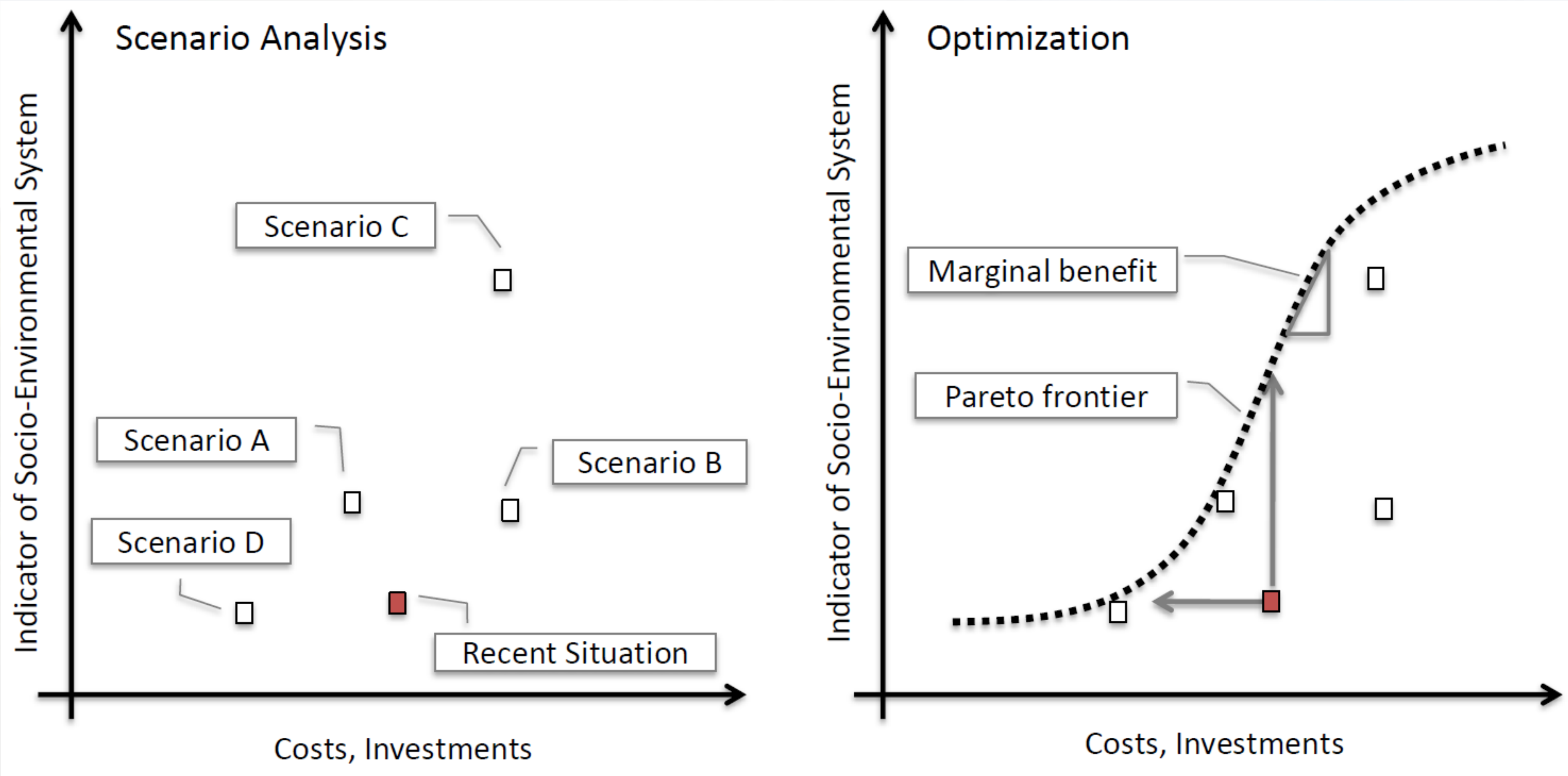
Method: Watershed modeling within an optimization framework



Trade-offs between:

- Food & fodder vs. bioenergy
- Bioenergy vs. nitrate conc.
- Total yield vs. low flow

Combining scenarios and optimization



Seppelt, Lautenbach, Volk (2013), Current Opinion in Environmental Sustainability
DOI: 10.1016/j.cosust.2013.05.002

