Nine steps to risk-informed wellhead protection and management via probabilistic vulnerability criteria

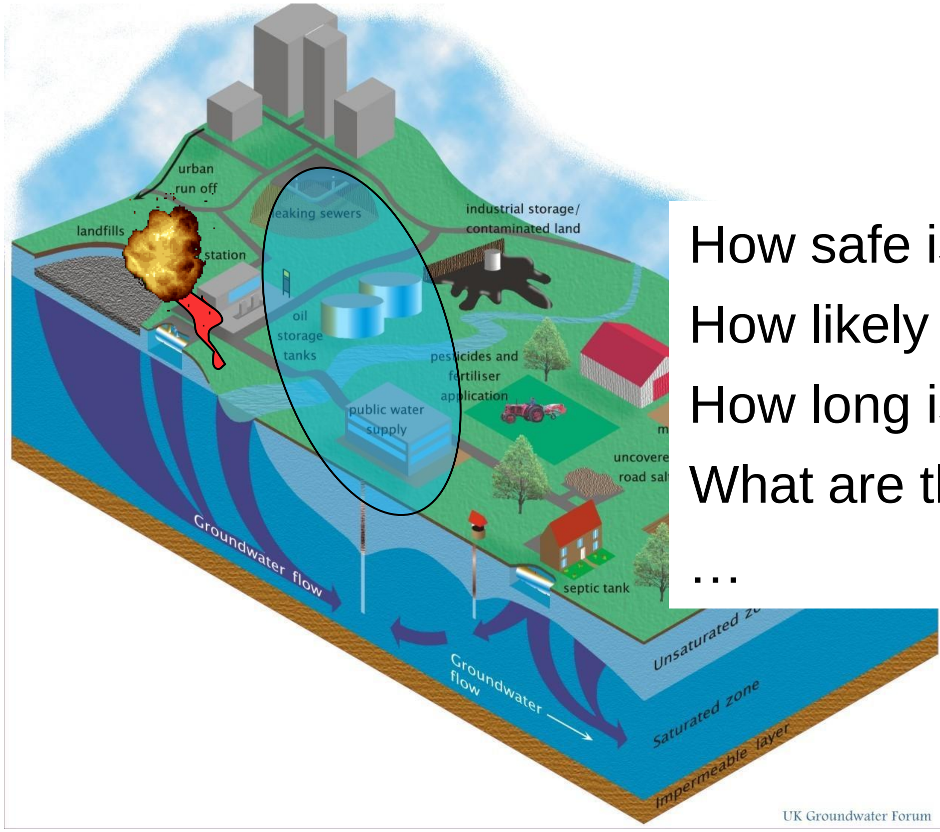
R. Enzenhoefer[1)], T. Bunk[2)] and W. Nowak[1)]

[1)] University of Stuttgart
Institute for Modelling Hydraulic and Environmental Systems
Department of Hydromechanics and Modeling of Hydrosystems

[2)] Zweckverband Landeswasserversorgung
Schützenstr. 4, 7082 Stuttgart, Germany

Drinking water resource protection

- Water Safety Plan (Davidson et al., 2005; WHO 2004)
  - *Hazard Identification, Risk Control, Monitoring*
- Deterministic time-related wellhead delineation (Frind et al., 2006)



How safe is my well production?

How likely it is to impact us? How much mass?

How long is my well contaminated?

What are the costs to enhance resillience?

