

FracSYS

A software tool for modelling fractured aquifers dedicated to groundwater resources management

Phase 1- Conceptualisation and methodological approach for modelling fractured aquifers

Concluding report on phase 1

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Resume

FracSYS is an innovative software tool designed for modelling fractured aquifers, essential for sustainable groundwater management in Switzerland. This report outlines the conceptualisation and methodological approach for Phase 1 of the FracSYS project.

The FracSYS project aims to develop a user-friendly, no-cost, web-based tool to build explicit conceptual models of fractured aquifers. The tool is intended to be accessible to a broad spectrum of stakeholders, including water operators, practitioners, environmental agencies, and policymakers. It enables users to identify, delineate, and characterise groundwater bodies effectively in a spatial context, providing outputs that are easily understood by a wide audience.

The project is structured into two work packages. The first work package focuses on developing a conceptual and methodological approach for modelling fractured aquifers. This involves creating pragmatic and explicit 3D conceptual models of fractured aquifers, which will serve as a foundation for the second work package. The second work package, scheduled for 2024–2025, will involve the development of the FracSYS IT solution. This will integrate the Visual KARSYS platform and implement functionalities tailored to the FracSYS approach.

The development team comprises CREALP and SISKA, who are responsible for conceptualisation and technical specifications. i4DS manages the technical implementation with support from SISKA. The project also involves users and testers, including representatives from various cantons and Danone, who contribute ideas and feedback on the functionalities being developed. Followers, such as swisstopo, Forces Motrices Valaisannes, Nagra, and Georessources Switzerland, remain informed about the project's progress and outcomes.

Modelling fractured aquifers requires understanding key concepts such as fracture networks, rock matrix, and fracture infillings. Fracture networks serve as pathways for fluid movement, while the rock matrix constitutes the primary porosity that stores groundwater. Fracture infillings influence permeability and storage within the fractures. The hydrogeology of fractured rock involves understanding the scale effect, zoning of fractured rocks, and hydraulic properties like permeability and transmissivity.

The FracSYS solution includes a conceptual model that defines the geometry and hydraulic properties of the top and low fracture zones, as well as the transmissive fractures. The workflow for applying FracSYS involves five main steps: hydrolithology, 3D geology, fractures hydraulic, groundwater zones, and flowlines. These steps enable users to define lithologies, construct the 3D geological model, assign hydraulic conductivity values to fractures, model saturated zones within the fracture zones under different hydrological scenarios, and visualise flow characteristics in 3D.

The applicability of the FracSYS approach depends on the hydrogeological contrasts between 1st-order fractures and the fracture zone. However, the tool has some limitations, including simplifications in the conceptual model, scale effects, and computational challenges.

In conclusion, FracSYS aims to provide a practical and accessible tool for modelling fractured aquifers, addressing the unique dynamics of these environments. The tool's development will enhance groundwater management practices in Switzerland, ensuring sustainable use and protection of groundwater resources.

1 Introduction

1.1 Stakes and challenges in sustainable groundwater management in Switzerland

Groundwater as a vital resource in Switzerland

Groundwater serves as a cornerstone of Switzerland's water infrastructure, supplying 80% of the nation's drinking water and representing a socio-economic asset of national significance. Despite Switzerland's abundant water resources and generally high groundwater recharge rates, sustainable management requires a comprehensive, quantitative approach at the national level.

Surface and groundwater resources face mounting pressures due to population growth, intensified human activities, and climate change. These pressures manifest as water shortages, seasonal fluctuations in availability, overexploitation, user conflicts, diffuse pollution, and changes in the physico-chemical quality of water caused by climate change (Hunkeler et al., 2021; Jeannin et al., 2016). The Federal Office for the Environment (FOEN), in its report on sustainable water management in Switzerland within NRP 61 (Comité de direction NFP 61, 2014), identified several **stakes** as part of the recommended measures package :

- **Ensuring adequate access to water**, both in quantity and quality, for diverse users.
- **Addressing increasing energy** demands while transitioning to decarbonized production methods.
- **Mitigating risks** associated with civil engineering projects, natural hazards and water pollution.

Stakeholders in groundwater management

A variety of stakeholders are actively involved in groundwater management, each with specific roles and responsibilities:

- **Water Operators (public and industrial):** Responsible for decision-making on water allocation, extraction, and management strategies.
- **Practitioners**: Develop and implement effective groundwater production and remediation strategies and assess impacts of surface and underground civil works.
- **Environmental Agencies and Policy Makers**: Evaluate the impacts of activities on groundwater quality and availability, disseminate information, establish regulations and policies for sustainable management, and identify new water resources.

Enhancing understanding of groundwater systems

To ensure effective groundwater management, stakeholders must delineate their understanding of aquifers by delineating their spatial extent, characterising media types (porous, fissured, or karstified), and quantifying their hydraulic properties, productivity, vulnerability, and interconnections. Developing 3D conceptual models is a critical step for visualizing and validating these characteristics. Such models facilitate understanding of groundwater systems, including recharge, storage, flow, and drainage/discharge processes.

Baseline data and modelling challenges

Baseline knowledge in groundwater studies is built on diverse data sources, including geophysical surveys, field observations, satellite imagery, borehole logs, and long-term monitoring datasets. Although Switzerland possesses a wealth of such data, it is often underutilized. Interpreted datasets—such as geological, structural, and hydrogeological maps, cross-sections, and 3D models—form the foundation for understanding groundwater systems. However, the availability of detailed hydrogeological maps at scales smaller than 1:50,000 remains limited. Such fine-scale maps are critical for effective local water resource management, particularly at the catchment level.

In the Alpine context, the scarcity of 3D aquifer models poses additional challenges. This gap can be attributed to several factors:

- **Complex lithological units:** Fractured and/or karstified networks within lithological units are difficult to delineate and translate into coherent hydrogeological units.
- **Geological structures:** Tectonic stress and metamorphic processes create intricate geological formations that are challenging to represent geometrically in models.
- **Hydrogeological complexity:** The diverse flow mechanisms through porous, fissured, and karstified media result in complex behaviour, making it difficult to accurately model aquifers and predict their dynamics.

Addressing these challenges requires advanced methodologies, interdisciplinary collaboration, and the integration of emerging technologies to improve data interpretation and model development in these intricate geological settings.

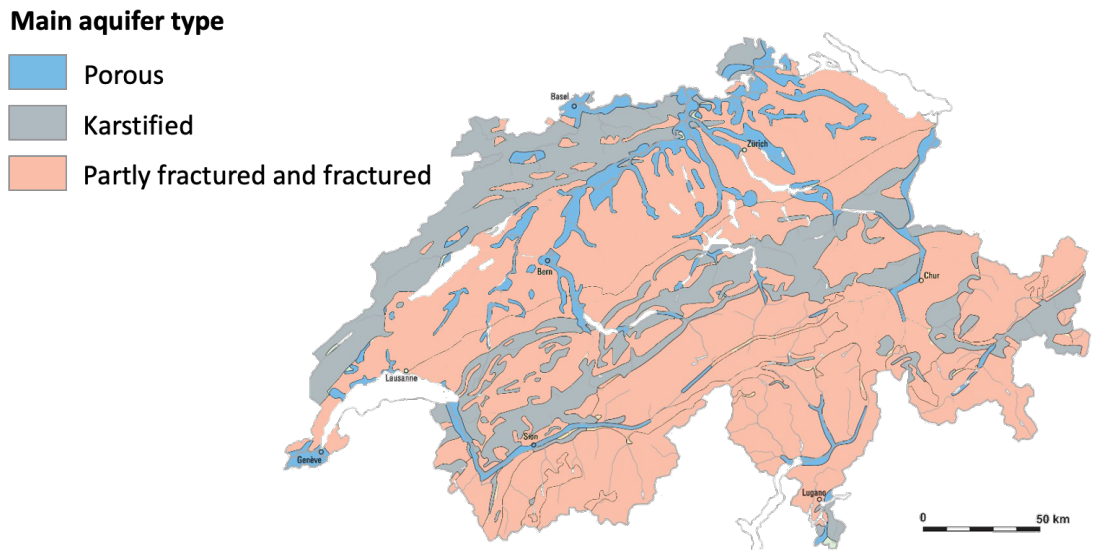
1.2 Fractured rock aquifers in the context of water resources in Switzerland

Fractured rock aquifers are characterised by their dependence on fracture networks, which create pathways for water flow. Unlike porous media aquifers, where groundwater is stored within the pore spaces of sedimentary rocks such as sandstone or gravel, fractured rock aquifers transmit groundwater through networks of fractures, joints, and faults within harder rock formations, including sedimentary, igneous, and metamorphic rocks.

Globally, fractured rock aquifers constitute a significant component of groundwater resources, and in Switzerland, they cover more than 60% of the country's surface area. These aquifers are predominantly found in the Plateau, Pre-Alps, and Alpine regions (Sinreich et al., 2012). The characteristics and lithological properties of these reservoirs vary by region:

- **Plateau region**: Fractured aquifers here are composed of weakly tectonised consolidated rocks, typically with low surface relief and a modest hydraulic gradient. These rocks include sandstones, sandy conglomerates, and sandy marls (molasse du Plateau). Groundwater quality in this region is significantly influenced by agricultural activities, which can introduce pollutants and affect overall water quality
- **Prealps and Alps**: In contrast, fractured aquifers in the Pre-Alps and Alps are found in strongly tectonised consolidated rocks with steep surface relief and high hydraulic gradients. Lithologies in these areas include sandstones, sandy conglomerates, and sandy marls (subalpine molasse, flysch, and verrucano), as well as shales, siliceous limestones, and crystalline rocks. These aquifers are particularly valuable because they provide generally high-quality water resources, often in sufficient quantities, especially at higher altitudes where human impact is reduced, and natural recharge conditions are favourable.

Fractured rock aquifers play a critical role in Switzerland's water resource management, not only because of their prevalence but also due to their importance in meeting ecological and socio-economic needs. Effective characterisation and management are essential to optimise their use and protect their quality



Modified after Pochon and Zwahlen (2003a)

Figure 1 : Hydrogeological sketch of Switzerland showing the distribution areas of the various dominating aquifer types (Pochon and Zwahlen, 2003)

Across Switzerland, the volume of water stored in fractured rock aquifers is estimated to account for 13% of the country's total groundwater resources. This is significantly less than karstic aquifers, which store 80%, but greater than porous aquifers, which hold just 7%. The annual volume of water renewed in fractured rock aquifers (equivalent to recharge) is estimated at 3.7 km³/year, representing 20% of the total recharge. This figure is comparable to the recharge of karstic aquifers (also 20%) but is only half that of porous aquifers, which contribute 60% of the total recharge (Sinreich et al., 2012).

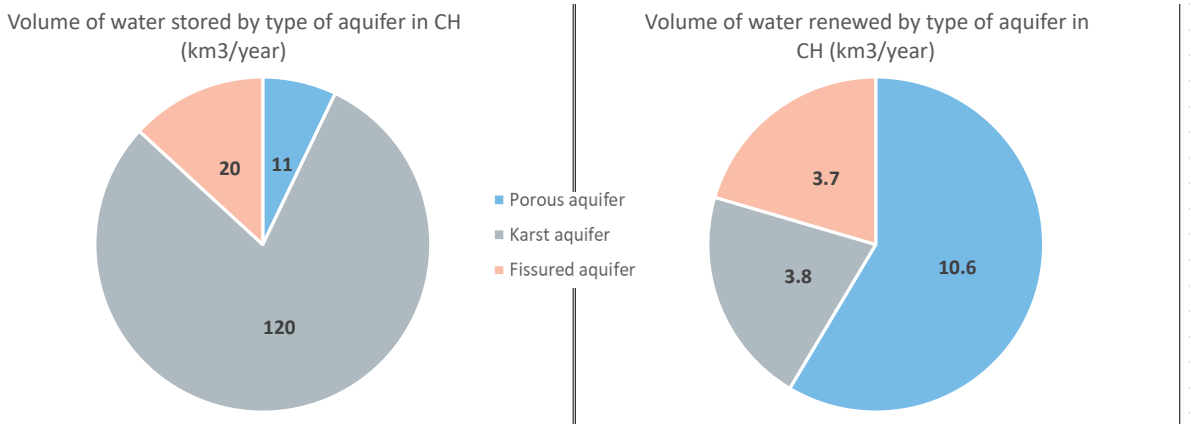


Figure 2 : Groundwater resources by aquifer type in Switzerland, in terms of stored volume and recharge (Sinreich et al., 2012).

Proportionally, fractured rock aquifers cover the largest surface area in Switzerland. They play a crucial role as recharge zones for all types of aquifers and contribute nearly 30% of the nation's drinking water supply (Spreafico and Weingartner, 2005).

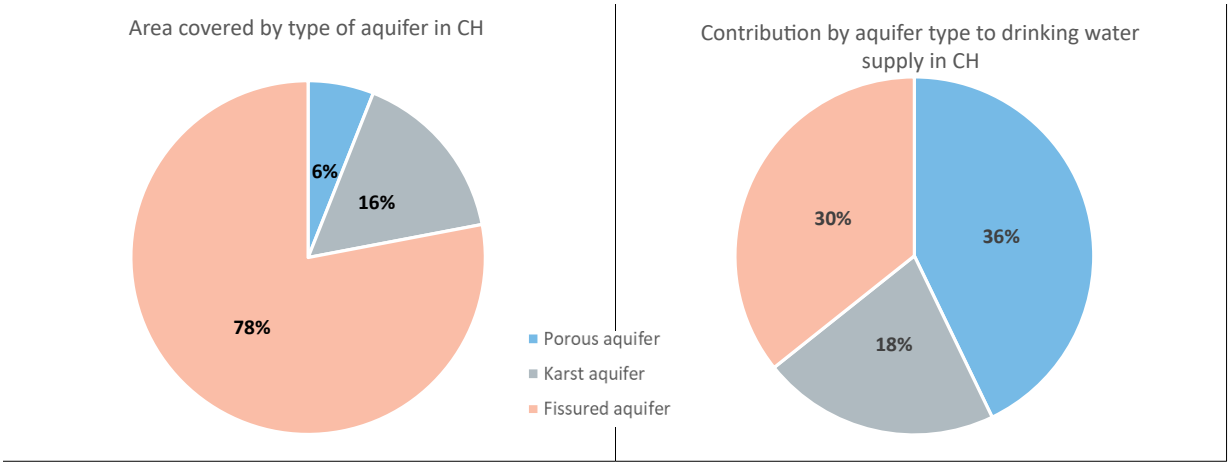


Figure 3 : Spatial extent and respective contribution of the different types of aquifer represented in Switzerland (after Spreafico and Weingartner, 2005)

Despite their significance, fractured rock aquifers are often poorly documented. This lack of information makes it difficult to evaluate, exploit, and protect the groundwater resources associated with these aquifers. Consequently, this can result in complex challenges, such as conflicts between users, inadequate protection measures, and unforeseen impacts from construction projects.

Although methods and tools exist to characterise and describe the properties of fractured aquifers, many rely on advanced numerical or simulation models. These models often require extensive datasets to function and produce outputs that are understandable to only a small group of experts. Moreover, they frequently involve significant uncertainties, which complicate the interpretation of results. Integration of these models with existing or planned projects can also be difficult, further limiting their practical utility.

Given the crucial role fractured rock aquifers play in water accessibility in Switzerland, the associated stakes are substantial. In this context, it is both necessary and strategic to equip stakeholders with decision-support tools, particularly in the form of 3D conceptual models specifically designed for fractured aquifers.

Regarding available numerical modelling tools, while numerous solutions exist for modelling porous media aquifers, there are far fewer options tailored to the unique dynamics of karstic and fractured media. Conventional approaches developed for unconsolidated porous media are often inappropriately applied to fractured rocks, leading to unreliable or unsuccessful results. These specialised solutions are largely confined to academia and highly technical scientific circles, leaving local practitioners and decision-makers without effective resources.

Numerical models are valuable for simulating and estimating hydrogeological parameters, such as hydraulic heads and groundwater flow. However, they rarely provide a comprehensive 2D or 3D visual representation of groundwater resources. Additionally, they lack the capacity to integrate results and parameters effectively within real-world environmental contexts, limiting their application for practical water resource management.

2 FracSYS initiative

2.1 Initial idea of FracSYS

CREALP [1] actively engages in various projects related to (ground)water management and protection in Valais, focusing on innovative solutions in this domain. One notable example is CREALP's involvement in the RESERVAQUA project, conducted under the INTERREG V-A Italy-Switzerland 2014–2020 Programme. This project aimed to characterise water resources on a cross-border scale, encompassing the Canton of Valais, the Autonomous Region of Aosta Valley, and the Piedmont Region. A key conclusion of the project highlighted the need for continued efforts to develop new knowledge of groundwater reserves in the area, particularly through modelling. However, existing hydrogeological modelling tools for fractured environments face limitations in both functionality and accessibility.

Since 2016, SISKA 2 has developed Visual KARSYS, a web-based service specifically designed for 3D modelling of karst aquifers. Its proven applicability and accessibility have supported a wide range of projects. Leveraging this expertise, CREALP proposed a collaboration with SISKA and i4DS [3] to create a modelling tool tailored to fractured environments, inspired by the success of Visual KARSYS. This proposal, termed FracSYS, was submitted by CREALP to the Federal Office for the Environment (FOEN) under the Environmental Technology Promotion Programme in November 2022 and received approval the following month.

2.2 Overall objectives

The FracSYS project aims to achieve the following overarching objectives:

- **Development of a User-Friendly Tool:** Create a no-cost, web-based tool to build explicit conceptual models of fractured aquifers. The FracSYS conceptual model is intended to address practical issues directly and can also serve as a foundation for more detailed numerical models that produce "physically based" quantitative results.
- **Cost-Effective Accessibility:** Provide a modelling tool with a low cost-benefit ratio to attract a broad spectrum of stakeholders, including water operators, practitioners, environmental agencies, and policymakers, regardless of their level of hydrogeological expertise.
- **Groundwater Body Characterisation:** Equip users with the ability to identify, delineate, and characterise groundwater bodies effectively in a spatial context.
- **Accessible Outputs:** Ensure that the tool's outputs are readily accessible and easily understood by a wide audience.

Figure 4 : illustrates the critical role conceptual models play in bridging scientific or technical approaches with outputs that are accessible to non-specialists. Conceptual models synthesise data and information into a simplified representation of settings and processes, addressing many practical issues directly. Furthermore, they form an essential foundation for dev eloping more complex numerical models when the situation or stakes warrant further analysis (Malard et al., 2022). The lack of accessible tools for fractured aquifers was a key motivator for initiating the FracSYS project. By addressing these gaps, the

[1] Research center on alpine environment *www.crealp.ch*

[2] Swiss Institute for Speleology and Karst Studies *www.isska.ch*

[3] FHNW / i4Ds Institute for Data Science *www.fhnw.ch/en/about-fhnw/schools/school-of-engineering/institutes/institute-for-data-science*

initiative seeks to provide practical solutions while enhancing broader understanding and management of groundwater resources.

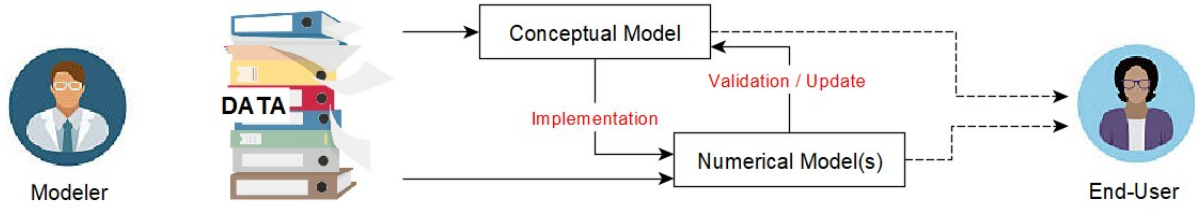


Figure 4 : The integration of conceptual models in scientific and technical workflows

2.3 Methodology

The FracSYS project is structured into two work packages:

- **WP1** focuses on developing a conceptual and methodological approach for modelling fractured aquifers. This involves creating pragmatic and explicit 3D conceptual models of fractured aquifers. The present report addresses key aspects that will serve as a "cookbook" for defining the specifications of the web tool to be developed in WP2 (2024–2025).
- **WP2** will involve the development of the FracSYS IT solution during 2024–2025. This work package will produce a web-based tool that integrates the Visual KARSYS platform while implementing functionalities specifically tailored to the FracSYS approach.

2.4 Development team and partners

The project involves multiple partners operating at different levels (Figure 5):

- **Development Team**: The team comprises CREALP and SISKA, who are responsible for conceptualisation and technical specifications. i4DS will manage the technical implementation, with support from SISKA.
- **Users & Testers:** Working alongside the project team, this group contributes ideas and feedback on the functionalities being developed. It includes representatives from the cantons of Fribourg (FR), Bern (BE), Vaud (VD), Valais (VS), Ticino (TI), as well as Danone.
- **Followers:** While not directly involved in development, this group remains informed about project progress and outcomes. It includes organisations such as swisstopo, the Forces Motrices Valaisannes, Nagra, and Georessources Switzerland.