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Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment

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ABSTRACT

Political agendas worldwide include increased production of biofuel, which multiplies the trade-offs among conflicting objectives, including food and fodder production, water quantity, water quality, biodiversity, and ecosystem services. Quantification of trade-offs among objectives in bioenergy crop production is most frequently accomplished by a comparison of a limited number of plausible scenarios. Here we analyze biophysical trade-offs among bioenergy crop production based on rape seed, food crop production, water quantity, and water quality in the Parthe catchment in Central Germany. Based on an integrated river basin model (SWAT) and a multi-objective genetic algorithm (NSGA-II), we estimated Pareto optimal frontiers among multiple objectives. Results indicate that the same level of bioenergy crop production can be achieved at different costs with respect to the other objectives. Intermediate rapeseed production does not lead to strong trade-offs with water quality and low flow if a reduction of food and fodder production can be accepted. Compared to solutions focused on maximizing food and fodder yield, solutions with intermediate rapeseed production even improve with respect to water quality and low flow. If rapeseed production is further increased, negative effects on low flow prevail. The major achievement of the optimization approach is the quantification of the functional trade-offs for the feasible range of all objectives. The application of the approach provides the results of what is in effect an infinite number of scenarios. We offer a general methodology that may be used to support recommendations for the best way to achieve certain goals, and to compare the optimal outcomes given different policy preferences. In addition, visualization options of the resulting non-dominated solutions are discussed.

1. Introduction

Increasing energy demand together with fluctuating oil prices and concerns about the negative effects of climate change have focused attention on alternative energy resources. Bioenergy plants designed for biofuel production offer one of the major alternatives (Graham-Rowe, 2011; Robbins, 2011; Zinoviev et al., 2011). The Renewable Energy Roadmap of the European Union (European Commission, 2007) sets the goals of a 20% share of European energy consumption by 2020 and a binding 10% share of renewable energy use in the fuel sector. Within that framework, the member states define their own national targets. Germany aims at increasing its share of energy from renewable resources in final consumption from 5.8% in 2005 to 18% in 2020 (Fräss-Ehrfeld, 2009). Supported by tax exemptions and quota obligations, the use of biofuels in the German transport sector has already increased from 3.8% in 2005 to 7% in 2007 (German Environmental Ministery, 2009). In 2008, the largest share (69%) of renewable energy production in Germany was from biomass (German Environmental Ministery, 2009).

While the target for bioenergy production has already been set by legislation, a quantitative evaluation of the costs and benefits of bioenergy production is just starting. At present, the first generation bioenergy crops compete with food and fodder production on arable land. Negative effects of increasing bioenergy production are

