Ce n'est pas so(u)rcier. Contribution à l'hydrogéophysique; de la mesure géophysique à l'exploration, à l'exploitation et à la gestion durable des ressources en eau souterraine – Approches intégrées

Konstantinos Chalikakis

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HAL Id: tel-03158530

https://univ-avignon.hal.science/tel-03158530

Submitted on 4 Mar 2021

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Habilitation à Diriger des Recherches

Ecole Doctorale 536
Agrosciences et Sciences

Spécialité
Hydrogéophysique-Hydrogéologie

UMR 1114 EMMAH

Ce n'est pas so(u)rcier

Contribution à l'hydrogéophysique; de la mesure géophysique à l'exploration, à l'exploitation et à la gestion durable des ressources en eau souterraine – Approches intégrées

Presentée par
Konstantinos CHALIKAKIS

Soutenue publiquement le 17/12/2020 devant le jury composé de :

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« Ce qu'on le demande à l'hydrogéologue, c'est donc d'abord d'expliquer ce qui se passe dans le sous-sol, puis d'en déduire une estimation d'une ou plusieurs grandeurs intéressant le citoyen ou le scientifique :une réserve, une hauteur d'eau, une concentration, un temps de transfert, par exemple… » (de Marsily G., 1981).

« …
Ithaque t'a offert le beau voyage.
Sans elle, tu n'aurais pas pris la route.
Elle n'a plus rien à te donner.

Et si tu la trouvais pauvre, Ithaque ne t'a pas trompé.
Sage à présent et plein d'expérience,
tu as certainement compris
ce que pour toi Ithaque signifie. »

(K. Kavafis, L'Ithaque, 1911)

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Remerciements

Quelle idée ! Finaliser mon HDR, après quelques années d'hibernation, au milieu de la pandémie de Covid-19… Maintenant, arrivé au bout, je voudrais rendre hommage à tous ceux qui, près ou de loin, ont contribué à mon cheminement de recherche.

Je tiens d'abord à remercier les membres du jury qui, en première ligne, ont accepté de m'accompagner dans cette aventure. Colette, Nathalie, Olivier, Catherine, Olivier et Roger, je vous en suis reconnaissant. Par ailleurs, Roger je m'excuse de ne pas avoir pu tenir une vieille promesse !

Mes travaux de recherche sont le résultat d'un travail collectif en interaction avec les étudiants, les collègues de l'UMR EMMAH et un grand nombre de collègues français et étrangers. Rassurez-vous, je ne remercierai que les essentiels (du moins ceux qui risquent de lire un jour ce document ou juste les remerciements) !

Je tiens à remercier très sincèrement les « roues motrices » de mes travaux, les doctorants et post-doctorants que j'ai (co)encadré /suivi durant mon parcours : Simon, Akis, Naomi, Chloé, Laura, Florian, Fatim-Zara, Angélique et Matthieu. Sans vous les choses auraient avancé beaucoup moins vite ! J'ai beaucoup appris de vous et grâce à vous. J'espère que le bout de chemin, plus ou moins long, que nous avons fait ensemble vous a aussi été profitable. Parmi eux, certain(e)s sont devenu(e)s des excellent(e)s collègues de travail. Ils/elles s'y reconnaitront ! Mes remerciements vont aussi aux nombreux étudiants M1 et M2 qui ont participé activement à mes activités de recherche.

Tout au long de mon parcours scientifique j'ai eu la chance de me retrouver dans des cadres motivants, dynamiques et très variés. Principalement, l'UMR METIS (ex-Sisyphe), l'UMR IGE (ex-LTHE) et depuis 2009 l'UMR EMMAH.

Il faudra saluer et souligner l'importance du cadre de mes activités d'enseignant-chercheur à Avignon au sein de l'équipe HYDRO de l'UMR EMMAH. Naomi, Christophe, Vincent et Vincent, Olivier, Marc, Adriano, Anne-Laure, Marina, Milanca, Roland, Fabienne, Charles et les deux nouveaux arrivants Rémi et Julien, je vous remercie pour cette ambiance de travail agréable et dynamique. J'apprécie beaucoup notre quotidien, nos échanges fructueux et notre solidarité à dépasser les difficultés ensemble. Une pensée spéciale pour Naomi et Christophe avec lesquels nous partageons l'aventure « karst ». Merci pour la belle route cheminée ensemble…j'espère qu'elle sera encore plus longue.

Je ne peux pas me permettre d'oublier mes chers collègues des autres équipes de l'UMR EMMAH : Claude, Albert, Stéphane, Annette, Fred, Marie, André, Line, Dominique, Marta, Lise, Gilles, Gaëlle, Arnault, Frank, Bruno,… et la liste est encore longue ! Je vous remercie pour notre quotidien motivant, dynamique et surtout très enrichissant le long de toutes ces années.

Je tiens à remercier les collègues des SNO H+ et KARST, de l'UMR METIS, de l'UMR IGE et d'ACF pour nos échanges très fructueux et enrichissants. Je ne mentionnerai même pas l'intérêt et le plaisir à faire du terrain ensemble.

Ma vive reconnaissance va aussi à l'équipe du LSBB qui a su toujours aider et assurer avec bienveillance et humour toutes nos demandes techniques ou administratives, parfois compliquées et surtout du dernier moment !

Je garde pour la fin ceux qui me sont les plus chers : mes familles !

D'abord ma famille française : mes très chers Agnès et Denis ! Une pensée spéciale pour Denis qui grâce à ces précieux conseils, sa bienveillance et sa disponibilité aux moments critiques, m'a donné le coup de pouce/pied nécessaire pour finaliser ce manuscrit. Un Grand Merci mon cher Denis.

Ensuite ma grande famille grecque : Maria, George, Despina, Virgo, George, Vivi, Lenia,….. et ce n'est pas tout !

Pour la fin, je tiens beaucoup à remercier ma petite famille grecque du 7bis Rue Saluces, les 3 grands amours de ma vie, mes « sources » d'inspiration et de motivation : Iliana, Yorgos et Virginia. Un très grand merci à vous trois. Je vous ai tellement pris la tête avec cette HDR… Je vous dédie ce travail en vous remerciant de tout mon cœur.

De quoi l'Habilitation à Diriger des Recherches est-elle le nom ? (1/2)

Je me suis longtemps posé de nombreuses questions sur l'utilité et, le sens même, de l'HDR. Quelle est la réelle différence entre quelqu'un qui n'a pas encore soutenu son HDR par rapport à son collègue qui l'a déjà passée ? Qu'apporte cette aventure, qui semble au premier abord inutile, à un chercheur confirmé? Les avis des personnes expérimentées étaient mitigés, parfois troublants. Voici les questions que je me posais avant la rédaction et que je me devais de creuser à comprendre pour trouver la motivation à, enfin, structurer et à rédiger mon mémoire d'HDR.

Qu'est-ce que j'ai appris à la fin de cet exercice, j'avoue, enrichissante ? Attachons nous aux termes.

Diriger les Recherches se déploie, à mon avis, en deux volets. Le premier concerne l'encadrement des jeunes chercheurs.

En avant-propos de ce mémoire d'HDR je me permets de présenter, de façon très informelle (voire détendue) - via une métaphore[1], ma vision de cet encadrement des jeunes chercheurs. Je reviendrai sur le deuxième volet à la fin du mémoire.

Encadrement de jeunes chercheurs

La recherche est le voyage pour l'Ithaque[2]. Un voyage dans des eaux troubles avec beaucoup d'aléas.
Le doctorant ou le post-doctorant est le pilote. Le directeur est la boussole.
Encadrer la recherche signifie:

- Identifier le cap à suivre, qui présente un ou plusieurs intérêts / enjeux majeurs.
- Connaitre la position exacte de départ et faire une estimation du voyage à réaliser.
- Identifier et choisir le navire ayant les capacités techniques adaptées pour la traversée.
- Anticiper au mieux les difficultés rencontrées durant le voyage.
- Assurer la partie logistique avant et durant le voyage.
- Identifier et choisir le pilote en adéquation avec le navire et le cap à suivre.
- L'accompagner durant tout le voyage. Ne jamais le laisser seul. Mais attention, c'est lui qui pilote.
- Lui transmettre toutes les connaissances nécessaires sur les navires, le pilotage et la navigation.
- Le laisser modifier le cap s'il le souhaite. Il peut ne pas toujours faire confiance au cap initialement proposé.
- L'aider à reprendre le cap si besoin. Peut-être que le nouveau cap propose un meilleur voyage.
- Lui apprendre à respecter le temps du trajet.
- Lui apprendre à aimer le voyage et en profiter.
- Apprendre de lui et avec lui. De son regard neuf. De son pilotage. Du voyage parcouru ensemble.
- Utiliser ton réseau de navigateurs pour mieux cartographier les eaux.
- A la fin du trajet le pilote doit être capable d'instruire de nouveaux pilotes. Sinon, il faut retravailler le voyage.
- Ce n'est pas l'Ithaque qui compte. C'est le voyage!

[1] Inspiré de « l'Ithaque » de Konstantinos Kavafis (1911).

[2] Ithaque : l'île d'origine d'Ulysse (Odysseas en grec).

Préambule ou Introduction générale

Les travaux présentés dans ce document d'HDR s'inscrivent dans la problématique générale de la caractérisation des ressources en eau souterraine en vue de leur gestion durable. Ce manuscrit synthétise les travaux de recherche et d'enseignement que j'ai menés depuis l'obtention de ma thèse de doctorat en 2006. Ils sont le résultat d'un travail collectif en interaction avec les doctorants, les post-doctorants, les enseignants-chercheurs et les chercheurs, principalement de l'UMR EMMAH mais aussi avec l'UMR IGE (anciennement LTHE) et l'UMR METIS (anciennement Sisyphe). Pour y arriver j'ai pu également bénéficier des étroites et fructueuses collaborations au travers de partenariats nationaux et internationaux avec un grand nombre de collègues français et étrangers.

Le manuscrit est organisé de la façon suivante:

Pour mieux cerner mon profil je propose de présenter dans une première partie mon parcours scientifique avec un Curriculum Vitae détaillé (formation et parcours professionnel, collaborations et projets nationaux et internationaux, encadrement d'étudiants et publications, rayonnement et animation de la recherche, tâches administratives et d'enseignement). Dans la deuxième partie j'introduirai d'abord au travers d'une brève revue bibliographique l'histoire, l'évolution, et les enjeux de l'hydrogéophysique. Je présenterai ensuite ma vision sur les évolutions qui ont permis l'émergence de l'hydrogéophysique ainsi que la prise en considération de cette sous-discipline transversale. La troisième partie est consacrée à mes activités de recherche qui s'inscrivent aux interfaces des deux grands champs disciplinaires : de l'hydrogéologie et de la géophysique. Je ferai une synthèse (non exhaustive) de ma contribution à la problématique générale autour de deux thèmes qui structurent aujourd'hui mon activité de recherche :

I. Apport de la mesure géophysique aux connaissances hydrogéologiques ; différentes échelles temporelles et spatiales à des milieux géologiques divers.
II. Approches méthodologiques intégrées pour la gestion durable de la ressource en eau en milieux complexes.

