

Risk assessment and mitigation for the energy sector

(Task 4.1 und NFP70 project ‘Risk
Governance’)

Stefan Wiemer
ETH Zürich

In cooperation with the CTI



Energy funding programme

Swiss Competence Centers for Energy Research



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

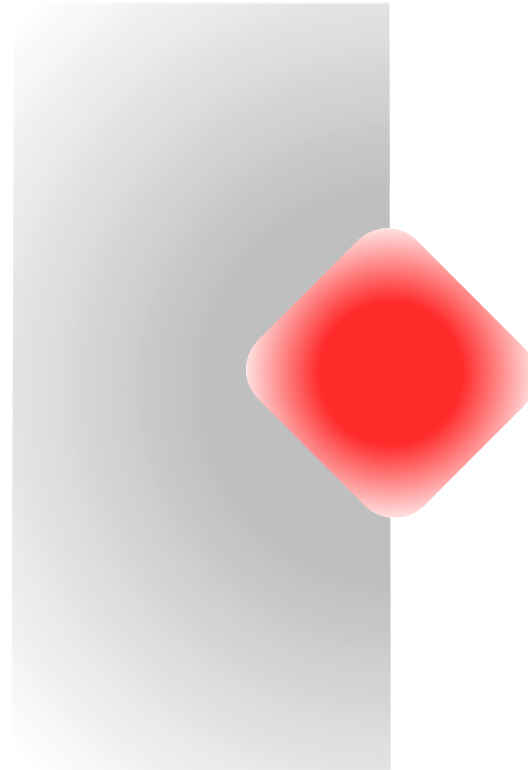
Swiss Confederation

Commission for Technology and Innovation CTI

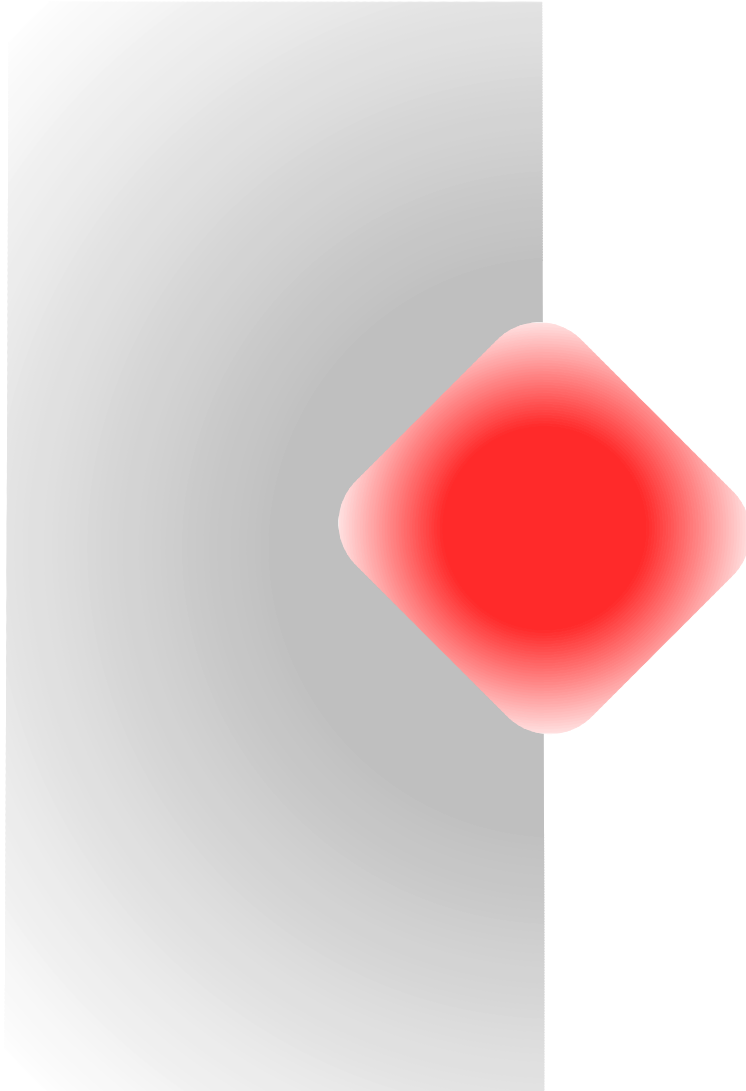
Risk Governance of **GeoEnergies** and **HydroPower**

We adopt/develop a **holistic concept of risk governance and community resilience** advocating a broad picture of risk:

- not only does it include '**risk management**' and '**risk analysis**',
- It also looks at how **risk-related decision-making** unfolds when a range of actors is involved.



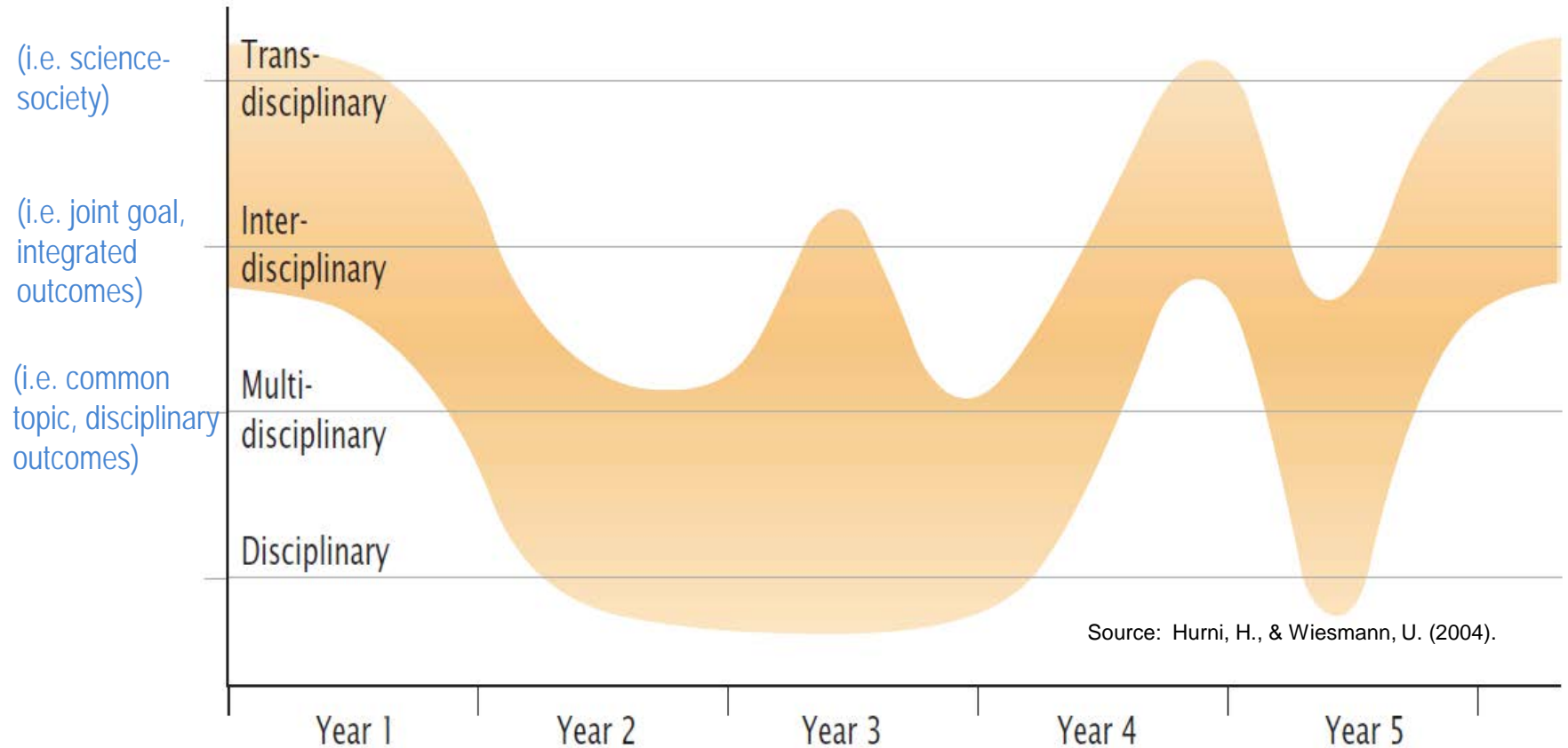
Risk requires interdisciplinary thinking!



Risk requires an interdisciplinary team!

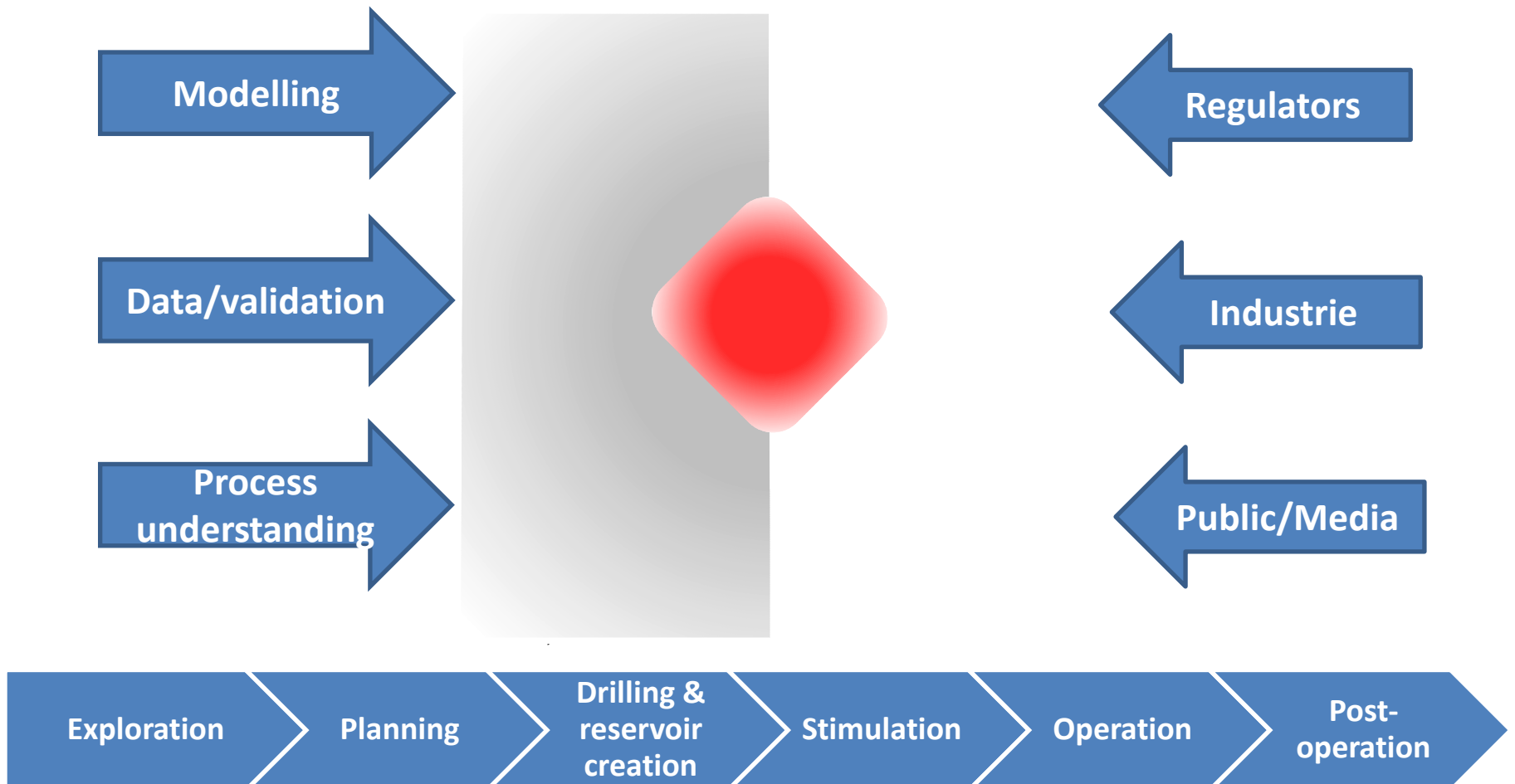


Interdisciplinary research: A dynamic process



Risk governance requires interfaces!

