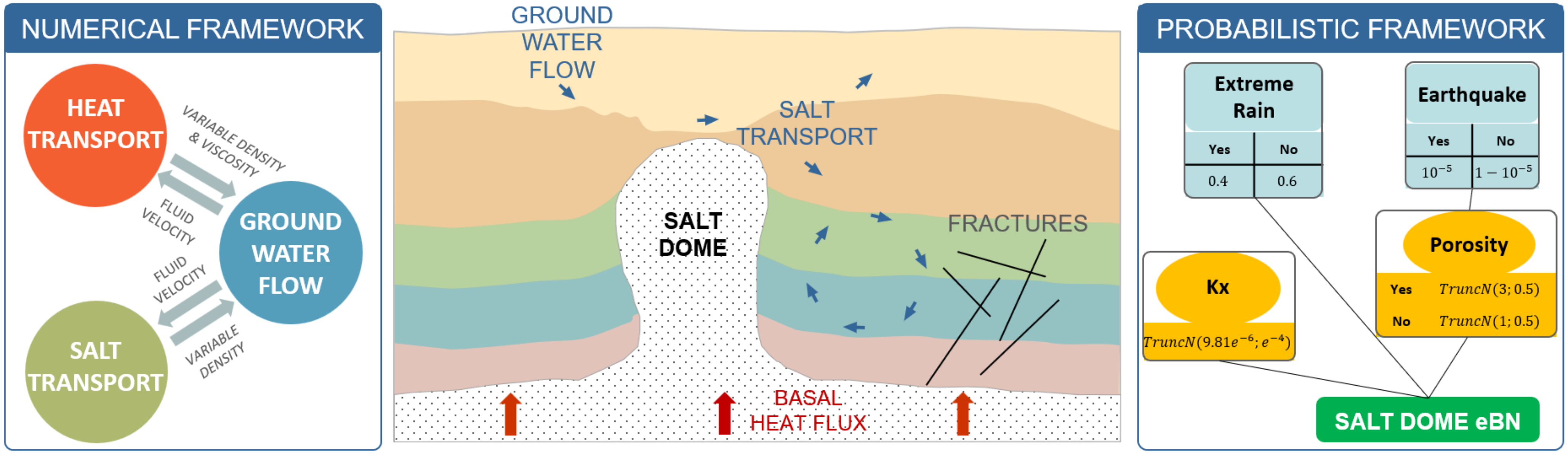
Institute of Fluid Mechanics
and Environmental Physics
in Civil Engineering

INSTITUTE FOR RISK AND RELIABILITY

Leibniz Universität Hannover

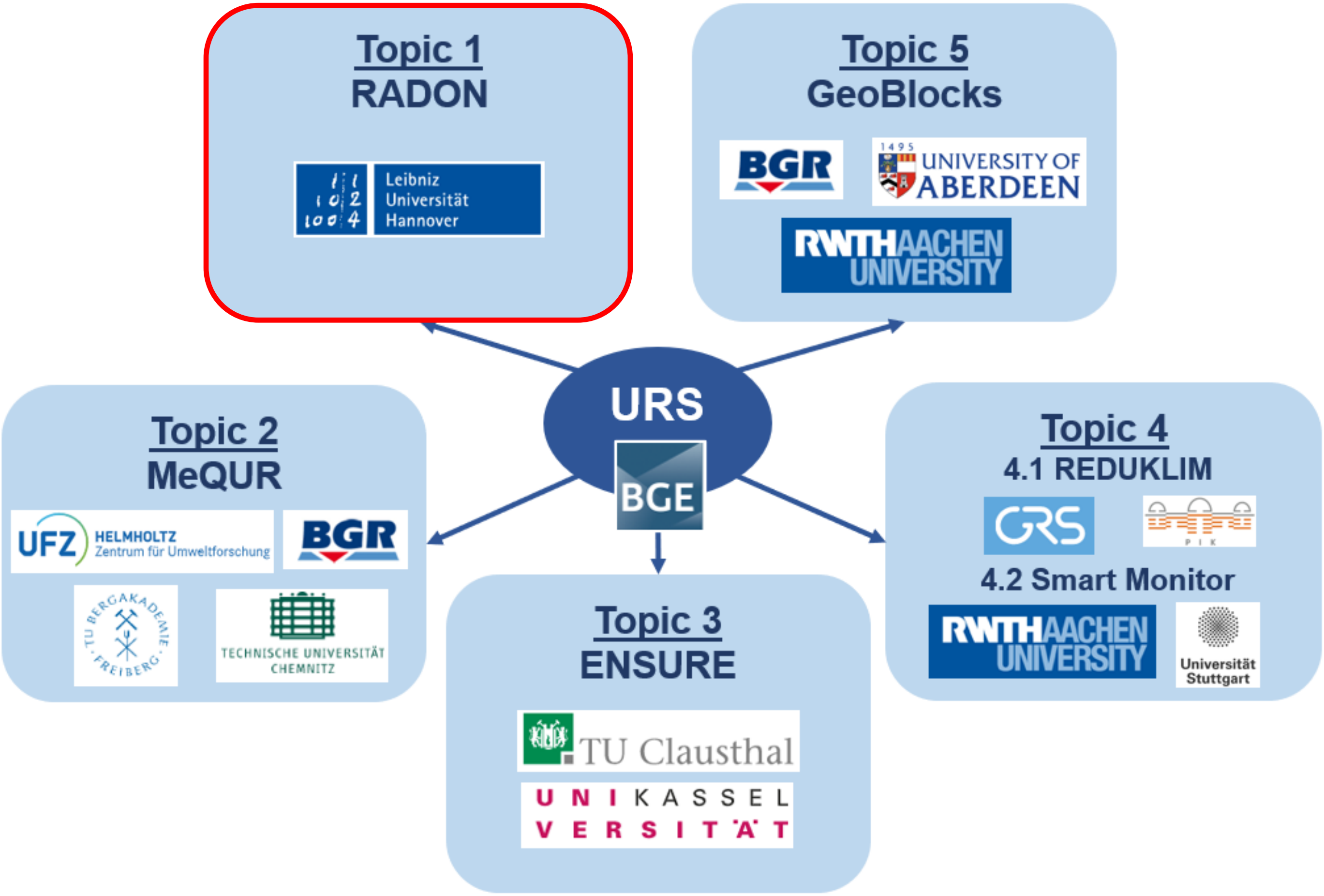
RADON – Risk-based Assessment of Salt Domes as Disposal Sites for Nuclear Waste

Matteo Broggi ••• Thomas Graf ••• Andrea Perin ••• Jonas Suilmann



06.02.2025

Topic Orientation



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Team

Inst. of Fluid Mechanics:

Jonas Suilmann (PhD cand.)
Thomas Graf (PI)

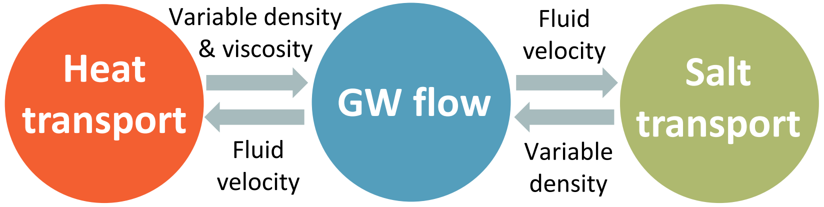
Inst. of Risk and Reliability:

Andrea Perin (PhD cand.)
Matteo Broggi (PI)

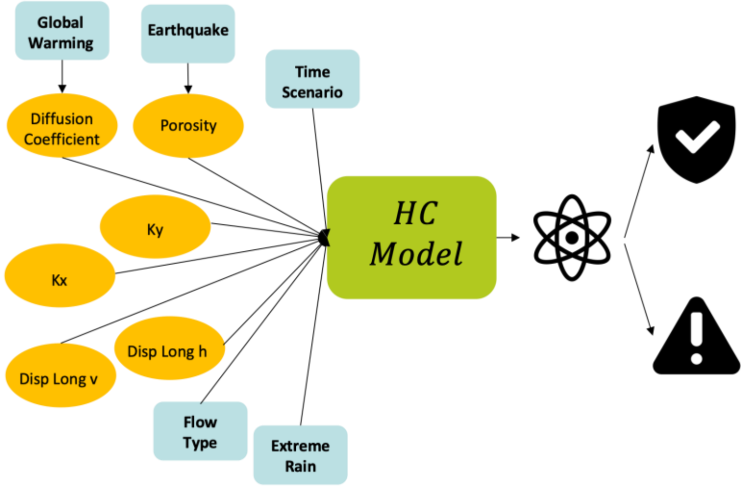
All from LU Hannover

Motivation

<u>Goal</u>: Develop a **numerical framework** for **risk assessment** of hazardous events of a final nuclear waste repository (salt dome)

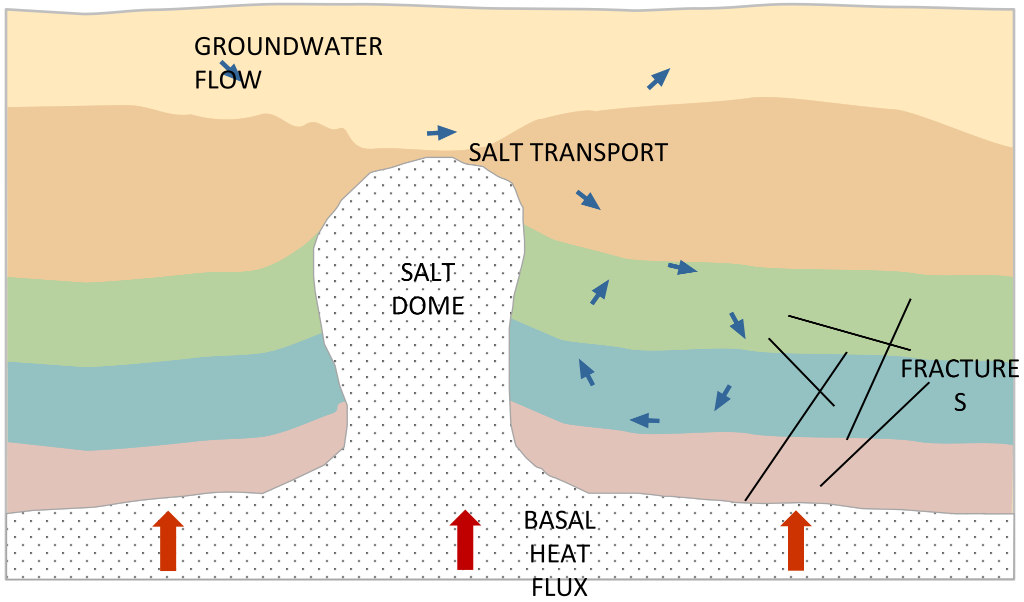


- Salt rock (salt domes) have been investigated intensively in Germany
- Numerical model of flow and transport in far field
- Uncertain model parameters and boundary conditions
- Uncertainty quantification
- Framework is a coupling between numerical model and an Enhanced Bayesian Network (EBN)



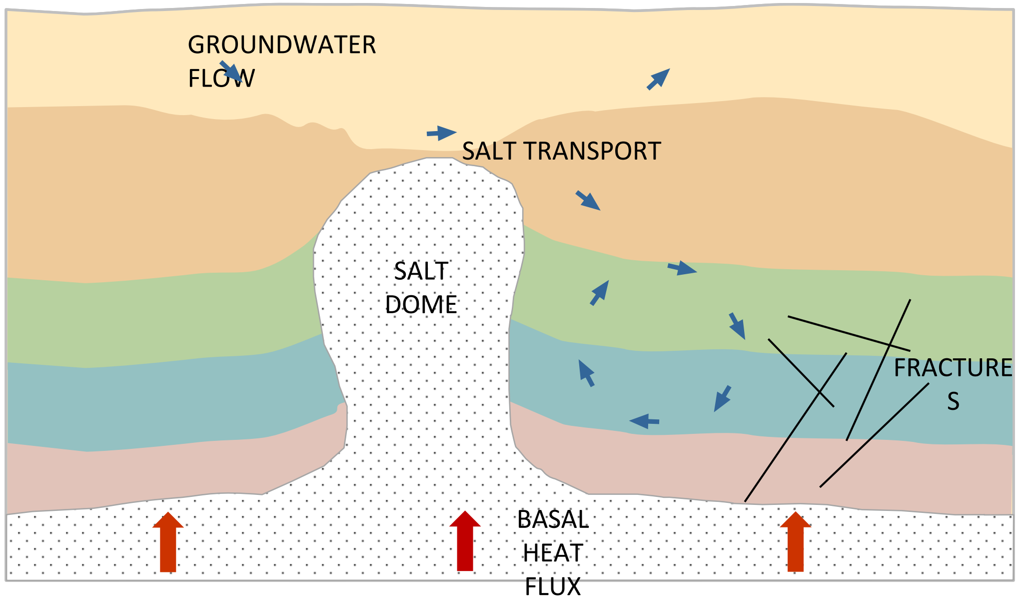
Numerical Assessment of Mixing Parameter Uncertainty on Thermohaline Groundwater Flow in Fractured-Porous Media

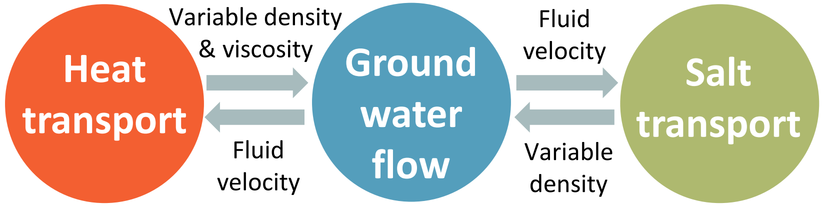
Jonas Suilmann, ISU



Motivation

- Potential radionuclide migration through groundwater flow near **salt dome**
- Relevant processes:
  - Solute transport (variable-density flow)
  - Heat transport (variable-viscosity flow)
  - Uncertain transport parameters
  - Life expectancy (as radionuclide travel time estimate)





