

FracSYS

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

Phase 2 - Demonstration of the feasibility of the FracSYS tool through prototyping based on case studies

Concluding report on phase 2

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Table of contents

1 INTRODUCTION 5

2 OBJECTIVES AND METHODOLOGY 5

3 PROJECT SET UP 6

4 CASE STUDIES SELECTION AND GEOLOGICAL MODELLING 6

4.1 Selection Criteria 6

4.2 Site Selection 7

4.3 Methodology of Geological Modelling 8

4.4 Results 8

5 DEVELOPMENTS & TESTING OF THE FRACSYS PROTOTYPE 9

5.1 Objectives and modelling approach 9

5.2 Geometrical preparation and fracture connectivity 9

5.3 Construction of the Hydraulic Network 10

5.4 Hydraulic Boundary Conditions and Recharge 10

5.5 Calculation of Hydraulic Heads and Active Flow Paths 11

5.6 Flow Representation and Visualisation 12

5.7 Configuration and run 12

5.8 Outputs and Interpretation 13

5.9 Dynamic Visualisation 15

6 LIMITATIONS OF THE FRACSYS PROTOTYPE 16

7 CONCLUSION AND PERSPECTIVES 18

8 ACKNOWLEDGEMENTS 19

9 REFERENCES 20

APPENDICES 21

APPENDIX 1 TERMINOLOGY, PRINCIPLES AND PROCESSES 22

Introduction 22

The FracSYS conceptual model 22

Methodology description 28

APPENDIX 2 FRACSYS MOCK-UP 31

APPENDIX 3 CASE STUDY #1 SOURCE DE BIENVENUE 33

Site Location and Characteristics 33

The Spring's System 34

Geological and Hydrogeological Settings 35

Baseline Spatial Dataset and Geological Modelling 35

APPENDIX 4 CASE STUDY #2 CLEUSON-DIXENCE GALERY 37

Site Location and Characteristics 37

DRAFT

The Galery *37*

Geological and Hydrogeological Settings *38*

Baseline data and Geological Modelling *42*

APPENDIX 5 VISUALISING THE FLOW SIMULATION **43**

OVERVIEW 43

SELECTING THE DATA FORMAT 44

THE WORKFLOW 44

Arranging the rows in three dimensions *44*

Creating the animated flow *44*

List of figures

FIGURE 1: WORKFLOW OF ACTIVITIES OF FRACSYS THROUGH THE THREE PHASES. PHASE 3 IS SUPPOSED TO ANNOUNCE A FUTURE PROJECT. 5

FIGURE 2 : LOCATION MAP OF SOURCE DE BIENVENUE AND CLEUSON-DIXENCE GALERY AREAS OF INTEREST 7

FIGURE 3 : LEFT: TWO INTERSECTING FRACTURES. RIGHT: SUPPOSED GEOMETRY OF THE DAMAGE ZONE ASSOCIATED TO THE FRACTURES NETWORK (NOT TO SCALE). 10

FIGURE 4 : GROUNDWATER FLOWS ORGANIZE IN THE DAMAGE ZONE OF THE FRACTURE ACCORDING TO A HYDRAULIC GRADIENT. 10

FIGURE 5 : ORGANIZATION OF THE HYDRAULIC GRADIENT IN THE FRACTURES NETWORK ACCORDING TO THE CONNECTIVITY OF THE NETWORK AND THE APERTURE OF THE FRACTURES. 12

FIGURE 6 : OVERVIEW OF THE FRACTURES NETWORK AND THE ASSOCIATED FLOWS AND HEADS. HYDRAULIC HEAD VALUES ARE ATTACHED TO THE SATURATED NODES, RANGING HERE FROM 160 M ASL (THE ELEVATION OF THE OUTLET) TO 1'130 M ASL. THE FLOW RATES VALUES ARE ATTACHED TO THE EDGES (HERE RANGING FROM 2.E-4 M3/S FOR LOW CONDUCTIVE EDGES TO ~6E-3 M3/S FOR HIGHER CONDUCTIVE EDGES). THE OUTLET IS LOCATED AT THE RIGHT EXTREMITY OF THE FRACTURE IN THE FOREGROUND EXTENDING FROM LEFT TO RIGHT. 14

FIGURE 7 : ANOTHER EXAMPLE WITH THE SAME FRACTURES NETWORK, BUT THE LOCATION OF THE OUTLET CHANGED. INSTEAD OF BEING ON THE RIGHT EXTREMITY OF THE FOREGROUND FRACTURE, IT IS NOW LOCATED AT THE LEFT EXTREMITY. THE FLOW NETWORK CHANGES ACCORDING TO THIS NEW SITUATION: THE HYDRAULIC GRADIENT INVERSES, AND MOST OF THE UNSATURATED NODES REORGANISE CLOSE TO THE OUTLET. 14

FIGURE 8 : OVERVIEW OF THE CLEUSON-DIXENCE GALLERY PROTOTYPE HOSTED ON THE FRACYSY.ISSKA.CH WEBSITE. THE FRACTURES NETWORK IS DISPLAY AS VOXELS. GREY VOXELS ARE INACTIVE (NO FLOWS), BLUE VOXELS ARE "ACTIVE" BUT FLOWS ARE CONSIDERED AS NEGLIGIBLE (BELOW A GIVEN THRESHOLD). GREEN TO RED VOXELS SHOW HIGHER VALUES OF CONDUCTIVITY. MOST OF THE FLOWS ARE DRAINED BY THE GALLERY TOWARD THE OUTFLOW. 15

FIGURE 10: SPRINGS LOCATION ESTIMATED FROM TISSIÈRE 1988 34

FIGURE 11: OVERVIEW OF THE ARPILLE MASSIF FROM THE EAST (GEOLOGICAL ATLAS OF SWITZERLAND 1:25 000). RED LINES CORRESPOND TO THE 1ST ORDER FAULT. BLUE SQUARE CORRESPONDS TO SOURCE DE BIENVENUE. 34

FIGURE 12: CROSS-SECTION OF THE SPRINGS AND WELL VICINITY. TISSIÈRE 1988 35

FIGURE 13 : SCHEMATIC MAP OF THE CLEUXON-DIXENCE GALLERY (NORBERT, 1998) 37

FIGURE 14 : GALLERY CROSS-SECTION, DETAILS ON THE DIFFERENT STAGES FOR TUNNELING WORKS ('LOT') 38

FIGURE 15 : GEOLOGICAL AND TECTONIC CONTEXT (A-LOCATION OF THE CROSS-SECTION, B) CROSS SECTION 1, C) DETAIL FROM CROSS-SECTION 1 ON THE NENDAZ REGION, D) TECTONIC 500) FROM GOUFFON, 2024. 39

FIGURE 18 : GEOLOGICAL UNITS INTERSECTED BY THE CLEUSON-DIXENCE GALERY – NORBERT, 1998 41

DRAFT

List of tables

TABLE 1: LIST OF THE PREDEFINED VIEWS AND THE 3D LAYERS ASSOCIATED TO EACH VIEW.....16

TABLE 2: TECTONIC UNITS IN MAIN TECTONIC UNITS – GOUFFON, 2024; LOPRIENO ET. AL. 2010 ; PANTET ET. AL., 2020 ; SWISSTOPO, 2024).....40

TABLE 2: SCHEMATIC CROSS SECTION WITH GEOLOGICAL UNITS (ALPIQ, 2015).....41

DRAFT

1 Introduction

The finalised Phase 1 of the FracSYS project (WP1) focused on the theoretical development of a conceptual, hydrogeological and hydraulic modelling approach for fractured aquifers, including:

1. the identification of the necessary inputs (basic data),
2. the description of the modelling processes and details of the successive steps (processes),
3. the definition of the products and results that would be obtained at the end of the modelling process, and
4. the development of a 3D modelling strategy based on the concepts and principles of a pragmatic approach.

This intermediate report aims to resume activities on FracSYS's **phase 2** on going from April 2025 until the end of 2026.

2 Objectives and Methodology

The actual Phase 2 of the project is be dedicated to mitigating risks related to the development and implementation of FracSYS functionalities, relying on iterative prototyping steps based on case studies.

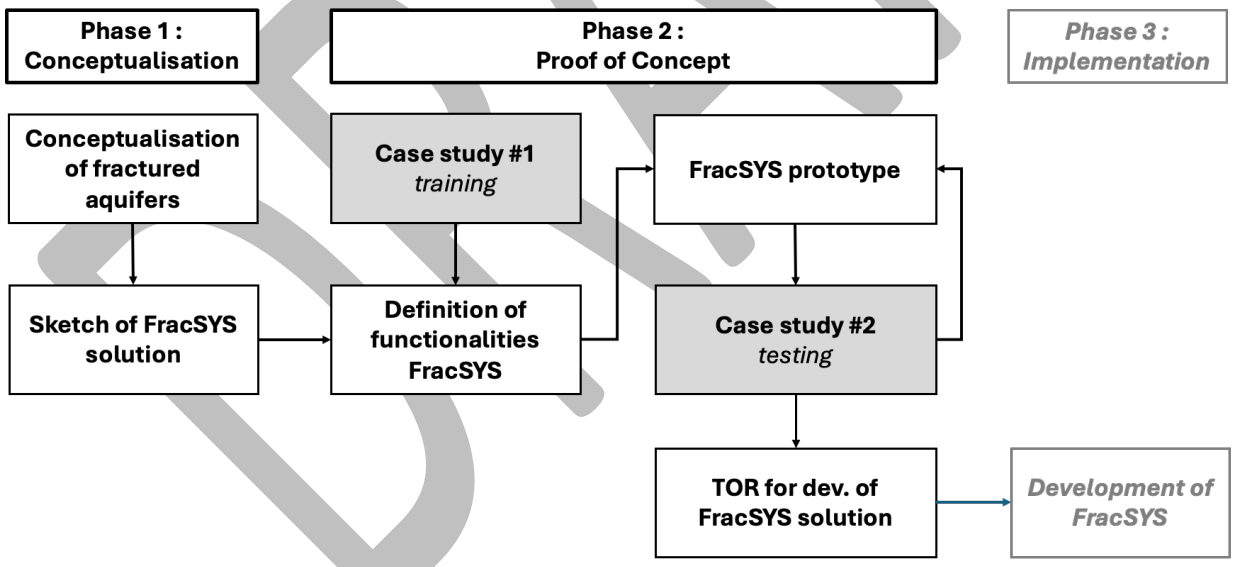


Figure 1: Workflow of activities of FracSYS through the three phases. Phase 3 is supposed to announce a future project.

The tasks of **Phase 2** listed are listed below:

1. **Project set up:** Development of the technical workflow of the approach, i.e., the successive steps of data/information processing, the principles, and the tools to be implemented,
2. **Case studies selection and objectives settings:** Selection of two distinct case studies, data collection, and definition of expected results,

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3. **Case studies geological modelling:** Geological modelling for both case studies on visualkarsys.com,
4. **Developments & testing of the FracSYS prototype.** Developments & tests of the FracSYS prototype. Definition and testing of FracSYS functionalities to develop derived from cases study #1 and #2. Implementation of identified functionalities through FracSYS prototype: Defining FracSYS functionalities for the conceptual model of cases study #1 and #2.
5. **External feedback from followers through workshops:** Feedback from external project institutions and future FracSYS users through the organisation of two exchange workshops on the results, and
6. **Reporting.**

3 Project Set Up

The objectives and preliminary results of the project are:

- The rationalisation of the terminology, principles and processes defined in Phase 1 (cf. Appendix 1 Terminology, Principles and Processes),
- The development of a detailed technical framework based on Phase 1, including the identification of key processes to be implemented and their comparison with the technical and scientific capabilities of visualkarsys.com,
- The establishment of a detailed implementation roadmap identifying components to be reused, adapted or developed, while defining priorities and dependencies, and
- The identification of relevant data and information sources, together with the development of an analytical framework for assessing issues, contexts and associated challenges.

The last three points are addressed through a workflow diagram (cf. **Appendix 2 FracSYS Mock-up**). which enables a comparative analysis between visualkarsys.com and the FracSYS tool to be developed. This document is continuously evolving and serves as the project roadmap.

4 Case Studies Selection and Geological Modelling

The objectives of this phase were to:

1. Identify potential case studies and select two study sites with distinct fractured aquifers that are representative of common Swiss hydrogeological contexts and water uses, and
2. Compile available data and define the expected outputs of the study.

4.1 Selection Criteria

Candidate sites must:

- Possess water level/ pressure measurements and data openly accessible to the project,
- Represent significant and exploited groundwater resources (discharge > 1–10 l/s),
- Have a catchment area greater than 1 km², and

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- Be set in a homogeneous, well-documented geological and hydrogeological context (in terms of medium type).

4.2 Site Selection

Site selection relied primarily on data availability, favouring the Valais dataset, which is accessible and well known to CREALP. Local practitioners' input further supported the selection. Suitable candidates were difficult to find, and many were set aside because groundwater contribution to the catchment was rarely predominantly linked to the fractured aquifer, being instead largely controlled by Quaternary deposits (alluvial deposits, gravitational deposits, and landslide masses).

Two candidate springs were identified: (i) **Source de Bienvenue** located just north of Martigny and (ii) **Cleuson-Dixence Galery** located south of Nendaz (Cf. **Erreur ! Source du renvoi introuvable.**).