Risk Governance: A highly integrative SCCER-SoE activity, please see the 14 posters!



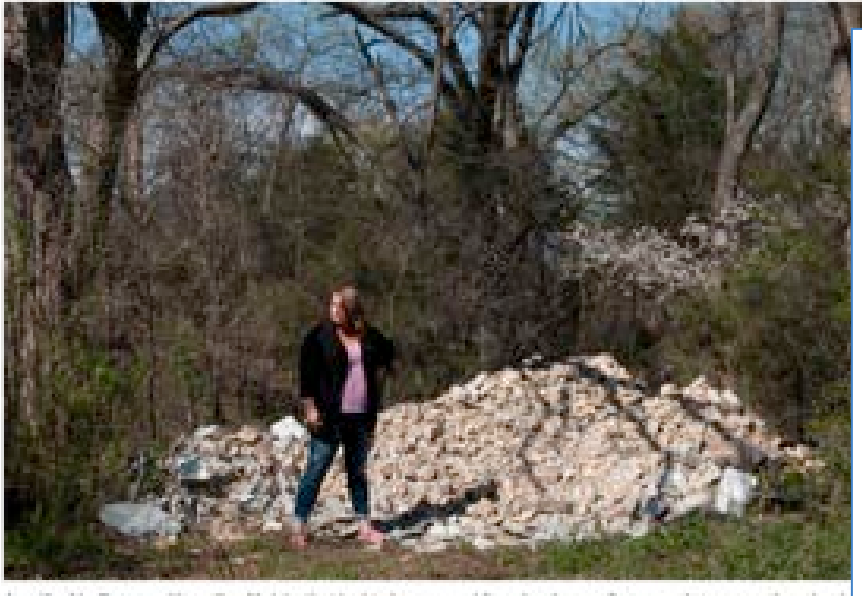
An international perspective

U.S.

390 COMMENTS

As Quakes Rattle Oklahoma, Fingers Point to Oil and Gas Industry

By RICHARD A. OPPEL Jr. and MICHAEL WINES APRIL 1, 2015

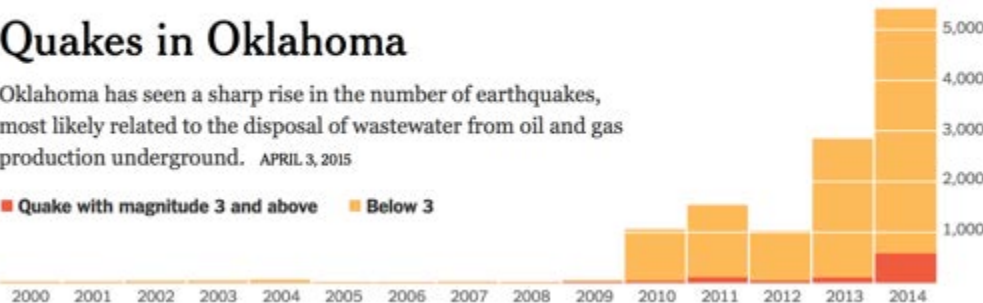


U.S.

Quakes in Oklahoma

Oklahoma has seen a sharp rise in the number of earthquakes, most likely related to the disposal of wastewater from oil and gas production underground. APRIL 3, 2015

■ Quake with magnitude 3 and above ■ Below 3



INSIGHTS | PERSPECTIVES

GEOPHYSICS

Coping with earthquakes induced by fluid injection

Hazard may be reduced by managing injection activities

By A. McGarr,^{1*} B. Bekins,² N. Burkardt,³ J. Dewey,⁴ P. Earle,⁴ W. Ellsworth,¹ S. Ge,⁵ S. Hickman,¹ A. Holland,⁶ E. Majer,⁷ Y. Rubinstejn,¹ A. Sheehan⁵

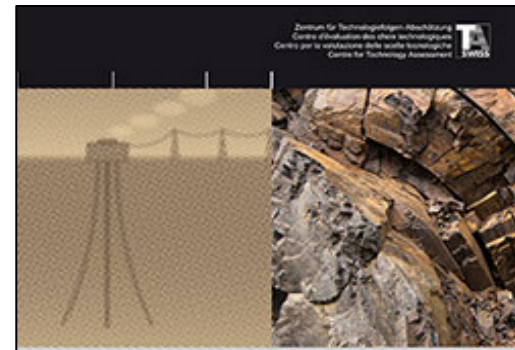
SHARE

as of the United States long

are so many disposal wells that this contributes significantly to the total seismic hazard, at least in the mid-continent (1, 2). EOR has been associated with earthquakes as large as $M4.5$, but felt earthquakes are rare (7). For the most part, fracking indu

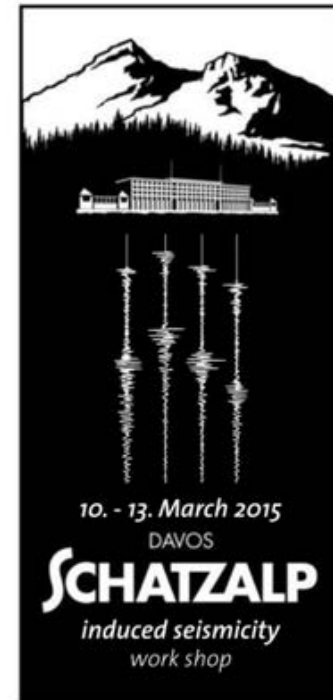
Science, Feb. 2015

Outreach Highlights: TA Swiss study and Schatzalp workshop on induced seismicity



*Stefan Hirschberg, Stefan Wiemer,
Peter Burgberr (eds.)*

Energy from the Earth
Deep Geothermal as a Resource
for the Future?



Non-technical aspects of risk governance

for hydropower and deep geothermal energy

Context

Society plays an important role in shaping the future of hydropower and deep geothermal energy and their risk governance

Activities

- Non-technical aspects of induced seismicity risk governance
- Retrospective assessment of the St. Gallen geothermal project
- Research-informed risk communication (including low probability-high consequence events) for hydropower and geothermal
- Media analysis at local and national scales
- Public and stakeholder engagement



M. Stauffacher et al. / *Technological Forecasting & Social Change* 98 (2015) 60–70

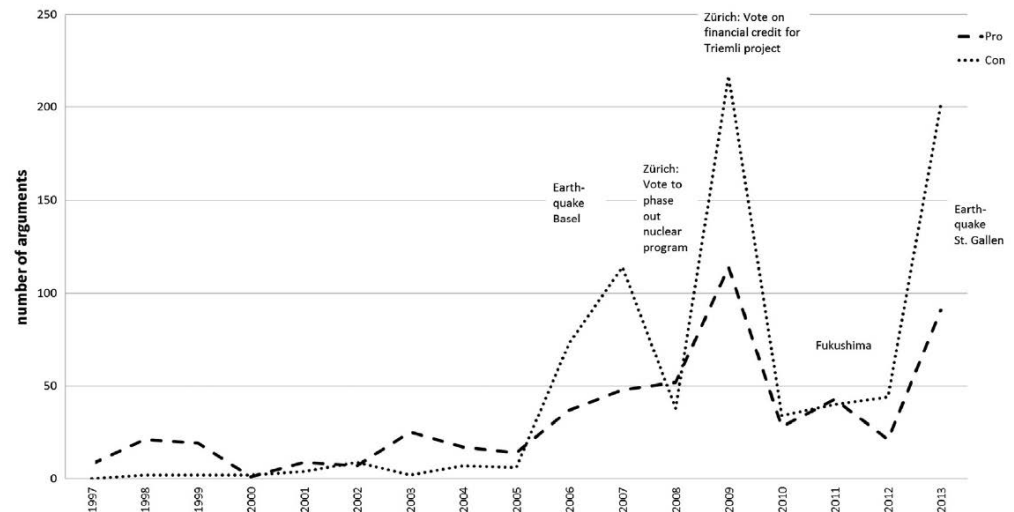


Fig. 2. Frequency of pro and con arguments in TA and NZZ over time ($N = 1350$ arguments; based on the filtered sample 2, $N = 193$ articles).

Transdisciplinary Case Study 2015

«Deep Geothermal Energy: the St. Gallen project»

- Elective teaching course for ETH MSc Environmental Sciences
 - 7 ECTS (approx. 210 hrs.)
 - Spring semester 2015
- Lecturers
 - Dr. Michael Stauffacher & Prof. Stefan Wiemer (SED, D-ERDW)
 - Dr. Evelina Trutnevyte (& others for specific inputs)
- <http://www.tdlab.usys.ethz.ch/education/tdcs/current.html>

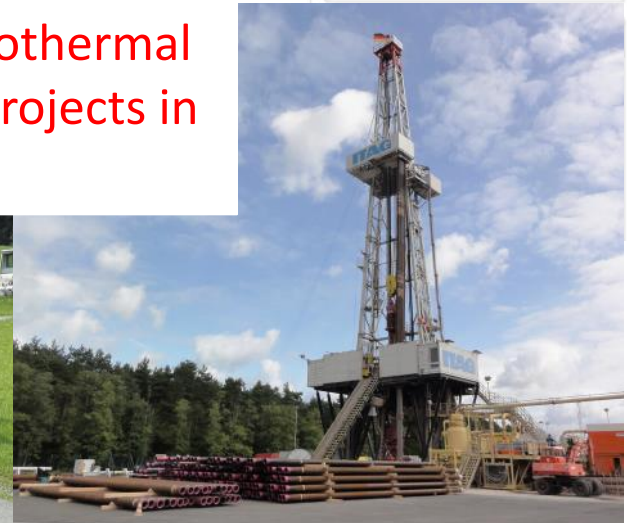


St. Gallen as success story and blueprint for other projects?



Guiding question

What can we learn from the geothermal project in St. Gallen for future projects in Switzerland?



Multi-risk

By A. Mignan (ETH Zurich) and colleagues



Multi-risk = All dynamic processes in the risk chain, i.e., hazard interactions, damage-dependent vulnerability, etc.

Activities

- Multi-risk analysis and multi-risk governance (in collaboration with ETH Zurich Climate Policy Group)
- Multi-risk analysis of **hydropower dams** (in collaboration with EPFL, A. Schleiss' group)
- Multi-risk analysis in **Switzerland** (NRP70 PhD WP5, A. Jafarimanesh)
- Upcoming: application of multi-risk to **Deep Geothermal Energy**

To learn more, don't miss the **multi-risk triptych** in the poster area.

