Optimizing monitoring networks for the detection of contaminant dispersion

A case study using the dispersion of a radioactive plume (model) in the first phase after a nuclear accident

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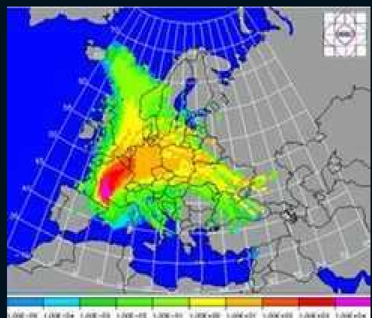
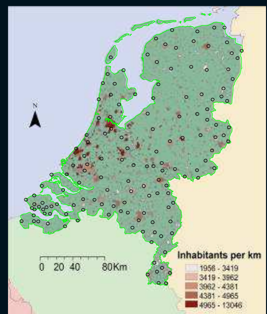
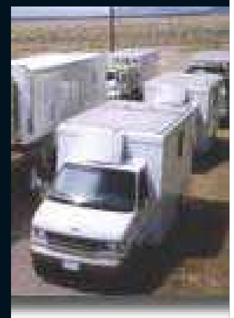
Monitoring gamma-dose rate measurements

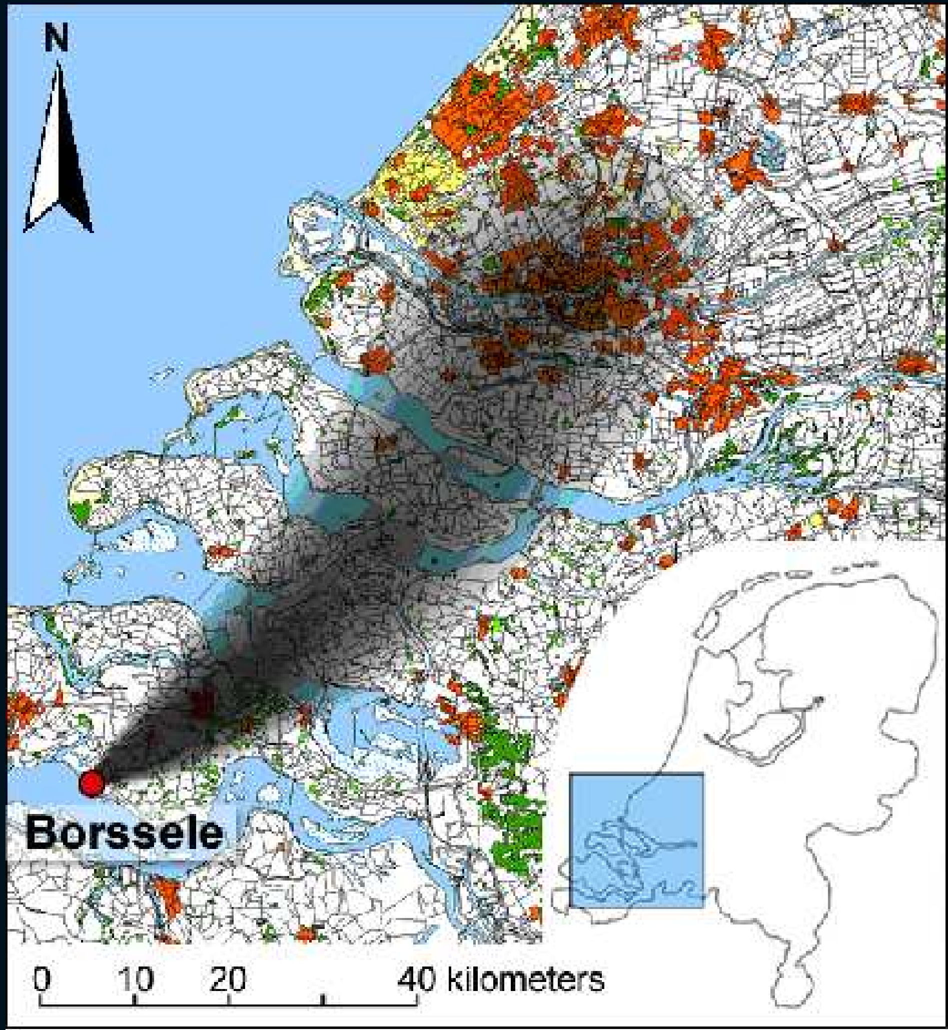
- Chernobyl (1986) → Monitoring system RIVM
- Monitoring system:
  - NPK-PUFF atmospheric dispersion model
    - diffusion by wind
    - diurnal cycle of boundary layer height and stability
    - dry and wet deposition
    - chemical transformation or radioactive decay
  - Static measurement network
- Extra: mobile measurement devices

Pseudo emergency: large radioactive release

simulated using NPK-PUFF



Consider uncertainty in:

- input variables (WS, WD, MLH, AS)
- Model error

Account for:

- static measuring network
- population density

Research Question: Where to locate mobile measuring devices (n=8)?

