The Management of Karst in Switzerland : methods, tools and applications

Autor(en): **Malard, Arnauld / Luetscher, Marc / Jeannin, Pierre-Yves**

Objekttyp: **Article**

Zeitschrift: **Swiss bulletin für angewandte Geologie = Swiss bulletin pour la géologie appliquée = Swiss bulletin per la geologia applicata = Swiss bulletin for applied geology**

Band (Jahr): **23 (2018)**

Heft 2

PDF erstellt am: **24.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-832402

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

Swiss Bull. angew. Geol. Vol. 23/2, 2018 S. 13-24

The Management of Karst in Switzerland: methods, tools and applications

Arnauld Malard[1], Marc Luetscher[1], Pierre-Yves Jeannin[1]

Abstract

Carbonates represent up to 20% of Switzerland's outcrops, most of them being karstified. The high permeability and intrinsic spatial heterogeneity characterizing karst environments require specific tools to address geotechnical and conservation issues. KARSYS was specifically developed to provide a pragmatic approach in addressing karst related issues including groundwater reserves, natural hazards, building works and geothermal resources. Here, we present the general concepts behind the KARSYS approach and illustrate it with case studies from Porrentruy (JU) and Ligerz (BE) as well as from the cantons of St.Gallen and Fribourg.

Résumé

Les roches carbonatées représentent, en Suisse, près de 20% des affleurements et sont largement karstifiées. Caractérisé par une forte perméabilité et une grande hétérogénéité spatiale, le karst requiert des outils spécifiques pour faire face aux défis géotechniques et de protection. KARSYS a été spécialement développé pour gérer la problématique inhérente au karst, incluant les réserves d'eau, les risques naturels, les travaux de génie civil et les ressources géothermiques. Ici, nous présentons le concept général derrière KARSYS et l'illustrons avec des exemples de Porrentruy (JU) et Ligerz (BE) de même que des cantons de St Gall et Fribourg.

Zusammenfassung

In der Schweiz stellen Karbonatgesteine fast 20% der Aufschlüsse dar und sind mehrheitlich verkarstet. Weil der Karst durch eine hohe Durchlässigkeit und eine hohe räumliche Heterogenität geprägt ist, erfordert es spezifische Werkzeuge, um geotechnische und Schutzaufgaben zu bewältigen. KARSYS wurde speziell dafür entwickelt um karstrelevante Probleme zu meistern, einschließlich Wasserreserven, Naturgefahren, Bauarbeiten und geothermische Ressourcen. In diesem Beitrag stellen wir das allgemeine Konzept von KARSYS vor und illustrieren es mit Beispielen aus Porrentruy (JU) und Ligerz (BE) sowie den Kantonen St.Gallen und Fribourg.

1 Introduction

Karst aquifers represent nearly 80% of Swiss groundwater reserves (ca. 120 km^3) and up to 40% of groundwater resources (8.4 km^3/year), although they only extend over 20% of the territory (Malard et al. 2016). High infiltration rates and large permeabilities make karst aquifers highly interesting for water abstraction. However, karst groundwater flow-systems are also characterized by highly heterogeneous structures including quick- and slow-flow components (conduit network, phreatic and epikarst storage) leading to important hydrodynamic variabilities and complex flow dynamics which cannot be solved with standard hydrogeological tools. Overall, karst aquifers are vulnerable to contamination and require specific attention for protection. Despite representing interesting groundwater resources karst aquifers are often disregarded and/or their management is far from optimal. KARSYS is a pragmatic and systematic approach developed at the Swiss Institute for Speleology and Karst Studies (SISKA) for the documentation of karst aquifers (Jeannin et al. 2013). KARSYS has readily been applied over large areas in Switzerland and serves as incentive to further develop a large array of methods specifically designed to assess karst-related hazards during underground construction (KarstALEA, Filipponi et al. 2012) or issues associated with karst hydraulic processes (flood hazards, hydropower, etc.).

---

[1] SISKA, Swiss Institute for Speleology and Karst Studies, La Chaux-de-Fonds, Switzerland – info@isska.ch

2 KARSYS

KARSYS is a conceptual approach that provides an explicit model of the groundwater flow system, based on a 3D geological modelling of the karst aquifer. The approach is organized in four steps and comprises an initial literature review and/or field investigations on site (Fig. 2):
Steps 1 and 2 aim at building the karst aquifer geometry in 3D. In step 3, hydrological data are interpolated according to some fundamental hydraulic principles. The fact that karst networks are usually well drained keeps the hydraulic gradient upstream the main perennial springs very low, usually less than 0,1% (Bögli 1980, Worthington 1991). If no indication about the gradient of the water table is available, a flat water table can thus be assumed and can be extrapolated throughout the aquifer volume (in 3D). This provides a first idea of the extension of the phreatic zone at low water. In step 4, the catchment area can be delineated by considering the organization of the flow network. Flow paths or «drainage axes» are constructed assuming: (i) a vertical flow path through the unsaturated zone, (ii) a down-dip flow path on top of aquicludes and (iii) a subhorizontal flow path in the phreatic zone towards the spring(s). Accordingly, KARSYS delineates, for each flow-system, the hydrological catchment area and provides the extension of the saturated zone (including the confined part), the main drainage axes and the expected hydraulic heads.

Based on this 3D explicit model, several extensions have been developed to address specific and recurrent issues in karst environments associated with construction, natural hazards, renewable energies, etc. In particular, the analysis of a number of tunnels in