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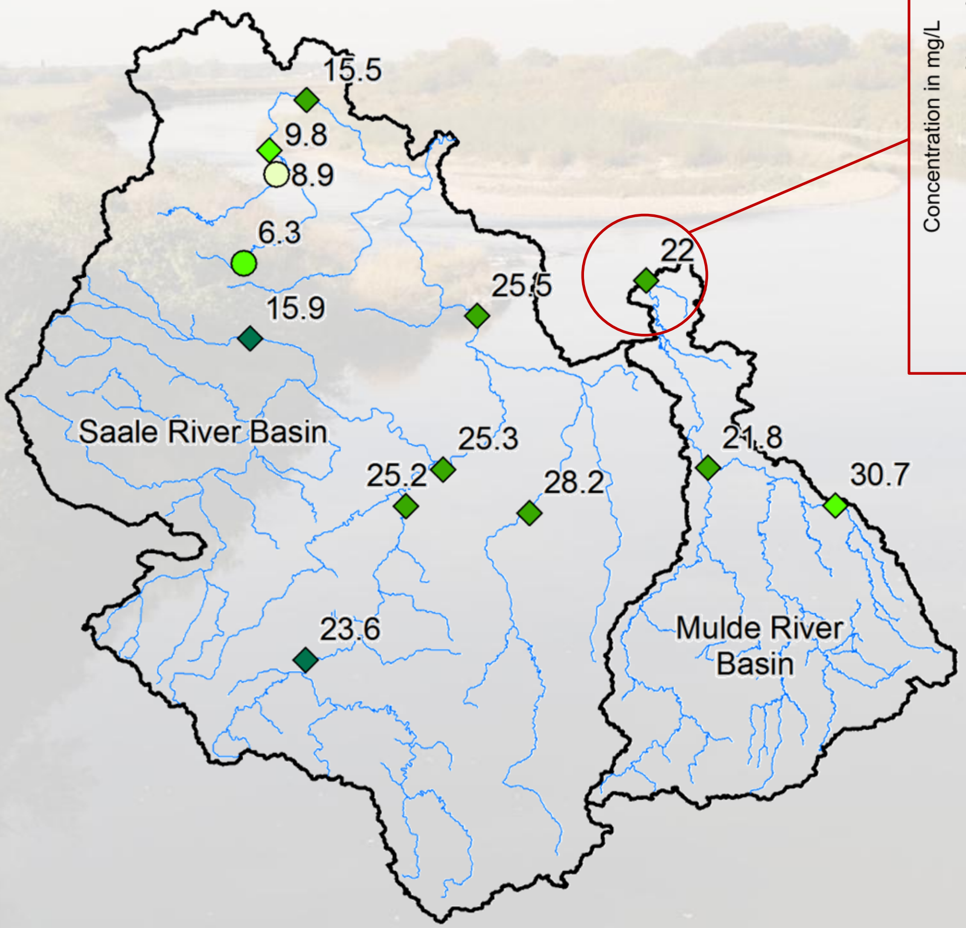
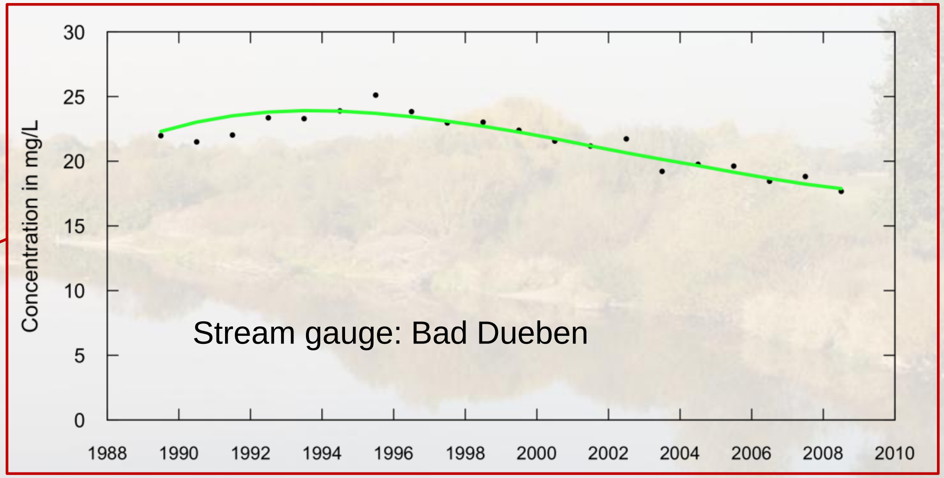
Challenges and key considerations

Pre-analysis of historical data, e.g. trends in water quality

Average Nitrate-N conc. [mg/l] in period 1992-2009





Trends (trend-free-pre-whitening procedure):

Nitrate-N reduction per year (average of 1992-2009)