Objective: Optimize locations of mobile devices

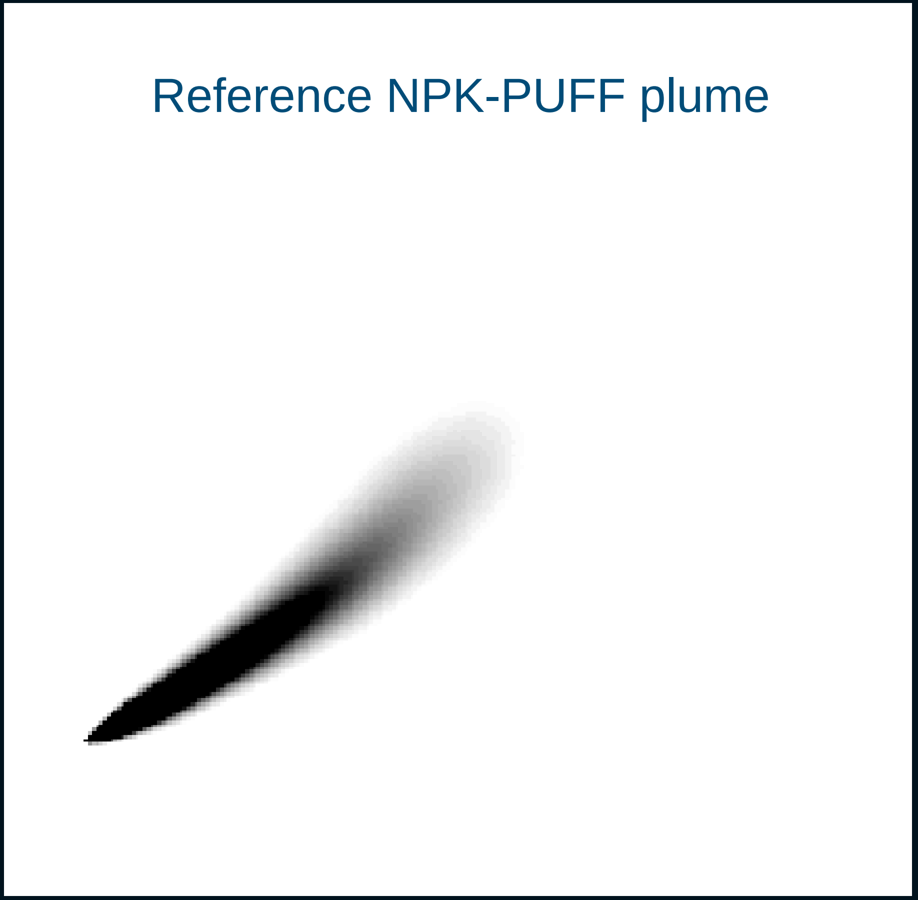
- Define realistic pdfs of uncertain input variables
- Propagate errors through dispersion model (NPK-PUFF)
- Incorporate measures from static network (n=153)
- Take population density into account

Sources of uncertainty considered

- Input uncertainty: model parameters are uncertain (based on other models or measured with error)
  - simulate range of possible input values
    - conditional Gaussian simulation
  - Examine how errors propagate (ideally in time and space)
- Model uncertainty: model -> real processes
  - assume unbiased
  - represented by a zero mean, spatially-correlated residual
    - unconditional Gaussian simulation

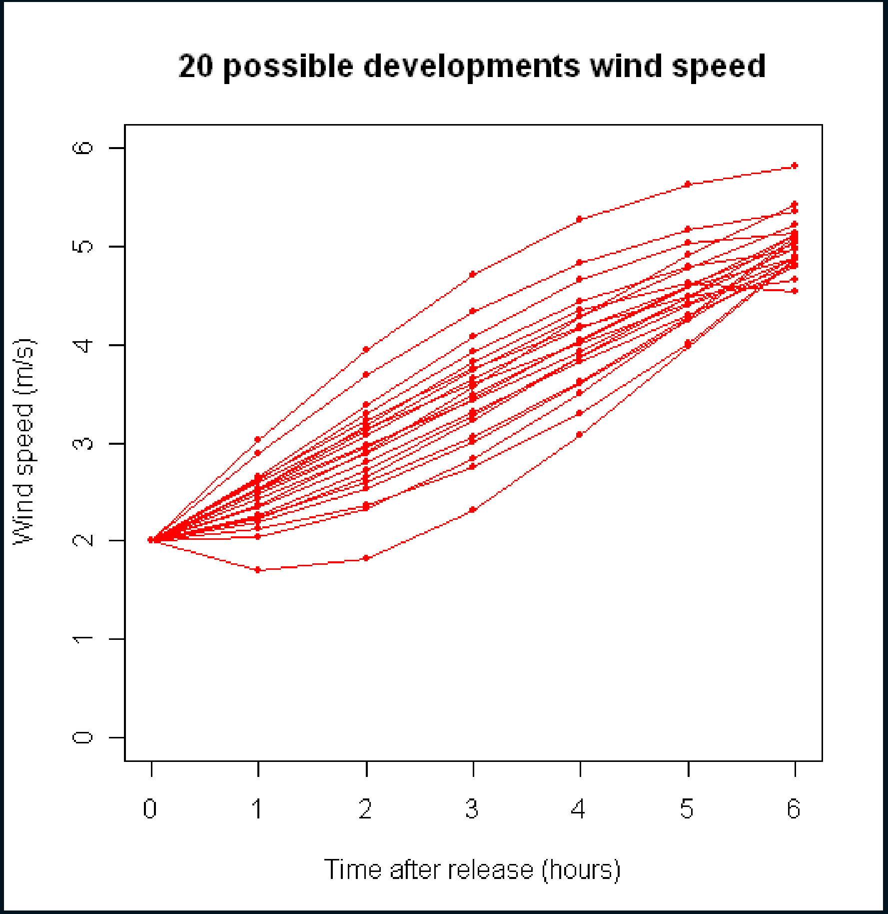
Flowchart of simulation and optimization methods

Create a reference dose map (best possible NPK-PUFF prediction)