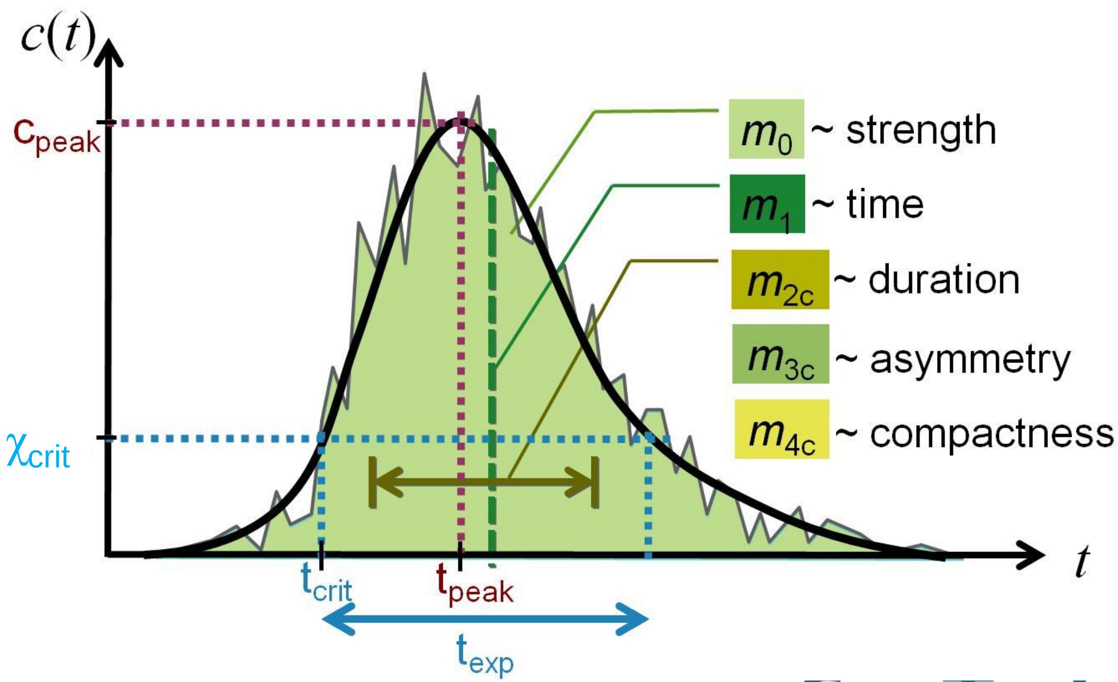
…

Fundamental basis for risk-informed decisions

Intrinsic well vulnerability criteria (WVC) (Frind et al., 2006):

1) Time of peak arrival: t_{peak}
2) Max. concentration: c_{peak}
3) Time to react: t_{crit} (threshold level χ_{crit})
4) Exposure time: t_{exp}

Arrival time, impact, ...



An imperfect world – epistemic uncertainty

- Error sources
  - Natural variability (e.g., geologic windows, fault zones, …)
  - Data (e.g., parameterization (upscaling), measurement error, …)
  - Models (e.g., ideal world, model and data scale, boundary conditions, …)

- Risk assessment = Uncertainty quantification

How safe is the well production?
How likely it is to impact the well?
Costs regarding increased well safety?