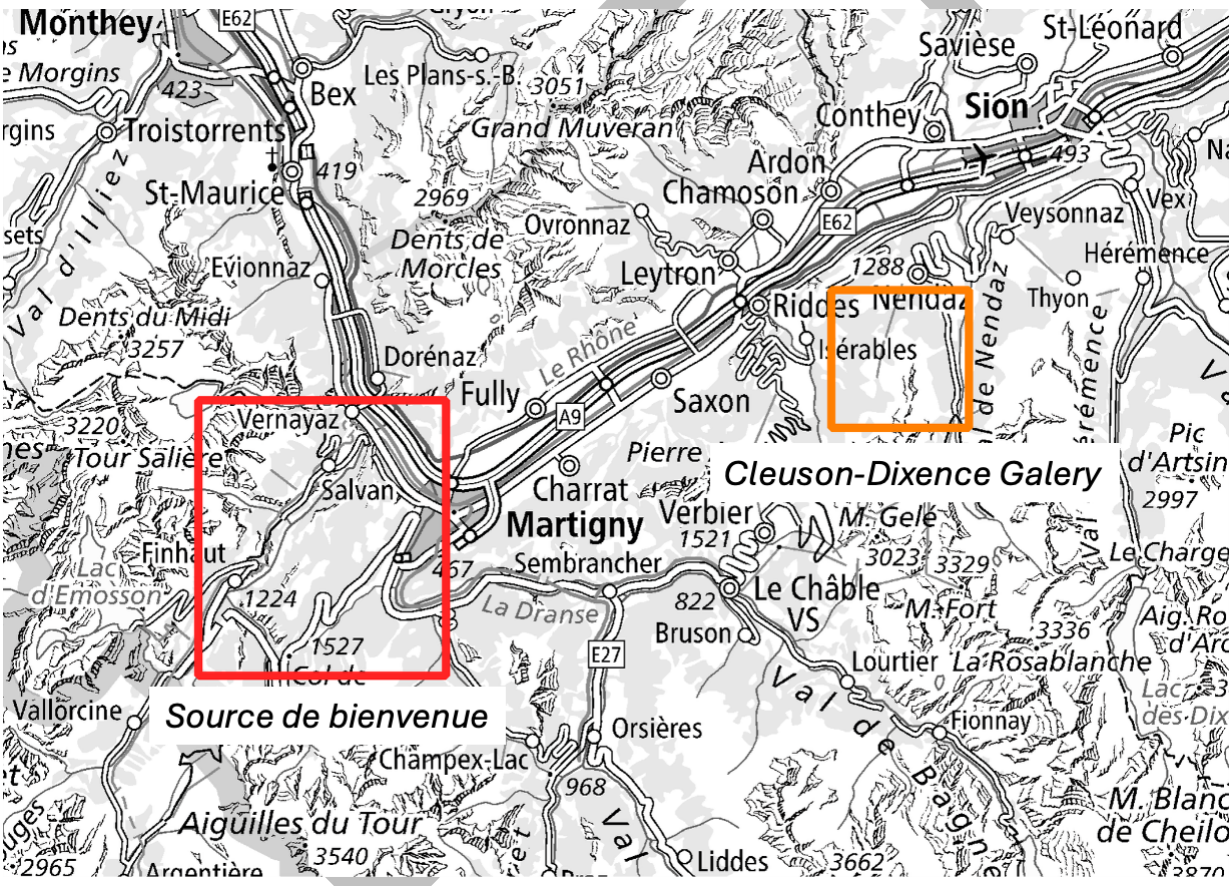


Figure 2 : Location map of Source de Bienvenue and Cleuson-Dixence Galery areas of interest

4.3 Methodology of Geological Modelling

The methodology's pipeline is the following:

1. Data collection and compilation into a GIS project. Datasets are sourced from open data providers (SEN-VALAIS, swisstopo, FOEN), as well as restricted data obtained from practitioners with the data owner's authorisation.
2. Completion of existing datasets in 2D, such as the fracture network, using GIS tools through the delineation of lineaments and structural discontinuities from digital elevation model-derived products (slope, roughness, hillshade, etc.) not recorded by existing geological mapping.
3. Import of relevant datasets into visualkarsys.com, an online platform and web service dedicated to 3D modelling and groundwater management in karstic environments, developed by ISSKA. It allows the import of digital elevation models, cross-sections, maps, galleries, boreholes and water observation points to delineate geological contacts and faulting. Visual KARSYS is used as well to complete existing datasets in 3D.
4. Export of the resulting lithology and faulting geometries for the FracSYS prototype.

4.4 Results

Both case studies were selected to deploy the FracSYS prototype, and the definition and testing of its functionalities derive from case studies #1 and #2. The geological model of the Source de Bienvenue proved unsuitable for finalising the prototype, for the following reasons:

- The fracture network through Mont d'Ottan is not spatially well defined.
- The fracture network is difficult to separate from the local recharge coming from the debris cones and debris slopes of the Rhône Valley.
- In addition, the groundwater flow estimated at the pumping station is difficult to link to the fracture network of Mont d'Ottan.
- The Cleuson-Dixence Gallery model was therefore evaluated as a better candidate, even though it is not located in crystalline rocks.

The Cleuson-Dixence Gallery has been chosen to finalise the prototype, as :

- The predominant role of fractures in the flow pattern,
- A better knowledge of the fracture network at depth, thanks to the geological logs of the gallery cross-sections and the related boreholes, and
- A better characterisation of groundwater flows (springs, pressure gauges and calibrated drainage gallery).

The detailed description of case studies 1 and 2 is available in

- **Appendix 3 Case study #1 Source de Bienvenue,** and
- **Appendix 4 Case study #2 Cleuson-Dixence Galery**

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5 Developments & Testing of the FracSYS Prototype

5.1 Objectives and modelling approach

The objective of the workflow is to identify the main **groundwater flows** through a 3-dimensional network of discrete fractures. The model starts from 3D fractures planes represented by STL[1] files. Each STL fracture defines the geometry of individual fracture.

The triangulated surfaces are converted into a **hydraulic graph** composed of **nodes** and connecting **edges**. Groundwater **recharge** is applied to the upper parts of hydraulically connected fractures, while downstream connected fractures act as a preferential drainage structure leading toward a specified **outflow**.

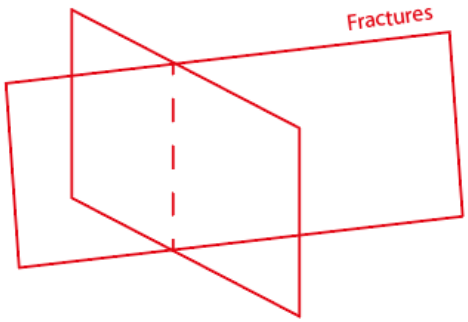
The resulting model provides a graph-based approximation of flow through connected **discontinuities**.

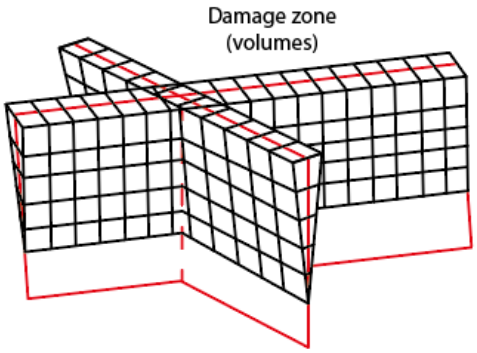
5.2 Geometrical preparation and fracture connectivity

The first step consists of importing the triangulated STL surfaces representing the **fractures** that are modelled with a geological modelling software. Depending on their initial resolution, fracture meshes can be decimated to reduce computational cost while maintaining their general geometry.

Pairwise **intersections** are then calculated between the different surfaces. These intersections represent locations where groundwater can potentially transfer from one fracture to another. The resulting intersection traces are resampled to provide a sufficiently regular spatial discretization.

Vertices located near an intersection trace are snapped to it, and vertices closer than a specified tolerance are merged. This geometrical processing is important because surfaces that appear connected visually may remain disconnected numerically if their vertices do not share the same coordinates. After snapping and merging, intersection points can be represented by common graph nodes, thereby establishing hydraulic communication between the intersecting structures.





[1] STL files are common 3D mesh files

Figure 3 : Left: two intersecting fractures. Right: supposed geometry of the damage zone associated to the fractures network (not to scale).

The reliability of the simulated flow network strongly depends on this stage. Missing or poorly represented fracture intersections can create artificial hydraulic barriers. Consequently, the intersection and merging tolerances must be selected according to the accuracy and resolution of the original geological model.

5.3 Construction of the Hydraulic Network

Each processed triangulated surface is converted into an individual **hydraulic graph**. Mesh vertices become graph nodes, while the sides of the triangular elements become graph edges. Every node retains information about its source fracture, elevation, and possible membership in several surfaces. Nodes shared by multiple fractures are identified as hydraulic **junctions**.

The individual graphs are subsequently combined into **one connected discrete fracture network**. When two fractures share a node, groundwater can pass between them. Duplicate edges are merged, and their hydraulic attributes are preserved or updated according to the most conductive contributing structure.

A **hydraulic aperture** is assigned to each fracture according to its expected permeability class. In the current parameterization, low-, medium-, and high-permeability fractures are represented by **different aperture values**. The conductance of an edge is derived from a parallel-plate approximation:

$$C_{ij} = \frac{w\, a^3}{12\, \mu\, L_{ij}},$$

where $\mathbf{C_{ij}}$ is the edge conductance, **w** is the representative flow width, **a** is the hydraulic aperture, **μ** is the dynamic viscosity of water, and L_{ij} is the edge length. The cubic dependence on aperture means that relatively small differences in fracture opening can produce large contrasts in transmissive capacity.

The resulting graph therefore incorporates both geometrical **connectivity** and **hydraulic heterogeneity**. Large-aperture fractures generally provide preferential flows, while narrow fractures transmit smaller flows.

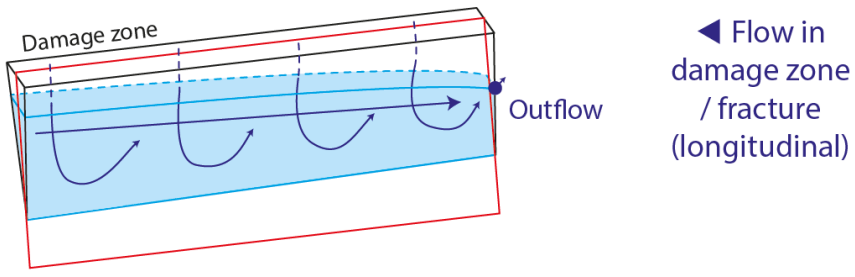


Figure 4 : Groundwater flows organize in the damage zone of the fracture according to a hydraulic gradient.

5.4 Hydraulic Boundary Conditions and Recharge

The model **outlet** (**outflow**) is defined by a reference coordinate located near the discharge point. The **closest graph node** is selected as the hydraulic target. Its hydraulic head is fixed to its elevation, representing an atmospheric-pressure drainage boundary.

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An initial **head distribution** is calculated using the network distance from the outlet. This produces an initial **hydraulic gradient** directed generally toward the outlet. **Hydraulic head** limits are also calculated for the different fractures to prevent unrealistic values during the numerical relaxation.

The prescribed total **recharge** is **distributed among selected nodes** situated in the upper portions of the fractures. Recharge candidates can be restricted to nodes that have a directed connection to the outlet. This avoids applying recharge to hydraulically isolated parts of the network.

The recharge distribution is weighted using the **fracture aperture** and the number of selected recharge nodes. Within each fracture, its allocated recharge is distributed uniformly among the selected nodes.

⚠ This formulation ensures that the sum of the **nodal recharge values** equals the prescribed **total recharge**. Nevertheless, the weighting remains a modelling assumption and should be adjusted when field information on infiltration area, fracture transmissivity, or spatial recharge distribution becomes available.

5.5 Calculation of Hydraulic Heads and Active Flow Paths

The **hydraulic graph** is initially oriented according to **decreasing hydraulic head**. Edges with a clear head difference are directed toward the lower-head node, whereas nearly horizontal edges may be retained in both directions. The outlet / outflow is forced to act as a “sink” by removing outgoing connections from the target node.

Hydraulic heads are then iteratively relaxed at every node. For a node *i*, the updated head is determined from the conductance-weighted heads of its neighbouring nodes and the recharge assigned to the node. In simplified form:

$$H_i = \frac{R_i + \sum_j C_{ij} H_j}{\sum_j C_{ij}},$$

where H_i is the hydraulic head, R_i is the nodal recharge term, and C_{ij} represents the conductance between connected nodes. The resulting heads are constrained by the calculated elevation and head limits. Once the head field has converged, the discharge along an edge is estimated from:

$$Q_{ij} = C_{ij}(H_i - H_j),$$

provided that the head difference is positive in the direction of the edge. This calculation produces a distributed hydraulic-flow field controlled by recharge, head differences, fracture aperture, edge length, and network connectivity.

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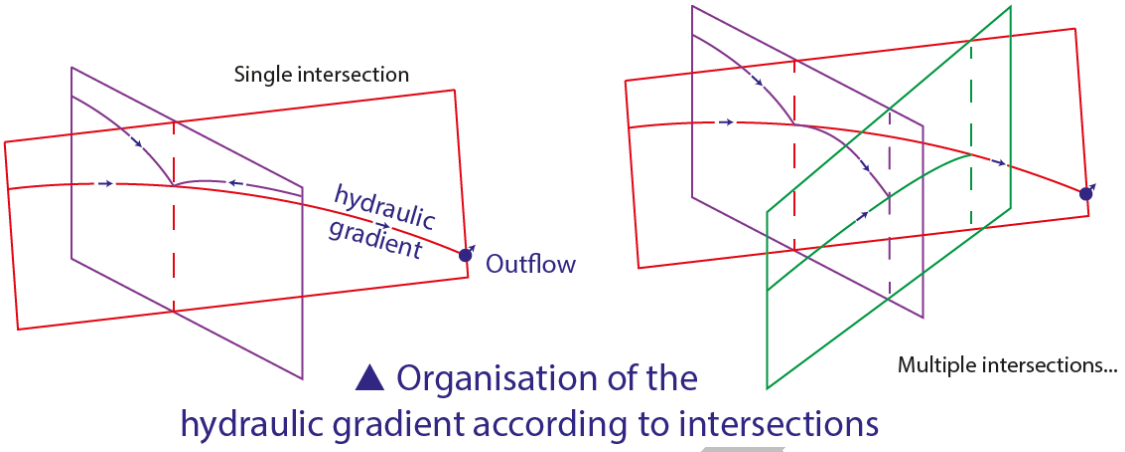


Figure 5 : Organization of the hydraulic gradient in the fractures network according to the connectivity of the network and the aperture of the fractures.