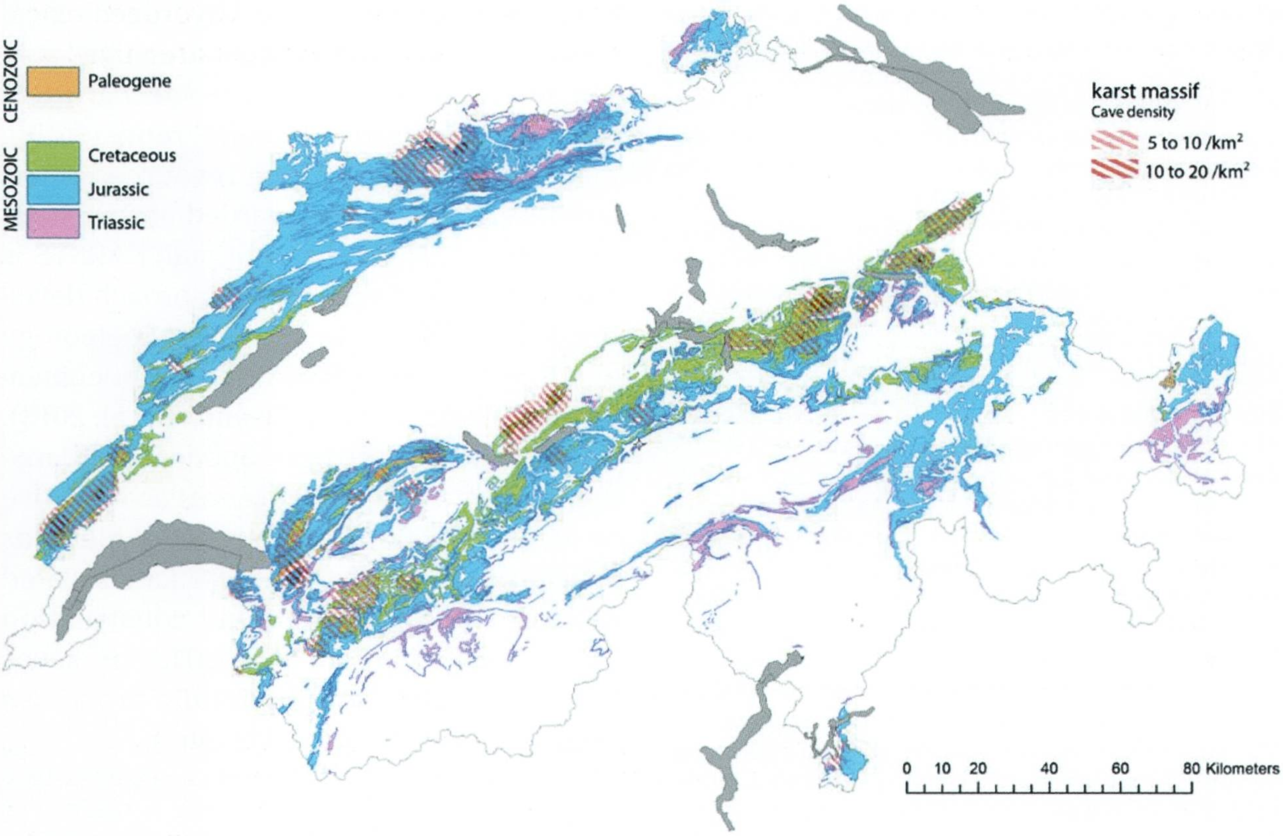

Fig. 1: Distribution of carbonate outcrops over the Swiss territory which may be potentially karstified. Red hatches locate high density cave areas (from 10 to 20 known entrances per km2 for the most investigated sites). Geological data comes from Swisstopo.

Switzerland showed that many of the encountered geological or hydrological disorders were related to karst processes. Most of these problems were unexpected and led to delays and additional costs in the realization (see Table 1).

KarstALEA was specifically developed for predicting karst occurrences in tunneling (Filipponi et al. 2012) and is now recognized as an official method for assessing karst by Swiss civil engineers. The first principle of KarstALEA assumes that karst conduits preferentially develop along a restricted number of geological horizons (bedding planes or tectonic features), known as «inception horizons» (Filipponi et al. 2009). Field observations reveal that more than 70% of the conduits within the scale of a tunnel project are determined by such horizons. The second principle assumes that, within a karst massif, the conduit density varies according to present and past hydrogeological conditions. This commonly results in a larger number of conduits at elevations corresponding to past base-levels (paleo-valley floors). Combining this speleogenetic information with the identified inception horizons (Fig. 3) predicts the potential position of karst channels as well as their characteristics (expected size, shape, infilling, etc.). This approach is suited to any type of underground construction in karst and can be extended to the near-surface to anticipate the position of sinkholes and collapses.

3 Examples of application

3.1 Flood-hazard assessment in the Jura Mountains – the Porrentruy (JU) case study

The Beuchire-Creugenat system in the northern Jura Mts (Ajoie, Switzerland) is characterized by recurrent overflows of the Creugenat spring which represent a significant flood risk for the city of Porrentruy. Major flood events in 1804 and 1901 led to heavy damages throughout the city and its vicinity (BG Ingénieurs Conseils 2011). Over the last 30 years, five small-scale floods have additionally been recorded, each resulting in substantial costs for the local community.

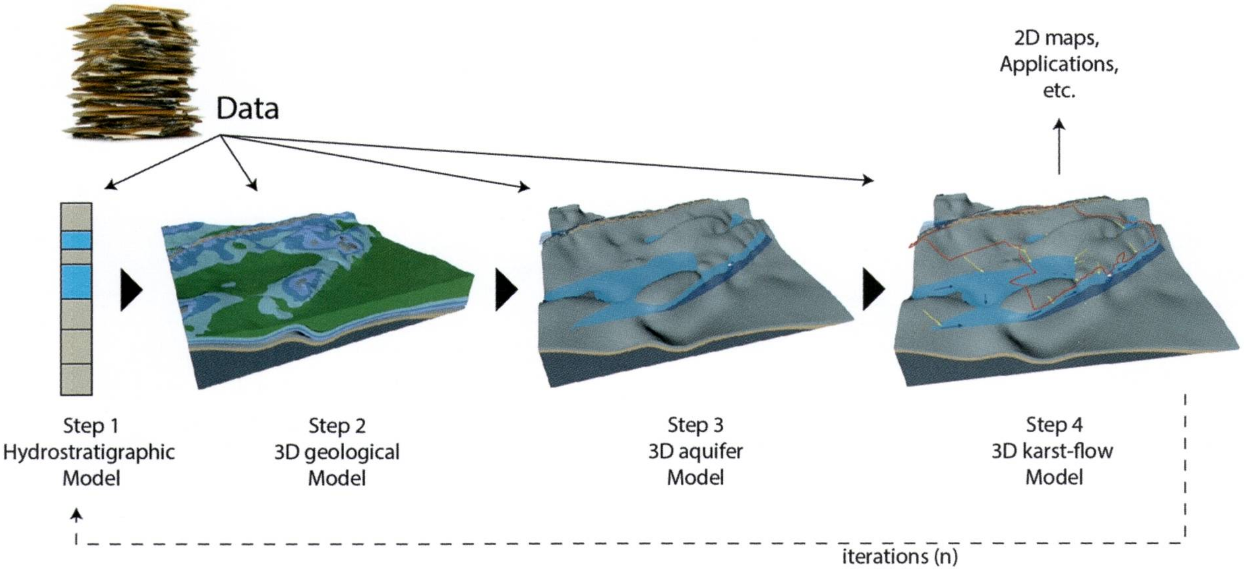

Fig. 2: Workflow of the KARSYS approach (modified from Jeannin et al. 2013). Geological data are first used to produce a hydrostratigraphic model for the identification of karstified rocks (aquifer) and aquicludes. 2) A 3D geological model of the karstified rocks and aquicludes is built. 3) Hydrological information is added to the 3D geological model and a model of the karst aquifer is produced. 4) By applying some rules of the hydraulics of flow in karst, the groundwater flow system can be sketched explicitly. Finally maps and other outputting information can be produced for dedicated applications (e.g. groundwater resource assessment). The approach can be iterated each time new data have been collected.