Figure 5: Overview of the different partners involved in the FracSYS project

3 Modelling fractured aquifers

As outlined in Chapter 1, it is vital for stakeholders to understand groundwater bodies by defining their spatial boundaries, media type (porous, fissured, and karstified), hydraulic properties, water head, productivity, vulnerability, recharge and flow mechanisms, and interconnections within aquifers.

A groundwater model is any computational method that approximates a natural (groundwater) system (Anderson and Woessner 1992, modified). Modelling fractured aquifers

As outlined in Chapter 1, it is crucial for stakeholders to comprehend groundwater bodies by defining their spatial boundaries, media type (porous, fissured, and karstified), hydraulic properties, water head, productivity, vulnerability, recharge and flow mechanisms, as well as interconnections within aquifers.

A groundwater model is any computational method that represents an approximation of a natural (groundwater) system (Anderson and Woessner 1992, modified). As such, groundwater models are, by definition, a simplified representation of a complex reality. Groundwater modelling can be applied to investigate and/or solve a broad range of groundwater issues. Two types of models are classically implemented:

- Groundwater flow model (simulate the water levels and flow process)
- Solute transport model (simulate the migration of solutes or heat)

A groundwater modelling study involves multiple steps. One critical stage is compiling all relevant geological and hydrogeological data related to the area of interest. This dataset forms the basis for designing a conceptual model of the study area.

A 3D conceptual model serves as an effective tool for a, as well as understanding the comprehensive working mechanism of groundwater bodies (including recharge, storage, flow, and drainage/discharge). The initial step involves creating a geological model. This "dry" model forms the foundation for the subsequent development of the "wet" model, which incorporates our understanding of groundwater bodies.

An essential feature for the FracSYS project, is to define fractured aquifers and describe how they are documented and modelled from a hydrogeological perspective using "classic" approaches. We will explore the key concepts, methodologies, steps, and minimum data sets involved to set up a model. Furthermore, we will discuss how these models are useable to address relevant issues relative with groundwater management. Lastly, we will examine potential limitations of these approaches, which will serve as a foundation for the development of FracSYS solution.

3.1 Fractured rock genesis

The hydrogeological behaviour of fractured rock aquifers is determined by the interplay of three essential components, each exhibiting distinct porosities that influence flow, storage, and transport processes (NACSEM, 2020):

- **Fracture networks:** Pathways for fluid movement.
- **Blocks of rock matrix:** Constitute the primary porosity, which stores groundwater.
- **Fracture infillings:** Materials within fractures that influence permeability and storage.
- The genesis of fractures is primarily governed by:
- **Lithology**: The type of rock determines both primary porosity (within the rock matrix) and secondary porosity (fracture networks). These lithological properties vary by site and region.
- **Structural geology and tectonic setting:** Forces such as compression, extension, decompression, and shear generate a variety of fault structures, including normal faults, reverse (thrust) faults,

strike-slip faults, brecciated zones, foliation, inclined or folded sedimentary bedding, rift zones, tabular intrusions, isostatic rebound zones, and relaxation effects from glacier retreat. These phenomena significantly influence fracture genesis, evolution, and fluid flow pathways.

- **Geomechanical, biochemical, and hydrogeological processes:** Fracture development and evolution are further influenced by fluid flow composition and pressure, rock alteration, weathering, and pore pressure. These interactions modify the porosity and permeability of the rock over time.

3.2 Intrinsic characteristics of fractured rock influencing flow and storage

The characteristics of fractured rock that govern its ability to store and transmit groundwater are outlined below (Figure 6):

Rock matrix lithology

The rock matrix refers to the lithology of the rock (considered from a mineralogical and petrological perspective, rather than stratigraphic) and its primary attributes:

- **Grain size distribution and fabric**, including voids within the rock matrix.
- **Cementation materials and bedding planes**, which influence permeability and connectivity.
- **Palaeochannels and sedimentary sequences**: Variations in grain size, grain imbrication, lineations, and nonconformities contribute to the primary porosity network.

Fracture intensity or density

Fracture intensity refers to the degree of fracturing, which can be quantified per unit length, per unit planar surface area, or per unit rock volume. Increased fracture density enhances fracture connectivity and overall void space, resulting in greater fluid flow and storage potential.

The volume of groundwater flow through a network of closely spaced, small-aperture fractures can be equivalent to the flow through a single large fracture, depending on the aperture size and length.

Fracture intensity can be categorised into three groups:

- **Highly fractured rocks:** These are typically found in damage zones around faults (e.g., breccias) or in the top layers of rock affected by weathering or stress release (e.g., from civil works or glacier retreat). Hydrogeologically, they behave similarly to unconsolidated media.
- **Rocks with low fracture intensity:** These may exhibit few hydraulically significant fractures, with fracture spacing exceeding 15 m.
- **Rocks with intermediate fracture intensity:** These are more challenging to conceptualise due to contrasts in fracture spacing, which may be uneven and range from several centimeters to metres.

Fracture density can be expressed in three forms:

- **Linear density:** Fractures per unit length
- **Areal density:** Fractures per unit surface area
- **Volumetric density:** Fractures per unit rock volume

The connectivity of fractures, governed by their density and spacing, determines the extent of void space available for groundwater flow and storage. Depending on aperture size and fracture length, closely spaced fractures can provide flow volumes comparable to those of larger, individual fractures.

Fracture orientation

Fracture orientation is a critical factor that governs the flow pathways in fractured rock aquifers. It includes:

- **Dip**: The angle at which a fracture is inclined relative to a horizontal plane
- **Strike:** The compass direction of a horizontal line along the fracture surface

Orientation affects flow dynamics in both unsaturated and saturated zones:

- In the **vadose zone (**above the water table), gravity causes fluids to move down-dip along structural features.
- In the **saturated zone** (below the water table), fluids primarily flow along strike due to pressure gradients and fracture alignment.
    - **Dip angle:** Steeper dips can concentrate flow along a narrow pathway
    - **Gradient direction:** Determines whether flow moves preferentially up or down structural features

Tectonic stress often dictates the original orientation of fractures and influence whether fractures remain open (favorable for flow) or close (restricting flow). Shear or extensional forces, for example, can create dominant fracture sets that channel fluid flow.

Fracture aperture and infilling

Fracture aperture refers to the width of an open fracture, which directly controls the permeability and volume of water that can flow through. Aperture is dynamic and influenced by:

- **Depth**: Apertures decrease with increasing depth due to lithostatic pressure compressing fractures
- **Weathering and biochemical activity**: Surface-level weathering can dissolve minerals, widening fractures, while mineral precipitation or biogenic activity can reduce apertures by depositing material

Fracture infilling includes the deposition of clays, carbonates, or other minerals within fractures, which can:

- Reduce flow by narrowing or completely sealing the aperture
- Create heterogeneous permeability by affecting certain sections of a fracture network

Infilling often depends on the geochemical environment, such as the saturation state of flowing water and the surrounding rock composition.

Fracture length

The length of a fracture determines its capacity to facilitate flow:

- **Longer fractures:** Allow fluid to travel farther without encountering barriers, thereby enhancing aquifer connectivity
- **Fracture intersections:** Longer fractures are more likely to intersect other fractures, increasing the overall permeability of the system

However, fractures with high length variability within a network can create flow bottlenecks, limiting overall transport efficiency

Fracture connectivity

Fracture connectivity refers to the degree of interlinking among individual fractures, significantly impacting aquifer functionality:

- Well-Connected Networks: Enable large volumes of fluid to flow through the system, acting as high-permeability zones
- Poorly Connected or Isolated Fractures: Trap water with minimal flow between fractures, leading to stagnant zones or reduced permeability

Interconnectivity depends on fracture density, orientation, and the spatial distribution of intersecting fractures. The weakest link—a poorly connected fracture—can act as a limiting factor, reducing overall aquifer flow capacity.

Fracture planarity or waviness

The geometry of a fracture influences its ability to conduct fluids:

- **Planar fractures:** Provide smoother pathways for water flow, reducing resistance. However, if planar fractures are compressed by overburden pressure, they can become barriers to flow.
- Wavy or irregular fractures:
    - These fractures tend to remain open even under stress due to misalignment between fracture walls
    - Their irregularity can promote turbulence and may trap pockets of water, affecting flow continuity

Fracture roughness

Roughness refers to the unevenness of the fracture surfaces, impacting both flow and storage:

- Higher roughness:
    - Increases surface area, enhancing interaction between the water and rock matrix
    - Causes frictional resistance, reducing flow rates
    - Encourages infilling, further narrowing the fracture aperture and decreasing permeability
- **Smoother fractures**: Allow more uniform flow, particularly in systems with minimal infilling
- Rough fractures may also promote preferential pathways for flow if channels align with fracture topography

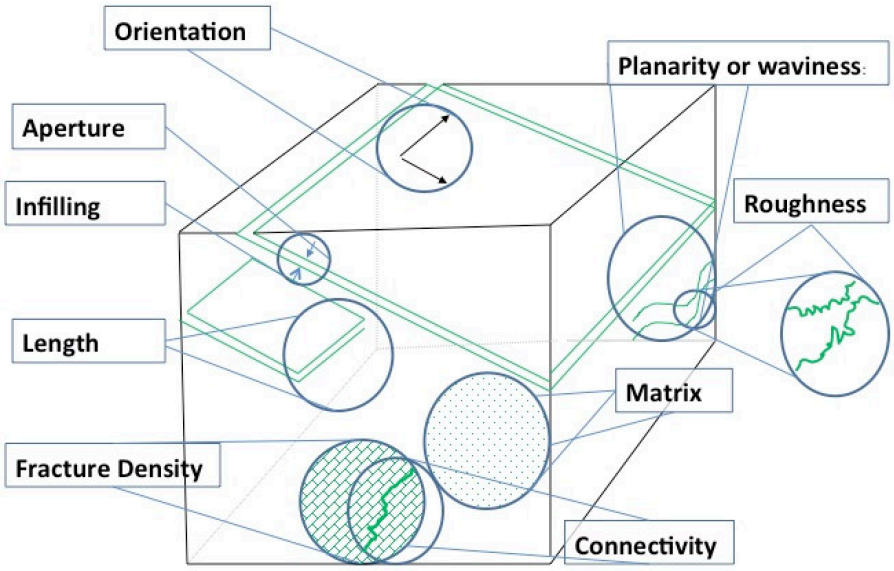


Figure 6: Diagram Fracture characteristics after ITRC (2017)

Interaction of characteristics

The overall behaviour of fractured aquifers is the result of complex interactions among these characteristics (Figure 6). For example:

- A network with high fracture density, long fractures, and good connectivity can yield significant water flow even if individual fractures have small apertures
- Conversely, poor connectivity or extensive infilling can severely restrict flow, even in highly fractured zones

3.3 Hydrogeology of fractured rock

3.3.1 Scale effect

The fractured rock system contributes to water flow and storage at various **scales**, ranging from microscopic to mesoscopic to macroscopic. Figure 7 illustrates the range of fracture characteristics, hydraulic properties, and flow and transport mechanisms that are relevant to scale effects. At the site-to-regional scale level, the focus should be on fracture characteristics such as orientation, length, density, and connectivity to gain a better understanding of the flow patterns and mechanisms.

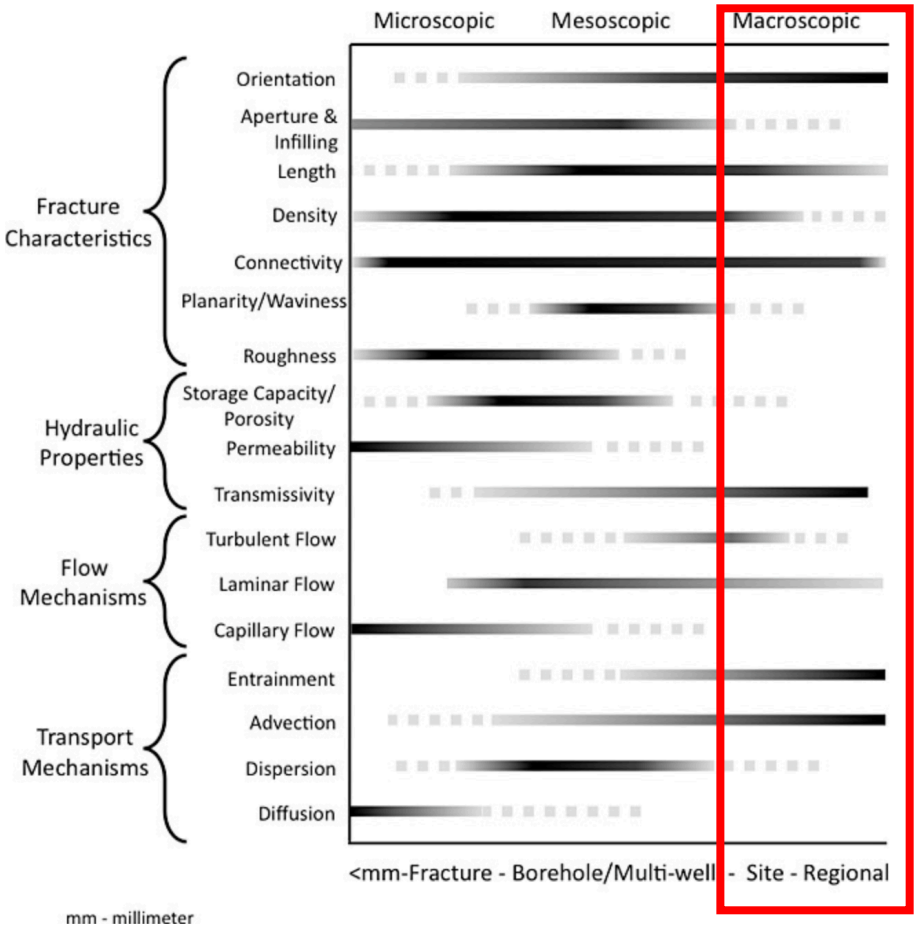


Figure 7: Range of fracture characteristics, hydraulic properties, and flow and transport mechanisms (ITRC, 2017)

3.3.2 Zoning of fractured rocks

Based on fracture characteristics and their hydraulic roles, a general zonation scheme is proposed to encompass most cases (Figure 8). The four suggested zones are:

1. Network of main fractures (i.e. 1st-order fractures)
2. Top fracture zone (TFZ)
3. Low fracture zone (LFZ)
4. Damage zone (FZ)

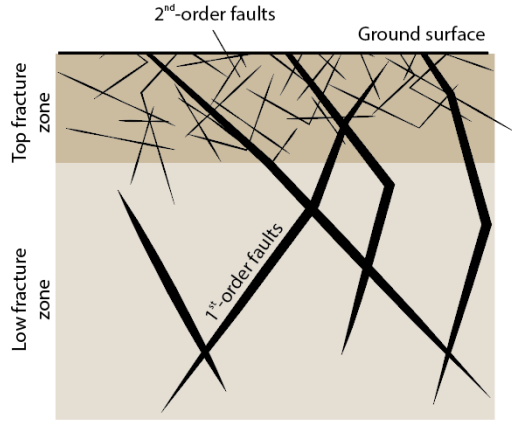


Figure 8: Schematic representation of the top fracture zone, illustrating a high density of 2nd-order fractures surrounding the 1st-order fractures that intersect the low fracture zone.

3.3.3 Network of main discontinuities & damage zone

The presence of a network of main discontinuities (i.e., fractures) is associated with tectonic and structural processes. These discontinuities, referred to as "1st-order fractures," primarily serve a conductive function, with a secondary capacitive role. They act as drains and contribute to the main outflow zones.

Authors (Bense et al., 2013; Childs et al., 2009) conceptually define the fracture field or "**fault zone**" as the combination of the "**fault core"** and the "**damage zone"** (Figure 9). From a hydrogeological perspective, the fault zone represents the volume of rock where permeability has been altered due to the fracture field. Other authors, including (Sutherland et al., 2013) distinguish between the "**alteration zone**" adjacent to the fault and the "**damage zone**" (Figure 10).

An empirical relationship exists between the thickness of the damage zone and the displacement generated by the fault zone (Figure 11). In theory, other parameters also influence the thickness of the damage zone (Bense et al., 2013) such as rock type and fault zone movement (e.g., normal or reverse faults).

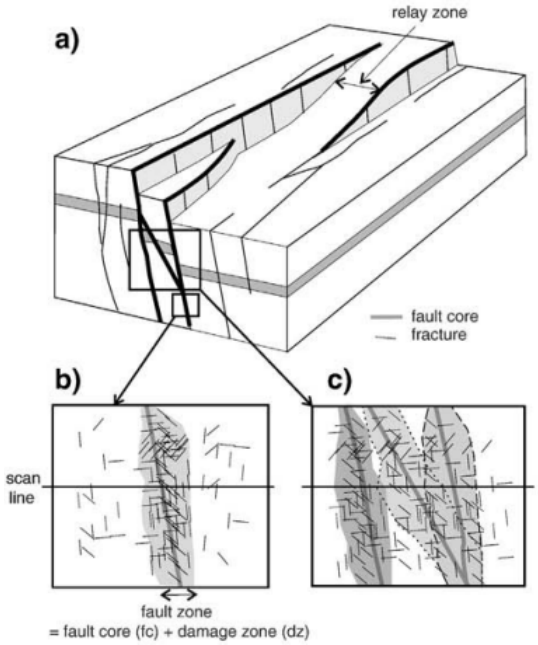


Figure 9: Conceptual model illustrating the definition of a fault zone, fault core, relay zone, and fault damage zone (Bense et al., 2013; Childs et al., 2009)

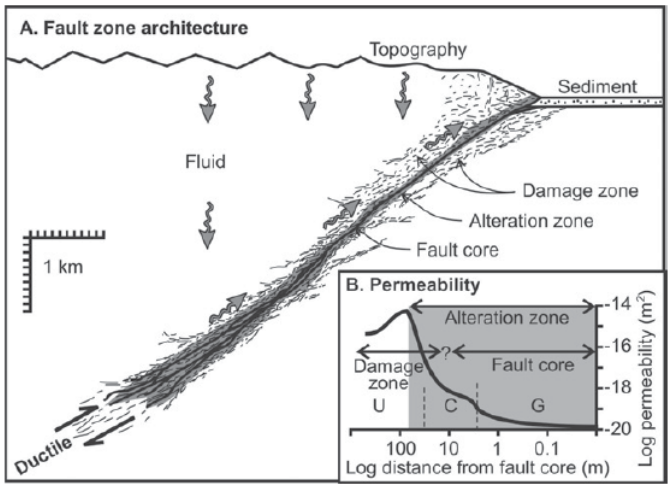


Figure 10: Schematic representation of an oblique reverse fault, highlighting the damage zone, alteration zone (shaded), and fault core (Sutherland et al., 2013). The permeability decreases significantly with increasing distance from the damage zone.

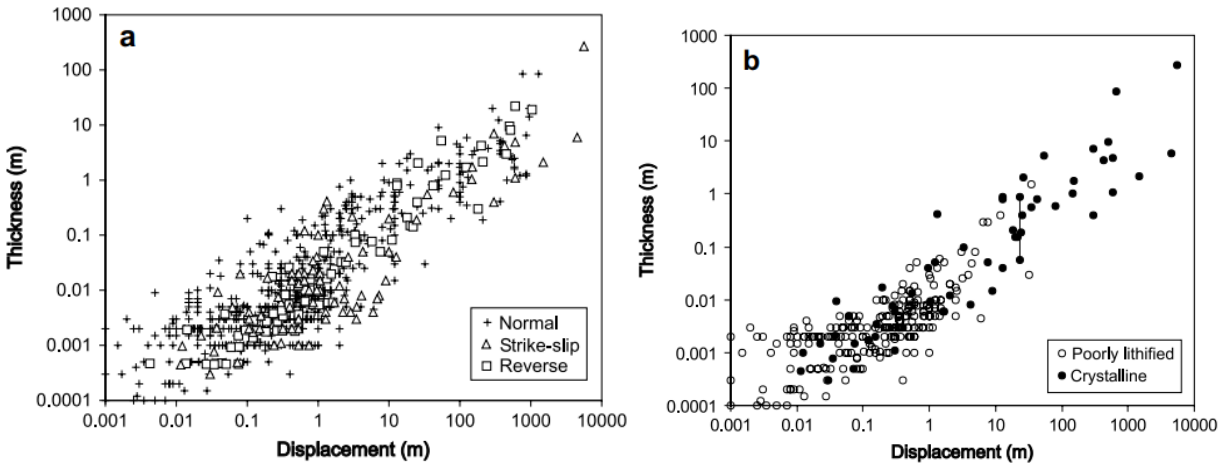


Figure 11: Relationship between damage zone thickness and fault displacement length (Childs et al., 2009)

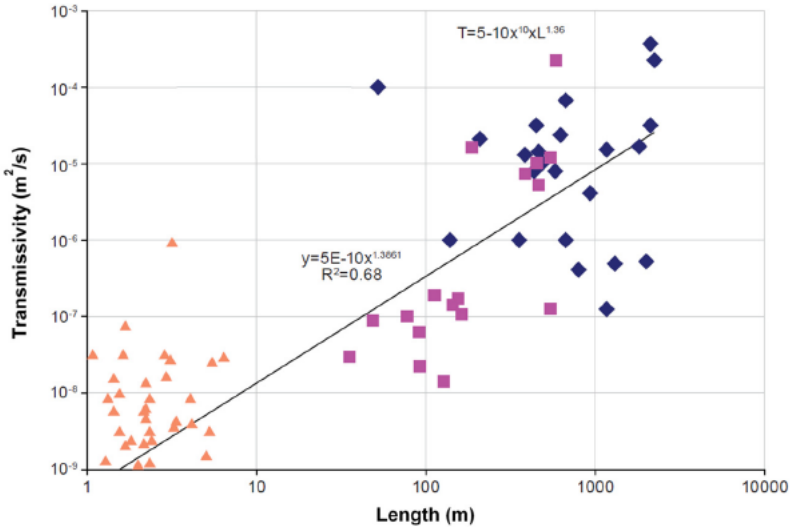
According to the literature, faults exhibit contrasting hydrogeological behaviours. In some cases, faults act as **hydrogeological barriers**, particularly when they concentrate material dislodged during

displacement (e.g., breccias) or when late-stage injections within the fracture plane result in crystallisation, effectively sealing the plane. In other cases, faults function as **hydrogeological drains**, especially in extensional contexts or when fracture planes have undergone leaching or erosion.