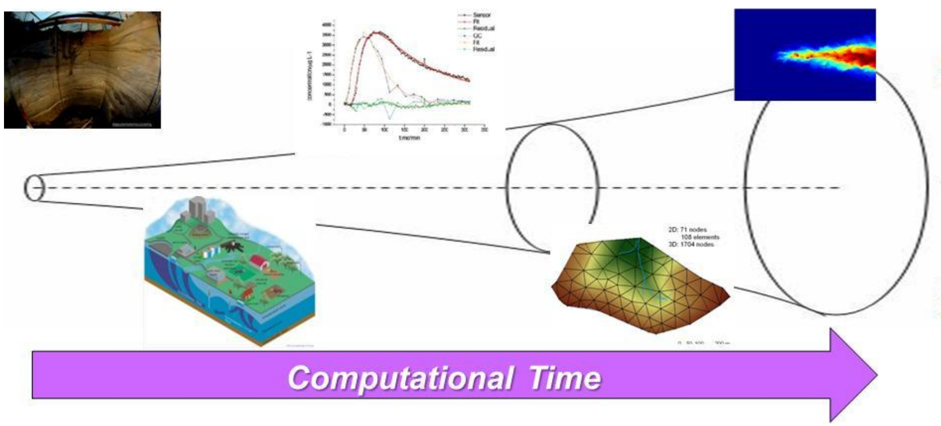
Borden, Canada

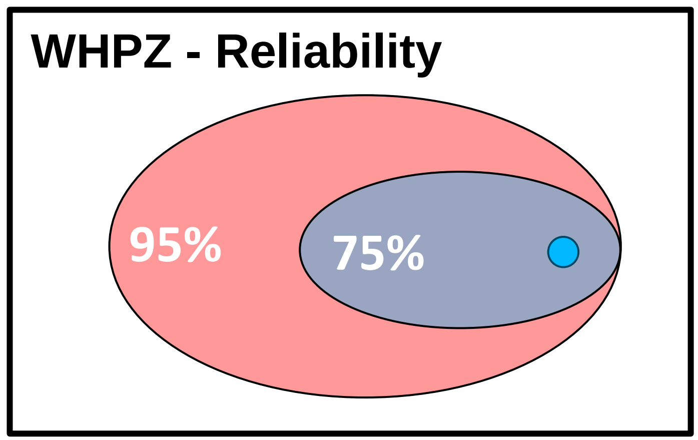
photo: Dave Thomson

- **Probabilistic Well Vulnerability Criteria (PWVC)** (Enzenhöfer et al., 2012)

Reasons not to perform uncertainty quantification

- Practicioners still refrain
  - High computation times (Renard, 2007)
  - Time intensive computer code development (Renard, 2007)
  - Decisions are binary (Pappenberger and Beven, 2006)
  - High reliability levels are high mitigation costs