The **saturated or hydraulically active part of the network** is identified using the **difference between hydraulic head and node elevation**. Nodes that do not satisfy the selected saturation criterion are **removed from the active graph**. This step reduces the final network to the portions most likely to transmit groundwater under the simulated hydraulic conditions.

5.6 Flow Representation and Visualisation

Following the head calculation, recharge is routed conservatively toward the outlet. Edges are oriented according to their hydraulic distance from the outlet, and **accumulated recharge** is transferred downstream. At junctions, flow is divided according to the conductance of the available downstream edges. This procedure provides a **mass-conservative estimate** of the recharge-supported discharge reaching the outlet.

5.7 Configuration and run

The main parameters to tune before running a computation are the following ones:

- The set of fractures that potentially intersect with each other,
- The “equivalent opening” for each of the fractures (aperture in meters),
- The “outlet” that drains the fracture network (location in space along the fracture network and associated flow rate), and
- A “recharge” applied on the top of the fractures.

And a few more hydraulic parameters used for the calibration and the upscaling:

- The decimation rate of the fracture (simplification),
- The initial head distribution,
- The tolerance values, and
- The distribution of the recharge.

All these parameters can be modified from runs to runs. The calculation works by iteration, attempting to find a balance between recharge and flow rate at the outlet. This also allows to model the unsaturated zone of the fractures (and resp. the saturated zone where the flows are supposed to take place) which is difficult from a numerical point of view.

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5.8 Outputs and Interpretation

The workflow exports the active flow network as **VTK PolyData** files for three-dimensional visualisation. The output contains the **flow-carrying edges** and associated discharge values. Additional exports include **recharge nodes**, **shared fracture-intersection nodes**, **saturated and unsaturated nodes**, the outlet position, voxelized flow-network data, and optional flowline representations. The main results should be interpreted in terms of:

- fractures contributing recharge to the system,
- hydraulic connections between fractures,
- preferential pathways toward the outlet / outflow,
- accumulated discharge along the flow-network, and
- disconnected components and internal flow sinks.

Diagnostic calculations compare the prescribed recharge with the conservatively routed outlet discharge. They also identify recharge assigned to dead ends, nodes disconnected from the outlet, and the number of active edges. These controls are essential for detecting geometrical or numerical discontinuities.

PyVista or **VTK Paraview** can be used to calculate/visualise:

- The flow network in the saturated zone of the fractures in the form of an oriented graph of nodes and edges,
- The assumed unsaturated zone of each fracture (gray cubes), and
- The hydraulic gradient (the pink line separating the saturated zone from the unsaturated zone).

Flow paths from random points in the network can be simulated. These flow paths comply (with varying degrees of tolerance) with the principle of flow from nodes with high hydraulic heads to nodes with lower hydraulic heads, up to the main outlet. Along the trajectory, upstream flows are added/accumulated up to the outlet of the fracture network. Examples are provided in Figure 6 and Figure 7.

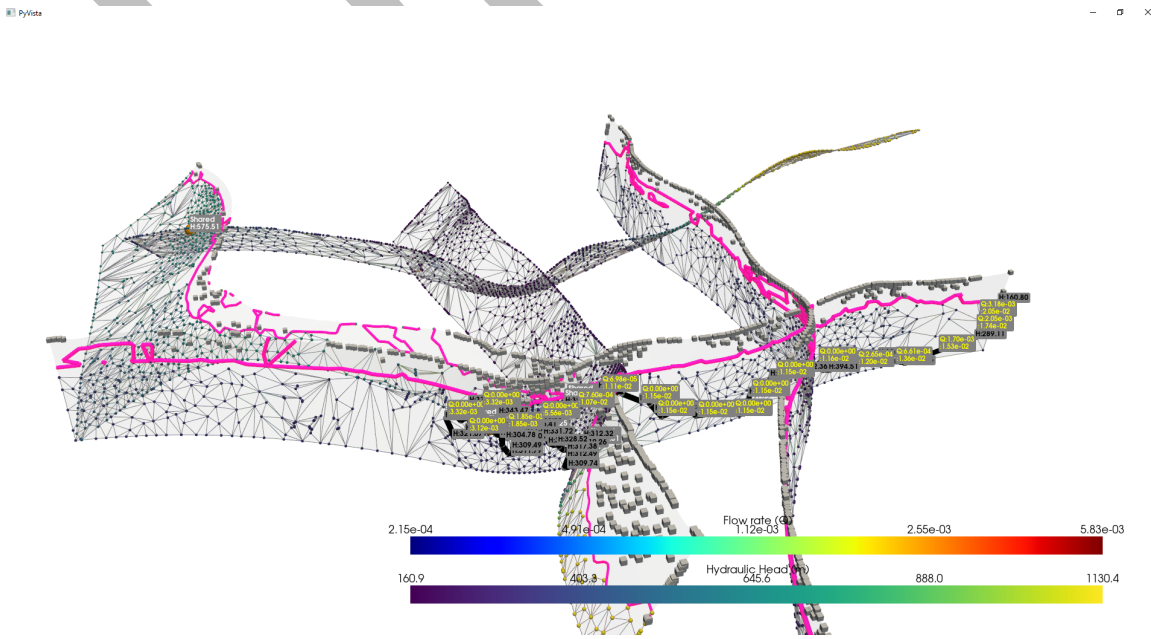


Figure 6 : Overview of the fractures network and the associated flows and heads. Hydraulic head values are attached to the saturated nodes, ranging here from 160 m asl (the elevation of the outlet) to 1'130 m asl. The flow rates values are attached to the edges (here ranging from 2.e-4 m3/s for low conductive edges to ~6e-3 m3/s for higher conductive edges). The outlet is located at the right extremity of the fracture in the foreground extending from left to right.

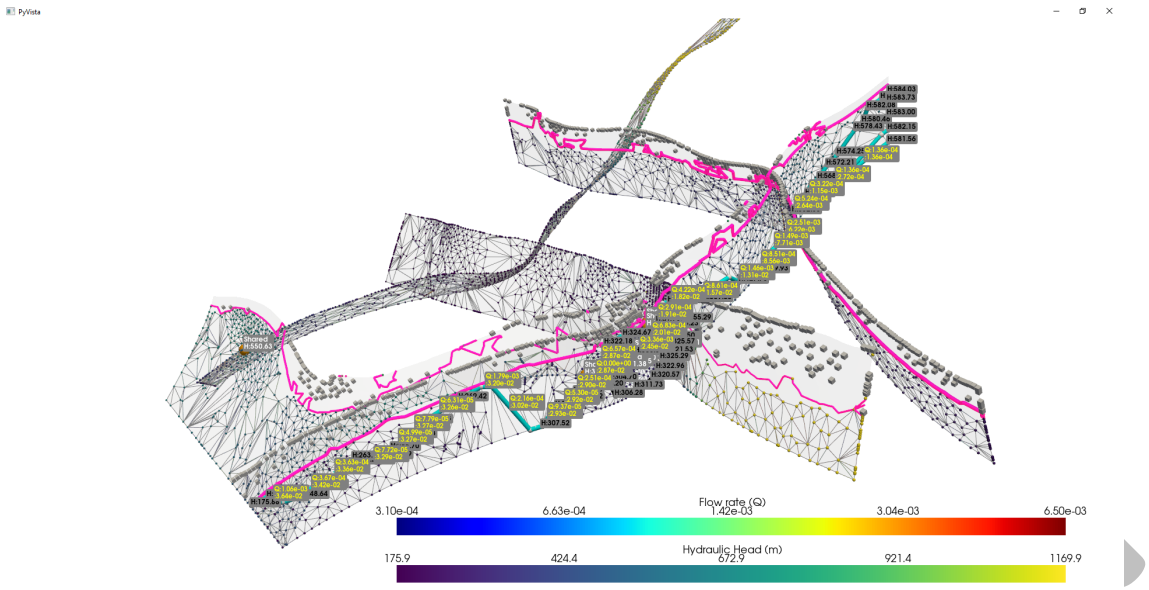


Figure 7 : Another example with the same fractures network, but the location of the outlet changed. Instead of being on the right extremity of the foreground fracture, it is now located at the left extremity. The flow network changes according to this new situation: the hydraulic gradient inverses, and most of the unsaturated nodes reorganise close to the outlet.

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5.9 Dynamic Visualisation

The computed fracture network and flows (heads and discharge) are uploaded in a 3D dynamic scene (threejs viewer). This viewer allows to inspect the whole model in detail and to initialize the run of **animated particles**. These particles are injected at **the inlet "nodes"** as **recharge** and move through the fractures from the upstream parts to the downstream parts according to the hydraulic conductivity of the flow network. These particles allow for a clearer visualisation of the flows and make it easier to identify the most **productive parts** of the flow network.

This "prototype" of the Cleuson-Dixence gallery test site is accessible on the web at the following URL:

https://fracsys.isska.ch/

The following

Figure 8 provides an overview of the prototype.

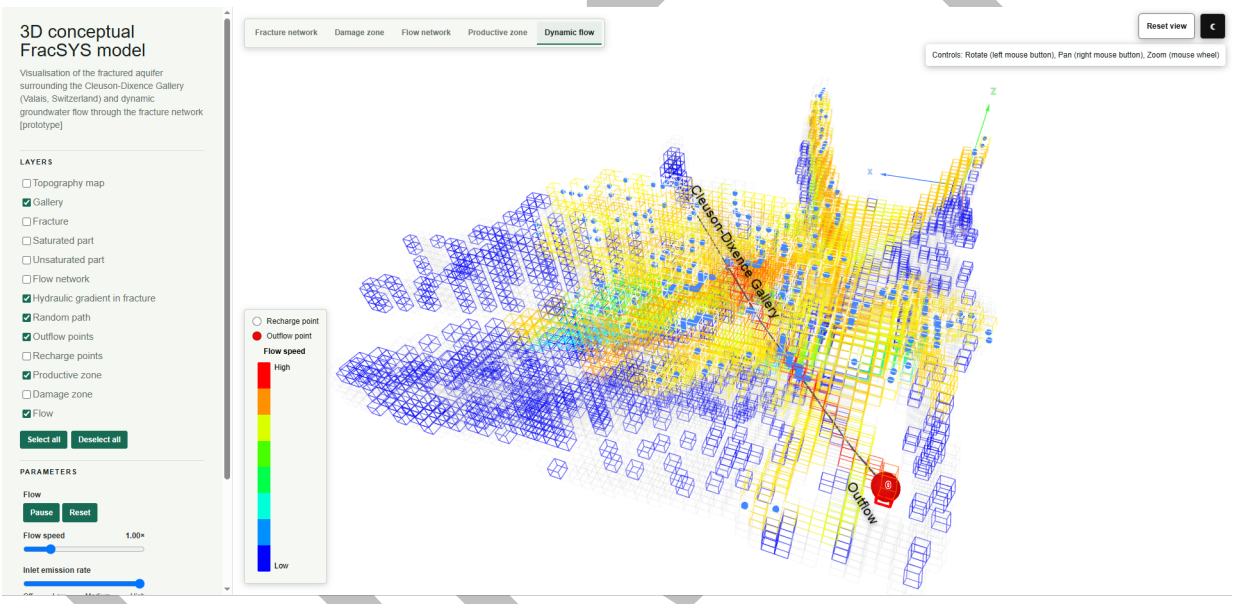


Figure 8 : Overview of the Cleuson-Dixence gallery prototype hosted on the fracysy.isska.ch website. The fractures network is display as voxels. Grey voxels are inactive (no flows), blue voxels are "active" but flows are considered as negligible (below a given threshold). Green to red voxels show higher values of conductivity. Most of the flows are drained by the gallery toward the outflow.

The **"flow animation"** starts at the launching of the webpage. A few buttons allow the user to (i) **pause / start** the animation and (ii) reset the emitted particles to zero. Two other functionalities are available: (i) a slider to densify / de-densify the number of particles that are injected at the inlet nodes and (ii) a slider to accelerate / decelerate the velocity of the particles.

A few **predefined views** are set and allow the users to jump to different views of the same model but with specific layers. 5 views are defined. The below informs on the displayed layers for each view.

Table 1: List of the predefined views and the 3D layers associated to each view.

Layers \ Views	Fracture network	Damage zone	Flow network	Productive zone	Dynamic flow
Topography map	X	X	X	X	X
Gallery	X	X	X	X	X
Fracture (meshes)	X				
Flow					X
Saturated part			X		
Unsaturated part			X		
Flow network			X		
Hydraulic gradient in fracture			X		X
Random path					
Outflow point	X	X	X	X	X
Recharge points			X		
Damage zone		X			

The technical construction of the web viewer is detailed in **Appendix 5 Visualising the Flow Simulation.**

6 Limitations of the FracSYS Prototype

Simplification

The FracSYS model remains a simplified representation of the hydrogeological system in fractured aquifers by focusing on the main aspects that are considered of interest for the hydrogeologists working in groundwater resources assessment, exploitation and protection. The assigned apertures, recharge distribution, saturation threshold, intersection tolerance, and routing preference all influence the resulting network. Matrix flow, transient storage, unsaturated infiltration, and local head losses at intersections are not represented explicitly. Model results are supposed to provide a first “outlook” of the hydrogeological system and must be challenged with additional data, investigations or numerical models to be validated.