- 0-1 %
- 1-2 %
- 2-3 %
- >3 %

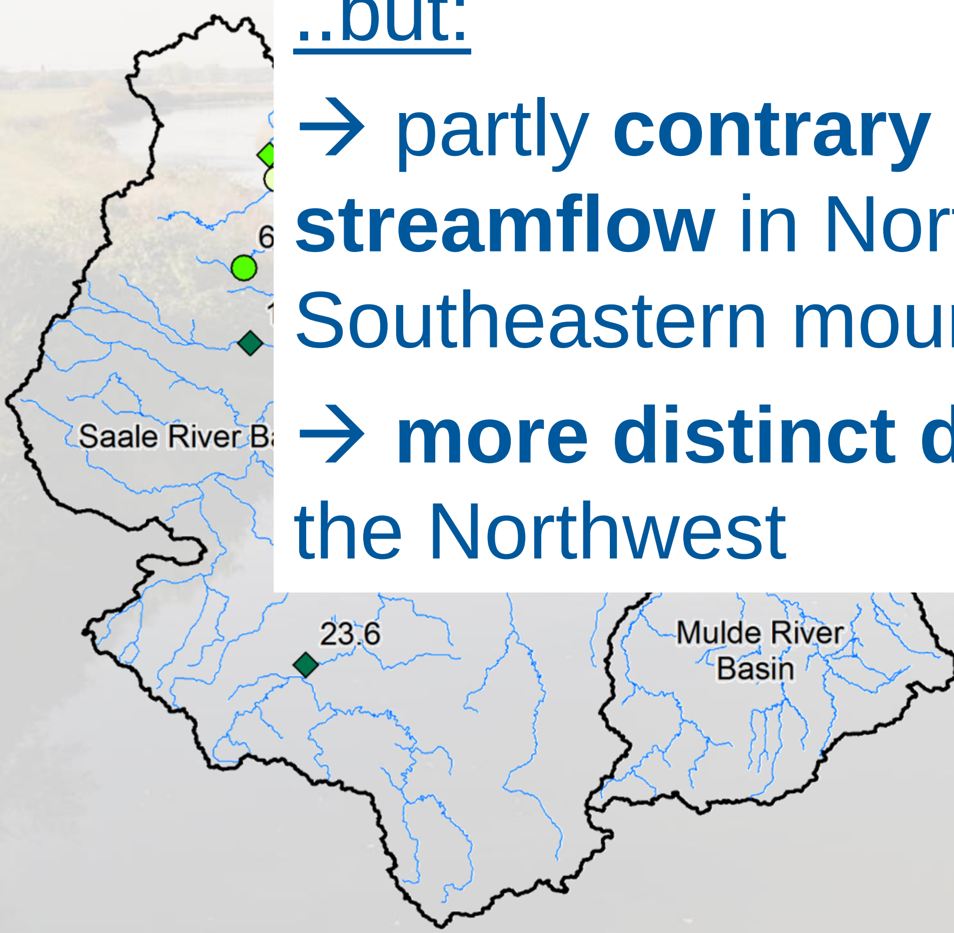
Significance

- no trend
- significant ($p<0.05$)

Challenges and key considerations

Pre-analysis of historical data, e.g. trends in water quality

Average Nitrate-



<u>..but:</u>

→ partly **contrary development** of **streamflow** in Northwestern and Southeastern mountains

→ **more distinct decrease** of MQ in the Northwest

edure):

-2009)

1-2 %

2-3 %

>3 %

Significance

no trend

significant (p<0.05)