Additionally, observations reveal that groundwater flow is generally favoured along the fracture plane but is limited when crossing it. However, this represents a simplification, as faults are more complex and heterogeneous than simple planes. Hydraulic properties can vary significantly along different sections of the fault zone

A weak correlation has been observed between fracture length and transmissivity (Figure 12).

Figure 12: Correlation between fracture size and measured transmissivity. Larger fractures tend to exhibit higher transmissivity, with an increase of three orders of magnitude in size resulting in a four-order increase in transmissivity.



Broadly speaking, groundwater flow is generally more favourable along the fracture plane and limited across it (see Figure 13). However, as faults are inherently complex and heterogeneous, the hydraulic properties of a given section or sector of a fault may vary further along its extent.

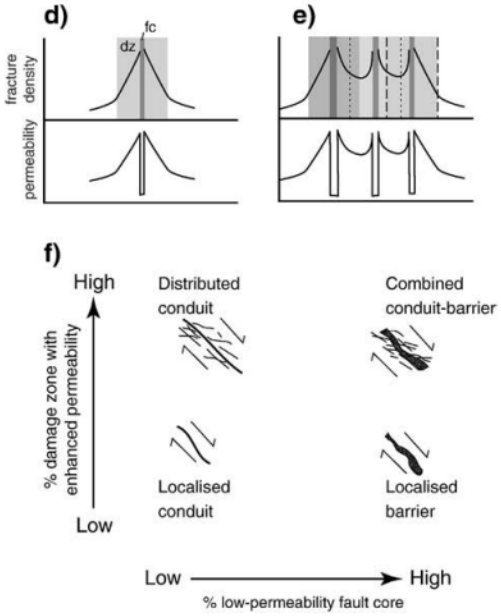


Fig. 5. (a) Block diagram showing aspects of the three-dimensional normal fault zone such as a relay zone from Childs et al. (2009). Fault zone width has been defined (b) as the combined width of the fault core and damage zone for faults with a single core (Chester and Logan, 1986; Caine et al., 1996) or (c) as the distance between the outer slip surfaces belonging to the same fault structure where multiple strands of high-strain material enclose lenses of fractured protolith (Faulkner et al., 2004, 2010). Fracture density and permeability for a crystalline bedrock lithology for a single fault zone strand (d) and multiple fault zone strands (e) (for other models see Fig. 9 and Section 3.2), modified from (Faulkner et al., 2010). (e) A description of fault behavior based on the proportion of fault core to damage zone, from Caine et al. (1996).

Figure 13:Permeability is significantly higher in the damage zone, ranging from 2 to 3 orders of magnitude greater than in the undeformed zone, but it decreases in the fault core (Bense et al., 2013).

Flow equations for fractured aquifers depend on their properties—such as hydraulic conductivity, storage, and porosity—which are primarily determined by the characteristics of the fractures themselves, including size and connectivity (Kiraly, 1994; Leblanc, 1986).

The **transmissivity** along these features is commonly calculated using the "cubic law" (Snow, 1969a) which is a function of fracture aperture. Hydraulic properties of discrete features (particularly aperture) can be determined through deterministic approaches—using field investigations, geophysics, or borehole tests—or through stochastic methods, such as Monte Carlo simulations. However, performing such analyses remains a significant challenge.

Characterizing these fractures as deterministically as possible is essential, as a small number of discrete fractures (i.e., "1st-order fractures") typically dominate groundwater flow.

3.3.4 Top fracture zone

The **top fracture zone** develops in the first tens of meters of fissured rocks. In fissured crystalline rocks, aquifers may extend to depths of up to 100 m below the ground surface. This zone is characterized by a high density of 2nd-order fractures (e.g., fissures, cracks) that form near the surface due to decompression and surface processes.

Although the permeability of the top fracture zone is relatively low compared to 1st-order fractures, it has significant porosity, which gives it a capacitive function for aquifers. In geological formations with moderate to low permeability, the thickness of the unsaturated zone is low to very low compared to high-permeability environments such as karst or volcanic aquifers. Consequently, the roof of the saturated zone tends to follow the massif's topography, resulting in significant hydraulic gradients. The permeability of the fracture zone decreases with depth as fracture density declines.

In reality, the Figure 8 s already a simplification. The lower limit (or depth) of the top fracture zone transitions progressively into the low fracture zone, where 2nd-order fractures disappear (see "Density of CFZ" in Figure 14).

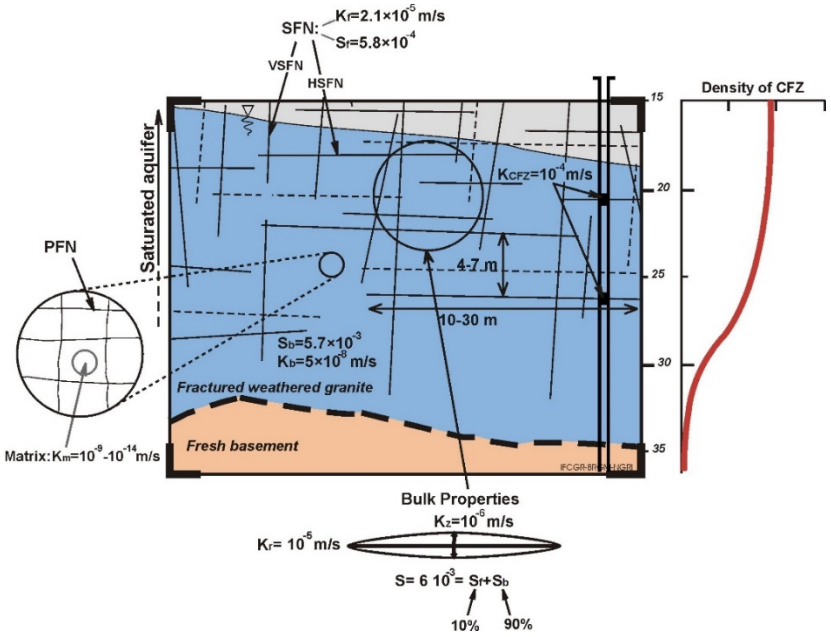


Figure 14. This example illustrates the decrease in CFZ ("conductive fracture zone") density with depth (Maréchal et al., 2004). In this case, the bottom of the top fracture zone is assumed to be at approximately 30 m. Below this depth, the low fracture zone (which is less relevant hydrogeologically) develops.

Depending on the context (i.e. climate, weathering processes, rock exposure, etc the **top fracture zone** may also be referred to as the alteration zone (**"weathering zone", "saprolite", "regolith**", etc.). Near 1st-order fractures, the top fracture zone merges with the damage zone (Figure 15).

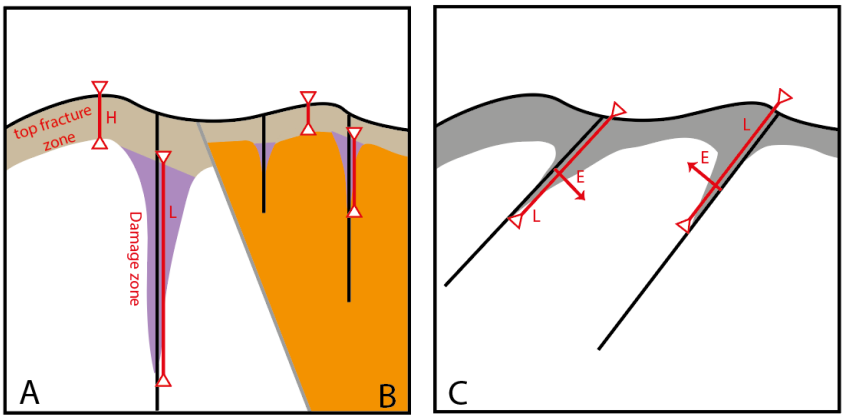


Figure 15. The top fracture zone forms near the surface and along 1st-order fractures, extending downward to a certain depth. The extent of this zone is influenced by the size of the 1st-order fractures.

Fractures in the top fracture zone may be referred to as **"background" fracture** (NACSEM, 2020) nd do not necessarily require explicit characterization. Instead, they can be represented using implicit or geostatic approaches, such as discrete fracture network (DFN) modeling.

From a hydrogeological perspective, the top fracture zone can be treated as a porous medium with low to moderate permeability, drained by the 1st-order fractures (Figure 16). The groundwater level in this medium is influenced by:

- The thickness of the fracture zone,
- The location of the groundwater base level (boundary conditions),
- The permeability of the fracture zone (dependent on fracture density),
- The transmissivity of the 1st-order fractures, and
- The recharge rate.

Depending on these factors, a pseudo “groundwater body” may form within the fracture zone. Groundwater flow in this zone is organized based on the permeability/transmissivity differences between the 1st-order fractures and the surrounding fracture zone. This results in heterogeneous spatial piezometric loads in the water table (Figure 16) under specific hydrological conditions.

Hydraulic interactions between the 1st-order fractures and the fracture zone's groundwater table largely control the hydrogeological behavior of the aquifer.

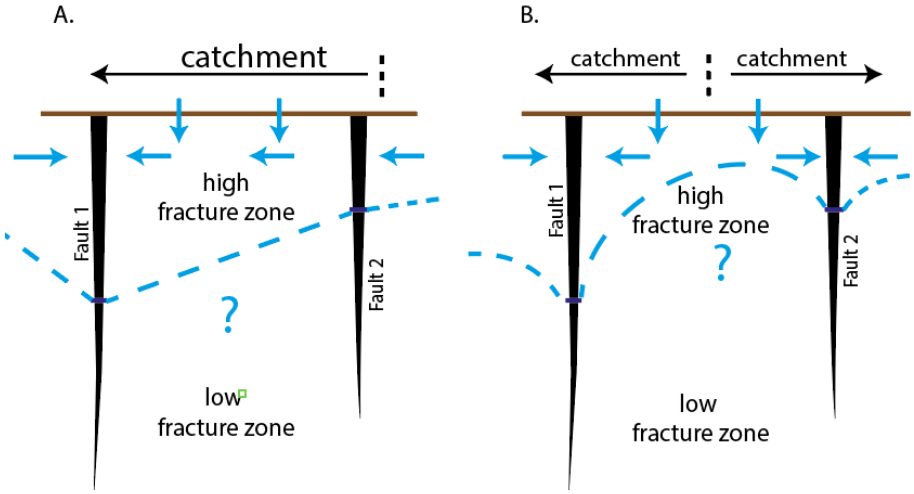


Figure 16: Groundwater flows within the high fracture zone of low to moderate permeability, eventually being drained by the 1st-order fractures (faults). Case a: The permeability of Fault 2 is very low, directing most of the

flow toward Fault 1. Case b: Fault 2 has higher permeability but is still less permeable than Fault 1, leading to partial flow toward Fault 2 and a "dome" in the groundwater table. These complex geometries are best analyzed in 3D.

The **storage capacity** of the top fracture zone depends on its thickness and the network of open fissures. The **effective porosity** in this zone can reach up to 5% (Maréchal et al., 2003), depending on the degree of the fracturing / weathering.

3.3.5 Low fracture zone

As previously discussed, rock matrix properties control the storage of water, the connection of fractures, and flow through the matrix. The key features influencing storage and flow potential in fractured rock are matrix porosity (primary porosity). Matrix porosity is not always higher than fracture porosity in a given fractured rock. In general, fracture porosity typically determines the overall potential for contaminant flow.

The ability of fractures in rock aquifers to transmit groundwater can vary across many orders of magnitude (Freeze and Cherry, 1979) as confirmed by transmissivity measurements of individual or closely spaced fractures in boreholes in various rock types (Shapiro and Hsieh, 1998).

Changes in transmissivity within fractured rock aquifers can also be abrupt, meaning that hydraulic properties of fractures cannot be assumed to be uniform. For this reason, it is essential to develop an appropriate geomechanical framework of fracturing to use as the basis for inferring groundwater flow pathways.

Fresh rocks, or the basement, represent the deeper rock volume that is not affected by 2nd-order fractures. This “unfractured” medium does not play a significant hydrogeological role, either capacitive or transmissive (apart from the 1st-order fractures), as both hydraulic conductivity and porosity are quite low compared to other geological settings (Table 1). In these conditions, fresh rock forms the **low fracture zone**, where no fault network can be considered.

Rock	Total Porosity n (%)	Effective Porosity n_e (%)	Hydraulic Conductivity K (m s^{-1})
Granite	0.1	0.0005	3×10^{-14}–2.0×10^{-10}[a]
Limestone	5–15	0.1–5	1.0×10^{-9}–6.0×10^{-6}
Sandstone	5–15	0.5–10	3.0×10^{-10}–6.0×10^{-6}
Shale	1–10	0.5–5	1.0×10^{-9}–6.0×10^{-6}

[a] Hydraulic conductivity value for “unfractured igneous and metamorphic rocks;” total porosity and effective porosity are for crystalline granite.

Table 1. Intact Rock Porosity (Total and Effective) and Hydraulic Conductivity (Domenico and Schwartz, 1991)

3.4 Review of hydrogeological conceptual models

As mentioned by Betancur V et al., 2012, “a conceptual model in hydrogeology is a representation of the hydrogeological units and the flow system of groundwater.” Due to the global lack of data and knowledge, geologists and hydrogeologists are usually constrained to produce "models" (representations) based on extrapolations (numerical) or interpretations (deterministic) rather than using geostatistical interpretation tools to describe their datasets. Conceptual models might be simple sketches, drawn by hand, and based on the user’s experience, but they may also include a numerical component to aid extrapolation or data interpretation. Conceptual models can be 2D (profiles, schemes) or 3D (models, block diagrams, etc.), generic or site-specific, and may present different degrees of abstraction, from the most schematic to the most explicit. Most of them usually offer a general representation, meaning that an additional conceptual abstraction is required to conceptualize geometries and processes on a particular site. At the extreme, a 100% numerical model can also be considered "conceptual"—but the link with "reality" is more remote, as the model produces quantitative results rather than merely describing characteristics and processes.

The need for a robust and clear conceptual model is essential when dealing with a "real" site to study practical or theoretical issues. In this view NACSEM, 2020 wrote: "Without a conceptual framework, numerical modelling will likely misrepresent hydrologic behavior at even the smallest project site. Conceptual (or **hydrostructural**) model templates are available for different geologic environments and can be used to develop suitable conceptual models that incorporate the rock and hydrologic structures in a systematic way." A few lines further, they add: "It is good practice to follow a systematic and well-documented approach to hydrostructural conceptual model development to understand the nature of underlying assumptions and simplifications, especially in the absence of supporting data," but they only briefly explain how to establish it and, above all, do not propose any concrete method or workflow to achieve it or to validate it.

Hydrogeological conceptual models are used to describe: (i) the physical settings of an aquifer (i.e., the system), and (ii) the groundwater content and flow (i.e., the processes). Figure 17 presents a minimalistic conceptual model of a generic aquifer (i.e., one that does not refer to an existing site, as opposed to a model of a specific aquifer site). Although the model was initially designed for karst, it could be applied to most aquifer types, as the concepts and principles are basic.

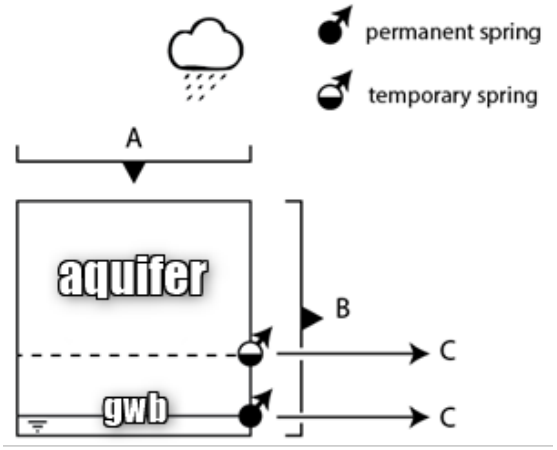
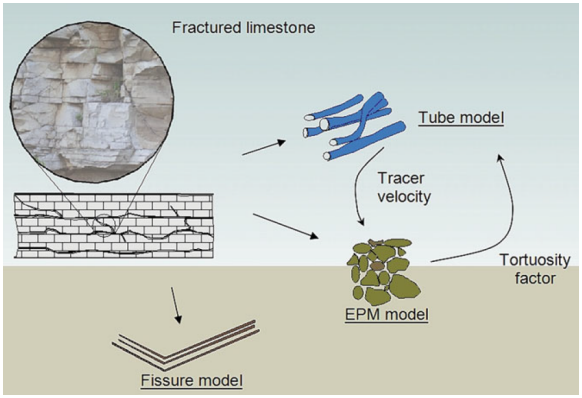
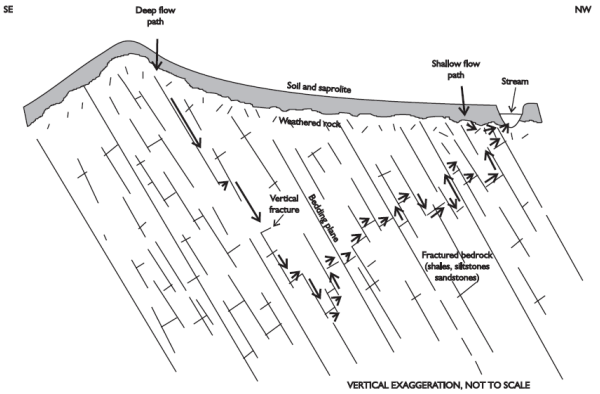


Figure 17. Minimalistic conceptual model of a generic (karst) aquifer (Malard, 2018). "A" refers to the system recharge, "B" refers to the groundwater flow and storage (gwb), "C" refers to the drainage or discharge of the system outlets.

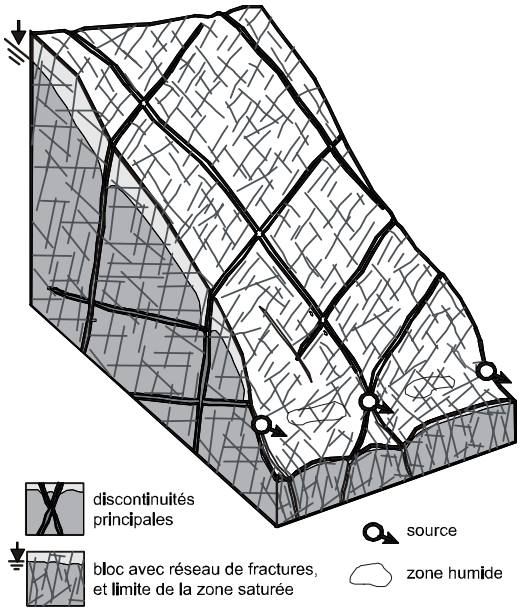
Main **elements** and **processes** that should be pictured or described by a conceptual model include: (A) **recharge**, (B) **storage**, and (C) **drainage/discharge**. Many different conceptual models have been proposed to illustrate how groundwater **recharges, stores**, and **flows** through fractured aquifers. (Banks et al., 2009; Dewandel et al., 2006; Goode and Senior, 2000; Lachassagne et al., 2021; Masciopinto and Palmiotta, 2013; Pochon and Zwahlen, 2003; Van Meir et al., 2007, etc.). A few of them are presented in Figure 18.



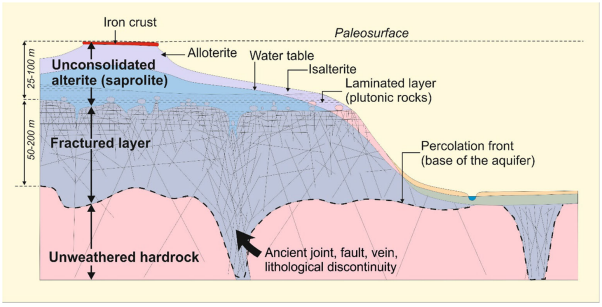
A. Simple conceptual model of a fractured limestone aquifers (Masciopinto and Palmiotta, 2013)



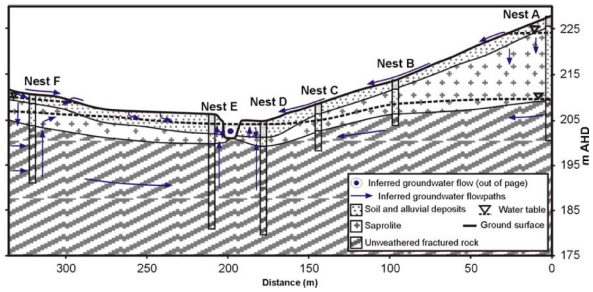
B. Generic conceptual model of a groundwater flow system for a fractured sedimentary rock aquifer with dipping beds (Goode and Senior, 2000).