A KARSYS model of the aquifer delineates the catchment area of the flow-system. Recharge is simulated and calibrated with local meteorological data and provides control on the flow entering the aquifer. Meanwhile, a karst conduit-network is integrated in the KARSYS model (Malard et al. 2015). The organization and connectivity of this conduit-network are adjusted to reflect known hydraulic relations in the Beuchire-Creugenat flow-system (perched conduits, thresholds, narrowing, etc.). Eventually, the simulated recharge is implemented as input to the conduit-network in order to reproduce the flow dynamics (overflowing, discharge rates and hydraulic heads) of the system's

Swiss Cases	**Incidence on the construction**	**Incidence on the environment**	**Karst hazards initially expected**	**Modification of the initial plans during construction**
Concise tunnel (VD / NE) 2000-2004	Water inflows, instabilities, additional equipment	Weak	Yes	Yes
Engelberg tunnel (OW) 2001-2010	Water inflows, declogging and sediment infilling	-	Yes but underestimated	Yes (Additional costs ~70 Mio Fr., the initial project was estimated ~80 Mio. Fr)
Flimserstein tunnel (GR) 1998-2007	Water inflows	Partial and irreversible dewatering of lake and springs	No	Yes (additional costs ~100 Mio Fr.)
Kerenzerberg tunnel (GL) 1986	Water inflows + flooding during the operation phase	Weak	-	No
Mont d'Or tunnel (CH / France) 1910-1915	Water inflows, declogging and sediment infilling	Irreversible springs dewatering	Yes but underestimated	Yes
Ölberg tunnel (SZ) 90ies	Water inflows	No	No	Yes
Raimeux tunnel (JU), 1999-2007	Weak	Weak	Yes	No
Rawil gallery (BE / VS) 1976-1978	Water inflows	Relevant (micro-displacements of the Tseuzier dam)	No	Yes (construction stopped)
Twann tunnel (BE), 1989-1991	Water inflows	Weak	Yes but underestimated	Yes
Vue-des-Alpes Tunnel (NE) 1999	Instabilities, additional equipment	No	Yes	Yes

Tab. 1: Overview on some of the problems faced in Swiss tunnels passing through a karst massif (sources: Schneider 1980 Bianchetti 1993 Jeannin and Wenger 1993 Wildberger 1994, Bollinger and Kellerhals 2007 Jeannin 2007 Filipponi et al. 2012 and Anagnostou and Ehrbar 2013).

outlets (permanent springs, overflow springs, drillholes, etc.). This explicit 3D model allows, thus, advanced prediction of flood risks based on meteorological forecasts. Figure 4 summarizes the specific workflow selected for this issue.

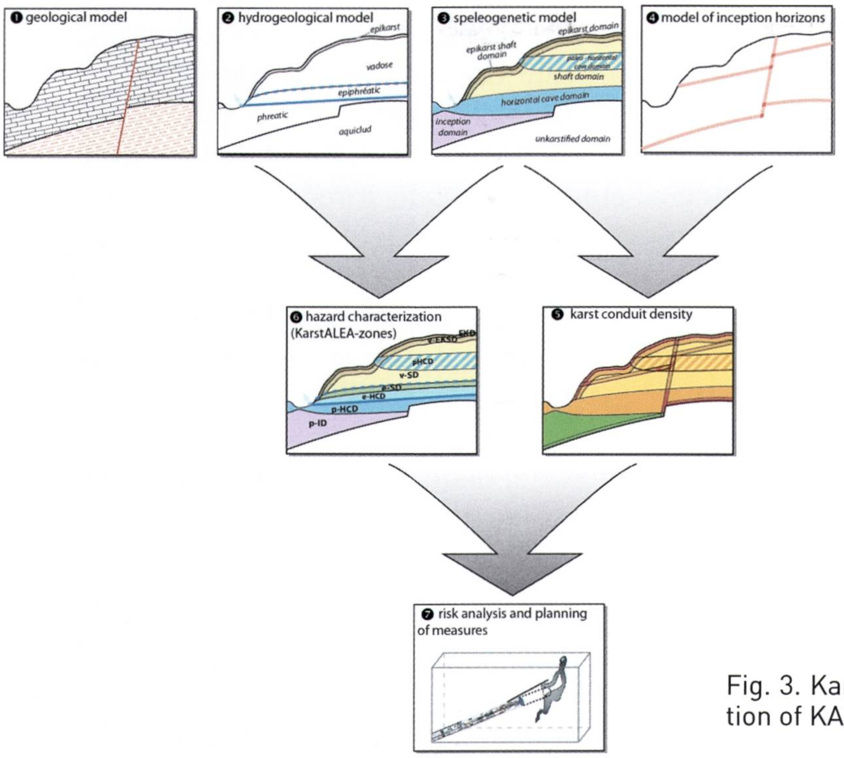

Fig. 3. KarstALEA requires the initial application of KARSYS.

