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Risk Assessment of Hydropower in Switzerland with focus on dams

Energy Turnaround
National Research Programme NRP 70

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Introduction

This 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. It is funded by the National Research Program "Energy Turnaround" (NRP 70) within the project "Supply of electricity for 2050: hydropower and geo-energies", and is closely linked to PSI's activities in Task 4.1 on "Risks, Safety and Societal Acceptance" of SCCER SoE. The supervision of this PhD is shared 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 the Swiss Federal Institute of Technology in Zurich (ETHZ).

Methodological approach

The main focus of the research is the quantification of the numerous uncertainties in the modeling of dam break consequences.
The PhD project will be **completed in three distinct phases**:

Phase 1: Historical dam failures

- Update of hydropower accidents in PSI's Energy-related Severe Accident Database (ENSAD)
- Probabilistic analysis of historical data

Phase 2: Scenario modeling

- Modelling of dam-break flood
- Modelling of dam-break consequences

Phase 3: Uncertainty and sensitivity analysis

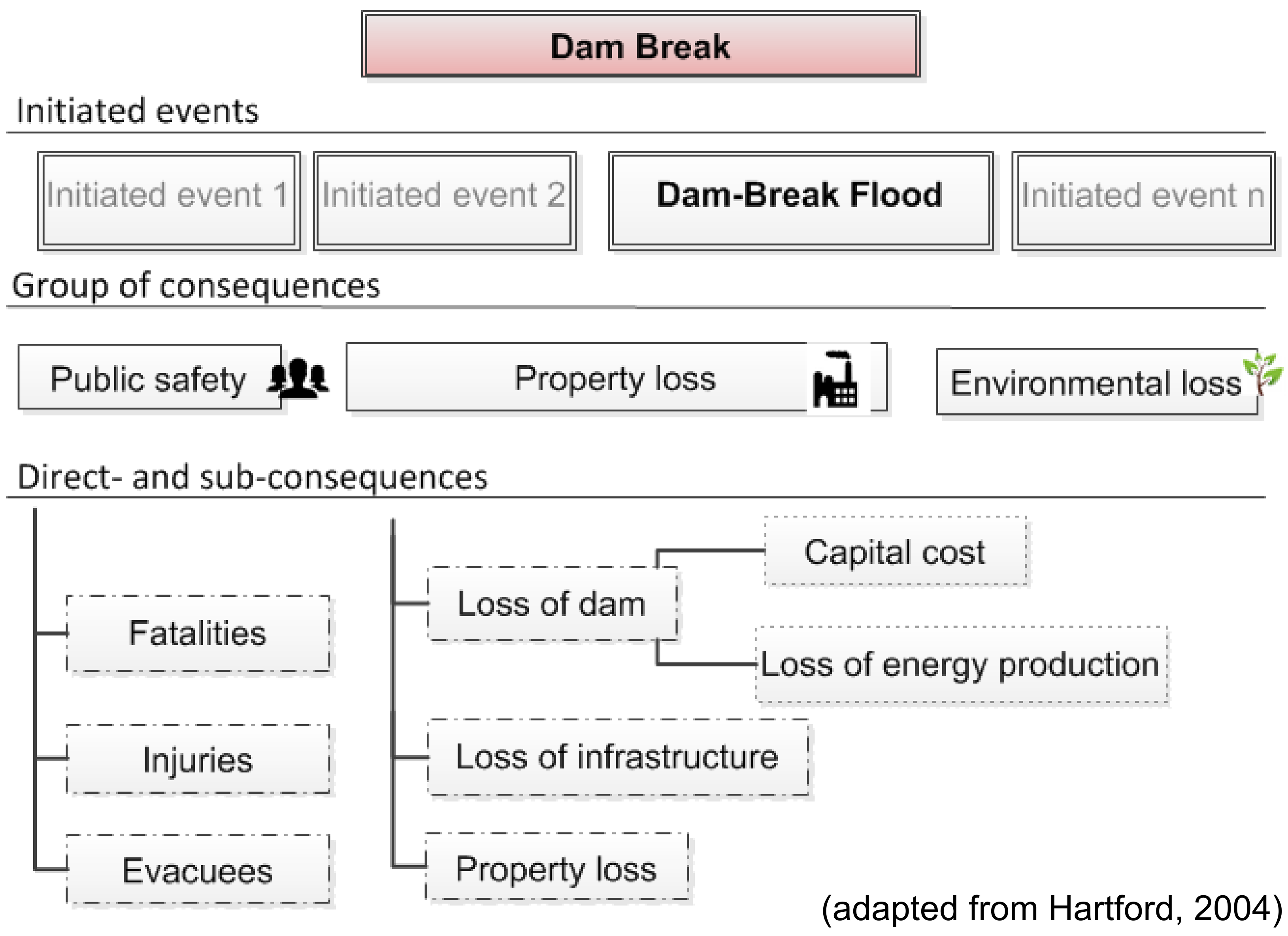
- Modelling of uncertainties and sensitivities for dam-break consequences
- Swiss case study

Phase 1 – Historical dam failures

Within PSI's framework for comparative risk assessment, the empirical analysis of dam accidents was already included when ENSAD was first released (Hirschberg et al., 1998). Although several incremental updates were carried out since then (Burgherr et al., 2013), the current study aims to provide a comprehensive update and extension both in terms of available historical experience and advanced statistical methods for the actual data analysis. The aim of this first phase is threefold: First, it will ensure that comparisons of accident risks across technologies are based on most up-to-date ENSAD data. Second, the results and insights will directly feed into the dam-break scenario selection and analysis of phase 2. Third, these generic results will be helpful to design realistic case studies in phase 3.

Phase 2 – Scenario Modeling

A broad range of dam-break consequences will be considered in the study. Different states of completed scientific research regarding public safety, property and environmental losses due to dam break will allow their modelling at different level of details.

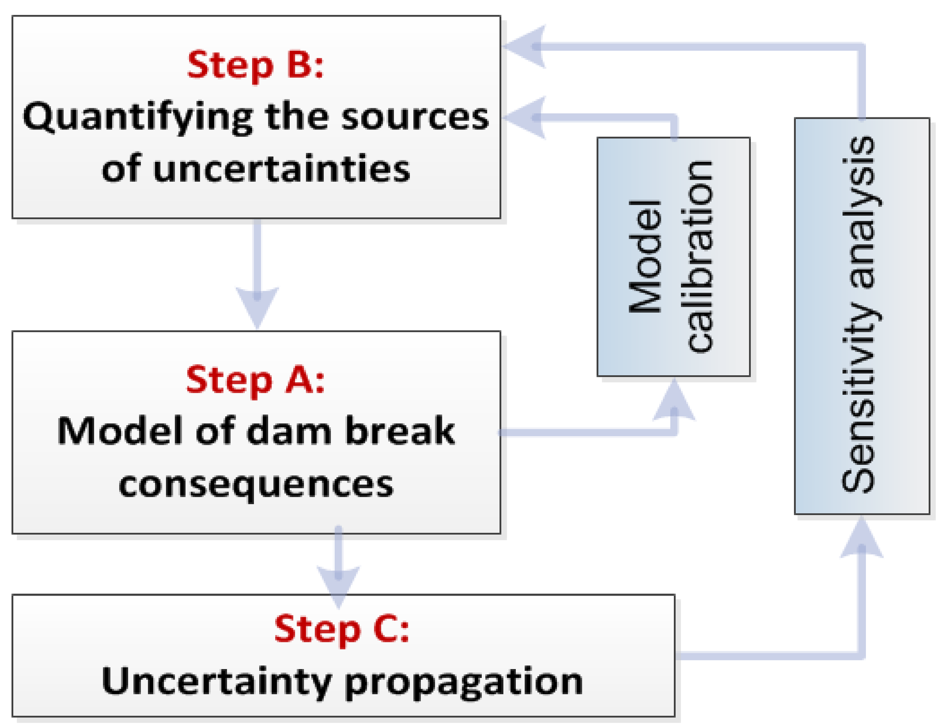


(adapted from Hartford, 2004)

The modelling of a dam-break flood (one of the main initiated events) will build upon earlier works by PSI (e.g. Hosein, 2011), with extension to other damage types than just loss of life.
This project aims to build a generalized framework that is applicable to a broad range of dam-break scenarios and topographies, and thus overcomes the limitations of previous analyses. The modelling framework will be developed, using BASEMENT v2.5.1 and GIS tools to provide results at high-spatial resolution.

Phase 3 – Uncertainty and sensitivity analysis

The uncertainty and sensitivity analysis of dam-break consequences will be developed within the universal framework of the Uncertainty Quantification Lab (UQLab; http://www.uqlab.org) that was established at the Chair of Risk, Safety and Uncertainty Quantification. This type of systematic and comprehensive treatment of uncertainties has not been used before in dam-break scenario modeling. The methodology developed will be applied to a specific Swiss case study.



(adapted from Sudret, 2007)

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Accident Risk Assessment for Deep Geothermal Energy Systems

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Introduction

Within SCCER SoE this work is part of PSI's contribution to Task 4.1 on "Risk, Safety and Societal Acceptance" of geoenergies and hydropower.

Deep geothermal energy systems are, like all energy technologies, not fully risk free. Although the risk of induced seismicity is frequently pointed out, geothermal systems present additional potentially risky aspects such as borehole blowout or chemical related incident. In this study, the different technological risks associated with deep geothermal energy systems are identified, characterized and quantitatively analyzed. Normalized risk indicators (e.g. fatality rate, injury rate) are used to compare risks of blowouts in the drilling phase, and the use of hazardous substances in drilling, stimulation and operational phases.

Overview and estimation of the potential risks of deep geothermal systems

Historical accidents related to the use of hazardous substances and blowouts, causing at least one consequence (e.g., 1 fatality, 1 injury, etc.), were collected for the time period 1990-2013 for countries belonging to the OECD. Only relevant accidents for geothermal systems were considered. In addition to PSI's Energy-related Severe Accident Database (ENSAD) several other databases were used in order to collect accidents related to the use of hazardous substances, i.e. ERNS, ARIA, HSE, MHAID and FACTS.

Hazardous Substance	Fatalities (Fat)	Injuries (Inj)	Evacuees (Eva)
	Acc/Fat	Acc/Inj	Acc/Eva
Caustic Soda	13/30	139/1146	30/14880
Hydrogen Chloride	1/3	87/659	104/14513
Hydrogen Fluoride	3/3	24/77	23/9843
Benzene	9/19	39/673	31/87027
Toluene	16/20	68/676	47/2036

Summary of the numbers of accidents and associated

Country	Fatalities	Injuries	Evacuees
	Acc/Fat	Acc/Inj	Acc/Eva
Alberta (Canada)	0/0	4/11	3/503
USA	4/10	8/12	9/6065

Summary of onshore blowout accidents in USA and Alberta since no specific historical experience for deep geothermal systems is available

Methodology

The table below summarizes the key physical parameters of the three capacity cases for deep geothermal plants that were considered in this study. These are the same cases that are used for Life Cycle Assessment and Cost Assessment in Task 4.2 "Global Observatory".

All risk indicators are normalized to the unit of energy production (i.e. Gigawatt-electric-year, GWeyr) using specific normalization factors for each substance and blowout.

	Medium capacity (Base case)	High capacity	Low capacity
Net plant power	1.45 MW_e	3.28 MW_e	1.18 MW_e
Production over the entire lifetime (P_{GWeyr})	2.99e-2 GWeyr	6.56e-2 GWeyr	2.36e-2 GWeyr
Well depth (WD)	5 km	5 km	5 km
Number of wells (NW)	2 (1 well doublet during total lifetime)	2 (1 well doublet during total lifetime	2 (1 well doublet during total lifetime)
Surface plant life time (LT)	20 yrs	20 yrs	20 yrs
Caustic Soda as additive in the drilling mud per Well (CS_{Well})	1 kg/m	1 kg/m	1 kg/m
Additives in Hydraulic Stimulation (total average) per Well (HS_{well})	HCl: 10722.90 kg HF: 2240.75 kg	HCl: 10722.90 kg HF: 2240.75 kg	HCl: 10722.90 kg HF: 2240.75 kg
Working Fluids used at the power plant at year 1 (WF_{Year1})	Benzene: 436 kg Toluene: 432 kg	Benzene: 436 kg Toluene: 432 kg	Benzene: 436 kg Toluene: 432 kg
Yearly losses of the working fluids (YLWF)	8%	8%	8%

Key physical parameters of the three capacity cases for deep geothermal plants considered in this study.

$$NF_{Caustic\ Soda} = \frac{CS_{Well} * WD * NW}{total\ production\ 1990-2013} * \frac{1}{P_{GWeyr}}$$

$$NF_{Stimulation} = \frac{HS_{Well} * NW}{total\ production\ 1990-2013} * \frac{1}{P_{GWeyr}}$$

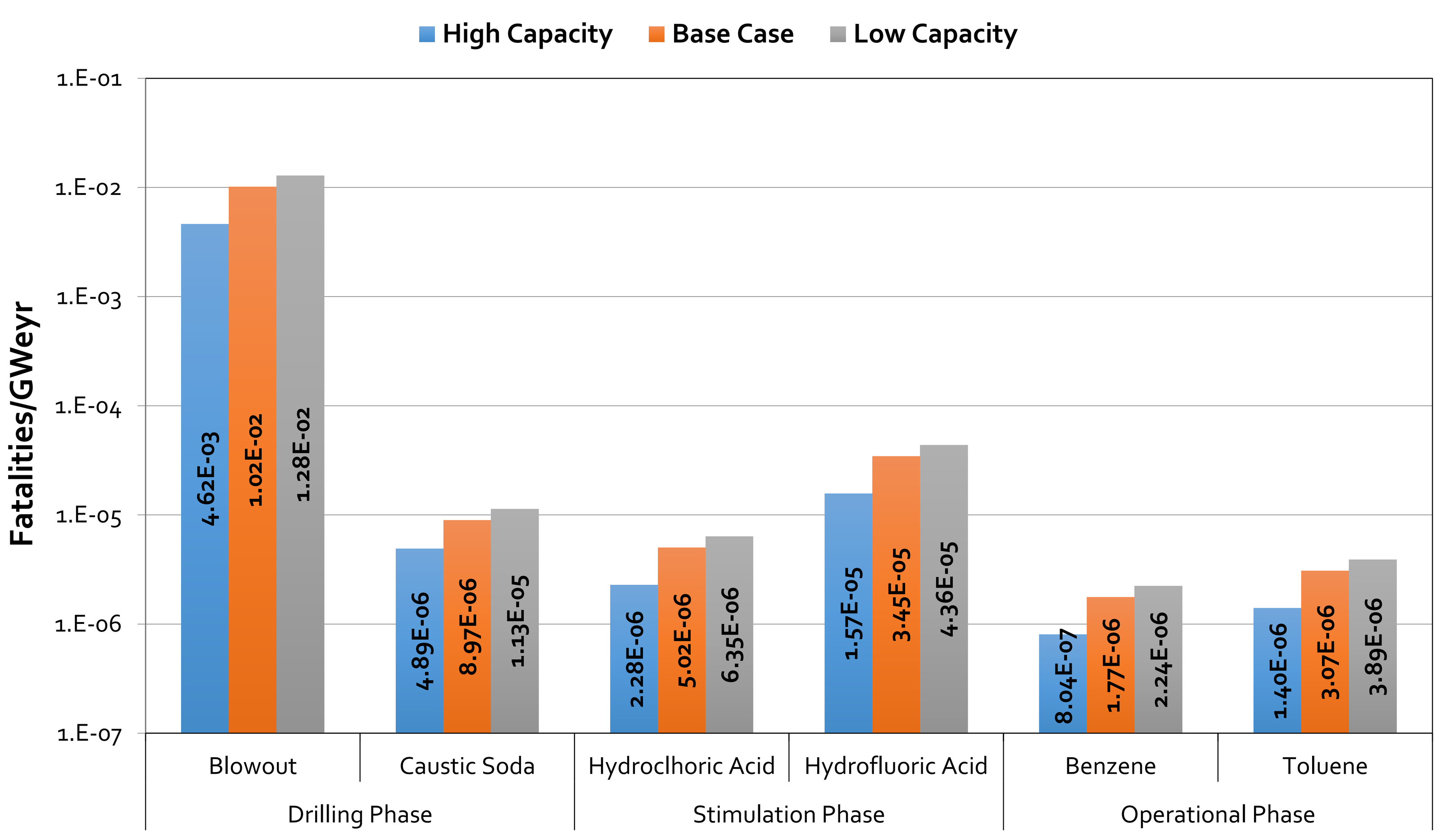
$$NF_{Working\ Fluid} = \frac{WF_{Year1} + (kg\ of\ substance\ refilled * LT)}{total\ production\ 1990-2013} * \frac{1}{P_{GWeyr}}$$

$NF_{Caustic\ Soda}$ is the normalization factor for Caustic soda; CS_{Well} is the amount of Caustic soda used per m of well; WD is the well depth; $NF_{Stimulation}$ is the normalization factor for Hydrochloric or Hydrofluoric Acid; HS_{Well} is the amount of Hydrochloric or Hydrofluoric Acid used per well; NW is the total number of drilled wells over the plant lifetime; $NF_{Working}$ Fluid is the normalization factor for Benzene or Toluene; WF_{Year1} is the amount of Benzene or Toluene used at the power plant at Year 1; LT is the lifetime of the plant; P_{GWeyr} is the net production over the entire lifetime per year of the plant:

$$NF_{Blowout} = \frac{NW}{total\ number\ of\ drilled\ wells\ 1990-2013} * \frac{1}{P_{GWeyr}}$$

$NF_{Blowout}$ is the normalization factor for Blowouts; NW is the total number of drilled wells over the plant lifetime; P_{GWeyr} is the net production over the entire lifetime per year of the plant.

Results: example of fatality rates



Fatality rate for the drilling, stimulation and operational phases analyzed in this study for OECD countries (1990-2013).

- Among hazardous substances, Hydrofluoric Acid exhibits the highest risks whatever the type of consequences (fatalities, injuries, evacuees)
- Blowout risk is largely higher than the most accident-prone hazardous substance, for all three consequences indicators (fatalities, injuries, evacuees)
- Deep geothermal system compares favorably to, for example, natural gas (7.19E-2 fatalities/Gweyr for OECD countries, according to Burgherr and Hirschberg, 2014).

Conclusions

- Results for hazardous substances in drilling, stimulation and operational phases point towards low risk levels in OECD countries, except for evacuees (particularly hydrofluoric and hydrochloric acids).
- Accident risk of blowouts is significantly higher than the risk related to the use of hazardous substances.
- Based on these results, the drilling phase in deep geothermal systems exhibits higher risks compared to the stimulation and the operational phase.
- Environmental impacts due to accidental releases of hazardous substances should not be neglected: toxicity and exposure levels as well as location-specific factors should come also into consideration.

Reference: Burgherr, P. & Hirschberg, S. (2014) Comparative risk assessment of severe accidents in the energy sector. *Energy Policy,* 74 (S1), S45-S56.

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The Static Behaviour of Induced Seismicity

A. Mignan

Abstract

The standard paradigm to describe seismicity induced by fluid injection is to apply nonlinear diffusion dynamics in a poroelastic medium. I show that the spatiotemporal behaviour of induced seismicity can, instead, be expressed by geometric operations on a static stress field generated by volume change at depth. I obtain laws similar in form to the ones derived from poroelasticity while requiring a lower description length (i.e., following the law of parsimony, static stress wins).

1. Introduction

Induced seismicity is a growing concern for the energy-sector industry relying on fluid injection in the deep parts of the Earth's crust (e.g., Mignan et al., 2015). At the same time, fluid injection sites provide natural laboratories to study the impact of increased fluid pressure on earthquake generation. Induced seismicity is characterised by two empirical laws, namely (*i*) a linear relationship between cumulated injected volume $V(t)$ and cumulative number of induced events $N(t)$ and (*ii*) an induced seismicity cloud envelope radius $r(t)$ of the parabolic form $V(t)^{1/n}$ with n a positive integer. These two descriptive laws can be derived from the differential equations of poroelasticity under various assumptions (Shapiro and Dinske, 2009). The full description of the process requires complex numeric modelling coupling fluid flow, heat transport and geomechanics. These models, numerically cumbersome, can be intractable because of the sheer number of parameters (Miller, 2015). Here I demonstrate that a simple static stress model can explain the main characteristics of induced seismicity without requiring any concept of poroelasticity, i.e., induced seismicity can be explained without involving fluid flow in a porous medium (even if fluid flow exists). Historically, a similar static stress model was proposed for the tectonic regime under the Non-Critical Precursory Accelerating Seismicity Theory (N-C PAST) (Mignan, 2012).

2. Non-Critical Precursory Accelerating Seismicity Theory

The N-C PAST has been proposed to explain the precursory seismicity patterns observed before large earthquakes from geometric operations in the spatiotemporal stress field generated by tectonic stress accumulation (**Fig. 1**) (Mignan, 2012). In particular, it provides an algebraic expression of temporal power-laws without requiring local interactions between the elements of the system. Therefore earthquakes are passive tracers of the stress accumulation process, in contrast with active cascading in a critical process (hence the term "non-critical") (Mignan, 2011).