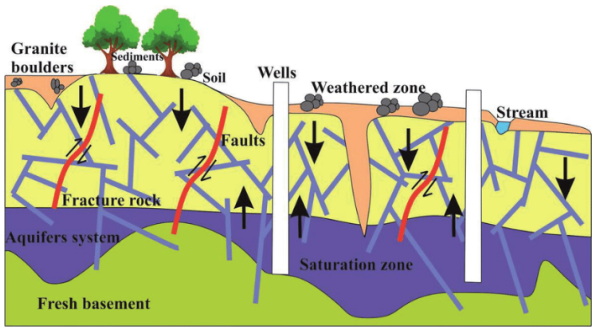
C. Conceptual 3D model of a generic fractured aquifer in hard rock (Pochon and Zwahlen, 2003)



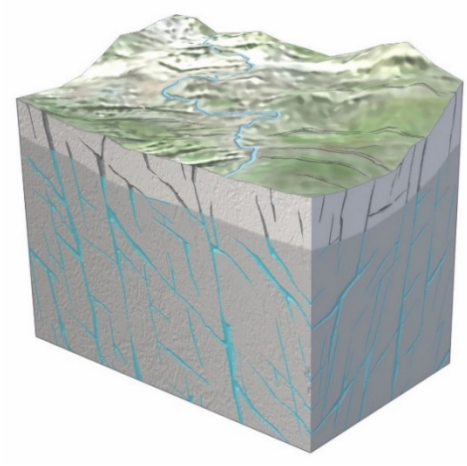
D. Conceptual model of a weathered profile of a generic fractured aquifer in hard rock (Dewandel et al., 2006; Lachassagne et al., 2021).



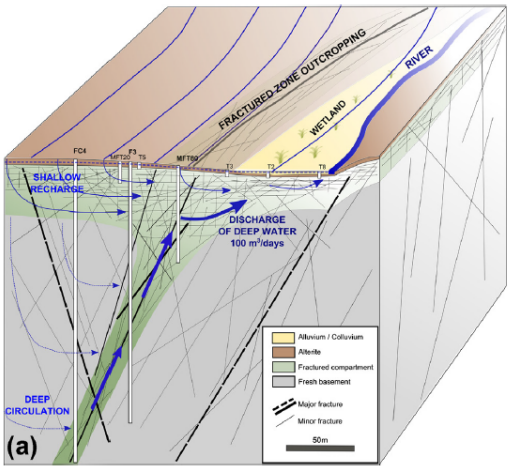
E. Conceptual model of the “Scott Bottom” study site (site-specific). Arrows indicate direction of inferred groundwater flow (Banks et al., 2009).



F. Conceptual model of a generic fractured aquifer (Akhtar et al., 2020)



G: Schematic representation of a fissured aquifer (source OFEV).



H: Conceptual model of a specific fractured aquifer in NW France (Roques et al., 2014)

Figure 18. Examples of hydrogeological conceptual models from literature

The presented models show differences in how geometries and processes are represented. One common observation is that they all consider a certain degree of homogeneity within their heterogeneity.

Model A: This is a purely conceptual scheme without dimensions, focusing solely on the flow aspects. It does not aim to reproduce the spatial characteristics of the aquifer in either 2D or 3D (i.e., it is not explicit). Groundwater is not even represented. Such a scheme is typically used to design a numerical model, but it cannot validate the outputs of a numerical model.

Model B: This is a simplified representation of groundwater flows in a fractured aquifer. It shows how water circulates through the fault network and connects to the springs. However, it does not display groundwater reserves or resources, nor does it show the hydraulic gradients that control the flows. As a result, readers cannot fully grasp the general behavior of the groundwater body.

Model C: This model is the opposite of Model B. It provides an idea of the groundwater body and the related gradients, but it does not show where or how groundwater flows. This is a 3D model, allowing for a better understanding of the spatial distribution, but it lacks detailed flow information.

Model D: This is a more sophisticated version of Model C. Groundwater storage (i.e., reserves) is partitioned between the overlying weathered units (saprolite) and the fissured zone near the fractures. However, the model does not display groundwater flows.

Model E: This site-specific model provides an approximate idea of where groundwater is stored and how it flows from the saprolites to the aquifer outflow. It relies on the principles of Model D but sketches the heterogeneous fractured media as a homogeneous medium. Despite this simplification, it offers a useful representation of the groundwater movement.

Model F: A generic model describing a fractured aquifer with high permeability in the fracture zone. The fracture zone is divided into two parts: the lower part is saturated, while the upper part is in the vadose zone. This model shows where most of the water is stored but does not adequately describe recharge and flow patterns.

Model G: A generic model designed to highlight the governing role of fractures in alpine aquifers. It emphasizes that fractures are the main storage for groundwater, which could be misleading. Additionally, the model suggests a "thick" unsaturated zone even in the less-fractured regions, which might not be accurate.

Model H: This site-specific model describes (i) how groundwater flows are drained from the recharge zone to a major fracture via a network of secondary fractures and (ii) how groundwater is discharged in the valley (wetland). While this model gives a comprehensive picture of groundwater flow, it does not provide information on where the groundwater is stored.

The following table summarizes the **characteristics** of the 8 conceptual models.

Table 2. Comparative analysis of FM conceptual models and the information they provide.

Models	Type	Recharge	Storage	Drainage / discharge	Main focus
A	Conceptual scheme	Not explicitly represented	Not explicitly represented	Simplified representation of the drainage mechanisms	Drainage
B	Generic scheme	Not explicitly represented	Not explicitly represented	One single flowpath (i.e. drainage) and one single outlet (discharge) is represented	Drainage
C	Generic 3D (block diagram)	Not explicitly represented	Storage is represented as a saturated zone and flooded fractures	The drainage is not explicitly represented. The discharge is symbolized as a spring	Storage and discharge
D	Generic 2D (section)	Not explicitly represented	Storage is represented as a saturated zone and flooded fractures	Not explicitly represented	Storage
E	Specific 2D (section)	Explicitly represented (infiltration, runoff as arrows)	The representation of the storage is simplified	The representation of the drainage is simplified	Recharge and drainage
F	Generic 2D (section)	The representation of the recharge is simplified	The storage is explicitly represented	Not explicitly represented	Storage and drainage
G	Generic 3D (block diagram)	Not explicitly represented	Storage is represented as a saturated zone and flooded fractures	Not explicitly represented	Storage
H	Specific 3D (block diagram)	The recharge is represented, coupled with the drainage	The storage is not really represented	The representation of the drainage is simplified	Recharge, drainage and discharge

The table shows that none of the models presented explicitly represents all **hydrogeological characteristics** (recharge, storage, drainage and discharge) in a satisfactory manner. Most of them focuses on some of the characteristics **but do not cover all those which allow to give a full representation of fractured aquifers.**

3.5 Modelling approaches

With the exception of simple **analytical** models, which usually provide results over time or 1D results, two main approaches are described in the literature to model spatial flows over time: (i) the **discrete fracture network (DFN)** approach (Li et al., 2020) and (ii) the **stochastic continuum (SC)** approach (Dershowitz et al., 2004). These are **numerical approaches** as both provide quantitative results.

The **DFN** assumes that most groundwater flows within fractures. Fractures are generated stochastically, with properties inferred from reference site data, and fracture networks are converted to three-dimensional networks of one-dimensional pipes (using topological graph theory), with properties equivalent to each fracture. **Darcy's law** applies for each fracture, and the mass balance is achieved at each fracture intersection. In this approach, fractures are explicitly considered, whereas the matrix, i.e., the rock surrounding the fracture network, is not assumed to play a role in the flow.

The **SC** approach is based on the concept of a representative elementary volume. The rock media is considered an equivalent porous medium, and the flow is computed using the distribution of hydraulic conductivity values. In this approach, fractures are not explicitly considered, and groundwater flows through the representative elementary volume, governed by Darcy's law. It is important to limit the applicability of **SC** models to cases where the problem scale is much larger than the scale of the fractured rock mass. The applicability of the **SC** approach thus depends on scale, and it increases with increasing scale.

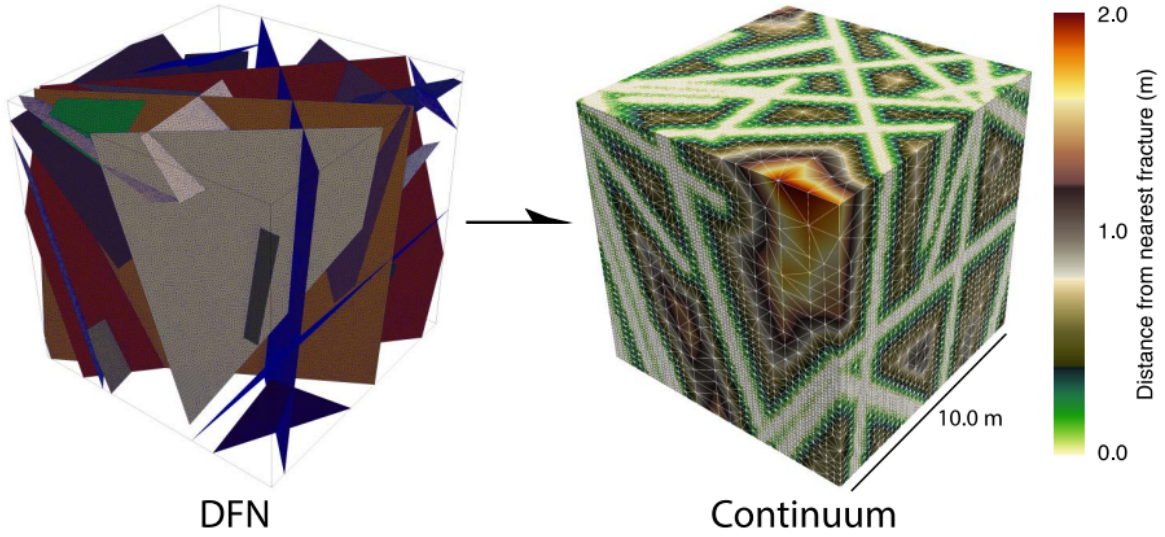


Figure 19. left the DFN approach, right the Equivalent Continuum porous media (Hyman et al., 2015a)

A third approach, using a "**channel network"** (CN) to model flow through fracture networks, is mentioned by a few authors (Selroos et al., 2002). This assumes that flows are distributed non-uniformly across the fracture plane in preferential paths or channels.

Finally, a few hybrid approaches combining DFN and SC also exist, such as the **fracture continuum** (FC) approach (Svensson, 2001). In this case, small-scale fractures are represented by equivalent continuum, while largescale discontinuities are modelled in a discrete manner.

n practice, SC approaches are much more widely used than DFN approaches, which are often limited to the academic sector. The choice of modelling approach depends on site conditions (system), the intended use of the model (issue), and available financial, data, human, and computational resources.

The ITRC (ITRC, 2017)[4] provides a table with the suitable modelling (i.e., numerical) approach to apply depending on the issue (Table 3).

Hydrogeological issue	**Potentially Suitable Approach**
Estimating and tracking the possible migration pathways of groundwater contamination	DFN, EPM/DFN, CN
Designing and evaluating hydraulic containment and pump-and-treat systems	Analytical, DFN, EPM, EPM/DFN, CN
Designing and evaluating groundwater monitoring networks	Analytical, DFN, EPM, EPM/DFN, CN
Estimating the possible fate and migration of contaminants for risk evaluation	DFN, EPM/DFN
Estimating contaminant removal rate and cleanup time	Analytical, DFN (with dual porosity), EPM/DFN (with dual porosity)
Evaluating the potential impact on downgradient receptors such as surface water bodies or potable water supply wells	EPM with appropriate anisotropy coupled with particle tracking, DFN, EPM/DFN
Predicting contaminant concentrations for natural attenuation remedies	Analytical, DFN (with dual porosity), EPM/DFM (with dual porosity)
DFN – Discrete Fracture Network, EPM – Equivalent Porous Medium, CN – Channel Network	

Table 3. List of the suitable approaches to apply depending on the hydrogeological issues (ITRC, 2017).

An example of an application is given Figure 20. The author (Bense et al., 2013) demonstrates the sequence of steps leading to the creation of numerical models using a) the DFN approach or b) the continuum approach. This is done by collecting and formatting field data and creating one or more conceptual models, the principles and information of which feed into the numerical model.

[4] Interstate Technology and Regulatory Council (https://fracturedrx-1.itrcweb.org/8-modeling-fractured-rock/)

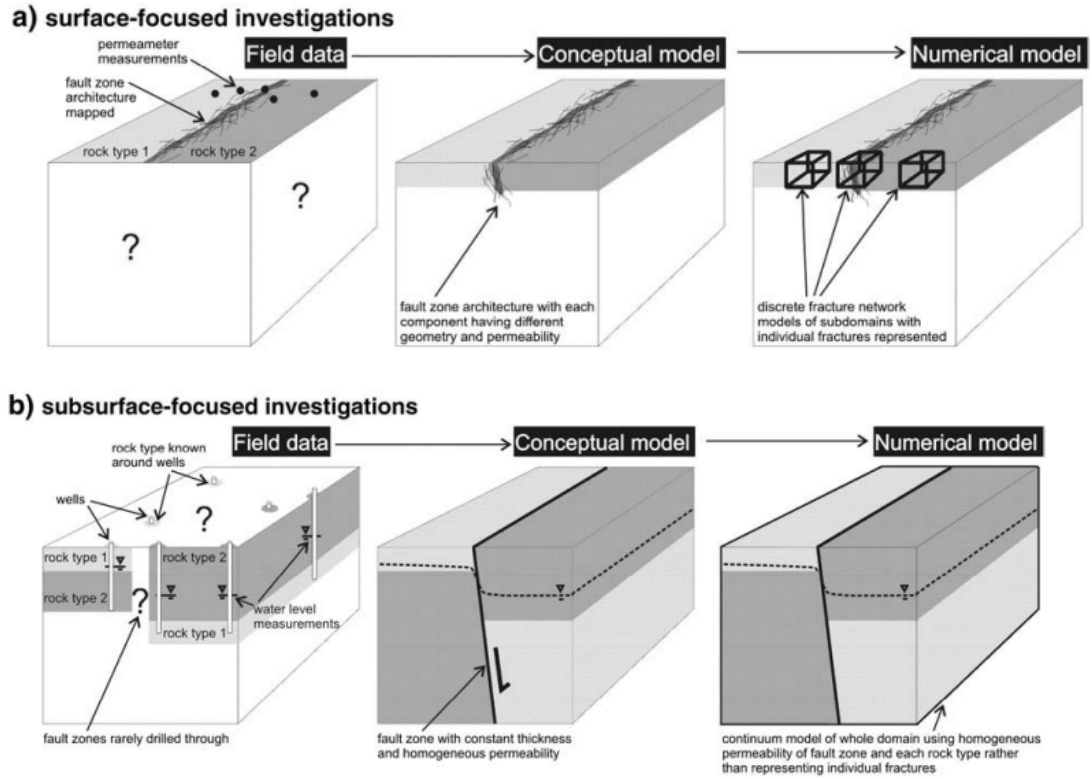


Fig. 1. Investigation of fault zone hydrogeology has often focused on (a) characterization of surface outcrops often by structural geologists or (b) by investigation of borehole data providing information on geology and direct hydrogeological evidence of the impact of faults on fluid flow. The source of field data leads to different conceptual models, numerical modeling assumptions and methods. Table 1 lists examples of studies employing the different modes of investigation and field methodologies. Surface investigations sometimes have a more three-dimensional surface exposure (i.e. at mine sites or in mountainous topography) and some sub-surface investigations include tunnels or underground mines.

Figure 20. Two different workflows (a) and (b) from field data to hydrogeological numerical models, passing through conceptual models. The type of field data and the way they are selected significantly influence the construction of the conceptual model, as well as the principles and assumptions incorporated into the numerical model (Bense et al., 2013).

Behind these two approaches lies the question of scale and computational resources. At a large scale, the stochastic continuum approach is attractive because it requires less data, fewer computational resources, and the calibration is easier. However, the results must also be considered on a large scale, as local processes cannot be properly modelled. At intermediate scales, hybrid approaches may prove effective, and finally, at fine scales, the DFN approach may apply. In this case, fractures may be implemented explicitly or generated stochastically if measurements are missing or if there are too many fractures.

3.6 Limitations

This section lists the inherent **limitations** of the current **conceptual and modelling approaches**. These limitations are related to the **principles** of the approaches or their **application** and may lead to **uncertainties** in the results

3.6.1 Related to its principles

3.6.1.1 Simplification

As models are conceptual descriptions, or approximations, that describe physical systems using numerical equations, they introduce concepts, principles, or features that are **significantly simplified** compared to “reality”. This is especially the case with the SC approach, which ignores the spatial heterogeneity of fault networks in favour of a more homogeneous matrix. In all cases, model results must therefore be carefully balanced against these simplifications

3.6.1.2 Scale effect

Scale is always a limitation in hydrogeology, as flow processes may differ by 6 to 7 **orders of magnitude**. In relation to this spectrum, all processes cannot be addressed, or even approximated, in a single model (i.e., for one specific site with fixed dimensions and a specific timescale). Local flows are generally difficult to properly assess in a large-scale model, particularly when using the SC approach

3.6.2 Related to its application

3.6.2.1 Site conditions

The application of the models is constrained by certain site-specific conditions:

- These approaches typically focus on a specific aquifer type. They do not usually **integrate multiple aquifer environments** (karst, porous, fractured), and when they do, it is often in an indirect way.
- All numerical approaches require the specification of **boundary conditions** (e.g., no-flow, constant/variable flow or heads), which may be difficult to infer from field data.
- With the exception of the SC approach, most flow modelling approaches assume that the flow domain is **fully saturated**. They cannot properly model flow in the unsaturated zone, which could be a significant limitation in practical applications

3.6.2.2 Required data (quantity, quality)

Most of the approaches cited usually require a large amount of data and parameters to enable computation (ITRC, 2017). As this data is often difficult to obtain, users are frequently forced to make **assumptions** about many parameters, leading to greater uncertainties in the results. In other words, the benefits of the model's complexity must be weighed against the importance of the assumptions made. A **sensitivity analysis** is therefore required to identify which data/parameters have the largest impact on model results (high sensitivity) versus those that produce smaller changes (less sensitive).

3.6.2.3 Calibration, realizations & computation time

Most modelling approaches require a considerable amount of effort and time for **calibration** (which can become very complex when using **calibration models** such as PEST or UCODE), multiple **realisations** (to make the results converge), and significant computing resources to solve the calculations. Depending on the settings, the DFN approach can be **computationally very demanding** and is usually not suitable for simulating flow in large-scale sites (El-Kharakany et al., 2022).

3.6.3 Related to the dissemination / communication

Results from modelling approaches are often only accessible to **specialists** who know how to interpret them and make the necessary abstractions to translate these results into real-world applications. This is a limitation when **communicating results** to the target audience, often local or regional administrations or authorities. The fact that the processes involved cannot be explicitly communicated, and that these results cannot be readily understood by the target audience, represents a real challenge in practical applications.

4 FracSYS solution

This section presents the assumed **user needs**, the **conceptual model**, and the **workflow** used to implement the **FracSYS approach**. Technical information related to the implementation of the FracSYS tool is provided in Annex 3.

4.1 Definition of needs / requirements

Needs are defined as the information that should be addressed by the FracSYS approach to answer questions or issues related to groundwater in fractured aquifers (Table 4). These needs are expressed as hydrogeological questions (i.e., pragmatic, general) that most hydrogeologists are expected to address at a site during most studies (groundwater tapping, management, remediation, impact of construction, protection zones, etc.). The needs are inferred from the scheme in Figure 17 but they are also drawn from experience gained through the development of VisualKarsys. The following table is intended to inform the initial needs that will guide the tool's development.

Table 4. Description of needs, i.e., the pragmatic information that most users want to know about groundwater in fractured aquifers

Needs (from the users)	**Expected answers (from FracSYS)**
Where are the main groundwater bodies located, and what are the main reserves/resources I'm studying?	FracSYS must provide an explicit representation of the location of the main groundwater reserves/resources that might have hydrogeological significance. Users should be able to easily link the (geometric) results of the model to the real-life context.
How does groundwater flow? In other words, what paths do most of the groundwater flows take from their entry into the aquifer to the place of outflow? Time transit (slow/fast), residence time, hydro-bio-chemical processes, thermal processes (interaction).	FracSYS should provide a semi-physical 3D representation of groundwater flows, so that users can intuitively understand the organisation of flows from upstream to downstream, through fracture networks. A weighting could be assigned to the representation to distinguish "important" flows from "low" flows (or even represent only the "important" ones).
How is the groundwater flow system recharged? This question actually raises two sub-questions: (i) the first is quantitative and aims to assess the importance of the resource (i.e., water availability), (ii) the second is qualitative and aims to assess the protection of the aquifer from surface pressures.	To address this question, FracSYS should enable users to: (i) evaluate the surface area contributing to the aquifer's water supply, and (ii) understand the recharge mechanisms (essentially infiltration), to be able to assess the vulnerability of groundwater to surface pressures.
Are there any hydrogeological or hydraulic relationships with other aquifer types (karst, porous, etc.) and what are they?	To address this question, FracSYS must be able to: (i) model several types of aquifers within a single model, and (ii) reproduce the hydraulic relationships between them (e.g., karst draining a fractured aquifer, or a fractured aquifer draining a porous aquifer).