Les aquifères karstiques sont les hydrosystèmes privilégiés de mes travaux de recherche. Le manuscrit se conclut avec les perspectives de recherche qui s'ouvrent à court et moyen termes au travers des projets de recherche, d'innovation et de transmission du savoir.

1. CV détaillé

1.1. Synthèse du parcours scientifique 2002-2020

Mes activités de recherche sont à la croisée de l'hydrogéologie et de la géophysique. Géologue de formation, spécialisé en hydrogéologie (Université de Patras / Grèce, 1995-2000) j'ai approfondi mes connaissances en géophysique appliquée (Master 2 de géophysique appliquée (ancien DESS) : 2000-2001) à l'Université Paris 6 (actuellement Sorbonne Université). A la fin de mon DESS et pendant 6 mois, durant le montage des projets pour le financement de ma thèse de doctorat, j'ai suivi l'ensemble des cours du DEA Hydrogéologie-Hydrologie de l'Université Paris 6 afin de renforcer mes connaissances en hydrogéologie et d'obtenir ainsi l'équivalence DEA-DESS qui permettait, à l'époque, l'inscription en thèse. Durant ma thèse de doctorat (2002-2006), au sein de l'UMR Sisyphe (actuellement METIS), j'ai orienté mes recherches sur la reconnaissance et l'évaluation des ressources en eau souterraine des milieux karstiques. Ma thèse de doctorat a consisté à choisir et à appliquer des méthodes et techniques géophysiques apportant le maximum d'informations géologiques et hydrogéologiques, pour diverses régions karstiques présentant des problèmes de ressources en eau. Aux frontières entre la géophysique et l'hydrogéologie, j'ai pu ainsi développer, jusqu'à la fin de ma thèse, une approche pluridisciplinaire et multi-méthodes en hydrogéophysique. Les principaux chantiers liés à ma thèse ont été situés en France (Rocamadour) et en Grèce (Paralio Astros et Loussoi) mais j'ai également été menés à réaliser des mesures de terrain en Jordanie et en Israël, autour de la Mer Morte, sur des formations karstiques en milieux salins.

Six mois avant la fin de ma thèse de Doctorat, j'ai initié l'implémentation de la méthode RMP (Résonance Magnétique des Protons) au Danemark en collaboration avec la compagnie Rambøll, tout en étant le formateur principal des ingénieurs danois. Cette première collaboration avec le monde industriel a permis, entre autres, d'introduire et de confirmer l'utilité de la méthode RMP en tant qu'outil opérationnel pour la caractérisation et l'exploitation des ressources en eau à l'échelle du Danemark. Cette collaboration s'est poursuivie activement durant mes deux années de post-doc au CNRS aussi qu'après l'obtention de mon poste à Avignon Université. Elle a permis à plusieurs de mes étudiants de réaliser des stages ou une première expérience professionnelle au sein de Rambøll.

Suite à la soutenance de ma thèse, j'ai travaillé en tant qu'expert en hydrogéologie et géophysique au sein du réseau ACF (Action Contre la Faim – International Network). J'ai assuré la mise en place d'une méthodologie hydrogéophysique pour l'exploitation des ressources en eau en Ouganda du nord. J'ai aussi assuré la gestion et la formation des équipes WASH (Water Sanitation and Hygiene) d'ACF (27 personnes dont deux ingénieurs expatriés). J'ai également conçu et réalisé un module d'autoformation en prospection hydrogéophysique ; ce module, toujours utilisé pour la formation des ingénieurs ACF, est destiné à rappeler les connaissances hydrogéologiques de base sur les aquifères, à introduire les étapes de la prospection pour l'exploitation durable des ressources en eau potable, et à présenter les méthodes et les techniques de mesures géophysiques actuellement utilisées par ACF. Au retour de mon expatriation, j'ai élaboré un projet de recherche sur le suivi de la qualité des ressources en eau et sa relation avec les populations en déplacement en Ouganda du nord qui a été financé par la Fondation Buffett. La collaboration avec le réseau ACF est restée très active durant la suite de ma carrière et a permis la réalisation de plusieurs projets de recherche ainsi que de nombreux stages d'étudiants d'Avignon Université dans des contextes hydrogéologiques et socio-économiques très diversifiés.

Privilégiant un retour dans le monde de la recherche, j'ai obtenu un post-doctorat CNRS de deux ans (2008-2009) au LTHE (Laboratoire d'étude des Transferts en Hydrogéologie et Environnement) – actuellement IGE (Institut des Géosciences et de l'Environnement) à Grenoble. Mon travail portait sur la caractérisation des paramètres hydrodynamiques des sols saturés ou non par les méthodes géophysiques (électriques, électromagnétiques, RMP). Le suivi des transferts d'eau dans la zone non saturée vers (ou depuis) la nappe était la principale ligne de recherche. J'étais amené à travailler sur plusieurs chantiers expérimentaux très variés ; du Lac Tchad (Diffa, Niger) pour caractériser des aquifères sédimentaires sous climat aride, aux aquifères sédimentaires du Danemark pour leur caractérisation hydrodynamique et au glacier de la Tête Rousse (Chamonix, France) pour localiser des poches d'eau tempérée faisant porter un important risque d'inondations sur les villages en aval du glacier.

La suite de ma carrière scientifique depuis décembre 2009 au poste d'enseignant-chercheur au sein d'Avignon Université et de l'UMR 1114 EMMAH (INRAE-AU), m'a permis d'élargir encore mes activités de recherche en hydrogéophysique au sein de la Zone Critique dans divers milieux géologiques. Je me suis également intéressé à la recharge des aquifères, à leur vulnérabilité aux impacts anthropiques et climatiques et j'ai travaillé pour la mise en place et des suivis hydrogéologiques et hydrogéophysiques à long-termes en vue d'une gestion durable des ressources en eau souterraines.

Au sein d'AU et de l'UMR EMMAH, j'ai démarré mes activités de recherche par la conception et l'encadrement de la thèse de Doctorat de Simon CARRIERE (2010-2014) sur l'étude hydrogéophysique de la structure et du fonctionnement de la ZNS de l'aquifère de la Fontaine de Vaucluse à l'échelle du site expérimental du LSBB (Laboratoire sous terrain à Bas Bruit) à Rustrel. J'ai également participé activement à l'encadrement de la thèse de Laure TORRES-RONDON (2010-2013) sur l'étude et la modélisation des transferts d'eau et de sel en milieu deltaïque agricole en Camargue. J'ai co-encadré aussi les travaux post-doctorat de Naomi MAZZILLI (2011-2012) qui portaient sur la caractérisation des propriétés hydrodynamiques de la zone non saturée du karst : apport des techniques géophysiques (résonance magnétique des protons, électrique et électromagnétique) à l'échelle du bassin de Durzon.

Suite à la thèse de Simon CARRIERE et afin d'élargir l'échelle spatiale de mes travaux de recherche, en 2014 j'ai initié et co-encadré la thèse de Chloé OLLIVIER (2014-2019) qui portait sur la caractérisation et la spatialisation de la recharge des hydrosystèmes karstiques avec une application à l'aquifère de la Fontaine de Vaucluse. Ce travail a permis, entre autres, de consolider la collaboration avec un important partenaire socio-économique régional : le Syndicat Mixte de Bassin des Sorgues (SMBS). J'ai encadré en parallèle la recherche post-doctorale de Simon CARRIERE (2014) au sein d'ACF sur l'exploitation durable des ressources en eau dans des milieux carbonatés en zones arides (sud-ouest de Madagascar et nord-est d'Haïti) et j'ai piloté la recherche post-doctorale de Nerantzis KAZAKIS (2018) au sein de l'UMR EMMAH sur les outils de gestion des aquifères karstiques en Grèce.

En parallèle de cette période d'encadrement de la recherche j'ai également participé au montage et à la mise en place des nombreux projets de recherche en France et à l'international qui, ancrés sur les axes thématiques d'AU et de l'UMR EMMAH, ont permis de nouer et consolider plusieurs collaborations académiques en France et à l'international, ainsi que des collaborations industrielles (TOTAL, ANDRA, OCP-Maroc, Danone Waters, Vikos Waters). En 2017, j'ai réalisé un séjour de recherche de deux mois, financé par AU, à l'Université de Thessaloniki et à l'Ecole Polytechnique d'Athènes (Grèce). Ce séjour a permis le montage d'un projet européen que je coordonne actuellement et d'un projet industriel.

Au total, depuis 2005 j'ai participé activement à 10 projets scientifiques internationaux (dont 3 en tant que responsable), 9 projets nationaux (dont 3 en tant que responsable) et 6 projets/collaborations industrielles (dont 3 en tant que responsable).

L'ensemble de mes travaux de recherche m'ont conduit à effectuer des missions de terrain (parfois plus d'un mois) sur des aquifères karstiques (France, Italie, Grèce, Israël, Jordanie, Palestine, Algérie, Maroc et Madagascar), des aquifères sédimentaires au Danemark, en France, au Niger et au Panama et des aquifères de socle en Ouganda, au Kenya, au Burkina Faso, au Benin et à Madagascar. Ces travaux visant à répondre à des problématiques hydrogéologiques et socioéconomiques différentes, diverses approches couplant plusieurs outils hydrogéologiques et géophysiques ont été développés et employées.

Néanmoins le travail d'un enseignant-chercheur nécessite aussi une forte implication en direction des responsabilités pédagogiques et collectives et les tâches administratives. Ainsi, en septembre 2012 j'ai pris la responsabilité de la licence L3 SVT. A ce titre j'ai coordonné sa restructuration en Licence Terre et Eau (STE). En mai 2013, j'ai laissé la responsabilité de la L3 STE pour piloter le nouveau Cursus Master en Ingénierie (CMI) parcours Agro-Hydrosystèmes (actuellement intitulé Ressources en Eau et Environnement – R2E) dont je suis toujours le responsable. Cette formation d'excellence en 5 ans, en effectif d'étudiants réduit et très exigeante, est adossée à des laboratoires de recherche et elle a été la première formation accréditée par le réseau Figure au sein d'AU. Soucieux de l'importance de la pédagogie innovante par la recherche j'ai monté un consortium et je coordonne actuellement un projet international (France, Grèce, Bulgarie et Belgique) d'innovation pédagogique ERASMUS+ sur l'utilisation des plateformes open-sources pour l'enseignement supérieur en SIG (Systèmes d'Informations Géographiques) liant l'Eau, les Agrosciences et la Santé.