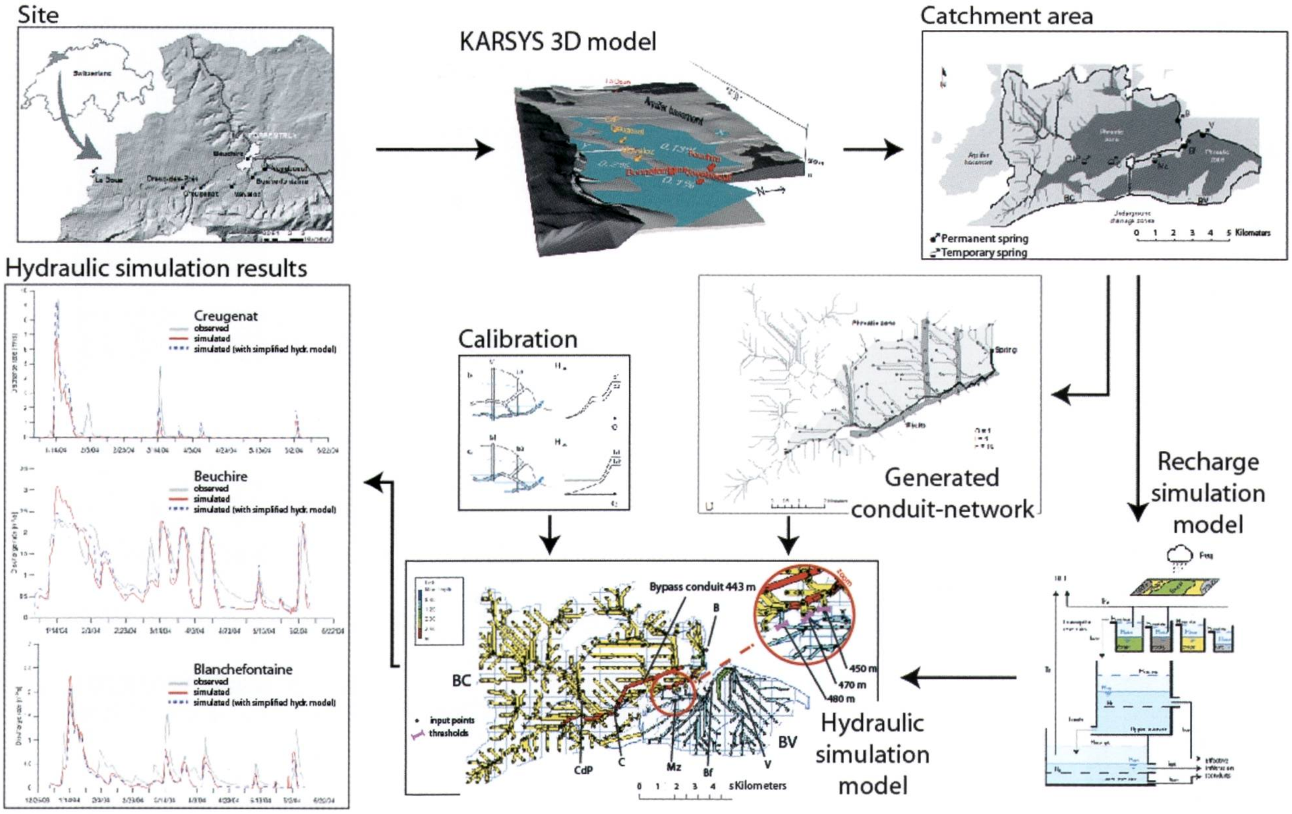

Fig. 4: Workflow for addressing flood related hazards in karst based on the KARSYS approach. The KARSYS 3D model is complemented with a set of specific extensions including (i) groundwater-recharge simulation, (ii) conduit-network generation and (iii) hydraulic simulation in the conduit network.

3.2 Predicting karst-related hazards in tunneling – the Ligerz case study (BE)

The drilling of a safety gallery along the Ligerz tunnel prompted a detailed assessment of karst-related hazards (voids locations, expected size and filling). The gallery develops in the Malm aquifer downstream a major overflow springs, raising a risk to encounter active karst channels with diameters close to 1 m and potential discharge larger than 2 m/s. As inrush of water in the downward section of the drilling would have been problematic for workers and engines, all precautions were taken to manage the risks.

The application of KarstALEA along the drilling trace pointed out zones with a high probability of crossing karst conduits. Their characteristics (morphology, diameter, filling, hydrological regime, etc.) could be assessed as well. This risk assessment is reported along a longitudinal profile (Fig. 5).

In parallel, a monitoring network encompassing the measurement of spring discharge, hydraulic-head in the karst conduits and meteorological data were coupled with a flow simulation model (Fig. 6). The hydraulic forecasts are linked with an alarm which activates at a specified hydraulic head allowing for engineers to anticipate precaution measures before the actual flooding. The simulations are operated at hourly intervals and updated according to meteorological forecasts provided by Meteoswiss.

3.3 Assessing admissibility of geothermal probes: the Fribourg and St.Gallen case studies

In Switzerland, cantons are responsible for authorizing the implementation of geothermal heat probes. They must take reliable and reasoned decisions regarding this authorization but, in practice, often meet difficulties in karst area. Typical concerns include elevated risks of soil and groundwater contamination by the fluids, aquifer bypass, stability of the ground, etc. (Fig. 7). Even in cantons prohibiting geothermal probes in karst areas, the distinction