Research Objectives

1. **Effects of uncertain transport parameters** (finished; published)

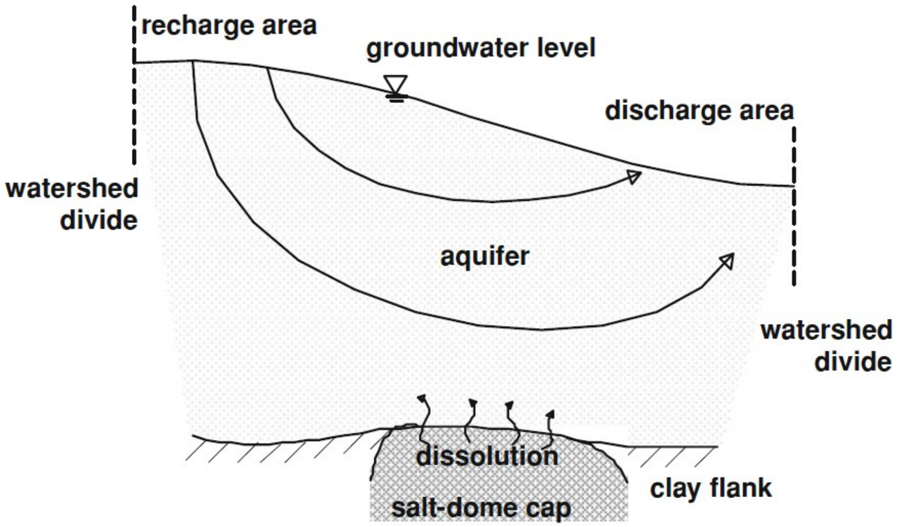
   Effect of mixing on groundwater age and life expectancy simulations in density-dependent flow above salt domes

2. **Thermohaline flow near a salt dome** (ongoing)

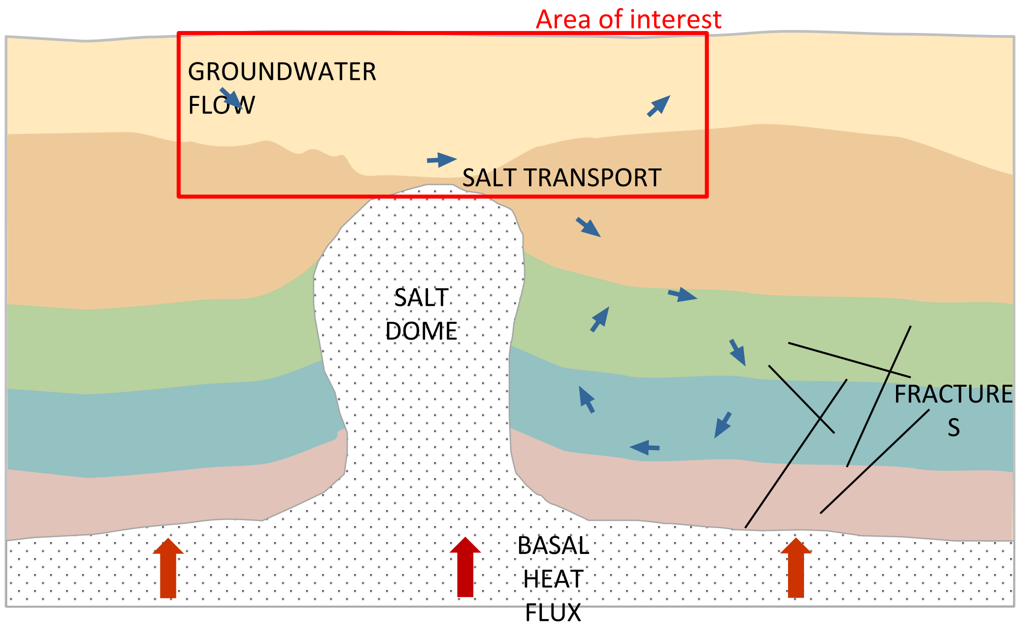
   Numerical assessment of thermohaline groundwater flow in fractured-porous media near salt domes

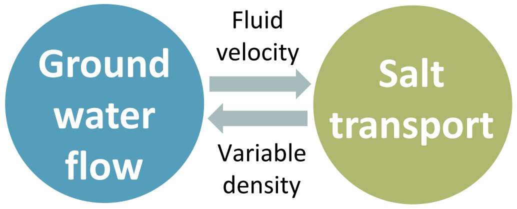
1. Effects of Uncertain Transport Parameters

- **Density-dependent flow** above a salt dome
- Potential migration of radionuclides through groundwater flow
- Uncertain transport processes (dispersion, diffusion)



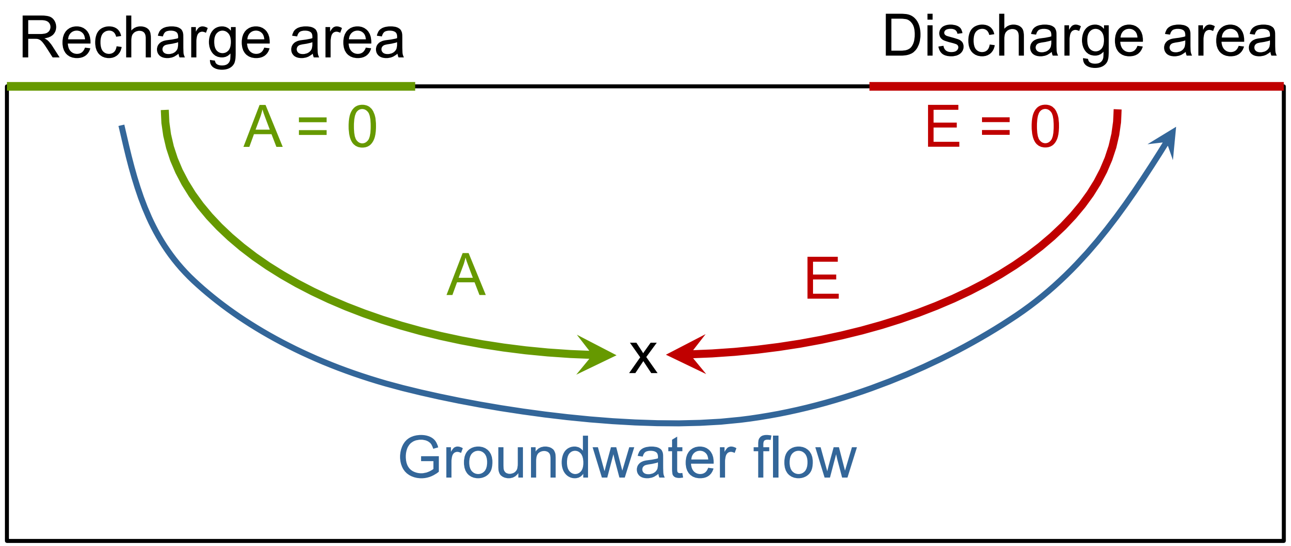
Holzbecher et al. 2010



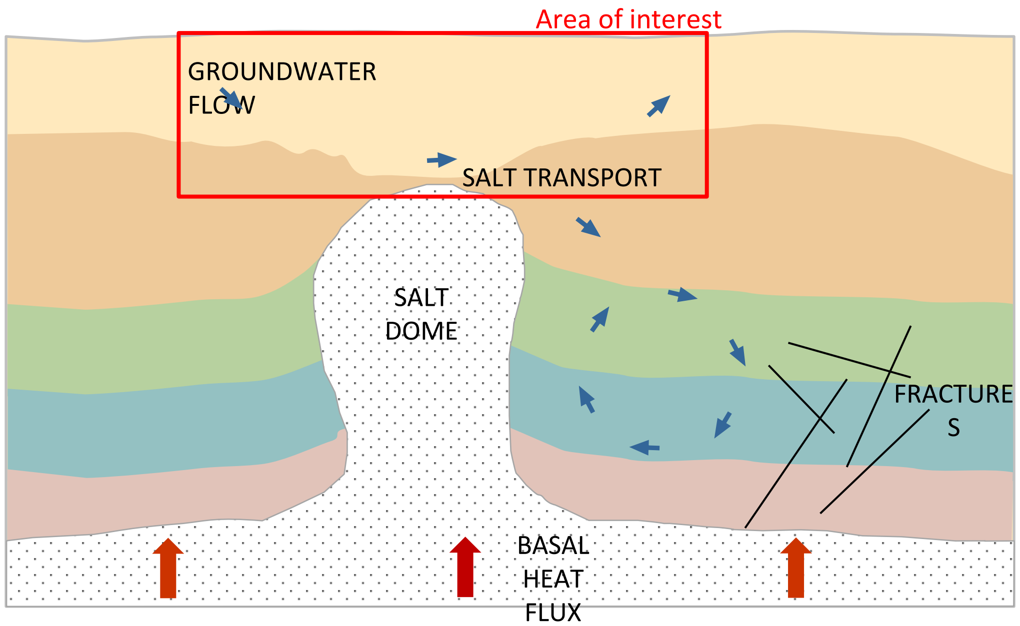


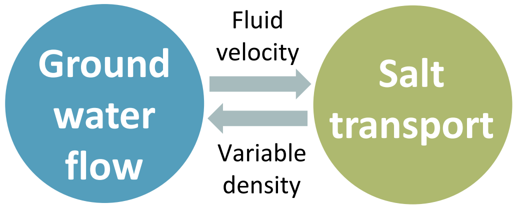
1. Effects of Uncertain Transport Parameters

- **Groundwater life expectancy** as estimate for radionuclide travel times
- Investigations of density-dependent flow and uncertain transport processes



A - groundwater age, E - life expectancy





1. Effects of Uncertain Transport Parameters

Principle study using the Salt Dome Problem for:

- Investigating effects of **uncertain transport parameters**
  - on **density-dependent flow** above salt dome
  - on resulting **groundwater age** and **life expectancy** above salt dome

- Investigating effects of density-dependent flow on groundwater age and life expectancy as used in the **safety assessment** for potential disposal sites

1. Effects of Uncertain Transport Parameters

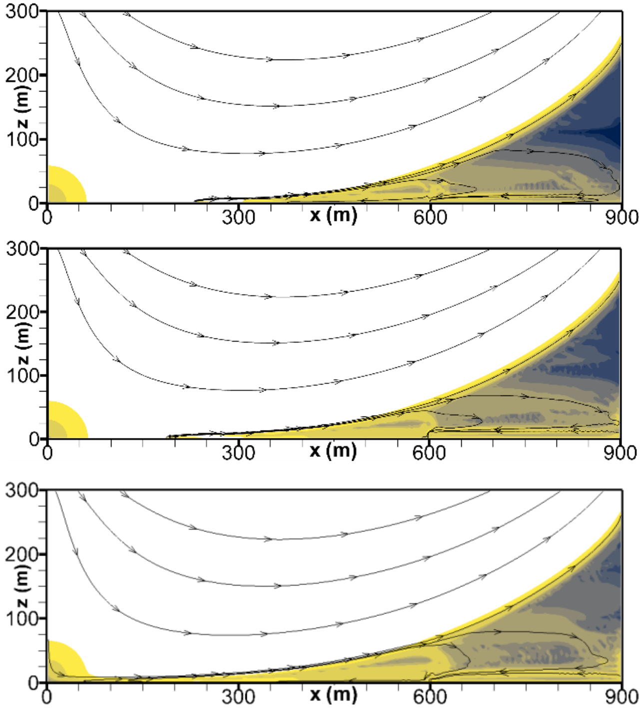
Results

- Effect of longitudinal and transverse dispersivity on DDF flow

$\boldsymbol{\alpha_L}$ **= 5 m**
α_T = 0.4 m

$\boldsymbol{\alpha_L}$ **= 10 m**
α_T = 0.4 m

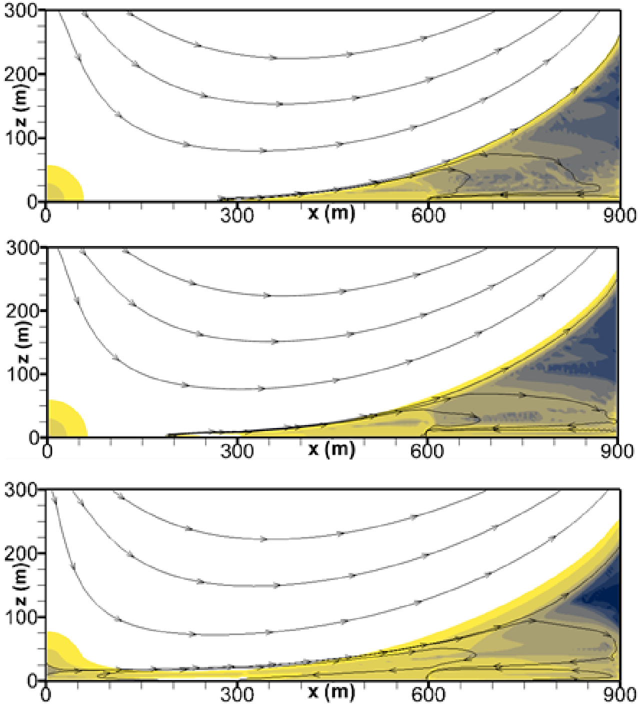
$\boldsymbol{\alpha_L}$ **= 20 m**
α_T = 0.4 m