Despite these limitations, the workflow provides a practical framework for integrating three-dimensional structural geology with hydraulic properties. It enables the identification of connected groundwater pathways and provides a physically interpretable representation of how fractured rock contributes flow toward the outflow.

Working scale

FracSYS is designed for fractured-rock environments at a scale of a few square kilometres, where small and largely independent flow-systems drain toward their respective outlets. Generalising to larger areas makes little sense, since a wider domain is better described as a juxtaposition of n systems that are disjoint from one another. In our view, the implemented conceptual model does not account for regional circulation. Representing it would require a different conceptual model, rather than an extension of the current one.

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Site condition

As seen during the project, “pure” (or “strictly”) hydrogeological systems developed in fractured aquifers are difficult to isolate from “hybrid” hydrogeological systems that developed in fractured media and unconsolidated rocks without exactly knowing which component is the most prevalent in storing and transferring flows. The test-site of the “source de Bienvenue” is a good example of such “hybrid” hydrogeological system draining fractured aquifer and unconsolidated rocks. Finding sites that meet all the criteria for the FracSYS application isn't that easy.

Data condition

The method can only be applied where site conditions allow a three-dimensional description of the fracture network. Two constraints stand out:

- No reference framework exists for fracture indices at the working scale. Reprocessing a 20 cm DEM, for instance, can give useful results only where there are no Quaternary deposits.
- The 3D structure relies on direct subsurface access. In this case, the gallery and boreholes made it possible to refine the geometry of the faults. How to proceed at sites without this information remains an open question.

The reliability of the explicit mapped / documented fractures network is an issue as well. Fractures geometries / extension are often approximated on maps - as they are often hidden by surface formations – and their properties are far from being known. Again, simplification and drastic assumptions must be done on the hydraulic properties for each of the fractures.

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7 Conclusion and Perspectives

This two-phases project, spanning nearly three years, explored the construction and explicit representation of fractured aquifers and the organization of hydrogeological flow systems in three dimensions.

The phase **1** established a generic conceptual model of hydrogeology in fractured media. It was primarly based on a literature review and drew on analogies with the earlier KARSYS and visualKARSYS projects.

The phase **2** applied this conceptual model to a test site in the form of a prototype, in order to (i) test the steps of the FracSYS approach and (ii) produce an explicit, pseudo-realistic visualization of the site under study.

The project was carried out in collaboration between CREALP (project management, site selection and modelling), SISSKA (development of general concepts and hydraulic principles) and i4ds (3D visualization and animations).

The main conclusions of the project (phases 1 and 2) are:

- The concepts of the FracSYS approach can be applied to a real hydrogeological system and provide an explicit visualisation of the flow system, in a way that had not been explored before.
- Applying FracSYS to the Cleuson-Dixence (VS) test site made it possible to assess the dimensions and extent of the hydrogeological system and to identify: (i) the main fractures acting in recharge, (ii) the main fractures acting in groundwater transfer (i.e. the main flow “routes”), (iii) the unsaturated and saturated portions of the fractures, and (iv) the outlet/outflow zone(s).
- The prototype is available at address fracsys.isska.ch. Considerable effort went into visualization, to help end users understand the structure of the aquifer and the organization of the flow systems.

The main limitations of FracSYS stem from the drastic simplification of hydrogeological processes, which keeps the focus on spatial geometries, concepts and principles that can guide end users in their understanding. FracSYS is a complementary approach: in its current state, it cannot replace classical tools that deliver more physical and quantitative results.

A further limitation concerns the applicability of the approach. Identifying “ideal” test sites, i.e. sites fully representative of fractured aquifers, proved more complex than initially thought. Most of the preselected aquifers also include a non-fractured component that significantly influences the hydrogeological processes.

In terms of **perspectives**:

- Apply the developed approach to the selected test sites for more complete evaluation and detailed feedback from FracSYS followers.
- As with KARSYS, the methodology will evolve through its application cases: new features emerge from case studies, so further case studies are needed.
- These applications will show which uses can be satisfied, by category (knowledge production / water resource managers).

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- Other test sites, and therefore other applications, will follow through future mandates.

8 Acknowledgements

We thank the Federal Office for the Environment (FOEN) for its support throughout the project. We also thank the members of the follow-up group, Norbert SA and Tissières SA, for their monitoring and contributions.

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Appendices

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Appendix 1 Terminology, Principles and Processes

Introduction

The FracSYS conceptual model

The FracSYS conceptual model has been described in the report [...]. The following sections summarise the main definitions, concepts and principles.

Terms

The following terms are used to describe the approach. They are therefore subject to a specific definition.

Fractures

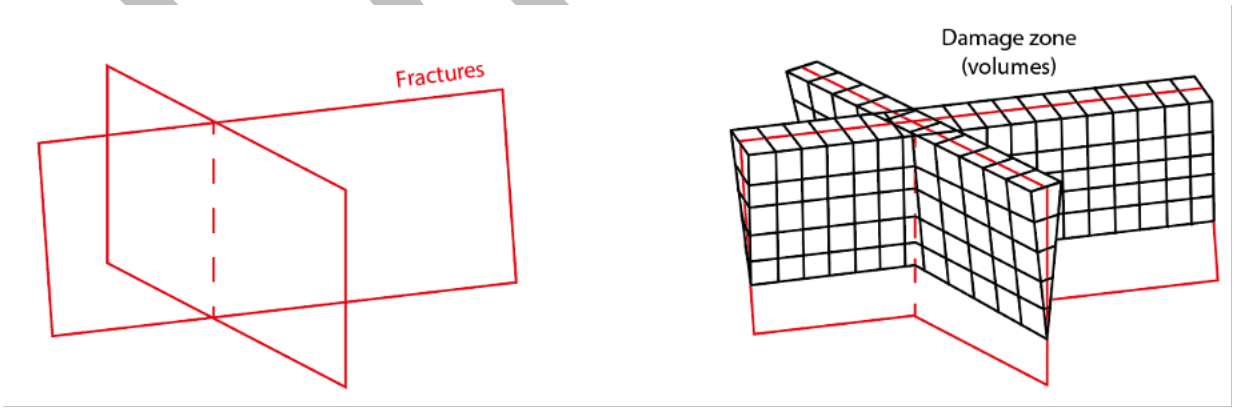
Fractures are defined as cracks or discontinuities in consolidated (i.e. low permeable) rocks. Depending on their size, their aperture, their roughness and their orientation, fractures are the main hydrogeological vector allowing groundwater to flow.

Fractures network

A fractures network is defined by as an interconnected system of fractures whose properties (size, geometry, connectivity, aperture, roughness) control the groundwater flow (transmissive function).

Damage zone

The damage zone is defined as the volume of rock surrounding the fractures that present strong deformation due to the strain and stress associated with the fracture development. The thickness of the damage zone is somehow related to the size / displacement of the fracture. It could be a few meters or dozens of meters, but it might reach a few hundreds of meters for "big" fractures. From a hydrogeological point of view, the damage zone might present a higher permeability than the consolidated rocks surrounding the damage zone. It then acts as a storage feature for the groundwater (capacitive function).

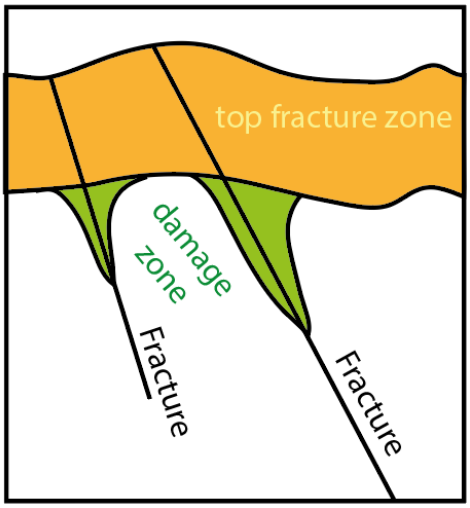


Left: two intersecting fractures. Right: supposed geometry of the damage zone associated to the fractures network (not to scale).

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Top fractures zone

The **top fractures zone** is defined as a highly fractured, shallow horizon in consolidated rocks. These top fractures **zone** results from microfracturing due to the processes of rocks decompression near the surface.



The top fracture zone is defined as a near-surface shallow horizon (a few meters or dozens of meters) presenting a permeability higher than the hardrock and where the groundwater may store before being drained by the damage zone / fractures network.

From a hydrogeological point of view, the **top fractures zone** usually presents a higher permeability than the deepest consolidated rocks and acts as a **storage** feature for the groundwater (**capacitive function**).

Hardrock

The **hardrock** is defined as the consolidated rocks surrounding the fractures network. From a hydrogeological point of view, the **hardrock** is considered as rather impervious compared to fractured zones.

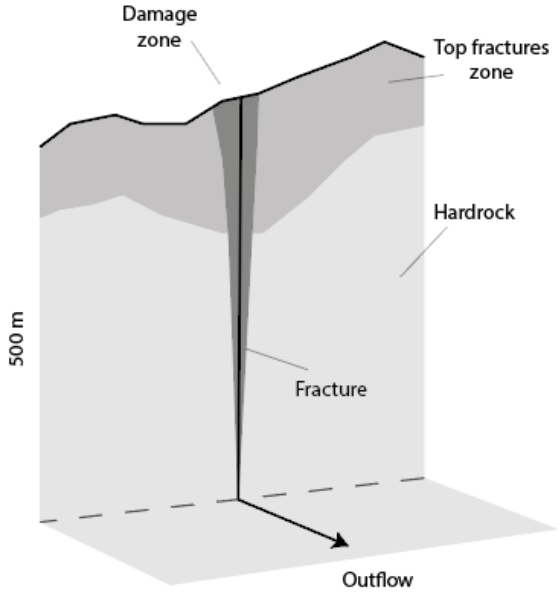
Outflow

The **outflow** is defined as the area where groundwater emerges from a fracture network. This could be a srping or a group of springs which emerge in a string along the fracture downstream of the fractures network.

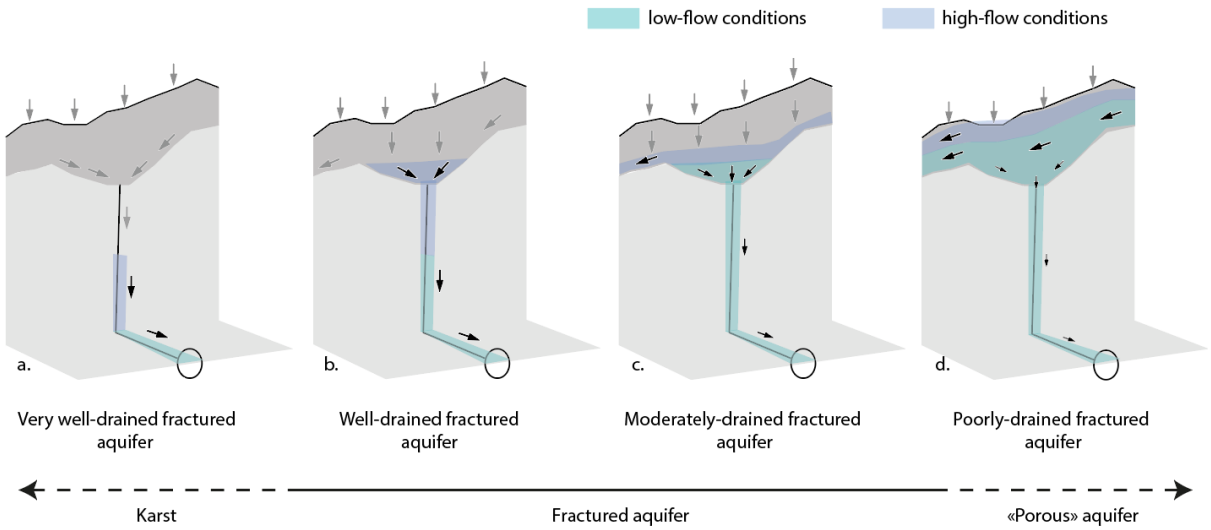
Principles

The following illustrations shows the main components and principles of the FracSYS conceptual model. This model is mainly based on the permeability contrasts between the top fracture / damage zones and the fractures network.

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Main components of the FracSYS conceptual model.



Depending on the permeability contrasts between the top fracture / damage zones and the fractures network, the FracSYS conceptual model might be considered.

Regarding the here-above illustration, 4 hydrogeological cases might exist: a. The hydraulic conductivity of the fractures network is very high. In this case the hydraulic gradient through the fractures network is low and flow can be laminar to turbulent depending on the aperture of the fractures network. The top fracture / damage zones might be mostly unsaturated and. This case is not very common in fractured aquifer. However, it is common in karst aquifers, to which the KARSYS approach can be applied. b. The hydraulic conductivity of the fractures network is high. In this case, a part of the top fracture / damage zones can be unsaturated. Most of the groundwater still flows through the fractures network (laminar). c. The hydraulic conductivity of the fractures network is moderate. The top fracture / damage zones are partly saturated and a part of the groundwater might be drained by the top fracture zone as the permeability of the top fracture zone is somehow similar to the "permeability" of the fractures network. The flow through the fractures network is laminar. d. The hydraulic conductivity of the fractures network is quite low. In this case, the fractures network is not supposed to play a

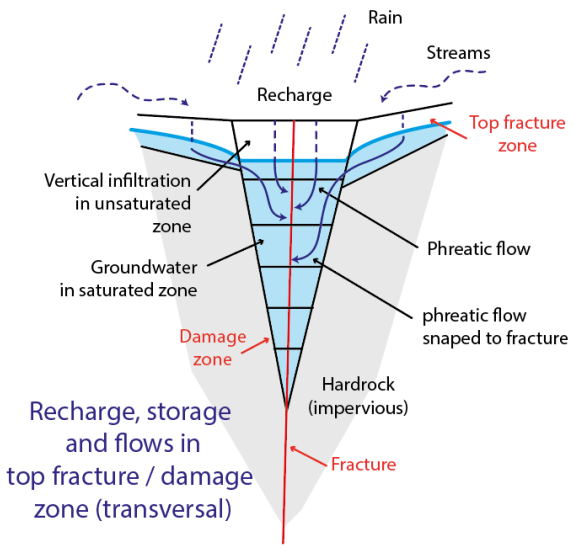
significant hydrogeological role and most of the groundwater flow is drained by the top fracture zone.