SCCER SoE Swiss Competence Center for Supply for Electricity Annual Conference 2015

The Generic Multi-Risk GenMR framework: Part A. From multi-risk analysis to multi-risk governance

A. Mignan, A. Scolobig and N. Komenkova

Abstract
As opposed to single-risk settings, multi-risk environments are characterized by natural and/or man-made hazards co-occurring in time and space. Hydropower and geothermal sites are not immune to these risks, requiring a timely assessment and management of multi-risk. Here we present the Generic Multi-Risk GenMR framework, which is based on a variant of the Markov Chain Monte Carlo method. GenMR is currently tested in the case of a strongly large Alpine earthquake dam (see Part B) and will soon be tested for all of Switzerland for different multi-risk processes and energy sites (see Part C). Cascading and convergent effects pose specific challenges to decision makers. For this reason we also present a multi-risk governance scheme, which is grounded on governance theories and on the GenMR multi-risk science. This work is part of T4.1 "Risk, safety and societal acceptance" in collaboration with the MATRIS and STREST European projects.

1. Introduction
Multi-risk is a reality as proven by the infamous 2005 Hurricane Katrina and 2011 Tohoku earthquake. These events triggered other events, such as levee breach and city flooding, tsunami and nuclear accident, business interruptions, etc. In the London Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015), the adoption of a multi-hazard and multi-risk approach is considered a key requirement for risk reduction, which reflects a growing awareness of the importance of understanding, hazard and risk interactions to improve protection for risk management. The European MATRIS (2010-2017) project formed a platform to develop harmonized multi-risk methods (COM 2014), such as GenMR, described below. The framework is now tested at critical infrastructure (e.g., dams, retention facilities) in the STREST project (2013-2016) and specifically at hydropower and geothermal sites in SCCER-SoE and NRP70 (see Parts B-C). Multi-risk governance is the most recent development, including social and institutional context analysis as well as stakeholder processes.

2. Generic Multi-Risk (GenMR) Framework
GenMR generates probabilistic multi-risk scenarios based on a variant of the Markov Chain Monte Carlo method (Fig. 1) (Mignan et al., 2014).

Fig. 1 Simulation sets. It is composed of M_{sim} scenarios, populated by hazardous events. Event combinations are defined in a Hazard Interaction Matrix (HIM). Also, it includes event dependent vulnerability and exposure (not shown). Examples are shown in Parts B and C.

3. Multi-Risk Governance Scheme
Risk governance processes are critical steps in which stakeholders manage their common risk issues (e.g., Riman, 2006). Fig. 2 shows its extension to multi-risk governance (Scolobig et al., sub.). Note that the process does not equate to the sum of single-risk governance.

Fig. 2 Multi-risk governance scheme (Scolobig et al., sub.).

Phases are:
1. **Diagnosis:** Complex, uncertain, external
2. **Identify & contextualize context:** Possible conflicts between agencies (who should be in charge of multi-risk? What established laws?)
3. **Multi-risk knowledge generation:** GenMR, including virtual City concept (see Part B), already tested at stakeholders' knowledge in Part A (Mignan et al., in press).
4. **Established procedures:** Expert-assisted stakeholder participatory process, decision making under uncertainty.

Fig. 3 Virtual City concept: an virtual region artistic representation (Mignan et al., in prep.). See also Part C.

4. Conclusions
✓ GenMR can now be systematically used to quantify multi-risk (see Parts B and C).
✓ Although multi-risk scenarios are already considered for dam safety, systematic multi-risk modeling is lacking (see a solution in Part B).
✓ The multi-risk governance scheme (Fig. 2) will be tested for deep geothermal energy (DGE) by considering fault injection as the initial triggering event.
✓ A DGE virtual site (variant of Fig. 2) will be developed to improve communication with stakeholders.

5. References
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.

SCCER SoE Swiss Competence Center for Supply for Electricity Annual Conference 2015

The Generic Multi-Risk GenMR framework: Part B. Vulnerability of large dams considering hazard interactions

J.P. Mello, A. Mignan and J.A. Schleiss

Abstract
Owing to the complex nature of dam-reservoir interactions, both design verifications and attempts of risk assessment of dams are typically focused on a small subset of hazard types and/or depart from specific initial conditions. While both simplifications help reducing the position of risk assessment, they neglect numerical interactions and are not adequate in order to comprehensively estimate all the risks associated with the system's operation. Here, the GenMR framework (described in Part A) was specifically adapted to dams and employed as a tool to assess the risk of dam failure due to extreme global risks associated with hydropower dams. This work was done in the European STREST project; the proposed method applies to both T2 (3rd infrastructure adaptation) and T4.1 (Risk, safety and societal acceptance).

1. Introduction
When dams fail, all the potential energy stored in the reservoir is converted into a destructive dam-break wave. Traveling fast and loaded with debris, such waves pose a real threat to downstream areas. Safety is, therefore, a main source of concern for the dam industry. This is reflected in research topics, design standards, and safety recommendations. Traditionally, risk assessments are usually focused on one or a few different hazards and require considering assumptions about the initial state of the system. Several approaches have historically been applied to the problem: i) event trees, fault trees, or failure modes and effects analysis. Here, the Generic Multi-Risk (GenMR) framework (Mignan et al., 2014) is applied to dams as an alternative that is capable of treating the global risk associated with a dam facing multiple hazards (see Part A) and enables the evaluation of the importance of hazard interactions.

2. Method
The integration of multiple hazards and system elements is accomplished within GenMR according to Fig. 1. Interdependencies are described and entered through the network's correlation and time-order matrices (Mignan et al., 2014, see Part A).

Fig. 1 Scheme of hazards, elements, interdependencies, correlation matrices and interactions. The GenMR framework is applied to the evaluation of the risk of dam failure due to large dams (Mello et al., 2015).

Fig. 2 Example simulation (adapted from Mello et al., 2015).

3. Results
Preliminary results for a large Swiss dam show that:
✓ The GenMR framework can be applied to dams.
✓ It can be used to estimate the overall risk associated with a dam during its complete usage operation cycle.
✓ Uncertainty plays a major role and accurate description of hazards and elements is paramount.
✓ Probabilistic disaggregation results to prevent high risk causes.
✓ The system's vulnerability is increased when interdependencies are incorporated in the analysis, particularly due to combinations of events. The likelihood of such extreme scenarios remains, however, and failure safety design standards to be tested (conventional dam case).

4. Conclusions
✓ The proposed approach represents an innovation in the field of dam risk assessment.
✓ Unlike established alternatives, it is not conditional on prior states of the system or very reduced subsets of hazards (see also Part C).
✓ Although providing but a rough estimate of the true risks associated with a dam at the present stage, the approach can already enable owners, regulators, and designers to gain insight into the most likely causes of events.
✓ Using the multi-risk governance frame proposed in Part A could facilitate the implementation of GenMR in hydropower dam risk management.

5. References
Mello, J.P., A. Mignan, J.A. Schleiss (2015), Correlation of large dams considering hazard interactions: combined application of the Generic Multi-Risk GenMR framework. International Risk Engineering Conference (IERC), London, Switzerland, 2015.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.

SCCER SoE Swiss Competence Center for Supply for Electricity Annual Conference 2015

The Generic Multi-Risk GenMR framework: Part C. Hazard interactions & dynamic risk in Switzerland

A. Jafarimanesh, A. Mignan & D. Giardini

Abstract
Triggered chains of events and their combined impact on infrastructure may itself unaccounted for (e.g., increased likelihood of hydropower dam failure due to increased change around geothermal exploitation sites). This paper describes the use of the GenMR (GenMR) project on "Multi-risk and interdependencies" applied to dams and related to T4.1 "Risk, safety and societal acceptance". Using a modeling approach the Generic Multi-Risk (GenMR) framework of Mignan et al. (2014) (see Part A), we investigate the possible hazard interactions and dynamic risk processes, which can be expected of these hydropower and geothermal sites. Hazards of interest are mainly earthquakes, storm, mass slides and lake surges. Dynamic risk processes of interest are mainly damage-dependent building vulnerability and network failures. A better understanding of multi-risk, small slow emerging triggering processes and future energy site planning.

1. Introduction
Switzerland is prone to hazard interactions due to its mountainous landscape. Historical earthquakes are known to have triggered afterwards landslides, rock falls and avalanches, as well as lake surges (e.g., Frutiger et al., 2010). Obviously, dams are also subject to hazard interactions. Examples include cascading dam failures due to history (e.g., 1975 Bonassio dams, China) and dam overtopping due to landslides (e.g., 1963 Vaiont dam, Italy) (see Part B). Potential hazard interactions at geo-energy production sites, on the other hand, have not so far been systematically addressed. Since one of the main risks due to induced seismicity, one especially needs to investigate the triggering potential of small to moderate size events (magnitudes up to ~4.5) as well as the impact of repeated moderate size events (magnitudes up to ~4.5) as well as the impact of repeated moderate size events (magnitudes up to ~4.5) as well as the impact of repeated moderate size events (magnitudes up to ~4.5).

2. Method
Multi-risk processes (i.e., hazard interaction & dynamic risk) are quantified in the GenMR framework, which is based on a variant of the Markov Chain Monte Carlo Method (Mignan et al., 2014, see details in Part A). The present PhD project uses the following top-down approach to multi-risk analysis:
✓ **Applied tool:** Development of multi-risk models using best mathematical tools (e.g., distributed functions, cellular automata).
✓ **Generic level:** Virtual City concept, Mignan et al., in prep. Testing of simplified but realistic enough multi-risk models in a controlled environment for benchmarking and parameter sensitivity analysis (Fig. 1A-B, LONGOSCO TAGE).
✓ **Site specific level (LONGOSCO TAGE):** Application of multi-risk models to local site conditions, using existing topography and projects, building portfolio, etc. (LONGOSCO TAGE).

Fig. 1 Virtual region concept: an virtual region artistic representation (Mignan et al., in prep.). See also Part C.

Fig. 2 Impact of repeated minor earthquake shaking on building integrity for different performance (see Fig. 1). Although the earthquake orography yields negligible damage (D1), its impact may lead to building collapse (D2). Developed by Mignan et al. (in prep.), this model could be used in the PhD for related seismicity multi-risk in Switzerland.

3. Examples of multi-risk processes
✓ **Landslides triggered by infrastructure and hazard chain:** This is the first process considered in the PhD. A cellular automaton was developed based on the concept of Network susceptibility to model the dynamic landslide propagation following an earthquake under different water saturation conditions (positive in both hydro- and geomechanics).

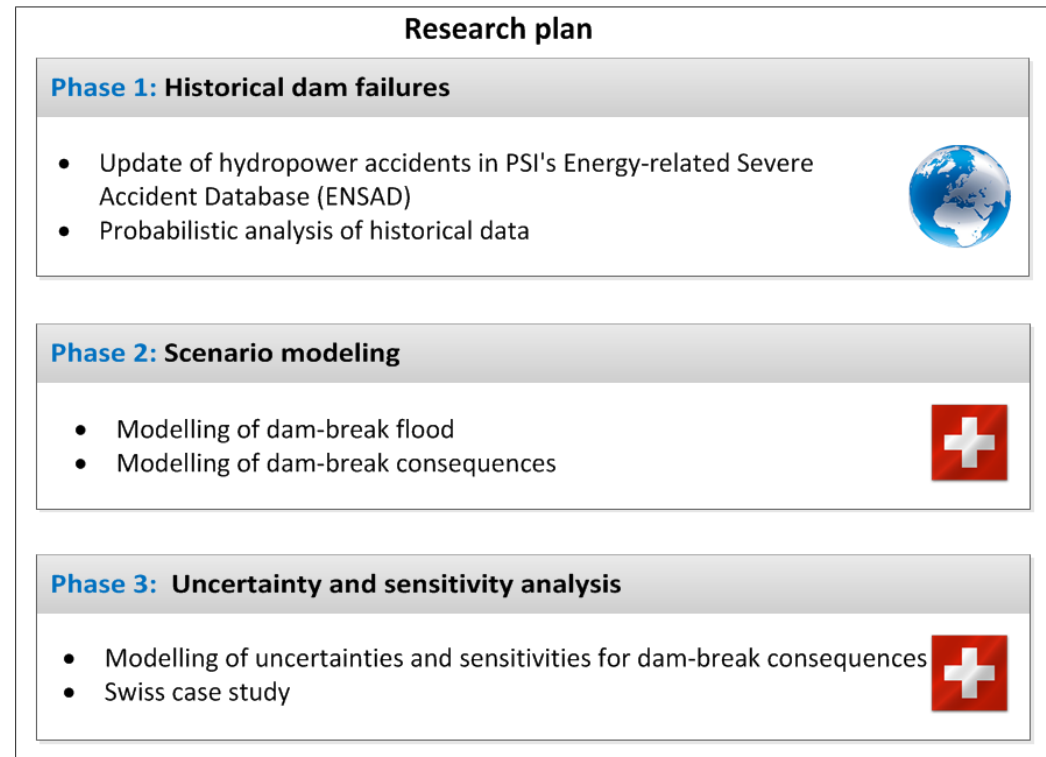
Fig. 3 Damage-dependent vulnerability due to repeated earthquakes.