En parallèle de mes tâches pédagogiques, je me suis aussi engagé dans l'animation de la recherche depuis ma prise de fonction. Ainsi depuis février 2010 et jusqu'à janvier 2016 j'ai co-animé avec Frédéric BARET (INRAE) l'axe 2 de l'UMR EMMAH intitulé « Description des paysages et de leur évolution ». A ce titre j'ai participé activement à la rédaction du rapport d'activités de l'UMR EMMAH et de son nouveau projet quadriennal (2017-2021). Depuis janvier 2016, j'ai participé au montage et pendant un an à la co-animation de la nouvelle équipe « Hydro » de l'UMR EMMAH. Optant pour une co-animation tournante au sein de cette nouvelle équipe j'ai repris la co-animation en janvier 2020 pour une période d'un an. Depuis 2015, je suis le responsable du site du LSBB pour le réseau d'observation de sites hydrologiques SNO H+. Depuis 2016, je suis membre du CDST (Comité de Direction Scientifique et Technique) de l'UMS (Unité Mixte de Service) LSBB. Depuis 2014, je suis membre de l'International Scientific Council (ISC) d'ACF et depuis 2016 membre du Conseil Scientifique de la Fondation ACF pour la Recherche et l'Innovation sous l'Egide de l'Institut de France. En 2019 j'ai été élu au Conseil Académique d'AU et je suis membre de la Commission Recherche. A ce titre, en 2020, j'ai coordonné la procédure de recrutement d'un nouveau MCF au sein du département d'Hydrogéologie. En octobre 2019, j'ai été invité par la NSGD (Near Surface Geosciences Division) de l'EAGE (European Association of Geoscientists and Engineers) à organiser et coordonner (chairman) la 1ère conférence internationale en Hydrogéophysique qui aura lieu en 2021.

1.2. Curriculum Vitae

Identification

CHALIKAKIS Konstantinos

Date de naissance : 31/03/1977

Poste actuel : Maître de Conférences depuis le 01/12/2009

Etablissement d'affectation : Avignon Université (AU), Département d'Hydrogéologie

Section de CNU : 35

Unité de recherche d'appartenance : UMR 1114 EMMAH (Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes) INRAE-AU, équipe HYDRO.

Formation

2002-2006	**Thèse de Doctorat en Hydrogéophysique**, Ecole Doctorale « Géosciences et Ressources Naturelles », Univ. Paris 6, intitulée : « Application des méthodes géophysiques à l'exploration et la protection des ressources en eau dans les milieux karstiques ».
2000-2002	**Master 2 (ex-DESS) en Géophysique Appliquée** Université Paris 6 (Pierre et Marie Curie). Suivi des cours Master 2 (ex-DEA) Hydrologie-Hydrogéologie Université Paris 6 (Pierre et Marie Curie).
1995-2000	**Diplôme de Géologie**, Université de Patras (Grèce). Spécialisation Hydrogéologie.

Carrière Scientifique et Professionnelle

Depuis déc.. 2009	**Enseignant-Chercheur (Maître des Conférences),** Avignon Université, France. Hydrogéologie – Hydrogéophysique. Section CNU 35.
2007-2009	**Chercheur (Post-doc) CNRS (LTHE – Grenoble, France);** Caractérisation des paramètres hydrodynamiques des ressources en eau souterraines à des différents contextes géologiques (Pourtour Méditerranéen et Afrique de l'Ouest).
2006-2007	**Expert en hydrogéologie-hydrogéophysique, ACF-USA** (Action Contre la Faim – International Network); Exploration et gestion des ressources en eau souterraine - Ouganda du nord (dont 7 mois en expatriation). Manager et responsable de formation des équipes WASH (Water Sanitation and Hygiene)-(prospection, foration and développement des points d'eau - 27 pers.).

2004-2006	**Chef sommelier (dégustation et œnologie),** musée du Vin de Paris, France; Conférences et dégustation, visite guidées du musée, vin et géologie. Manager de 4 pers. permanents et 6 non-permanents.
2003-2004	**Jeune chercheur,** Université d'Athènes (Grèce) dans le cadre du projet PAI (Programme d'Action Intégrée) – PLATON (France-Grèce); Hydrogéophysique du karst.

1.2.1. Activités et Responsabilités Scientifiques

Projets scientifiques[3] et responsabilités associées

Projets nationaux :

1. **PiKarstEau** - AAP d'Excellence 2017 AU. Budget alloué: 10K€ : Compréhension des propriétés hydrodynamiques des hydrosystèmes karstiques ; approche innovante couplant hydrodynamique et hydrochimie-isotopique - Observatoire du LSBB-Fontaine de Vaucluse. *Co-responsable et coordinateur du projet.*
2. **WIK**–Région PACA (2015-2017). Budget alloué (Cofinancement des équipements): 150K€ : Wells in Karst. *Responsable du volet hydrogéophysique (choix et achats des appareils).*
3. **PHYDROMED**–Région PACA (2010-2013). Budget alloué (Cofinancement des équipements): 100K€ : Caractérisation multi-Physique des HYDROsystèmes carbonatés MEDiterranéens. *Responsable du volet hydrogéophysique (choix et achats des appareils).*
4. **EQUIPEX – CRITEX** (2012-2021) : Parc national d'équipements innovants pour l'étude spatiale et temporelle de la Zone Critique des Bassins Versants. *Coordinateur des actions hydrogéologiques et géophysiques pour le bassin de Fontaine de Vaucluse et le site du LSBB.*
5. **ANR HYDROKARSTG2** (2008-2012) : Etude de la dynamique 4D de l'eau dans le karst par une approche géodésique et géophysique. *Co-responsable du volet Résonance Magnétique des Protons*
6. **BQR – UAPV** (2010). Budget alloué: 6K€ : Couplages Hydro-magnétiques en milieu bas bruit. *Responsable du projet.*
7. **ECCOREV – CNRS** (2010-2011) : Etude et caractérisation des eaux souterraines des causses du Moyen Atlas par couplage de mesures isotopiques, électriques et électromagnétiques multi-échelle. Région de Fès-Meknès (Maroc). *Responsable du volet hydrogéophysique.*
8. **WATERSAN – volet karst** (2005-2006) : Géophysique appliquée à l'étude des systèmes karstiques *Organisation et réalisation de missions géophysiques régulières en France (2 missions de terrain de 20 jours par an).*
9. **HYKAR du ECCO/PNRH** (2004-2005) : Description géophysique de karst par la méthode de résonance magnétique des protons (RMP). *Organisation et réalisation de missions géophysiques régulières en France (2 missions de terrain de 20 jours par an).*

[3] Le budget n'est mentionné que pour les projets pour lesquels j'ai participé à leur gestion financière.

Projets internationaux :

1. **FuseGI – Projet ERASMUS+** (2019-2022). Financement Agence Erasmus+. Budget alloué : 388 k€. https://ec.europa.eu/programmes/erasmus-plus/projects/eplus-project-details/#project/2019-1-FR01-KA203-062767 : Cooperation for fusing skills on Cloud-based Open Geoinformatics: Innovative Environmental Management. *Coordinateur et responsable du projet.*
2. **ITN** (Innovative Training Network) **ENIGMA** (European training Network for in situ imaGing of dynaMic processes in heterogeneous subsurfAce environments) (2016-2020) – Projet Européen. https://enigma-itn.eu/. *Coordinateur des actions pour le site du LSBB au sein du réseau ITN.*
3. **SIWA** (2016). Financement ACF. Budget alloué : 38K€ : Mise en place d'un observatoire hydro-climatique sur le plateau karstique de Mahafaly (sud-ouest de Madagascar). *Coordinateur et responsable scientifique du projet*.
4. **PHC Toubkal** (coopération France-Maroc) (2015-2017). Budget alloué : 20K€ : Alimentation groupée en eau potable dans le monde rural (région de Marrakech-Haouz-Tensift): prospection des ressources, étude des installations de stockage et de distribution et place des organisations non gouvernementales. *Formateur sur la méthode de la RMP (Résonance Magnétique des Protons) et missions de terrain au Maroc.*
5. **Ressources en Eau à Madagascar** (2014). Financement ACF-UAPV. Budget alloué : 80K€ : Exploration et exploitation des ressources en eau du plateau de Mahafaly (sud-ouest de Madagascar). *Coordinateur et responsable scientifique du projet. Montage des missions de terrain. Post-doctorat de S. Carrière.*
6. **GroundWater et Quality Monitoring (GWQM)** – ACF / W. Buffett Foundation (2008-2011) : Suivi temporel des ressources en eau potable au nord d'Ouganda et sa liaison avec les populations en déplacement. *Concepteur du projet et responsable scientifique.*
7. **PHC Volubilis** (2010-2012) : Les Ressources en eau dans la région de Marrakech. Prospection, caractérisation, sources de pollution, périmètreσ de protection. Apport de l'outil géophysique. *Mise en place de la RMP (Résonance Magnétique des Protons) et formation des équipes marocaines.*
8. **PSP Lac Tchad – volet géophysique** (2007-2009) : Recharge des ressources en eau souterraine autour du Lac Tchad, approche hydro-géophysique. *Mise en place d'une méthodologie d'exploration géophysique, planification et réalisation des missions de terrain au Niger*.
9. **Security through science, science for peace** (2005-2007) : Financement OTAN **:** Effondrements de terrain autour de la Mer Morte, apport de la RMP. *Organisation et mission de terrain géophysique-hydrogéologique en Proche-Orient (Israël-Palestine-Jordanie) en octobre-novembre 2005.*
10. **PAI-Platon** (2003-2005). Financement France 11 k€ : Applications des nouvelles approches géophysiques et hydrogéologiques à la recherche et la protection des ressources en eau dans les milieux karstiques. *Organisation et réalisation de missions géophysiques et hydrogéologiques régulières en Grèce (3 missions de terrain de 20 jours par an).*

Collaborations industrielles :

1. **ANDRA** (2020-2022). Financement thèse de Mathieu BERTRAND. Collaboration ANDRA / AU / Univ. Franche-Comté. Budget total 330 k€. Budget alloué à AU 82 k€. Caractérisation des propriétés hydrogéologiques des calcaires de Barrois ; approche couplée hydrochimique et

hydrogéophysique. *Codirecteur de la thèse, coordination en hydrogéophysique, responsable du budget alloué à l'AU.*