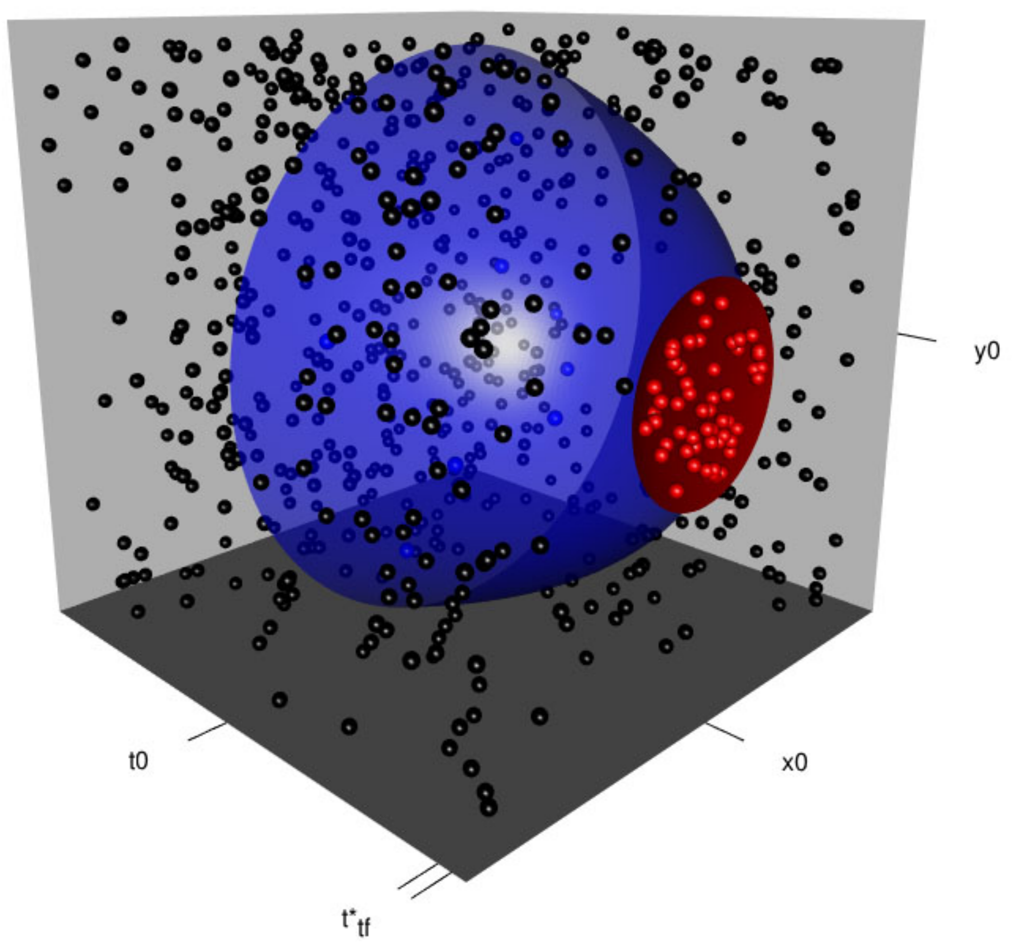

Fig. 1: N-C PAST illustration (Mignan, 2012). A tectonic mainshock occurs at (x_0, y_0, t_f) and is preceded by a quiescence phase on [t_0, t^*) and by an activation phase on [t^*, t_f).

Analogy with induced seismicity:

- ✓ activation = overloading = fluid injection
- ✓ quiescence = underloading = bleed-off

The N-C PAST postulates that earthquake activity can be categorised in 3 regimes: background, quiescence and activation depending on the tectonic loading stress field $\sigma(r,t)$. Event densities δ_{b0}, δ_{bm} and δ_{bp} then correspond respectively to $|\sigma| \leq \pm\Delta\sigma^*$, $\sigma < -\Delta\sigma^*$ and $\sigma > \Delta\sigma^*$ with $\Delta\sigma^*$ the background stress amplitude range.

3. Application to 2006 Basel Induced Seismicity Sequence

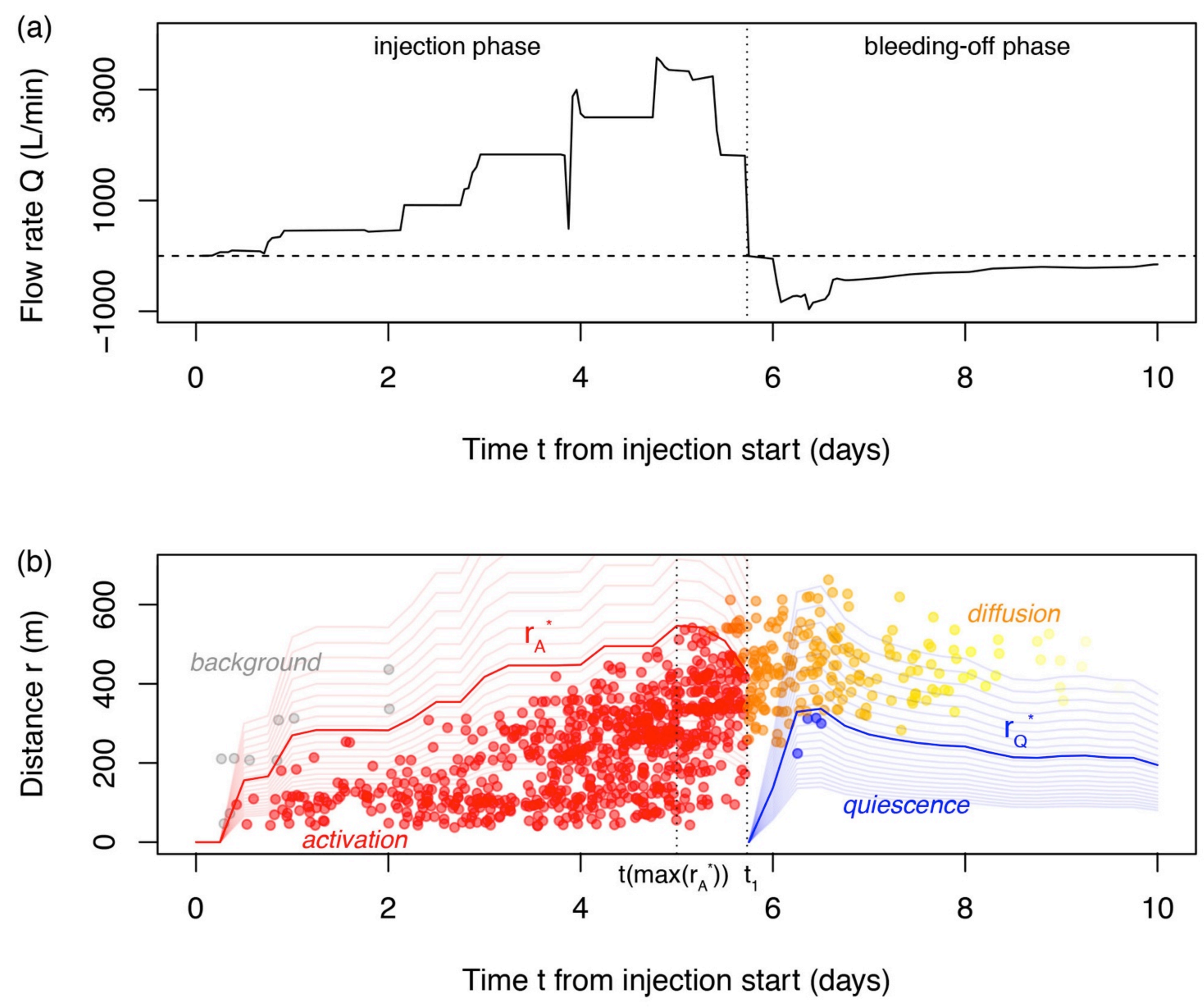

Fig. 2: An algebraic expression derived from the N-C PAST relates the induced seismicity cloud envelope $r^*(t)$ to the n-th root of the flow rate profile $Q(t)$ with n = 3 (static stress diffusion). $Q(t)$ from Häring et al. (2008); induced seismicity catalogue from Kraft and Deichmann (2014).

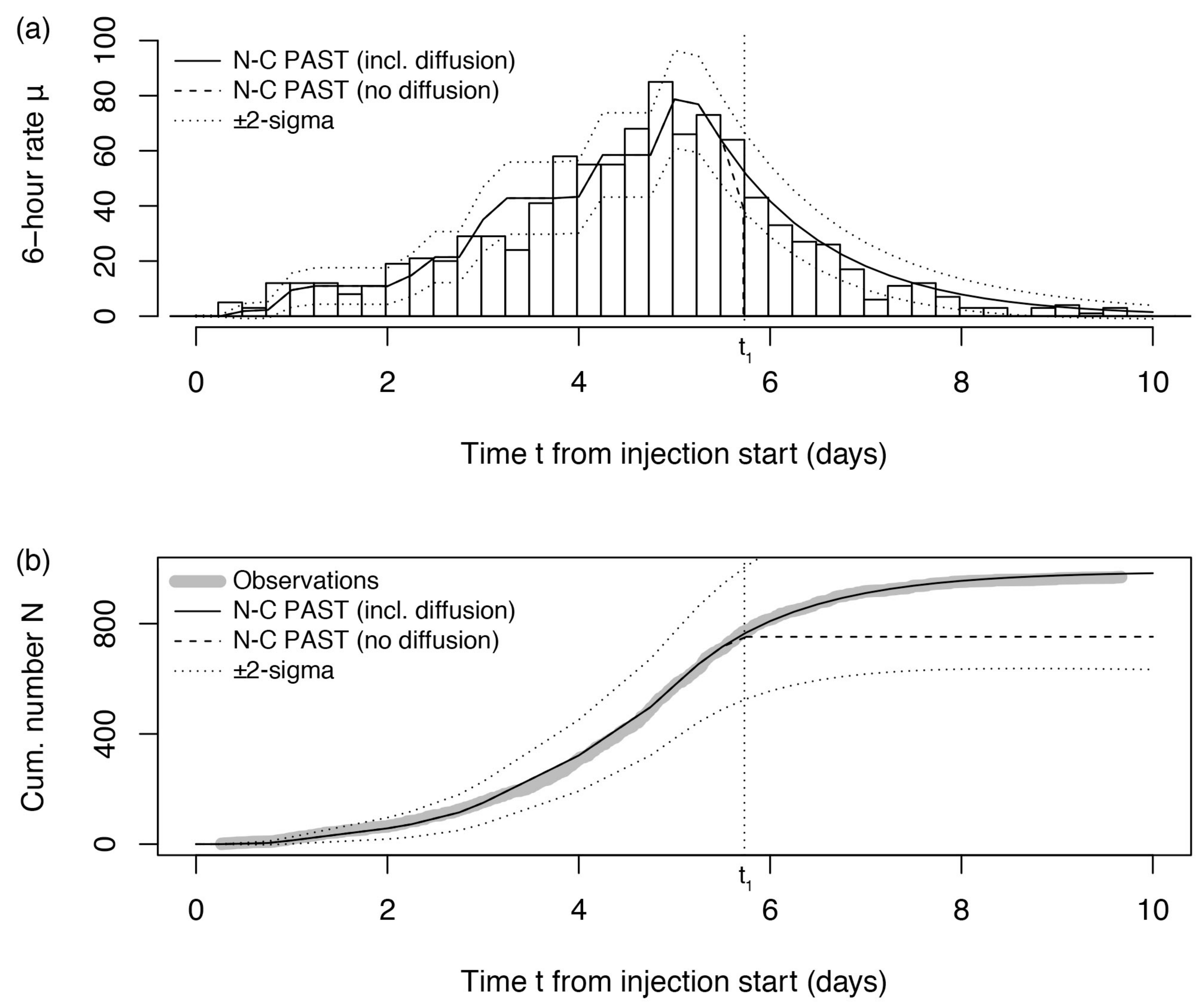

Fig. 3: Assuming a spherical volume of radius $r^*(t)$ and induced seismicity production δ_{bp}, the cumulative number of events $N(t)$ is shown to be proportional to the cumulative injected volume $V(t)^{d/n}$ where $d = n$ = 3 (with d the spatial dimension).

4. Conclusions

- ✓ Nonlinear poroelasticity (dynamic, numeric, numerous parameters and assumptions, cumbersome) is NOT necessary.
- ✓ Static stress (static, algebraic, two parameters $\Delta\sigma^*$ and δ_{bp}) well explains induced seismicity characteristics (**Figs. 2-3**).
- ✓ Due to its simplicity, can be used in real-time forecasting.
- ✓ Yields fundamental questions about the Earth's crust behaviour.

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Experimental investigation of induced seismicity in granitic rock on centimeter scale

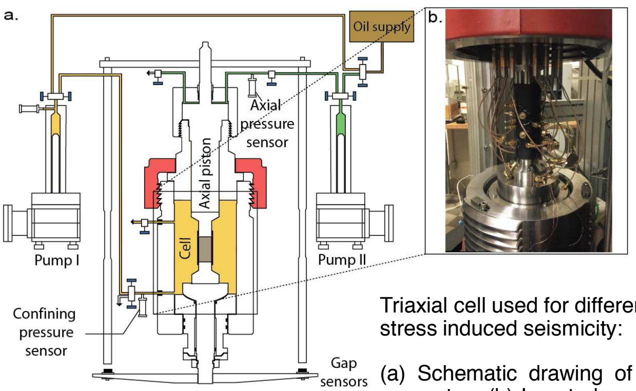
Linus Villiger, Dr. Claudio Madonna, Dr. Valentin Gischig, Prof. Dr. Stefan Wiemer

1. Introduction

Enhanced Geothermal Systems (EGS) foresee the exploitation of geothermal energy in deep, dry and impermeable formations of Earth's crust. For permeability creation fluids are intensively pressed into these deep formations and cause injection-induced seismicity. Occurring large magnitude seismic events can lead to nuisance and infrastructure damage. **The desire to better understand the physical processes causing large magnitude events so that they can be avoided or mitigated lead to this work.** Its focus lies on localization and associated analysis of differential stress-, resp. injection-induced seismic events on a laboratory scale. On one hand, granite samples were subjected to axial compression under confinement until shear failure occurred. Detected differential stress induced small scale seismic events, so called acoustic emissions (AE), were localized and made microcrack initiation, fault nucleation and fault propagation visible. Magnitude analysis of induced AE showed temporal b-value variation over the experiment. On the other hand, AE were detected during fluid injection into uniaxially loaded, cylindrical, granite samples until breakdown pressure was reached. Temporal b-values over one pressure cycle show a decrease with increasing injection pressure and are lowest at breakdown pressure.

2. Methods

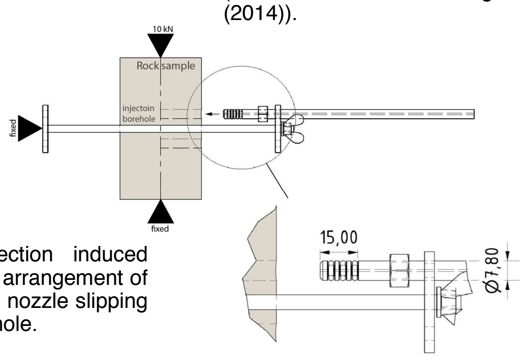
• Setup 1



Triaxial cell used for differential stress induced seismicity:

(a) Schematic drawing of the apparatus, (b) Inserted sample (modified after: Passelègue (2014)).

• Setup 2



Setup for injection induced seismicity: The arrangement of rods avoids the nozzle slipping out of the borehole.

• Velocity model

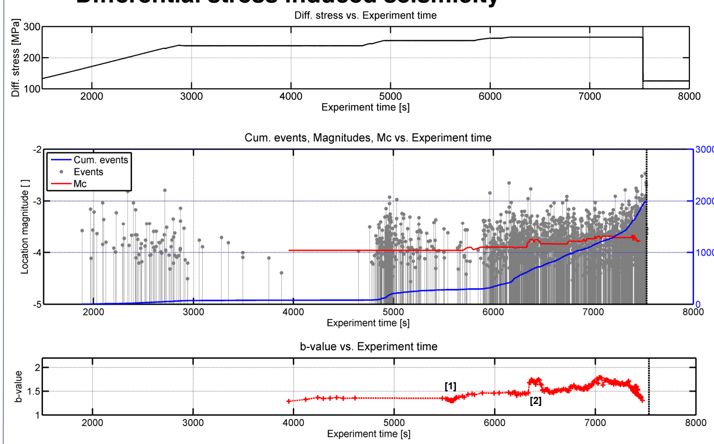
For localizing recorded AE a time-dependent transversely isentropic velocity model was employed. Velocities are assumed to vary in respect to the sample axis. $V_{||}, V_{\perp}$ represent velocities parallel and perpendicular to the cylinder axis, respectively. Velocities were obtained through surveys taken over the experiment.

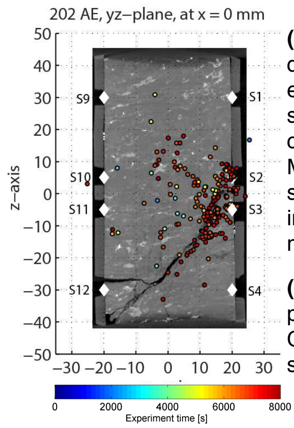
$$V_r = \left(\frac{V_{||} + V_{\perp}}{2}\right) - \left(\frac{V_{||} + V_{\perp}}{2}\right)\cos(\pi - 2\theta)$$

$$V_{\perp} = \alpha \cdot V_{||}$$

3. Results

• Differential stress induced seismicity

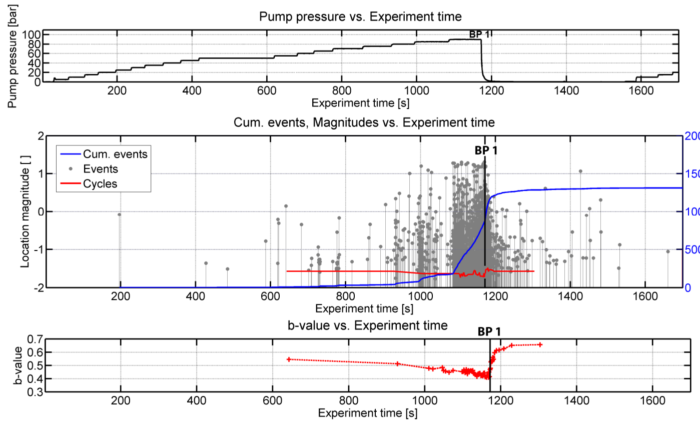




(above) Temporal b-value variation over the differential stress induced seismicity experiment. Moving window settings (step size: 10 events, number of events per calculated Mc/b-value: 350, bin width: 0.05). Magnitudes are presented on a experiment specific scale. Values of Mc and b are plotted in the center (time wise) of each particular moving window.

(left) Localized AE on CT scan image. Sensor positions are marked with white diamonds. CT scan image is aligned according to the sensors labeled.

• Injection induced seismicity



Temporal b-value variation during the injection induced seismicity experiment over one pressure cycle. Moving window settings (step size: 20, number of events per calculated Mc/b-value: 200, bin width: 0.1). Magnitudes are presented on a experiment specific scale. Values of Mc and b are plotted in the center (time wise) of each particular moving window.

4. Conclusions

- Differential stress induced b-values increase with increasing uniaxial stress and reveal the well-known drop towards failure of the sample.
- Injection induced b-values over a pressure cycle decrease with increasing injection pressure and are lowest at breakdown pressure.
- An accurate modeling of occurring heterogeneities and anisotropies in seismic velocities plays an essential role to an accurate localization of AE emitted during brittle failure of rock.

Acknowledgement
Special thanks to Dr. Alex Schubnel and Dr. François Passelègue at the "Laboratoire de Géologie de l'Ecole Normale Supérieur" in Paris for their excellent cooperation during the triaxial experiment.

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Best practice in risk assessment for induced seismicity as part of the risk governance framework for deep geothermal activities.

Marco Broccardo, Max Didier, Bozidar Stojadinovic, ETH Zürich

1 Introduction

In recent decades, the significant increase in seismicity, caused by anthropogenic activities such as hydraulic fracturing, fluid injections, and mining, has posed the challenge of establishing a framework governing the rise. SCCER task 4.1 is has been designed to establish such an agenda within the context of deep geothermal activities. Risk analysis is a pivotal component of the risk governance framework, which provides the baseline for risk management and decision-making.

2 Risks and risk analysis

There are a variety of approaches that can be implemented (Table 1); however, all were developed for natural seismicity. This poses several problems, for natural seismicity is usually regarded as macro-seismicity, while induced seismicity is more confined to the domain of micro-seismicity, and, more important, to the domain of risk due to hazardous human activities.

Time Steps	(a) Source Representation	(b) Engineering Seismology	(c) Vulnerability Analysis	(d) Damage/Loss Analysis
(I)		*Single Intensity measure: e.g.* Im=[PGA]	*Fragility functions, Engineering Demand Parameters e.g.* edm	*Damage Analysis, utility/cost function*
(II)		*Vector Intensity measure: e.g.* **Im**=[PGA, PGV]	*Fragility functions, Vector of Engineering Demand Parameters e.g.* **edm**	*Damage Analysis, utility/cost function*
(III)	*Definition of a stochastic model given source/site characteristic*	*Synthetic times series/ ground motion selection*	*Linear/Non-linear time history analysis ☞ simulation methods*	*Damage analysis, utility/cost function ☞ simulation methods*
(IV)	*Definition of a stochastic model given source/site characteristic*	*Spatially correlated synthetic times series*	*Linear/Non-linear time history analysis ☞ simulation methods*	*Damage analysis, utility/cost function ☞ simulation methods*

PBEE Steps — *Simple* → *Sophisticated*

Table 1 Levels of risk analysis

This last aspect is key, since it introduces a different spectrum of risk analysis worth taking into consideration. A first major distinction is between physical risk and non-physical risk, Figure 2. Examples of the latter are vibrations felt, noise, public campaign against the project, NIMBI, etc. These risks are difficult, and in some cases impossible, to quantify. Within this context, the view presented here maintains that an effective approach should lean more on risk mitigation than on risk assessment. The physical risk is divided into three major categories, i.e., fatalities, economic loss and iconic loss. The first two categories are the most common and should always be computed when a risk assessment is needed. The third category is to be addressed at discretion and is introduced here to identify the risk of physical damage to specific iconic monuments that are part of the cultural heritage of a region.