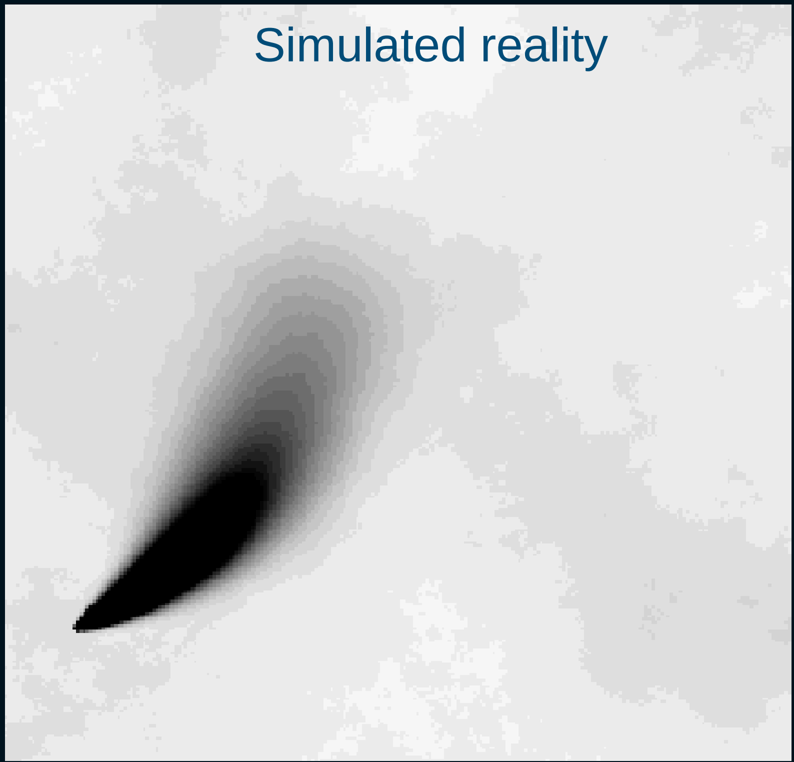
Flowchart of simulation and optimization methods

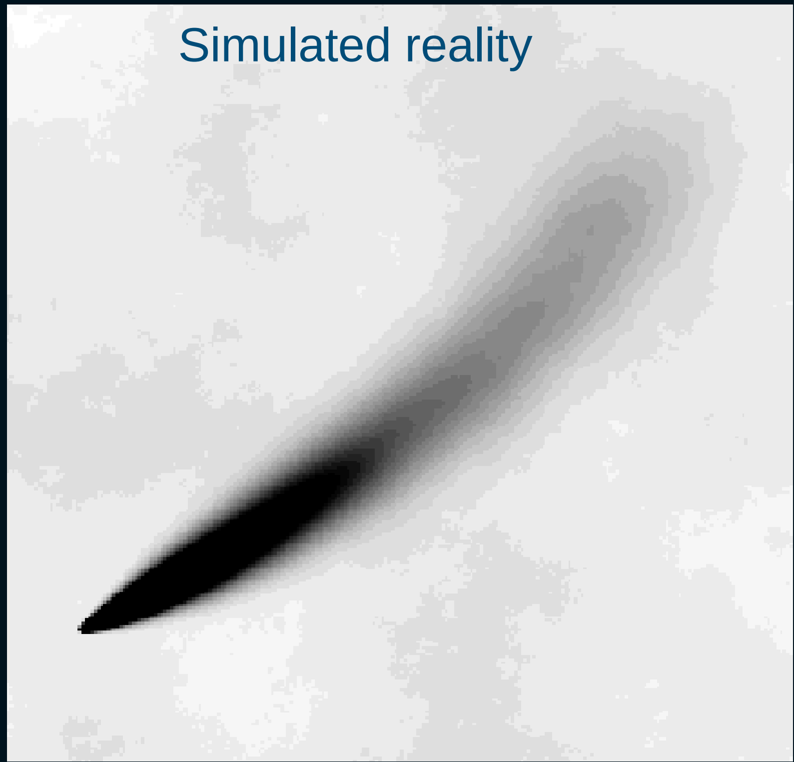
Determine uncertainty in the NPK-PUFF input variables



Flowchart of simulation and optimization methods

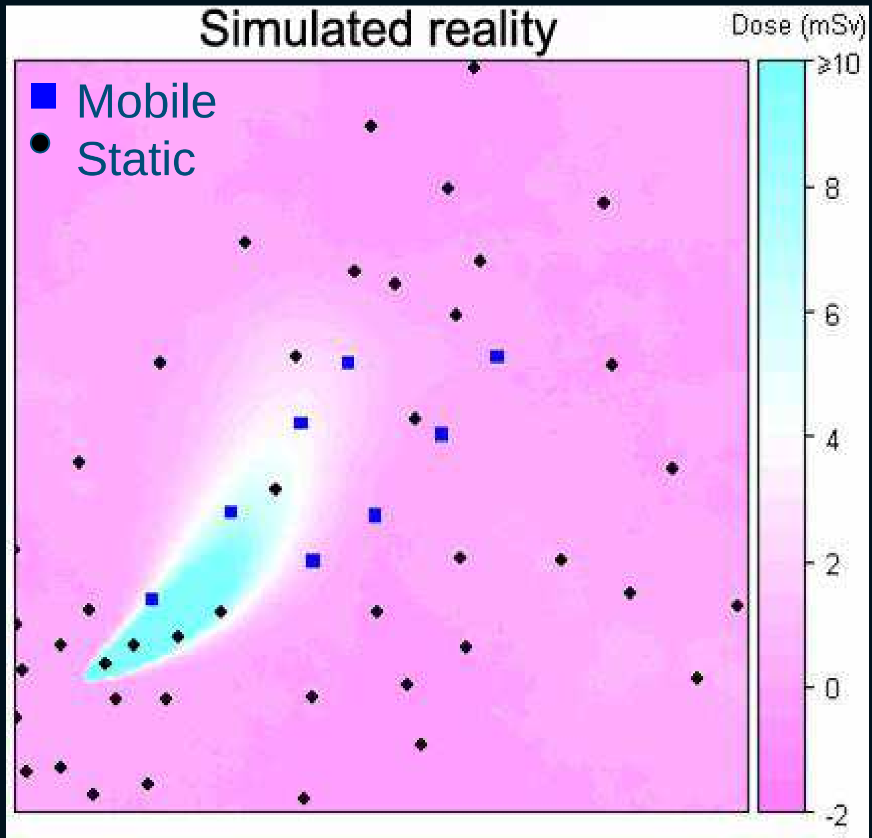
Simulate N possible output plumes, taking uncertainty in NPK-PUFF prediction into account, resulting In ***N* simulated realities**