2. **VIKOS Water** (2018-2019). Coordination Univ. de Thessaloniki. Compréhension des propriétés hydrauliques de l'aquifère karstique de Vikos pour l'exploitation durable de ses ressources en eau. *Conseiller scientifique du projet – responsable du volet vulnérabilité à la pollution.*
3. **APPHOS** (2016-2019). Financement Groupe OCP-Maroc. Budget alloué 188K€. Nouvelles techniques d'exploration géophysique pour la cartographie sous couverture des zones dérangées de la série phosphatée dans les gisements des Ouled Abdoun, la caractérisation de sa structure sous la plaine de Tadla et l'étude des ressources hydriques qu'elle encaisse dans les sites miniers de Youssoufia, Benguérir et Khouribga. *Coordinateur des missions hydrogéologiques et des campagnes RMP (Résonance Magnétique des Protons) au Maroc pour les équipes françaises de recherche (AU, UPMC). Co-encadrement de la thèse de Fatim-Zahra ISBACH.*
4. **Interwells 4D** (2014-2019). Financement TOTAL. Budget alloué : 179 k€. Caractérisation méso-échelle des propriétés hydrogéologiques entre forages. *Membre du comité de pilotage. Co-responsable des actions scientifiques menées par l'AU. Co-gestionnaire du budget alloué à l'AU.*
5. **RMP –ANDRA** (2013-2017). Financement ANDRA. Budget alloué : 125K€. Caractérisation de la structure et du fonctionnement hydrogéologique des Calcaires du Barrois par la Résonance Magnétique des Protons. *Coordinateur et co-responsable scientifique. Gestionnaire du budget alloué. Une mission de terrain de 15j/an à Bure.*
6. **Introduction de la Résonance Magnétique des Protons (RMP) au Danemark (2006-2011).** Mise en place et adaptation de la méthode RMP au Danemark. Relations des paramètres obtenus avec les propriétés hydrogéologiques des aquifères sédimentaires. *Co-initiateur du projet, formateur des équipes danoises et conseilleur scientifique.*

Participation à des conseils scientifiques

Depuis 2019 : Membre élu du Conseil Académique d'AU.

- *Membre de la Commission Recherche*
- *Membre de la Commission Recherche Double Parité*
- *Membre du Conseil Académique*
- *Membre du Conseil Académique restreint aux enseignants-chercheurs*

Depuis 2016 : Membre du Conseil Scientifique de la Fondation ACF pour la Recherche et l'Innovation sous l'Egide de l'Institut de France (http://isf.actioncontrelafaim.org/fondation.php)

- *Evaluation des projets de recherche appliquée ayant répondu aux appels d'offre de la Fondation*
- *Budget alloué à des projets de recherche en moyen/an : 400 à 300 K€*
- *Deux réunions par an à l'Académie des Sciences à Paris*
- *Je suis le rapporteur principal des projets en WASH (Water Sanitation and Hygiène)*

Depuis 2016 : Membre du CDST (Comité de Direction Scientifique et Technique) de l'UMS (Unité Mixte de Service) LSBB (Laboratoire Souterraine à Bas Bruit) (https://lsbb.cnrs.fr/)

- *Réunions mensuelles pour la coordination, la mise en priorité et le suivi des projets au sein de l'UMS*
- *Je suis le coordinateur des actions hydrogéologiques et hydrogéophysiques*

Depuis 2014 : Membre de l'International Scientific Council (ISC) d'ACF (Action Contre la Faim-International Network) (http://www.actioncontrelafaim.org/)

- *Support scientifique et orientation stratégique et éthique pour la recherche appliquée au sein du réseau*
- *Deux à trois réunions de deux jours par an aux sièges du réseau (Paris, New York, Madrid, Londres)*
- *Je suis le correspondant des actions de recherche en WASH (Water Sanitation and Hygiène) au sein du réseau*

Animation de la recherche

2020 – 2022 : Membre du comité de coordination de Hydrogeophysics Special Interest Community de l'EAGE (https://prod.eage.org/en/membership/special-interest-communities/hydrogeophysics).

- *Promotion des actualités de recherche en hydrogéophysique*

Depuis 2015 : Responsable du site expérimental de recherche LSBB pour le SNO H+ (http://hplus.ore.fr/lsbb)

- *Coordination des actions de recherche en hydrogéologie et géophysique sur le site expérimental du LSBB*
- *Gestion du budget annuel alloué (en moyen depuis 2015 ~10 K€)*
- *Rapport annuel des activités d'observation et programmation des actions pour l'année suivante*
- *Deux réunions par an au sein du SNO H+*

Janvier – Décembre 2020 : co-animation de l'équipe « Hydro » au sein de l'UMR 1114 EMMAH

- *Réunions mensuelles pour la coordination et le suivi des projets au sein de l'UMR*
- *Organisation des séminaires et réunions d'équipe*
- *Préparation du rapport d'activités et du nouveau projet quadriennal de l'UMR*

Janvier 2016-Janvier 2017 : co-montage et co-animation de la nouvelle équipe « Hydro » au sein de l'UMR 1114 EMMAH dans le cadre de sa restructuration pour le nouveau quadriennal (2017-2021).

- *Participation à la rédaction du rapport d'activités et du nouveau projet quadriennal de l'UMR*
- *Mise en place de la nouvelle gestion budgétaire de l'équipe Hydro*
- *Organisation des séminaires et réunions d'équipe*

Février 2010-Janvier 2016 : co-animation de l'axe 2 de recherche de l'UMR 1114 EMMAH, intitulé : Description des paysages et de leur évolution. (http://www4.paca.inra.fr/emmah/)

- *Réunions mensuels pour la coordination et le suivi des projets au sein de l'UMR*
- *Organisation des séminaires et réunions d'équipe*
- *Préparation du rapport d'activités et du projet quadriennal de l'UMR*

Conférences internationales

- **Chairman** de la **1ère Conférence Internationale en Hydrogeophysics** (https://eage.eventsair.com/nsg2021/1st-conference-on-hydrogeophysics) au sein de la Near Surface Geoscience Conference and Exhibition en 2021 à Bordeaux organisée par (European Association of Geoscientists and Engineers - https://eage.org/).
- **Membre du comité scientifique GEOFCAN 2021** (initialement prévu en 2020). (https://geofcan.inrae.fr/geofcan-2021/organisation/)
- **Keynote speaker** au sein de l'**International Conference on Phosphates (ICP) Octobre 2020**. Phosphates Research Network 12-17 Octobre 2020 (https://www.phoresnet.org/team-group/keynotes-speakers-icp2020/)
- **Organisation et Co-chairman** (avec Roger GUERIN et Lee SLATER) de la session 8.07 "Hydrogeophysics: innovative non-invasive technologies for groundwater resources exploitation

and management" du **43rd International Association of Hydrogeologists (IAH)**, à Montpellier, 26 au 29 septembre 2016 (http://www.60iah2016.org/en/)

- **Chairman** de la session "Geophysics" de la conférence **Eurokarst 2016**, à Neuchatêl (Suisse), 5 au 7 septembre 2016. (www.eurokarst.org/)
- **Membre du comité scientifique** de la conférence **i-DUST** (Inter-Disciplinary Underground Science and Technology) à Apt, 5 - 7 mai 2014. http://www.i-dust.org/component/content/article/9-news/223-i-dust-2014-5-7-may-2014-apt-provence-france
- **Membre du comité scientifique** de la conférence **i-DUST** (Inter-Disciplinary Underground Science and Technology) à Apt, 8 - 11 mai 2012.
- **Membre du comité scientifique** de la **9th International Hydrogeological Congress / 4th MEM Workshop of the hydrology in fissured rocks 2011**, Kalavrita, Greece (5-8 October 2011).

Evaluateur - expert

- **Décembre 2015-Janvier 2016 :** Evaluateur du projet GRIBA (Groundwater Resources in Basement rocks of Africa) implémenté sur 3 pays africains (Benin, Burkina Faso et Ouganda). Le projet GRIBA a été piloté par l'IRD et a été financé par l'Union Européenne et l'Union Africaine (Grant contract: AURG/098/2012 et CRS identification number: 2012/288-961).
- **Novembre 2015 :** Evaluateur du projet GEODIAMETRIS. Le projet a été piloté par TEI de Crète (Grèce) et co-financé par l'Union Européenne et l'Etat grec (projet Thalès).
- **Depuis 2012 :** Evaluateur des projets scientifiques IRG (Individual Research Grants) pour l'ISF (Israël Science Foundation). *J'ai rapporté 2 projets en 2013 et un projet en 2016.*
- **Mai 2012 :** membre externe du comité d'évaluation du Département de Géologie de l'Université de Patras-Grèce.
- **Octobre 2010 :** expert invité par le Ministère de l'Environnement du Danemark pour la mise en place de la méthodologie d'évaluation des ressources en eau par la méthode de la Résonance Magnétique des Protons (RMP)

Membre des comités de sélection

- Au sein d'Apella (https://apella.minedu.gov.gr/en), entre **2013 et 2018** j'ai participé à **9 comités de sélection** pour le recrutement des « Assistant Professor » et des « Associate Professor » pour des Universités en Grèce : *En **juin 2013** pour un poste d'Assistant Professor à l'Université de Thraki ; En **janvier 2014** pour un poste d'Assistant Professor à l'Université de Patras ; En **septembre 2014** pour un poste d'Associate Professor à l'Université Technologique de Crète ; En **novembre 2014** pour un poste d'Assistant Professor à l'Université Technologique de la Grèce de l'Ouest ; En **septembre 2015** pour un poste d'Associate Professor à l'Ecole Polytechnique d'Athènes ; En **février 2016** pour un poste d'Assistant Professor à l'Université d'Egée ; En **juin 2016** pour un poste d'Assistant Professor à l'Université Technologique de Crète ; En **juin 2017** pour un poste d'Assistant Professor à l'Ecole Polytechnique d'Athènes ; En **septembre 2018** pour un poste d'Assistant Professor à l'Université de Thraki. En **juin 2019** pour d'un poste Associated Professor à l'Ecole Polytechnique d'Athènes.*

- **Depuis 2012** : membre des experts de la section 35 de l'UPMC (Paris 6) ; ***Avril –mai 2013*** *membre de la commission de recrutement d'un poste de MCF à l'UPMC.*
- **2013, 2014, 2016, 2017, 2019 :** *Membre du comité de sélection d'ATER pour AU – Département d'Hydrogéologie*

Accueil collaborateurs scientifiques internationaux

- **Septembre 2019:** Accueil du Pr. Jacob Juul Larsen (Université d'Aarhus-Danemark) : *travaux communs relatifs à la réduction du bruit électromagnétique pour le traitement des signaux de Résonance Magnétique des Protons (RMP)* dans le cadre du programme de mobilité entrante courte durée de l'UA.
- **Septembre – décembre 2016 :** Pr. K. Voudouris de l'Université de Thessaloniki (Grèce) : *Echanges sur les outils méthodologiques hydrogéologiques développés notamment concernant la vulnérabilité des aquifères.*
- **Mai 2013 et Mars 2014 :** Pr. Habib Azzaz de l'Université de Mascara (Algérie) : *Mise à jour technologique pour l'exploration des ressources en eau en milieux karstiques.*

Reviewer (1 à 3 articles par an)

Journal of Hydrology, Hydrogeology Journal, STOTEN, Journal of Applied Geophysics, Near Surface Geophysics, Geophysics, Catena, Environmental Earth Sciences, Wetlands, Geologica Belgica, Comptes Rendus Géosciences, Water, Geosciences.