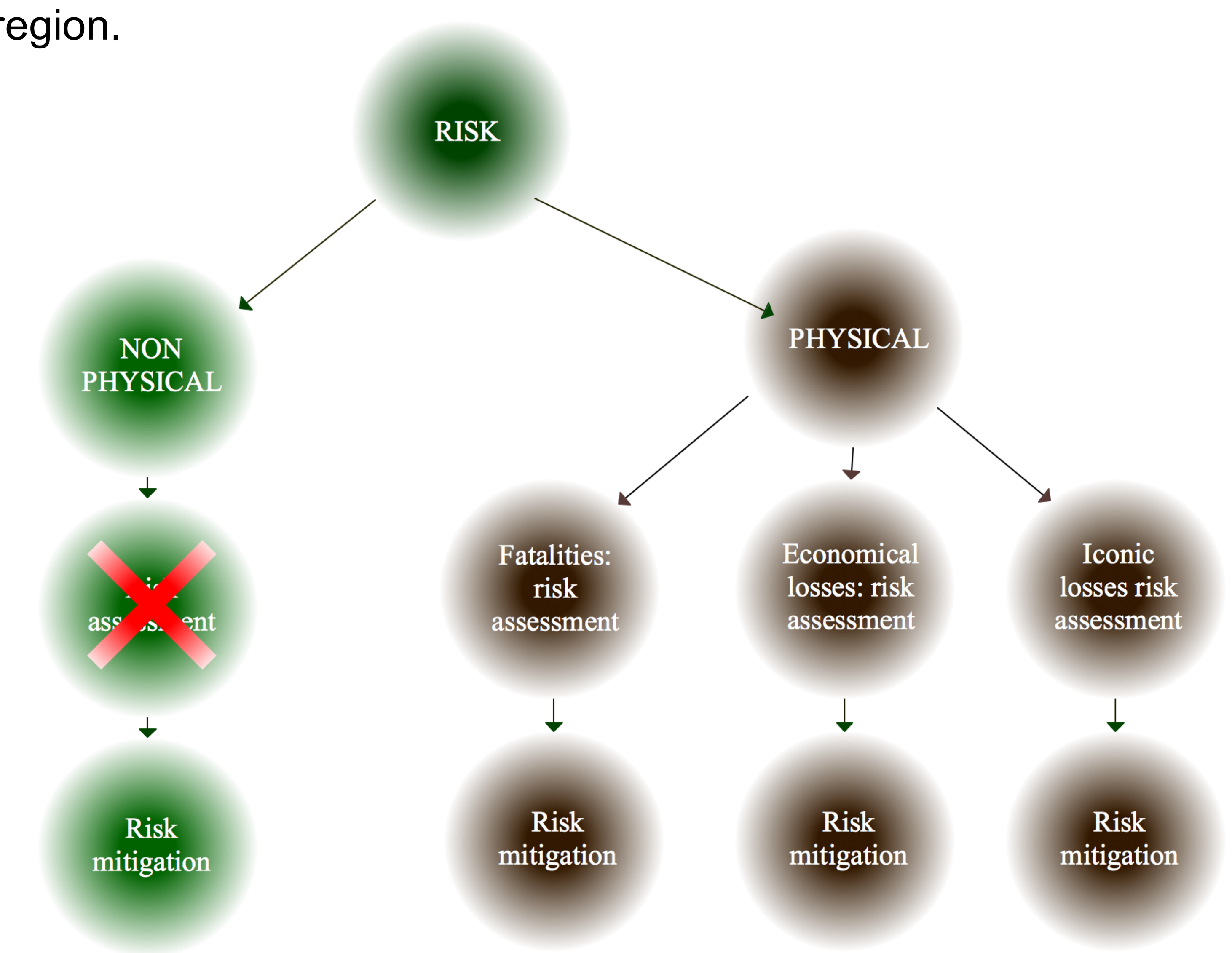

Figure 1 Risk classification

3 Risk metrics

The commonly used approach for risk assessments of economic losses and fatalities is the classical probabilistic seismic hazard analysis (PSHA) combined with the Pacific earthquake engineering research center (PEER) formula framework (Table 1, Row 1; Figure 3).

The choice of risk metric influences the decision making process, and is therefore one of the critical aspects of the framework. The risk analysis literature proposes several such metrics, and this generalized version introduced here allows for most of them. The metric is based on simple concept of functional analysis, i.e.

$$\mathcal{L}^{p}_{G_N}(\mathbb{R}^{+}) = [f : x \in \mathbb{R}^{+} \to \mathbb{R}^{+}, \int_x |f|^p dG_N|] < \infty$$

$$\mathcal{R}_s = ||x||_p = \left[\int_x |x|^p |dG_N|\right]^{1/p}$$

where x is the quantity of interest such as fatalities, injuries, monetary losses, $\mathcal{R}_d$ is the defined risk metric, and p is a risk aversion factor.

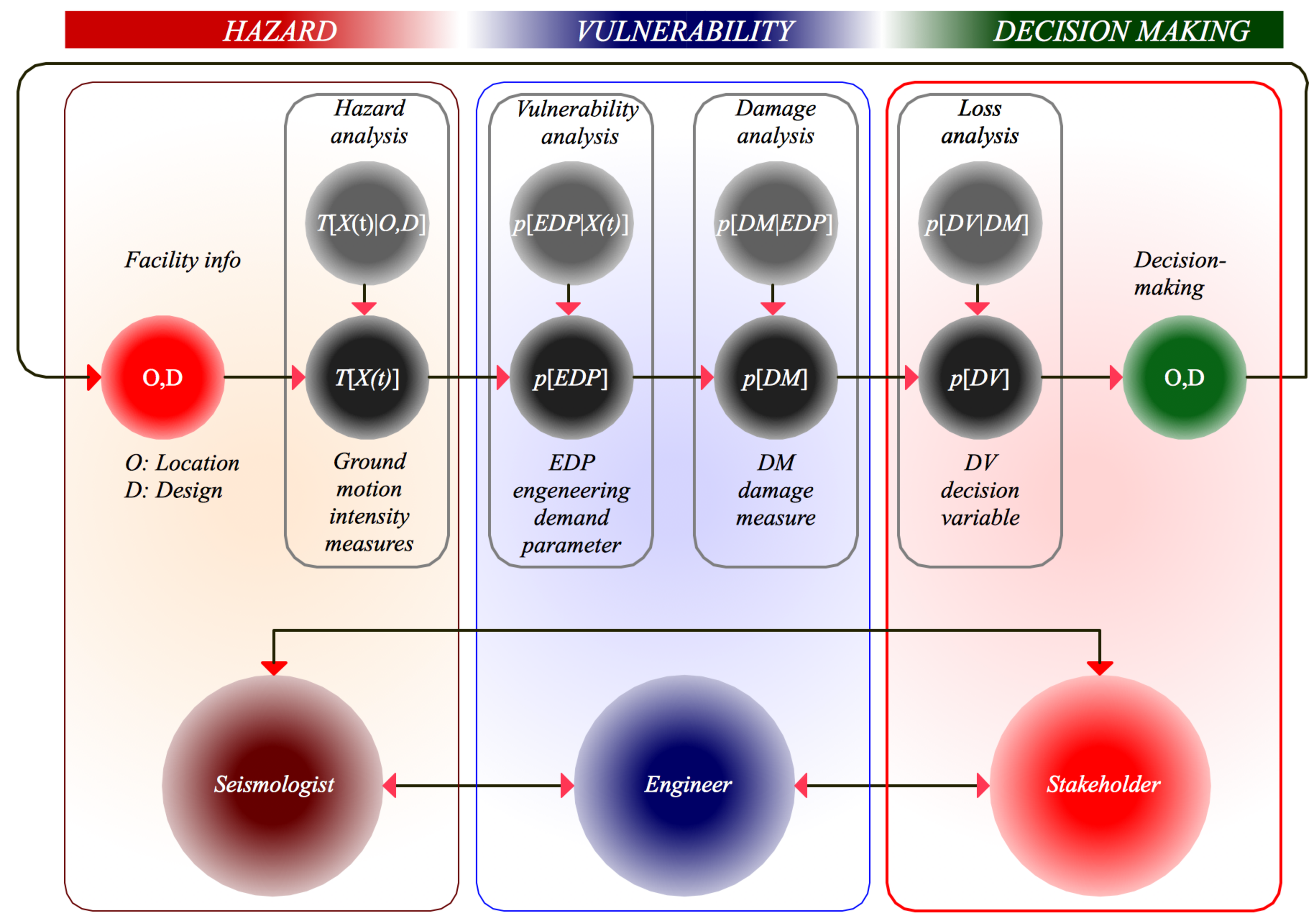

Figure 3 PSHA&PEER framework

4 Challenges

There are several challenges in the application of the framework for induced seismicity, the most important are:

- Determination of specific ground motion prediction equations (GMPE) for induce seismicity. Extrapolation of macro-seismicity GMPEs leads, usually, to large overestimations
- Time dependent PSHA, and spatial correlation effect
- Empirical fragility functions are calibrated for, and thus biased towards, macro-seismicity. Tail sensitivity problem
- The possibility of non-structural damage dominance and of the necessity to develop specific fragility functions exists.

5 Outputs

The output of the risk analysis is expressed in terms of fatalities curves (FN curves) and loss curves.

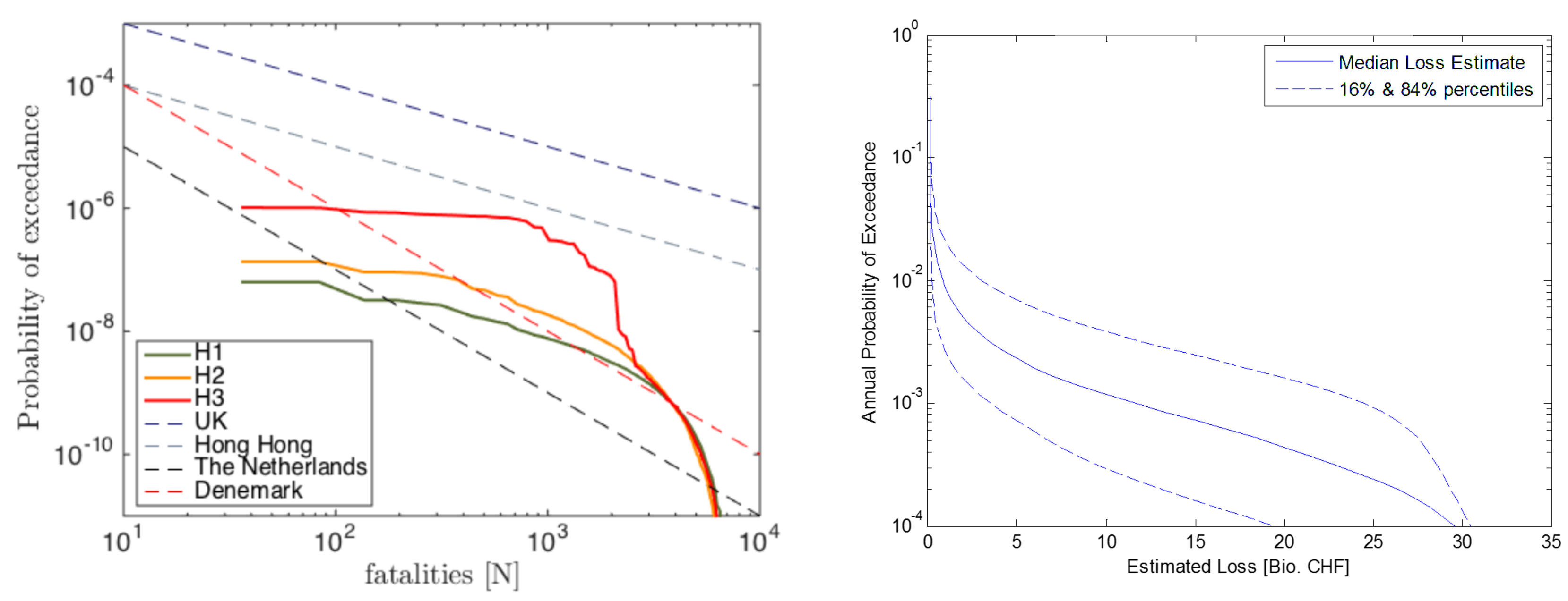

Figure 3 Outputs

6. Conclusions

The section of risk assessment as part of the more general risk governance framework for deep geothermal activities is under construction. The general procedure is based on risk classification of physical and non-physical risk. Risk assessment is only required for physical risk, while for non-physical risk, only risk mitigation should be implemented. At the present time, classical PSHA analysis combined with the PEER formula framework is used to compute different risk metrics based on the typology of physical risk. Finally, a generalized risk metric has been defined for risk management and decision making.

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Built Environment and Civil Infrastructure at Risk

Max Didier, Marco Broccardo, Bozidar Stojadinovic, ETH Zürich

Objective

The objective of this study is to develop a compositional model to quantify the risk exposure and resilience of the built environment and the civil infrastructure systems to the hazard produced by deep geothermal energy source exploration and energy generation facility operation.

The built environment includes all buildings and the interdependent infrastructure systems which supply their services to the community. The compositional model accounts for the initial losses of the components as well as the sequence, probability and time to recover of the supply systems and the community demand.

The output of the model will provide inputs essential for the risk governance framework for the exploration of deep geothermal energy.

Critical Infrastructures

Critical infrastructures include the electric power supply system, the water distribution or the gas network. The different systems are interconnected and interact with each other on different levels. To compute the risk exposure, the infrastructure is modelled in a bottom-up fashion, starting at a component level and taking into consideration the topology and operation model of the system. The seismic behavior of the components is represented using fragility functions for components or repair rates for geographically distributed transmission systems.

There is a need to develop the fragility functions and repair rates for small-magnitude seismic events.

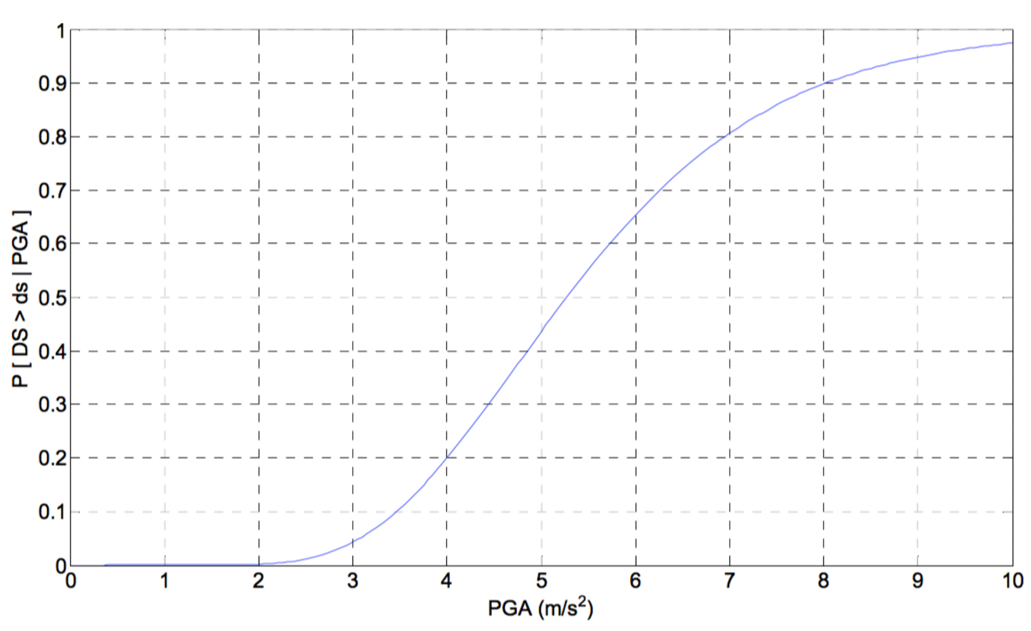


Figure 2 Fragility function of an electric circuit breaker, by [2]

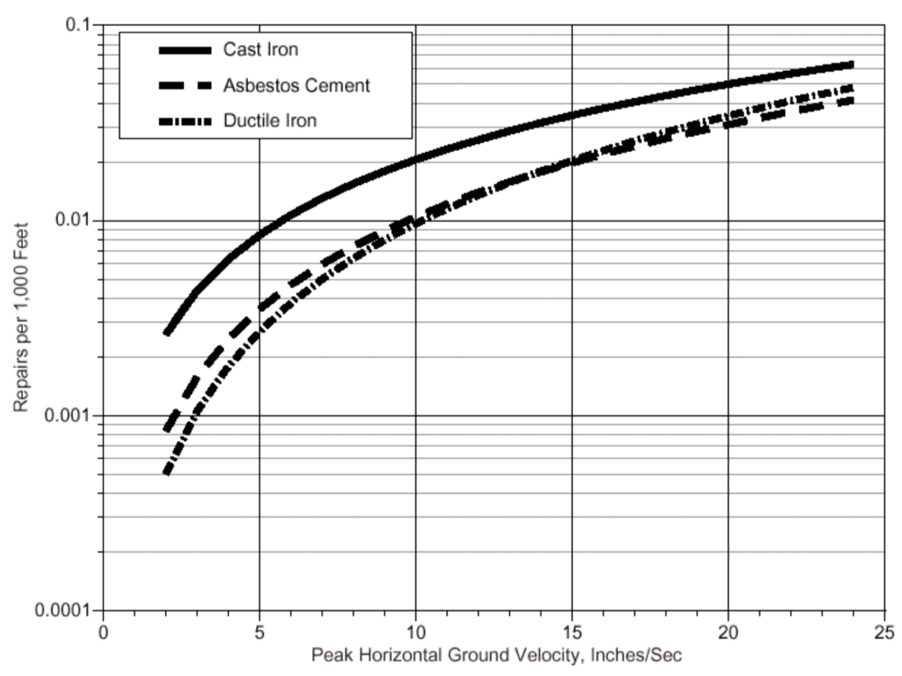


Figure 3 Repair rate for different pipe materials, by [3]

Urban Agglomeration

An urban agglomeration is characterized by its building stock, composed of residential, business or industrial buildings and critical facilities. The seismic behavior depends on different building characteristics, including their height, the structural systems and the applied design code. Fragility functions express the probability of a building to exceed a damage state (DS), given the seismic hazard intensity measure at its location.

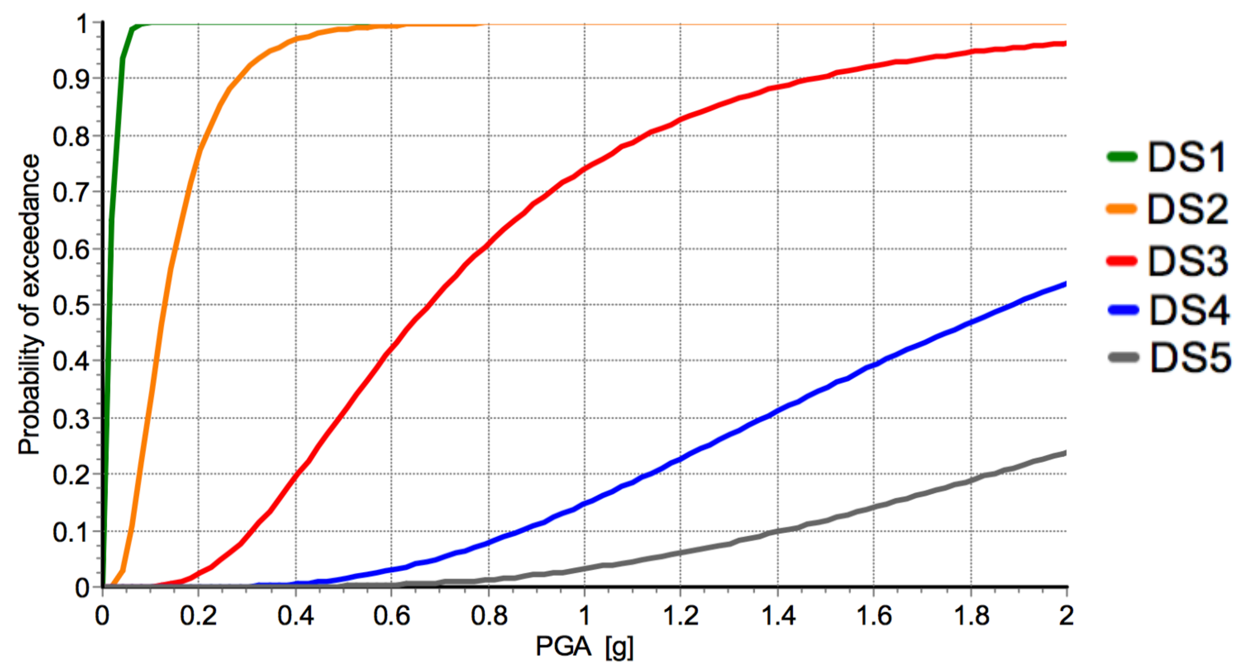
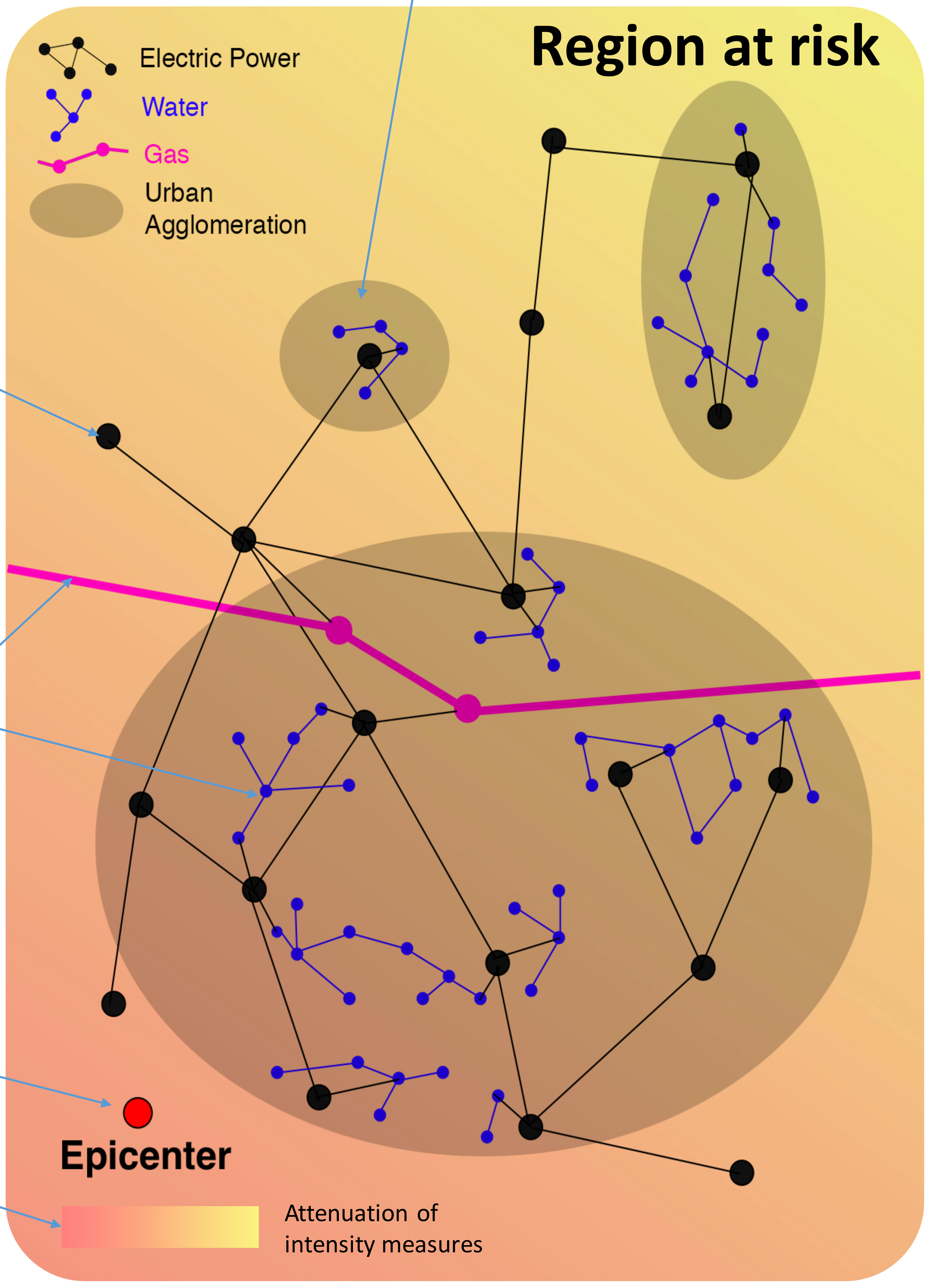


Figure 1 Fragility functions of a high-rise RC building, designed to modern seismic design code, by [1]



Input from Hazard Modelling

An array of different intensity measures (e.g. PGA, PGV, Sa, Sd) and their attenuation functions is needed to evaluate the fragility functions of the different components. *These intensity measures are needed at small earthquake magnitudes that characterize the exploration and the exploitation phases of a geothermal energy source.*

Output for Decision Modelling

The outputs of the compositional model, such as the probability of damage and losses in the region at risk, as well as the duration to recover from these losses, are inputs to the Decision Model and need to be computed. A Decision Model makes it possible to assess the risks of a particular geothermal energy project and to engineer measures and policies to mitigate the adverse effects of a temporary increase of induced seismicity hazard produced by this project.