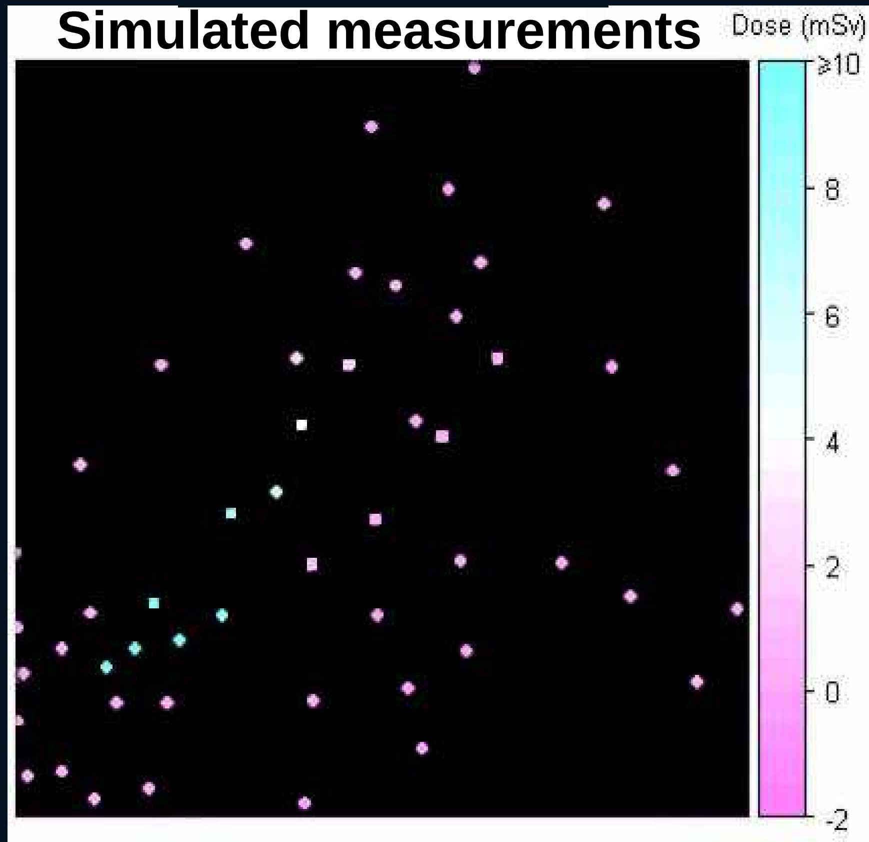




Flowchart of simulation and optimization methods

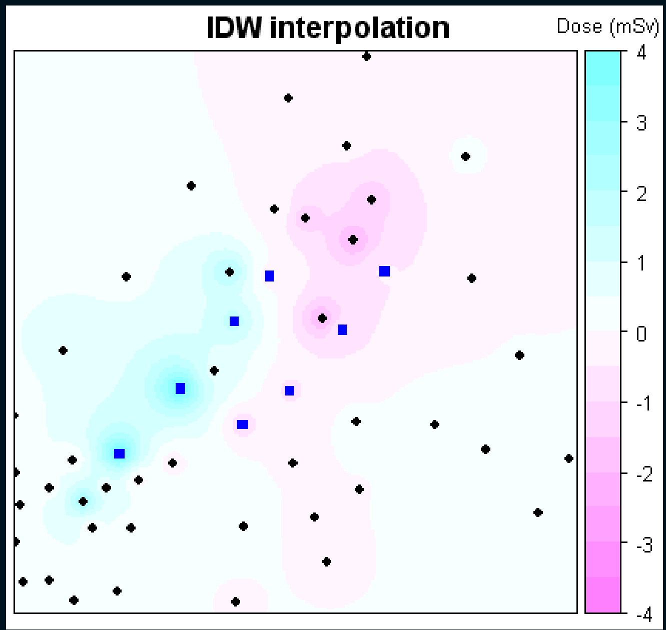
Obtain **simulated measurements** for mobile and static devices by sampling from the *N* possible plumes