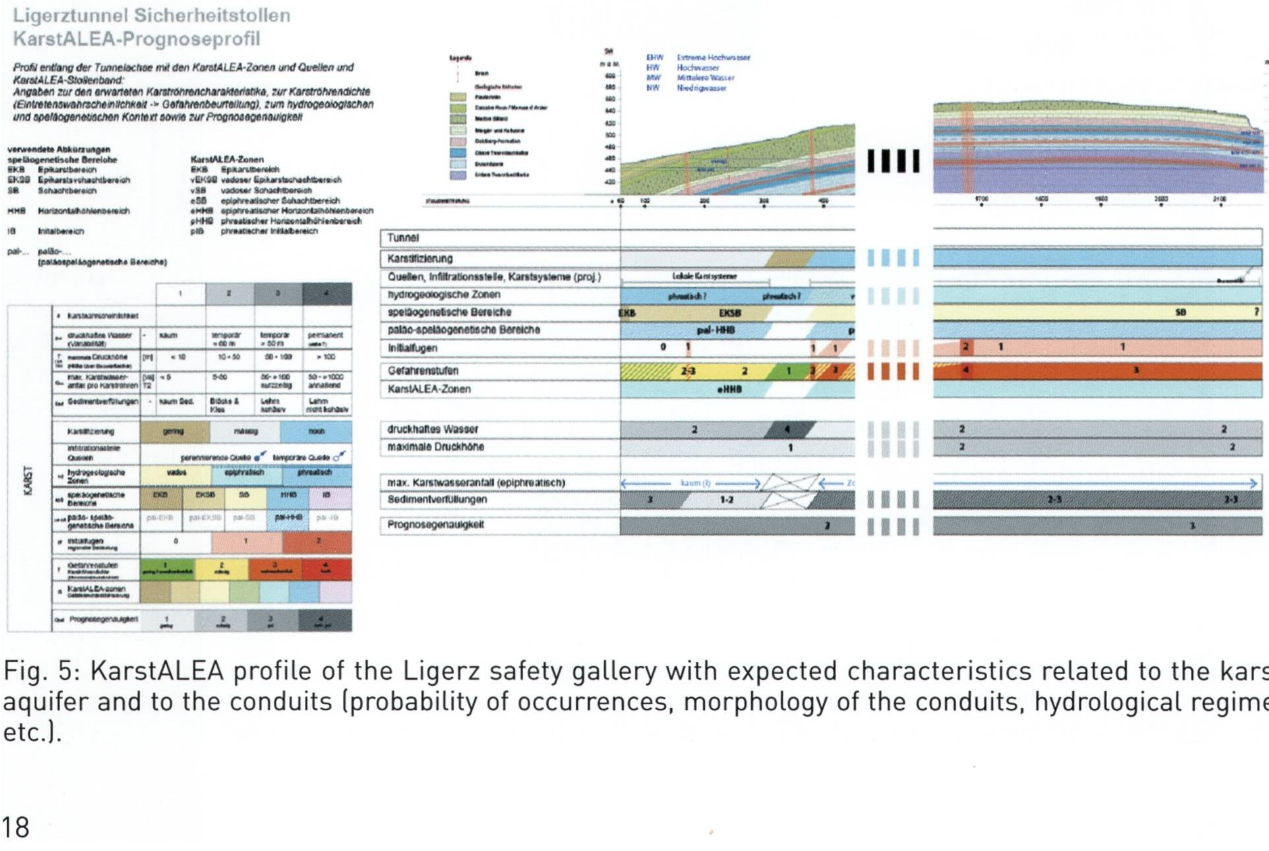

Fig. 5: KarstALEA profile of the Ligerz safety gallery with expected characteristics related to the karst aquifer and to the conduits (probability of occurrences, morphology of the conduits, hydrological regime, etc.).

between karst and non-karst areas remains sometimes difficult because of covering formations or due to the complex organization that results from tectonic arrangement.

KARSYS provides an efficient way to define admissibility criteria in karst environments and to deliver permits in a consistent way. The method has been applied successfully in the cantons of Fribourg (Fig. 8) and St.Gallen (Fig. 9). In both cantons, KARSYS was used to locate (i) the extension and depth of the groundwater bodies (confined or unconfined), (ii) the main drainage directions and (iii) the catchment areas of the main flow-systems. 3D results from the KARSYS model are transferred on GIS-compatible layers (Fig. 10) following formalized guidelines (see in Malard et al. 2014). Risks of by-passes between different aquifer zones or risks of contamination for a determined spring can be identified according to the location and the depth of the probes. The final result includes a series of admissibility maps depicting potential locations and maximal depths for geothermal probes (Fig. 11). The public administrations may use these maps to overlap additional criteria (e.g. infrastructures, biological conservations, etc.) to decide about individual authorizations.

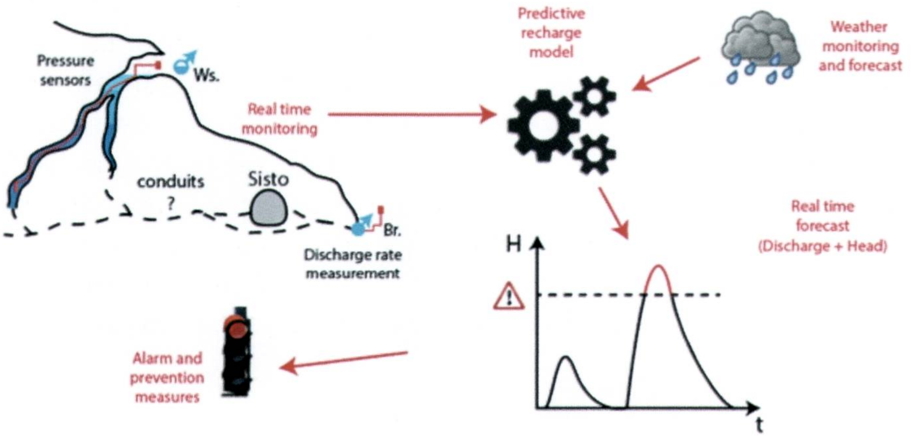

Fig. 6. Simulation model developed for the floods forecast in the Ligerz safety gallery.

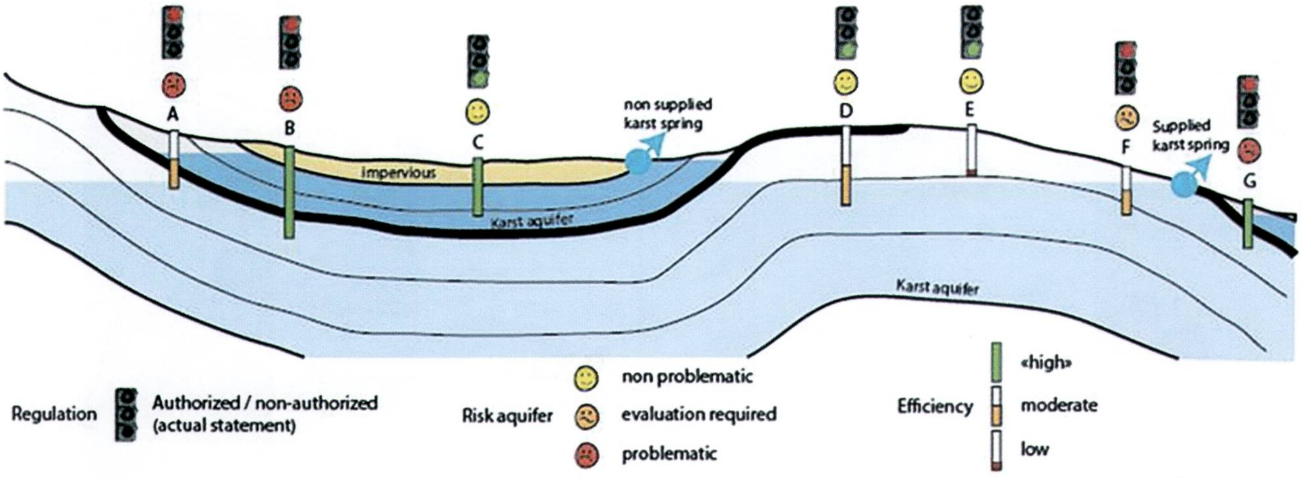

Fig. 7: Various scenarios for the implementation of geothermal probes in karst. Highest efficiency may be obtained in capturing confined aquifers (B; C; G) whereas the vadose zone (E) is typically less favorable. Groundwater protection proscribes connecting several distinct aquifers (A; B; G). The proximity of a karst spring used for drinking water also calls for caution (F) as groundwater contamination may not be excluded.

4 Discussion

KARSYS and its associated extensions provide a novel approach to manage karst environments in a systematic and consistent way. Advantages of KARSYS include:

- Broad applicability: KARSYS can be applied in most karst regions and addresses a large array of karst-related issues.
- Systematic: whatever the site and whatever the issue for which the model has been designed, individual steps and application principles of KARSYS remain the same and results are comparable.
- Explicit: unlike many standard approaches, KARSYS models may be compared on the same basis and are accessible to any users – even with a limited knowledge in hydrogeology.
- Iterative: new data and observations may be explicitly implemented in the conceptual 3D model and compared with modelled features. Alternatively, models obtained by KARSYS may be validated using additional data (for instance dye tracing tests) or hydraulic principles which have not been implemented into the modelling processes.