Hydrogéologue Agréé par le Ministère de la Santé

- **2016-2021 :** pour le département des Alpes de Haute-Provence (04). (1 à 2 avis sanitaires/an)
- **2017-2022 :** pour le département du Gard (30), suppléant du coordonnateur. (3 à 4 avis sanitaires/an)

1.2.2. Encadrement Doctoral et Scientifique

Mon encadrement doctoral et scientifique se résume en :

- Co-encadrement de **5 thèses de doctorat** (dont 2 en tant qu'encadrant principal et une en co-direction) et **de trois post-doctorats** (dont 2 en tant qu'encadrant principal).
- Participations **à 8 jurys de thèses** et à **11 comités de pilotage de thèses**.
- Co-encadrement de **13 stages de M2** (dont 7 l'encadrant principal), et de **2 stages de M1** (encadrant principal).

Co-encadrement Post-doctorat

1. **Nerantzis KAZAKIS (AU, bourse Institut Français d'Athènes), 2018 :** Gestion durable des aquifères karstiques de la Grèce. *(80 % encadrement)*
2. **Simon CARRIERE (AU/ACF, financement AU/ACF), 2014 :** Exploitation durable des ressources en eau dans des milieux carbonatés en zones arides (sud-ouest de Madagascar et nord-est d'Haïti). *(80 % encadrement)*
3. **Naomi MAZZILLI (Univ. Montp.II, IRD, financement ANR), 2011-2012:** Caractérisation des propriétés hydrodynamiques de la zone non saturée du karst ; Apport des techniques géophysiques (résonance magnétique des protons, électrique et électromagnétique) à l'échelle du bassin de Durzon. *(30 % encadrement)*

Co-encadrement doctoral

1. **Mathieu BERTRAND (Univ. Franche-Comté, financement ANDRA) 2019 - :** Caractérisation des propriétés hydrogéologiques des calcaires de Barrois ; approche couplée hydrochimique et hydrogéophysique *(40% de co-direction)*
2. **Fatim-Zara ISBACH (Univ. Cadi Ayyad à Marrakech, financement OCP), 2016-2020 :** Utilisation combinée des méthodes TDEM et MRS pour caractériser la géométrie de la série phosphatée et du système aquifère crétacé qu'elle encaisse : application aux gisements phosphatés de Khouribga, Youssoufia et Ben Guérir (Maroc) *(30 % encadrement)*
3. **Chloé Ollivier (AU, financement Région PACA), 2014-2019 :** Caractérisation et la spatialisation de la recharge des hydrosystèmes karstiques : application à l'aquifère de la Fontaine de Vaucluse. *(50 % encadrement)*
4. **Simon CARRIERE (AU, bourse ministérielle), 2010-2014 :** Etude hydrogéophysique de la structure et du fonctionnement de la ZNS du karst-Application au site expérimental du LSBB. *(70 % encadrement)*
5. **Laura TORRES-RONDON (AU, bourse état Vénézuélien), 2010-2013 :** Etude et modélisation des transferts d'eau et de sel en milieu deltaïque agricole (Camargue-France). *(30 % encadrement)*

Participation à des Jurys de Thèse de Doctorat

1. **Chloé OLLIVIER, 27/05/2019, Avignon Université:** Caractérisation et la spatialisation de la recharge des hydrosystèmes karstiques : application à l'aquifère de la Fontaine de Vaucluse. *Co-encadrant*
2. **Arnaud WATLET, 9/11/2017, Université de Mons – Belgique :** Hydrogeophysical monitoring of groundwater recharge processes through the karst vadose zone at Rochefort (Belgium). *Rapporteur*
3. **Moussa OUEDRAOGO, 25/11/2016 Université Paris Saclay :** Caractérisation des aquifères du socle pour l'amélioration de la productivité des forages d'hydraulique villageoise dans le bassin versant du Bandama blanc amont (Nord de la Côte d'Ivoire). *Examinateur*
4. **Sylvain PASQUET 17/11/2014 UPMC (Univ.Paris 6) :** Apport des méthodes sismiques à l´hydrogéophysique : importance du rapport VP/VS et contribution des ondes de surface. *Examinateur*
5. **Meriem LGHOUL 13/05/2014 Thèse en cotutelle UPMC (Univ. Paris 6) et l'UCAM (Université Cadi Ayyad de Marrakech) :** Apport de la géophysique, de l´hydrogéochimie et de la modélisation du transfert du drainage minier acide, au projet de réhabilitation de la mine abandonnée de Kettara (région de Marrakech, Maroc). *Examinateur*
6. **Simon CARRIERE 03/02/2014 UAPV** : Etude hydrogéophysique de la structure et du fonctionnement de la ZNS du karst-Application au site expérimental du LSBB. *Co-encadrant*
7. **Laura TORRES RONDON 19/12/2013 UAPV** : Etude et modélisation des transferts d'eau et de sel en milieu deltaïque agricole (Camargue-France). *Co-encadrant*
8. **Ján BERES 11/10/2013 Université Paris Saclay :** Investigation of karst by joined analysis of seismic and electrical anisotropies. *Examinateur*

Participation aux Comités de Pilotage des Thèses de Doctorat

En plus des 5 thèses co-encadrées, j'ai été invité à participer à 6 comités de pilotage de thèses :

1. **Amal EL HADMI**, 2018-2021, Université de Tétouan (Maroc) dir. V. VALLES: Distribution spatiale de la salinisation sur les périmètres irrigués du Taddla marocain.
2. **Yousra EL MOUINE**, 2018-2021, Université de Tétouan (Maroc) dir. V. VALLES: Pollution des nappes par des décharges d'ordures ménagères : impact entre les différents modes de gestion des décharges.
3. **Marine DANGEARD**, 2016-2019, UPMC (Univ.Paris 6) dir. R. GUERIN et L. BODET : Imagerie des variations spatiales et temporelles des propriétés mécaniques de la zone critique par sismique active.
4. **Donissongou Dimitri SORO**, 2013-2017, Cotutelle UPMC (Univ.Paris 6) – Institut International d´Ingénierie de l´Eau et de l´Environnement (2iE) à Ouagadougou (Burkina Faso), dir. H. YACOUBA et R. GUERIN : Caractérisation et modélisation d´un aquifère en milieu de socle fracturé : cas du site expérimental de Sanon (région du Plateau central au Burkina Faso)
5. **Arnaud WATLET**, 2014-2017, Université de Mons (Belgique). O. KAUFFMANN : Surveillance du stockage d'eau dans la zone partiellement saturée à l'aide de méthodes Géophysiques - Hydrosystème karstique de Rochefort – Belgique
6. **Benoit VIGUIER**, 2013-2016, Univ. Montpellier II, dir. H. JOURDE et V. LEONARDI : Caractérisation des facteurs de contrôle de la recharge et des écoulements souterrains à différentes échelles de temps en zone de piedmont aride et hyper-aride. Exemple de l'Aquifère de la Pampa del Tamarugal (Nord Chili).

Co-encadrement de stages M1 et M2

1. **Elia DRONHU 2019 (M2 HSE, AU) :** Ecoulements en zone non saturée d'un aquifère carbonaté (FDV-LSBB). *(50% encadrement)*
2. **Loïc SAVIGNAT 2018 (M1 HSE, AU / TOTAL) :** Mise au point de protocoles de monitoring hydrogéologique et d'essais hydrauliques sur le site de Buissonnière (LSBB, Rustrel, France). *(20 % encadrement)*
3. **Romane BERTHELIN 2017 (M2 HSE, AU) :** Caractérisation des propriétés hydrodynamiques des hydrosystèmes karstiques ; approche couplée hydrodynamique et hydrochimie isotopique au sein du LSBB - Fontaine de Vaucluse. *(50 % encadrement)*
4. **Florent ROBIN 2017 (M2 Montp.II, AU / TOTAL) :** Tests hydrauliques en zone non saturée des hydrosystème karstiques au Laboratoire Souterrain à Bas Bruit de Rustrel, France. *(10 % encadrement)*
5. **Jean KEMPF 2016 (M2 Montp. II, AU/ACF):** Suivi de la ressource en eau souterraine dans un contexte humanitaire sur le plateau Mahafaly (Sud-Ouest de Madagascar). *(60 % encadrement)*
6. **Outoumbé ELI 2015 (M2 HSE, AU/TOTAL) :** Etudes hydrodynamique et hydrogéophysique de la plateforme des forages du LSBB dans la Zone Non Saturée de la Fontaine de Vaucluse. *(60 % encadrement)*
7. **Rémy COTINET 2015 (M2 HSE, AU/INERIS) :** Mise en place d'un protocole de suivi hydrochimique d'un aquifère hétérogène profonde proche d'une ISDND. *(25 % encadrement)*
8. **Yoann LECOMPTE 2015 (M2 Montp.II, AU/SMBS) :** Vulnérabilité de l'impluvium de la Fontaine de Vaucluse selon PaPRIKa; cartographie et outils d'application. *(50 % encadrement)*