α_L = 10 m
$\boldsymbol{\alpha_T}$ **= 0.1 m**

α_L = 10 m
$\boldsymbol{\alpha_T}$ **= 0.4 m**

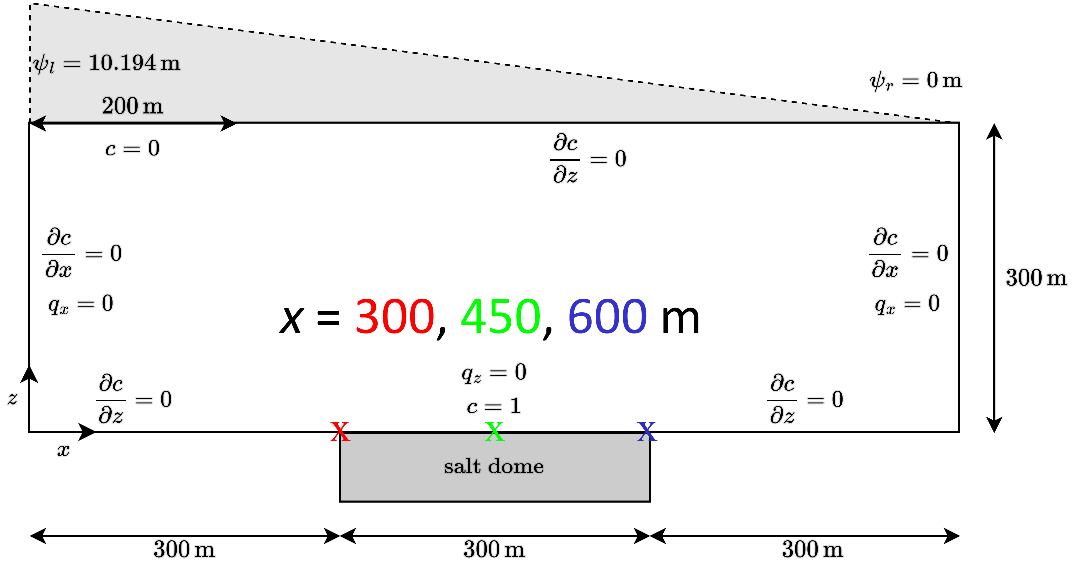
α_L = 10 m
$\boldsymbol{\alpha_T}$ **= 2 m**



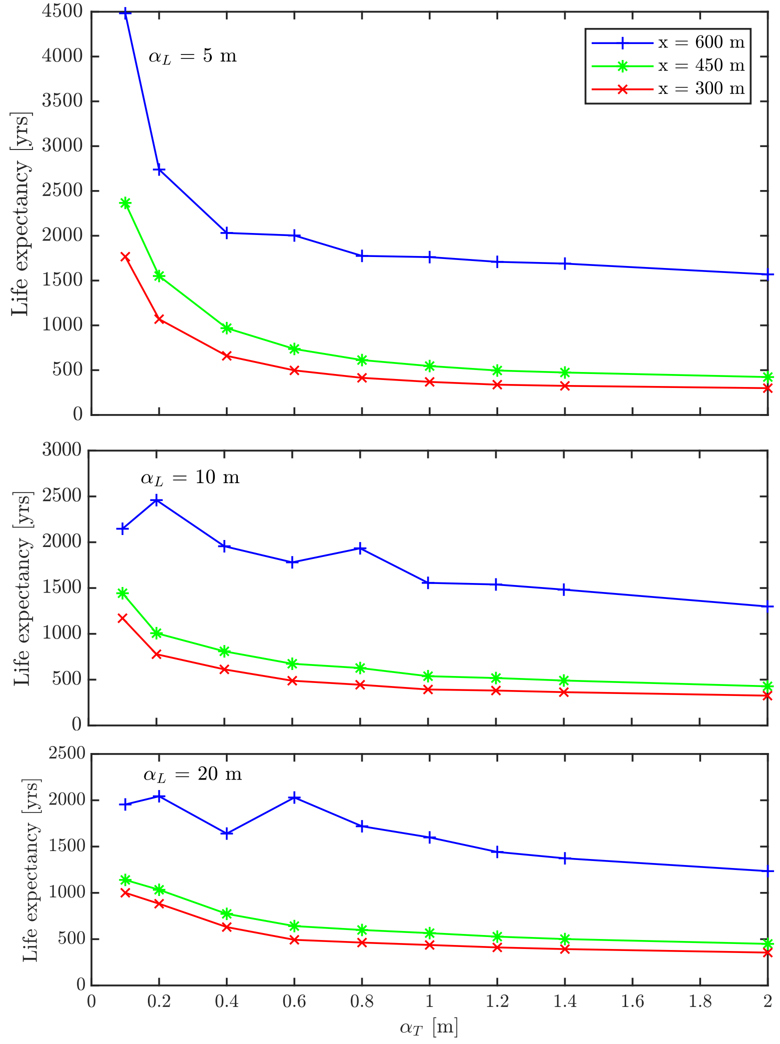
1. Effects of Uncertain Transport Parameters

Results

- Effect of dispersivity on **life expectancy** along lower boundary



Adapted from Herbert et al. 1988 and Diersch 2013



$D_m = 10^{-9}\ \mathrm{m^2\ s^{-1}}$

1. Effects of Uncertain Transport Parameters

Conclusions

- Uncertain dispersivities highly affect DDF system
- **Diffusion** has a significant effect on maximum life expectancies
- **Longitudinal and transverse dispersion** highly effect life expectancies as used in the safety assessment of repositories
- Underestimating longitudinal, transverse dispersivity or diffusion may lead to overestimating life expectancy close to a salt dome and, thus, to **overestimating safety** of nuclear waste disposal sites.

Importance of considering uncertain transport parameters in evaluating groundwater age and life expectancy as safety indicators for nuclear waste disposal

1. Effects of Uncertain Transport Parameters

Current status

1. Paper accepted:

- *Hydrogeology Journal* - Special Issue: "Role of Groundwater in Geologic Processes"
- Outcome of cooperation with Prof. John Molson (Université Laval, Québec, Canada)

Effect of mixing on groundwater age and life expectancy simulations in density-dependent flow

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Abstract

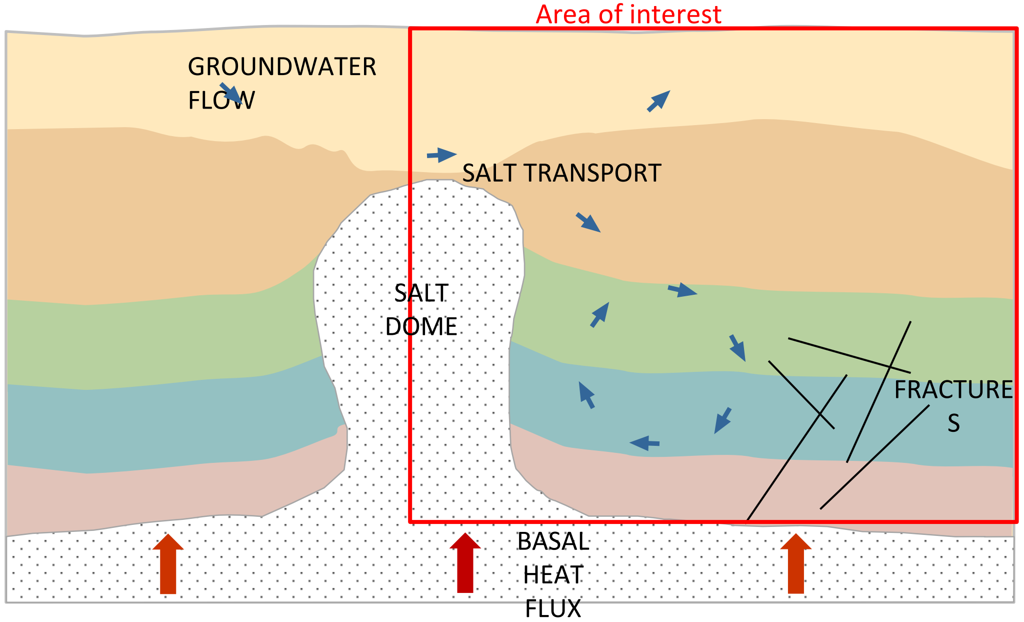
Keywords: Dispersion, Diffusion, Density-dependent flow, Groundwater age, Groundwater life expectancy, Nuclear waste disposal

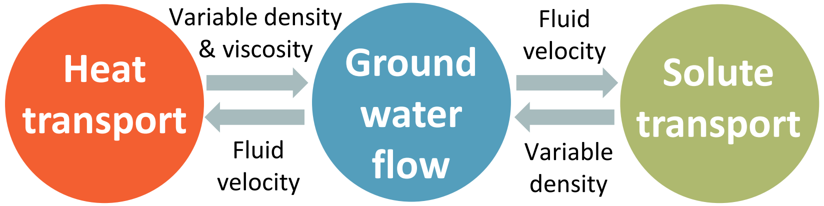
Groundwater flow above deep geological repositories in salt domes may lead to transport of radionuclides into the biosphere. To mitigate this risk, groundwater age is used as an exclusion criterion for repository site selection, and groundwater life expectancy is an established measure for radionuclide travel times. Complexities arise in computing age since groundwater flow above salt domes is highly density-dependent due to the presence of brine. Flow and solute transport are therefore strongly coupled and are also affected by mixing processes, including diffusion and mechanical dispersion, which is aquifer-specific and highly uncertain. Numerical simulations have been carried out to address this uncertainty for 2D topography-driven and density-dependent groundwater flow above salt domes. Simulation results show that the components of longitudinal and transverse dispersion have a strong influence on the density-dependent flow system and therefore, along with diffusion, significantly affect groundwater age and life expectancy. Underestimation of the associated parameters may lead to overestimation of life expectancy and thus to critical overestimation of repository safety. Selecting appropriate parameter values and

2. Thermohaline Flow near a Salt Dome

Large-scale model around a salt dome

- Including groundwater flow coupled with solute & **heat transport**
- **New processes** to investigate effects on thermohaline convection:
  - **Heat generation** of radioactive waste
  - **Fractures**





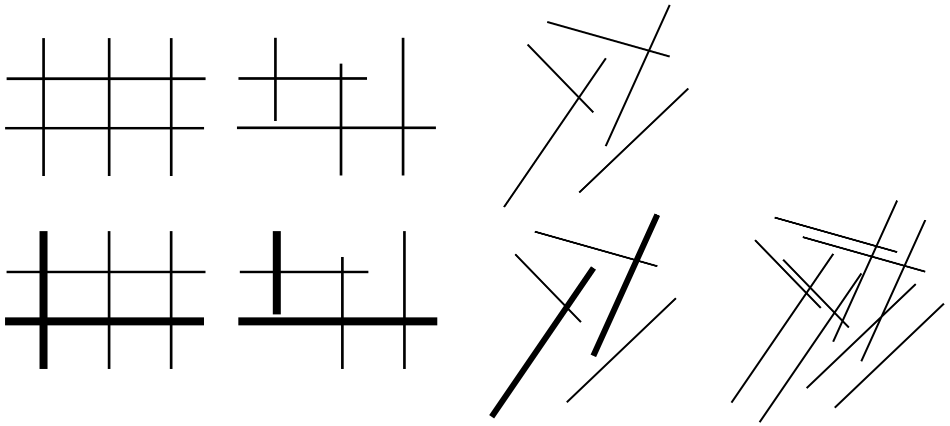
2. Thermohaline Flow near a Salt Dome

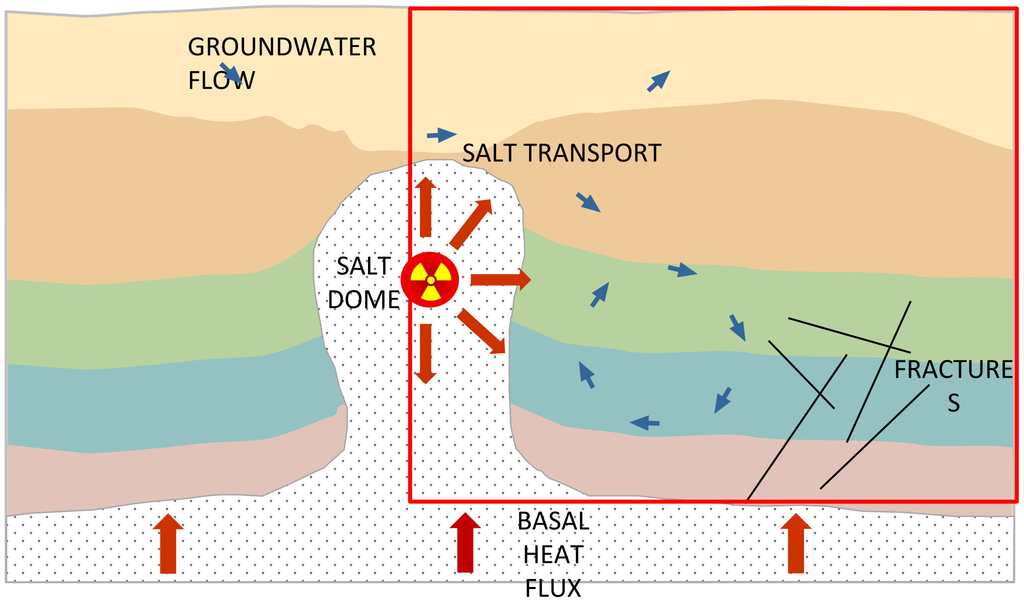
Open questions

Fractures in surrounding layers have not been taken into account

➢ Source of uncertainty in thermohaline flow

- **Effect of fractures** on thermohaline convection?
- Effect of **heat generation** by radioactive waste on thermohaline convection in fractured rock?