Goal

Probabilistic risk management tool for actively managed well catchments

» mass flux-based PWVC ***(peak arrival time)***

» easy to use (**known software**) at low computational costs

» risk-informed ***decisions*** in wellhead delineation (***reliability)***

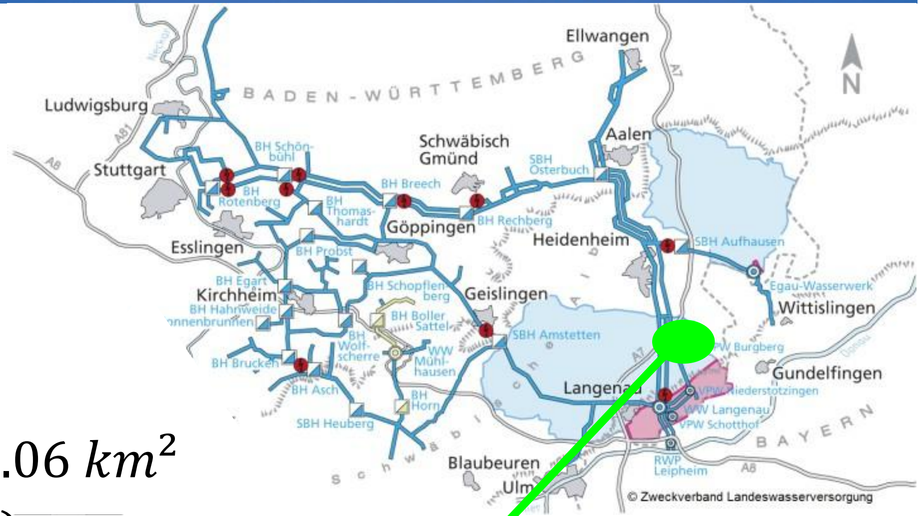
Nine step concept

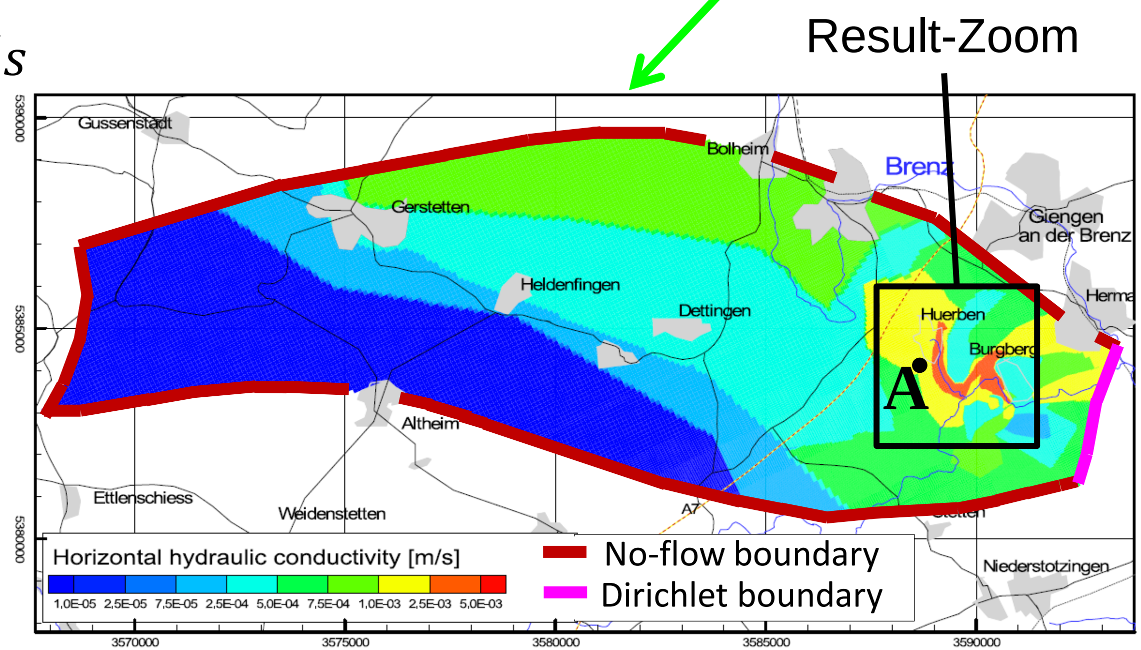
Management

Burgberg Test Case

Burgberg Test Case

- Location – Swabian Alb (Germany)
- Quaternary gravel channels
- Upper Jurassic karst aquifer
- Inner protection zone area $A^{(0)} = 1.06\ km^2$
- Mean Recharge $q_r = 10.5\ l/(s\ km^2)$
- Puming rate $Q_p = 300\ l/s$





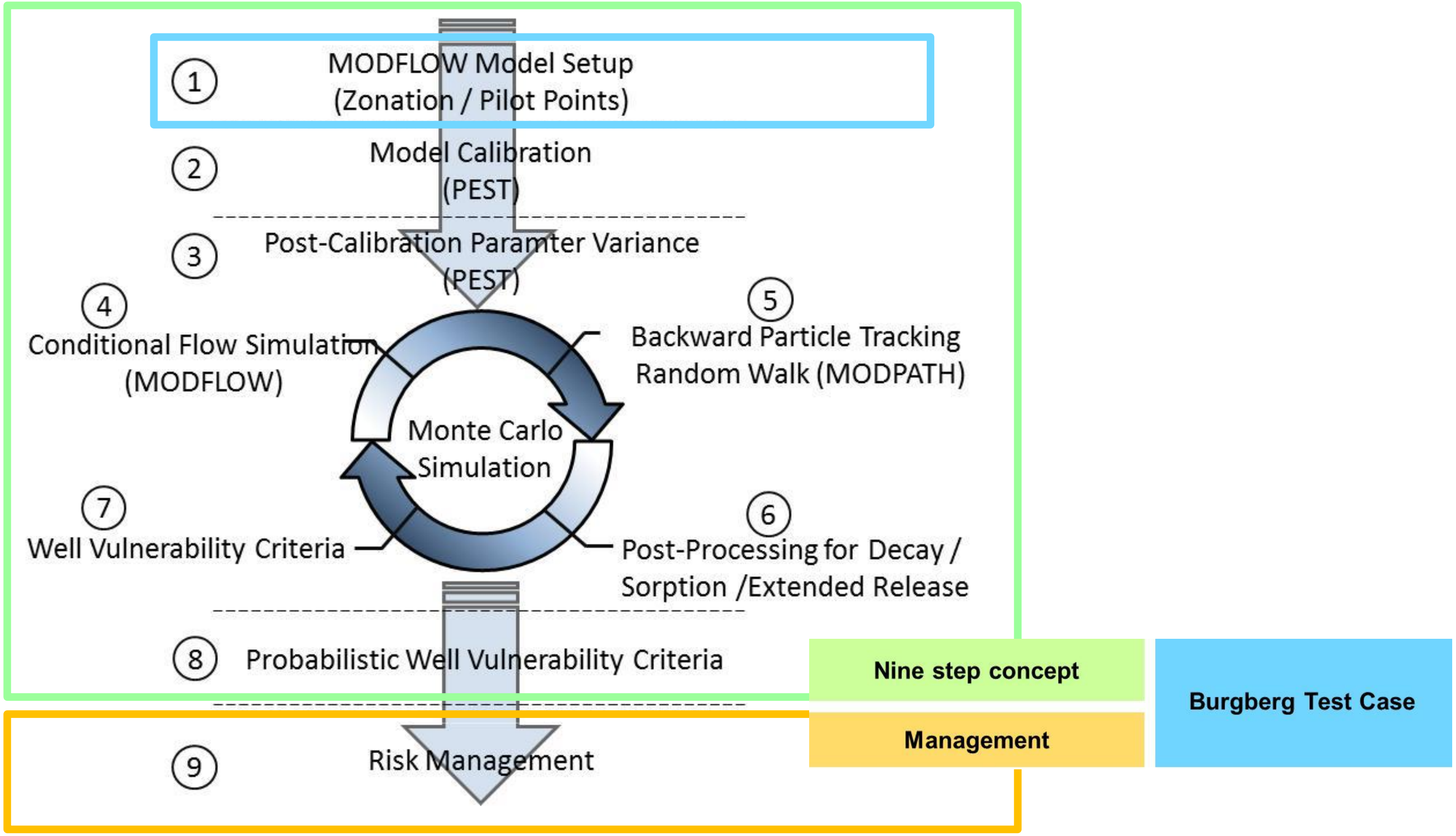
(Lang und Justiz, 2009)