4. Conclusions
1. An iterative triggering model has been developed and tested in the virtual region using GenMR. It will be later on applied to Switzerland, especially to hydro- and geo-energy sites (present and planned).
2. A damage-dependent vulnerability model can be implemented in GenMR for induced seismicity risk assessment in Switzerland.
3. History failure and lake surging triggering model will be investigated later on at a similar fashion (network City cellular automata modeling on the virtual region, application to Switzerland).
4. FINAL GOAL: Develop a multi-risk platform of Switzerland.

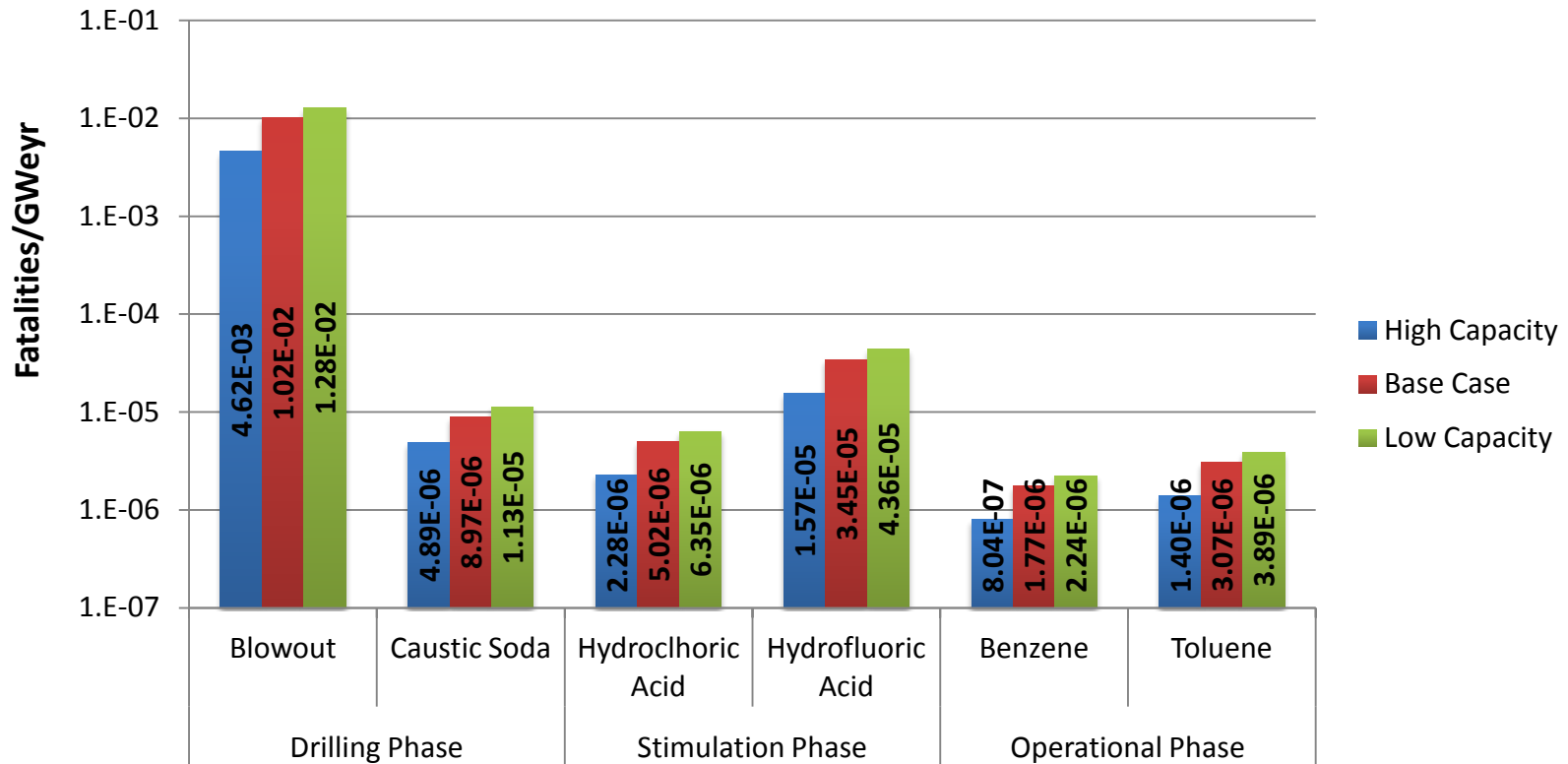
5. References
Frutiger, A., D. Giardini (2010), Historical events, earthquakes and the hazard of landslides in Switzerland. International Risk Engineering Conference (IERC), London, Switzerland, 2010.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.
Mignan, A., N. Komenkova, A. Scolobig, C. Furrer (in press), Multi-risk assessment and governance: a framework for hazard interaction and management. Chapter 10, in: "Complexity in Risk: Managing to achieve resilience", Springer (Ed.), International Risk Engineering Conference (IERC), 2014, pp. 103-118.

Risk Assessment of Hydropower in Switzerland with focus on dams (PSI)

- PhD at PSI co-supervised between the Technology Assessment group at the Paul Scherrer Institut (PSI) and Prof. Bruno Sudret from the Chair of Risk, Safety and Uncertainty Quantification at ETHZ.
- The PhD project investigates accident risks of hydropower dams using an integrated approach that considers available historical experience and models selected dam failure scenarios and their potential consequences
- **The main focus** of the research is the quantification of the uncertainties in the modeling of dam break consequences

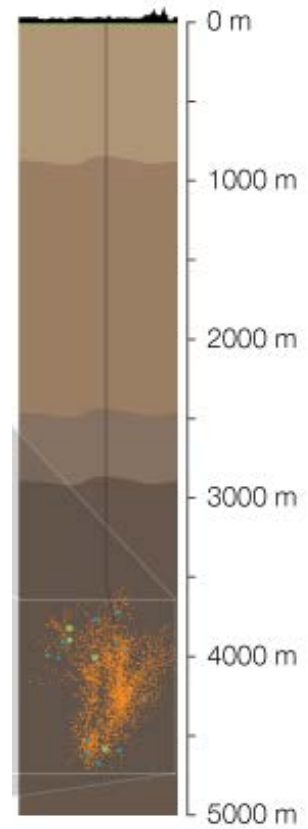
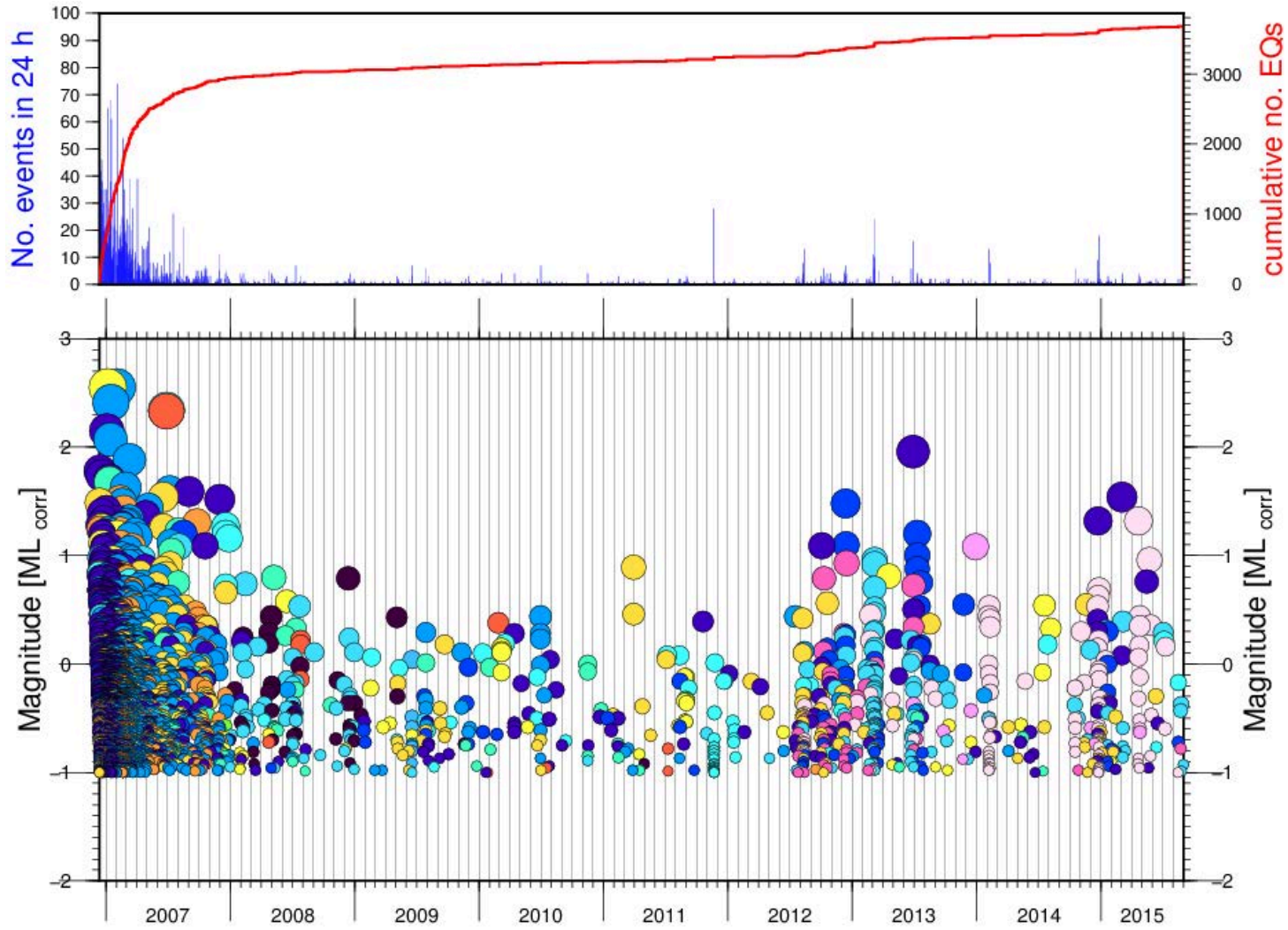


Accident Risk for Deep Geothermal Energy Systems (PSI)



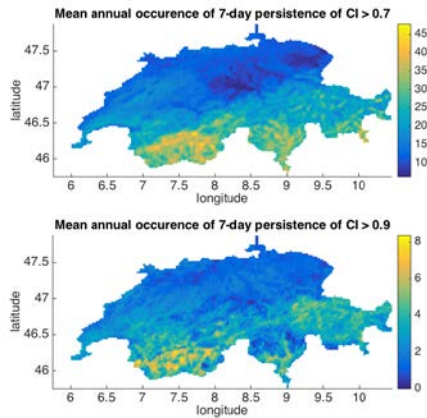
- Risk indicators for three geothermal plant capacity cases for Switzerland based on the same assumptions used in Life Cycle Assessment and Cost Assessment.
- Fatality rates are estimated as the ratio between the aggregated number of fatalities in the period 1990-2013 and the unit of energy production weighted by a factor dependent on, for example, number of wells, for each substance and blowout.