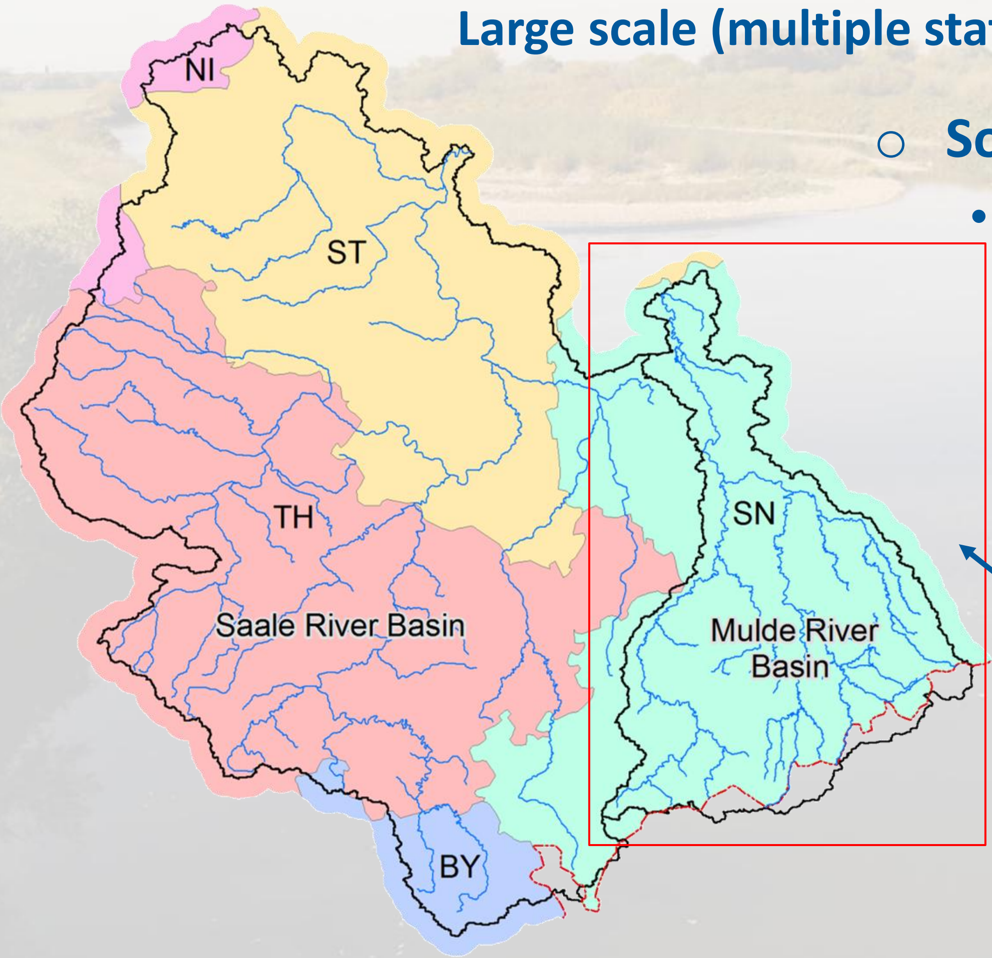
Challenges and key considerations

Water quality input data (point sources)

- **Problem:**

  Large scale (multiple states, huge amount of (different) data)

- **Solution:**
  - **Point source estimation (e.g. nitrate loads) using population equivalents of water treatment plants (readily available data)**



<u>**Only for this catchment:**</u>

350 WWTP

198 industrial discharge points

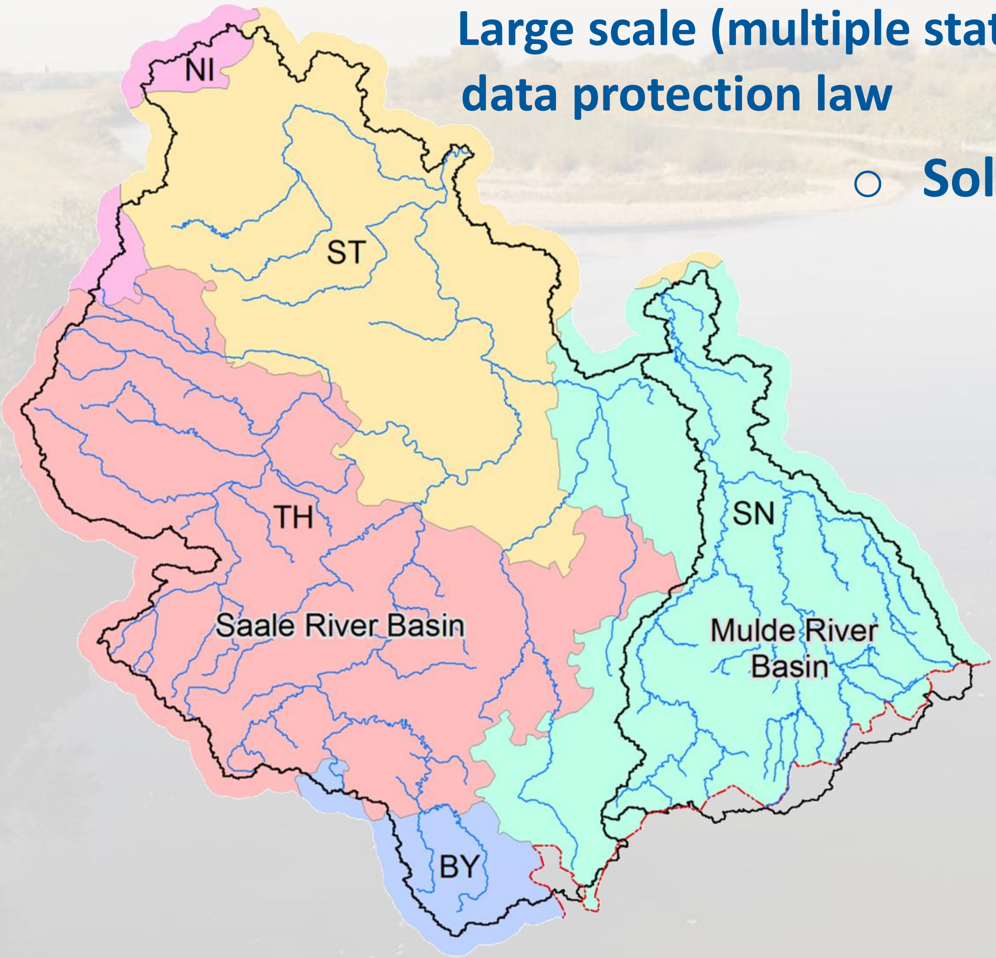
(in total >1000 t N and >100 t P / a)