Model implementation (Lang & Justiz, 2009)

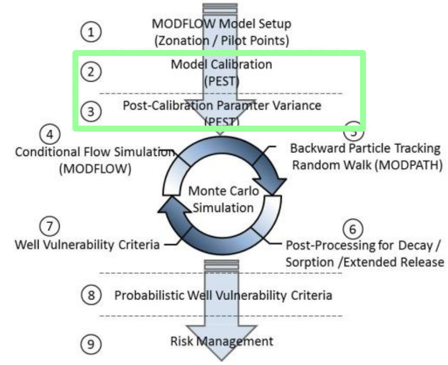
- Modflow (Harbaugh et al., 2000) and ModPath with Random Walk
- 3 model layers
- Zonation-based
- 150.192 elements ($\Delta x = \Delta y = 12.5m\ - 100m$)
- Simulation time $T_{end} = 30\ a$
- Uncertain parameters

			Layer I	Layer II	Layer III	Pdf-type
Porosity	ϕ	$[\%]$	$8\ - 23$	$2\ - 30$	$2\ - 30$	uniform
Dispersivity	α_L	$[m]$	$20\ - 500$	$20\ - 500$	$20\ - 500$	uniform
	α_{TH}	$[m]$	$1\ - 25$	$1\ - 25$	$1\ - 25$	$\alpha_{TH} = \alpha_L/20$
Conductivity	K	$[m/s]$	$4 \cdot 10^{-3}$	$1 \cdot 10^{-5} - 1 \cdot 10^{-3}$	$1 \cdot 10^{-6} - 5 \cdot 10^{-3}$	Post-calibration

Decision theoretic risk management framework



Calibration step



- Model conditioning (e.g., EnKF, Bayesian GLUE)
- Post-calibration matrix (PEST) (Fienen, 2009)

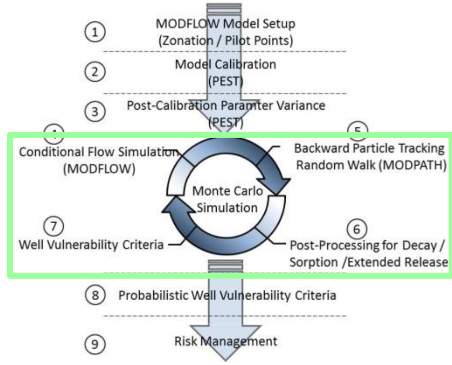
$$\mathbf{C}_{\mathbf{pp|d}} = \left(\mathbf{C}_{\mathbf{pp}}^{-1} + \mathbf{J}^T\mathbf{R}^{-1}\mathbf{J}\right) = \mathbf{C}_{\mathbf{pp}} - \mathbf{C}_{\mathbf{pp}}\mathbf{J}^T\left(\mathbf{J}\mathbf{C}_{\mathbf{pp}}\mathbf{J}^T\right)^{-1}\mathbf{J}\mathbf{C}_{\mathbf{pp}}$$