Although KARSYS reveals consistency from a conceptual point of view, a few limitations

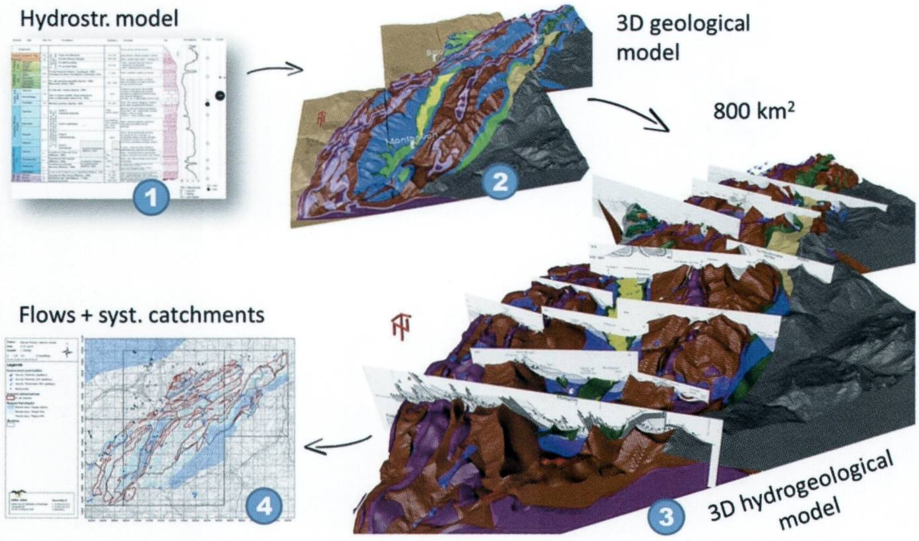

Fig. 8: KARSYS models of the canton Fribourg, ISSKA and GeoAzimut (2014).

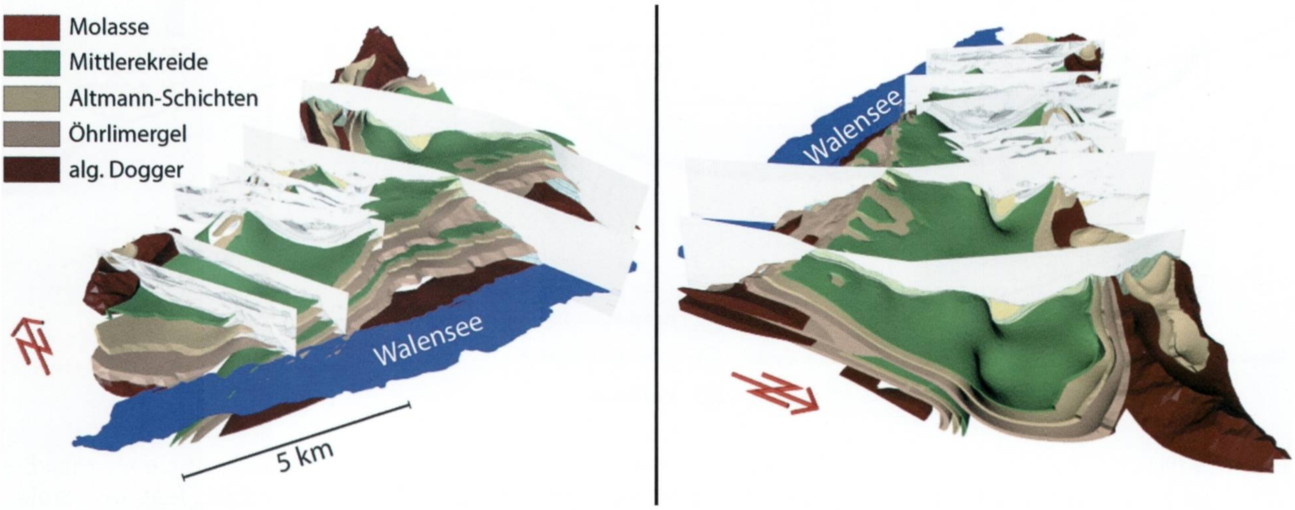

Fig. 9: KARSYS models of the Churfirsten in the canton St.Gallen, Rickerl (2016). (Left: View towards the northeast. Right: View towards the southwest)