Challenges and key considerations

Water quality input data (non-point sources)

- **Problem:**

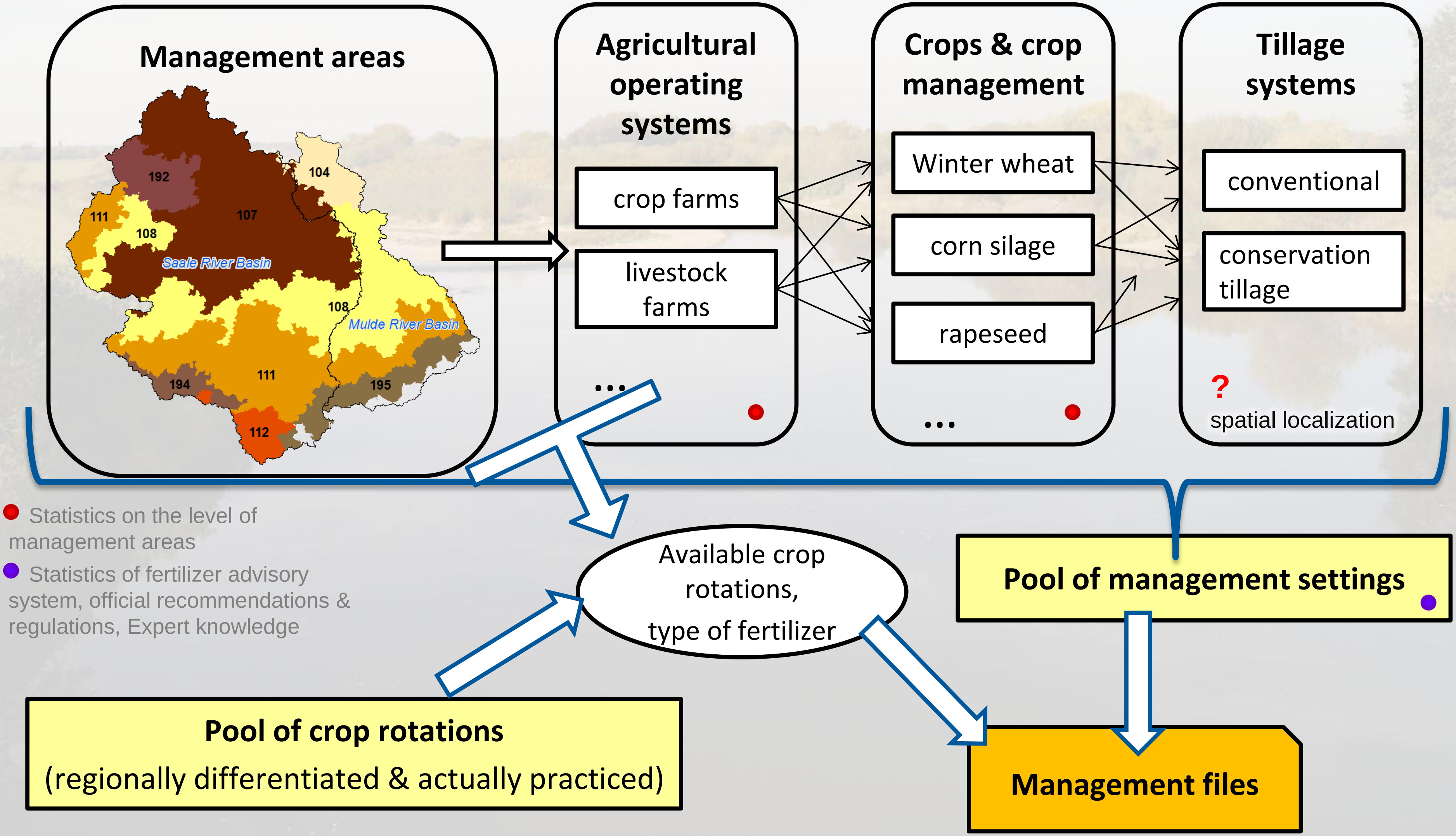
  Large scale (multiple states, huge amount of (different) data), data protection law