According to the previous cases, The FracSYS approach might be applied to cases b. and c., i.e. for cases in which the part of the groundwater drained by the fractures network is significant, but for which flows through the fractures network remains laminar.

Hydrogeological and hydraulic processes

Recharge

The recharge is defined as the amount of surface water that infiltrates through **the top fracture zone** and joins the fracture network via the **damage zone.** Due to their extension, the top fracture is the zone where most of the recharge take place (diffuse or concentrated recharge). Recharge of the damage zone from surface water is possible but not significant, except for concentrated recharge.



Recharge, storage and flows in top fracture / damage zone (transversal).

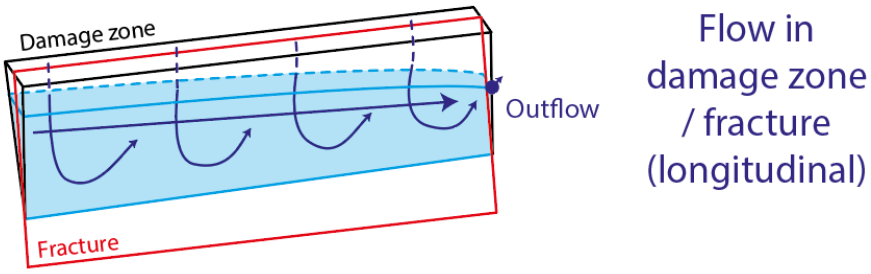
The recharge is made possible if both the top fracture zone and the damage zone are enough drained to allow the "old" groundwater to be replaced. If both the top fracture zone and the damage zone are fully saturated because of their respective low permeability, the recharge is no more possible and most of the surface water will runoff (see the here-above illustration).

Storage in top fracture / damage zones

The top fracture / damage zones are considered as reservoirs allowing the infiltration and storage of the groundwater. Depending on (i) their respective permeability and (ii) the downstream gradient, these zones might be fully or partly saturated.

Flow in fractures

The groundwater is supposed to flow within the fracture by draining the adjacent and permeable volumes of the damage zone. In the case of a single fracture, groundwater will flow toward the "downstream" part / segment of the fracture, i.e. the places where the fracture reaches the ground surface (the outflow) or the places where the fracture intersects another fracture presenting lower heads.



Conceptual representation (no scale) of flows and hydraulic gradients through a single fracture.

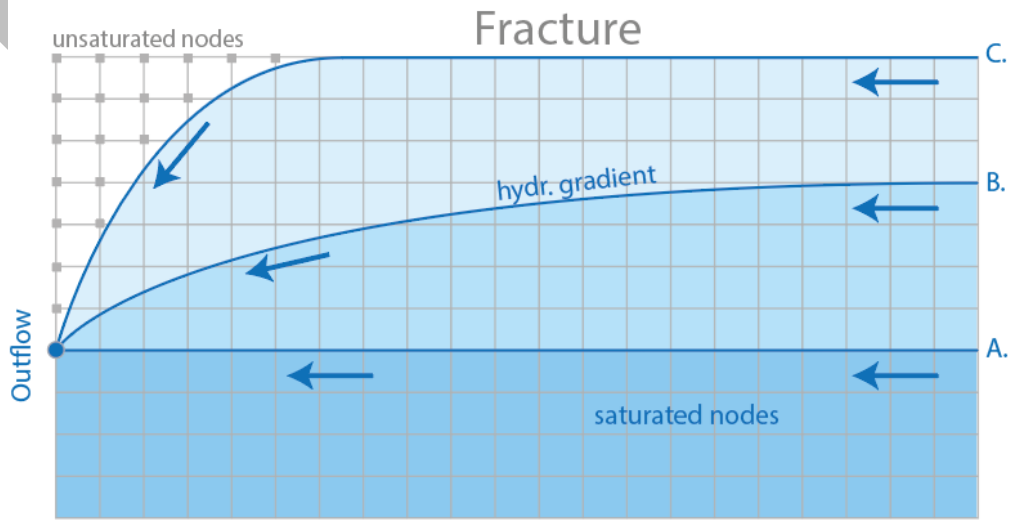
The water flowing through the unsaturated parts of the fracture / damage zone is supposed to flow downward up to the saturated parts. Flows are strictly vertical or controlled by the "slope" of the fracture.

In the saturated parts of the fracture / damage zone, the groundwater flows in the fracture plane, according to the hydraulic gradient.

The flow through a single fracture or through a fracture network mainly depends on 3 parameters:

- The hydraulic conductivity (i.e. the "resistance of the fracture to flow"). This parameter could be assigned to parts of fractures, entire fractures, or networks of several fractures.
- The potential recharge (i.e. the quantity of potentially infiltrated water).
- the location of the hydraulic base level.

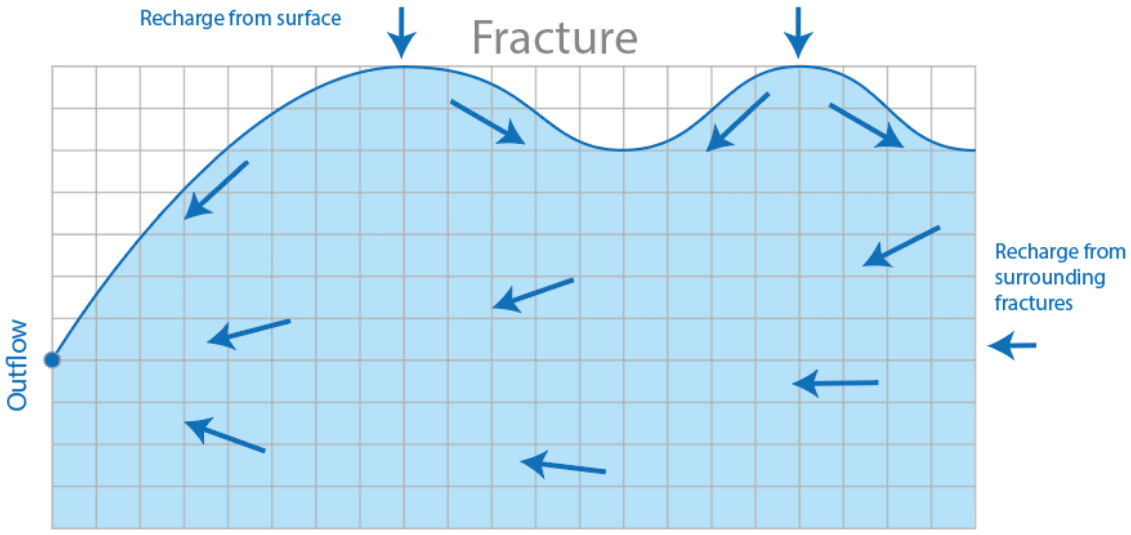
Regarding a single fracture, and for a given recharge and location (i.e. elevation) of the hydraulic base level (the outflow), the flow and the associated hydraulic gradient through the fracture is mostly controlled by the apparent aperture (i.e. combination between real aperture and roughness). On the following illustration, the aperture of the fracture decreases from case A. to case C. and the hydraulic gradient increases reciprocally. For case C., the gradient reaches the top of the fracture (i.e. the ground surface) and prevent the surface water to infiltrate (reduction of the unsaturated zone). Thus, the recharge by infiltration decreases...



Conceptual representation (no scale) of flows and hydraulic gradients through a single fracture. Input comes from the right and flows toward the Outflow. The aperture of the fracture decreases from cases A. to case C., resulting in an increase of the hydraulic gradient.

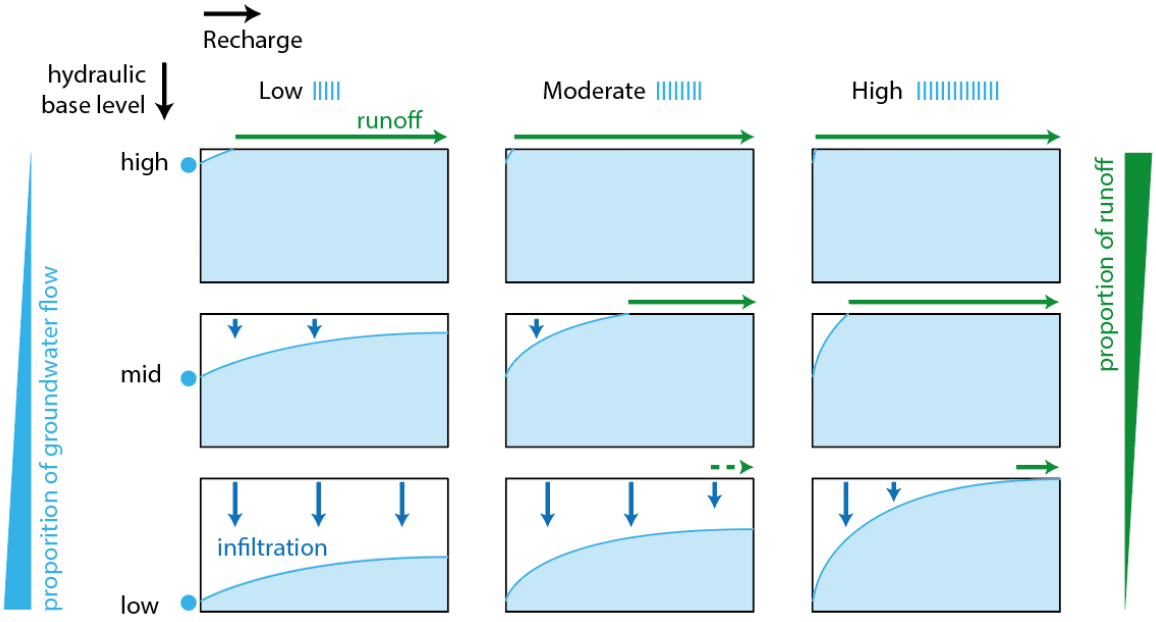
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This conceptual representation is a bit simplified as it considers the fracture with a uniform conductivity and a recharge applied on a single boundary (the one at right). In case where the recharge comes from both ground surface (infiltration) and surrounding fractures, the shape of the hydraulic gradient and of the groundwater flow paths might be completely different (see the next illustration).



The hydraulic gradient within a fracture might present a more complex shape due to the heterogeneity in the aperture et and the location of the recharge point.

The next illustration shows the evolution of the hydraulic gradient within a single fracture with a given hydraulic conductivity (weak to mid. conductivity) when varying the location of the hydraulic base level and the amount (i.e. quantity) of available recharge. The variation of the hydraulic base level (marked by the outflow) and/or the variation of the amount of available recharge have a significant effect on the potential infiltration / runoff. The 9 cases below show how the infiltration / runoff might evolve when varying the quantity of recharge and the location of the hydraulic base level.



Evolution of the hydraulic gradient within a single fracture with a given hydraulic conductivity when varying the available recharge and/or the location of the hydraulic base level.

The here-above illustration shows that the proportion of infiltrated water (and by extension groundwater flows) is enhanced in cases where the hydraulic base level is low and the available recharge is low to moderate. For high-elevated hydraulic base level and high recharge, most of the water cannot infiltrate as the fracture is fully saturated. In this cas, the proportion of runoff is significantly higher than infiltration.

The computation and the representation of the hydraulic gradient become more complex for networks with several fractures of different hydraulic conductivities and that might intersect each other. As the groundwater might flow through different routes, using different fractures, from the recharge points to the outflow, the distribution of the hydraulic heads might be reorganized, leading to new shapes of the hydraulic gradient. In this case, flows in each fracture might present different orientations, heads, velocities, etc. depending on the intersection / connectivity with other fractures.

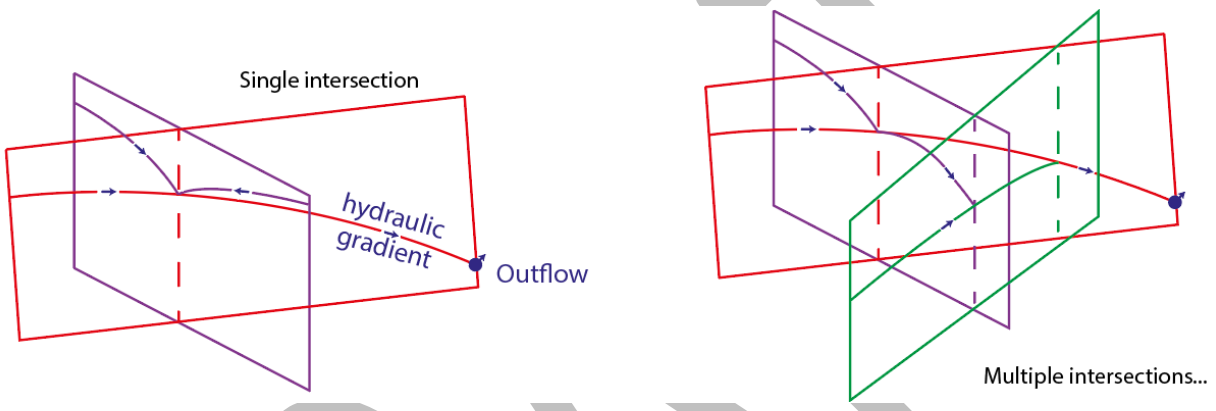


Figure Left: the purple fracture is drained by the red one. Right: the left part of the purple fracture is drained by te red one and the right part by the green one which is itself drained downstream by the red fracture. it can be deduced that the green fracture has probably a higher hydraulic conductivity or less infiltration from the surface, allowing thus to divert groundwater from the purple fracture.