Earthquake Template matching: 10-100 times more information (ETH/SED)

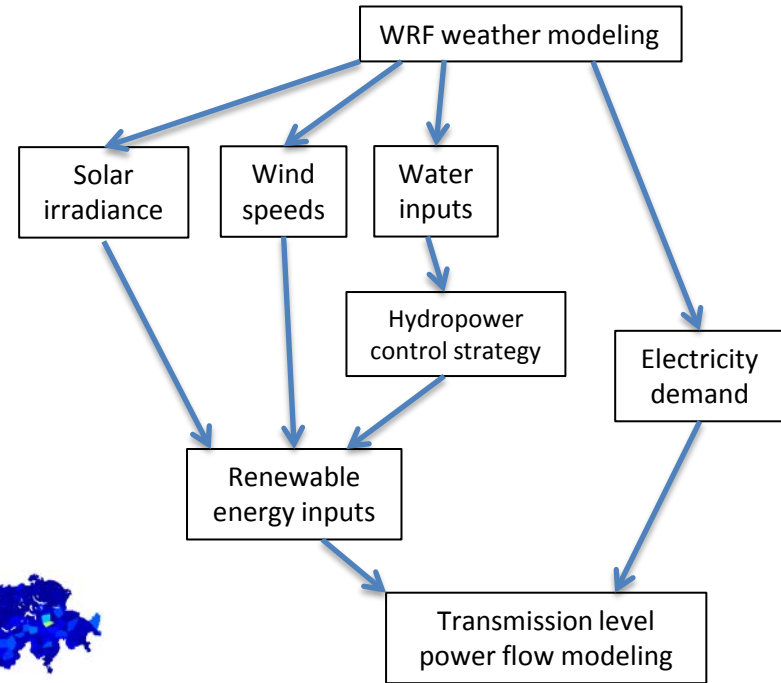


Swiss Renewable Energy Risk Analysis and Optimization (EPFL)

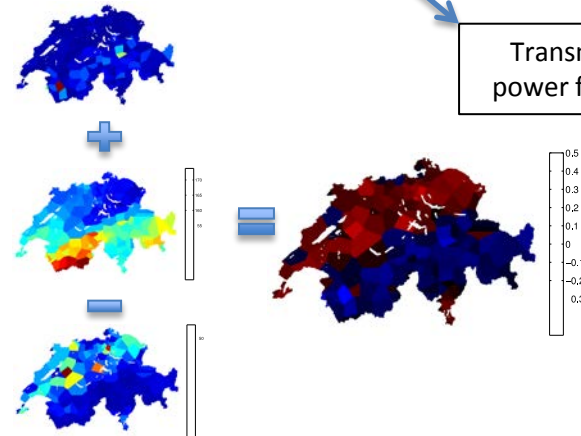
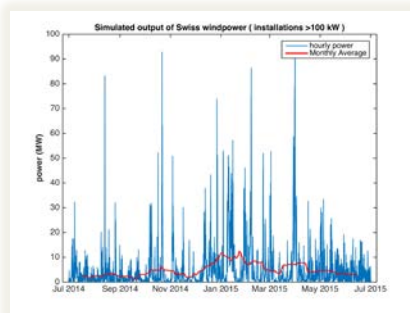
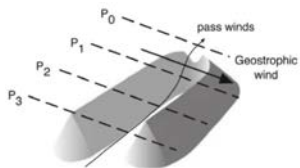
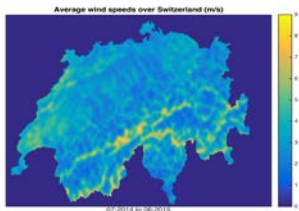
Extreme value statistics of Swiss Solar energy resource



Extreme event analysis and optimisation of a fully renewable Swiss power system



Risks and Opportunities for Wind Energy in the Swiss Alps



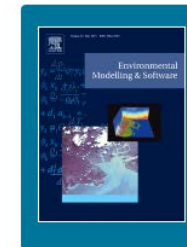
Ambizione Energy project by E.TrutnevYTE



Risk GOveRnance of electricity pOrtfolioS (RIGOROuS): Cross-technology and spatial tradeoffs of multiple risks

Aims:

- Examine cross-technology and spatial **risk tradeoffs** **in the whole Swiss electricity portfolio** (not only individual technologies)
- Adopt a more open view to risk, including uncertain outcomes, likelihoods, and uneven knowledge robustness
- Build two interactive tools RISKMETERS by linking electricity portfolio model with the risk information
- Measure expert, stakeholder, and public preferences concerning these risk tradeoffs



Environmental Modelling & Software

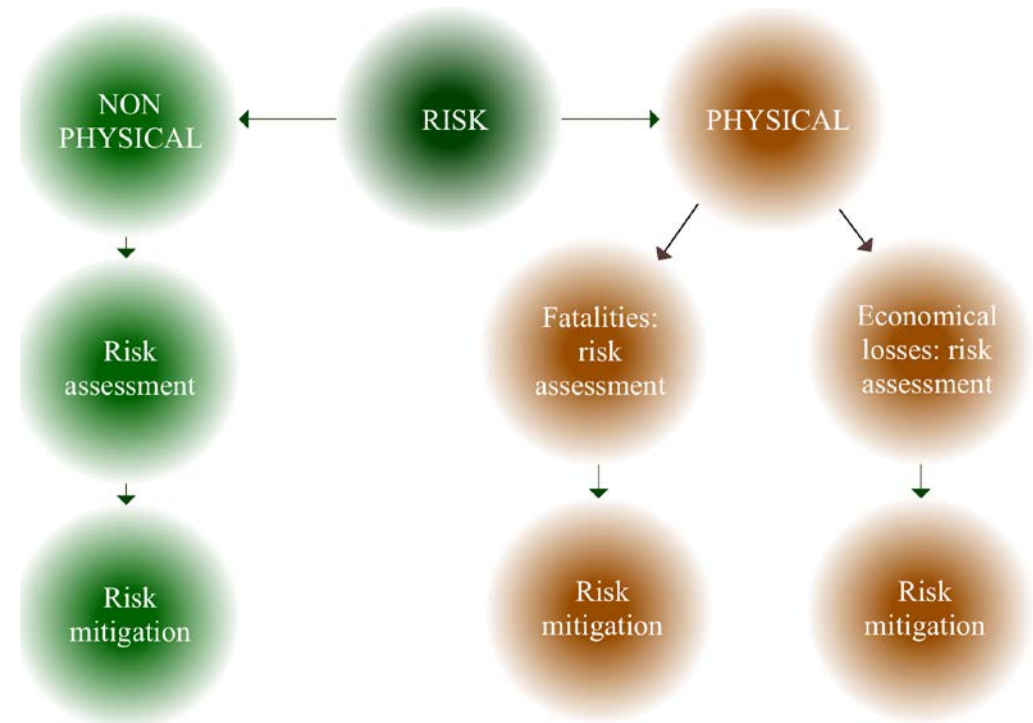
Special Issue on uncertainty modeling and visualization, interactive techniques



Exposure and risk assessment Swiss building stock for low intensity vibrations (ETHZ/BAUG)



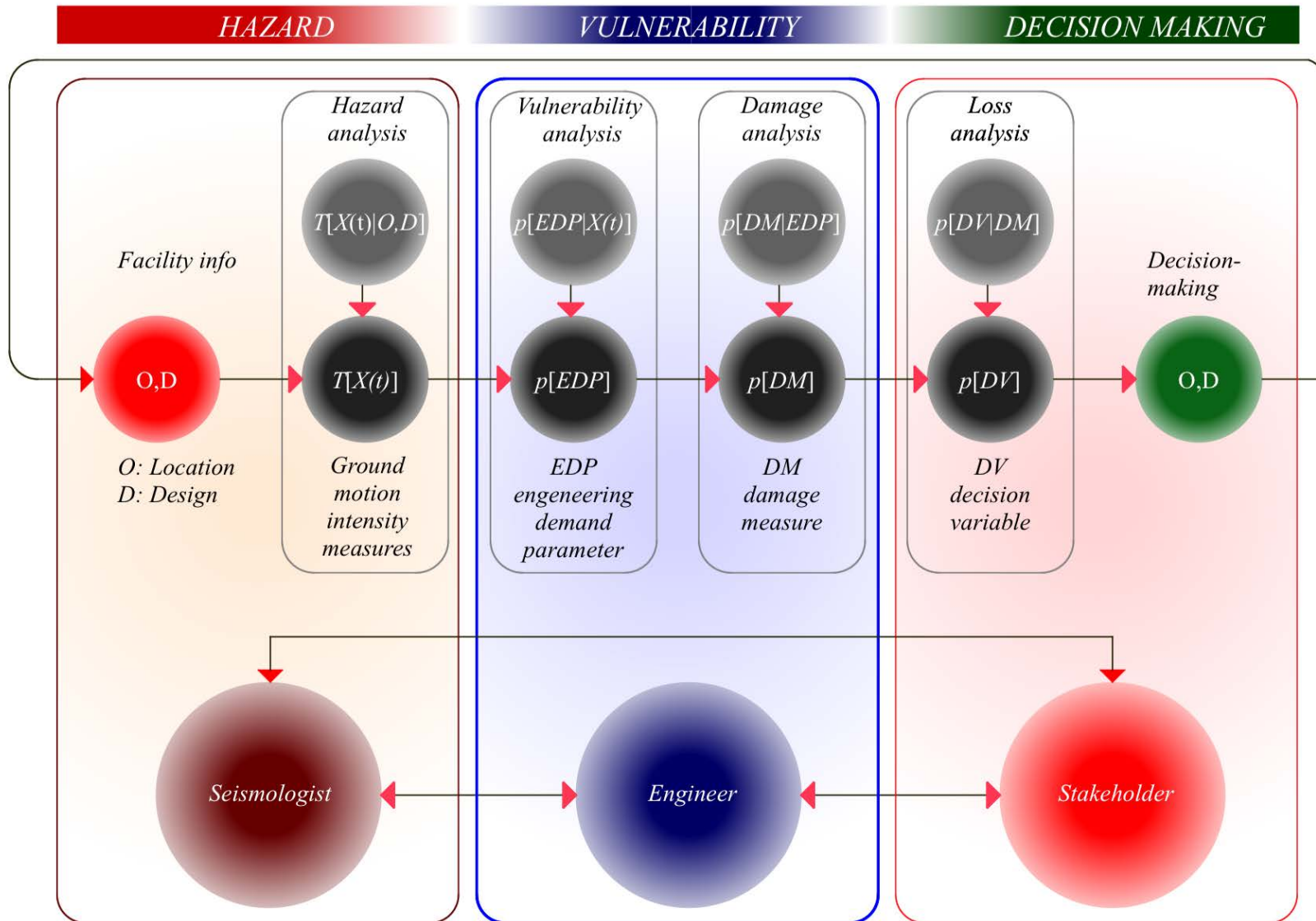
Risk classification



Challenges for the vulnerability model

- Which approach? Risk assessment and/or risk mitigation
- Which risk metrics to use for:
 - Fatalities
 - Monetary loss
 - Iconic loss, etc.
- Fragility function computed for macro seismicity not suitable for low intensity event
- Tail sensitivity of fragility functions
- Scale effect and spatial correlation
- Pure data driven models