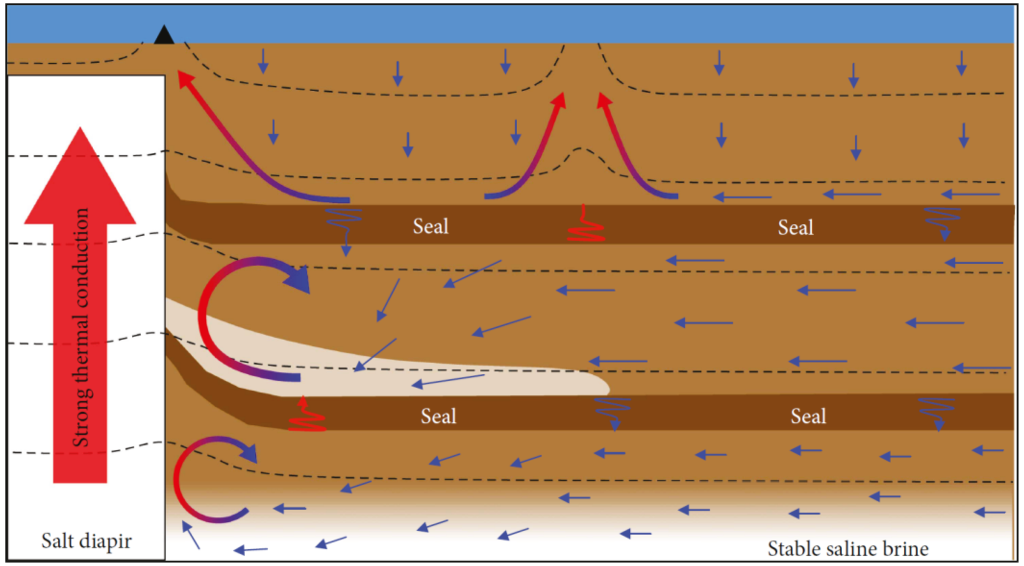




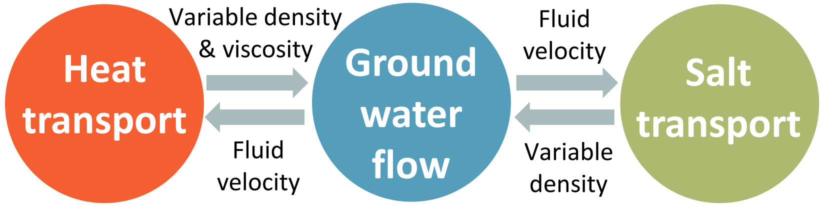
2. Thermohaline Flow near a Salt Dome

Salt chimney effect

- High thermal conductivity of salt compared to surrounding sedimentary rock
- Heat is conducted more efficiently through salt, leading to elevated temperatures
- Results in thermohaline convection



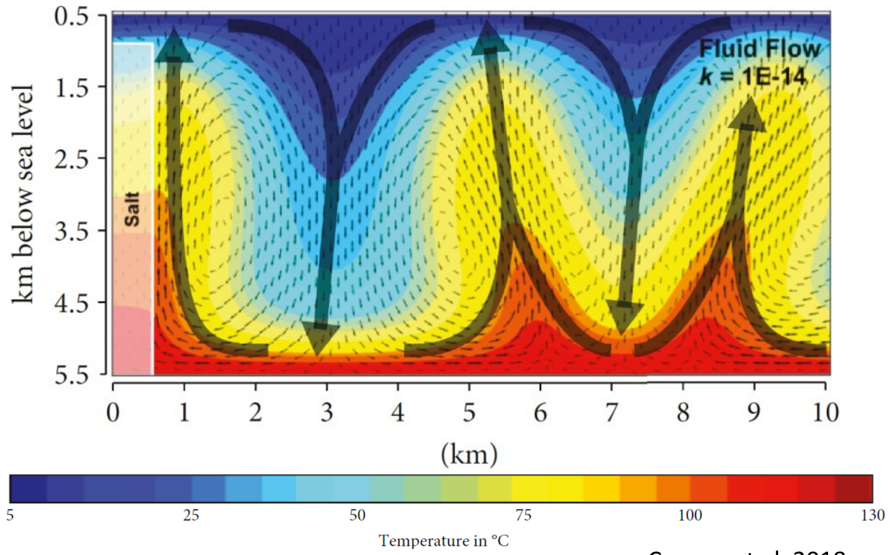
Canova et al. 2018



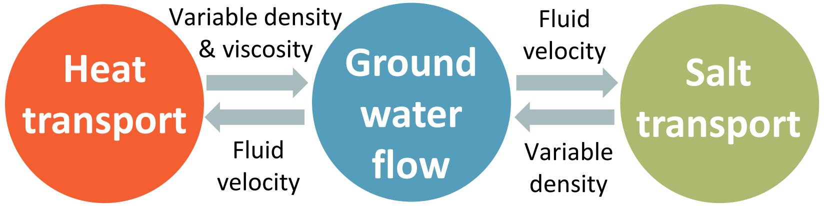
2. Thermohaline Flow near a Salt Dome

Literature

- Thermohaline convection around generic salt domes (e.g. Ranganathan and Hanor, 1988; Canova et al., 2018) and case studies (e.g. Jamshidzadeh et al., 2015; Zechner et al., 2019)
- Canova et al. (2018): Thermohaline convection for salt domes at different geological stages
- Inclusion of heterogeneous adjacent strata



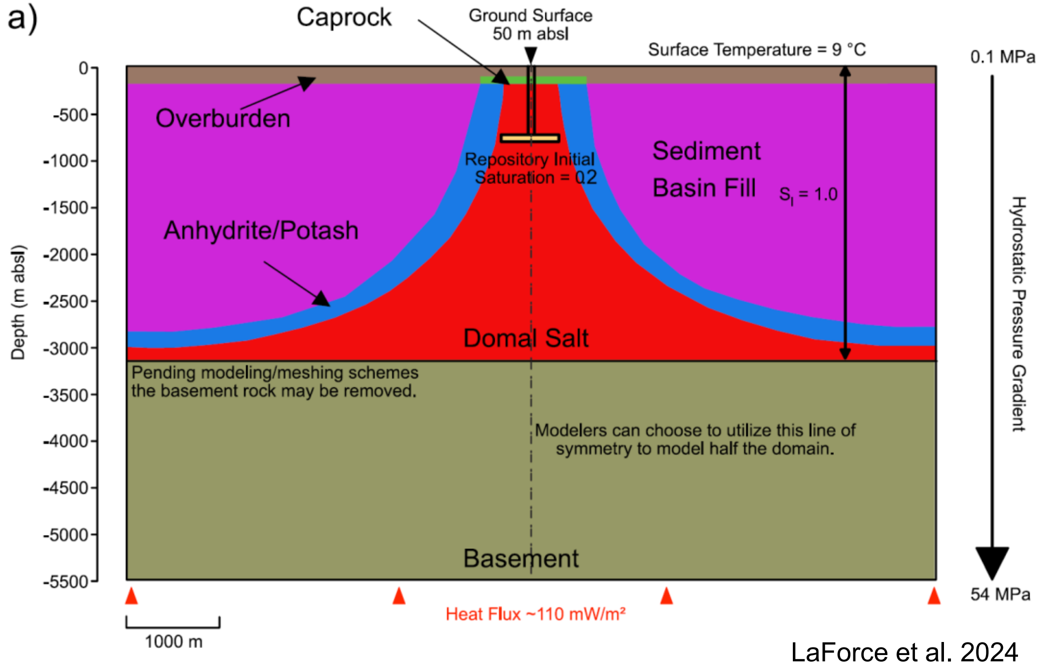
Canova et al. 2018



2. Thermohaline Flow near a Salt Dome

Literature

- Definition of a far-field salt dome repository problem in DECOVALEX-2023 (LaForce et al. 2024)
- Focus on repository post-closure performance assessments
- Isothermal scenario



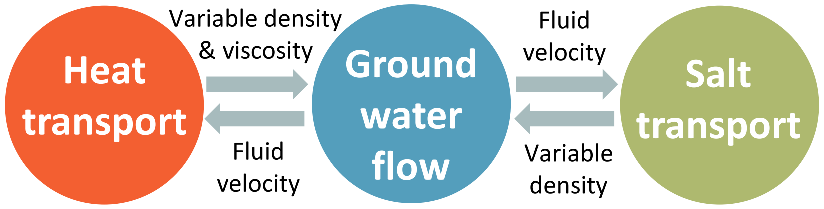
LaForce et al. 2024

2. Thermohaline Flow near a Salt Dome

Methods

- Numerical code
- Feflow (Diersch, 2014)
- Commercial, well established software

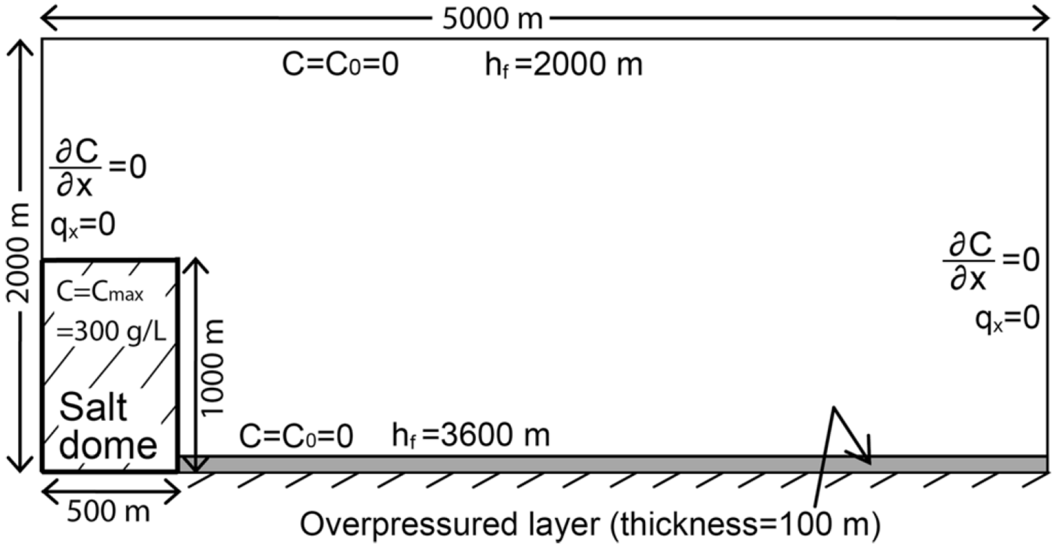
- Simulations of:
  - Variable density/viscosity flow coupled with solute and heat transport
  - Fractured-porous media
  - Discrete fractures



2. Thermohaline Flow near a Salt Dome

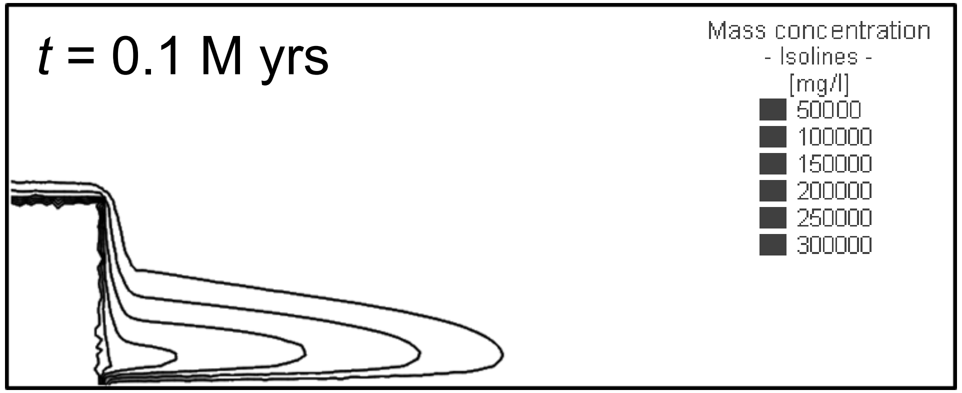
Results: Flow & Solute transport

- Using Feflow to simulate density-dependent flow
- Comparing to Ranganathan and Hanor 1988