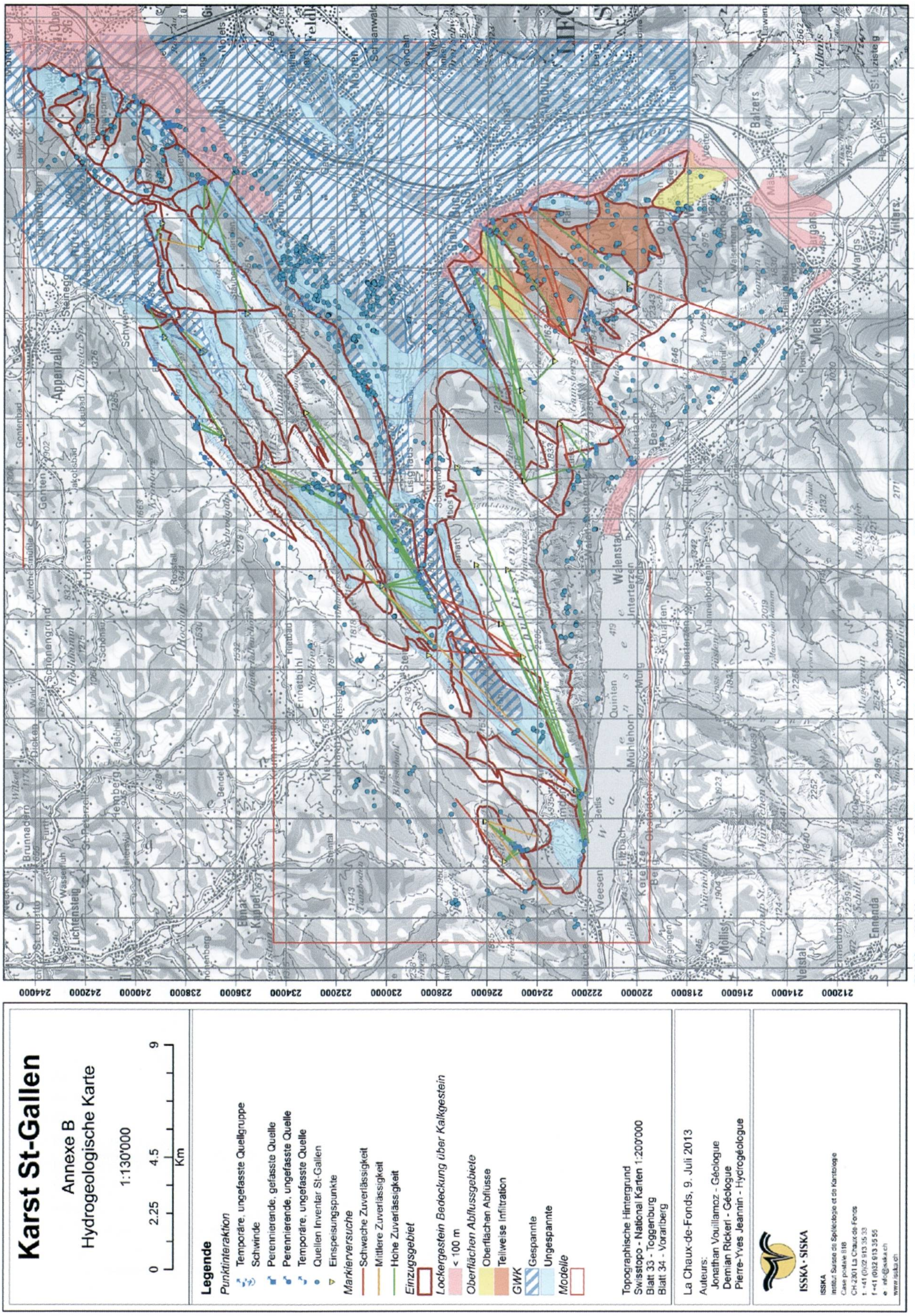

Fig. 10: KARSYS map of the canton St.Gallen (Säntis, Alvier and Churfirsten).

should be mentioned. First, KARSYS has been developed for epigenic karst aquifers in mountainous regions under temperate climate. In its actual form, KARSYS may not reveal fully appropriate to document hypogenic karst aquifers or epigenic karst aquifers in lowland/coastal areas. Applications in these fields would require adjustments.

The reliability of KARSYS is strongly conditioned by the density and the accuracy of the geological and hydrological data. While KARSYS may point out deficiencies or inconsistencies in the dataset, it cannot improve the accuracy of the original dataset. Thus, a special attention must be paid to the selection of the available data – regarding accuracy, scale, etc. The application continuously requires a critical view from the user.

The last limitation is related to the implementation of KARSYS and its different extensions. For now, the workflow requires the use of individual software, some being expensive and complex to use, as well as homemade scripts and routines that are only available at SISKA. To improve efficiency and offer turnkey solutions, SISKA is now developing Visual KARSYS, a web tool dedicated to the exploration, the documentation and the management of groundwater resources in karst aquifers (Malard et al. 2018). Visual KARSYS makes it possible for a large number of users (i.e. modelers) to address specific issues (construction, water supply, geothermic, natural hazards, etc.). At the same time, it makes it possible for end-users to consult and analyze the documentation at a site of interest. Visual KARSYS is available for scientists, engineers, managers and stakeholders facing environmental issues in karst environments worldwide: groundwater resource exploitation and protection, civil engineering projects, geothermal heat probes, natural hazards, waste deposits, etc. The web tool is accessible via the following link: https://visualkarsys.isska.ch/

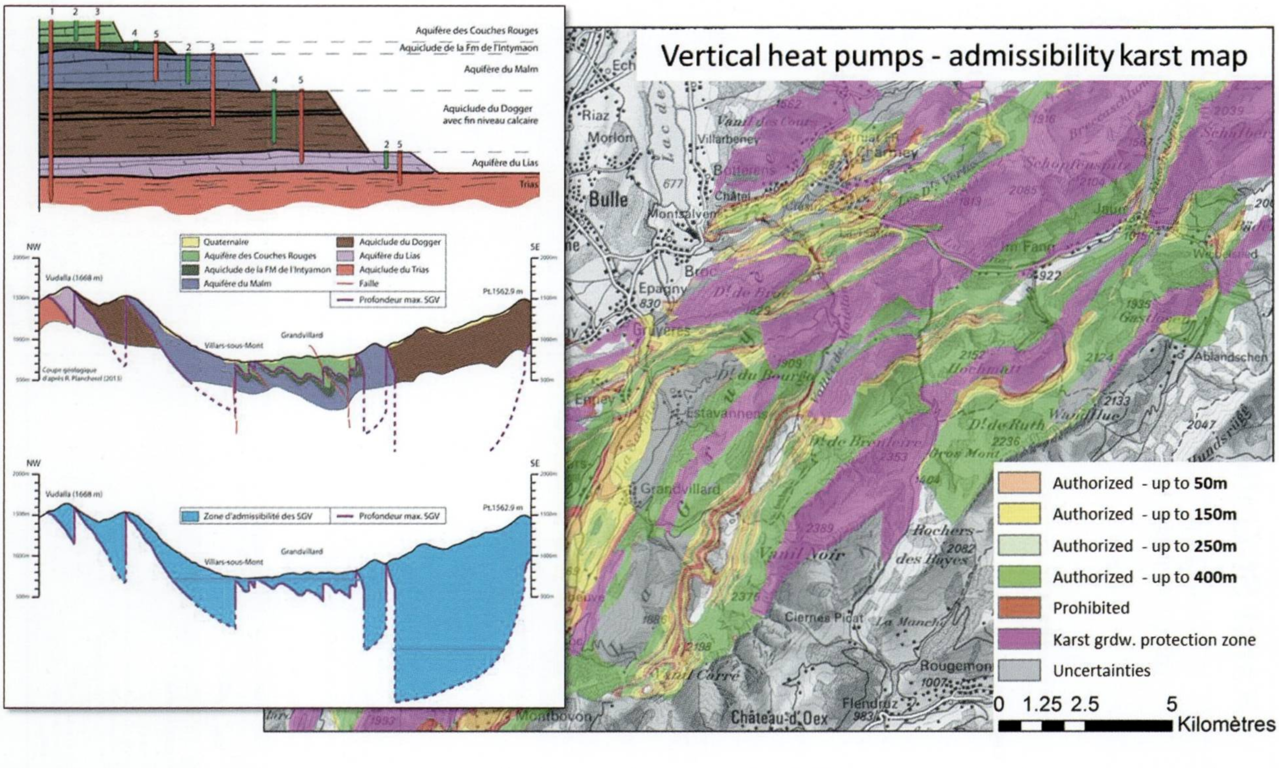

Fig. 11: Overview of the restriction rules (left) and of the pre-admissibility map for the implementation of geothermal probes in karst areas (right) of the canton Fribourg (ISSKA and GeoAzimut 2014).