4.2 The FracSYS conceptual model

Where does it come from? On which basis is it built? This conceptual model is based on a review of existing models for fractured aquifers. The criteria involved are: 1) where the reserves/resources (storage) are located, 2) where explicit flow depends on hydrogeological conditions (low/high flow), and 3) how the recharge process works. The aim is for the model to be as generic as possible and applicable worldwide. Is this the only approach? It is quite innovative.

The FracSYS conceptual model has been derived based on: (i) the principles of a hydrogeological conceptual model, explicit and in 3D, (ii) a review of existing models for fractured aquifers, and (iii) the expected needs of the users in terms of the information required.

From these, it has been possible to infer a more explicit, pragmatic, universal, and let's say "suitable" model that can describe the settings (geometry of the reservoir, drainage axes, etc.) as well as groundwater flows. This model is presented in Figure 21 as a 2.5D sketches.

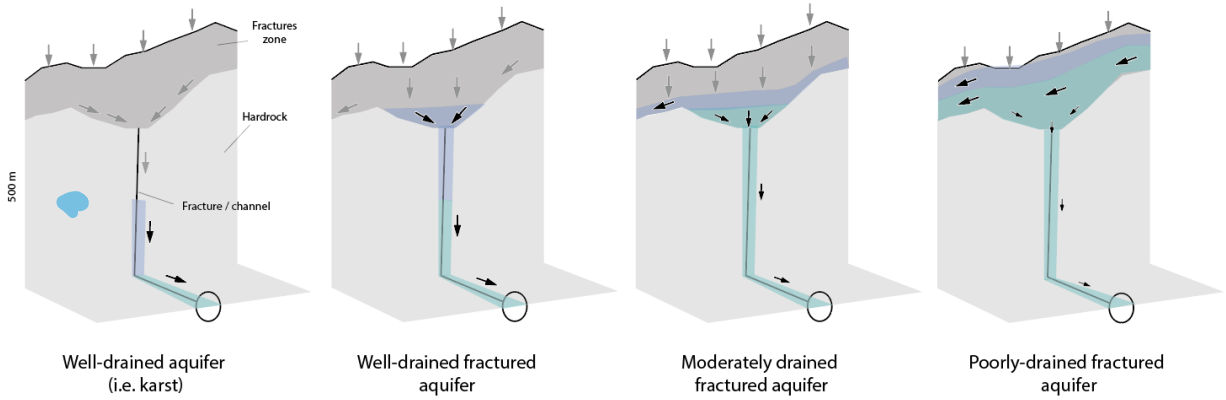
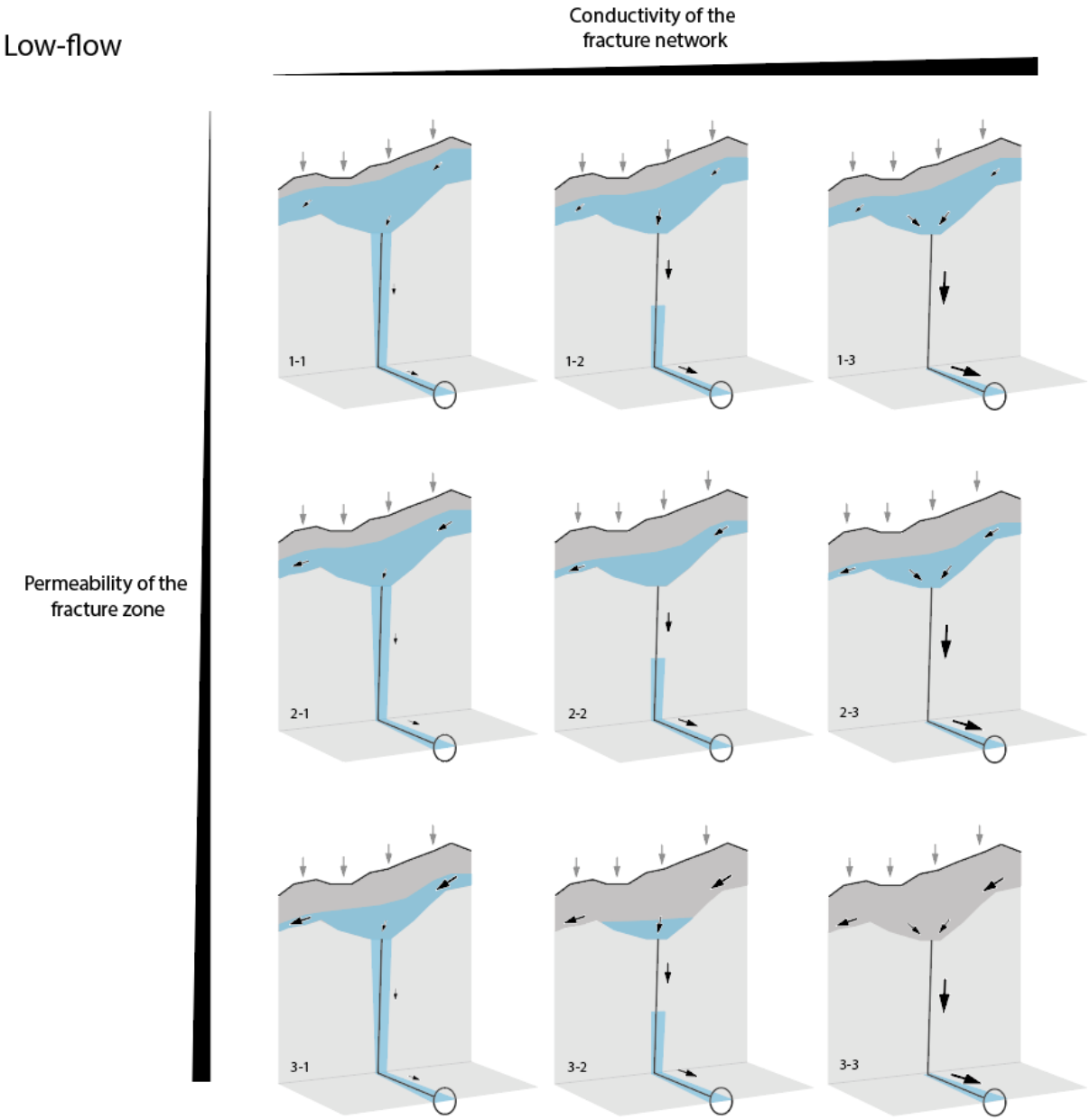


Figure 21. Illustrations of the FracSYS conceptual model in ~2.5D. The four images each represent a hydrogeological situation based on the permeability of transmissive fractures.

The main features of the FracSYS conceptual model are as follows:

- Geometry: the **thickness and extent of the top fracture zone** (the capacitive media), considered as the main storage zone for groundwater. The model may also indicate the porosity and permeability of the media.
- Geometry: the **thickness and extent of the low fracture zone**, where transmissive fractures are assumed to develop.
- Geometry and hydraulic properties of the transmissive fractures (i.e., 1st-order fractures).
- Location of the main groundwater resources/reserves.
- Organisation of the **flow system**: from recharge (ground surface), through accumulation and transit within the fracture zone, to transit through the fracture network. This flow depends on the equilibrium between (i) recharge, (ii) the permeability of the fracture zone, and (iii) the permeability of the fracture network.

Changes in groundwater and flow in the four examples shown in Figure 21 are related to variations in (i) recharge (low vs. high water conditions), (ii) permeability of the fracture zone, and (iii) conductivity of the 1st-order fractures. By considering (i) three levels of permeability in the fracture zone, (ii) three levels of conductivity in the 1st-order fractures, and (iii) two different hydrological conditions (one representing the normal "steady state" and one for "high-water" conditions), there are 18 possible scenarios, which are illustrated in Figure 22.


Low-flow
Conductivity of the fracture network
Permeability of the fracture zone
1-1
1-2
1-3
2-1
2-2
2-3
3-1
3-2
3-3

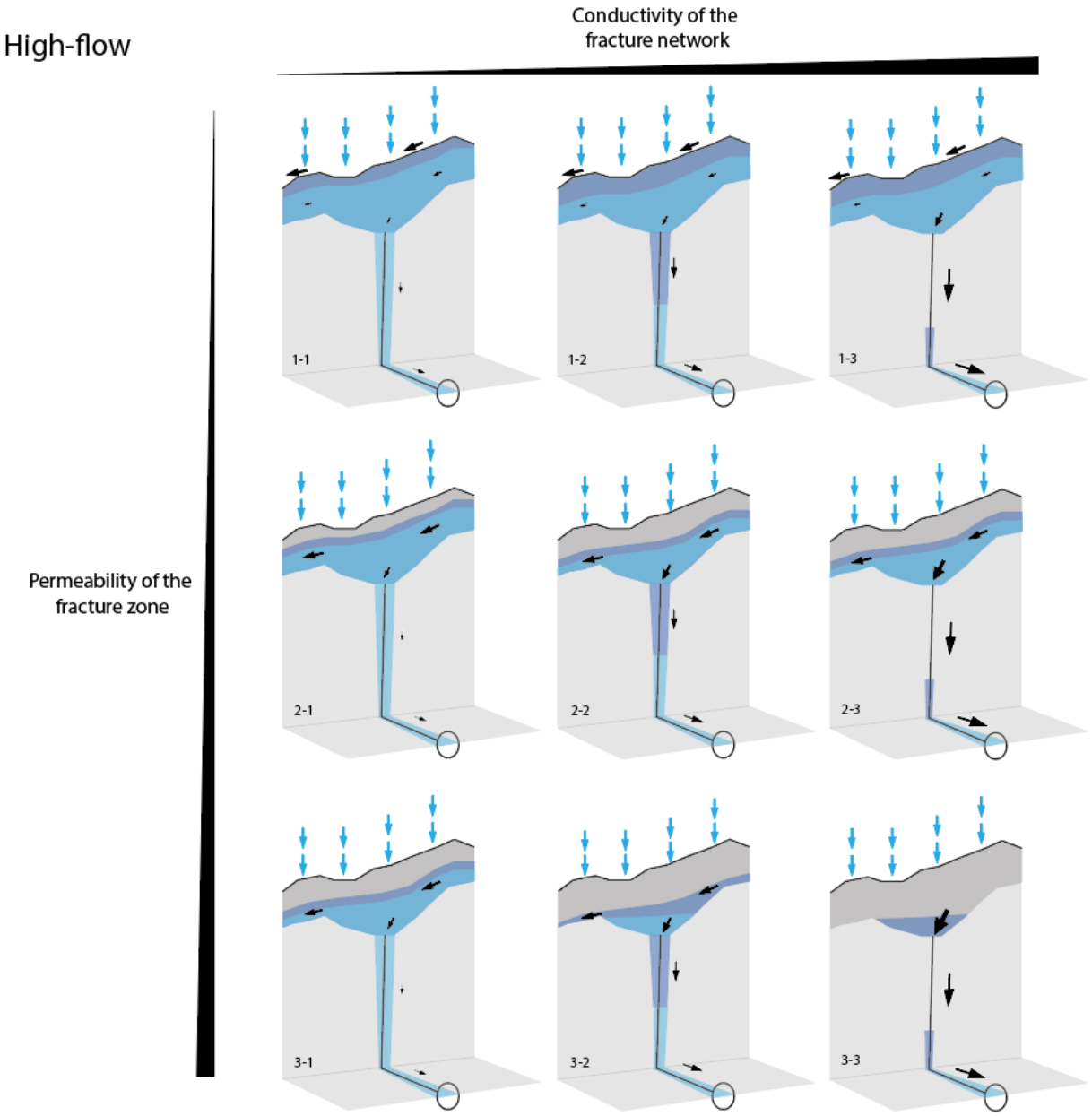


Figure 22. Different scenarii of the FracSYS conceptual model depending on (i) the permeability of the top fracture zone (tfz), (ii) the conductivity of the 1st-order fracture, and (iii) the hydrological conditions (low- vs high-water stage)

According to these scenarios, different observations can be made:

- For a given hydrological condition, the flow system is primarily controlled by the differences in permeability/transmissivity between the fracture zone and the 1st-order fracture.
    - If the permeability of the TFZ is greater than the conductivity of the 1st-order fracture (cases 2-1, 3-1), most of the groundwater will flow in the fracture zone, downward along the relief. Only a small amount of groundwater will enter and flow through the 1st-order fracture.
    - If the permeability of the TFZ is less than the conductivity of the 1st-order fracture (cases 1-3, 2-3, 3-3), most of the groundwater will be trapped by the 1st-order fractures and flow through the network. In the extreme case, all the groundwater is drained by the

1st-order fractures, and the fracture zone becomes unsaturated. This scenario is not rare but is strictly controlled by the conductivity of the 1st-order fractures.

- Depending on the contrast in permeability/conductivity between the fracture zone and the 1st-order fracture, a non-saturated zone may develop within the 1st-order fracture. In this case, the groundwater enclosed in the fracture zone forms a "perched groundwater body", and the hydraulic relationship between the fracture zone and the 1st-order fracture becomes disconnected.

4.3 The FracSYS workflow

This section describes the adopted workflow for the documentation of fractured aquifers, in other words, the different steps to achieve when applying FracSYS. The following Figure 23 shows the workflow and the associated steps.

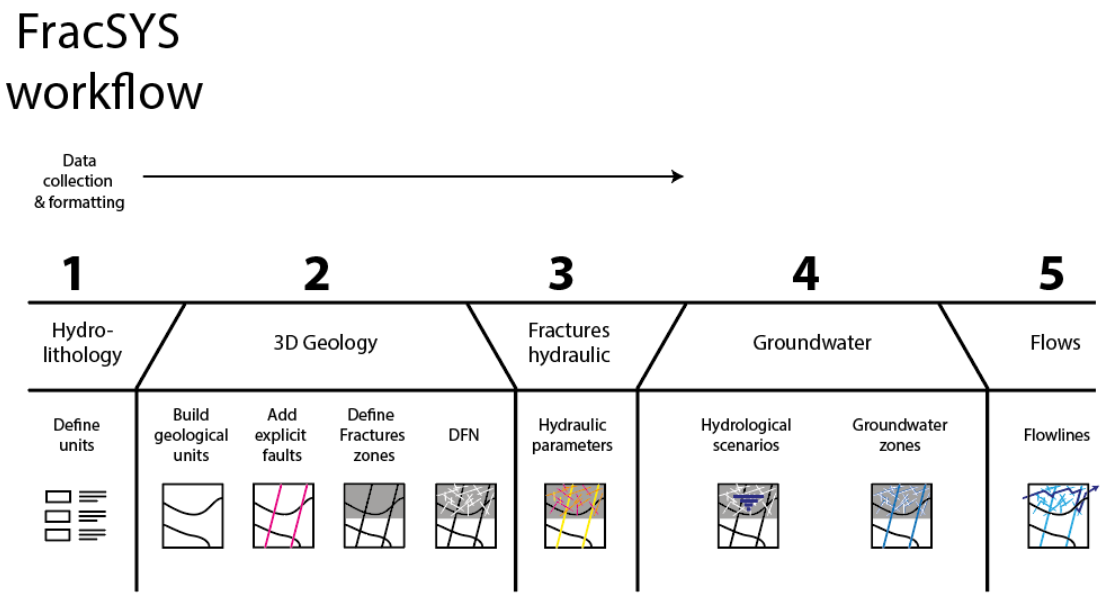


Figure 23. Proposed 5-step FracSYS workflow

The 5 main steps here-above mentioned are detailed in sub-steps:

4.3.1 Step 1 - Hydrolithology

In this step, users are required to define the lithologies to be discretised in the FracSYS model. The following steps should be performed:

- Define the different **lithologies** that will be modelled in the 3D geological model.
- Assign a "**type of aquifer media"** (i.e. "**fissured rock"**, along with "**permeability"** and **"porosity" values** for each lithology. These properties will differentiate permeable hard rocks (i.e. fractured aquifers) from impermeable ones (acting as aquicludes).
- For each geological unit, specify the depth of the top fracture zone (in metres) as defined in Section 3.

Comments	➔ Do we define the top fracture zone here or in Step 2? It seems easier to define it in Step 1, both for the user and for implementation. ➔ We assume there is only one top fracture zone, with a depth specific to each unit.

4.3.2 Step 2 - 3D Geology

In this step, users are required to construct the 3D geological model, which includes the geological units and explicit faults (1st-order faults).

4.3.2.1 Build geological units

Users should:

- Assign geological data to sections, drillholes, galleries, etc., for each geological unit (e.g., "**contact data**" and "**dips**").
- Compute the 3D geometry of the **geological units** using a 3D geomodelling tool (**GmLib**, see Section 8.1). These steps are like those in Visualkarsys.

4.3.2.2 Add explicit faults (1st-order faults)

Users should:

- Define **explicit faults** (1st-order faults) and related attributes: name, properties (finite, infinite), colour, relation to other faults, etc.
- Assign fault data to sections, drillholes, galleries, etc., for each fault (e.g., "**contact data**" and "dips").
- Compute the 3D geometry of the faults using a 3D geomodelling tool (**GmLib**, see Section 8.1)

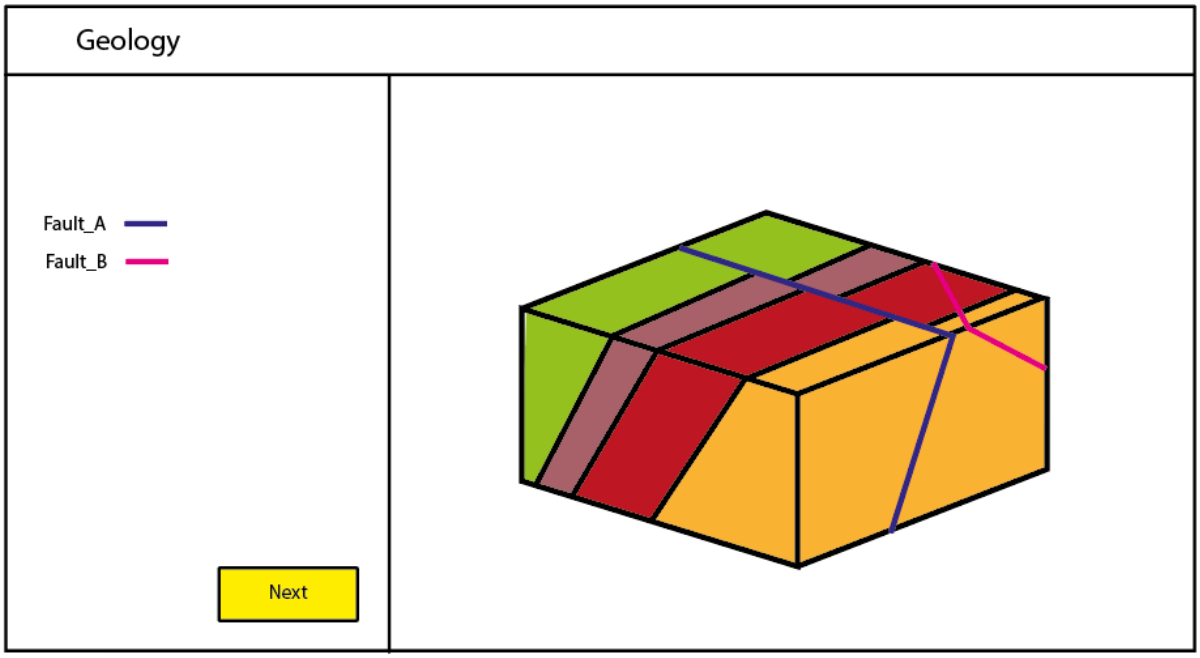


Figure 24: Overview of the 3D geological model, including the 1st-order faults

These steps are similar to those in visualkarsys, but a more advanced fault management system is required to handle a significantly greater number of faults. Additionally, enhancements are necessary to incorporate and support the extra data and hydraulic information (see Section 4.3.3).