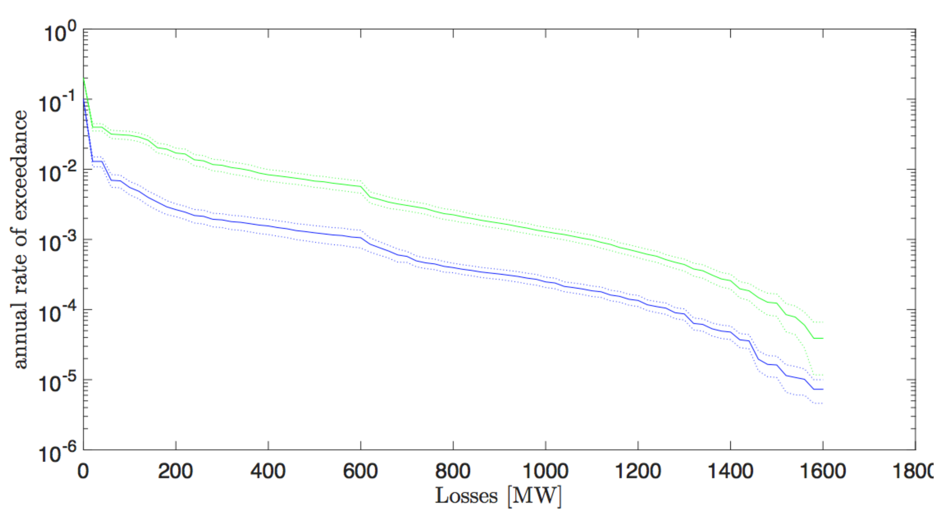


Figure 4 Simulated mean annual loss curves for an EPSS under seismic risk, by [4]

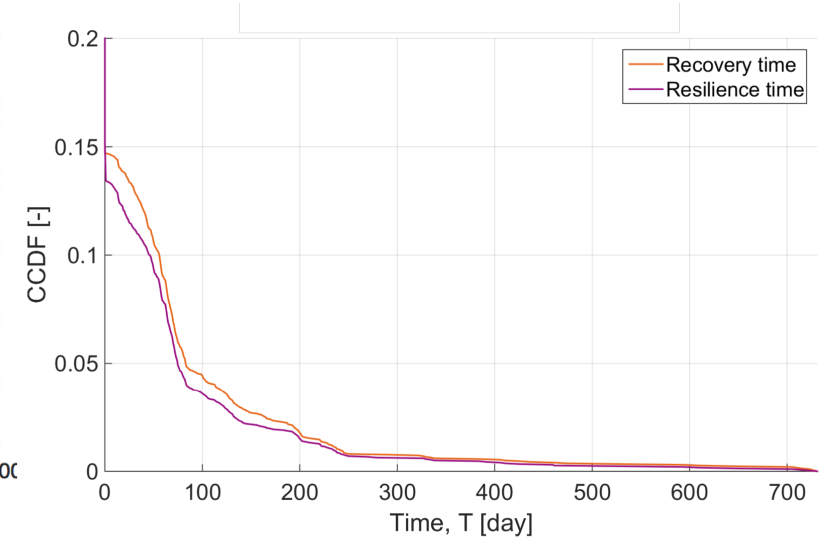


Figure 5 Simulated recovery time for a gas network, by [5]

References

[1] A.J. Kappos, G. Panagopoulos, C. Panagiotopoulos, G. Penelis, "A hybrid method for the vulnerability assessment of R/C and URM buildings" Bulletin of Earthquake Engineering, 4, 391-413, 2006.
[2] I. Vanzi, "Seismic reliability of electric power networks: methodology and application" Structural Safety 18(4), 311-237, 1996.
[3] American Lifelines Alliance –ASCE Seismic, "Fragility Formulations for Water Systems: Part 1: Guidelines", 2001.
[4|X. Bellagamba, "Seismic Resilience of a Gas Distribution Network", Master Thesis, IBK, ETH Zürich, 2015; [5] F. Meier, "A Framework to Quantify the Socioeconomic Resilience of Critical Infrastructure System Against Natural Disaster", Master Thesis, IBK, ETH Zürich, 2015

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Understanding the social relevance of risk related to deep geothermal energy (DGE)

Olivier Ejderyan, Evelina Trutnevyte, Theresa Knoblauch, Michael Stauffacher
TdLab, Department of Environmental Systems Science, ETH Zurich

Why take into account the social dimension of DGE?

Fig. 1: Drilling site of the St. Gallen DGE project (Photo: M. Stauffacher)

Risk governance is an essential component of wise decision making for enabling the required energy transition. Engineering and natural science perspectives to risk are not enough, because society plays a major role in perceiving, mitigating, adapting, tolerating, monitoring, and bearing the potential impacts of risks.

Risk governance for DGE thus requires a transdisciplinary approach that integrates the social dimensions of risk at different stages of project development. It implies that issues related to DGE such as induced seismicity, exploration risk, impact on estate value, etc. must be identified and addressed jointly at both policy and project levels by DGE developers, public authorities, and the populations.

This research aims at contributing to a better integration of social aspects in DGE by asking following questions:

- What risks are perceived? How do they influence the development of DGE?
- How to communicate the risks associated to DGE in a scientifically sound and effective manner?
- How can this social dimension of risk be integrated into a holistic risk governance of DGE?

Monitoring and engaging the public

Public concerns influence the share of DGE in transition strategies as well as political authorities' and citizens' support for single projects. Monitoring public concerns enables to assess the context of DGE policies and projects and develop implementation and planning procedures.

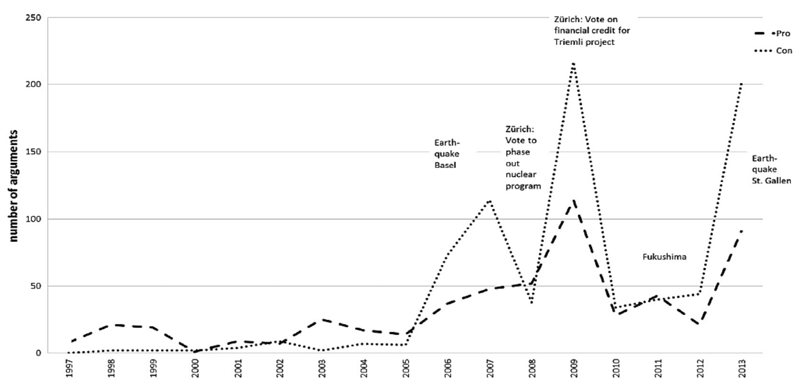

Fig. 2: Frequency of pro and con arguments in Tages Anzeiger and NZZ over time. (Source: Stauffacher *et al.* 2015)

Media analyses are a useful tool to monitor public concerns. They enable to assess the urgency of debates on DGE (Fig. 2 above) and the way arguments are framed in the public sphere. An analysis of Swiss-German newspaper (Stauffacher, 2015) identified 4 main frames (Fig. 3 below). The study is extended to French speaking newspaper. It is completed by a case study about the DGE project in Haute-Sorne (JU) that will assess how local concerns intersect with media frames and affect local publics' responses.

References:
Stauffacher, M. et al., *Technological Forecasting and Social Change*, 2015 (98) 60-70.

Actor groups	Risks		Energy transition		Technology		Costs		Total
	Uncertainties and risks (n = 71)	Risks under control (n = 66)	Opportunity (n = 90)	Unrealistic option (n = 12)	Benefits (n = 33)	Handicaps (n = 43)	Economical (n = 14)	Expensive (n = 53)	
Politicians (n = 128)	9.4	16.4	21.1	7.8	9.4	14.8	3.1	18.0	100%
Public authorities (n = 67)	19.4	17.9	25.4	0.0	4.5	13.4	1.5	17.9	100%
Industry (n = 99)	6.1	15.2	40.4	0.0	13.1	6.1	8.1	11.1	100%
Scientists (n = 88)	45.5	20.5	6.8	2.3	5.7	10.2	1.1	8.0	100%

Fig. 3: Main frames on deep geothermal energy identified in Tages Anzeiger and NZZ for the period 1997-2013 (Source: Stauffacher *et al.* 2015)

Social dimensions of risk influence public responses to DGE. This must be addressed adequately in order to develop acceptable projects.

Communication of low-probability high-consequence (LPHC) events related to DGE

Fig. 4: Cover of an information brochure for the DGE program in Geneva (Source: Géothermie 2020)

Understanding and discussing LPHC events related to DGE remains a challenge albeit the broad public's interest. Due to deep geothermal energy's novelty, society cannot yet rely on extensive experience in assessing these risks. Moreover there is little literature on how to communicate LPHC most effectively. Human tendency for risk aversion and biases in risk perception (Patt and Schrag, 2003) make discussion about LPHC events even more delicate. In absence of reliable knowledge and communication, beliefs and values fill in the gap (Fischhoff, 2013).

In order to enable more informed decision and better outcomes for individuals and society, this project aims at:

- Finding research-informed ways for transparent, scientifically sound, and user-oriented communication about LPHC events related to DGE;
- Understanding implications of LPHC on technology acceptance and the technology siting process.

References
Fischhoff, B.. *Proc Natl Acad Sci USA*, 2013 (110-S3) 14033-9.
Patt, A. G. & Schrag, D. P. *Climatic Change*, 2003 (61) 17-30

Socio-technical governance of induced seismicity risk

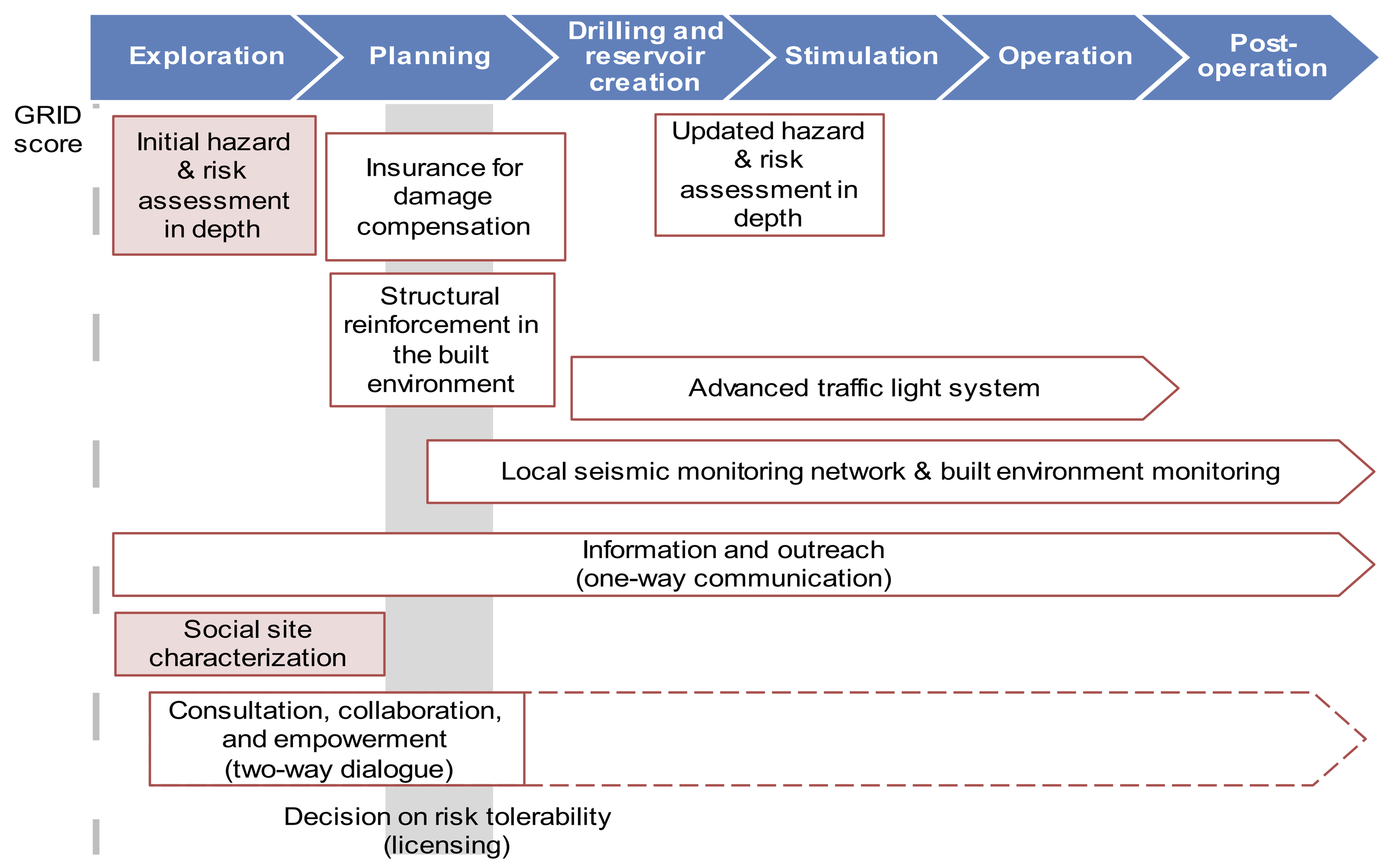

Fig. 5: Induced seismicity risk governance framework for DGE projects (Author: E Trutnevyte)

The risk governance of induced seismicity in DGE projects must take into account two dimensions of risk: the factual risk dimension and the value-laden societal and decision making dimension. In the proposed socio-technical governance framework (Fig. 5), the technical governance elements (e.g. initial hazard and risk assessment, traffic light systems) are complemented with social governance elements (e.g. social site characterization, communication, and public and stakeholder engagement).

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Swiss Renewable Energy Risk Analysis and Optimisation

Stuart Bartlett, Annelen Kahl, Michael Lehning, Bert Kruyt, Varun Sharma

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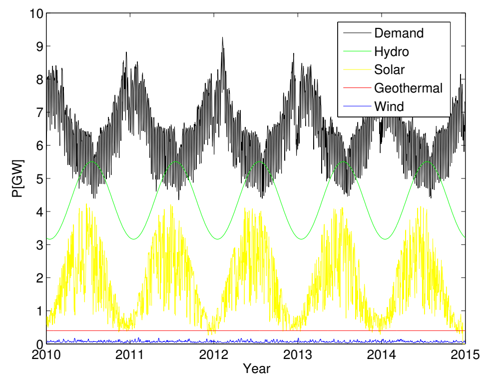
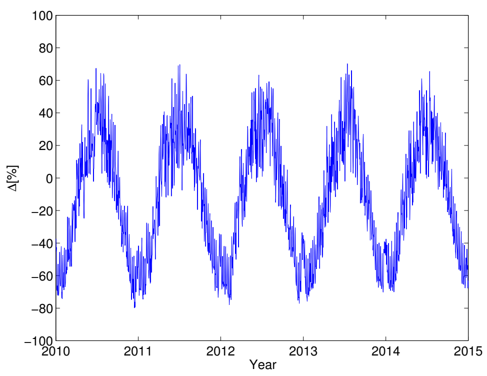
Abstract

In this project we aim to assess the weather-related risks to a hypothetical, fully renewable Swiss power system (wherein the current nuclear capacity is replaced by solar, wind and geothermal power). On average it is clearly possible to cater for Swiss electricity requirements with purely renewable sources, however there are a variety of natural hazards and meteorological scenarios which could disrupt the steady supply of power to consumers. Furthermore, the strong seasonal variation in solar and hydropower production will need to be dealt with. We have performed a first order assessment of the main sources of variability in the net electrical load under a fully renewable configuration. The next phase will make use of the WRF weather model to generate a range of meteorological scenarios, in particular extreme persistent weather patterns that would put large strains on a fully renewable power system. We intend to explore the extent to which nationally coordinated hydropower operating strategies may help alleviate this variability.

1. Temporal Analysis

We approximated the spatially averaged power injections from wind and solar power, based on meteorological data for the years 2010-2014.
Geothermal production was estimated based on the national targets of the 2050 Swiss Energy Strategy.
Hydro production was based on typical seasonal trends.
Power demand was taken from Swissgrid data.

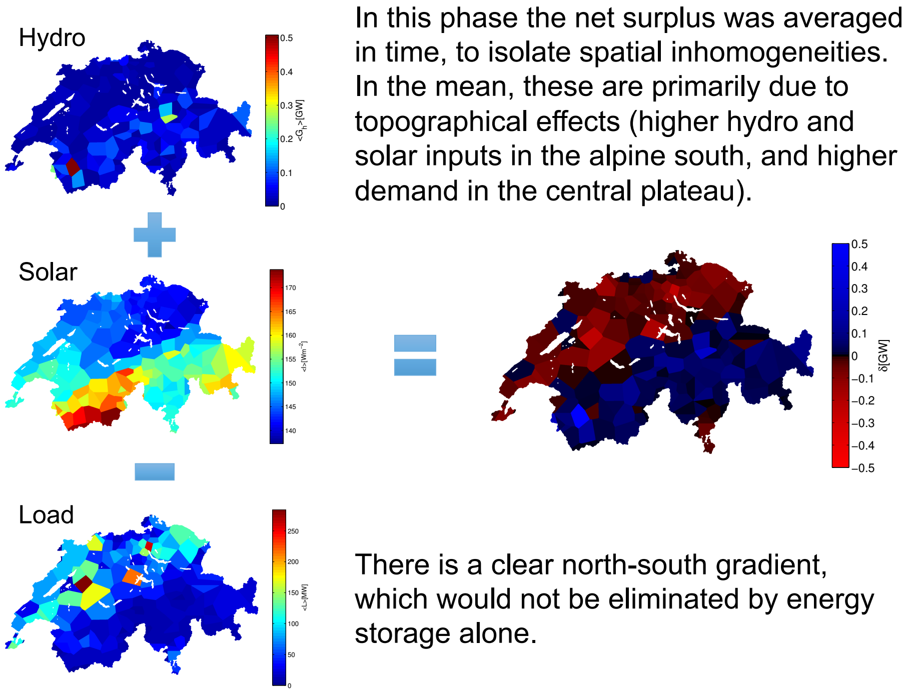




Here we see the net deficit (or surplus), normalised by the average annual demand, resulting from the combination of renewable sources and total national load.

We see that there is a very large seasonal trend, which would not be alleviated by increased transmission infrastructure.

2. Spatial Analysis

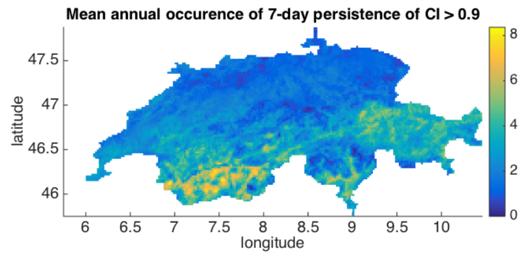


In this phase the net surplus was averaged in time, to isolate spatial inhomogeneities. In the mean, these are primarily due to topographical effects (higher hydro and solar inputs in the alpine south, and higher demand in the central plateau).

There is a clear north-south gradient, which would not be eliminated by energy storage alone.