9. **Marie MANGIN 2014 (M2 Montp. II, AU/ACF):** Etude de l'aquifère karstique des calcaires éocènes du plateau de Mahafaly pour une exploitation durable de ses ressources en eau potable. *(50 % encadrement)*
10. **Chloé OLLIVIER 2013 (M2 HSE, AU):** Interprétation couplée de données géologiques hydrogéologiques et géophysiques et réalisation d'un géomodèle locale de la zone non saturée du karst. *(50 % encadrement)*
11. **Alexandre JOSSE 2012 (M2 UPMC, AU/INRAE) :** Caractérisation géophysique de la structure géologique et de la dynamique des transferts hydriques de la surface vers la nappe de la Crau sur le Domaine du Merle. *(40 % encadrement)*
12. **Marie GUILLEMAIN 2012 (M2 UPMC, AU/Danone Waters) :** Inventaire et interprétation géologique et hydrogéologique des données géophysiques disponibles sur le site d'Evian. *(40 % encadrement)*
13. **Jérémie ROCQUES 2011 (M1 HSE, AU/ACF) :** Check on the northern Uganda groundwater hydro-geo-chemical dynamic. *(50 % encadrement)*
14. **Manon FUMET 2011 (M1 HSE, AU/Cerege) :** Étude hydrogéologique de la région du Saïs et de la nappe liasique à deux échelles : synthèse des connaissances à l'échelle du bassin et traitement de données géophysiques sur le site « atelier » de Bittit-Maroc. *(50 % encadrement)*
15. **Gilles ESBACH 2010 (M2 HSE, AU/ACF) :** Influence de la population et des précipitations sur la profondeur et la qualité des eaux souterraines; le cas du Nord-Ouganda. *(50 % encadrement)*

Coordination insertion recherche étudiants CMI R2E

Depuis 2013, les étudiants L2 et L3 du parcours CMI R2E, dont je suis le responsable, doivent effectuer durant l'année (une fois par semaine) leur insertion recherche. Il s'agit d'un suivi, durant toute l'année, des activités de recherche au sein de l'UMR EMMAH principalement. Je suis en charge de leur trouver l'équipe de recherche qui va les accueillir et de faire avec eux un suivi régulier sur les activités suivies.

1.2.3. Activités et Responsabilités Pédagogiques

Résumé d'activités d'enseignement au sein d'AU

- **Master 2 HSE :** Hydrogéophysique (CM+TD) / Resp. module
- **Master 2 HSE :** Professionnalisation (TD)
- **Master 1 HSE :** Géologie appliquée à l'hydrogéologie (CM + stage d'une semaine) / Resp. module
- **L3 STE :**
  - Cartographie géologique (sorties terrain + stage d'une semaine)
  - Hydrogéophysique (CM+TD) / Resp. module
  - Tectonique (CM + TD) *jusqu'à 2015*
  - Stratigraphie (CM+TD) *jusqu'à 2014*
- **L3 CMI R2E :** Projet intégrateur (TD) / Resp. module
- **L2 CMI IPA, IPV et R2E:**
  - Communication, expression, improvisation orale (TD) *jusqu'à 2019*
  - Communication et expression écrite (TD) *jusqu'à 2019*
- **L1 CMI R2E :** Environnement, Changements globaux et Adaptation (TD) / Resp. module
- **L1 CMI IPA, IPV et R2E:** Projet transversal (TD)

Mon service au sein d'AU est résumé dans le tableau ci-dessous :

Année académique	Heures enseignées (Licence/Master)	Responsabilité de filière d'enseignement
2020-2021	(170 / 102) Total de **259** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Ressources en Eau et Environnement (R2E)
2019-2020	(144 / 100) Total de **244** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Ressources en Eau et Environnement (R2E)
2018-2019	(265 / 95) Total de **360** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Ressources en Eau et Environnement (R2E)
2017-2018	(155 / 89) Total de **244** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Ressources en Eau et Environnement (R2E)
2016-2017	(177 / 89) Total de **266** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Agro-Hydrosystèmes (AHS)
2015-2016	(157 / 94) Total de **251** h eq. TD	Resp. Cursus Master en Ingénierie (CMI) parcours Agro-Hydrosystèmes (AHS)
2014-2015	(149 / 93) Total de **242** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Agro-Hydrosystèmes (AHS)
2013-2014	(106 / 94) Total de **200** h eq.TD	Resp. Cursus Master en Ingénierie (CMI) parcours Agro-Hydrosystèmes (AHS)
2012-2013	(130 / 76) Total de **206** h eq.TD	Resp. parcours Terre et Eau - L3 SVT (STE) et Resp. Cursus Master en Ingénierie (CMI) parcours Agro-Hydrosystèmes (AHS)
2012-2011	(170 / 66) Total de **236** h eq.TD	Resp. parcours Terre et Eau - L3 SVT (STE)
2011-2010	(150 / 62) Total de **212** h eq.TD	-
2009-2010	(103 / 35) Total de **138** h eq.TD	-

Enseignant invité hors-AU

En France

- **2009, 2010, 2011 :** *42h* (eq.TD)/an en Hydrogéophysique (stage de terrain) au sein du M2 GARE (Géophysique Appliquée Ressources et Environnement) de l'UPMC (Paris 6)
- **2011, 2012, 2013, 2014 :** *9h* (eq.TD)/an en Hydrogéophysique au sein du M2 GARE (Géophysique Appliquée Ressources et Environnement) de l'UPMC (Paris 6)
- **2013, 2014, 2015, 2016, 2017 :** *4.5h* (eq. TD)/an en Hydrogéophysique au sein du M2 SDUEE parcours Hydrogéologie-Hydrologie de l'UPMC (Paris 6), Mines ParisTech et Agro ParisTech, Paris Sud Saclay

A l'étranger

2010, 2011, 2012, 2013, 2014, 2016 : *27h* (eq.TD)/an en Hydrogéophysique-Exploitation des ressources en Eau au sein du M1 Eau et Assainissement de l'Institut International d´Ingénierie de l´Eau et de l´Environnement (2iE) à Ouagadougou –Burkina Faso.
2017, 2018, 2019 : *6h* (eq.TD)/an en Hydrogéophysique-Exploitation des ressources en eau au sein du M2 Applied Geology à l'Université de Thessaloniki – Grèce.

Formation à distance :

2013, 2014 : *30h* (eq. TD)/an en Hydrogéophysique au sein du M1 GIRE (Gestion Intégrée des Ressources en Eau) de l'Institut International d´Ingénierie de l´Eau et de l´Environnement (2iE) à Ouagadougou –Burkina Faso.

Responsable du CMI (Cursus Master en Ingénierie) – Ressources en Eau et Environnement (R2E)[4] :

Le parcours R2E a été la première formation CMI d'AU[5] accrédité par le réseau Figure (http://reseau-figure.fr/) en 2012. J'ai été invité à en prendre la responsabilité en mai 2013. En proposant 30% d'heures complémentaires, notamment en SHS et avec un suivi personnalisé de chaque étudiant, cette formation très exigeante adossée à des laboratoires de recherche d'appoint recrute des étudiants principalement en post-bac et sur dossier à la suite des résultats obtenus en L1 SVT. Cette formation d'ingénieurs par la recherche a gagné beaucoup d'attractivité les dernières années. A titre d'exemple en 2015 je devais étudier 60 dossiers via ParcourSup et en 2020, 330 dossiers ont été déposés via ParcourSup (phase principale et phase complémentaire) pour un total de 20 places d'étudiants en L1 au maximum.

En 2021, suite à la réussite croissante de la formation, j'ai été invité par le réseau Figure à monter le dossier de l'accréditation européenne EUR-ACE® de l'ENAEE (European Network for Accreditation of Engineering Education) (https://www.enaee.eu/eur-ace-system/).

Mes tâches en tant que responsable de parcours CMI-R2E sont résumées par :

- La **mise en place** (2013-2014) et depuis, la **coordination pédagogique des modules** d'enseignements complémentaires.
- Le **suivi personnalisé** de chaque étudiant CMI du parcours avec une charge croissante depuis 2013 (cf. tableau suivant) ; La **coordination de leur insertion recherche** (une fois par semaine au sein des laboratoires de recherche en L2 et L3) ; le **suivi de leurs stages** (dès le L1) ; Une **rencontre mensuelle avec chaque promotion**.
- Le **montage des partenariats internationaux** pour les **échanges pédagogiques et scientifiques** (Erasmus) et le **suivi du séjour des étudiants à l'étranger** :

[4] Depuis 2018, l'intitulé du parcours CMI dont je suis responsable a changé : Ressources en Eau et Environnement (R2E) au lieu de Agro-Hydrosystèmes (AHS)
[5] Actuellement AU dispose 7 autres parcours CMI (4 en Sciences et 3 en SHS) accrédités par le réseau Figure.. Pour AU les parcours CMI représentent une priorité pédagogique majeure.

Les étudiants CMI R2E doivent obligatoirement effectuer un séjour pédagogique et un stage à l'étranger[6]. Par conséquent depuis ma prise des fonctions, et en collaboration avec la Maison de l'International (MDI)I de l'AU et le responsable des échanges, nous avons mis en place des partenariats internationaux ainsi que réactiver des partenariats existants.

- **En 2013 :** Univ. de Patras (Grèce), Univ. de Mons (Belgique), Univ. d'Aarhus (Danemark)
- **En 2014 :** Univ. de Malaga (Espagne), Univ. de Milan (Italie), Univ. de Québec (Canada)
- **En 2015 :** Univ. de Toledo (Espagne), Univ. de Prague (Rep. Tchèque), Univ. de Turin (Italie)
- **En 2016 :** Univ. d'Adélaïde (Australie), Univ. de Montréal (Canada), Univ. de Neuchâtel (Suisse)
- **En 2018 :** Univ. de Thessaloniki (Grèce)

- Coaching scientifique et pédagogique lors des concours nationaux : **36HChrono de la création d'entreprise (organisé par le Pôle Pépite Paca Ouest) - Editions 2014, 2015, 2016, 2017, 2018 :** Entrainement et suivi des étudiants L3 CMI durant le concours. *En 2014, j'ai initié la participation des étudiants L3 CMI à ce concours (première édition du concours en 2013). En 2014 mes étudiants CMI ont obtenu le 1er prix, en 2015 ont obtenu le 1er prix et en 2016 ont obtenu les 1er, 2ème et 3eme prix, en 2018 ont obtenu le prix du jury.*

Année académique	Nombre d'étudiants CMI R2E suivis					
	L1	L2	L3	M1	M2	Total
2020-2021	11	6	1	5	4	27
2019-2020	6	4	4	4	1	19
2018-2019	7	5	4	1[7]	6	23
2017-2018	6	6	2[8]	6	1	21
2016-2017	8	6	6	1	4	25
2015-2016	6	6	1[9]	4		17
2014-2015	6	3	6			15
2013-2014	3	6				9
2012-2013	4					4

Parrainage des étudiants M2 HSE au sein de l'IAH

En tant que membre actif de l'International Association of Hydrogeologists (IAH) et du Comité Française d'Hydrogéologues (CFH), depuis 2014, dans un souci de redynamiser la participation des jeunes diplômées à la vie de la communauté, j'ai initié l'adhésion collective des étudiants en dernière année d'études. Ainsi je parraine l'ensemble des étudiants du M2 HSE (Hydrogéologie, Sol et Environnement) de l'AU et le département d'Hydrogéologie prend en charge leur première adhésion.