Exposure and risk assessment Swiss building stock for low intensity vibrations (ETHZ/BAUG)

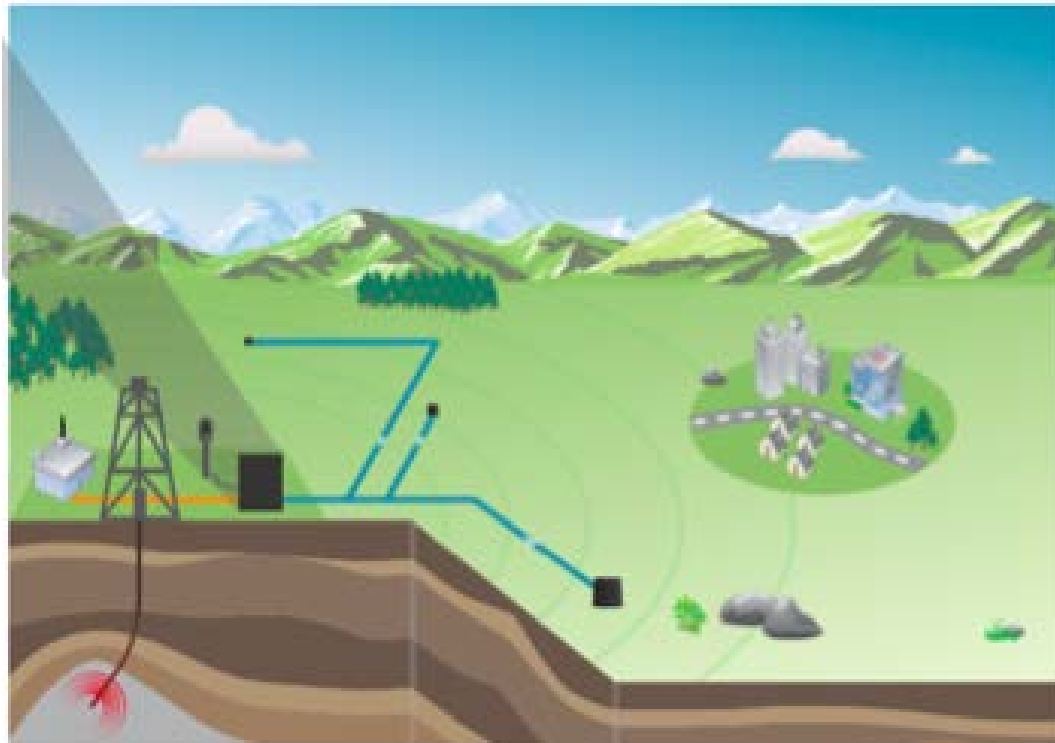


Framework, PEER formula

Hazard, risk, mitigation and society



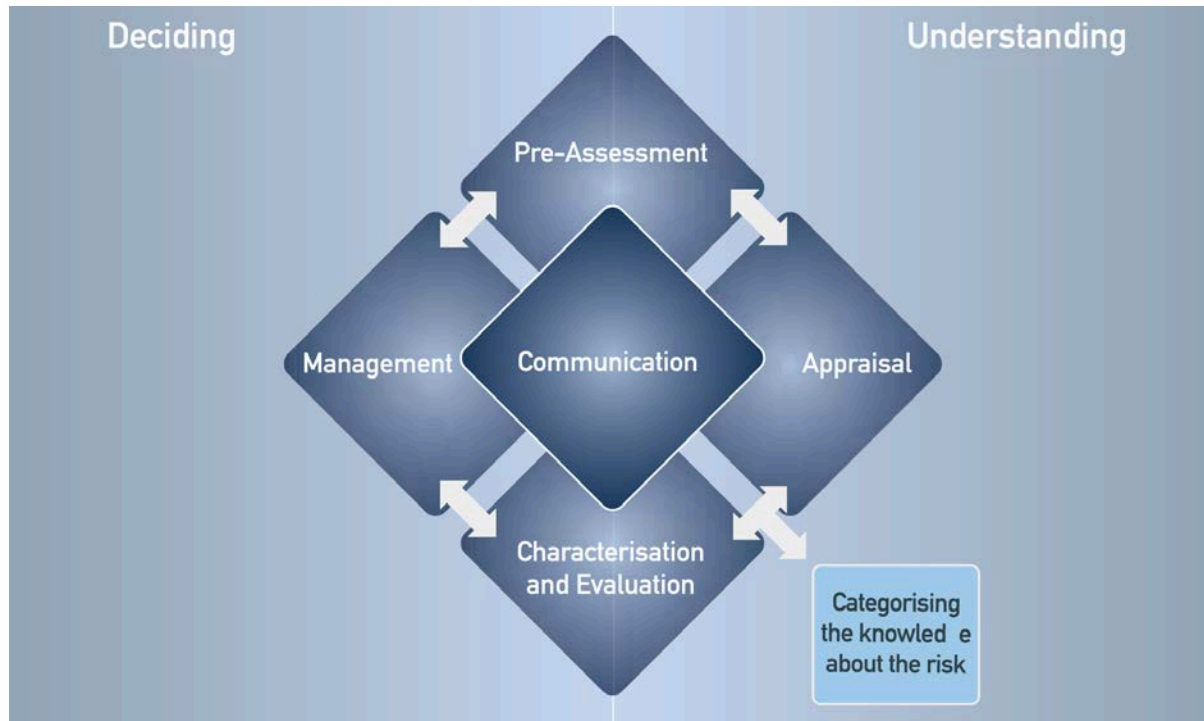
Society



Risk
(exposure & vulnerability)

Hazard

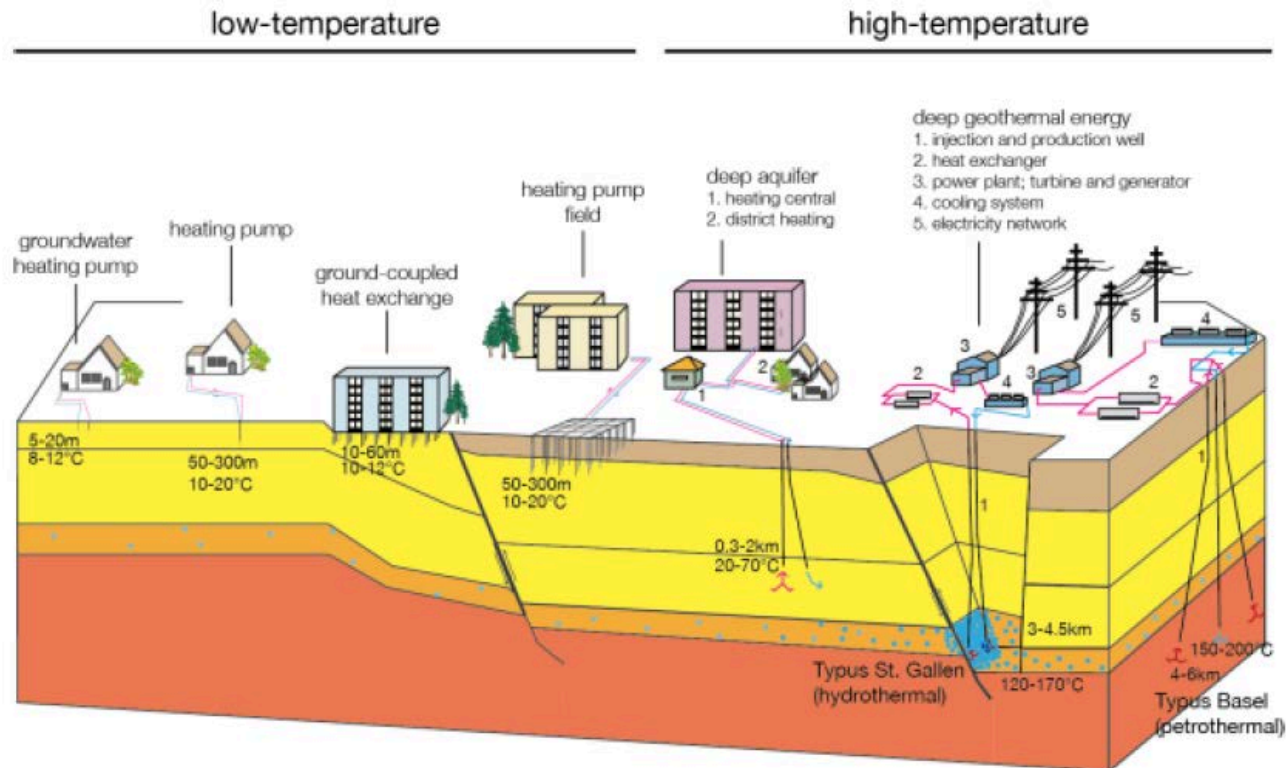
Adopting the General framework of the International Risk Governance Council for Geothermal Projects



➔ How should it be translated and tailored to induced seismicity risk governance?

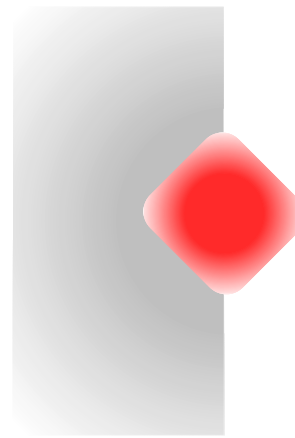
Categorizing Risk Profiles

- The (seismic) risk profiles of a deep heat pump, a hydrothermal project, a EGS, in an rural or urban environment etc. varies greatly.
- **Risk Governance workflows** must adopt, one size does not fit all.



GRID score

(Geothermal Risk of Induced seismicity Diagnosis)