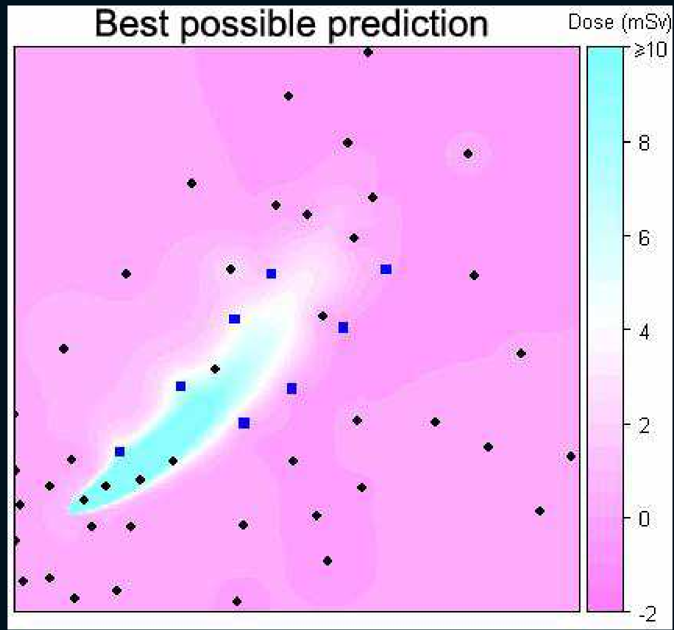




Flowchart of simulation and optimization methods

Use **simulated measurements** to locate the reference dose map more accurately, resulting in ***N* predicted dose maps**





- Subtract sampled values of reference plume from sampled values of simulated reality

- Add interpolated map to reference plume for best possible prediction

Flowchart of simulation and optimization methods

Create a reference dose map (best possible NPK-PUFF prediction)

↓

Determine uncertainty in the NPK-PUFF input variables

↓

Simulate N possible output plumes, taking uncertainty in NPK-PUFF prediction into account, resulting In ***N* simulated realities**

↓

Obtain **simulated measurements** for mobile and static devices by sampling from the *N* possible plumes

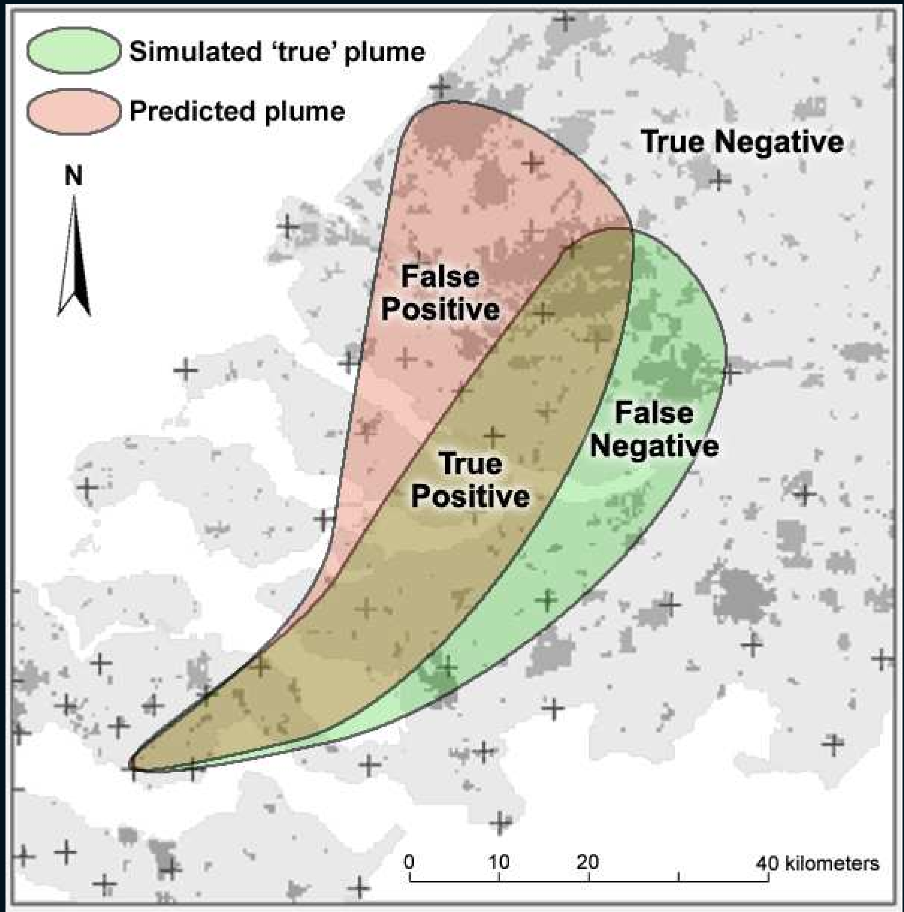
↓

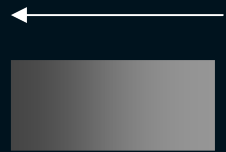
Use **simulated measurements** to locate the reference dose map more accurately, resulting in ***N* predicted dose maps**