- Calculation by hand:
  - Sensitivity matrix (Jacobian) $\mathbf{J} = \frac{\partial d_i}{\partial p_i}$
  - Measurement error matrix $\mathbf{R}$
  - Pre-calibration matrix $\mathbf{C}_{\mathbf{pp}}$

- Conditioned parameter set for flow simulation

$$\mathbf{p} = \hat{\mathbf{p}} + chol\left(\mathbf{C}_{\mathbf{pp|d}}\right)\epsilon_r$$

Intrinsic & specific transport simulation

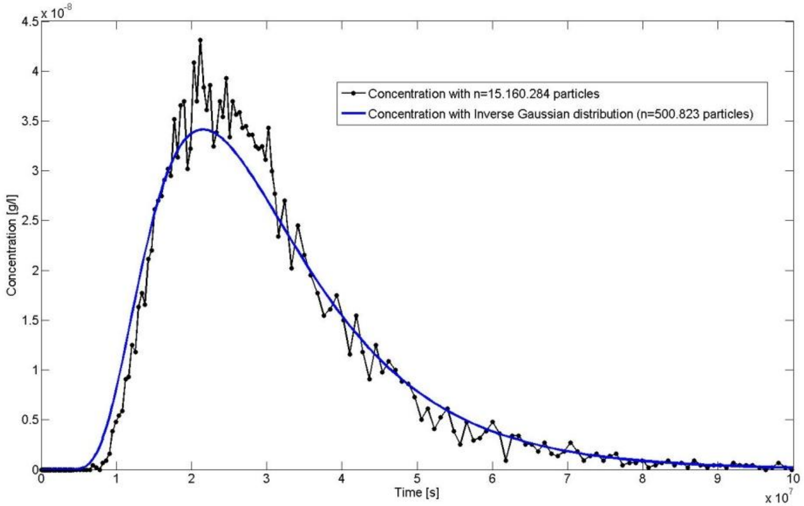


- Conditioned steady-state head fields
- ModPath extended with Particle Tracking Random Walk

$$\mathbf{X}_p(t+\Delta t) = \mathbf{X}_p(t) + \left(\mathbf{v}(\mathbf{X}_p, t) + \nabla \cdot \mathbf{D}(\mathbf{X}_p, t)\right)\Delta t + \mathbf{B}(\mathbf{X}_p, t)\cdot \xi(t)\sqrt{\Delta t}$$

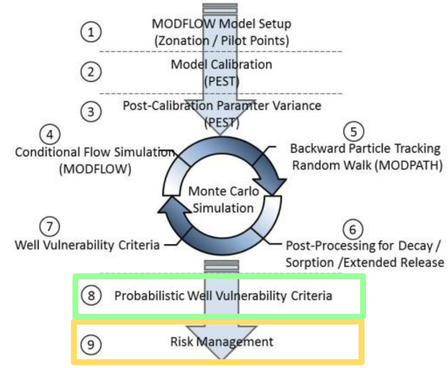
- Reverse approach
- Inverse Gaussian Distribution

$$c(t) \approx f(t;\mu,\lambda) = \sqrt{\frac{\lambda}{2\pi t^3}}\, exp\left\{-\frac{\lambda(t-\mu)^2}{2\mu^2 t}\right\}, \qquad t > 0$$



- 1st order degradation
- Retardation effects (sorption, natural attenuation potential)