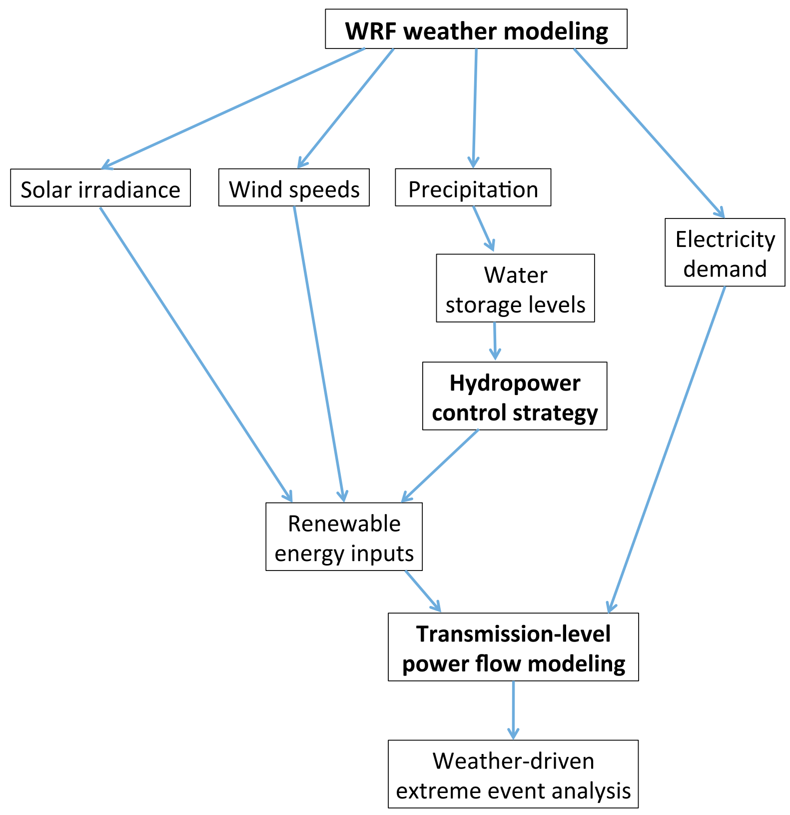
4. Solar and Wind Energy Analyses

Since solar energy would make up the bulk of the non-hydro renewable Swiss generating portfolio, we are carrying out an extreme value analysis of solar irradiance data for the whole country. Alongside this, we are assessing the potential for wind energy installations in favourable alpine locations.



5. Integrated Weather and Power Flow Modelling

We are now building upon the first work phase, by constructing a new holistic modelling framework driven by the high resolution WRF weather model. AC Power flows will be simulated using the Matpower package.



Collaborations:

We are working with multiple partners from various institutions:

- SCCER-SoE:
  - Laboratory of Hydraulic Constructions at EPFL
  - Chair of Hydrology and Water Resources Management at ETHZ
- SCCER-FURIES:
  - Distributed Electrical Systems Laboratory at EPFL
- Risk Analytics and Optimization Chair at EPFL
- WSL/SLF
- Meteoswiss

Conclusions

Our initial assessment highlighted the need for a nationally coordinated approach to the problem of variability in a fully renewable Swiss power system. A strong transmission system will be required to deliver excess power from the mountainous south to the load centres in the north. There is also a need to make optimal use of all hydro storage facilities to reduce temporal variability on a range of timescales. We intend to now further explore the greatest risks to this desirable future power system, and the optimal mitigation strategies for such risks.

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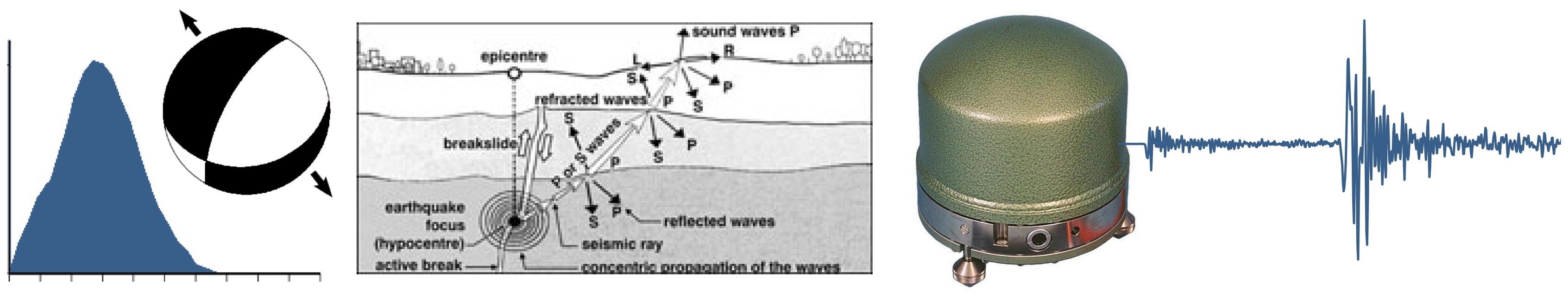
GEO BEST CH
induSED seismicity

Detecting Smaller Earthquakes

Marcus Herrmann[1], Toni Kraft[1], Tobias Diehl[1], Stefan Wiemer[1]
[1] Swiss Seismological Service, ETH Zürich, Switzerland; ✉ marcus.herrmann@sed.ethz.ch

Introduction

Geothermal projects are associated with induced seismicity, typically in form of a "seismic swarm". Within such a swarm, numerous smaller earthquakes stay undetected by the seismic network; they are too small to be detected at several stations of the network. However, some of them can still be recorded by one station. Like the larger earthquakes, smaller events are a response to induced activity. Including more events in our analysis can provide us additional information about the underground—and a better understanding of induced seismicity. We will utilize the high seismogram similarity within a swarm to find small earthquakes.
But first, what is a seismogram, and what does it include?



Source ○ Path, Medium ○ Receiver "=" Seismogram

Status and Highlights

- We found more earthquakes compared to standard analysis
  → decreased the detection limit (~1 magnitude unit)
  → increased spatio-temporal resolution, more information
    → allows better statistical analysis
    → allows to determine structures better (constrain fault plane)
- We observed a change in template association over time
  → change in spatio-temporal behavior
- We applied the method to several sequences
  (currently studying seismicity decay of the Basel Geothermal Project)

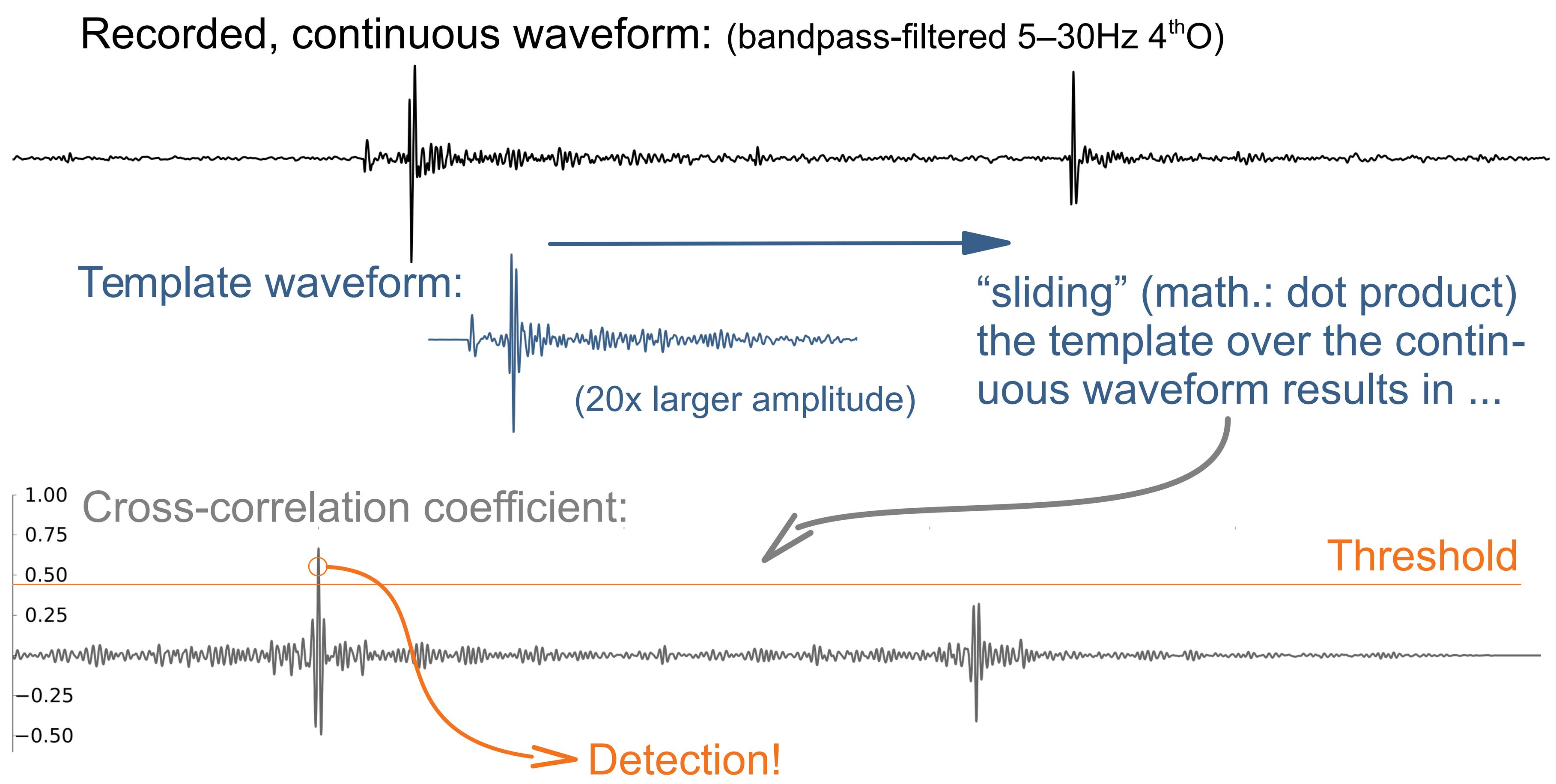
Outlook

- Compare different settings, optimize the process
- Implement a location algorithm based on template similarity
- Apply the method to more sequences (natural and induced)
  … and study their differences/similarities
- Automation for real-time processing

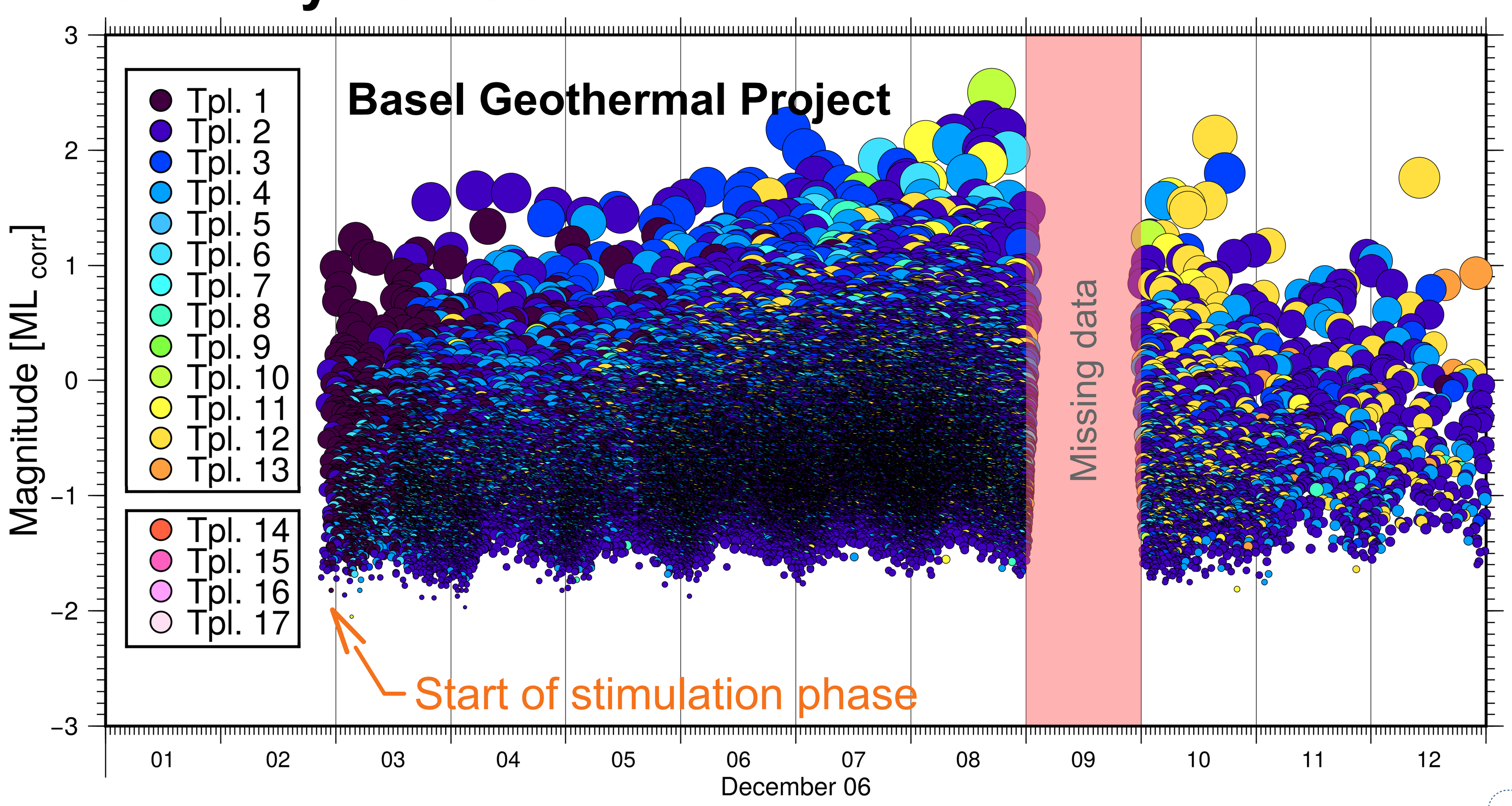
Method

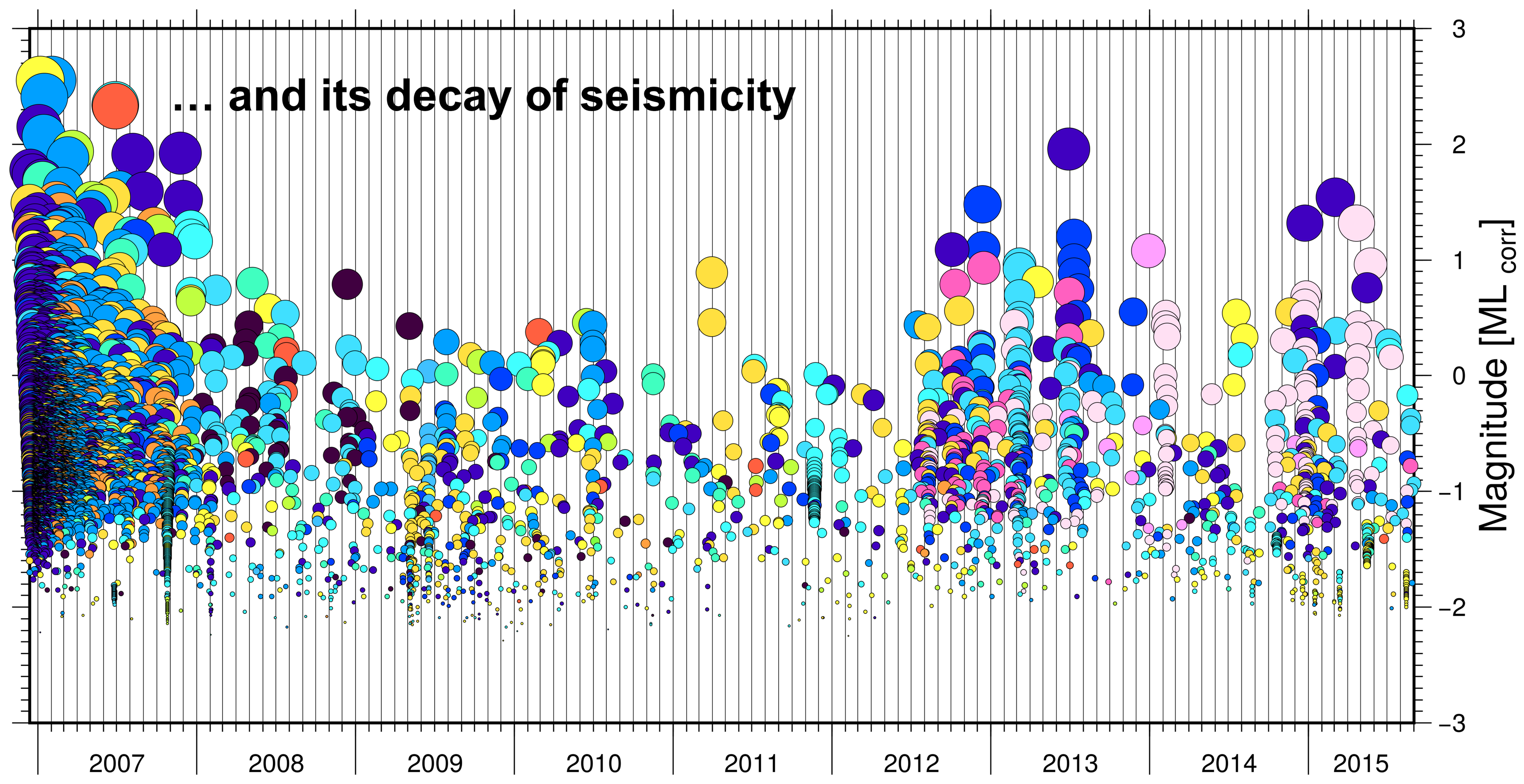
We search for smaller earthquakes using *Template Matching (see →)*. We regard waveforms as similar if their cross-correlation is high. But before we can apply this method, we need to

1. Select a template and its parameters (e. g., duration, frequency-filter ranges). The optimal template maximizes detections and minimizes false positives.
2. Scan the continuous data with a template. The detection depends on the noise level, epicentral distance, and the chosen threshold.
3. The process can be repeated for
   - other components/channels (vertical + horizontal)
   - more template events
   - other stations
4. Determine magnitudes of the detected events

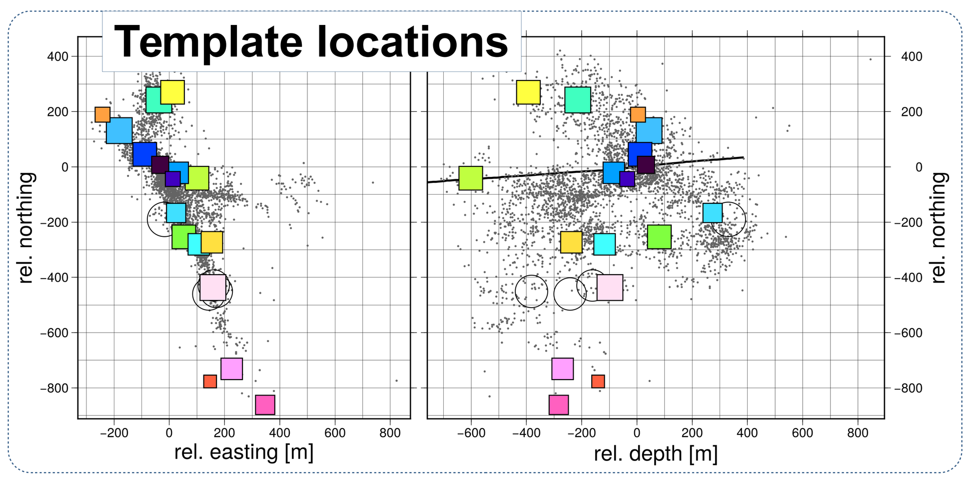


Preliminary Results





We applied *Template Matching* to sequences of induced (e. g. the **Basel Geothermal Project**, see ↑) and natural seismicity (e. g., the "**Diemtigen swarm**", see ↓). Since we can only detect events that are similar to the used template(s), the template set has to be updated over time. We were able to lower the detection threshold by at least one magnitude unit (i. e. finding ~10 times more earthquakes).

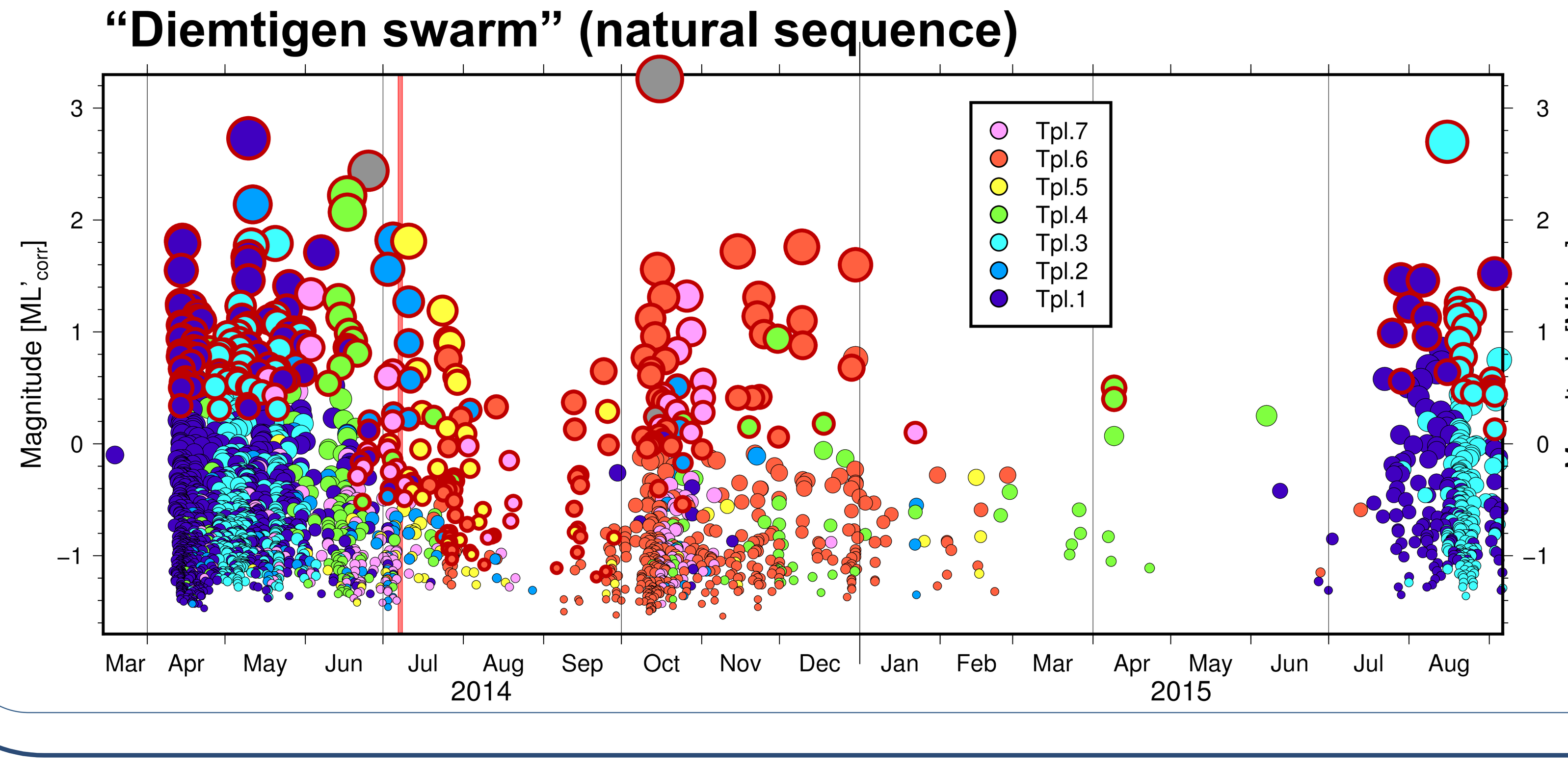


We thank *GeoEnergie Swiss AG* and *GeoExplorers Ltd.* for providing the seismometer recordings of the Basel Geothermal Project.