[6] Le réseau Figure impose une seule mobilité. Compte tenu de la nature de notre formation j'impose deux mobilités à l'étranger. Les mobilités pédagogiques sont autorisées en L2 et au premier semestre de M1 tandis que les stages à l'étranger durant tour le parcours.

[7] Réorientation des étudiants vers d'autres parcours CMI en France

[8] Réorientation des étudiants vers d'autres parcours CMI en France

[9] Réorientation des étudiants vers d'autres parcours CMI en France

1.2.4. Production scientifique / valorisation des travaux

La synthèse de ma production scientifique/valorisation des travaux depuis 2005 se résume ainsi :

- **ACL - publications de rang A**: 33 publications parues, 1 acceptée et 2 soumises.
- **ACL - ouvrages de rang A:** 4 chapitres d'ouvrages
- **ACTI - conférences internationales à comité de lecture avec actes:** 50 présentations

En souligné les étudiants (post-doctorants, doctorants et Master 2 que j'ai encadré).
Mon **H-index** (oct. 2020) est de **15** (Web of Sciences) et **18** (Google Scholar).

ACL (Articles à comité de lecture – Rang A)

2020

1. Mazzilli N., Chalikakis K., Carrière S.D. and Legchenko A., (accepted). Surface Nuclear Magnetique Resonance monitoring reveals karst unsaturated zone recharge dynamics during a rain event. *Water* (IF 2019, 2.54)
2. Carrière S.D., Ruffault J., Cakpo C-B., Olioso A., Doussan C., Simioni G., **Chalikakis K.**, Patris N., Davi H. and Martin St-Paul N.K., 2020. Intra-specific variability in deep water extraction between trees growing on a Mediterraneen karst. *Journal of Hydrology, 590, 125428,* https://doi.org/10.1016/j.jhydrol.2020.125428 (IF 2019, 4.5)
3. Carrière S.D., Martin St-Paul N.K, Cakpo C-B., Patris N., Gillon M., **Chalikakis K.**, Doussan C., Olioso A., Babic M., Jouineau A., Simioni G., Davi H., 2020. Tree xylem water isotope analysis by Isotope Ratio Mass Spectromertry and laser spectrometry: A dataset to explore tree response to drought. Data in Brief, 29, 105349, https://doi.org/10.1016/j.dib.2020.105349 (IF 2018, 1.5).
4. Carrière S.D., Ruffault J., Pimont F., Doussan C., Simioni G., **Chalikakis K.**, Limousin J-M., Scotti I., Courdier F., Cakpo C-B., Davi H., Martin St-Paul N.K., 2020. Impact of local soil and subsoil conditions on inter-individual variations in tree responses to drought: insights from Electrical Resistivity Tomography. *Science of the Total Environment*, *134247*, https://doi.org/10.1016/j.scitotenv.2019.134247 (IF 2019, 6.551).
5. Carrière S.D., Martin St-Paul N.K., Cakpo C-B., Patris N., Gillon M., **Chalikakis K.**, Doussan C., Olioso A., Babic M., Jouineau A., Simioni G. and Davi H., 2020. The role of deep vadose zone water in tree transpiration during drought periods in karst settings – insights from isotopic tracing and leaf water potential. *Science of the Total Environment, 134332,* https://doi.org/10.1016/j.scitotenv.2019.134332 (IF 2019, 6.551).
6. Ollivier C., Mazzilli N., Olioso A., **Chalikakis K.,** Carrière S.D., Daquigny C. and Emblanch C., 2020. Karst recharge-discharge semi distributed model to assess spatial variability of flows. *Science of the Total Environment,* https://doi.org/10.1016/j.scitotenv.2019.134368 (IF 2019, 6.551).

2019

7. Ollivier C., **Chalikakis K.**, Mazzilli N., Kazakis N., Lecomte Y., Danquigny C. and Emblanch C., 2019. Challenges and Limitations of Karst Aquifer Vulnerability Mapping Based on the PaPRIKa Method—Application to a Large European Karst Aquifer (Fontaine de Vaucluse, France). *Environments* 2019, *6*, 39, https://doi.org/10.3390/environments6030039 (IF indexed in 2020).
8. Ollivier C., Lecomte Y., **Chalikakis K.,** Mazzilli N., Danquigny C. and Emblanch C., 2019. A QGIS Plugin Based on the PaPRIKa Method for Karst Aquifer Vulnerability Mapping. *Groundwater*,

Wiley, 2019, 57 (2), https://doi.org/10.1111/gwat.12855 (IF 2019, 2.205)

9. Manakos A., Ntona MM., Kazakis N. and **Chalikakis K.**, 2019. Enhanced characterization of the Krania-Elassona structure and functioning allogenic karst aquifer in central Greece. *Geosciences, 9, 15;* http://dx.doi.org/10.3390/geosciences9010015 (IF 2019, 2.1)

2018

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2. L'hydrogéophysique : du métissage à une sous-discipline.

Ce mémoire intitulé "Contribution à l'hydrogéophysique" nécessite avant tout une présentation de l'hydrogéophysique. Cette partie du document ne prétend pas être exhaustive. Elle présente une vision, certainement parfois simplifiée, sur son évolution allant d'un panel d'outils utilisé par des géophysiciens et mis à disposition des hydrogéologues jusqu'à une véritable sous-discipline de l'hydrogéologie. J'y présente les principaux verrous scientifiques et techniques ainsi que les évolutions qui ont guidé cette émergence durant ces trois dernières décennies. Au fil des années, suite à l'avancement de connaissances sur la structure et le fonctionnement des hydrosystèmes et la pression anthropique et climatique sur les ressources en eau, ce métissage a eu lieu grâce aussi à la formation par la recherche d'une nouvelle génération de chercheurs/ingénieurs qui ont su dépasser les limites disciplinaires traditionnelles. Ces évolutions longuement débattues au sein de la communauté française et internationale ont été les verrous que le département d'Hydrogéologie de l'AU et l'équipe HYDRO de l'UMR EMMAH ont levé par les projets de recherche qui y ont mené, mais aussi au moment de leurs restructuration en 2010 et 2015, ainsi que pour la réforme de notre offre de formation. Ce chapitre se termine par un état de lieu et les perspectives au sens large en hydrogéophysique dans le cadre de l'organisation de la première conférence internationale dédié à l'hydrogéophysique. Celle-ci aura lieu à Bordeaux en fin août 2021 et j'ai été invité par l'EAGE pour en assurer son pilotage en tant que "chairman".

Il est évident que ce métissage et cette approche croisée ne sont pas au seul privilège de l'hydrogéophysique. Cette évolution existe depuis le début de l'histoire des sciences … Mais ceci est un autre débat!

2.1. L'émergence de l'hydrogéophysique

L'hydrogéologie est la science qui étudie les eaux souterraines. L'hydrogéologie est une science interdisciplinaire à plusieurs facettes, où se côtoient géologues, chimistes, biologistes, physiciens et mathématiciens dont le rôle aujourd'hui est essentiel à la protection et à la gestion environnementale des ressources naturelles (Banton and Bangoy, 1997).

Depuis l'abbé Paramelle, Henry Darcy, jusqu'à nos jours, pour l'exploration des ressources en eau souterraines l'hydrogéologue fait traditionnellement appel à des outils et des disciplines variés: la géologie, la tectonique, la géomorphologie, l'occupation du sol et l'étude de la couverture végétale.

Dans les années 1970 une première sous-discipline émerge: l'hydrochimie. Liant des approches chimiques et isotopiques, l'hydrochimie reste la sous-discipline de l'hydrogéologie la plus utilisée. Grâce à l'évolution constante des outils analytiques qui permettent des analyses plus rapides et plus précises et des approches méthodologiques couplant la modélisation avec l'utilisation des nouveaux traceurs, l'hydrochimie joue un rôle incontournable en hydrogéologie.

Parallèlement, la modélisation des écoulements (surface et souterrains) liant des outils et des approches mécaniques, physiques et mathématiques a permis la quantification des flux d'eau. Le développement informatique exponentiel qui marque les années 1990 et 2000 permet la création d'outils puissants qui sont toujours aujourd'hui en pleine expansion. Actuellement la modélisation s'intéresse aux transferts de masse, d'énergie et d'eau dans le continuum aquifère-plante-atmosphère au sein de la Zone Critique à diverses échelles spatiales et temporelles. La limite principale de la

modélisation hydrodynamique reste l'état de connaissances sur les processus dominants et la structuration interne complexe des hydrosystèmes.

Les outils géophysiques ont été développés en début du 20ème siècle principalement pour l'industrie minière et pétrolière. Depuis la moitié du 20ème siècle la géophysique est devenue une discipline incontournable pour ces deux dernières. On constate depuis un très fort développement des méthodes[10], des techniques de mesures et de codes d'inversion. L'industrie des fabricants d'appareils géophysiques est aussi en pleine voie de développement.

Depuis la fin des années 80 on remarque une croissance d'études géophysiques appliquées à la proche surface et la sous-discipline « near-surface geophysics » émerge sur le plan international. Les principaux champs d'application sont les études environnementales (dont l'hydrogéologie), les études géotechniques et l'archéologie. Les premiers travaux scientifiques de géophysique appliquée à l'hydrogéologie étaient principalement basées sur l'utilisation d'une ou d'une combinaison des méthodes géophysiques pour la caractérisation de la géométrie des couches aquifères ainsi que leur structure interne (ex. Goldman *et al.*, 1988; Goldman and Neubauer, 1994; Purvance and Andricevic, 2000; Albouy *et al.*, 2001; Vouillamoz *et al.*, 2002, 2003). On note ensuite peu à peu l'apparition des outils ou des approches méthodologiques explicitement développées pour l'hydrogéologie (ex. Guerin and Benderitter, 1995; Cardimona *et al.*, 1998; Al-fares *et al.*, 2002; Legchenko *et al.*, 2002; McGrath *et al.*, 2002; Melcher *et al.*, 2002; Zhou *et al.*, 2002; Danielsen *et al.*, 2003)

En France, avant les années 2000, une dichotomie est bien installée. Rares sont les hydrogéologues qui utilisent la géophysique en routine pour leurs travaux tant en recherche qu'en ingénierie. Les deux disciplines ressentent l'intérêt et les besoins d'une collaboration plus étroite mais il y a un gap de communication et de compréhension des outils (et de leurs limites) dont dispose chacune. Ce gap est principalement lié à la formation des géophysiciens issus des parcours plus physiques et des hydrogéologues issus des parcours plus naturalistes/géologiques. Il y a un manque de langage et d'objectifs communs. Dans la plupart des cas d'études la géophysique est sous-traitée et ses résultats sont intégrées sans aucun regard critique ni sur la méthodologie employée ni sur les résultats obtenus. Ainsi les interprétations des observables géophysiques manquent de compréhension et de compétences transversales.