Result: Probabilistic wellhead delineation



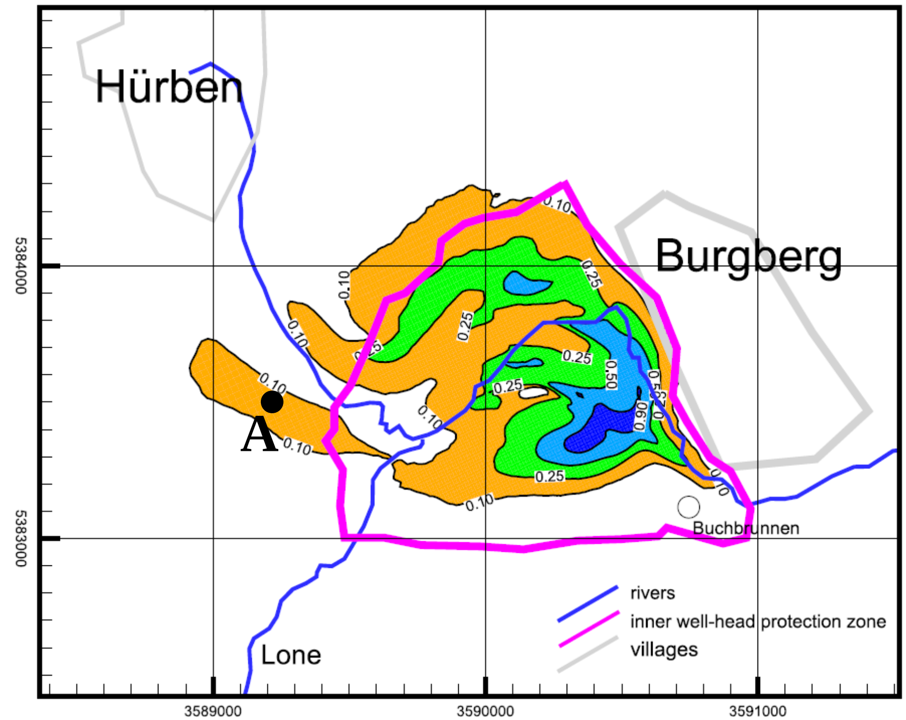
- 1000 Monte Carlo realizations
- Computation time: 5hrs (36cores)
  - Developed on: Intel Core2Duo, 2.26Ghz,4GB RAM (10min)
- Peak arrival time:

$$t_{peak,A} = 151\ d$$

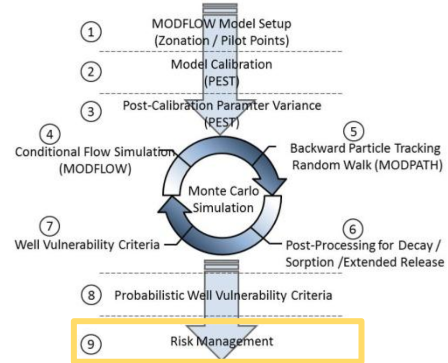
$$P_{t_{peak}<t_{crit}} = 21\%$$

- Current safety level:

$$\beta^{(0)} = 75\%$$



On the way to risk-informed decisions I

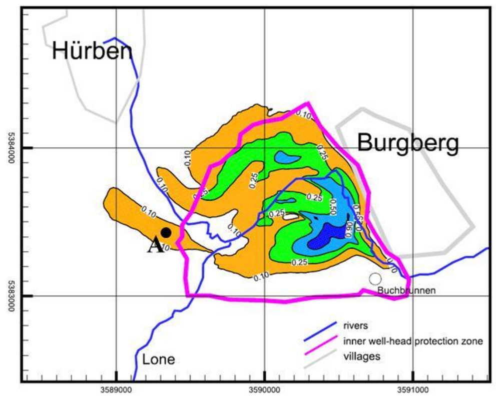


- How safe is my well production?
- What is the confidence in arrival time?

- **What are the costs to enhance resillience?**

Option: (II)