Comments	➔ Should hydraulic parameters for explicit faults be assigned at this stage to enable modelling of the fractures zone? For instance, assigning one of the four types described in Table 5. ➔ Assigning these parameters at this stage appears more straightforward, both for the user and for implementation purposes

4.3.2.3 Define fracture zones

Users should perform the following steps:

- Model the depth of the **top fracture zone** below the ground surface for each geological unit (from 0 to XX metres), based on the values provided in Step 4.3.1
- Model the depth and thickness of the **damage zone** along the 1st-order faults, according to the type assigned to the fault (see Section 4.3.2)
- Merge the **top fracture zone and the damage zone** to create the **"final" fracture zone** through a voxelisation process

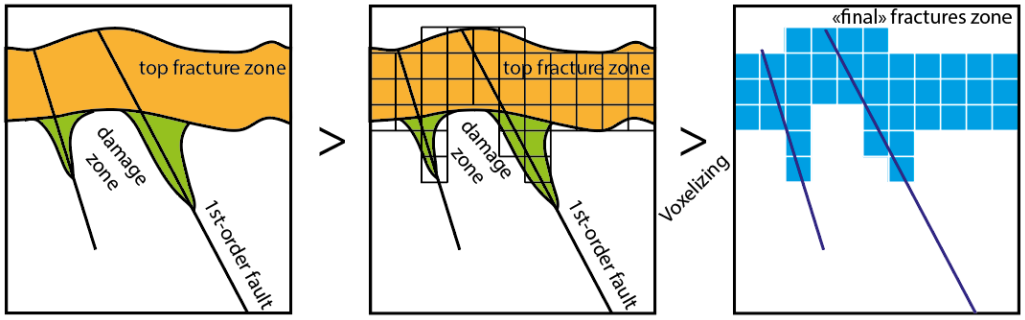


Figure 25. Modelling process of the final fracture zone (FZ)

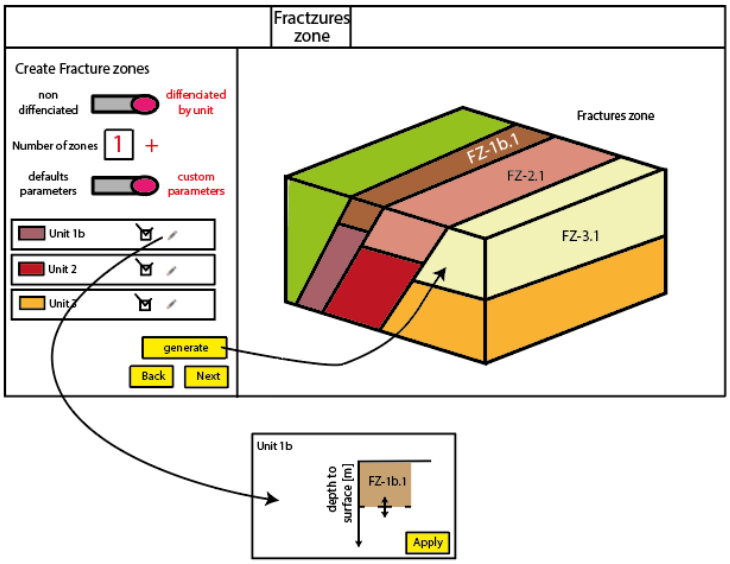


Figure 26: or each lithology, a specific top fracture zone is defined by assigning its depth

Comments	➔ The depth of the top fracture zone could be defined during the "Hydrolithology" step (Step 1) by specifying its thickness (in meters). ➔ For explicit faults, a uniform fixed depth (e.g., twice the thickness of the FZ in the geological unit) could be applied, or a specific depth could be assigned based on the fault's hydraulic type (1 to 4, as detailed in Table 5). ➔ The geometry of the final fracture zone is derived from the geometry of the geological units combined with the explicit faults through a voxelization process using meshtool. The extent of the fracture zone along an explicit fault depends on the fault's permeability (type 1 to 4) and the depth of the FZ within the intersected geological unit.

4.3.2.4 Add additional fractures (Implicit (DFN) or deterministic)

Users are supposed to perform the following steps:

- Add **additional faults** in the fractures zone (i.e. **2nd-order faults**). Two options are possible here:
  - First: draw fault "manually" by using a simple tool that allow the user to add plans in the 3D scene and to dimension, rotate, incline them as they wish.
  - Second: Generate faults stochastically using a DFN library. A few parameters / settings could be selected before the generation: (i) the number or density of faults, (ii) the min. / max. length of the faults, (iii) the orientation, etc. The idea is that implicit faults may connect the explicit faults to each other and allow groundwater to flow from faults to faults (or not…).

Comments	➔ The simple way would be to add 2nd-order fractures directly in the 3D scene (by drawing them on the map, or placing them in 3D directly) ➔ Other options are: built un implicit way by using a DFN engine (DFN.lab) allowing for statistic generation (for instance by using a simple library like PySimFrac?), or in a more deterministic by using DEM recognition / extrapolation (UNINE,)

4.3.3 Step 3 - Fractures hydraulic

Users are expected to perform the following steps:

- Assign a value of "**pseudo hydraulic conductivity**" or "**pseudo equivalent permeability**" to fractures (cf. Table 5).
- Each 1st-order fault is assigned a type as specified by the user.
- For 2nd-order faults, values can be assigned to group(s) based on their settings: size, orientation, etc.

Table 5. Fracture classes according to their equivalent "conductivity"

Type	Equivalent "conductivity" (i.e. as it appears to the user)	Fracture opening	Saturation - gradient
1	Non-transmissive	<< 1 mm	Saturated (full)
2	Low	1 – 5 mm	Saturated (full)

3	Mid	5 – 20 mm	Partly unsaturated (1/1 gradient from the downstream elevation)
4	High	> 20 mm	Unsaturated (flat gradient from the downstream elevation)

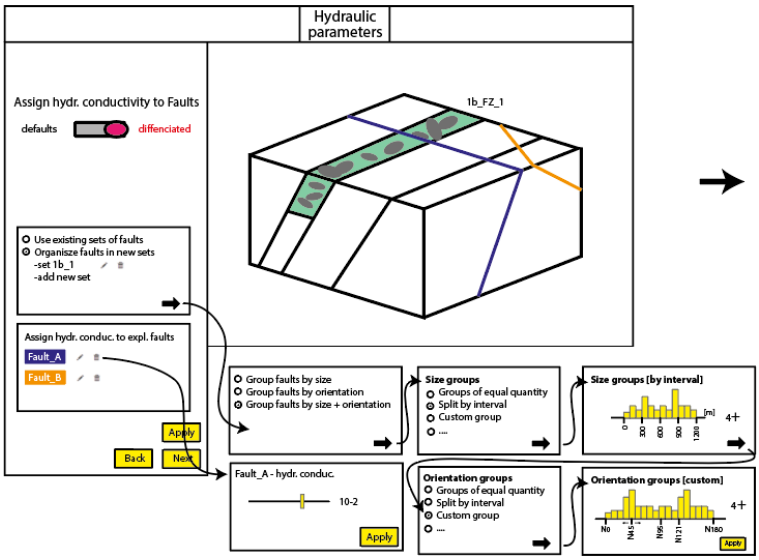


Figure 27: At this stage, the user is expected to assign types (i.e., indirect conductivity values) to 1st-order and 2nd-order faults. The method for assigning these values graphically is yet to be defined.

Provide empirical values for conductivity (e.g., low, mid, high) rather than numerical values that may cause confusion.

Consider incorporating the World Stress Map to assist the user in assigning hydraulic parameters

Comments	➔ Provide empirical values for conductivity (e.g., low, mid, high) rather than numerical values that may cause confusion. ➔ Consider incorporating the World Stress Map to assist the user in assigning hydraulic parameters

4.3.4 Step 4 - Groundwater zones

This step enables users to create and manage various hydrological scenarios to test the model under different conditions. The steps are as follows

4.3.4.1 Hydrological scenarios

This step enables users to create and manage various hydrological scenarios to test the model under different conditions. The steps are as follows:

- Define hydrological scenarios, such as low-flow versus high-flow conditions.
- Each scenario is documented and linked to a specific dataset, including:
- Groundwater level measurements.
- Spring zones.
- Flow discharge at spring zones, etc.

In this step, users are expected to model the saturated zones within the fracture zones in 3D, based on the given scenario (e.g., low-flow and high-flow conditions).

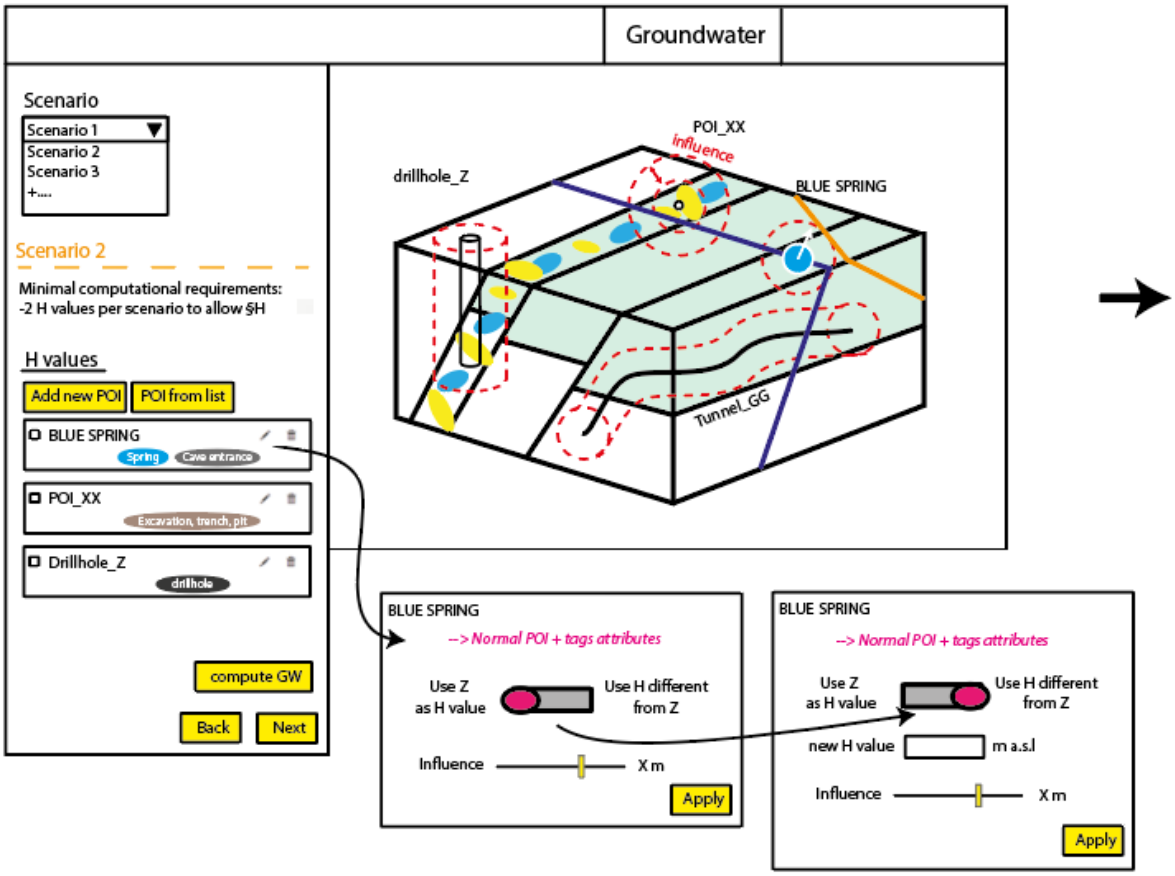


Figure 28: Hydrological scenarios could be defined and later used to model the hydrogeological conditions of the FracSYS model

4.3.4.2 Gradients in the1st-order fractures (specific to a given scenario)

This step aims to model the groundwater zones (i.e., within the fracture zone) under specific conditions. Users are first expected to compute the gradients in the 1st-order fractures by performing the following steps:

- Identify the outlet(s) that drain the fracture (manual assignment to specific fractures or auto-assignment).
- Create a graph representation of the fracture network (Andresen et al., 2013; Sanderson and Nixon, 2015; Srinivasan et al., 2020) with branches and nodes (Figure 29).
- Compute the **"least hydraulic resistance"** routes based on the graph topology and the "resistance" (i.e., the branch's "permeability"/length of the branch) using, for example, Dijkstra's algorithm. This process, illustrated in Figure 30. This will give the direction of the flows for each fractures branch, assuming that the fractures network is drained by the outlet(s).



Figure 29. Left: Perspective view of a fracture network. Right: Corresponding representation as a topological graph (Srinivasan et al., 2020).

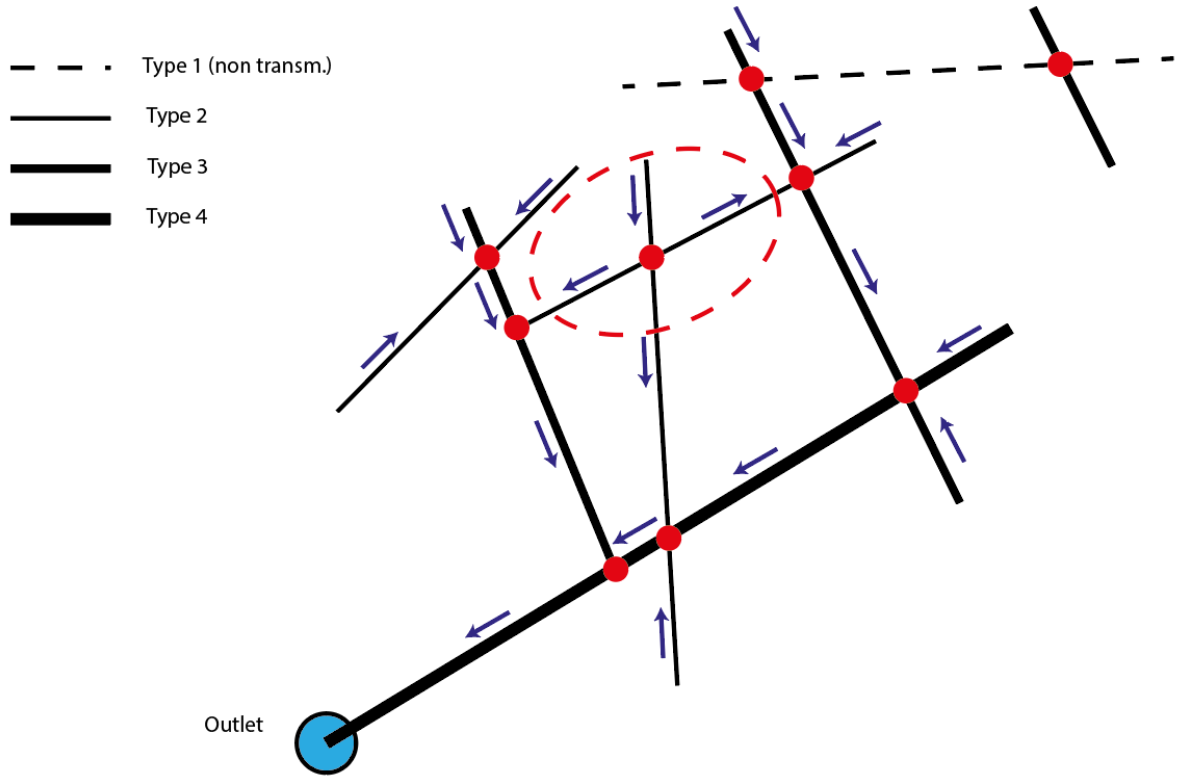


Figure 30. The computation of the least hydraulic resistance routes helps identify the flow direction (graph topology)

- Model (i) the **expected hydraulic gradient** for each branch of the fractures depending on the opening of the fractures and the length of the branch (see Table 5), and (ii) the resulting **hydraulic heads** at nodes. An example is given in Figure 31.
- Distribute relative flows by branch, from the downstream branches towards the upstream ones, according to the empirical rules in **Table 6**. An example is given in Figure 35.

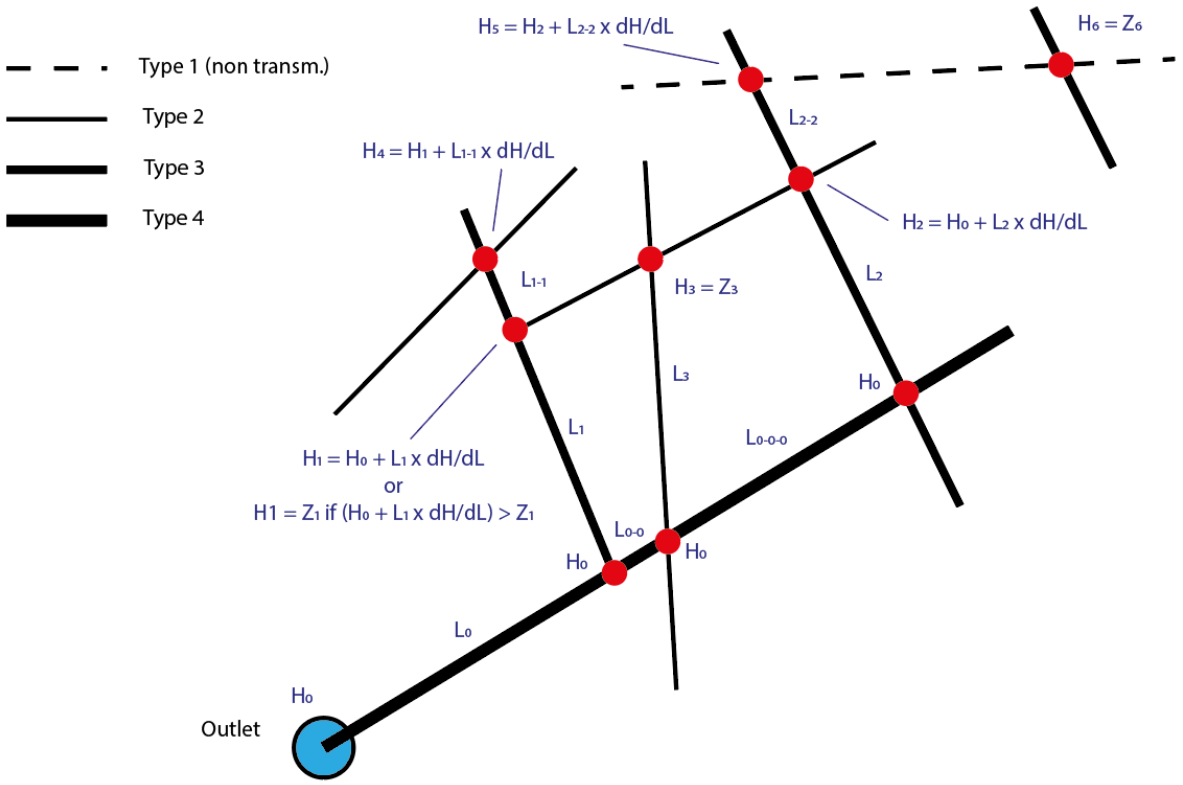


Figure 31. Top view of a topological graph of a fracture network, showing the expected gradients and hydraulic heads using a simplification of the cubic law (i.e. (Snow, 1969b))

Table 6. Flow distribution from downstream to upstream conduits

Downstream \ Upstream	1	2	3	4
1	0	0	0	0
2	0	0.5	0.9	0.9
3	0	0.1	0.5	0.9
4	0	0.1	0.1	0.5

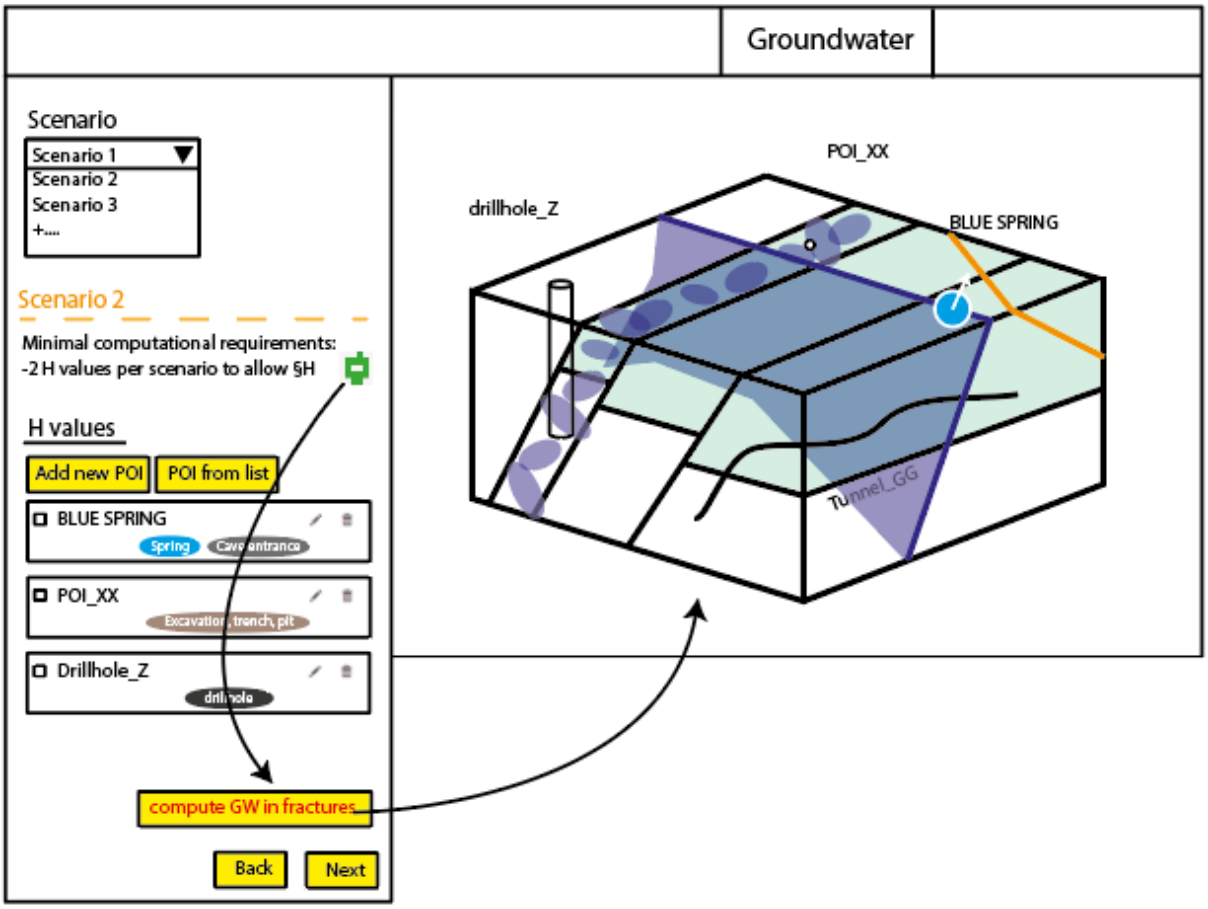


Figure 32. Overview of the step dedicated to the computation of the hydraulic gradient within the 1st-order fractures.