Methodology description

Goal

What should **FracSYS** do? Basically, the method is supposed to:

- Allow the description / visualisation of the geological components that play a significant hydrogeological role:
- The top fracture zone
- The damage zone
- The fractures (i.e. the fracture network)
- Allow the description / visualisation of the groundwater volume within the top fracture / damage zones.
- Allow the description / visualisation of the groundwater flows within the fractures (flows in the saturated parts of the fractures, as well as flows in the unsaturated parts). This requires to:
- Assess the hydraulic gradients within the fracture network as this gradient governs the orientation and the velocity of the flows through the successive fractures up to the outflow. it also indicates which fractures could be partly unsaturated, resp. saturated.

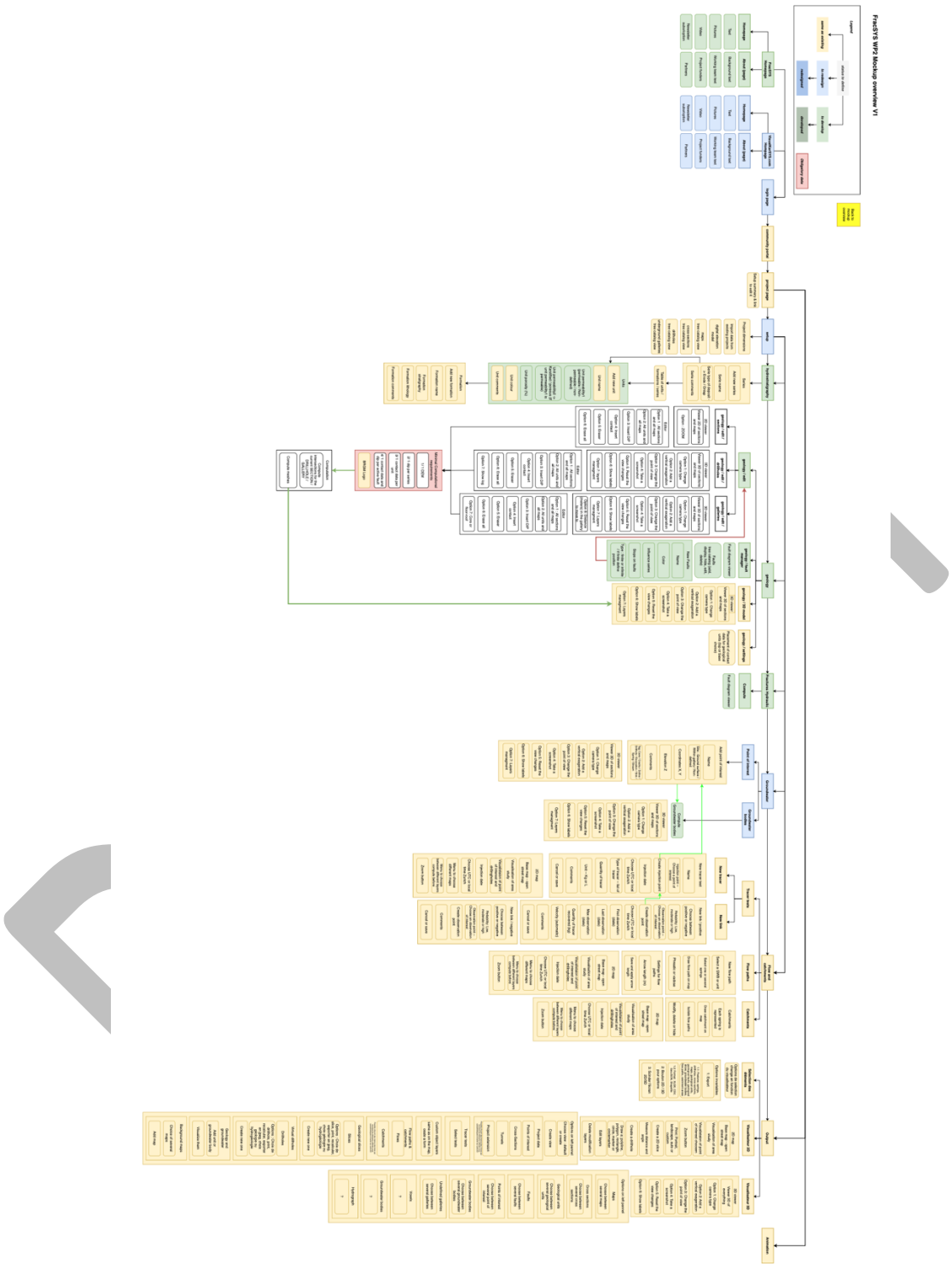
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- Assess the places where the surface water might infiltrate through the fractures, in the unsaturated zones or (but less probable) in the saturated ones.

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Appendix 2 FracSYS Mock-up



Mock-up of the FracSYS tool illustrating the technical framework and implementation roadmap derived from Phase 1. The diagram below shows the key processes to be developed, reused or adapted, identifies data and information sources, and supports the comparative analysis between visualkarsys.com and the future FracSYS platform, while defining priorities and dependencies for implementation.

The base of the diagram represents the existing visualkarsys.com workflow. Processes required for the FracSYS adaptation are specified either as redesigned existing processes or as newly developed processes. The diagram shows the identified obligatory dataset as well to provide.

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Appendix 3 Case study #1 Source de Bienvenue

Site Location and Characteristics

The Source de Bienvenue spring system is located at the footwall of the Mont d'Ottan, within the alluvial deposits of the Rhône River, between Martigny and Vernayaz. A pumping station collects this spring system through a pumping well, 12 m deep and 100 cm in diameter, dug entirely within the scree deposits and built in 1979.

The so-called "Source de Bienvenue" is best described as a diffuse discharge area rather than a single spring. Located at the foot of the Massif de l'Arpille in the Rhône Valley, 5 km north-west of Martigny, several springs have been reported by Tissière (1988), all situated within the unconsolidated material overlying the underlying gneiss (cf Figure 9). However, no precise location is given for these springs, only vague descriptions such as "a series of springs gushing at the foot of Mont d'Ottan", "these springs emerge in the scree", and "a whole series of springs spread over a 700 m front feed the Canal de Bienvenue". Based on this information, together with a simple freehand sketch that we georeferenced (cf Figure 10), we propose a potential location for this series of springs (cf Figure 9). The most probable location is depicted in light green and labelled "1". To account for the information regarding the 700 m front, a second area is proposed in dark green and labelled "2".

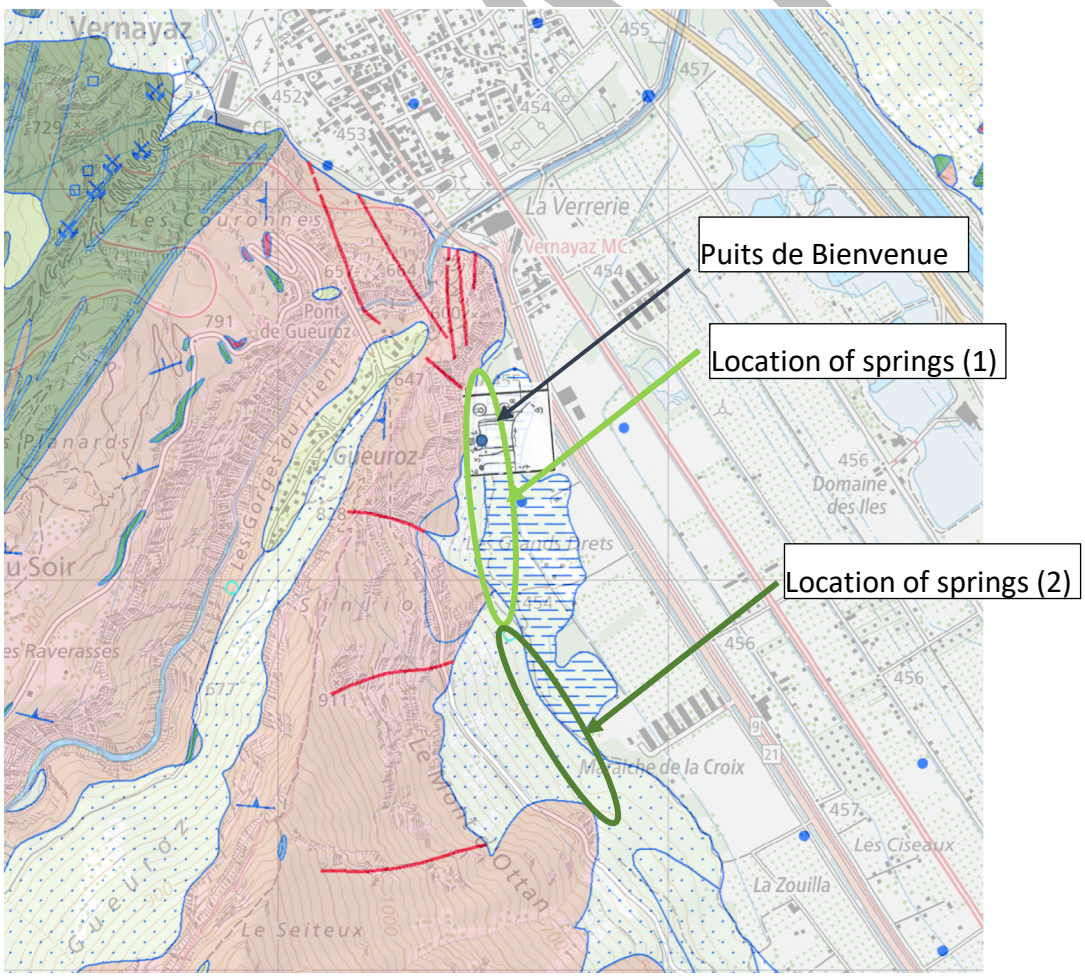


Figure 9: Springs location estimated from Tissière 1988

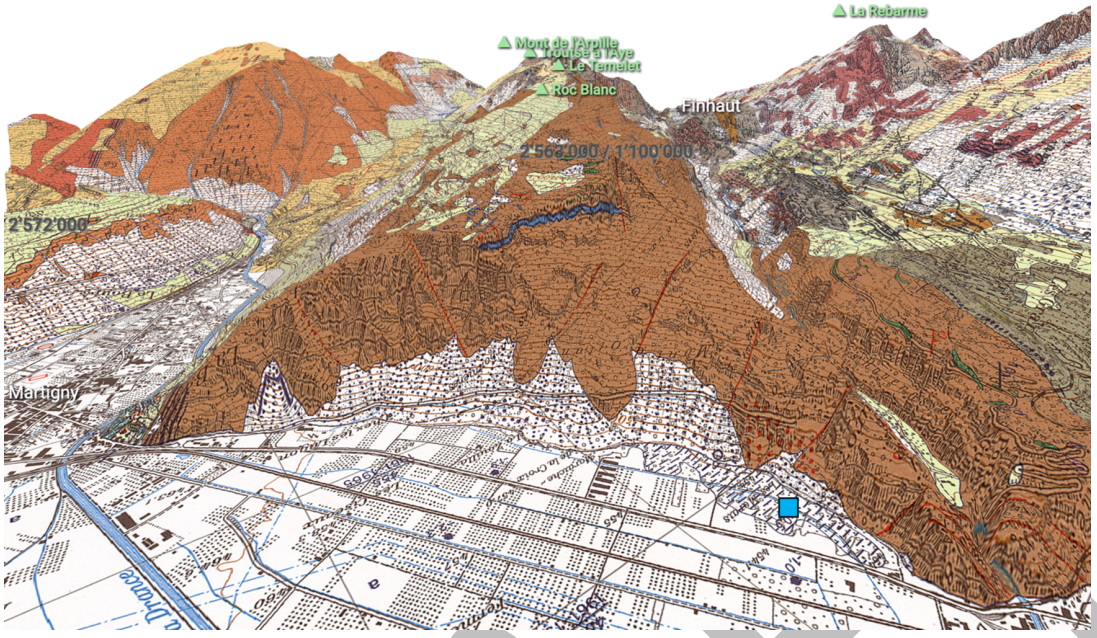


Figure 10: Overview of the Arpille Massif from the east (Geological Atlas of Switzerland 1:25 000). Red lines correspond to the 1st order fault. Blue square corresponds to source de Bienvenue.

The Spring's System

A pumping well was drilled in 1979 (12 m deep, 1 m in diameter) to drain this series of springs, and has proven effective, as the springs dry up when the well is pumped. The well is located upstream of the springs (cf Figure 11).

Several pumping tests have been carried out (in 1987 and 2012) at pumping rates ranging from 306 m^3/h to 708 m^3/h. The piezometric level stabilised in all cases, leading previous authors (Tissière, 1988, 2012) to consider an approximate flow rate of 10,000 l/min (600 m^3/h) as the maximum exploitation rate for these springs. The chemical composition of the water remained stable across these pumping rates, suggesting that a steady state was reached. These flow rates should nonetheless be treated as indicative, as no direct gauging of the springs has been reported in the literature.

Several tracer tests have been carried out to investigate possible mixing with waters from the Trient stream (to the north) or from the canal (to the east). All returned negative results, indicating that the water discharging from the springs, or abstracted from the Bienvenue well, is not diluted by these sources.

In addition, it is worth noting the low temperature measured at the well (approximately 8.5 to 9°C), which is highly consistent with recharge occurring at high altitude within the Arpille Massif.