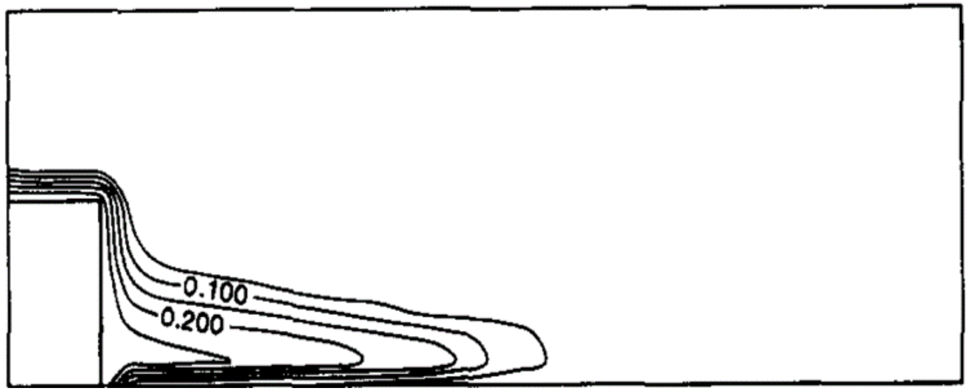


Ranganathan and Hanor 1988

Feflow, this study



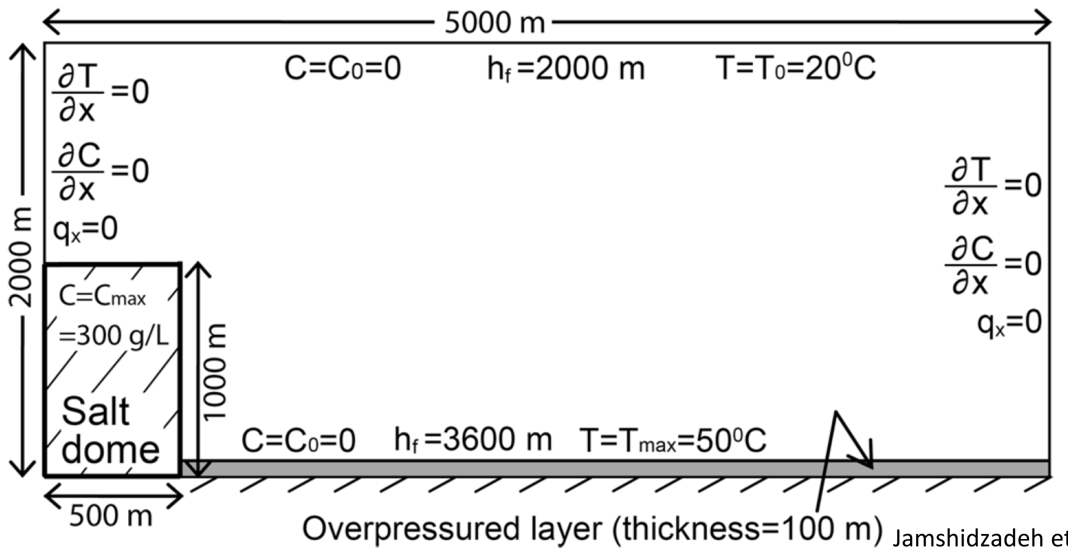
Ranganathan and Hanor 1988



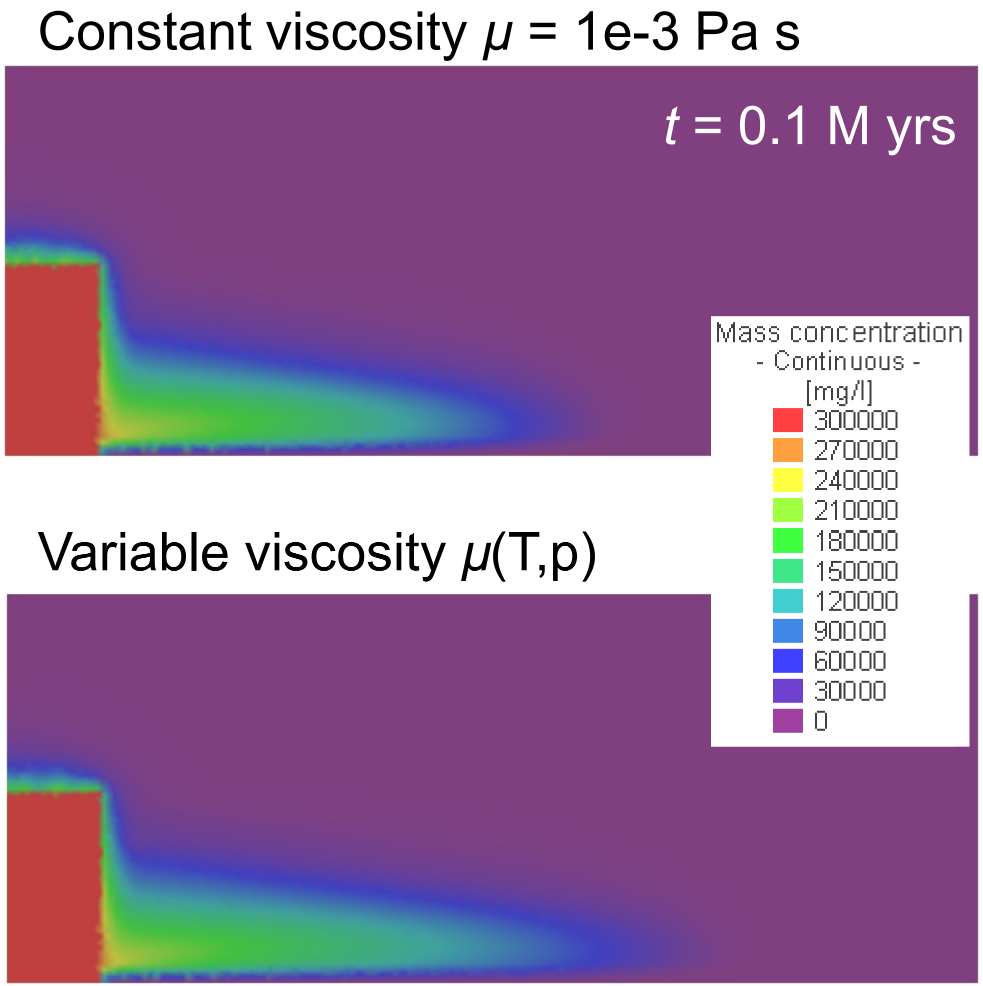
2. Thermohaline Flow near a Salt Dome

Results: Flow, Solute & Heat transport

- Thermohaline flow case (Jamshidzadeh et al., 2015:
- Increased salt transport due to temperature dependent viscosity

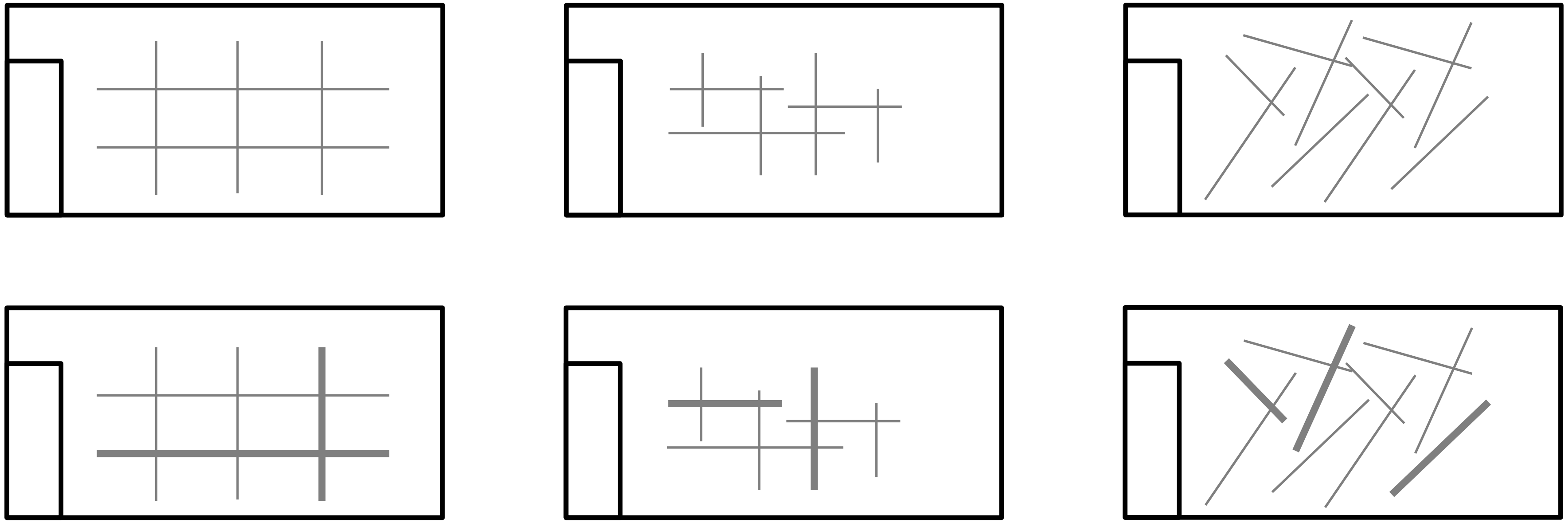


Jamshidzadeh et al., 2015



2. Thermohaline Flow near a Salt Dome

Definition of a thermohaline, fractured salt chimney problem



- Investigating effects of different fracture networks on thermohaline flow

2. Thermohaline Flow near a Salt Dome

2. Paper: Work in progress

Thermohaline convection in fractured-porous media near salt domes

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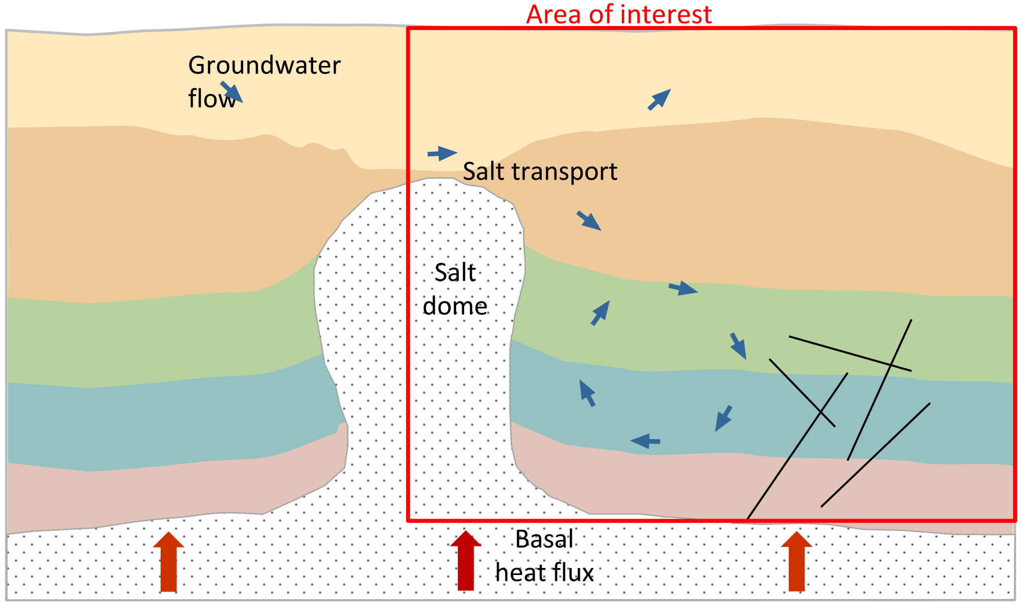
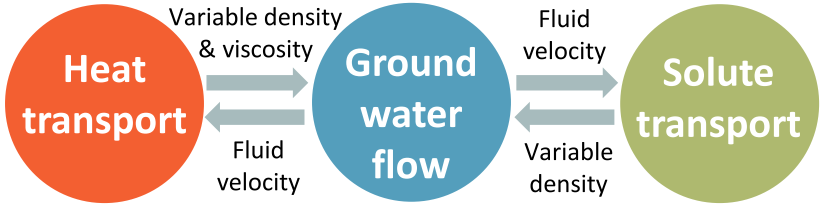
Abstract

Groundwater flow around salt domes, that are considered as host rocks for nuclear waste dispoal, may lead to transport of radionuclides into the biosphere. Due to higher thermal conductivity of salt rock, the temperatures above salt domes are increased, which is called "salt chimney effect". This effect leads to thermal convection in adjacent strata of the salt dome. The salt rock will consequently dissolute, which leads to thermohaline convection. The objectives of the present study are to investigate the effects of structured and unstructered fracture networks in adjacent strata of salt domes on: 1. salt dissolution, 2. thermohaline convection as a result of the salt chimney problem 3. preferential flow paths.

Keywords: Thermohaline flow, Variable density, Variable viscosity, Fractured-porous media, salt dome





Summary & Outlook (ISU)

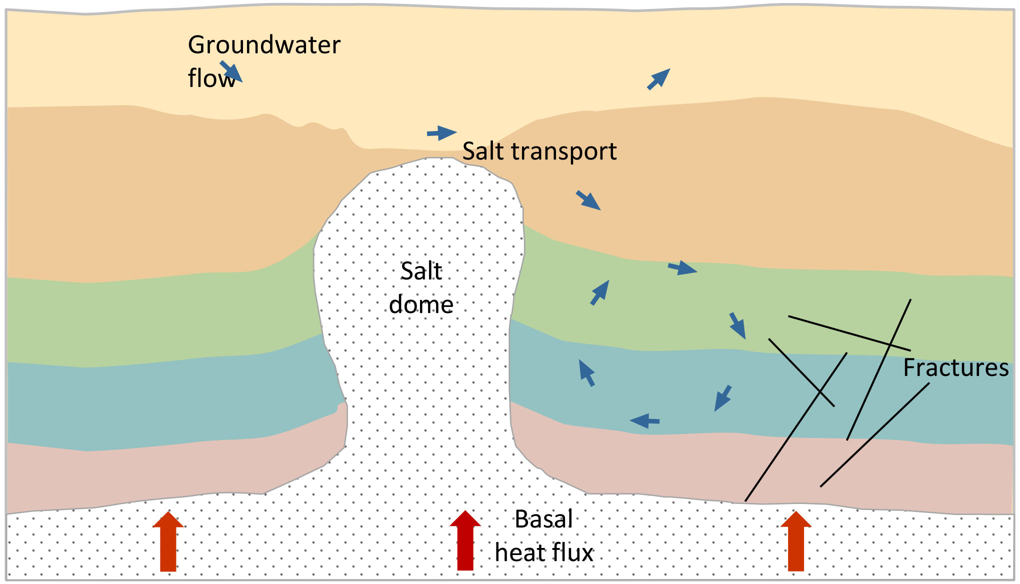
- ✓ 1. paper accepted
- ✓ Literature review on thermohaline flow near salt domes
- ✓ Testing thermohaline flow near salt dome (Literature comparison)
- ✓ Definition of a fractured salt chimney problem

- Inclusion of fractures and testing
- Systematic investigation of different fracture network effects on thermohaline flow near salt dome
- Possible consideration of halite dissolution
- ➢ Publishing results in 2. paper

- Joint (ISU – IRZ) Paper

Outlook with Reference to the Site Selection Process

- Results can be used when investigating far field of salt dome repository in generic or site-specific models
- Investigation of density-dependent or thermohaline flow for potential radionuclide migration (life expectancy) for safety assessment
- Incorporating mixing parameter uncertainty is crucial for safety assessment
- Uncertainty quantification with methods developed by IRZ



Molson and Frind 2023

Publications (ISU)

Journal article:

- Suilmann, J., Molson, J., & Graf, T. (2025). Effect of mixing on groundwater age and life expectancy simulations in density-dependent flow. Accepted for publication in *Hydrogeology Journal*