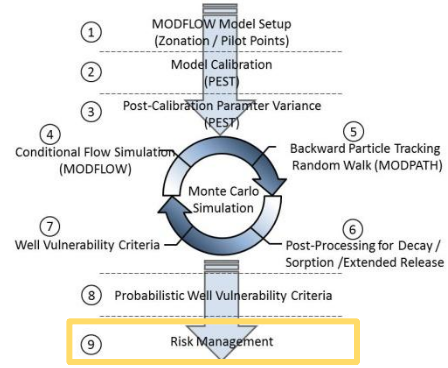
No additional costs



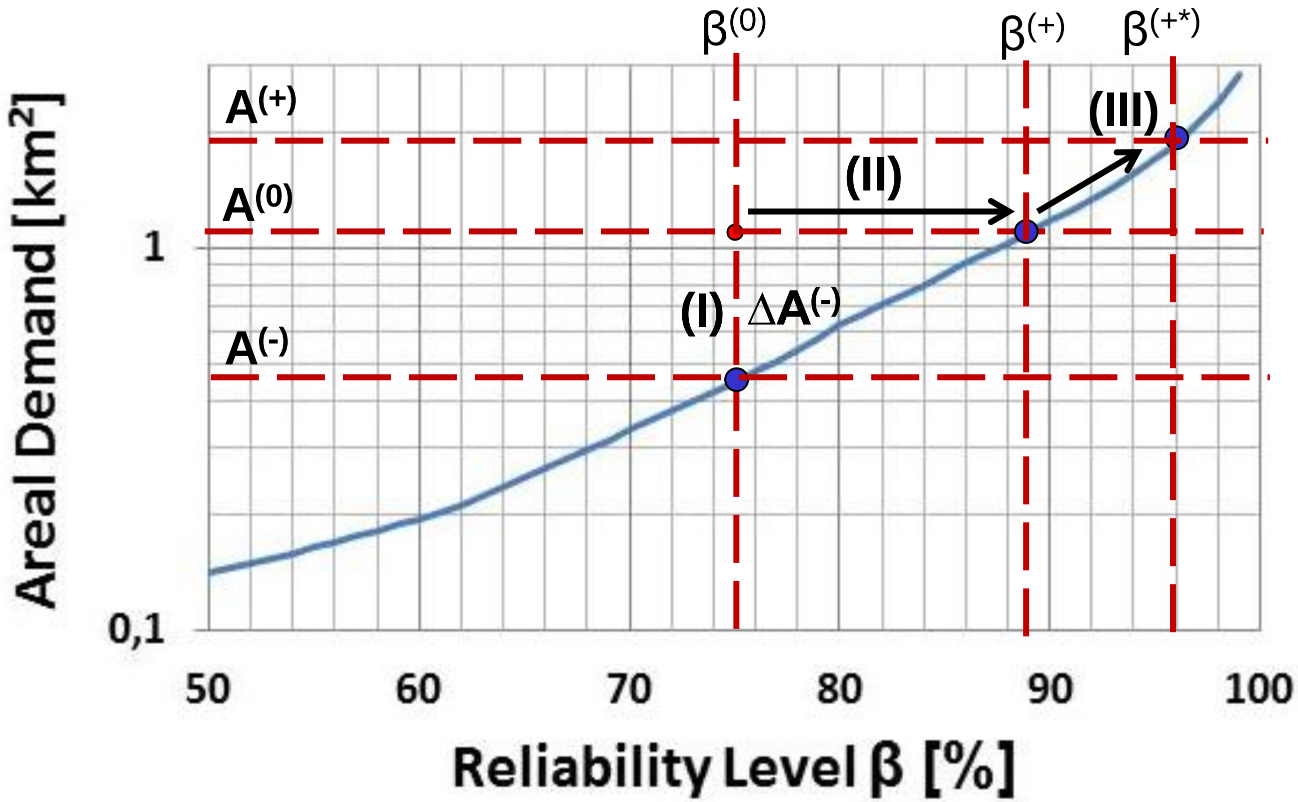
Option: (III)

Some additional costs

On the way to risk-informed decisions II



- Choice of safety margin β

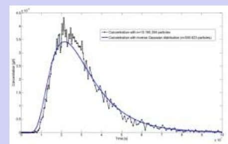


Summary

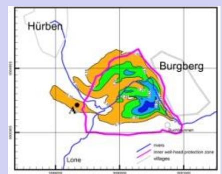
Probabilistic Risk management tool for actively managed well catchments for practioners

» PWVC are easy to implement

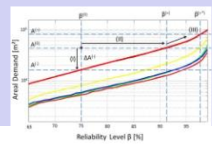
» computational costs are acceptable



» *risk-informed decisions are available*



» *higher reliability at acceptable costs*



Thanks to ...

Independent Junior Research Group “Stochastic modelling of hydrosystems” within the DFG cluster of excellence in Simulation Technology (EXC 310/1)

Kobus and Partner, Consultant, Stuttgart

[1] Enzenhöfer, R., Bunk, T. and Nowak, W. : Risk-informed wellhead protection and management via probabilistic well vulnerability: The Burgberg Case Study. (in prep.)

[2] Enzenhöfer, R., Nowak, W. and Helmig, R. (2012): Probabilistic exposure risk assessment with advective-dispersive well vulnerability criteria. Adv. in Water Res. (36), p.121-132.