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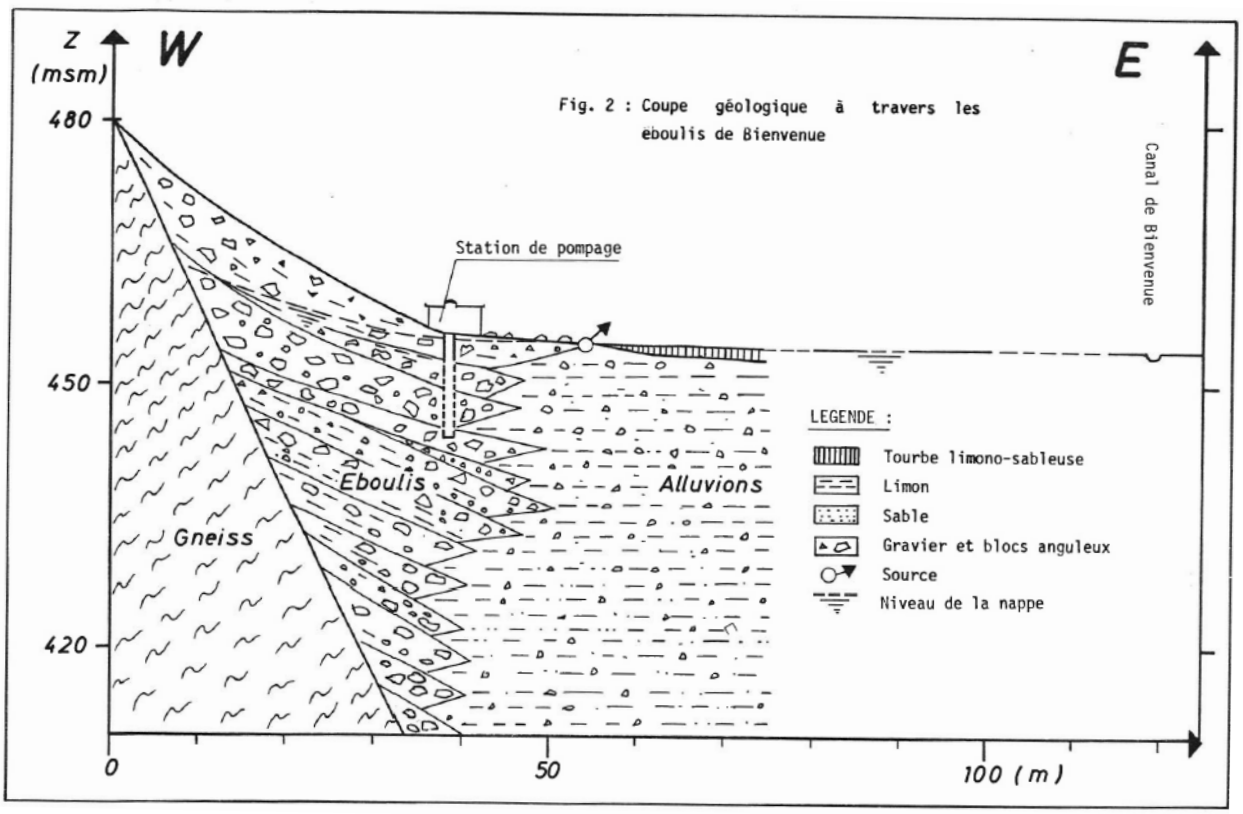


Figure 11: Cross-section of the springs and well vicinity. Tissière 1988

Based on the interpretation of chemical analyses, tracer tests and the water budget, several protection zones have been sketched, based on hypothesised flow paths. These depict the infiltration of meteoric water through the Massif de l'Arpille, followed by drainage via fissures and fractures towards the springs and the well.

Geological and Hydrogeological Settings

The geological context of the "massif de l'Arpille" (Mont d'Ottan) is described in Tissière 2012:

"The gneisses of Mont d'Ottan exhibit great variability: fine-grained gneiss with one or two micas, conglomeratic facies gneiss (with rounded pebbles) near the spring, amphibolitic eye gneiss, etc. They contain lenses and marble beds reaching up to 40 m in thickness at the upper part of Mont d'Ottan. From a tectonic perspective, these gneisses have undergone deformations due to the formation of the Caledonian, Variscan, and Alpine mountain ranges."

One should add, based on the Geological Atlas of Switzerland, the presence of quaternary deposits (glacial till) mostly on the southern face, but lenses are observed also on the northern face), and debris cone and debris slopes in the Rhône Valley, in the vicinity of well.

Fractures are also reported (in red) on the geological map.

Baseline Spatial Dataset and Geological Modelling

The following baseline data have been used for :

- Extract of the Digital elevation model (DEM) – derived from swissALTI3D model (swisstopo)

- Extract of the Bedrock elevation model (BEM) – derived from swissBEDROCK product (swisstopo)
- Extract of the geological Atlas of Switzerland 1:25 000 (raster version)
- Extract of the GeoCover of the Geological Atlas of Switzerland 1:25 000 (rasterised version)
- Traces profiles from Geological Atlas of Switzerland 1:25000
- Cross-sections #1 et 2 from AG25 Sembrancher geological sheet
- Cross-sections #2 and #3 Finhaut geological sheet
- Extract of the Tectonic Map of Switzerland 1:500 000 (swisstopo)

Other datasets remain to be imported / digitalised such as detailed fractures derived from DEM, etc.

The results of the geological modelling can be access through visual KARSYS page https://www.visualkarsys.com/vk/project/2309

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Appendix 4 Case study #2 Cleuson-Dixence Galery

Site Location and Characteristics

The Cleuson-Dixence hydroelectric scheme is in the canton of Valais. It connects the Grande Dixence dam to the Cleuson dam via an underground headrace tunnel crossing the massif beneath the Dent-de-Nendaz.

The tunnel is exploited by Alpiq and thus represents an equipment for which not all detailed are publicly available. Therefore, all the information on which we based our work cannot be included in this report. We include elements that are already public, or certain others whose details do not compromise the operator's interests.

The Galery

The Cleuson-Dixence headrace tunnel is a 15.8 km-long underground structure operated by Alpiq. It conveys water collected at the intake bored through the wall of the Grande Dixence dam to a surge chamber located beneath the Dent-de-Nendaz. From there, water is directed down an armoured shaft to the underground powerhouse of Bieudron, where electricity is generated. The tunnel crosses the Dent-de-Nendaz Member.

The digging of the tunnel occurred in the 1990's and has been heavily monitored before, during and after the tunnelling works. In addition to the gallery, several boreholes have been drilled along the gallery path, mainly to better characterized the rocks properties before the actual drilling.

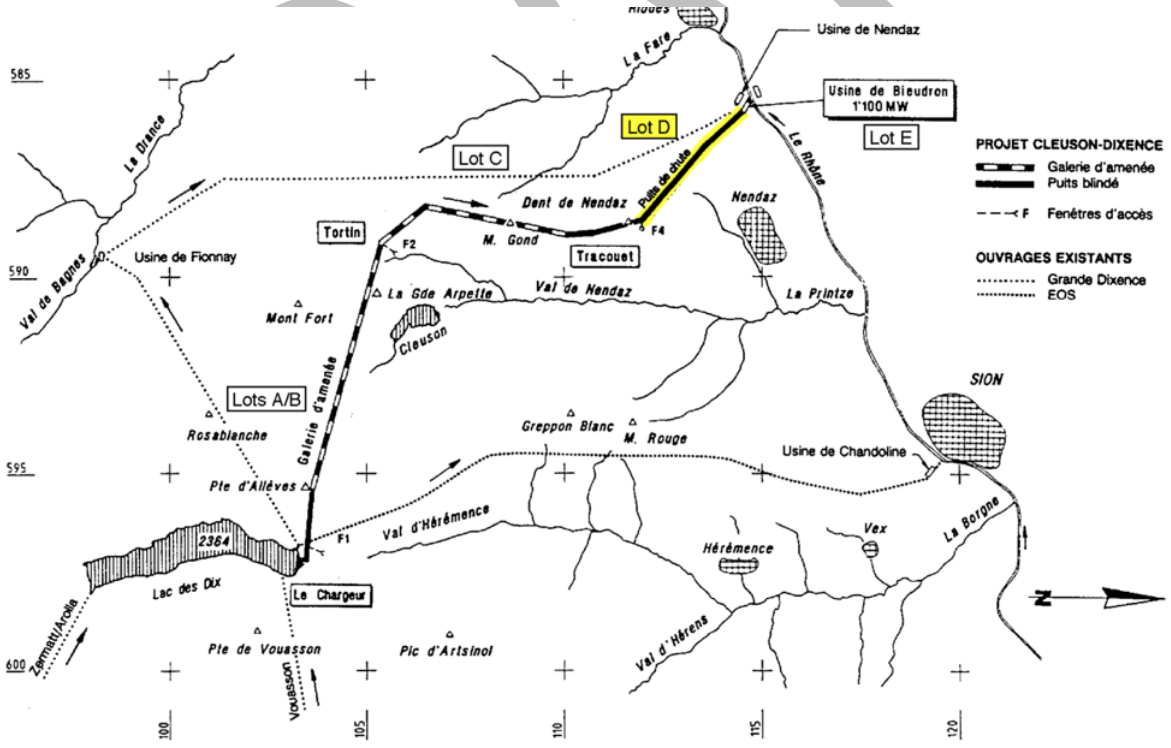


Figure 12 : Schematic map of the Cleuxon-Dixence Gallery (Norbert, 1998)

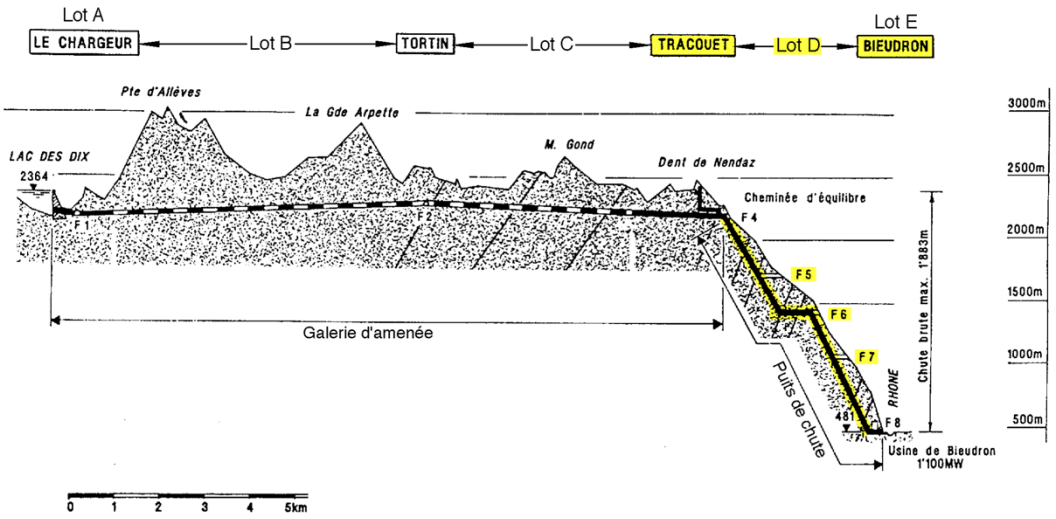


Figure 13 : Gallery cross-section, details on the different stages for tunneling works ('Lot')

Geological and Hydrogeological Settings

The Cleuson-Dixence galerie is located in the Souwthern Est part of the Wallis canton, south of the Rhône. This area belongs to the Penninic Domain (tectonic unit derived from Mesozoic basins, formed between the European and Adriatic continents). The Penninic domain is subdivided into Lower, Middle and Upper Penninic subdomains that are bounded by major thrust faults. [Gouffon, 2024]. The Rhône-Simplon Fault – SW-NE of orientation (RS on the map) marks the boundary Helvetic domain (to the North and to the West). All units within th e Penninc Domain contain far-traveled sedimentary cover rocks and basement rocks transported over considerable distances, and thus highly fractured.

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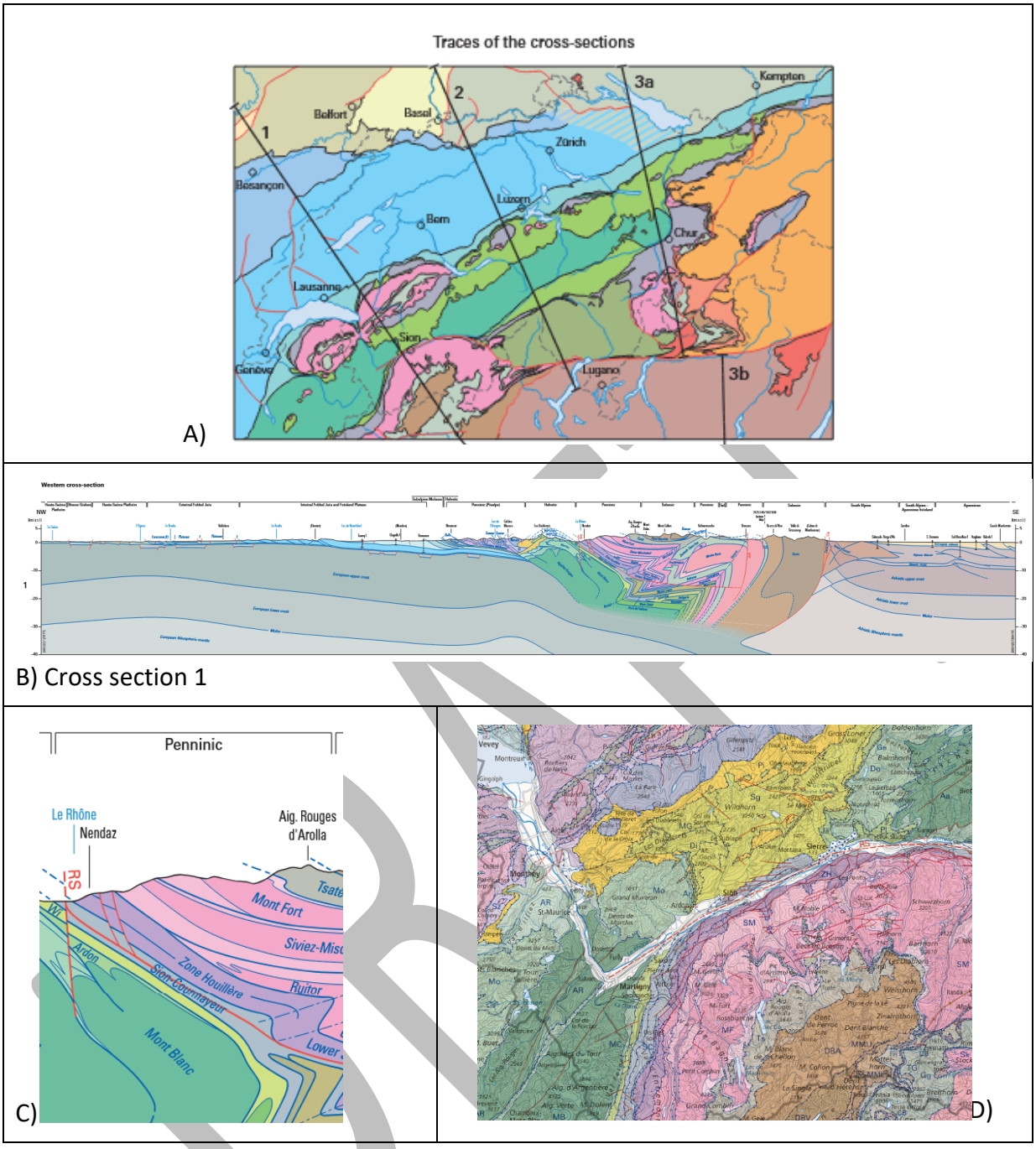


Figure 14 : Geological and Tectonic context (A-location of the cross-section, B) cross section 1, C) detail from cross-section 1 on the Nendaz region, D) Tectonic 500) from Gouffon, 2024.