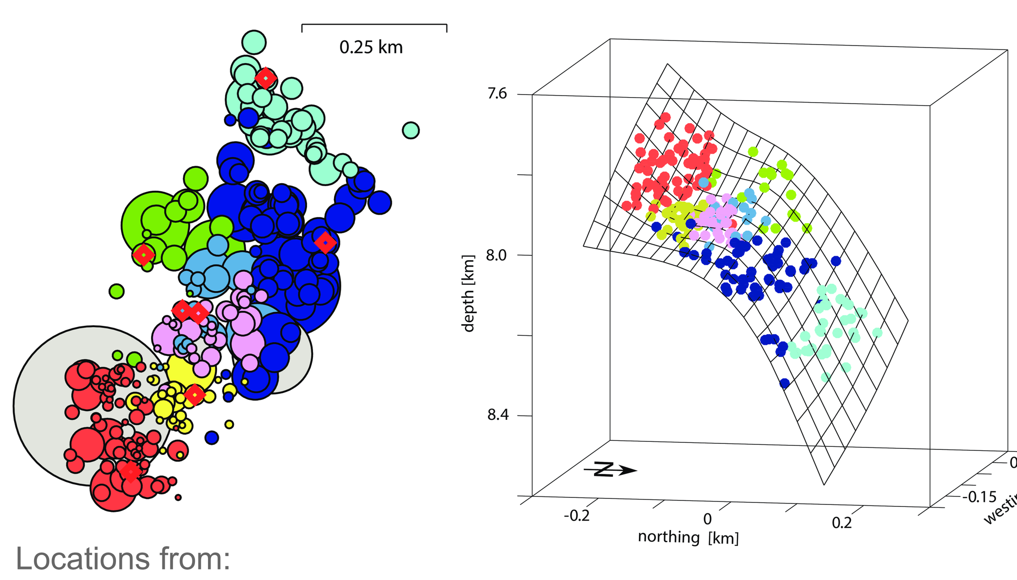
Locations from:

Dyer, B.C., et al., 2010. Application of microseismic multiplet analysis to the Basel geothermal reservoir stimulation events. Geophys. Prospect. 58.
Deichmann, et al., 2014. Identification of faults activated during the stimulation of the Basel geothermal project from cluster analysis and fault mechanisms for the larger magnitude events. Geothermics.

"Diemtigen swarm" (natural sequence)



After locating detected events, it becomes clear that different patches of the fault ruptured at different times; in 3D, the common fault structure becomes more imaginable.



Locations from:

Diehl et al. 2015, Earthquakes in Switzerland and surrounding regions during 2014. Submitted to Swiss J. Geosci.

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

A. Mignan, A. Scolobig and N. Komendantova

Abstract

As opposed to single-risk settings, multi-risk environments are characterized by natural and/or man-made hazards correlated in time and space. Hydropower and geo-energy sites are not immune to these issues, requiring a timely assessment and management of multi-risk. Here we first 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 conceptual large Alpine embankment dam (see Part B) and will soon be tested to all of Switzerland for different multi-risk processes and energy sites (see Part C). Cascades and conjoint 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 MATRIX 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 Sendai 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 considering hazard and risk interactions to improve practices for risk management. The European MATRIX (2010-2013) project formed a platform to develop harmonized multi-risk methods (COM, 2014), such as GenMR described below. The framework is now tested at critical infrastructures (e.g., dams, industrial districts) in the STREST project (2013-2016) and specifically at hydropower and geo-energy 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).

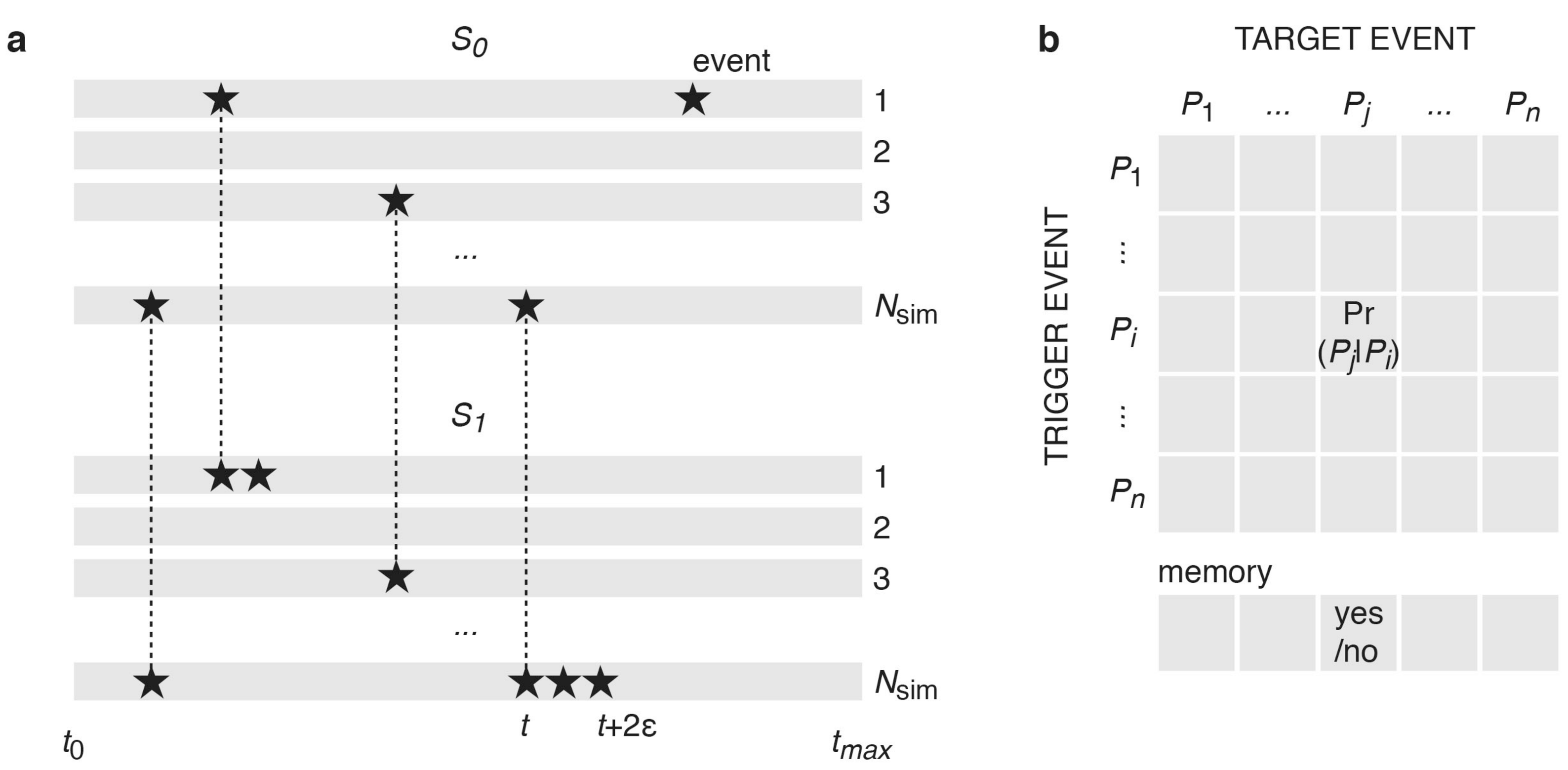
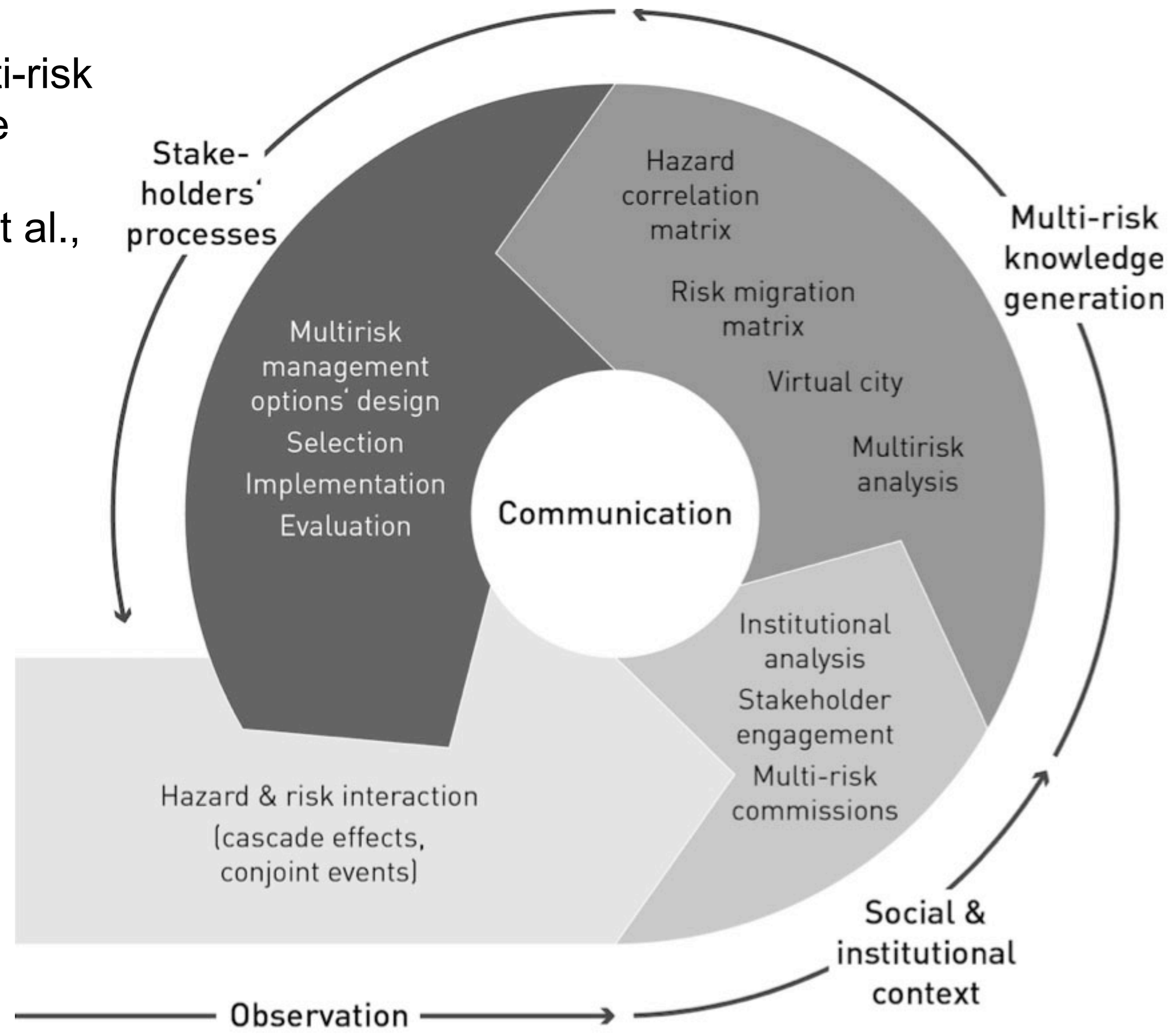


Fig. 1: Simulation sets *S* composed of N_{sim} timeseries, populated by hazardous events. Event correlations are defined in a Hazard Correlation Matrix (HCM). Also includes event-dependent vulnerability and exposure (not shown). Examples are shown in Parts B and C.

3. Multi-Risk Governance Scheme

Risk governance represents the various ways in which stakeholders manage their common risk issues (e.g., Renn, 2008). **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 governances.

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



Phases are:

1. <u>Observation</u>: Complex, uncertain, extreme!
2. <u>Social & institutional context</u>: Possible conflicts between agencies. Who should be in charge of multi-risk? At what institutional level?
3. <u>Multi-risk knowledge generation</u>: GenMR, including Virtual City concept (**Fig. 3**), already tested with stakeholders (Komendantova et al., 2014; Mignan et al., in press).
4. <u>Stakeholder processes</u>: Expert-informed stakeholder participatory process; decision making under uncertainty.

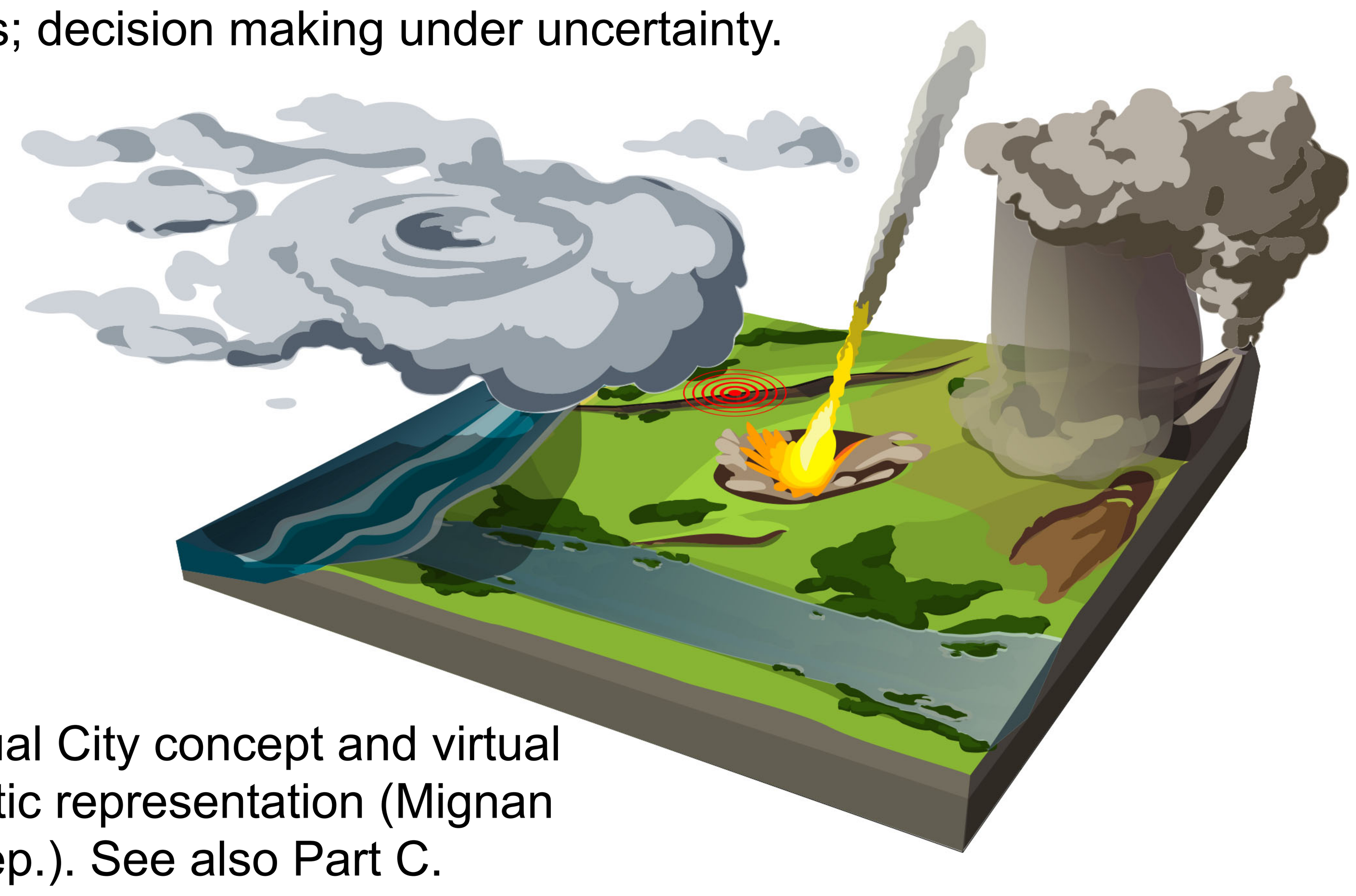


Fig. 3: Virtual City concept and virtual region artistic representation (Mignan et al., in prep.). See also Part C.

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 modelling 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 fluid injection as the initial triggering event.
- ✓ A DGE virtual site (variant of **Fig. 3**) will be developed to improve communication with stakeholders.

5. References

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

J.P. Matos, A. Mignan and A.J. 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 rendering the problem of risk assessment tractable, they neglect numerous 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 step forward in order to achieve just that: estimate global risks associated with hydropower dams. This work was done in the European *STREST* project; the proposed method applies to both *T2.3 "HP 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. Travelling 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 practises, and safety recommendations. Traditionally, risk assessments are usually focused on one or a few different hazards and require constraining assumptions about the initial state of the system. Several approaches have historically been applied to this problem (e.g. 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 broadly assessing the global risk associated with a dam facing multiple hazards. In particular, GenMR 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 enforced though the method's correlation and time-delay matrices (Mignan et al., 2014; see Part A).

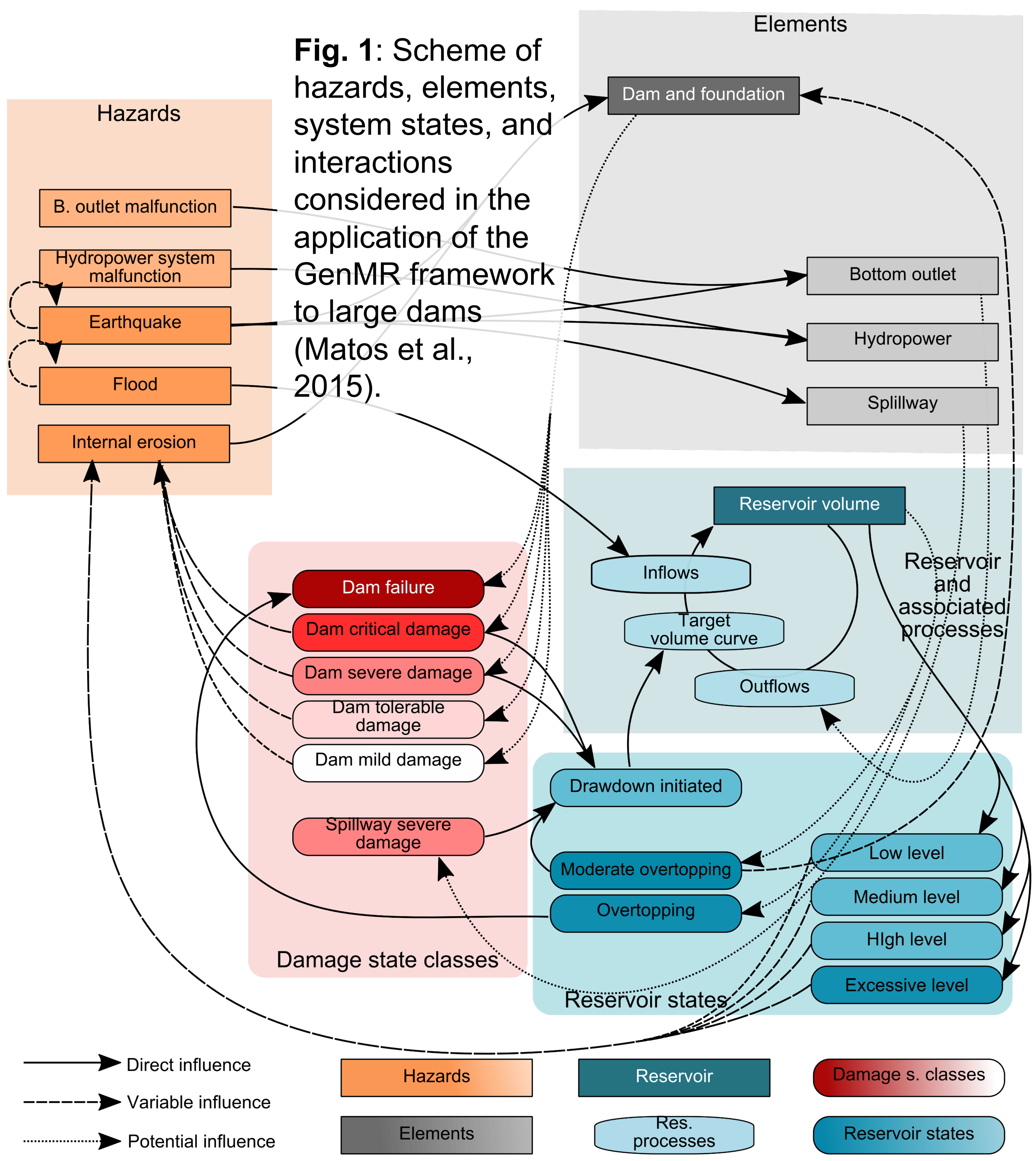

Fig. 1: Scheme of hazards, elements, system states, and interactions considered in the application of the GenMR framework to large dams (Matos et al., 2015).