↓

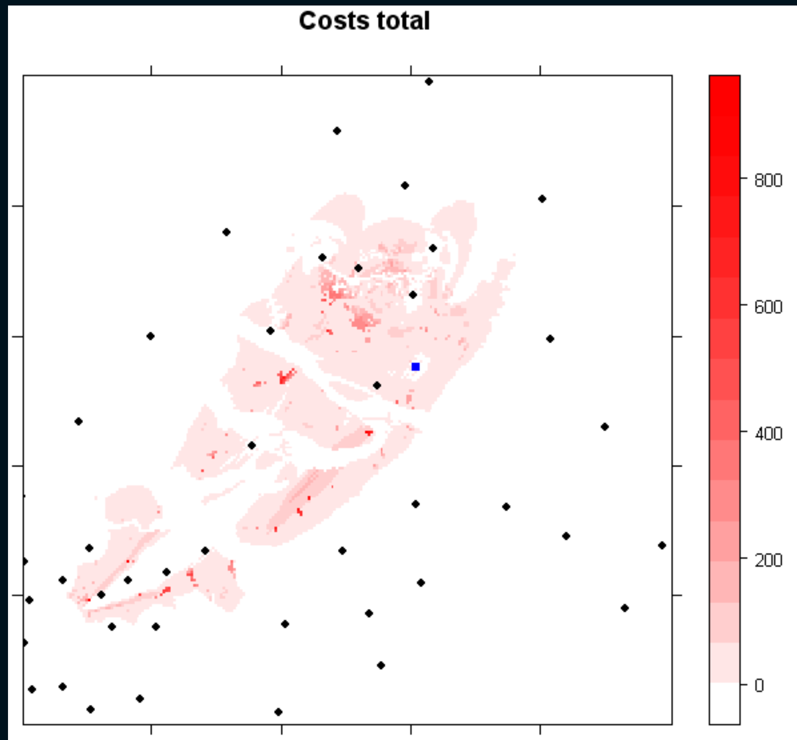
Determine the ‘fitness’ of the sampling design by comparing N times the predicted dose map with the simulated reality, resulting in **the costs**

Non-linear objective function: aggregate costs of falsely predicting radiation dose rates above acceptable thresholds, weighted by population density





Minimize Aggregate costs

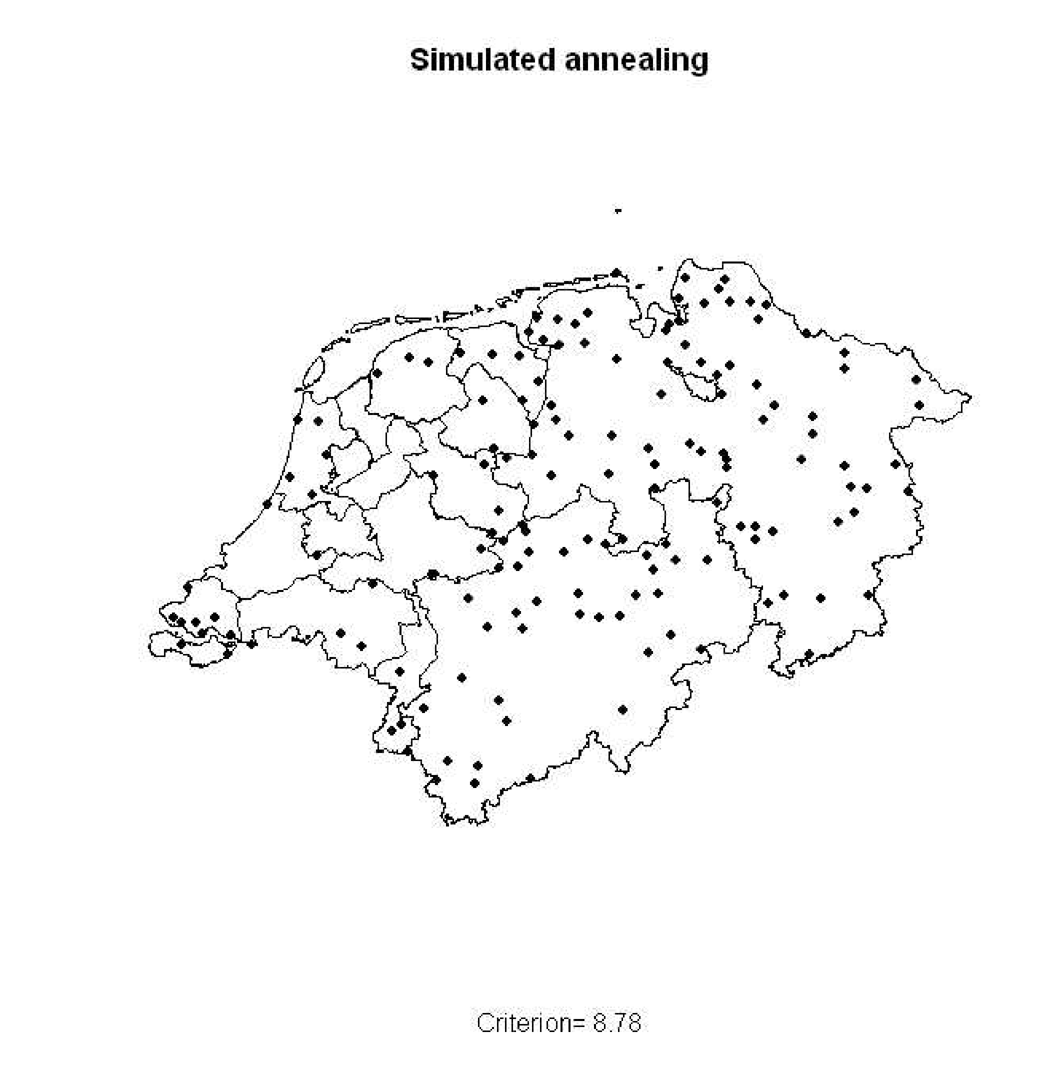


False negatives and densely populated areas weighted more highly than false positives