Comments	➔ Compare H_n at node and take the lowest one

4.3.4.3 Gradients in the fractures zone

The shape of the groundwater, including its geometry and hydraulic heads, in the fractures zone will be modelled using Flopy, a Python library that interfaces with Modflow 2005 or Modflow 6 (cf. section. 8.3). After the fractures zone has been modelled (i.e. merged with the damage zone and voxelized), a Modflow model is set up.

The model will use the voxels of the fractures zone, as well as the impervious voxels, to fill the remaining part of a rectangular scene. This rectangular configuration is necessary for technical reasons. The following fixed heads are applied:

- Heads at the Intersection of 1st-Order Faults with the Fractures Zone:
    - For faults of type 4, heads are fixed at the bottom of the damage zone (both the fractures zone and the damage zone are unsaturated).
    - For faults of type 3, heads are fixed at the top of the damage zone.
    - For faults of types 1 and 2, no heads are fixed.
- Heads from the Position of the Main Springs Draining the Fractures Zone.
- Heads from Drillholes or Wells.

These fixed heads are then used to extrapolate the groundwater heads within the fractures zone.

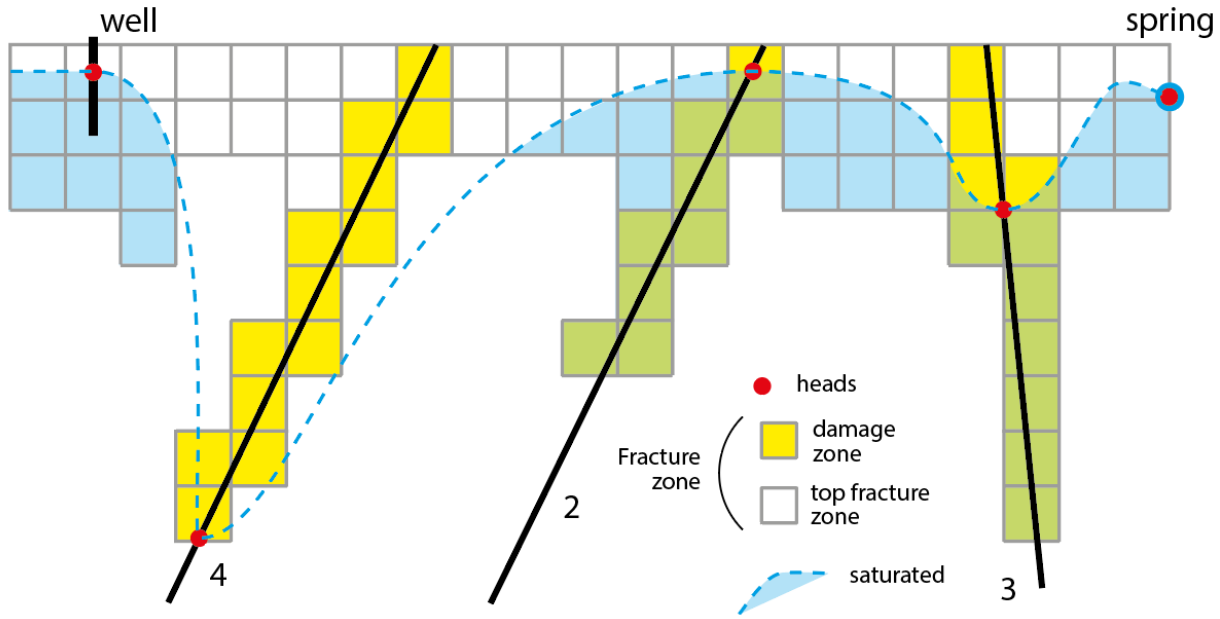


Figure 33. The geometry of the fractures zone, comprising the top fracture zone and the damage zones of the 1st-order fractures, is represented as voxels. Fixed heads (red dots), inferred from wells, springs, etc., are used alongside extrapolated heads derived from the presumed gradients in the 1st-order fractures, depending on the type (1, 2, 3, or 4). Hydraulic heads and gradients within the saturated zone of the fractures zone are then extrapolated using a continuous (equivalent porous) flow model.

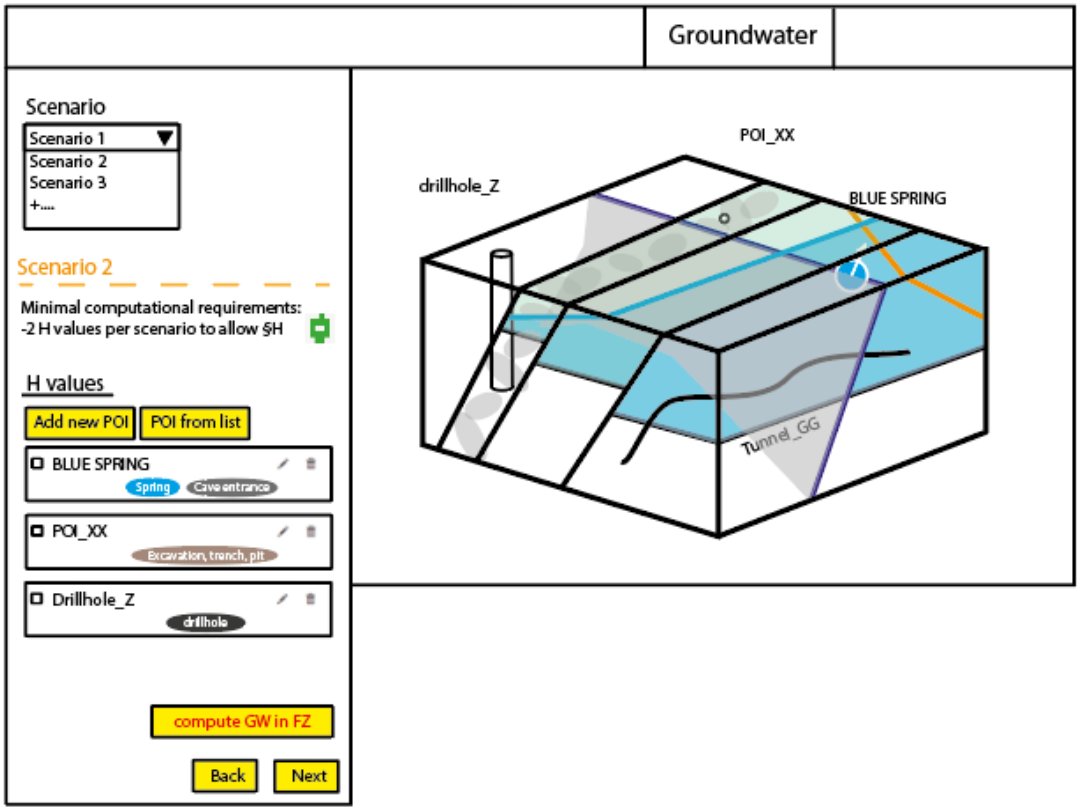


Figure 34. Overview of the step dedicated to the computation of the groundwater zone in the fracture zone.

Pending issues	➔ Boundary conditions should be discussed, as well as the parameters for the "steady-state" conditions.
Comments	➔ The permeability of the fracture zone (FZ) is provided in the hydrolithology step

4.3.5 Step 5 - Flowlines

In this step, users are supposed to run the FracSYS model. This will lead to the following:

- Infer and represent flow characteristics in 3D (paths, relative flux, etc.) from (i) the structuration of the aquifer, (ii) the groundwater zones and (iii) the hydrological conditions.
- Make flow visible, for instance as flowlines, vectors, or any other kind of markers that could make the information visible

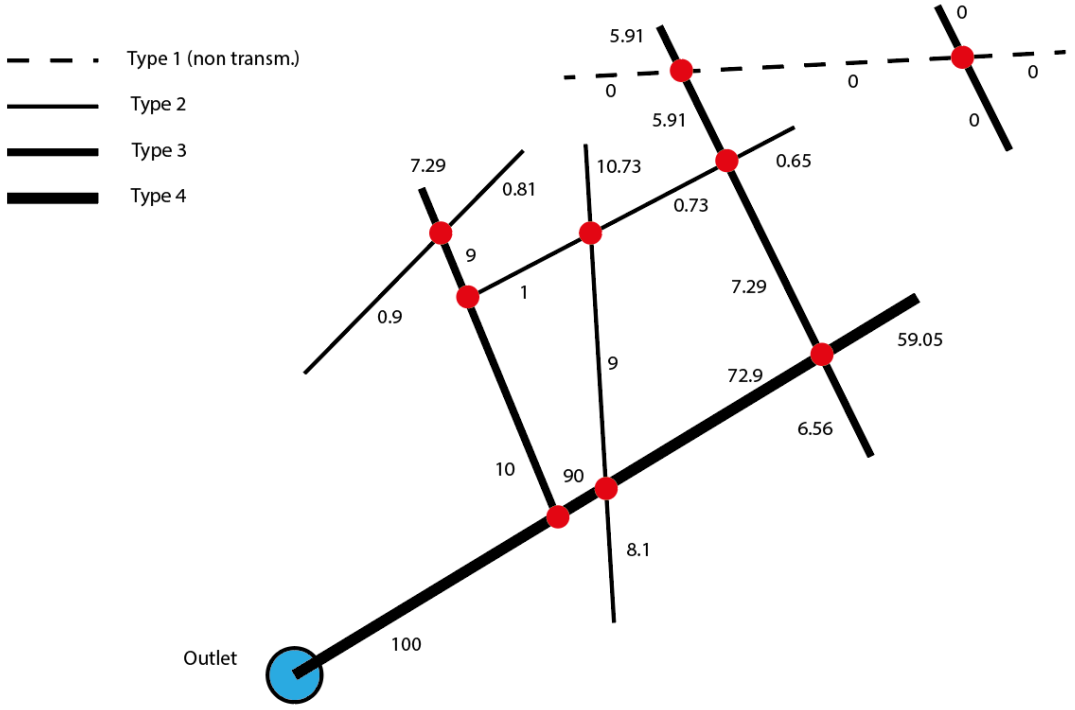


Figure 35. Distribution of the flows in the fractures branch from downstream (i.e. the outlet(s)) to upstream.

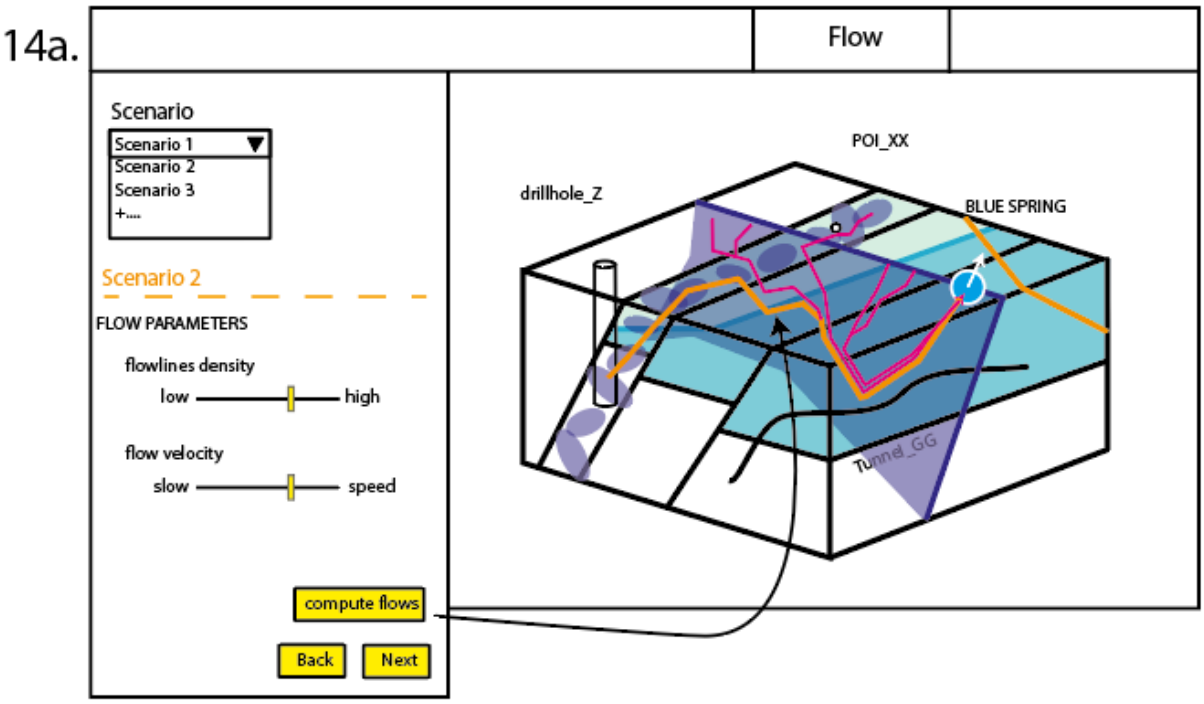


Figure 36. Overview of the "flowlines scene". Flowlines are generated in the 1st-order fractures and in the fracture zone

4.4 Applicability

As illustrated in Figure 22, the FracSYS conceptual model relies on the difference in "permeability" (i.e., flow and storage) between the fracture zone and 1st-order fractures. The applicability of the approach is assumed to depend on the hydrogeological contrasts between the 1st-order fractures and the fracture zone.

Figure 37 proposes a classification of fractured aquifers into 4 types according to the respective influence of the matrix (the fracture zone) or 1st-order fractures in the groundwater flow and storage of the aquifer (Nelson, 2001).

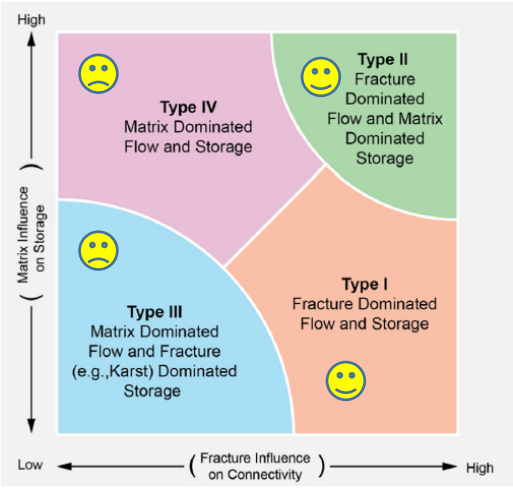


Figure 37: Main typologies of fractured aquifers depending on the respective roles of fractures and matrix in the groundwater flow and storage of the aquifer (Nelson, 2001)

According to Figure 37, it is possible to extend the applicability of the FracSYS approach to type I and II fractured aquifers, i.e., where flows are predominantly dominated by 1st-order fractures. Aquifers of type III are those for which the hydraulic role of 1st-order fractures is the weakest – in other words, these aquifers of type III could be compared to continuous media. Aquifers of type IV completely neglect the role of fractures (100% "homogeneous" environments).

4.5 Limitations

As with other approaches, FracSYS is also expected to present a few limitations that are inherent to the conceptual model (principles), the application, and its dissemination.

4.5.1 Related to the principles

FracSYS assumes a few principles for simplification that could be seen as limitations:

1. The transition between the top fracture zone and the low fracture zone is considered binary (i.e., a no-flow zone), while in reality, this limit can be considered progressive.
2. The structuring of the hydraulic gradient fields in the fault network could also be seen as a major simplification, as it does not explicitly take into consideration the spatial distribution of recharge over the ground. In reality, faults whose position and geometry result in higher recharge will normally have higher hydraulic gradients than others (due to infiltration). This parameter is not explicitly considered, so it will be up to the user to adapt the type according to their knowledge of the processes involved.

4.5.2 Related to the application

FracSYS has been designed to be general and applicable to most environments at a site or regional scale, where most groundwater flows are governed by a few or a few dozen fractures.

FracSYS considers only **4 types** of “conductivity” for the fractures. This could be seen as a limitation for the application, as more types exist in reality.

Resolution or precision, due to computational performance, could also be a limit for large sites or sites requiring high resolution. This limitation will be assessed after development.

4.5.3 Related to the dissemination

As FracSYS will be available for free and on a simple browser, we do not expect a limitation in the dissemination of the tool.

The only limitation is that users need an internet connection to run FracSYS. This could be seen as a limitation in field applications.

4.6 SWOT

The following table provides the SWOT analysis of the main features of FracSYS to list and discuss the risks associated with the developments.

Table 7: SWOT analysis of the proposed FracSYS solution's features

Strengths	Weaknesses	Opportunities	Threats
Delineation of the fractures zone			
Clear and explicit concepts. FracSYS is the only approach that explicitly takes this parameter into account.	The limit between the top fracture zone and the lower fracture zone is a binary limit. In reality, the limit is progressive..	The way the fractures zone is delineated could be seen as a first step. A more sophisticated method of delineation could be envisaged later.	There are no real technical threats to the delineation of the fractures zone. The uncertainty is more related to users' data.
Hydraulic through faults			
Takes into account explicit faults. Considers partially saturated faults. Explicit visualisation of faults.	Permeabilities are classified into four groups (simplification). The rules for the computation of hydraulic gradients are simplified. Gradients and heads in fractures do not take local recharge into consideration.	Evolving. More sophisticated rules for the computation of hydraulic gradients could be considered in the future.	Threats could be related to the number of faults, which may lead to performance issues.
Hydraulic heads and gradients in fractures zone			
FracSYS allows the computation of groundwater (GW) in the fractures zone for a given hydrological condition. Heads and gradients are extrapolated using a flow-continuous model. It is possible to simulate a perched groundwater zone within the fractures zone.	The use of the flow-continuous model requires assumptions for the initial and boundary conditions, which may introduce uncertainties. Gradients and heads in the fractures zone do not account for local recharge.	Further experimental and theoretical work on hydraulics in the fractures zone is needed, with limiting factors typically related to a lack of real data.	Performance issues (e.g. computation time) should be assessed. While these issues are not critical, they could be a limitation

Flowlines			
FracSYS explicitly shows flow dynamics through fractures and the fractures zone.	A simplification will be made in the computation/ visualisation of the flows to highlight the most important ones	This feature already exists in VisualKarsys and requires only a slight adaptation. Based on particle technology, there are many possible solutions for better flow visualisation.	There are no specific threats to the development of these features.

5 Conclusion

The FracSYS project represents a significant advancement in the modelling of fractured aquifers, addressing a critical need in sustainable groundwater management in Switzerland. By developing a user-friendly, web-based tool, FracSYS aims to make the complex process of modelling fractured aquifers accessible to a wide range of stakeholders, from water operators and practitioners to environmental agencies and policymakers. The tool's explicit conceptual models and comprehensive workflow enable users to effectively identify, delineate, and characterise groundwater bodies, providing valuable insights into groundwater flow and storage dynamics.

Through its structured methodological approach and innovative conceptual models, FracSYS offers a practical solution for understanding and managing groundwater resources in fractured environments. The integration of the Visual KARSYS platform and the development of tailored functionalities ensure that the tool is both robust and adaptable to various hydrogeological settings. While the tool has some limitations, such as simplifications in the conceptual model and computational challenges, these are outweighed by the benefits it provides in enhancing groundwater management practices.

In summary, FracSYS aims to become an essential tool for sustainable groundwater management in Switzerland, contributing to the effective use and protection of groundwater resources. Its development marks a step forward in addressing the unique challenges posed by fractured aquifers, ensuring that groundwater remains a reliable and sustainable resource for future generations.

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Van Meir, N., Jaeggi, D., Herfort, M., Loew, S., Pezard, P., Lods, G., 2007. Characterizing flow zones in a fractured and karstified limestone aquifer through integrated interpretation of geophysical and hydraulic data. Hydrogeology Journal 15, 225–240. https://doi.org/10.1007/s10040-006-0086-4

7 Appendices

8 Annexe 1 Third-party software, packages, codes, etc.

8.1 Modelling Geology

8.1.1 GmLib

GmLib (Lopez et al., 2018) is a C++ library developed by BRGM and used to compute 3D geological models using the implicit approach based on the Potential method. This library is utilised in VisualKarsys. GmLib is implemented on the VisualKarsys server with a Python wrapper, enabling communication with the REST API.

GmLib provides:

- The geometry of the geological units (meshes).
- The voxels of the fracture zones.
- The geometry (i.e., meshes) of the explicit faults.

8.1.2 GemPy

GemPy is an alternative to GmLib: https://www.gempy.org/

8.2 Flow through fractures only

8.2.1 Discrete Fractured Network (DFN)

DFN models were initially developed for fissured aquifers (Long et al., 1982). These models involve the discretisation of a set of fractures or equivalent 2D planes, which are assumed to be the permeable structures facilitating groundwater flow. The motivation for DFN model development arose from the observation that, in fractured aquifers, groundwater flow and transport are dominated by a limited number of discrete pathways, primarily open fractures, conduits, or similar features (Davy et al., 2006).