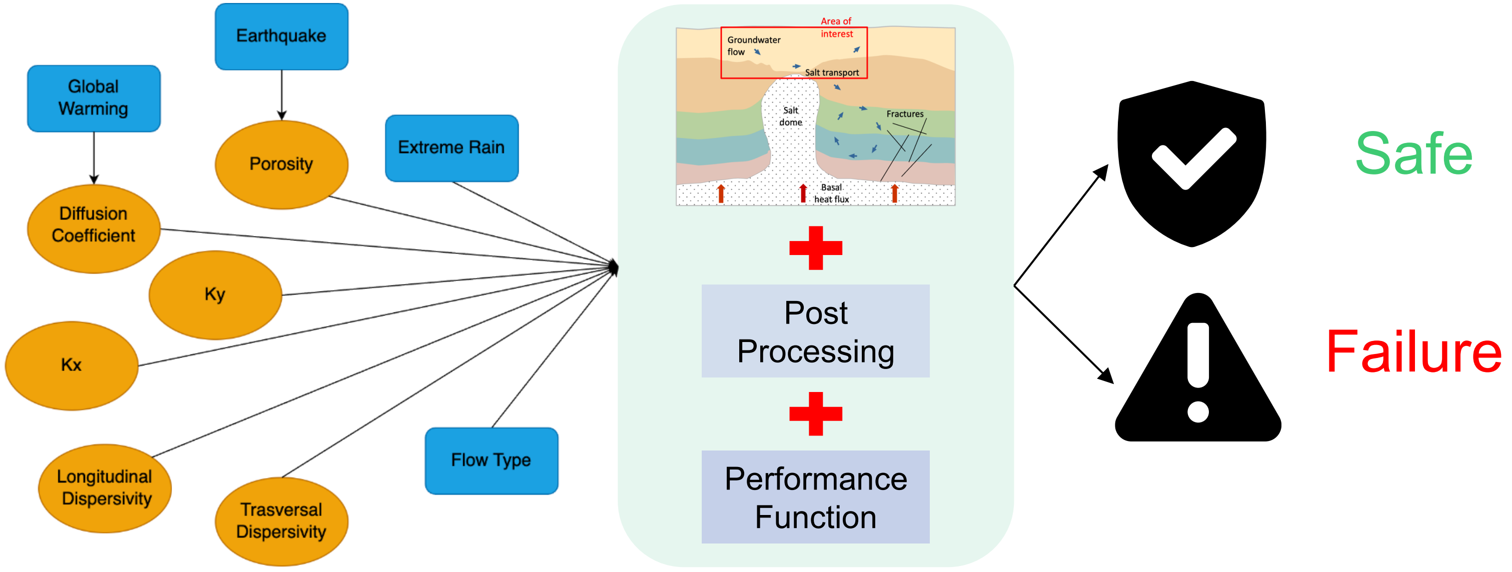
Conference Posters:

- Suilmann, J., Molson, J., & Graf, T. (2024). Groundwater life expectancy simulations in strongly coupled density-dependent flow above a salt dome. *EGU General Assembly 2024*, (S. 7840). Vienna, Austria. https://doi.org/10.5194/egusphere-egu24-7840

- Suilmann, J., Perin, A., Broggi, M., Graf, T., & Molson, J. (2023). Risk-based Assessment of Salt Domes as Disposal Sites for Nuclear Waste: Uncertainty of Groundwater Age in the Salt Dome Problem. *EGU General Assembly 2023*, (S. 14400). Vienna, Austria. https://doi.org/10.5194/egusphere-egu23-14400

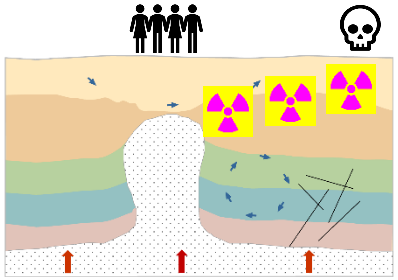
Risk assessment of long-term nuclear waste disposal with polymorphic uncertainties

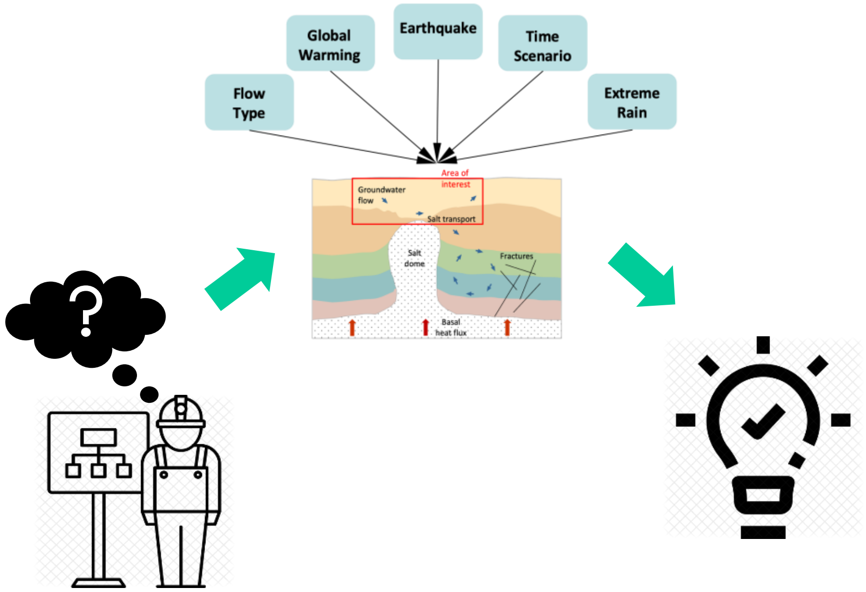
Andrea Perin, IRZ



Motivation

- *Deep geological long-term radioactive waste disposal* are a safety-critical system. A **failure** of these system has huge impact biosphere, population and public opinion
- An **accurate** evaluation of the risk associated to these system must involve *uncertainties* and *imprecision* quantification
- *eBNs* offer a comprehensive framework for dealing with a **multi-scenario** risk assessment
- *eBNs* enable exact algorithm for performing **inference** (diagnosis and prognosis) significantly improving the *decision-making process*





Research Objectives

1. Research Objective (finished)

   Risk assessment with external models (and surrogates) through eBN framework

2. Research Objective (finished)

   Imprecise probabilities in the eBN framework

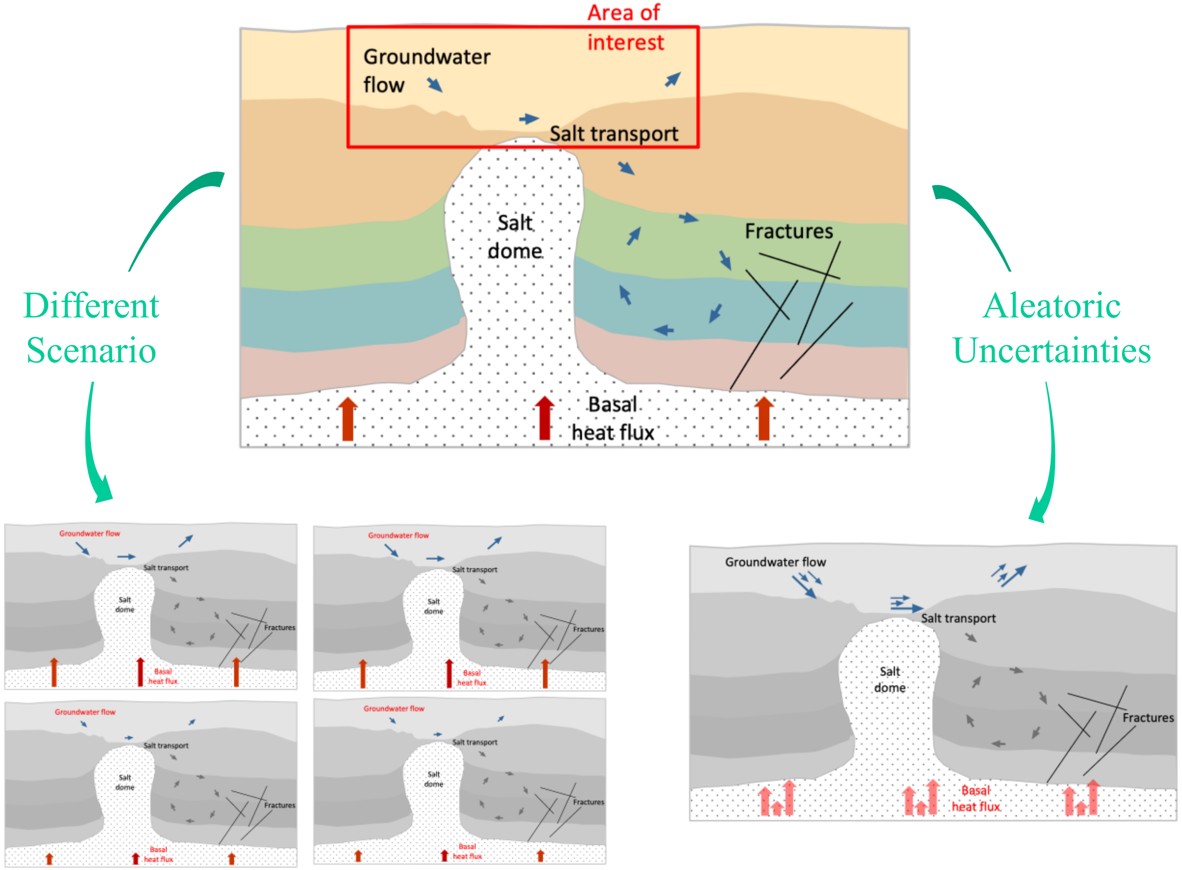
3. Research Objective (ongoing)

   Advanced algorithm to propagate imprecision in the eBN framework and improved network structure to reduce the exact-inference computational cost

1. eBN for risk assessment with external models

A reliable risk analysis for safety-critical system requires:

- **Multi-scenario** analysis
- **Uncertainties** analysis
- Capability to enhance decision-making process through “*What-if*” analysis
- **Prognosis** and **Diagnosis** algorithm
- **Bayesian update** (“*belief update*”)

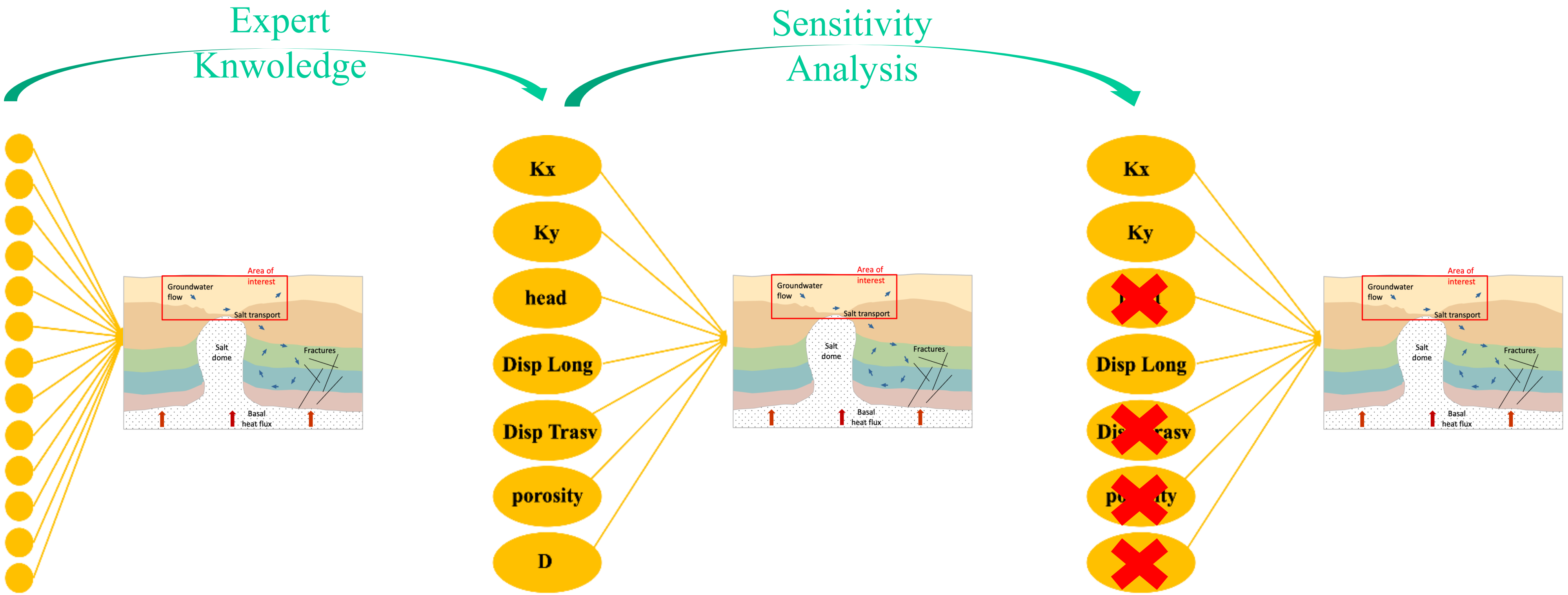


1. eBN for risk assessment with external models

Exploitation of Experts opinion and Sensitivity Analysis

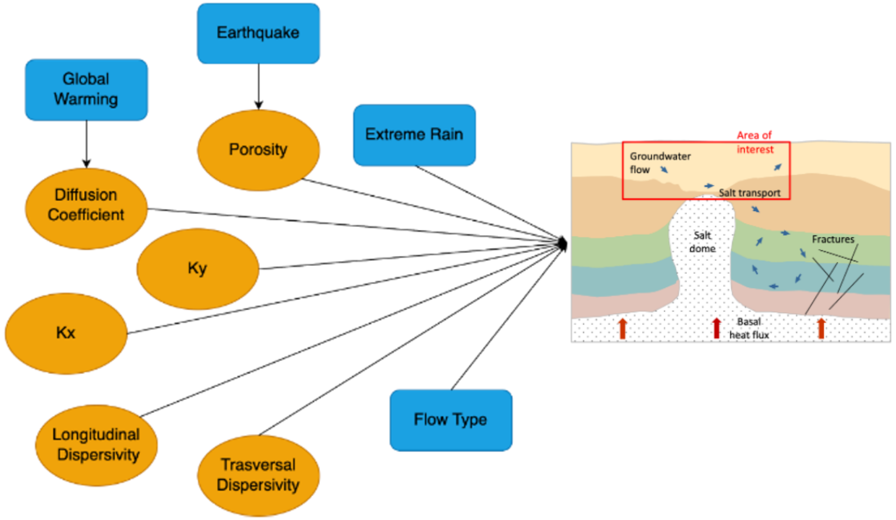
Expert-based knowledge for parameters identification