STREST
Harmonized approach to stress tests for critical infrastructures against natural hazards

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE — LCH LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES — ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

- ✓ Multiple possible outcomes are sampled in a Monte Carlo procedure where the system's evolution during one year is repeatedly simulated, including the seasonality of the target reservoir level (**Fig. 2**).
- ✓ At each step, the past history of the system is taken into account allowing for any kind of hazard ↔ element ↔ state interactions, thus accounting for the dynamical nature of the problem.

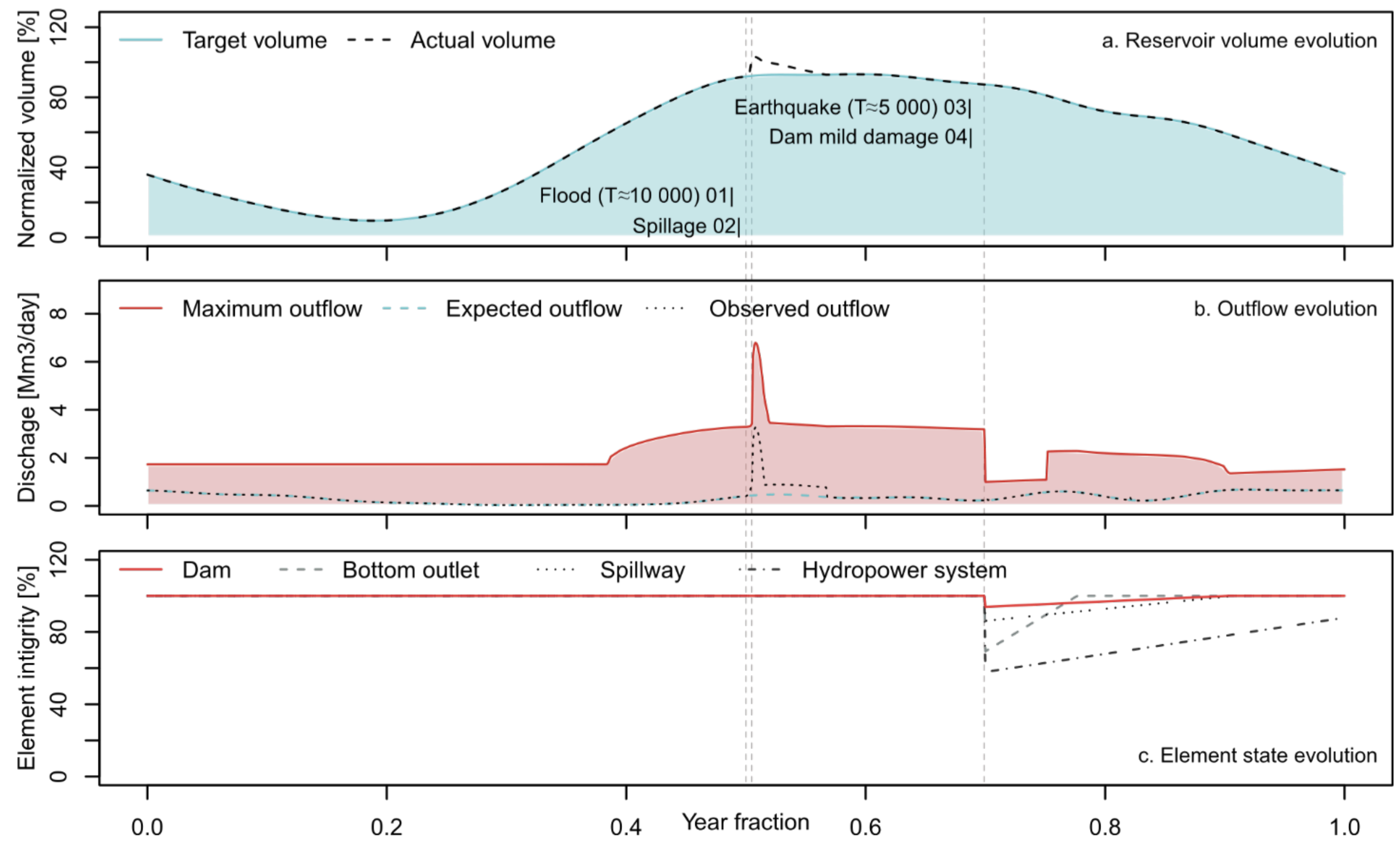

Fig 2: Example simulation (adapted from Matos et al., 2015).

3. Results

Preliminary results for a large earthfill dam show that:

- ✓ The GenMR framework can be applied to dams.
- ✓ Can be used to estimate the overall risk associated with a dam during its complete yearly operation cycle.
- ✓ Uncertainty plays a major role and accurate description of hazards and elements is paramount.
- ✓ Possible to disaggregate results to pinpoint high risk causes.
- ✓ <u>The system's vulnerability is increased when interdependencies are incorporated in the analysis, particularly due to rare combinations of events. The likelihood of such extreme scenarios remains, however, well below safety design standards for the tested conceptual dam case</u>.

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 accident.
- ✓ Using the multi-risk governance frame proposed in Part A could facilitate the implementation of GenMR in hydropower dam risk management.

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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 infrastructures may yield unsuspected consequences (e.g., increased likelihood of hydropower dam mal-functions – see Part B, increased damage around geo-energy exploitation sites). This paper describes the plan of the *NRP70 WP5* PhD project on *"multi-risks and interdependencies"*, started in January 2015 and related to *T4.1 "Risk, safety and societal acceptance"*. Using as modelling 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 at Swiss hydropower and geo-energy sites. Hazards of interest are mainly: earthquakes, storms, mass slides and lake tsunamis. Dynamic risk processes of interest are mainly: damage-dependent building vulnerability and network failures. A better understanding of multi-risk shall allow improving mitigation measures 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 aftershocks, landslides, rock falls and avalanches, as well as lake tsunamis (e.g., Fritsche et al., 2012). Globally, dams are also subject to hazard interactions. Examples include cascading dam failures due to heavy rains (e.g., 1975 Banquiao dam, China) and dam overtopping due to landslides (e.g., 1963 Vajont 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 there is induced seismicity, one especially needs to investigate the triggering potential of small to moderate size events (magnitude up to ~4) as well as the impact of repeated moderate ground shaking on infrastructures (buildings and networks). All of these aspects will be considered following the top-down approach described below.

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:

- ✓ Abstract level: Development of multi-risk models using basic mathematical tools (e.g., distribution 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 (**Figs. 1-2-3**). [*ONGOING TASK*]
- ✓ Site-specific level (Switzerland): Application of multi-risk models to real-site conditions, using existing topography, soil properties, building portfolios, etc. [*UPCOMING TASK*]

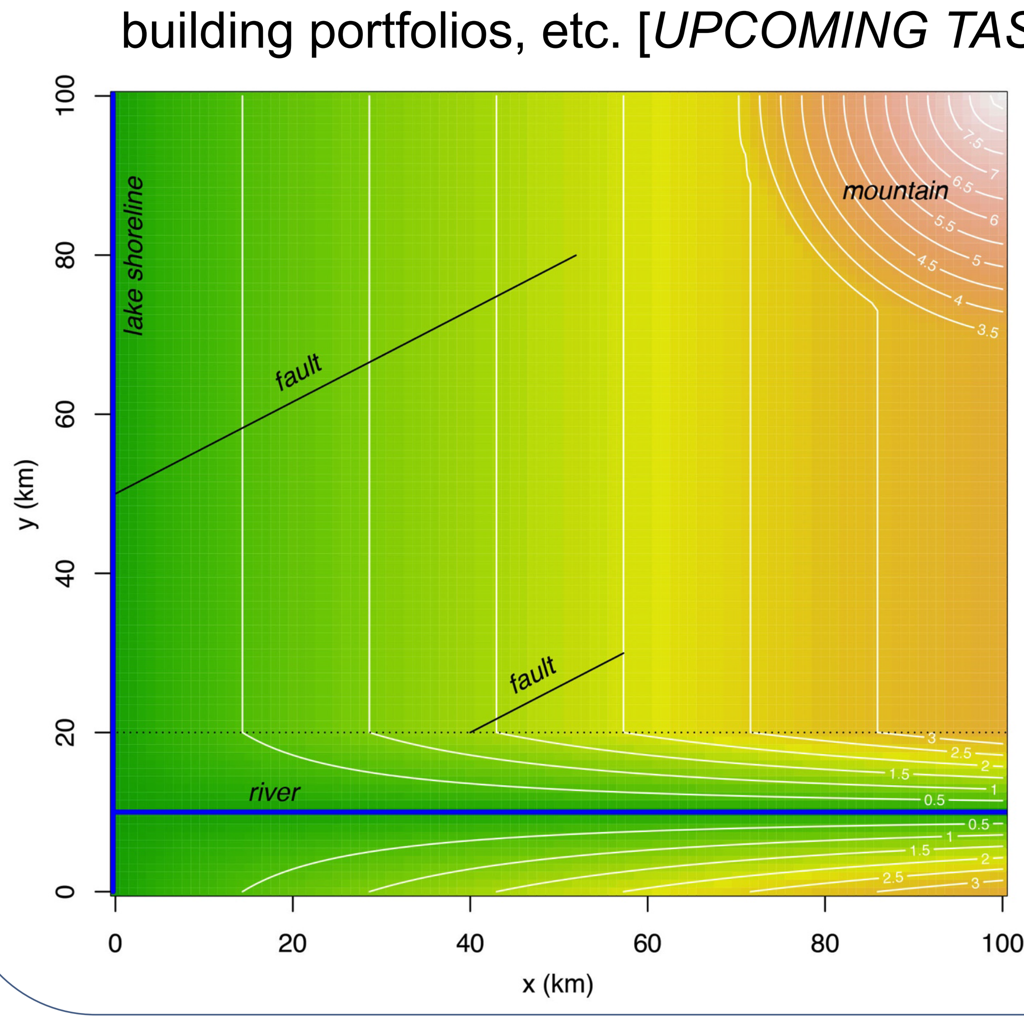

Fig. 1: Virtual region topography defined to investigate the combined roles of terrain slope, water saturation due to heavy rains and earthquakes on landslides (see artistic representation of the same virtual region in Part A).

3. Examples of multi-risk processes

- ✓ Landslides triggered by earthquakes and heavy rains: This is the first process considered in the PhD. A cellular automaton was developed based on the concept of Newmark displacement to model the dynamic landslide propagation following an earthquake under different water saturation conditions (applies to both hydro- and geo-energy cases).

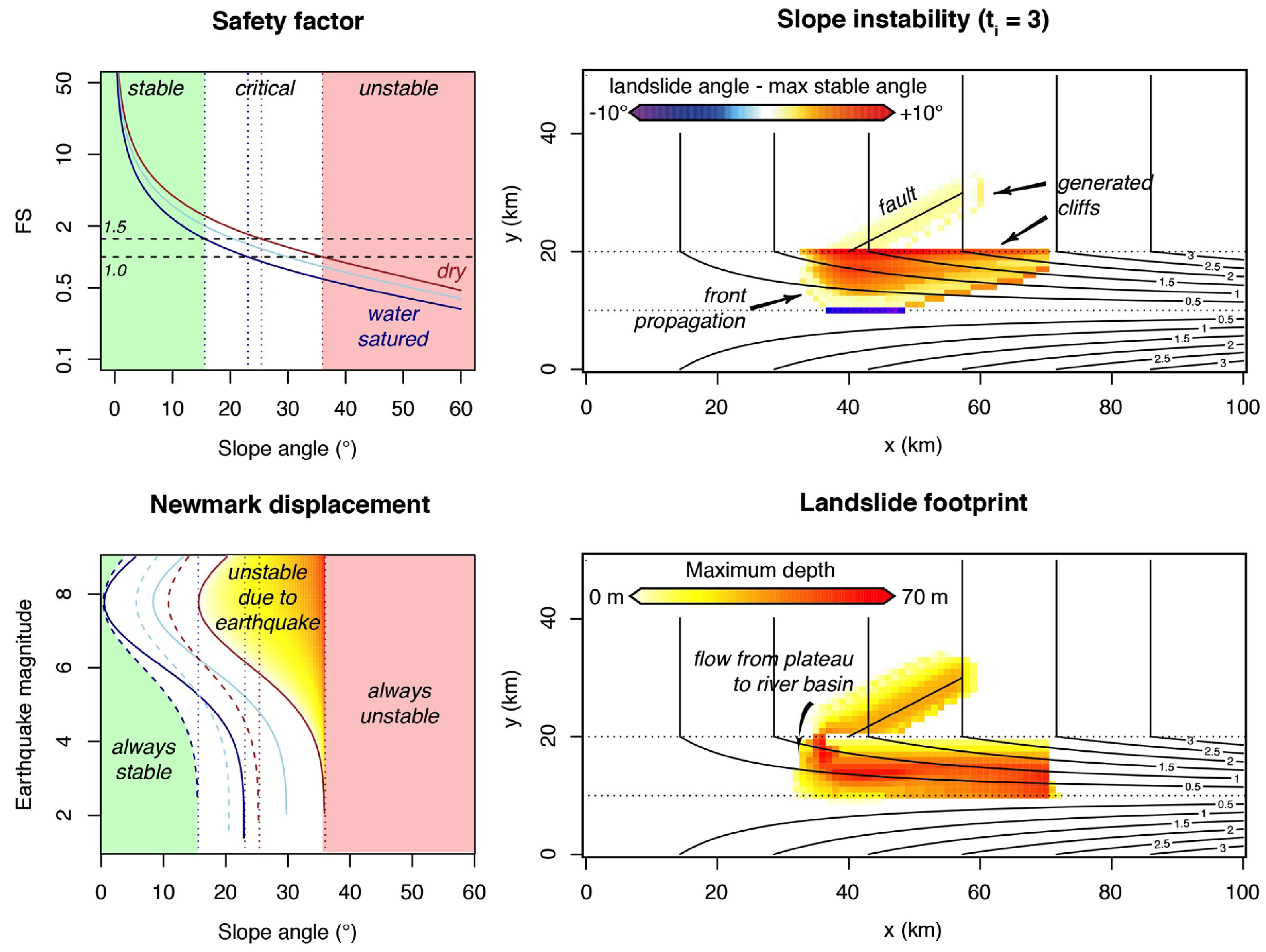

Fig. 2: Landslide triggering model tested in the virtual region for a magnitude 6.5 earthquake and water-saturated soil (10 m thick).

- ✓ Damage-dependent vulnerability due to repeated earthquakes:

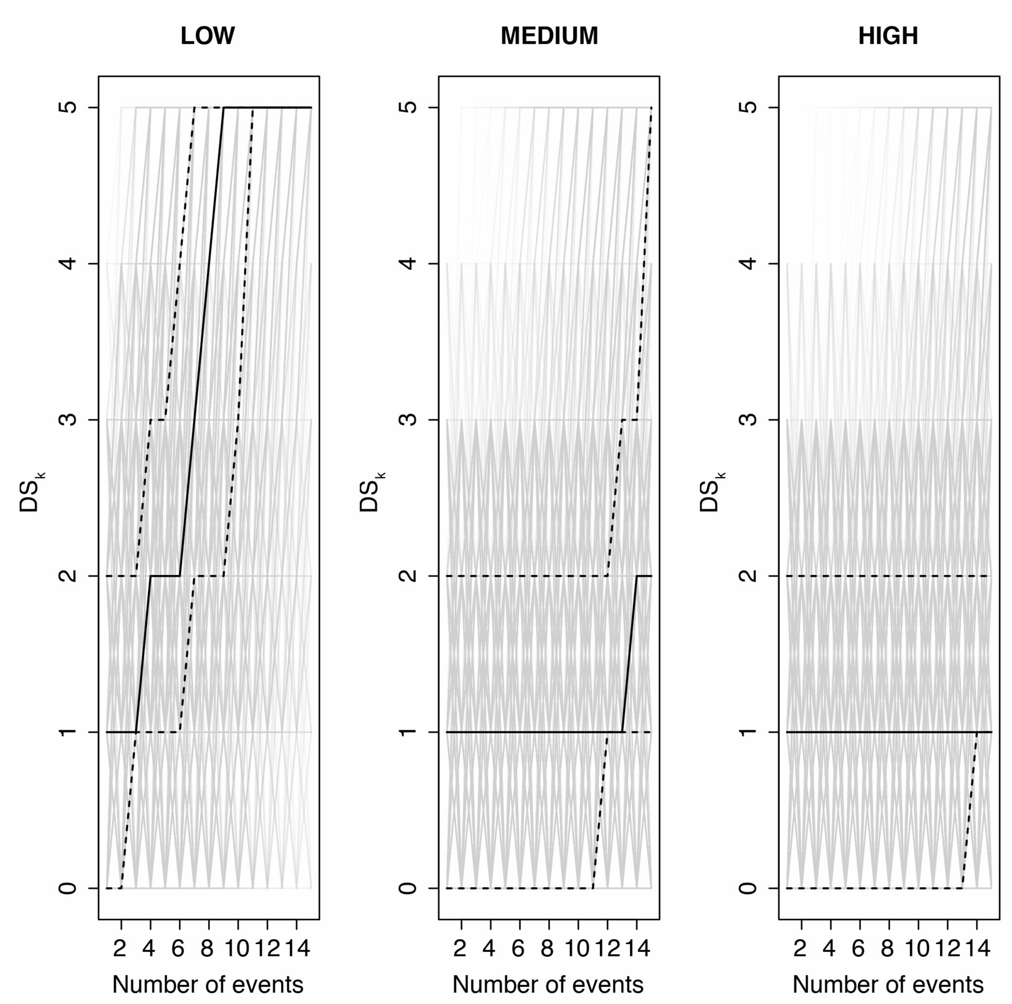

Fig. 3: Impact of repeated minor earthquake shaking on building fragility for different performances (low-high). Although the earthquake originally yields insignificant damage (DS_1), its repeat may lead to building collapse (DS_5). Developed by Mignan et al. (sub.), this model could be tested in the PhD for induced seismicity multi-risk in Switzerland.

4. Conclusions

1. A landslide 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. Network failure and lake tsunami triggering models will be investigated later on in a similar fashion (network theory / cellular automata, testing on the virtual region, application to Switzerland).
4. FINAL GOAL: Provide a unified multi-risk picture of Switzerland.

5. References

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Communicating low-probability high-consequence events in deep geothermal energy and hydropower

Theresa Knoblauch, Michael Stauffacher, Evelina Trutnevyte
Transdisicplinarity Lab, Department Environmental Systems Science, ETH Zürich

Introduction

The energy sector ranks second in man-made accidents (Burgherr and Hirschberg, 2014) and deep geothermal energy and hydropower are no exception albeit their advantage of providing reliably base-load electricity and one of the cleanest forms of energy now available (DiPippo and Renner, 2014; Gaudard and Romerio, 2014). Due to deep geothermal energy's novelty, society cannot yet rely on extensive experience in assessing these risks (Hirschberg et al., 2015, p. 52). Hydropower, even though a mature technology, might face new risks triggered by climatic change such as increasingly landslides, slope instability, etc. (Evans and Clague, 1994). The state-of-the-art knowledge is limited and fraught with uncertainty which becomes even more prevalent when considering low-probability high-consequence (LPHC) events. As society eventually bears these risks, the further deployment of deep geothermal energy and hydropower will depend on its acceptance and ability to balance them (Giardini, 2009; Trutnevyte, 2014). At the same time, it is yet unclear how to effectively communicate LPHC events related to energy technologies. Thus, transdisciplinary research is needed that focuses on the interface between scientific risk assessment and the society's needs concerning LPHC events.

Research objectives

Understanding and discussing LPHC events related to deep geothermal energy, hydropower, and other energy technologies remains a challenge (Burgherr and Hirschberg, 2014). In order to enable more informed decision and better outcomes for individuals and society (Bruine de Bruin and Bostrom, 2013), this project aims at:

1. finding research-informed ways for transparent, scientifically sound, and user-oriented communication about LPHC events related to deep geothermal, hydropower and other energy technologies;
2. understanding implications of LPHC on technology acceptance; and
3. contributing to the knowledge of how LPHC should be addressed and communicated during energy technology siting processes.

1. Communication of LPHC events

Literature does not consent on how to communicate LPHC most effectively (e.g. to include probabilities or not and how to describe the unknown unknowns, cf. Spiegelhalter et al., 2011). However, in absence of such knowledge and communication, beliefs and values fill in gap (Fischhoff, 2013). In addition, to the challenges for understanding LPHC events, human tendency for risk aversion and biases in risk perception (e.g. overestimating small probabilities, cf. Figure 1) make discussion about LPHC events even more delicate.