Hazard concern

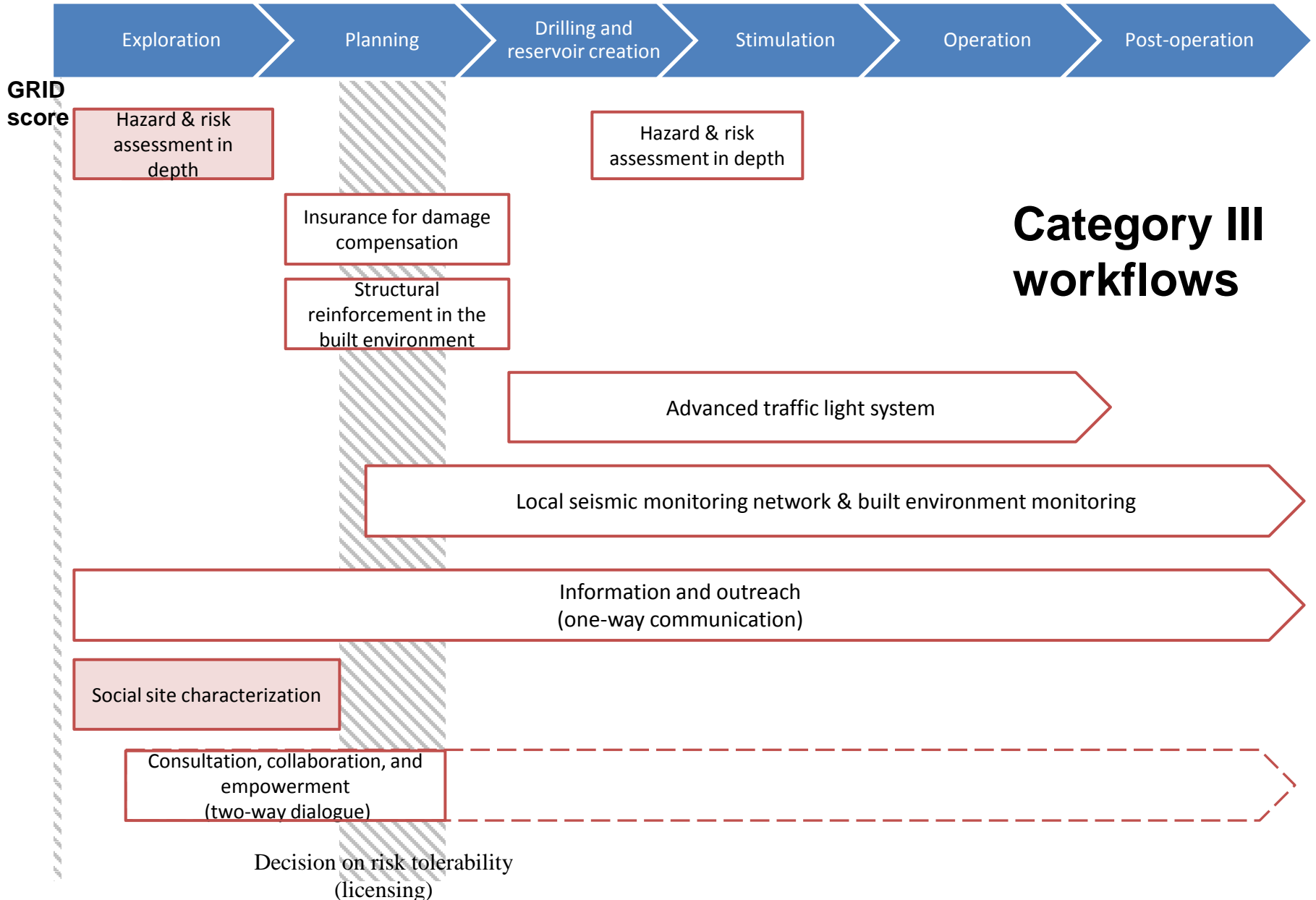
Social concern

$$GRID\ score = \frac{\sum_{i=1}^{11} a_i^{hazard}}{22} + \frac{\sum_{j=1}^5 a_j^{risk}}{10} + \frac{\sum_{k=1}^5 a_k^{social}}{10};$$

Risk concern

- Category 0** if GRID <33%
- Category I** if GRID 33-50%:
- Category II** if GRID 50-66%
- Category III** if GRID >66%





Category III workflows



GRID score

Hazard assessment

Updated hazard assessment

Insurance

Category I workflows

Voluntary magnitude-based traffic light system

Voluntary single station seismic monitoring

Information and outreach (one-way communication)

Voluntary social site characterization

Voluntary consultation, collaboration, and empowerment (two-way dialogue)

Decision on risk tolerability (licensing)

Advanced traffic light system: Workflow

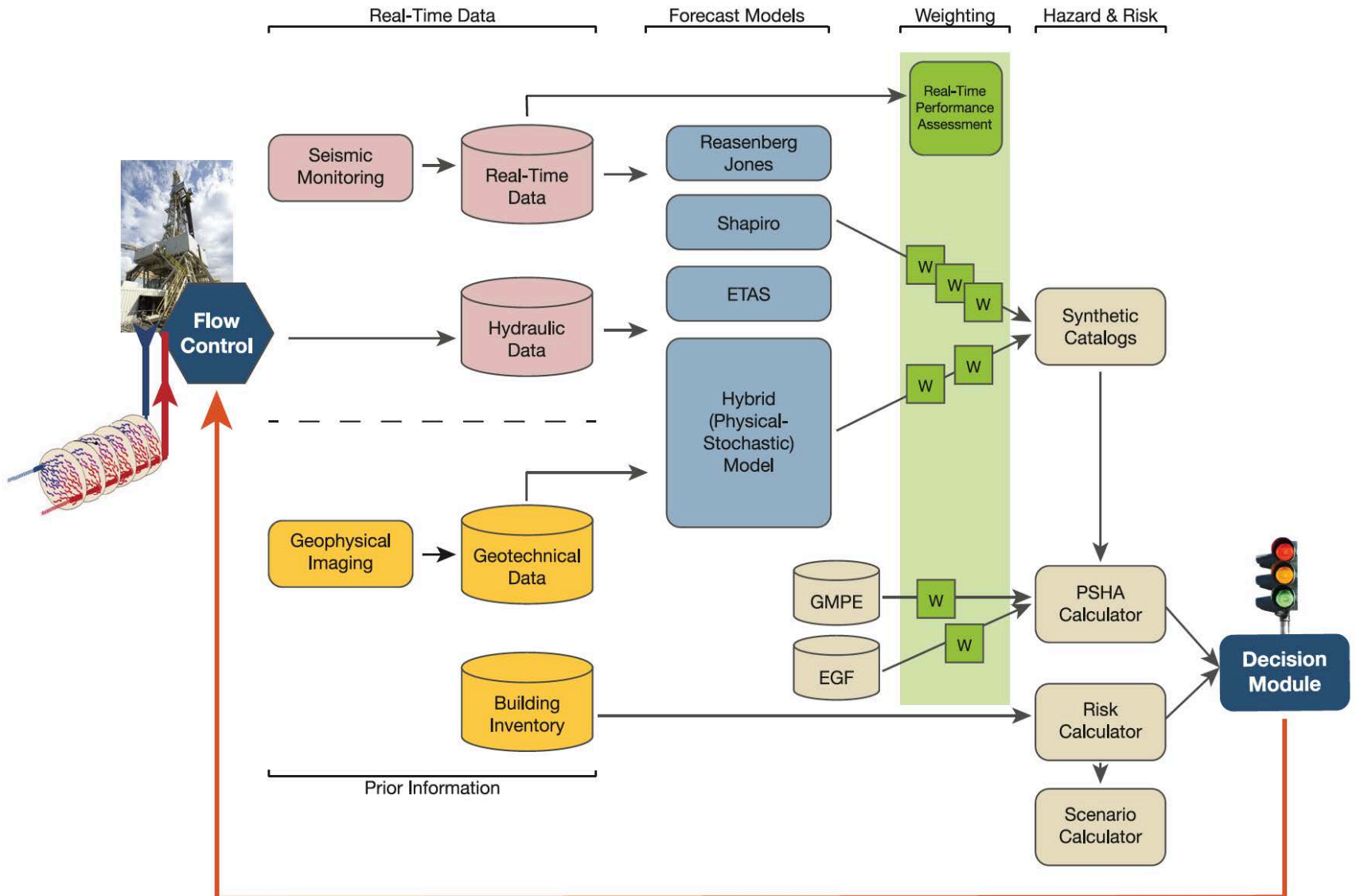


Figure: TA Swiss 2014

SED/SCCER Modellig Efforts



Model Complexity 

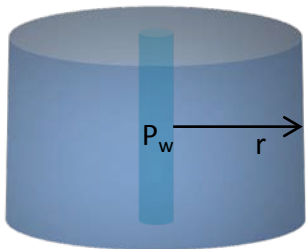
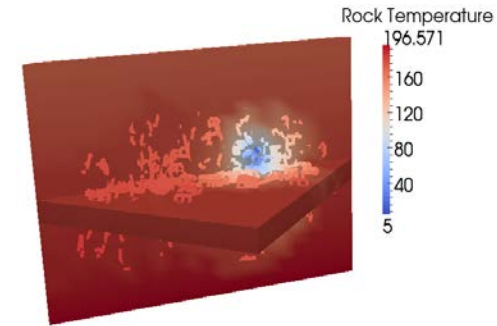
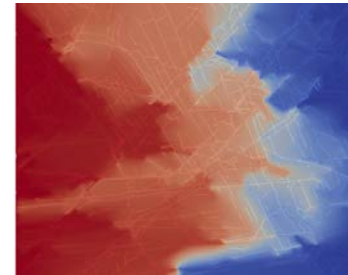
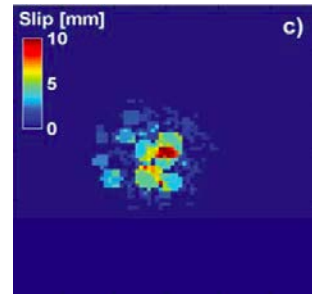
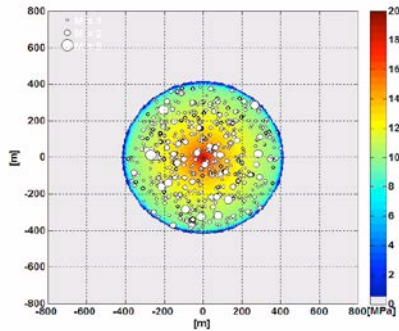
2012

2013a

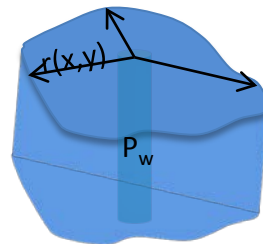
2013b

2014a

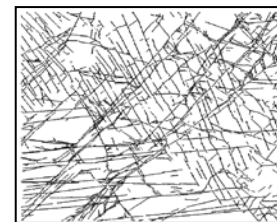
...



COMSOL



SUTRA



HFR-Sim



HFR-Sim+

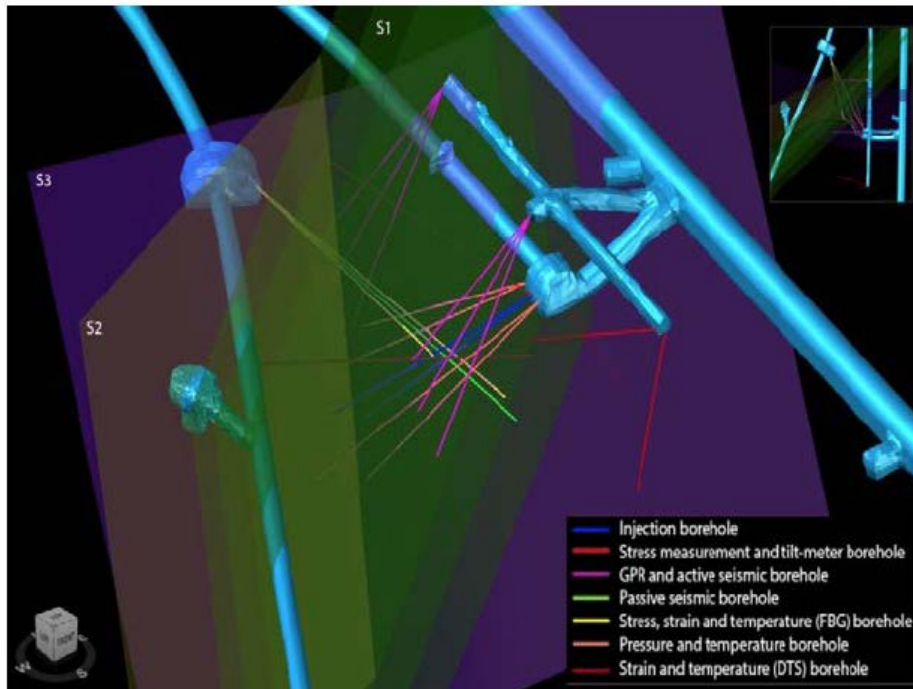
Gischig & Wiemer, 2013
Goertz-Allmann & Wiemer, 2013