Sensitivity Analysis for improving computational efficiency



1. eBN for risk assessment with external models

Aleatoric uncertainties are handled by eBN framework through continuous nodes

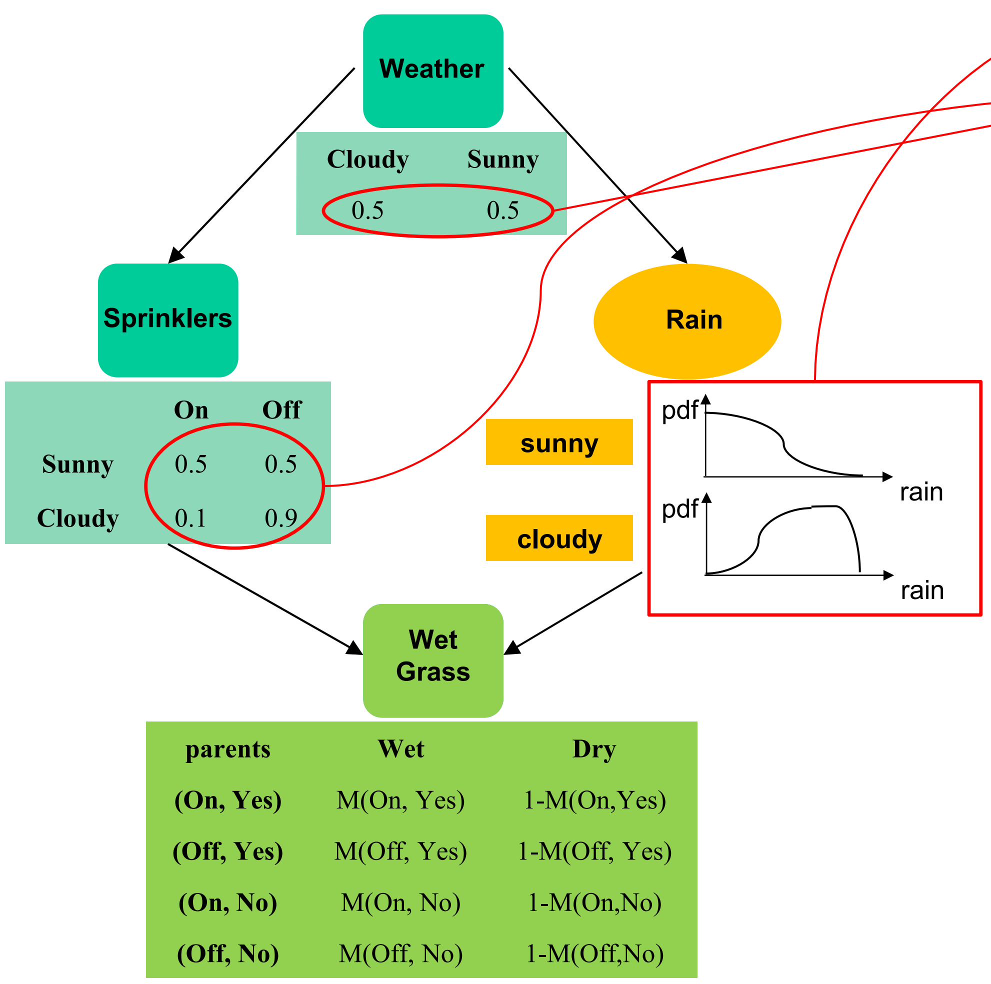


Scenario	P_failure	P_safe
comb 1	0.995	0.005
comb 2	1	0
comb 3	0.87	0.13
comb 4	0.885	0.114
comb 5	0.92	0.079
comb 6	0.875	0.125
comb 7	1	0
comb 8	0.83	0.17
{…}	{…}	{…}

eBN represent a framework for a reliable risk assessment

- Multiple Scenario Analysis
- Aleatoric uncertainties
- Bayesian Update
- Inference Analysis (Prognosis and Diagnosis)

2. Imprecise probabilities in the eBN framework



Cloudy	Sunny
0.5	0.5

	On	Off
Sunny	0.5	0.5
Cloudy	0.1	0.9

parents	Wet	Dry
(On, Yes)	M(On, Yes)	1-M(On,Yes)
(Off, Yes)	M(Off, Yes)	1-M(Off, Yes)
(On, No)	M(On, No)	1-M(On,No)
(Off, No)	M(Off, No)	1-M(Off,No)

Precise Distributions are known

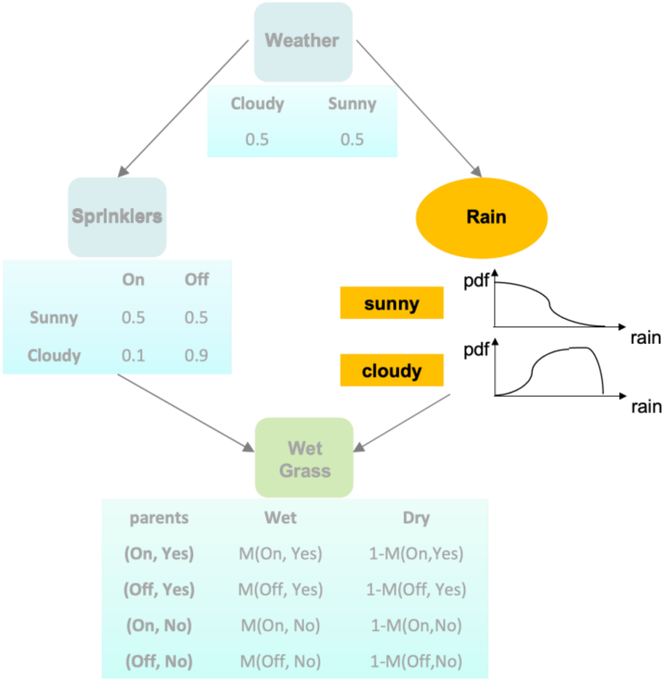
Precise probabilities values are known

Strong Assumptions!!

- Sparse Data, Limited Measurements, Subjective opinions
- Precise description in imprecise conditions => **misleading results**

Imprecise probabilities

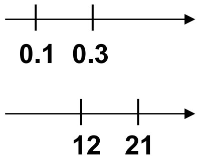
2. Imprecise probabilities in the eBN framework



Intervals

$I_1 = [12; 21]$

$I_2 = [12; 21]$

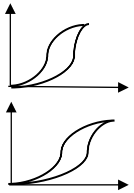


- No assumption on distribution
- Buonds are the only known property

Probability Boxes

$PB_1 = N[I_{1\mu}; \sigma_1]$

$PB_2 = N[I_{2\mu}; \sigma_2]$



- Parameteric formulation
- Distribution family is known
- Distributions parameter are Intervals

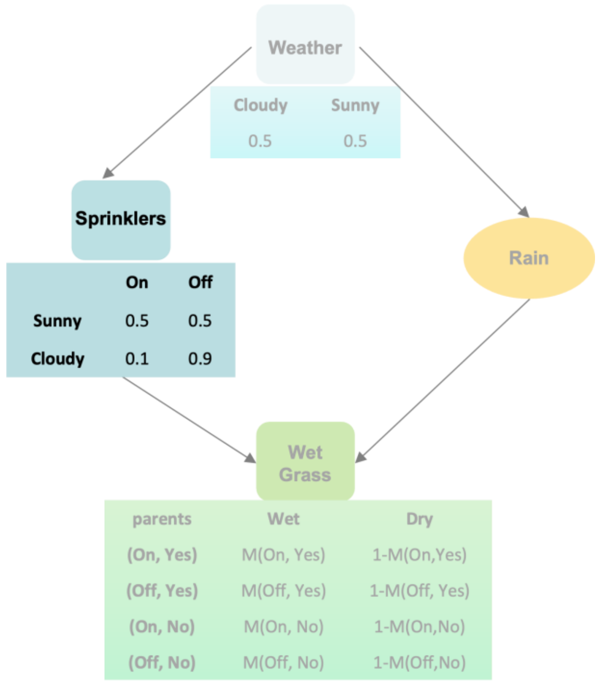
Evaluation Consequences

- **Double-Loop** or **Random Slicing** algorithm must be employed for failure probability evaluation

Inference Consequences

- **Credal sets** are used to describe model nodes states
- New **exact-inference** algorithm for inference probabilities bounds

2. Imprecise probabilities in the eBN framework



Sprinklers

	On	Off
Sunny	0.5	0.5
Cloudy	0.1	0.9

→

Sprinklers

	On	Off
Sunny	[0.5; 0.6]	[0.4; 0.5]
Cloudy	[0.1; 0.2]	[0.8; 0.9]

- Probabilities values for each state and in each scenario are described through **credal sets**
- When Imprecise nodes is **boolean** the bounds are uniquely identified

Evaluation Consequences

- **None**

Inference Consequences

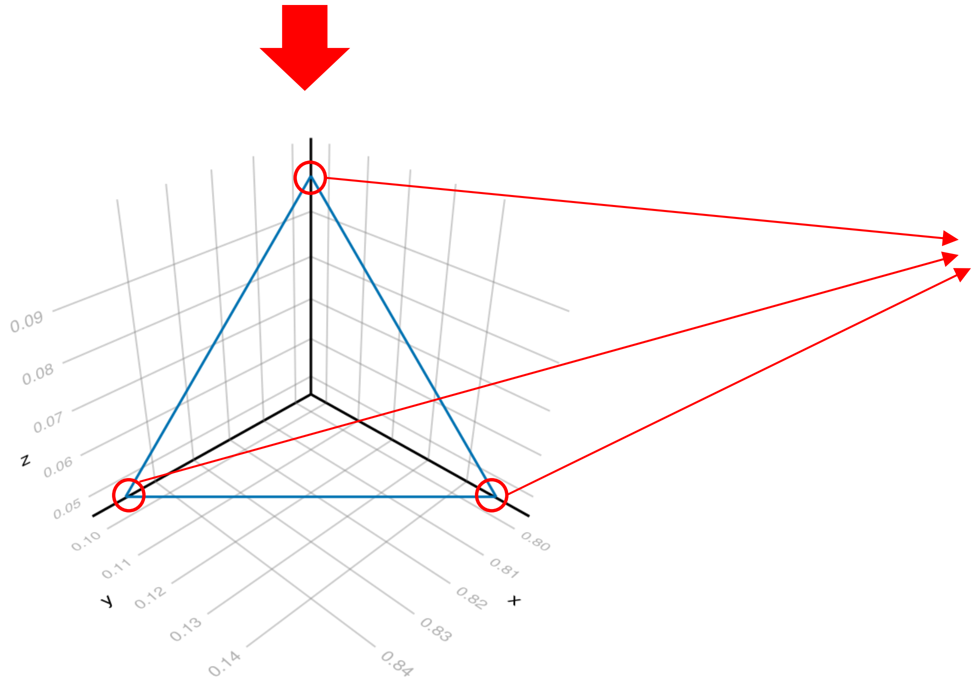
- **Credal sets** are used to describe discrete nodes states
- New **exact-inference** algorithm for inference probabilities bounds

2. Imprecise probabilities in the eBN framework

Non-Boolean Imprecise Nodes

Weather

Cloudy	Sunny	3rd
[0.05; 0.1]	[0.05; 0.1]	[0.7; 0.8]



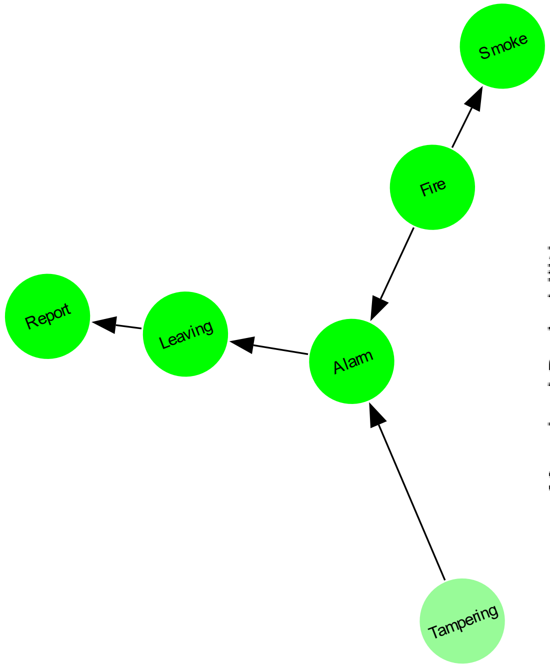
- *Credal sets* of non Boolen imprecise nodes identify a **polytope** in probability space
- Non boolean imprecise nodes have *infinite plausible combinations* of probabilities which identify infinite BNs
- **Vertices** of the n-dimensional polytope are used to identify the BNs for applying the same Inference algorithm of traditional BNs

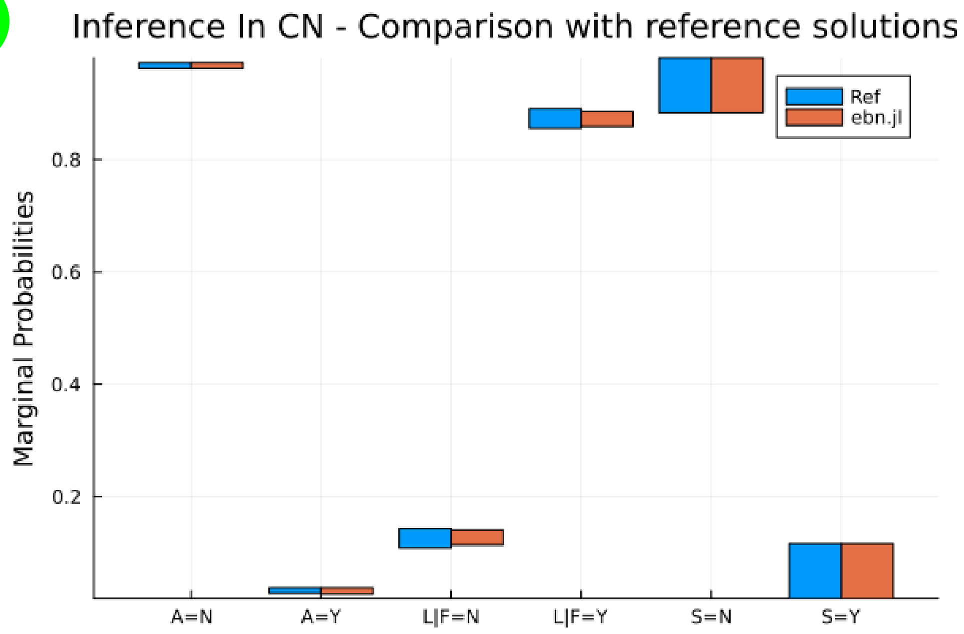
2. Imprecise probabilities in the eBN framework