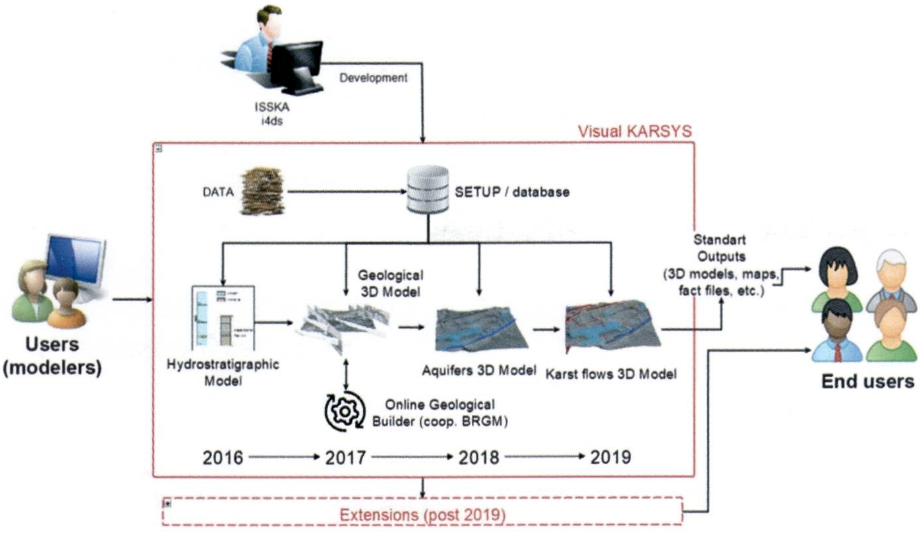

Fig. 12. Workflow of Visual KARSYS; users (Modelers) can process the successive KARSYS models step by step. On the other side, end users can access the documentation results.

5 Conclusion

A sustainable management of groundwater resources and land-use requires specific tools to address the peculiarities of karst environments. KARSYS is a conceptual 3D approach which has been developed to address geological and hydrogeological issues in karst environments. KARSYS makes it possible to describe the general characteristics of the aquifer and of the flow-system in a systematic and pragmatic way. In addition, different extensions have been developed to address specific and recurrent issues (groundwater exploration, tunneling, flood hazards, admissibility of geothermal probes, etc.). KARSYS is now recognized as a «standard» approach in karst environments allowing for different issues to be addressed on a single site with similar background concepts and principles. To encourage the use of KARSYS, SISKA is now developing «Visual KARSYS», a web-tool for modelers and end-users who desire applying KARSYS to make reasoned decisions regarding groundwater or land-use management.

References

Anagnostou, G. & Ehrbar, H. 2013: Tunnelling switzerland. vdf Hochschulverlag AG.

BG Ingénieurs Conseils 2011: Carte des dangers - Haute Ajoie et Mont Terri Sud - Données historiques, unpubl. rep. BG Ingénieurs Conseils.

Bianchetti, G. 1993: Hydrogéologie et géothermie des venues d'eau du tunnel du Rawil (Valais, Suisse). Bulletin du Centre d'Hydrogéologie de l'Université de Neuchâtel, 12: 87-109 p.

Bollinger, D. & Kellerhals, P. 2007: Umfahrungstunnel Twann (A5): Druckversuche in einem aktiven Karst. Bull. angew. Geol, 12/2: 49-61 p.

Bögli, A. 1980: Karst hydrology and physical speleology. Julius Beltz, Hemsbach/Bergstrasse.

Filipponi, M., Jeannin, PY. & Tacher, L. 2009: Evidence of inception horizons in karst conduit networks. Geomorphology, 106: 86-99 p.

Filipponi, M., Schmassmann, S., Jeannin, PY. & Parriaux, A. 2012: Karstalea: Wegleitung zur Prognose von karstspezifischen Gefahren im Untertagbau. Bundesamt für Strassen ASTRA.

ISSKA, GeoAzimut 2014: KARST Fribourg - Carte d'admissibilité pour l'implantation de sondes géothermiques en milieu karstique, unpubl. rep. ISSKA, Rue de la Serre CH-2301 La Chaux-de-Fonds, GeoAzimut, Route de la Fonderie 8, 1705 Fribourg.

Jeannin, PY. 2007: La problématique du karst lors du creusement d'un tunnel. Bull. Angew. Geol, 12/2: 27-38 p.

Jeannin, PY., Eichenberger, U., Sinreich, M., Vouillamoz, J. & Malard, A. et al. 2013: KARSYS: a pragmatic approach to karst hydrogeological system conceptualisation. Assessment of groundwater reserves and resources in Switzerland. Environmental Earth Sciences, 69(3): 999-1013 p.

Jeannin, PY. & Wenger, R. 1993: Grotte du TM 800, tunnel routier de la Vue-des-Alpes. Stalactite, 2: 63-68 p.

Malard, A., Jeannin, PY., Sinreich, M., Weber, E. & Vouillamoz, J. et al. 2014: Praxisorientierter Ansatz zur Kartographischen Darstellung von Karst-Grundwasserressourcen - Erfahrungen aus dem SWISSKARST-Projekt. Grundwasser - Zeitschrift der Fachsektion Hydrogeologie, 19 (4): 237-249 p.

Malard, A., Jeannin, PY., Vouillamoz, J. & Weber, E. 2015: An integrated approach for catchment delineation and conduit-network modeling in karst aquifers: application to a site in the Swiss tabular Jura. Hydrogeology Journal, 23(7): 1341-1357 p.

Malard, A., Randles, S., Hausmann, P., Bucev, M. & Lopez, S. et al. 2018: Visual KARSYS, a web-platform for the documentation of karst aquifers including online geological modelling. Delivering Subsurface Models For Societal Challenges - 4th meeting of the European 3D Geomodelling community, 21st to 23rd February 2018, Orléans, France. 39.

Malard, A., Sinreich, M. & Jeannin, PY. 2016: A novel approach for estimating karst groundwater recharge in mountainous regions and its application in Switzerland. Hydrological Processes, 30(13): 2153–2166 p.

Rickerl, D. 2016: Die Anwendung der Methode KARSYS im Kanton St. Gallen. Stalactite, 66 (2): 14-17 p.

Schneider, TR. 1980: Stauanlage Zeuzier - Geologisch-geotechnisch-hydrogeologische Aspekte der Mauerdeformationen. Eau, énergie, air, 7/8: 193-200 p.

Wildberger, A. 1994: Oelberg-Höhle (Gemeinde Morschach/SZ), unpubl. rep. Arbeitsgemeinschaft Höllochforschung.

Worthington, SRH. 1991: Karst Hydrogeology of the Canadian Rocky Mountain. Mc Master University, Hamilton, Ontario, Canada, PhD dissertation. 370 p.