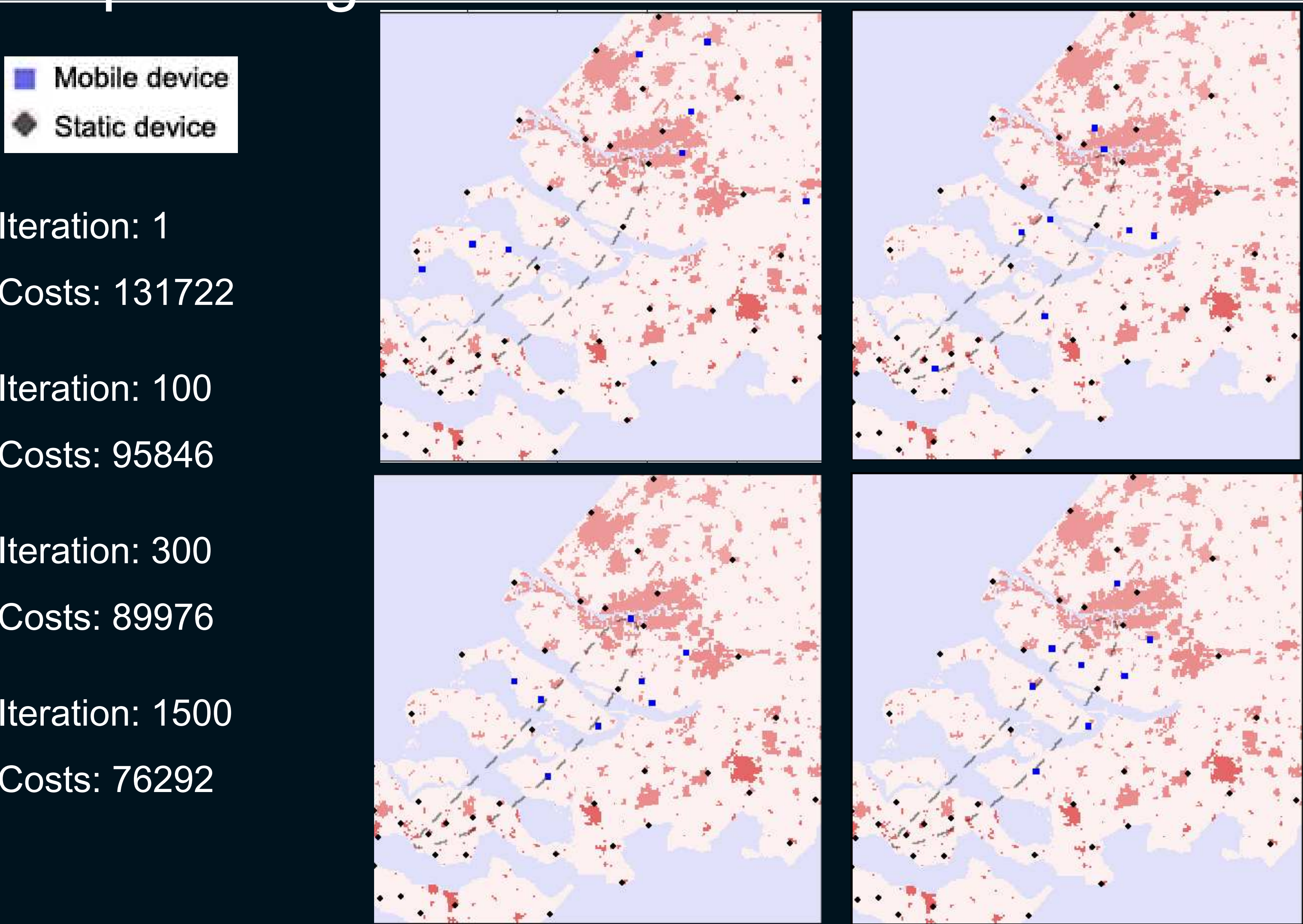
Optimising the location of mobile devices

Using simulated annealing (Kirkpatrick et al. 1983)

1. Start with an arbitrary sampling design
2. Construct new sampling design by moving a mobile device
3. Compute costs of sampling design
4. Compare costs with costs of previous sampling design
5. Accept if current cost are lower than previous
6. New sampling design constructed; loop back to step 1