For the purpose of FracSYS project, focus was kept on the Northen part of The Cleuson-Dixence Galerie. In this area, Lower and Middle Penninic Subdomains where in intersected.

Table 2: Tectonic units in Main tectonic units – Gouffon, 2024; Loprieno et. al. 2010 ; Pantet et. al., 2020 ; Swisstopo, 2024).

Domain	Subdomains	Units	Ages and dominant lithologies
Penninic	Middle	Mont Fort Nappe	Paleozoic basement, overlain by a thin, discontinuous cover of Triassic-Jurassic metasediments, mainly breccias. Tectonic contact with the Siviez-Mischabel nappe
		Siviez-Mischabel nappe	Crystalline basement (sedimentary and magmatic origin of Proterozoic to Ordovician age) and typical Briançonnais sedimentary cover
		Zone Houillère	Late Carboniferous to Permian metasediments, locally rich in coal, Early and Middle Triassic sediments
	Lower	Sion-Courmayeur Nappe ("Roignais-Versoyen" slice, and "Pierre Avoi" slice)	flysch-type rocks (Cretaceous) highly metamorphized

Detailed geological context and local terminology

Among the gallery digging reports and hydrogeological local studies, ways to describe geological units varies (in time and depending on authors), and differ from the tectonic units describes before. Terminologies differ also from more recent studies (Sartori et.al., 2006), but harmonization of terminologies what out of the scope for this study. Thus, only terminologies as described in the publicly available description of the galerie (Alpiq, 2015) were kept. Those names are also the ones found in Norbert, 1998. From Norbert, the local terminologies are given as in the table x.

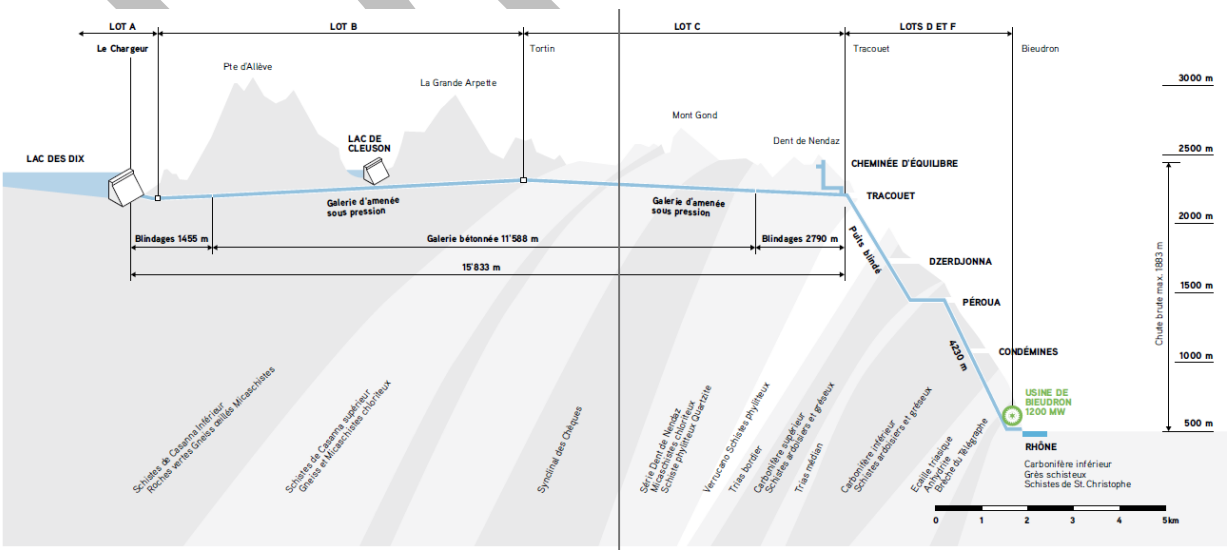


Table 3: Schematic cross section with geological units (Alpiq, 2015).

Terminology	Lithologies
Série de la Dent de Nendaz	metaconglomerates, coarse meta-arkoses, and light green quartzites with dispersed quartz pebbles, alternance with grey metagreywacke, quartz-sericite schists, and metapelites. All is highly folded with a superimposed schistositie
Verrucano	Sericitic sandstones and schists, Sericitic quartzites
Trias bordier	Quartzites, mylonitisées
Carbonifère supérieur	Schistes ardoisiers et gréseux, fortement tectonisés
Trias Médian	Anhydrite, niveau quartzo-phyllitiques
Carbonifère inférieur	Grès schisteux et schistes gréseux, schistes conglomératiques, interlits charbonneux,
Brèche du télégraphes	Calcaires gréseux et dolomitiques plus pou moins bréchifiés, niveaux de schistes séricito-phylliteux
Ecailles triasiques	Anhydrite et dolomie bréchique à ciment anhydritique
Grès et schistes de Saint Christophe	Grès et schistes, lentille triasique, peu fracturé

Figure 15 : Geological units intersected by the Cleuson-Dixence galery – Norbert, 1998

Fracturing and Groundwater Flow

Monitoring during drilling and monitoring after was extensively documented. Records of lithology, fracturing intensity, and water inflows were compiled. Precise positions of these various elements were provided and served as the basis for establishing this case study.

From the geological records, it was observed that all geological units encountered were metamorphosed, and that numerous indications of fissuring/fracturing were identified. The properties of these materials (anisotropy, porosity, mineralogy) must also be considered in relation to this metamorphism.

Groundwater circulations have been monitored during the tunnelling works and after within dedicated devices (pressure gauges in the fractured network, flowrate gauges at drainage facilities outlet, piezometers and springs).

Observations related to the gallery digging shows the alternance of completely dry sections of rock, and water inflows located in the fractured and mylonitized zones. Flow rates were reported within the range of 10 to 50 l/s at best during the tunnelling works, but most of the

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producing fractures yields about 5 l/s. It is stressed that this initial flow rate shows a rapid decrease.

Flowrates at outlet of drainage gallery (F6, F5 'windows' in Norbert, 1998) varies between 0.2 and 1 l/s approximately.

Pressure gauges measuring pressure at the outside of the armoured shaft, i.e. in the fractured medium, registers annual high and low pressures, in good accordance to snowpack melt (high pressure) and dry season.

These various observations demonstrate that the Cleuson Dixence sector exhibits the characteristics of a fractured system, in which water circulates through discontinuities related to fracturing. The aquifer systems remain of modest extent with respect to the relative low flow rates (few litres per seconds). Annual variations in flow rates or in piezometric heads demonstrate that these systems benefit from annual recharge and are drained toward natural outlets (surface springs) or anthropogenic ones (Cleuson-Dixence gallery). Thus, despite not being located in crystalline rock context, the Cleuson-Dixence case study seems to exhibit suitable properties to study fractured aquifers.

Baseline data and Geological Modelling

To build the conceptual model, and implement into the FracSYS prototype, following data where used :

From Norbert, 1998

- Gallery alignment, in plan and in depth
- Longitudinal Cross-section – LOT D, 1/50 000
- Boreholes location and geological logs

From public sources

- Borehole
- Extract of the GeoCover of the Geological Atlas of Switzerland 1:25 000 (rasterised version)
- Traces profiles from Geological Atlas of Switzerland 1:25000

Other datasets remain to be imported / digitalised such as detailed fractures derived from DEM, etc.

The results of the geological modelling can be access through visual KARSYS page https://www.visualkarsys.com/vk/project/2453

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Appendix 5 Visualising the Flow Simulation

Overview

After each flow simulation there is the task to visualize the results in 3D. We decided to write a viewer based on web technologies. The advantages of this decision are:

1. Users can access the results with no additional software
2. New results can be published easily
3. The technology is well-known and documented

We had a positive experience with the JavaScript-based package Three.js on a previous project. It is a library for creating 3D graphics and interactive experiences in a web browser. It is known to have good performance in rendering 3D graphics. Thus, we decided on the following technology stack:

Technology	What it is	What it does for the Flow Viewer
Three.js	A JavaScript library for creating 3D graphics in web browsers.	Creates the 3D scene, voxel outlines, moving particles, camera, lighting, and navigation controls. It uses the browser's built-in graphics capability, WebGL, to draw the model efficiently.
TypeScript	The programming language used for the application. It adds consistency checks to JavaScript during development.	Helps developers detect incompatible or missing data structures before a new version of the viewer is published. The browser ultimately receives ordinary JavaScript.
Vite	A tool for preparing and packaging web applications.	Combines the application code and its libraries into the files delivered to the browser. It also provides the local development version of the website.
HTML and CSS	Standard web technologies for page content and appearance.	Provide the canvas, buttons, sliders, legends, colours, and page layout around the 3D model.

We added Docker container technology later in the project. This provides another way to publish it without the need to set up and maintain a web server.

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Selecting the data format

The next step is to find a data format for the exchange of the results with the web viewer. The simulation algorithm can compute many properties. For this prototype, we use the following output data:

1. The location of the voxel (x, y, z) in yet arbitrary units. This is needed to display the geometry of the damage zone.
2. If a voxel is an Inlet. Then water will enter the network at this position. There can be multiple inlets.
3. If a voxel is an Outflow, also called a well. At this location, the water leaves the network. There may be several outflows in the simulation.
4. The velocity of the simulated water flow in a voxel. This value determines how fast the particles moves in the simulation. We do not use the true (physical) values since this is too slow. The app multiplies this value with a speed-up factor.
5. The ID of the next downstream voxel. This builds up a structure like a linked list and describes the flow of a particle through the grid. This allows for much faster processing.
6. And finally, we need to now whether a voxel is saturated or not. A saturated voxel has water flowing through it. We use this information to colour the voxel according to the flow speed.

We found that a CSV-file (Comma-Separated Values) is the most flexible solution for the data exchange. It is easy to process and to extend in the future.

The workflow

Thus, the workflow is as follows. The Flow Viewer reads a CSV-file that describes a network of small cubes called voxels. Each row represents one voxel and provides its position, its role in the flow network, and its flow speed. The viewer uses this information to create two visual layers:

- a 3D wireframe model showing the voxels; and
- moving blue particles showing the direction and relative speed of the flow.

Arranging the rows in three dimensions

The viewer collects all distinct x, y, and z coordinate values and sorts each axis from lowest to highest. It then places each row at the matching position in this ordered grid. This approach supports incomplete shapes: not every possible combination of x, y, and z needs to appear in the CSV. Missing combinations simply leave space in the 3D model. The model is placed in the view such that the source z axis appears vertically on the screen

The viewer assumes that the voxel grid is a regular grid of equally sized cubes. The first available gap between coordinate values is used as the size of every voxel. Irregular spacing is neither reproduced nor detected. This is a simplification done for this prototype. If coordinate gaps vary, or if x, y, and z use different spacing, the displayed geometry may have discontinuities. You may want to allow this in a future release because you then get a better approximation of the damage zone.

Creating the animated flow

Each voxel marked Inlet releases blue particles at the rate selected in the viewer. A particle follows the ID of the next downstream voxel from one row to the next. The path is therefore

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supplied by the CSV. The viewer does not calculate a new flow path, choose between neighbouring voxels, or run a physical groundwater simulation.

Particle travel speed is based on the velocity values at both ends of each connection. Faster values produce faster visible movement, and slower values produce slower movement. The viewer applies the same overall time adjustment to the entire network so that flows which would take years can be observed in a short animation. This adjustment preserves the relative speed differences in the CSV: a flow that is ten times faster in the data remains ten times faster in the animation.

All inlets release particles at the same selected rate, regardless of their velocity. As a result, particles appear closer together in slow sections and farther apart in fast sections.

A particle leaves the display when it:

- reaches a voxel marked Outflow;
- reaches the end of its downstream path; or
- remains in a repeating path for too long. A safety limit prevents incorrect circular links in the CSV from creating particles forever. This limit is set to 256 cell-to-cell hops. This was chosen to sit safely above the longest legitimate acyclic path, approximately 210 cells.

The number displayed at an outflow records how many particles have reached it. This is an animation count, not a direct measurement of physical water volume.

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