- **Solution:**
  - **Non-point sources (agriculture) using fertilizer inputs based on statistics of the fertilizer advisory systems (e.g. BEFU) of the state authorities and yield statistics**

Challenges and key considerations

Agricultural management settings

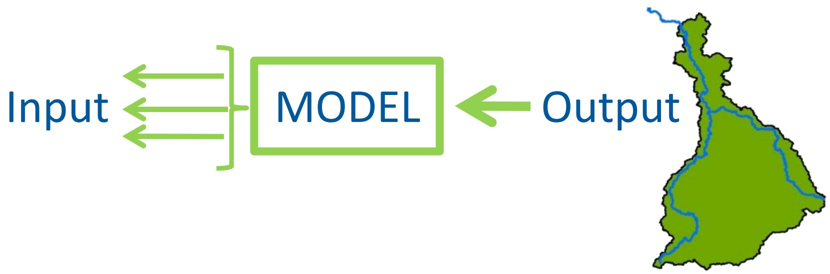


Challenges and key considerations

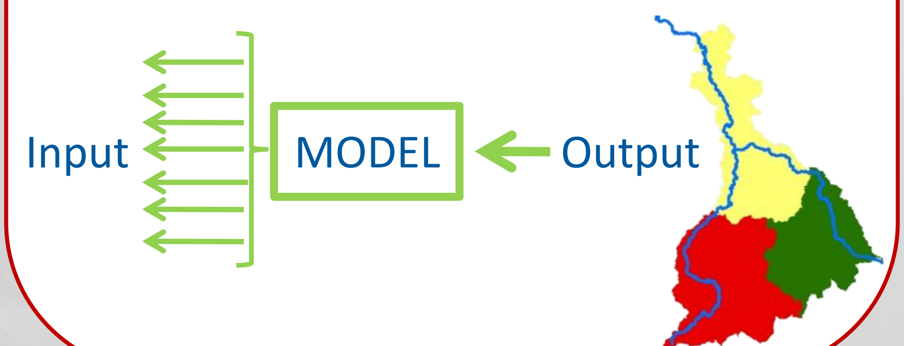
Spatial calibration strategies

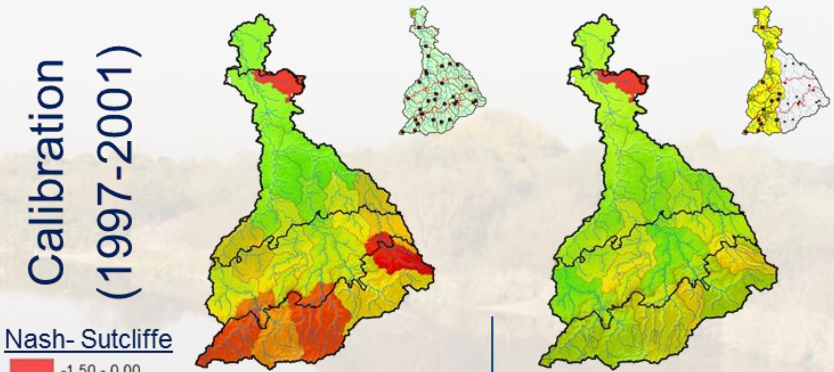
Equifinality in inverse modeling

- Smaller, relatively uniform catchment

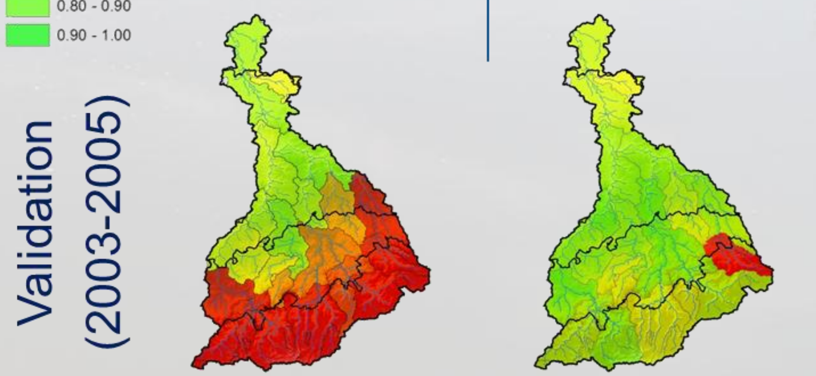


- Larger, heterogeneous catchment



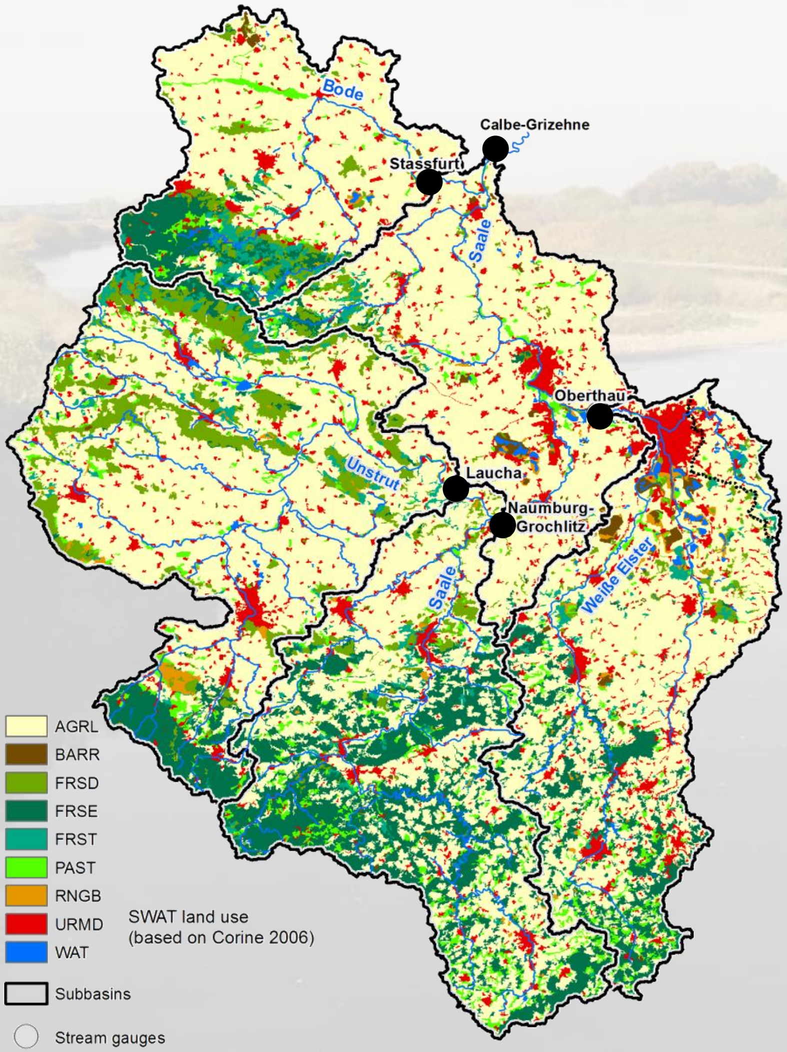


NSE	Valid	NSE	Valid	
0.74	0.65	0.64	0.57	**Outlet**
0.58	0.66	0.58	0.74	**Loess Region**
0.42	0.29	0.52	0.65	**Loess-Foothills**
0.45	0.10	0.65	0.67	**Foothills**
0.19	-0.49	0.57	0.58	**Mountain Ridge**



Challenges and key considerations

Spatial optimization strategies



Optimize spatial land management for whole River basin

OR

for smaller subbasins?

Both, relevant objective functions and „optimal" solutions might be scale dependent!

Conclusions

- Analyzing historical data before starting with the modeling helps to detect possible interferences and trends (improves systems knowledge)
- Modeling-optimization frameworks, such as SWAT-NSGA, are useful tools for identifying trade-offs between different ecosystem services
- However, modeling on larger scales has to account for:
  - scale-related needs to generalize input data (e.g. agricultural management)
  - appropriate (multi-site) calibration strategies
- …