Optimising the location of mobile devices



Iteration: 1

Costs: 131722

Iteration: 100

Costs: 95846

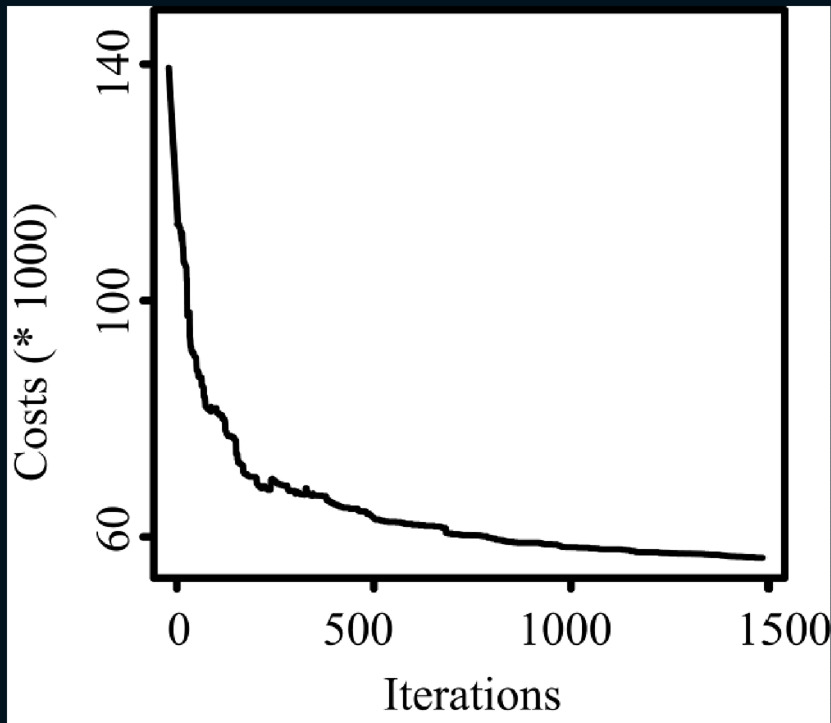
Iteration: 300

Costs: 89976

Iteration: 1500

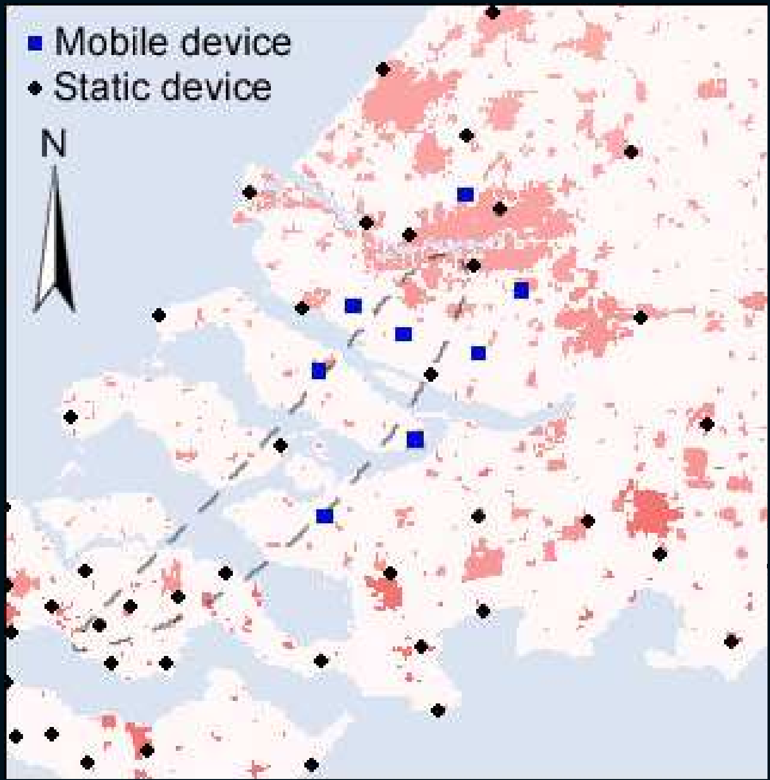
Costs: 76292

Avoiding local optima

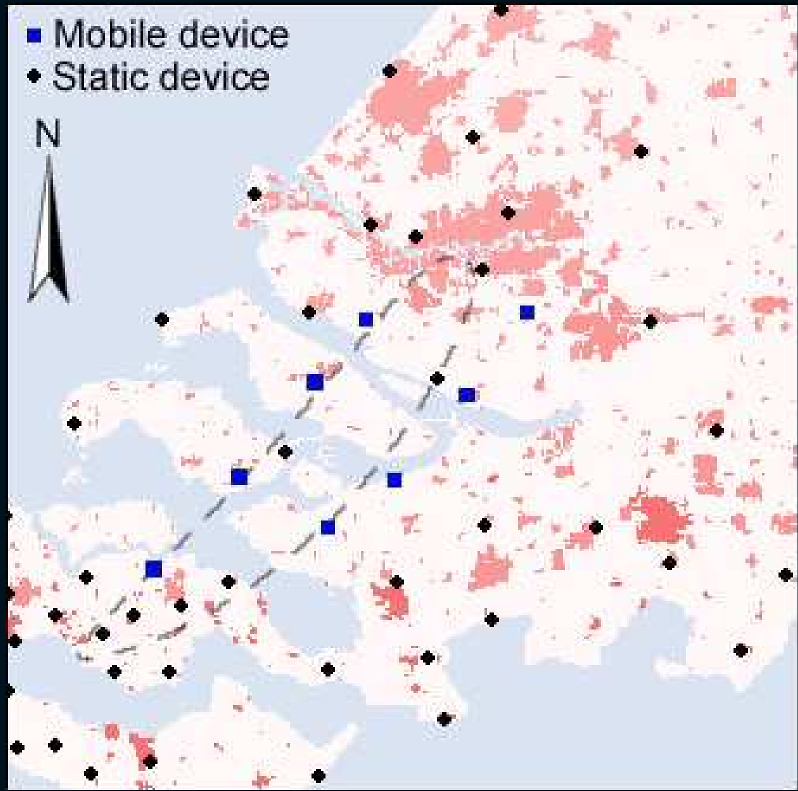


Accept worsening design with an exponentially decreasing probability function

Example final sampling designs



With population density



Without population density

Main limitations:

- Spatial distribution & correlation between NPK-PUFF input parameters not considered
- IDW interpolation extreme changes in measured values over short distances
  - sampled measurements did not always improve NPK-PUFF model predictions
  - inappropriate to use distant measurements to improve predictions
- Computation optimal sampling design takes too long (24 hours for 1500 iterations)

Possible solutions

- Bayesian updating
  - model, parameter, and input uncertainty
- Improve computation time
- Examine different weight and cost functions

Conclusions

- Promising method for minimizing risks of wrong decision
- Many interesting points for further research:
  - extend probability distribution functions of meteorological input parameters
  - enhance interpolation method for creating predicted map
  - optimize spatial simulated annealing algorithm
  - improve estimation of effective dose
- Applicable for all data assimilation approaches where mobile devices assist model predictions (e.g. toxic plume)

Questions / Discussion points

Thanks for your attention!

- Prediction, how to improve?
- Other “cost” indicators?