Various solutions exist today, such as **dfnWorks** (Hyman et al., 2015a), cf. Figure 45 -C., **DFN.Lab** (Le Goc et al., 2019), etc.

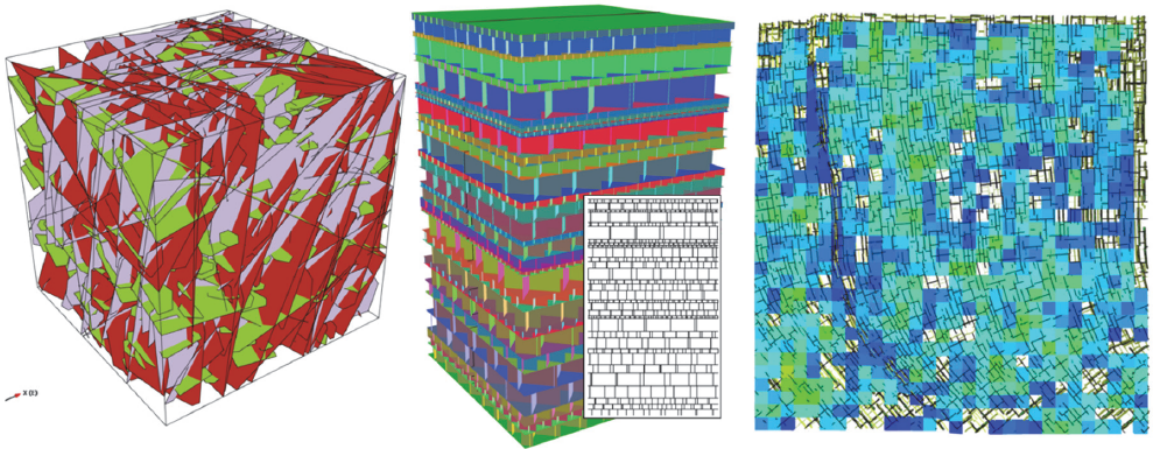


Figure 38. Example of different DFN models (Rogers et al., 2017). *Left*: conventional DFN model with uniform spatial distribution; Centre: layered joint model with spatial ordering; *Right*: spatially variable model with varying orientation.

The aperture of faults can vary from fault to fault (based on settings such as size, orientation, etc.), but it may also vary within the fault plane itself (Frampton et al., 2019; Hyman et al., 2021). Examples are provided in Figure 39, Figure 40 and Figure 41.

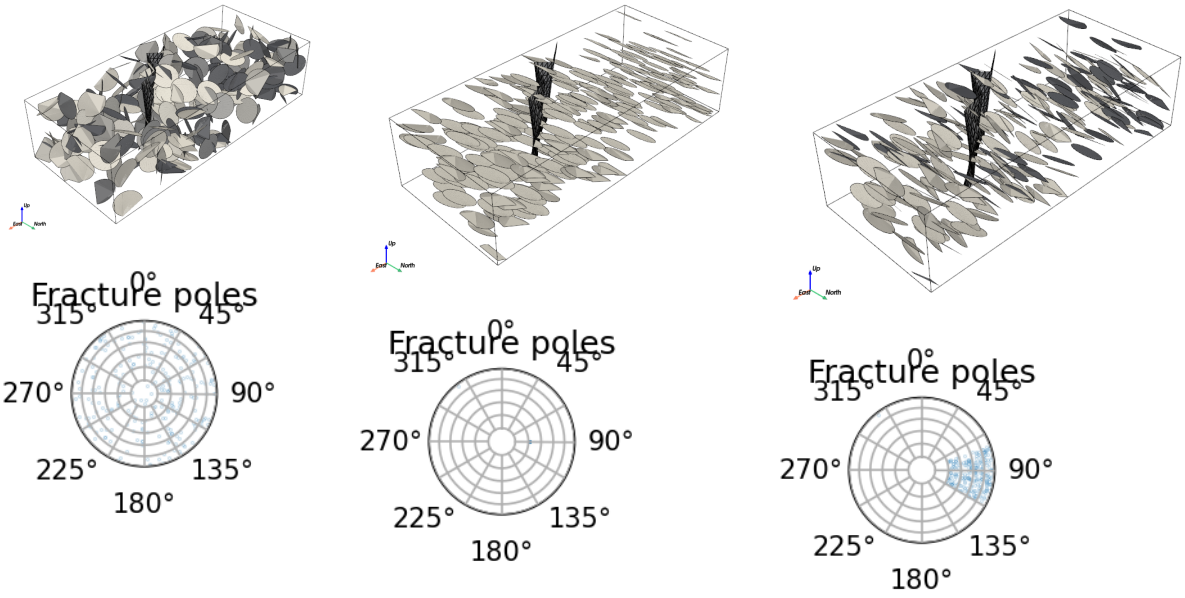


Figure 39. Parameters for DFN generation (Left: random fault distribution; Centre: single distribution; Right: random values within fixed ranges)

Most authors use shear stress to parameterise the variation in aperture within the fault plane (Bossennec et al., 2022; Hyman et al., 2021). DFNWorks can assign apertures based on the Barton-Bandis equation, which computes the shear strength of a failure plane.

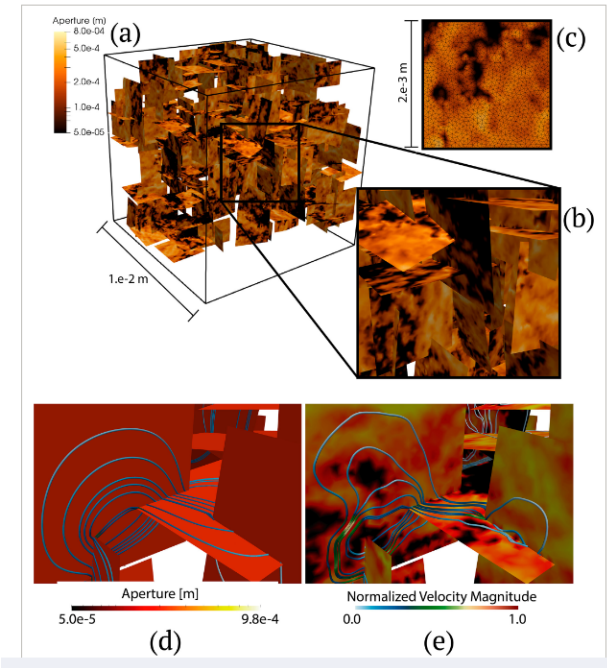


Figure 40. DFNWorks allows for the variation of aperture along a fault after meshing (Hyman et al., 2021)

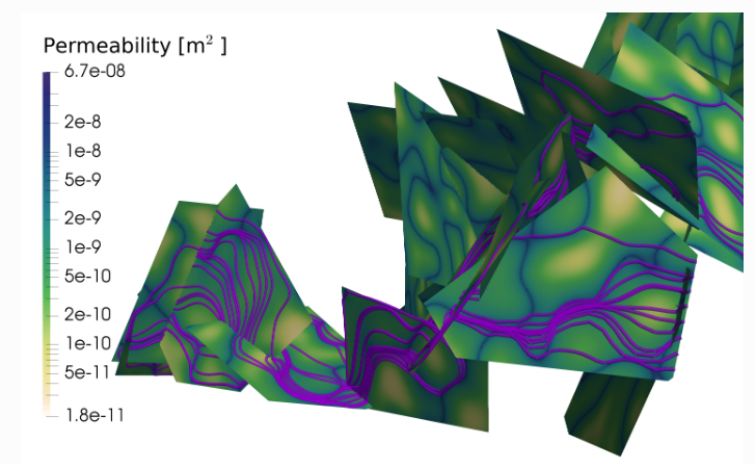


Figure 41. DFN with internal aperture variability. Particle pathlines (i.e., flowlines) are shown in purple (DFNWorks)

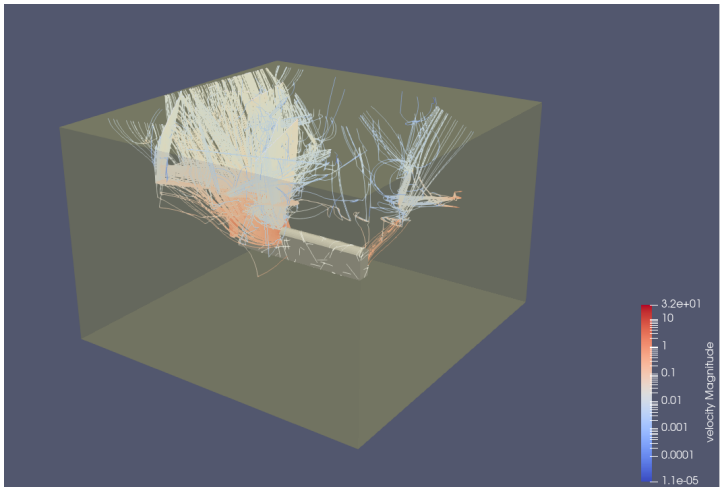


Figure 42. Simulated inflow of surface flow from the fracture network into the tunnel (DFN.Lab)

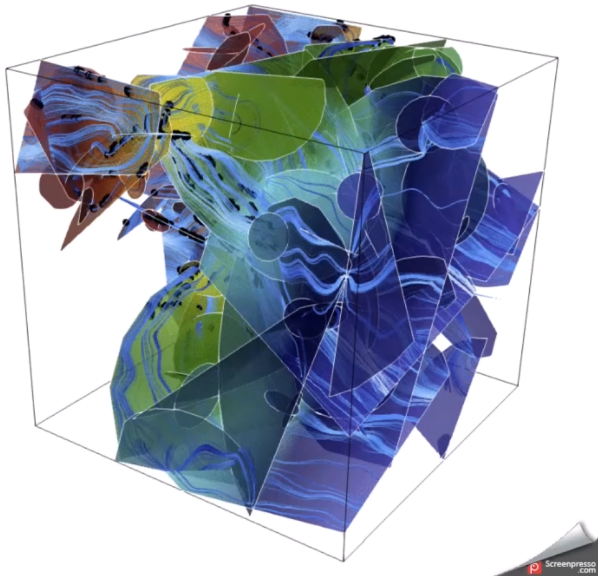


Figure 43. Visualization example of groundwater flows through fractures using DFNWorks (Hyman et al., 2015b)

8.2.2 PYSIMFRAC

PYSIMFRAC (Guiltinan et al., 2023) is an open-source Python library developed for the generation of 3D fractures, fluid simulation, and various statistical analyses. PYSIMFRAC allows users to choose between two different pore-scale simulators and the DFNWorks simulator. This library is applicable to complex fracture networks.

8.3 Flow in continuous media

Various libraries are available online to manage hydrogeological models or equations, such as those listed at https://hatarilabs.com/ih-en/a-comprehensive-list-of-specific-python-packages-for-hydrogeology-and-groundwater-modeling. Link to the Hataripy Git: https://github.com/hatarilabs/hataripy

8.3.1 ModFlow

Modflow is a generalized control-volume finite-difference model for groundwater (GW) flow, used to compute GW heads and flows based on:

- **System boundary conditions**: no-flow boundaries, constant heads, etc.
- **Regular or irregular grids and discontinuous layers**: enables modeling discontinuous aquitards (low-permeability layers) between aquifer layers.
- Linking models.
- Recharge and evapotranspiration.
- **New solvers**: Newton solvers, transient conditions, etc.
- **Pathlines with Modpath**: enables tracking particles and generating Quiver plots.

Modflow packages must be installed on a server or computer and can be run using a graphical user interface (GUI), such as Vista DMS, or with scripts using Flopy.

- **Tutorial**: How to Install Modflow and Flopy.
- **Building a Modflow Model from Voxels**: Hatari Labs Webinar.
- **Run Modflow 6 on a Server**: GitHub Modflow 6.
- **Cloud-Based Modflow Solutions**: Modflowserver.com by Aquaveo enables online hosting of Modflow codes.

8.3.2 Flopy

Flopy (GitHub) is compatible with Modflow 6 (2016) and allows importing geological models built as voxels into Modflow to generate 3D flow paths.

- Tutorial: Using Flopy with a Neural Network Model.
- Steps to build a geological model with Flopy using Anaconda:
- Create Model Geometry: Define X, Y, and Z extents.
- Set Resolution/Discretization: Specify parameters such as nCols and nRows.
- Add a Surface DEM.
- Support for Spatial References: Use mf = flopy.modflow.Modflow(mf, …) and mf.modelgrid.set_coord_info(…, epsg=…).
- Modflow supports spatial references: The spatial reference system can be set using mf = flopy.modflow.Modflow(mf, …) and mf.modelgrid.set_coord_info(…, epsg=…).

- Generate Geological Models from Neural Networks: Geological models can be generated using neural network techniques, which can then be interfaced into a groundwater model for further analysis and simulations.

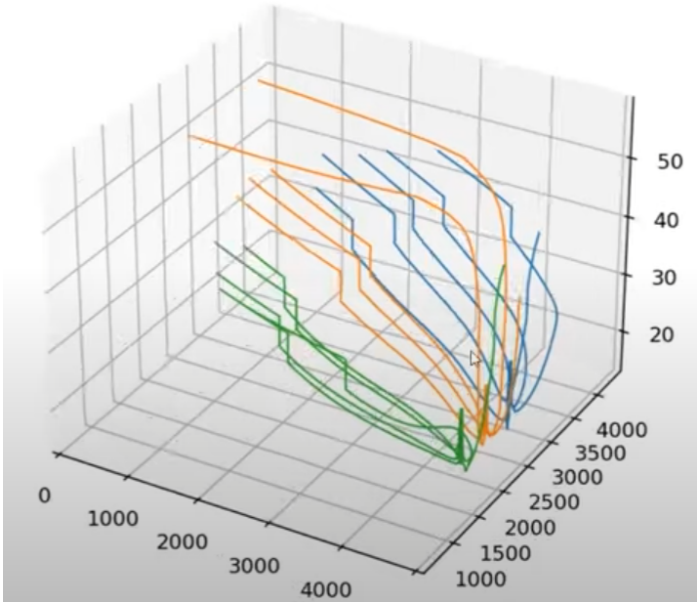


Figure 44: 3D flowlines computed with Python mplot3D

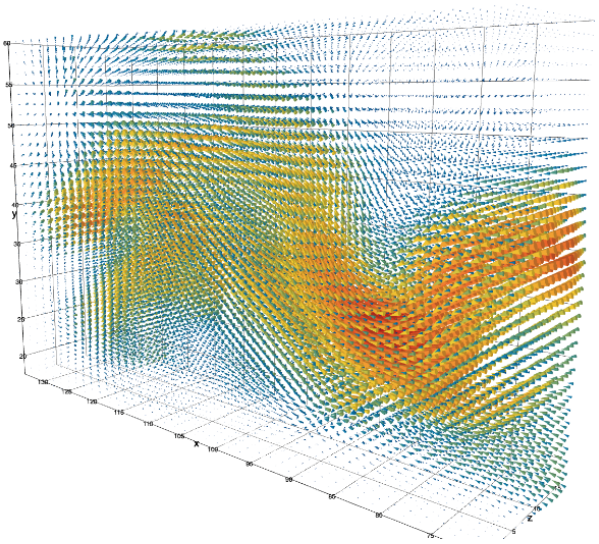
- Geological Modeling of Sedimentary Layers from Geospatial Rasters with Python and GemPy: A detailed tutorial on creating geological models of sedimentary layers using Python and GemPy can be found at Hatarilabs.

8.4 CLN package

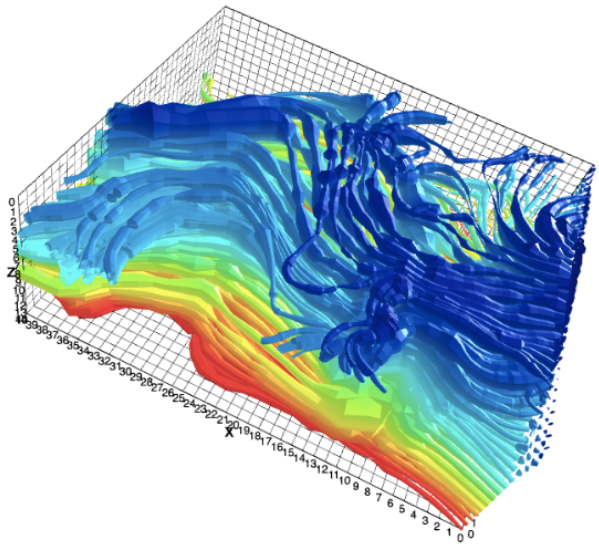
The CLN (Connected Linear Network) package allows simulation of flow through fractures using ModFlow. It can be used alongside ModFlow-USGS to model one-dimensional linear features within a three-dimensional simulation domain.

8.5 Display GW flowpaths as flowlines

Computed flowpaths can be displayed as static or dynamic flowlines in the 3D model (cf. Figure 45). Use streamline / quiver plots with plotly js: https://plotly.com/javascript/streamtube-plot/ in addition to basic 3D line plots https://plotly.com/javascript/3d-line-plots/.



A. Example of a 3D **streamline** plot /plotly.js



B. Example of a 3D **streamtube** plot /plotly.js

Figure 45: Examples of flow visualization using flowlines, streamtubes, particles, etc.

9 Annexe 2 The FracSYS tool / specifications

9.1 Objectives

For each step of the FracSYS workflow, specific functionalities or tools will be developed. These functionalities fall into three categories:

- Slight adaptation: Features already existing in VisualKarsys that require minimal modification.
- Full redesign: Existing features needing significant updates or reworking.
- New development: Features that do not currently exist and must be developed from scratch.

Integration and Challenges

One significant challenge lies in the integration and coexistence of FracSYS with the current VisualKarsys platform.

Ideal Solution:

- Develop a master service that can be accessed by both fracsys.com and visualkarsys.com.
- Transition the current VisualKarsys platform to this new master service.
- Create a nearly identical web service for FracSYS, acknowledging that this approach will increase maintenance efforts.

Hybrid Solution:

- Develop a new FracSYS webpage as the homepage for the tool.
- Route users to the current VisualKarsys web service from the FracSYS webpage.

Frontend (User Experience)

- Key considerations for frontend development include:
- Structuring and organizing the tool's operational workflow.
- Deciding on the level of integration with VisualKarsys (direct relationship or standalone).
- Packaging the functionalities effectively within the tool's interface.
- (Re)structuring the database for seamless functionality.
- Enabling data export options.
- Providing comprehensive documentation.
- Enhancing visualization features.

Backend (Functionalities)

Conceptualizing the features to be developed is essential. A wishlist of functionalities could include:

- Functionality 1: Description, input data, concepts/principles, process, and expected output.
- Functionality 2: As above, with specific details on the functionality.

Each functionality will require detailed specifications to ensure proper implementation.

9.2 Data & information

Various database (BD) architectures can be employed for the implementation of FracSYS, with or without integration with VisualKarsys. These options are illustrated in Figure 46.

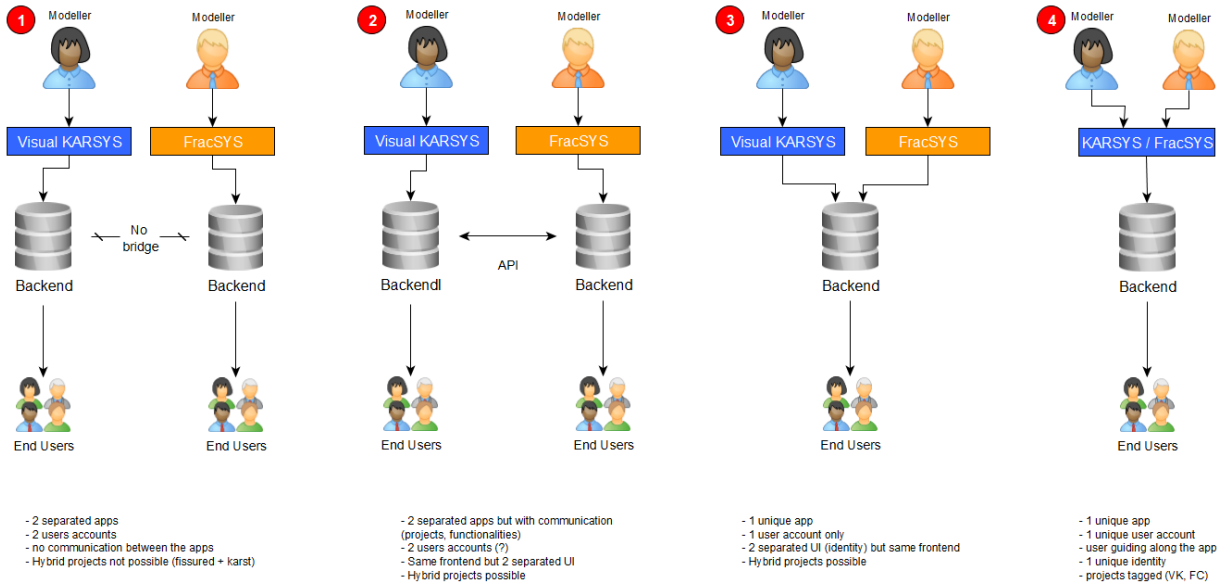


Figure 46. Possible database architectures for the implementation of FracSYS with or without visualkarsys.