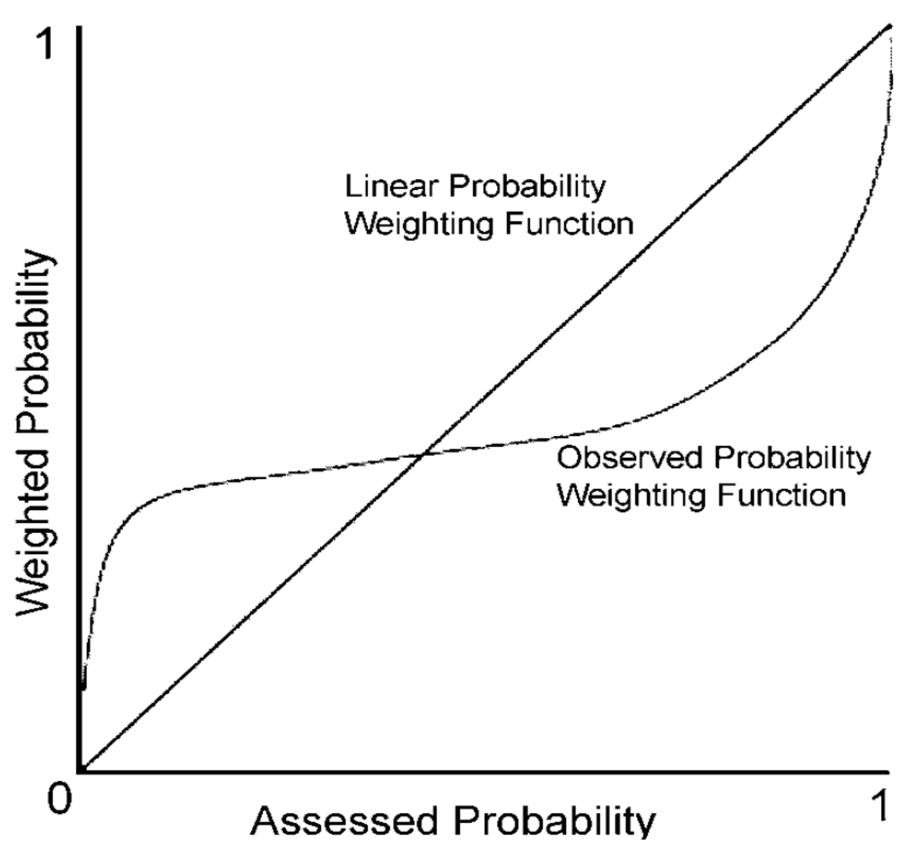

Figure 1: Probability weighting (Patt and Schrag, 2003, p.19)

Different possibilities of communicating LPHC will be tested in an experimental or quasi-experimental design (e.g. conjoint analysis).
Finding research-informed ways for transparent, scientifically-sound, and user-oriented communication about LPHC will contribute to a more informed discussion about different energy options.

2. Technology acceptance and public preferences

An interactive experiment (Figure 2) will reveal if and to what extent awareness of LPHC events and their spatial occurrence matter to an individual's technology acceptance. As risks constitute only one part of the discussion about deep geothermal energy (Stauffacher et al., 2015) the individuals' trade-offs among LPHC events, their spatial occurrence, environmental aspects, costs, as well as preferences for siting (Carr-Cornish and Romanach, 2014) will be examined by means of a virtual map of Switzerland.

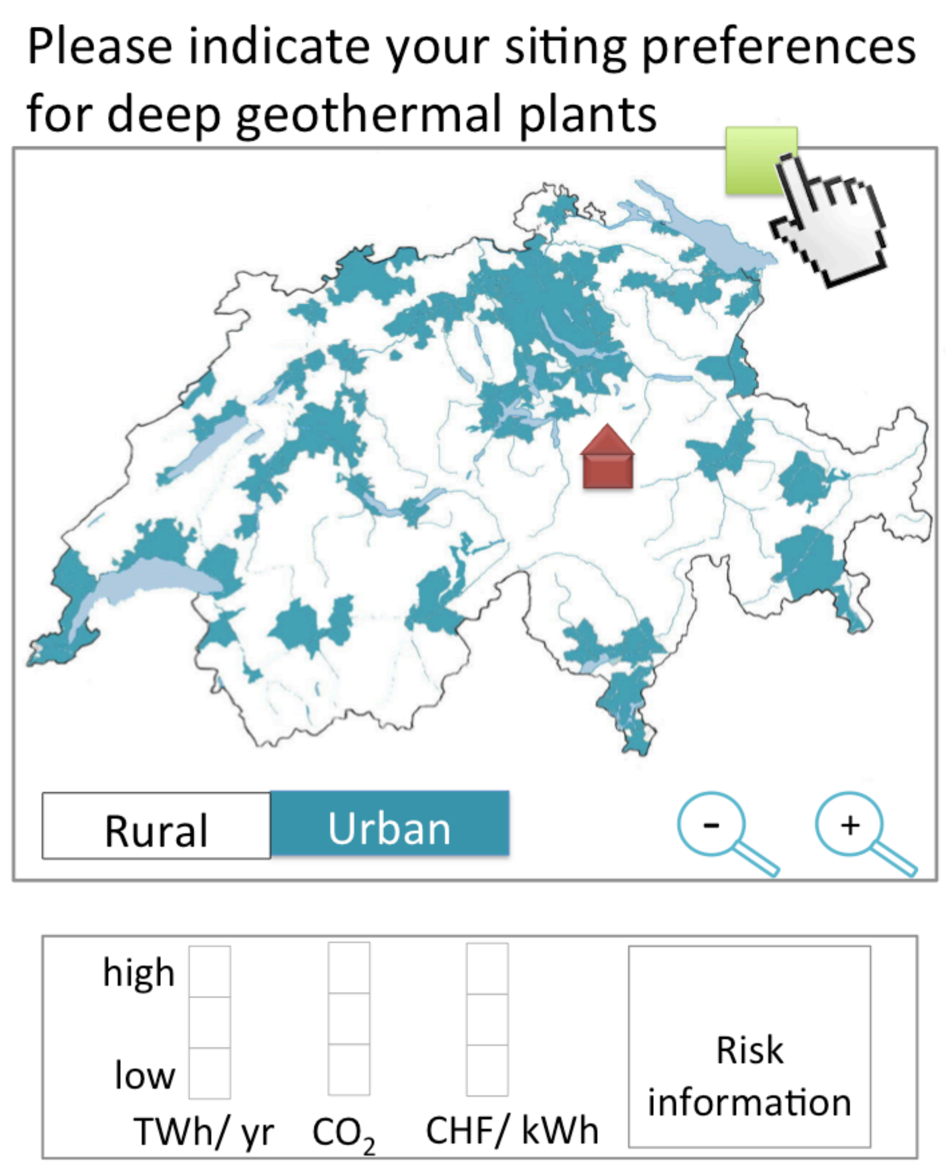

Figure 2: Draft of experimental map

3. Process

Direct or delegated public participation enhances decision robustness and risk acceptance (Arvai, 2003; Krütli et al., 2012). Various models of implementing energy technologies that bear LPHC events exist, such as corporate initiative, participation, shared-ownership, or moving the project away from communities (Hoşgör et al., 2013). As effort and costs of each model vary, analysing their trade-offs and potentials, combined with actors' interviews will provide evidence for robust decision processes for siting deep geothermal energy and expanding hydropower.

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Mitigating the Risk of Intermittent Power Sources

Bert Kruyt, Stuart Bartlett, Annelen Kahl and Michael Lehning

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Abstract

- Wind & photovoltaic electricity generation are inherently **stochastic** due to **weather variability.**
- As stochastic power generation increases, so do the **risk** of supply-demand imbalance and the risks due to **extreme weather**.
- The topography of the Alps causes large climatic fluctuations on small geographic scales.
- Can the systematic differences in wind distribution be exploited to
  1. Reduce **variability** of power output.
  2. Provide resilience under **extreme** weather scenarios and **persistent** weather?

Introduction

- Variability of renewable sources calls for costly **backup capacity** or storage to **dampen fluctuations** (or dedicated hydro strategies).
- With increasing shares of intermittent power production, its stochastic nature becomes an issue.
- In open terrain, **wind speeds are correlated over long distances** (see fig 1).
- Yet in the Alps: low correlations on a small geographic scale (fig 2).

➢ **Can the allocation of wind turbines be optimised to minimise output variation and associated risks?**
➢ **What is the trade-off between yield maximisation and variance reduction?**

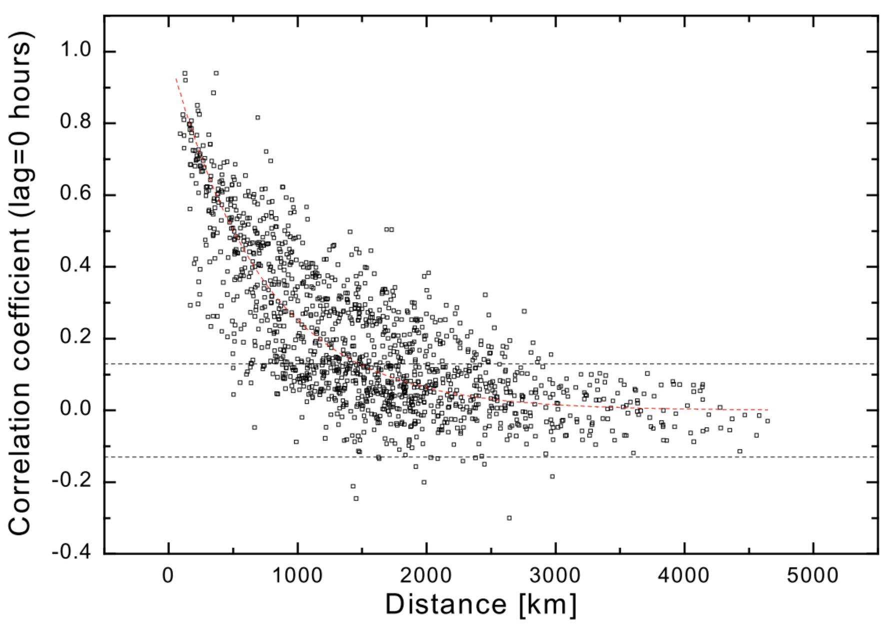


Fig 1: Correlation between wind speeds in Europe, from Giebel et al 2003 (Used with permission). Fitted distribution in dashed red, which is also displayed in fig 2 for comparison. Black dashed lines are merely to guide the eye.

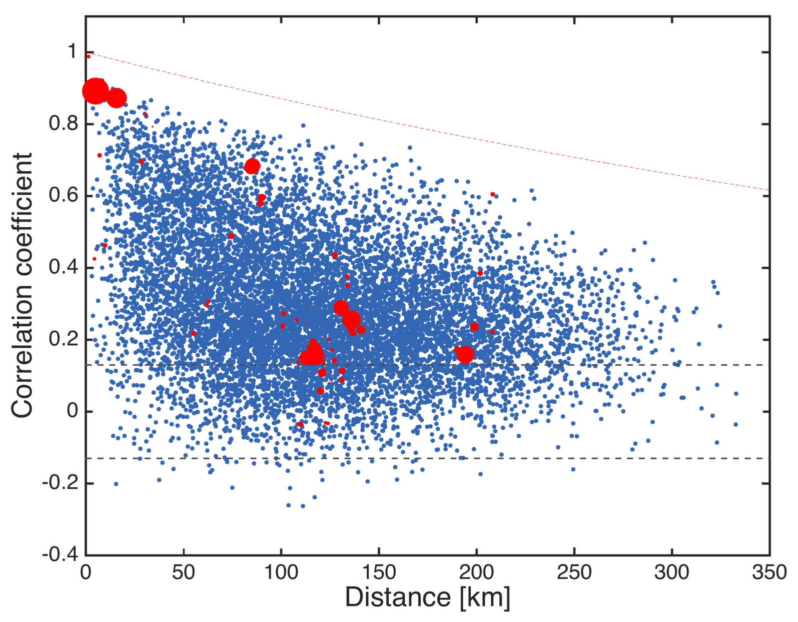


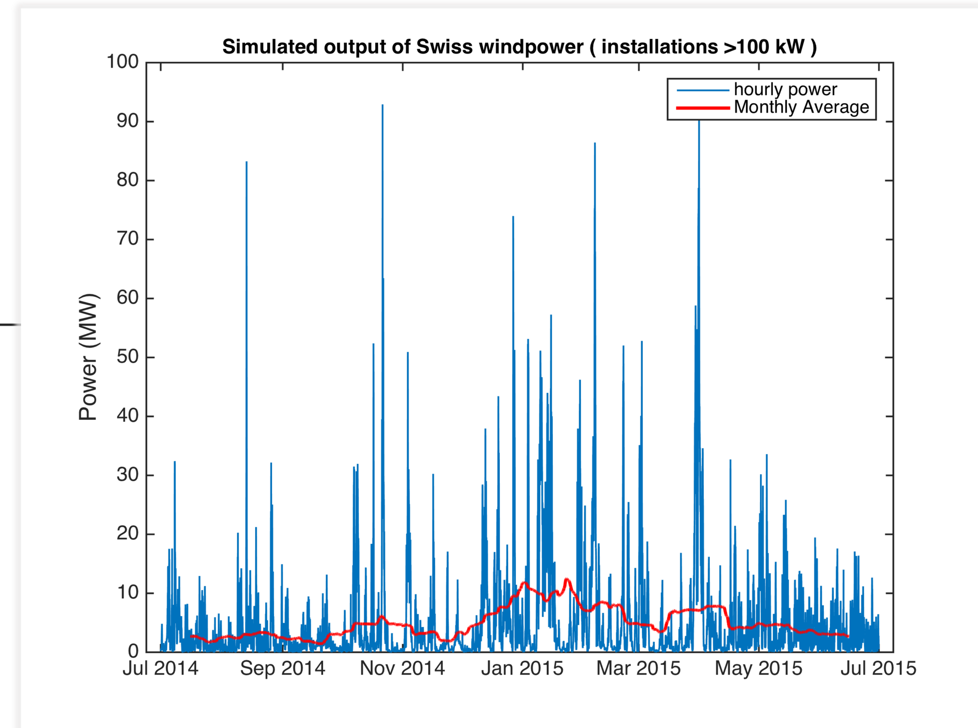
Fig 2: Correlation between wind speeds at SwissMetNet stations in Switzerland (blue) and wind power installations (red). The size of the red dot indicates the pairwise product of installed capacity.

Proposed outcome

Optimal spatial configuration of wind generation that minimises variation (fig 4) and maximises power output.

Return levels for extreme events:
- Long periods without wind (persistence).
- High winds that either lead to
  - high power input and danger of violating grid constraints.
  - Low power because turbines need to be shut down

Fig 3: a year of wind power production in Switzerland. Simulation of the 13 largest installations.



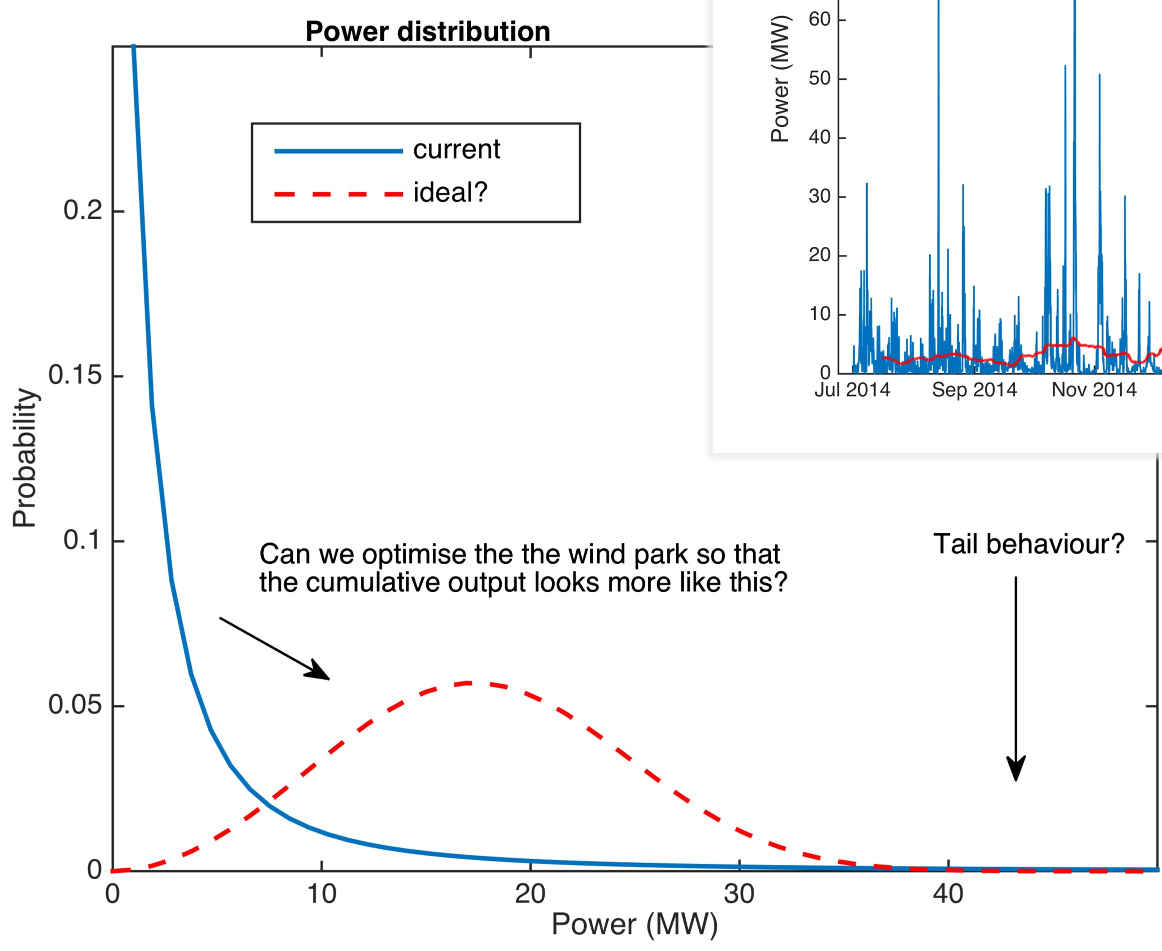


Fig 4: Blue: The distribution of hourly power generation over the same year (as fig 3). Red: an idealised stable power distribution.

Related work at EPFL/CRYOS

- Identification of **high potential wind areas** in the Alps using computational fluid dynamics.
- Solar Photovoltaics: assessment of **resources and extremes**; optimisation in space and time.
- Modelling of **hydropower strategies** w.r.t. balancing of intermittency
- Combined, these should lead to a model that allows us to investigate **the effects of extreme weather on a Swiss power system** with increasing levels of weather dependent renewables.

Methods

- Data: Hourly wind speeds for Switzerland from the **COSMO model** and Swiss MetNet (SMN) Stations .
- Identify useful **statistical measures** to investigate **variability** (coefficient of variation), **persistence** (autocorrelation, conditional probability, speed duration curves), and **extremes** (extreme value theory, return levels/periods).
- Compare different system configurations based on these metrics.
- **Optimise** with regards to **risk** and to cumulative power production.
- Investigate the **trade-off** between yield maximisation and variance reduction.
- Explore the **resilience** under longer and extreme weather scenarios.

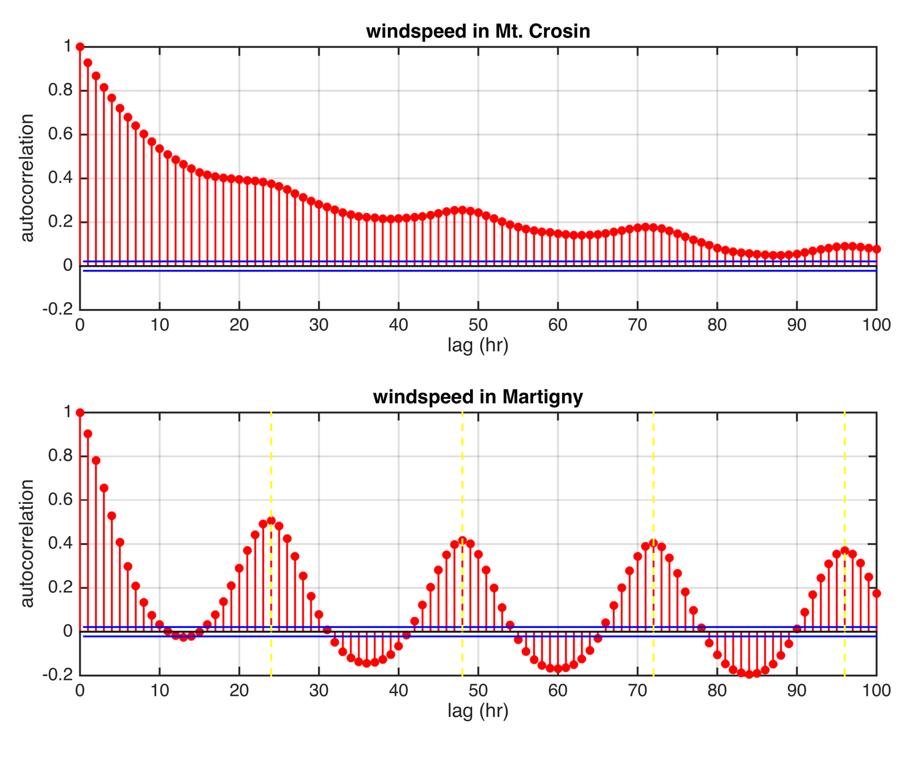


Fig 5: Autocorrelation functions of wind speeds at two locations: Mt. Crosin in the Jura (homogenous terrain) and Martigny in a valley in Valais. The latter shows a strong diurnal pattern.

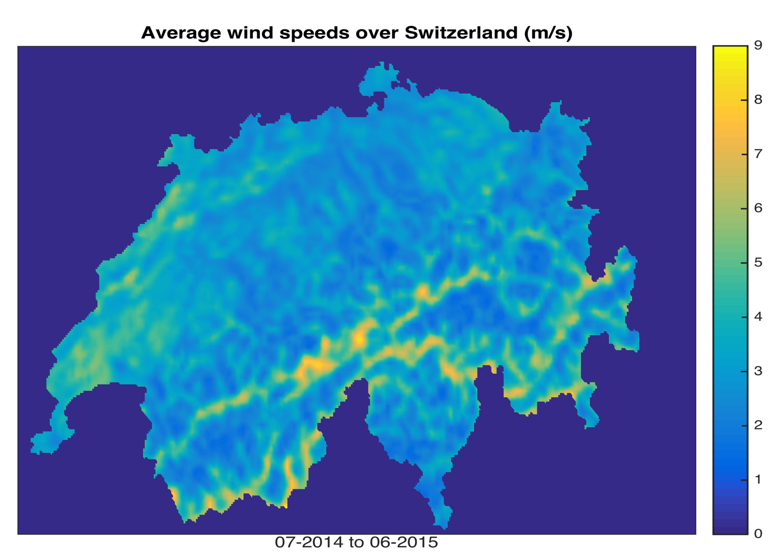


Fig 6: Map of mean wind speeds in Switzerland (07/2014- 06/2015)

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Acknowledgements:

- Cosmo data supplied by MeteoSwiss.
- Fig 1. from Giebel, G., Czisch, G. & Mortensen, 2003. Effects of large-scale distribution of wind energy in and around Europe. (Presentation at Risø International Energy Conference).