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

R. Enzenhoefer\textsuperscript{1)}, T. Bunk\textsuperscript{2)} and W. Nowak\textsuperscript{1)}

\textsuperscript{1)} University of Stuttgart
Institute for Modelling Hydraulic and Environmental Systems
Department of Hydromechanics and Modeling of Hydrosystems

\textsuperscript{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 resilience?

...
Fundamental basis for risk-informed decisions

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

1) Time of peak arrival: $t_{\text{peak}}$
2) Max. concentration: $c_{\text{peak}}$
3) Time to react: $t_{\text{crit}}$ (threshold level $\chi_{\text{crit}}$)
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?

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

photo: Dave Thomson
Reasons not to perform uncertainty quantification

- Practitioners 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

![Diagram showing computational time and WHPZ reliability](image)
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 $T_{end} = 30 \text{ a}$
- Uncertain parameters

<table>
<thead>
<tr>
<th>Porosity</th>
<th>$\phi$</th>
<th>Layer I [%]</th>
<th>Layer II</th>
<th>Layer III</th>
<th>Pdf-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispensivity</td>
<td>$\alpha_L$ [m]</td>
<td>20 – 500</td>
<td>20 – 500</td>
<td>20 – 500</td>
<td>uniform</td>
</tr>
<tr>
<td>Conductivity</td>
<td>$\alpha_{TH}$ [m]</td>
<td>1 – 25</td>
<td>1 – 25</td>
<td>1 – 25</td>
<td>$\alpha_{TH} = \alpha_L / 20$</td>
</tr>
<tr>
<td>Conductivity</td>
<td>$K$ [m/s]</td>
<td>$4 \cdot 10^{-3}$</td>
<td>$1 \cdot 10^{-5} - 1 \cdot 10^{-3}$</td>
<td>$1 \cdot 10^{-6} - 5 \cdot 10^{-3}$</td>
<td>Post-calibration</td>
</tr>
</tbody>
</table>
Decision theoretic risk management framework

1. MODFLOW Model Setup (Zonation / Pilot Points)
2. Model Calibration (PEST)
3. Post-Calibration Parameter Variance (PEST)
4. Conditional Flow Simulation (MODFLOW)
5. Backward Particle Tracking Random Walk (MODPATH)
6. Post-Processing for Decay / Sorption / Extended Release
7. Well Vulnerability Criteria
8. Probabilistic Well Vulnerability Criteria
9. Risk Management

Nine step concept

Burgberg Test Case

Management
Calibration step

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

\[ C_{pp\mid d} = (C_{pp}^{-1} + J^T R^{-1} J) = C_{pp} - C_{pp} J^T (J C_{pp} J^T)^{-1} J C_{pp} \]

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

- Conditioned parameter set for flow simulation

\[ p = \hat{p} + chol(C_{pp\mid d}) \epsilon_r \]
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

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

- 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:
  \[ t_{peak,A} = 151 \text{ d} \]
  \[ P_{t_{peak} < t_{crit}} = 21\% \]
- 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 resilience?**

**Option: (II)**
No additional costs

**Option: (III)**
Some additional costs
On the way to risk-informed decisions II

- Choice of safety margin $\beta$

<table>
<thead>
<tr>
<th>$A^{(+)}$</th>
<th>$A^{(0)}$</th>
<th>$A^{(-)}$</th>
<th>$\beta^{(0)}$</th>
<th>$\beta^{(+)}$</th>
<th>$\beta^{(+\ast)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>$\Delta A^{(-)}$</td>
<td>(I)</td>
<td>(II)</td>
</tr>
<tr>
<td>Areal Demand [km²]</td>
<td>0,1</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
</tr>
</tbody>
</table>
Summary

Probabilistic Risk management tool for actively managed well catchments for practitioners

» 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