Name	Scenario	states	
Tampering	-	**:noT**	**:yesT**
		0.98	0.02
Fire	-	**:noF**	**:yesF**
		[0.958978, 0.959989]	[0.040011, 0.041022]
Alarm		**:noA**	**:yesA**
	[:noT, :noF]	[0.999800, 0.999997]	[0.000003, 0.000200]
	[:noT, :yesF]	[0.010000, 0.012658]	[0.987342, 0.990000]
	[:yesT, :noF]	[0.100000, 0.119999]	[0.880001, 0.900000]
	[:yesT, ::yesF]	[0.400000, 0.435894]	[0.564106, 0.600000]
Smoke		**:noS**	**:yesS**
	[:noF]	[0.897531, 0.915557]	[0.010000, 0.102469]
	[:yesF]	[0.090000, 0.110000]	0.890000, 0.910000]]
Leaving		**:noL**	**:yesL**
	[:noA]	[0.585577, 0.599999]	[0.400001, 0.414423]
	[:yesA]	[0.100000, 0.129999]	[0.870001, 0.900000]
Report		**:noR**	**:yesR**
	[:noL]	[0.809988, 0.828899]	[0.171101, 0.190012]
	[:yesL]	[0.240011, 0.250000]	[0.750000, 0.759989]

Fire-Detection System

H.D. Estrada-Lugo "Credal Networks for Risk and Resilience Assessment of Complex Safety Systems Subject to Severe Accidents"





3. Advanced algorithm to propagate imprecision in the eBN framework

- Improving computational efficiency perfroming all graph-based operation through **adjacency matrix**
  [Under internal code-review]

- Improving computational efficiency through *Non-Intrusive Imprecise Stochastic Simulation* (**NISS**) and *Collarborative and Adaptive Bayesian Optimization* (**CABO**)
  [WIP in UncertaintiesQuantification.jl]

- Add **Dynamic Bayesian Network** for dealing with time serie and sequences
  [WIP in EnhancedBayesianNetworks.jl]

Summary & Outlook (IRZ)

- ✓ Literature review on imprecise probabilities and Credal Networks
- ✓ Implementation of Double Loop approach and Credal Networks
- ✓ Testing with benchmark cases
- ✓ First release v.0.1.0 of “EnhancedBayesianNetworks.jl”
- ✓ Literature review for Dynamic Bayesian Networks
- ✓ Literature review for NISS and CABO
- 1st paper under internal review

- ✓ Implementation of network structure
- Benchmarking new computational cost and memory usage
- Implementation of Advanced algorithm for breaking Double Loop
- Implementation of Dynamic Bayesian Networks
- Pusblish results in 2nd paper

- ➢ Joint (ISU – IRZ) Paper

Outlook with Reference to the Site Selection Process

- **eBNs** offer a powerfull tool for performing a *reliable risk assessment* while considering *aleatoric uncertainties* and *different scenarios*

- **Imprecise probabilities** incorporation in the eBN framework allow for a systematic way of dealing with *imprecise knowledge* and *epistemic uncertainties*

- **“Belief update”** capability, typical of standard BN, is kept in the eBN framework and strongly enhance the decision-making process

- The under-development algorithm for “*breaking*” the Double Loop enhance the **computational efficiency** of the tool in order to mitigate the need of surrogate models

Publications (IRZ)

Conference Paper (accepted)**:**

- Perin, A., Broggi, M., & Beer, M. (2024). EnhancedBayesianNetworks.jl: A new Julia framework for multi-scenario risk assessment. 8th *International Conference on System and Reliability and Safety* , ICSRS 2024**.**

Journal Paper 1st draft finished (under internal review) **:**

- Perin, A., Broggi, M., & Beer, M. (2024). Enhanced Bayesian Networks with imprecise probabilities.

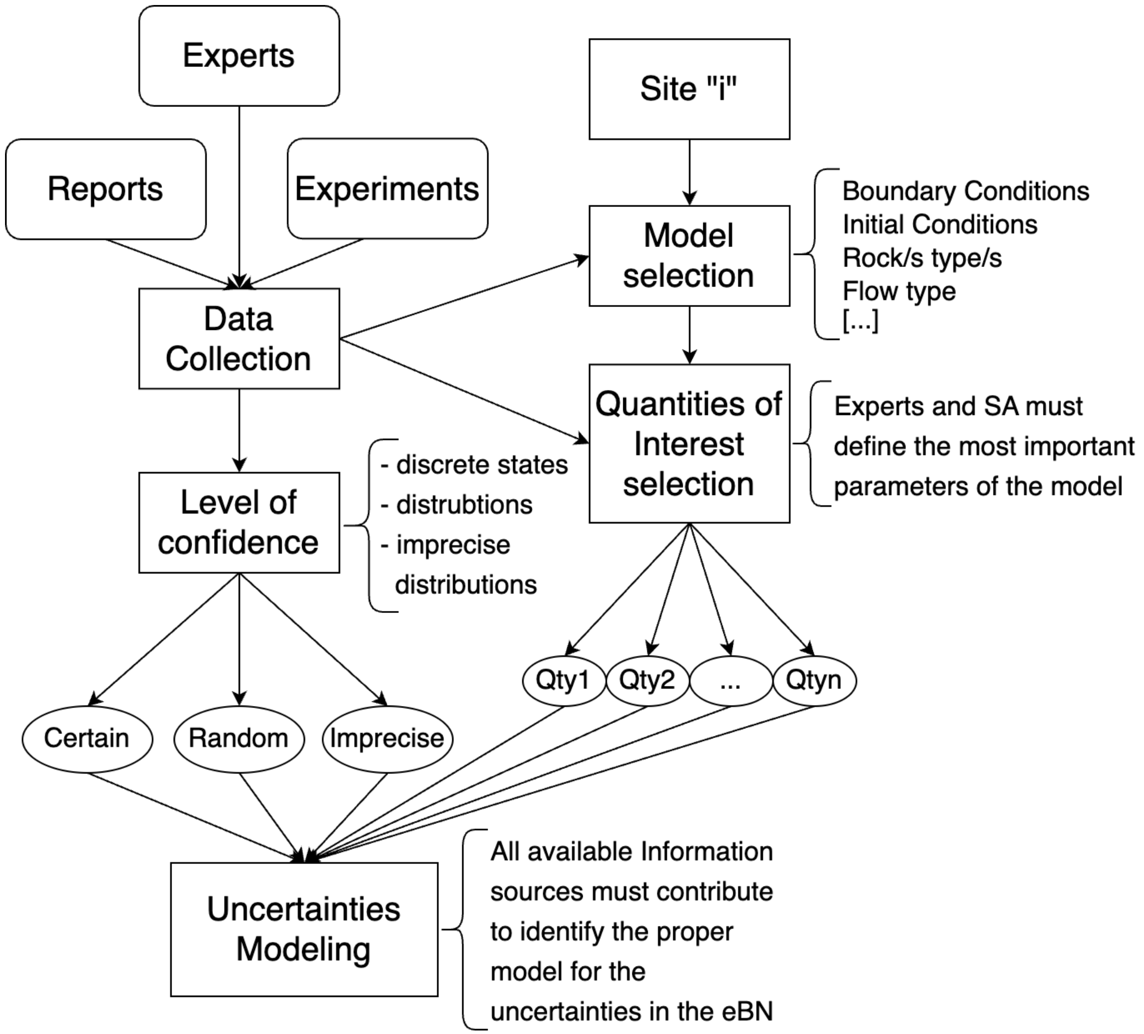
Repository

- "EnhancedBayesianNetworks.jl", 1st release v.0.1.0
- **discretization**, **evaluation**, **reduction**, **multiple functional nodes,** and **inference**, with the relative **optimization** strategies
- https://doi.org/10.5281/zenodo.14054153

Joint (ISU – IRZ) Paper

Flowchart for eBN construction (part I):

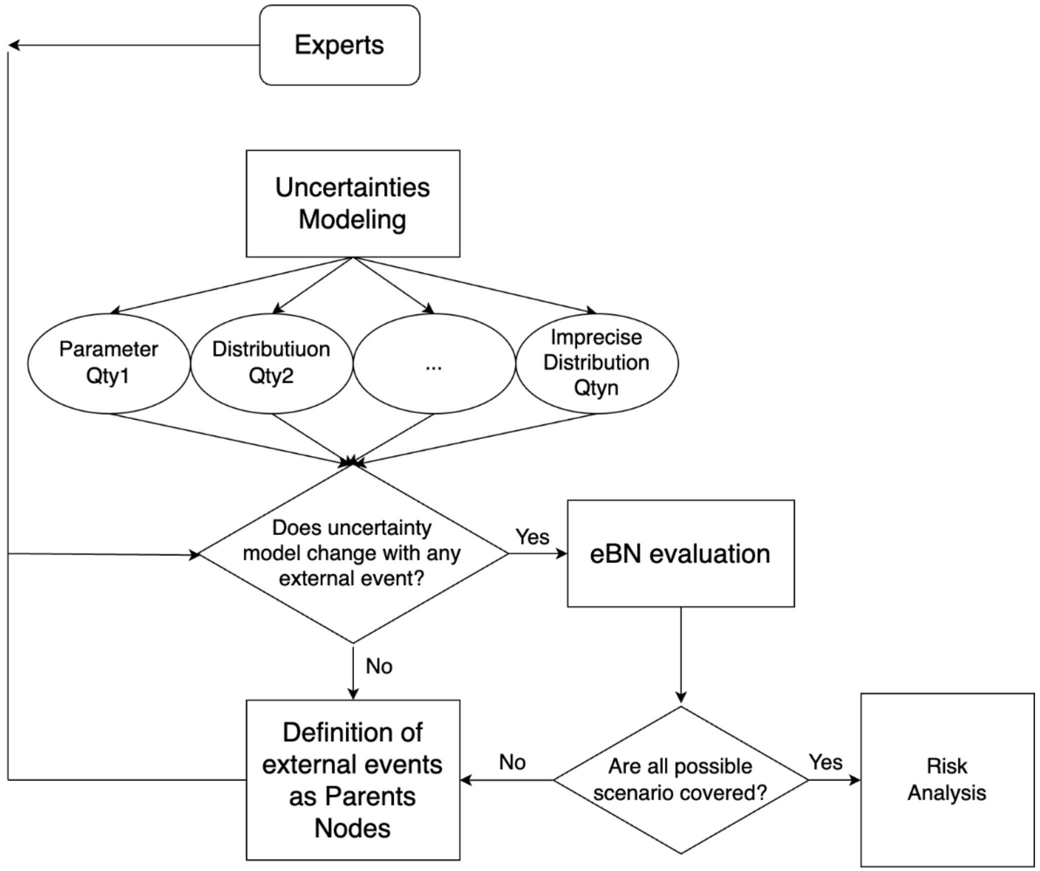
- The process must be repeated for all possible sites. Site “i” is the one considered
- From Data collection until the model of all the uncertainties
- At the end this step all the parents of the node containing the selected model are established
- Parents of the model node are Root nodes



Joint (ISU – IRZ) Paper

Flowchart for eBN construction (part II):

- Uncertainties modeling give the structure of the “first-attempt”-eBN
- Together with expert knowledge further investigation on possible parents events must be performed
- This step involve an iterative procedure for establish if the detail level is sufficient



Joint (ISU – IRZ) Paper

- **An enhanced Bayesian Network approach for risk assessment of a nuclear waste repository (salt dome)**
- Advances in Water Resources
- Preparation of the manuscript of this Joint Paper is ongoing.

An Enhanced Bayesian Networks approach for risk assessment of a nuclear waste repository (salt dome)

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Abstract

Radioactive waste disposal are safety-critical systems that present unique challenges due to the high levels of radioactivity and prolonged hazard potential involved. Salt domes offer natural advantages, including low permeability and structural stability, which help mitigate radionuclide migration. Conducting a comprehensive risk assessment of these complex systems is essential to ensure isolation from the biosphere. It also aids in regulatory compliance, enhances public confidence, and supports the development of contingency plans. Effective risk assessment tools must identify and quantify risks under various scenarios, addressing both uncertainties and imprecise epistemic knowledge that influence system failure probabilities. Enhanced Bayesian Networks fulfill these criteria by improving standard Bayesian Networks through the use of probability density functions, and they exploit structural reliability methods for precise failure probability assessment. Enhanced Bayesian Networks improve decision-making through detailed multi-scenario analyses, utilizing exact inference algorithms and dynamic updating of conditional probabilities. Key elements of risk assessment for using salt domes as deep geological repositories for radioactive waste include radionuclide transport and density-driven groundwater flow modeling in site-specific hydrogeological evaluations, studies on the impact of these factors on transport parameters, and pathway assessments for human exposure to establish performance functions. With most data based on expert knowledge and experiments, this paper aims at demonstrating the applicability of the Enhanced Bayesian Networks approach to these systems, focusing on methodology rather than empirical data.

*Preprint for submission to **Advances in Water Resources*** *November 11, 2024*

Conclusions

- Generated a stochastic tool for **Risk-based Assessment of Salt Domes as Disposal Sites for Nuclear Waste (RADON)**
- Gained new insights into flow/transport processes near salt domes.
- Included additional processes in the numerical simulation of flow/transport near salt domes.
- Developed eBNs for reliable risk assessment.
- Useful for the site selection process.
- Published/will publish research results in journal papers and conferences.