Gischig et al, 2014

Karvounis et al., 2013

Karvounis and Wiemer, 2015

Lab Scale: Model development, calibration and validation



Amann, 2015

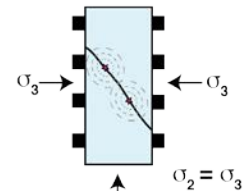
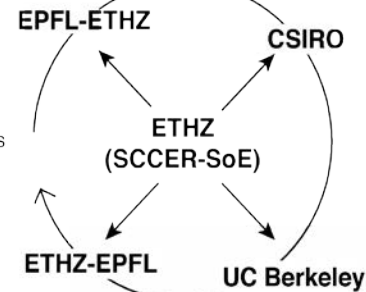
WP1: Poroelasticity

- micro-CT
- Poroelasticity
- Elastic constants
- Attenuation
- Permeability
- Dynamic triggering
- Micro structures analysis



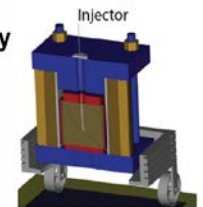
WP2: Fault slip reactivation:

- Spatial anomalies in AE
- Hydraulic fracture initiation
- b-values spatial distribution
- Micro structures analysis σ_1
- micro-CT



WP3: Failure mode on true triaxial stress state

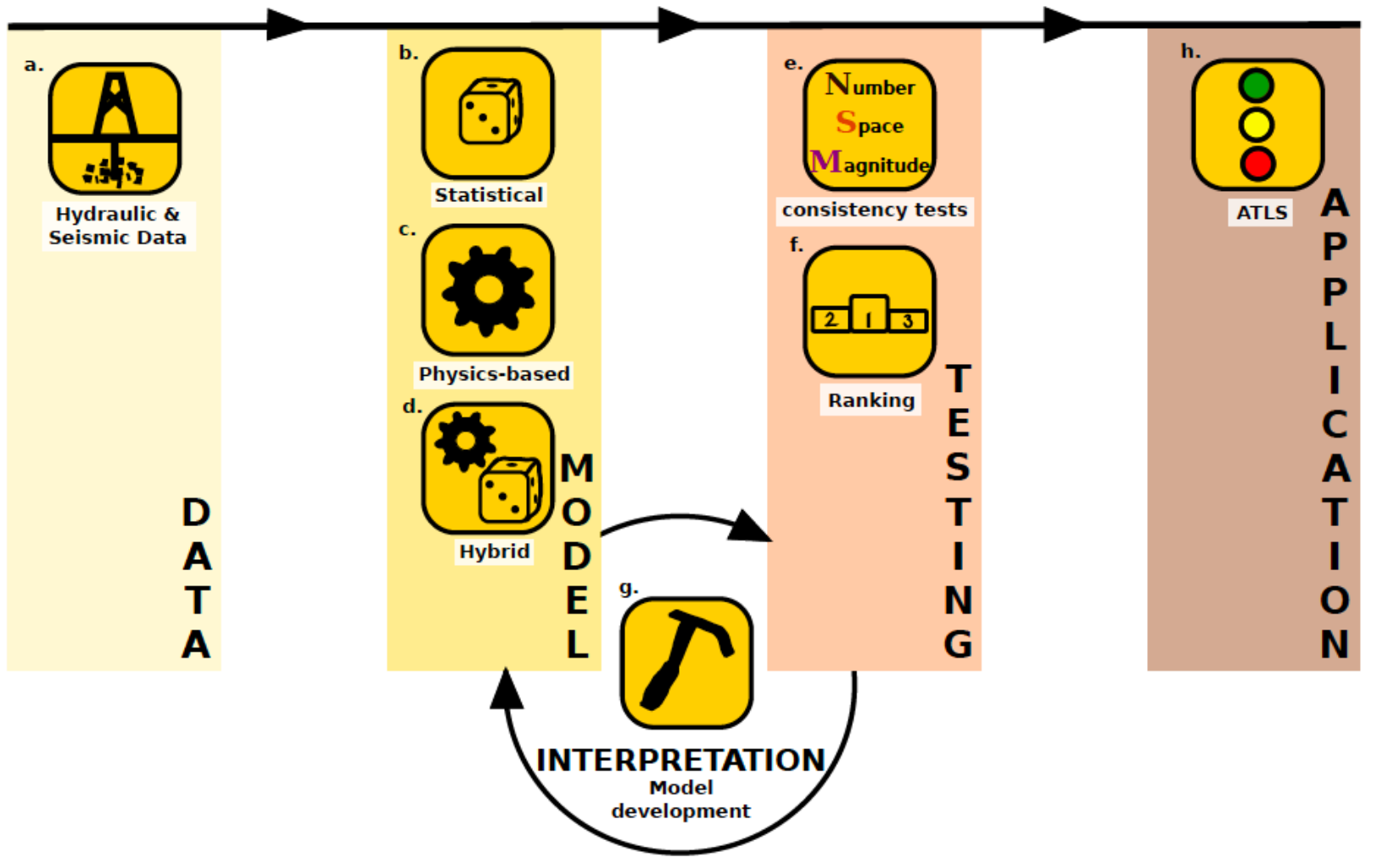
- Failure mode considering σ_2
- Hydraulic fracture initiation
- Thermal strain
- Micro structures analysis
- b-values spatial distribution



$$\sigma_1 > \sigma_2 > \sigma_3$$

Madonna, 2015

INDUCED SEISMICITY MODELING TEST BENCH



Project Haute-Sorne as a test case

The project at a glance:

- est. power: 5 MW_{el}
- type: EGS (enhanced geothermal)
- plant type: ORC (Organic Rankine Cycle)
- source rock: crystalline
- depth range: 3.5km-5km
- estim. temperature: ~150°C - 180°C
- Stimulation method: multi-stage hydro-shearing

Safety and mitigation measures:

- risk studies (continuously updated)
 - ✓ naturally occurring seismicity
 - ✓ deterministic study
 - ✓ probabilistic study
 - ✓ logic tree risk analysis (link-up study)
- stimulation test
- traffic light system
- advanced (forecasting) traffic light system
- micro-seismic monitoring
- conservation of evidence (e.g. fissure protocols)

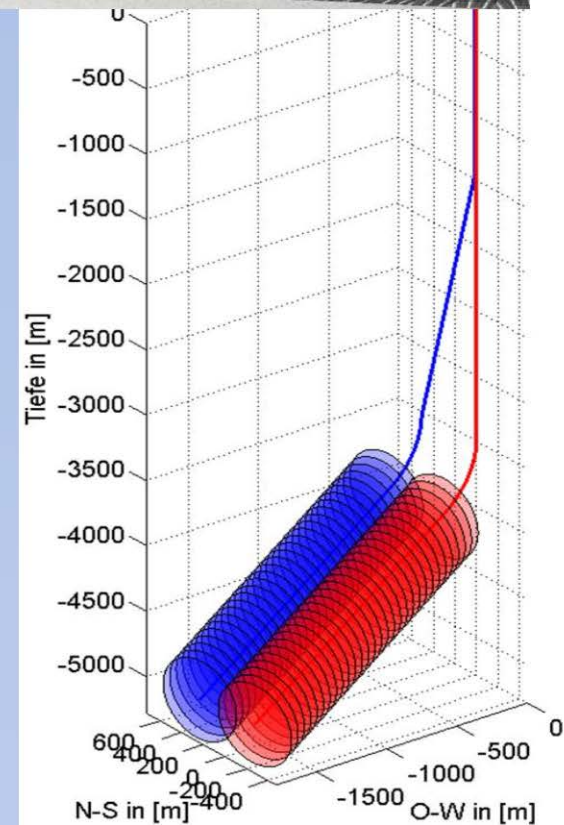


Figure 1: schematic view of the power plant and heat exchanger (not to scale)

Thank you!



Hazard score

	0 (no concern)	1 (medium concern)	2 (high concern)
Depth	< 1 km	1 - 3 km	> 3 km
Injection volume during stimulation	<1'000m ³	1'000-10'000m ³	>10'000m ³
Injection volume during operation	<1'000m ³ /day	1'000-10'000m ³ /day	>10'000m ³ /day
Extraction volume during operation	<10'000m ³ /day	10'000-100'000m ³ /day	>100'000m ³ /day
Rock type	sediments	near crystalline basement	crystalline
Separation between background and induced seismicity	low activity	medium activity	high activity
Pore pressure perturbation	<0.1MPa	0.1-1MPa	>1MPa
Distance to critically pre-stressed extended fault	>5 km	2 - 5 km	<2km
Differential stress	litostatic	medium stress	high stress
Local soil amplification	predominately hard rock	mix	predominately soft rock
Susceptibility to secondary hazards (rock falls etc.)	none	does exist	high

Risk score (exposure and vulnerability)

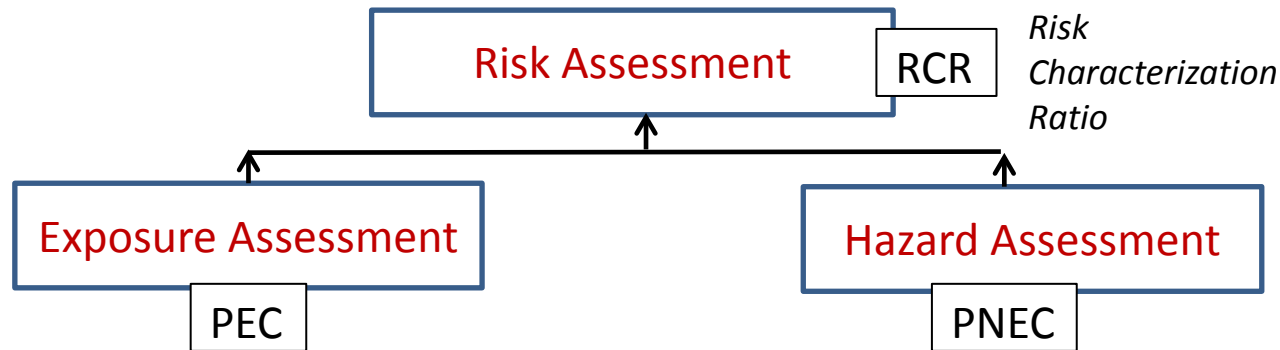
	0 (no concern)	1 (medium concern)	2 (high concern)
Population density	remote	rural	urban
Industrial or commercial activity	none or small	does exist	high
Buildings with structural damage potential	none	does exist	high
Critical infrastructures	none	does exist	high
Sensitive cultural heritage	none	does exist	high

Social concern score

	0 (no concern)	1 (medium concern)	2 (high concern)
High public concern potential	none	does exist	high
Highly vulnerable or opposing stakeholders	none	does exist	high
Previous negative experiences	none	does exist	high
Lack of trust in the project developers or authorities	none	does exist	high
Benefits to the local community	direct benefits	compensation only	none

Accident Risk for Deep Geothermal Energy Systems – Work in Progress

Environmental and Human Health Risk Assessment on the use of Chemicals in Deep Geothermal Energy systems



- **Collect information** for all the **chemicals** used in geothermal systems in drilling, stimulation and operational phase, including information about quantity (if possible).
- Assess the most **commonly used chemicals** in the different phases in geothermal energy systems.
- **Environmental and human health risk assessment** following the standardized **European Registration, Evaluation, Authorization and Restriction of Chemicals (REACH)** methodology:
 - Collection of the **Predicted No Effect Concentrations (PNEC)** values for the chemicals under interest based on a literature survey;
 - Definition of the **Predicted Environmental Concentrations (PEC)** based on possible accidents scenarios;
 - Estimation of the risk based on the comparison between the PEC and PNEC.