Le terme hydrogéophysique émerge et commence à être largement répandu et employé à partir de 2005 (al Hagrey *et al.*, 2004; Guérin, 2005; Rubin and Hubbard, 2005). Guérin en 2005, a proposé la définition suivante : « quand la prospection géophysique vise à définir des paramètres qui sont en liaison directe ou indirecte avec les ressources en eau souterraine, il s'agit de l'hydrogéophysique ». Sur les plans national et international on constate l'introduction de l'hydrogéophysique dans les formations universitaires en hydrogéologie et la formation par la recherche d'une nouvelle génération des chercheurs notamment via des thèses de Doctorat et des travaux post-doctoraux. On observe même la création des équipes dédiées à l'hydrogéophysique (ex. Hydrogeophysics Group of Aarthus University – Denmark).

[10] La méthode géophysique est liée au phénomène physique qu'on exploite et la technique de mesure au dispositif mis en place sur le terrain. Ex. La méthode électrique et ses techniques de mesure : sondage électrique, panneau électrique etc…

Binley *et al.*, en 2015 ont présenté un état de l'art sur l'apparition des travaux scientifique en hydrogéophysique dans le journal Water Resources Research (**Figure 1**). On constate depuis 1990 une croissance constante.

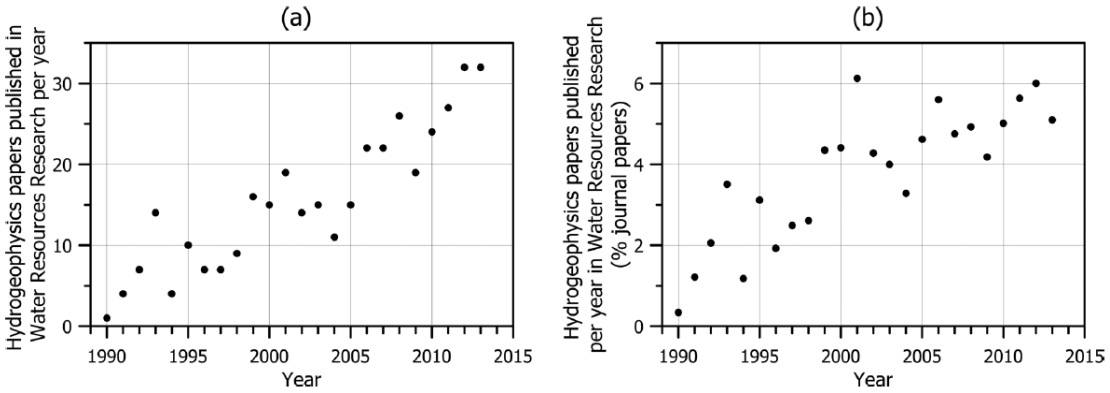

Figure 1 : *(a) nombre d'articles en hydrogéophysique par année et (b) le nombre d'articles en hydrogéophysique (en %) sur le nombre total des articles publiés dans le journal Water Resources Research (Binley* et al.*, 2015)*

Inspiré par les travaux de Binley *et al.,* en 2015, j'ai, à mon tour, élargi la recherche bibliographique et je démontre cette émergence de l'hydrogéophysique via deux illustrations (**Figure 2** et **Figure 3**). Elles sont issues des analyses bibliographiques réalisées dans deux bases de données. La première, dite grande public, est réalisée dans Google Scholar (**Figure 2**) et la deuxième, plus restreinte à la production scientifique, dans Web of Sciences (**Figure 3**).

Le nombre d'apparition dans Google Scholar du terme « hydrogeophysics » et « hydrogéophysique », inclus dans les mots clés de tous les documents répertoriés, a été comptabilisé par année depuis 2002. Le nombre d'apparition du terme « hydrogeophysics » dans Web of Sciences, inclut dans les mots clés de toute production scientifique répertoriée, a été également comptabilisé. Pour cette dernière je propose aussi une distinction entre le type des journaux (géophysiques ou hydrogéologiques / environnementaux). Clairement les journaux géophysiques ont hébergés plus de publications scientifiques répertoriées avec le terme « hydrogeophysics » dans un de mots clés proposés par les auteurs.

Ces deux illustrations nous permettent de constater cette émergence de l'hydrogéophysique en tant qu'outil opérationnel de la recherche hydrogéologique. Toutefois, dans cette analyse, la prise de conscience du terme hydrogéophysique est considérée. C'est-à-dire que les auteurs indiquent le mot clé "hydrogeophysics" pour leurs travaux. Après vérification, il a été constaté qu'à partir de 2011 - 2012, les auteurs mentionnent de moins en moins "hydrogeophysics" en tant que mot clé dans une publication scientifique. Très certainement un nombre croissant des scientifiques ne sent plus ce besoin d'identité et par conséquence, dans cette recherche bibliographique simplifiée, la dynamique de l'évolution croissante de l'hydrogéophysique est probablement sous-évaluée. Le métissage est fait !

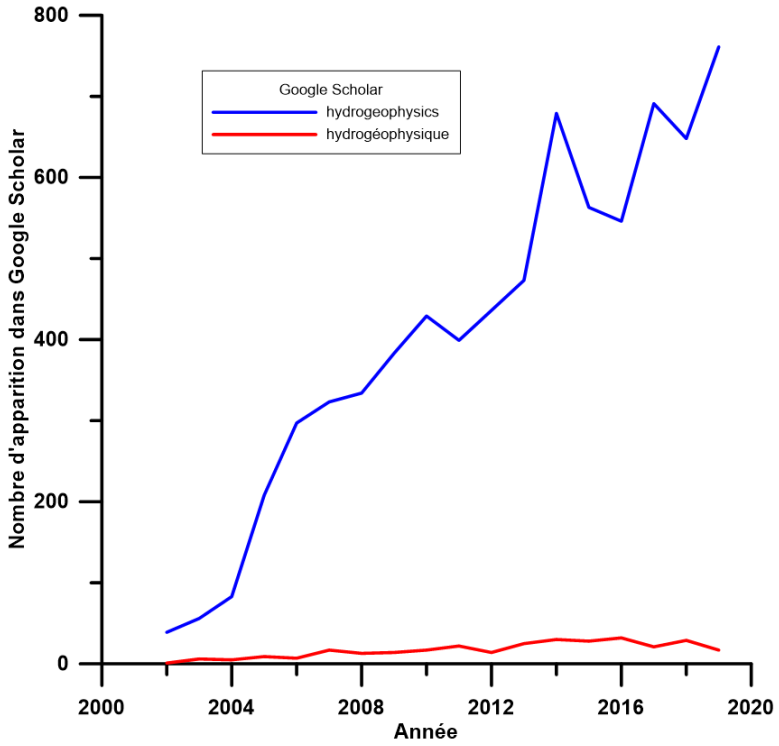

Figure 2 : *Nombre d'apparition des termes « Hydrogeophysics » et « Hydrogéophysique » en Google Scholar.*

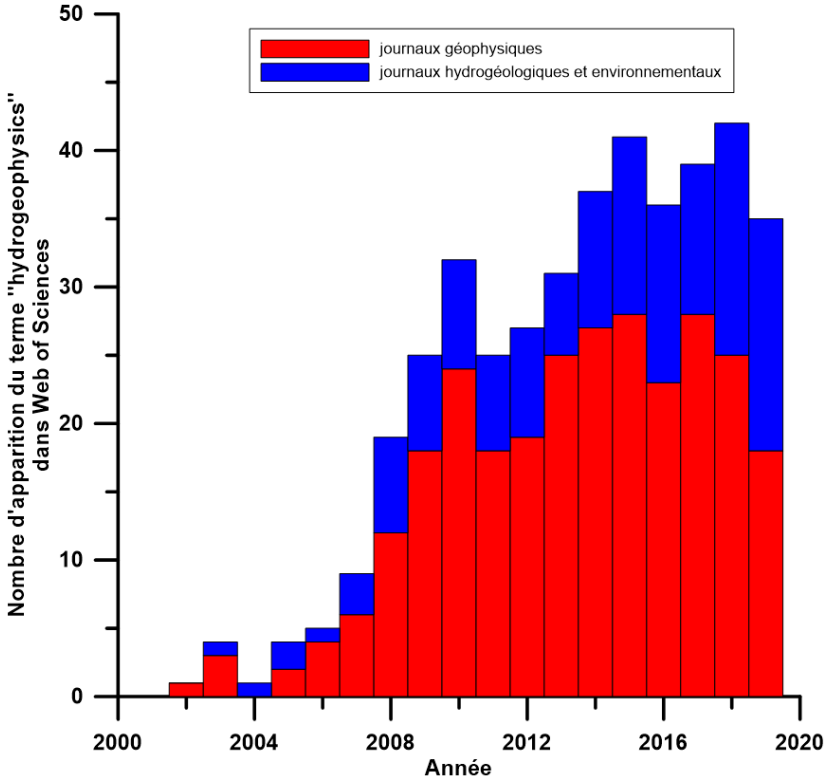

Figure 3 : *Nombre d'apparition du terme « Hydrogeophysics » dans Web of Sciences. On distingue les journaux géophysiques des journaux hydrogéologiques et environnementaux.*

2.2. Les moteurs de la croissance : la Zone Critique, la formation par la recherche et les avancées technologiques

On peut distinguer trois évolutions qui ont permis, à mon sens, la croissance de l'hydrogéophysique durant les dernières décennies.

En premier lieu, l'amélioration des connaissances des hydrosystèmes et par conséquence la prise de conscience de leurs complexité structurale et fonctionnelle a généré une multitude de questions scientifiques qui ne pouvaient pas être étudiées par les outils traditionnelles d'hydrogéologue. Des approches plus intégrées étaient nécessaires qui devraient combiner l'ensemble des sous-disciplines de l'hydrogéologie avec d'autres disciplines environnementales ainsi qu'avec des sciences humaines (Brooks *et al.*, 2015). Le concept de la Zone Critique (ZC), introduit en 2001 par le National Research Council aux Etats-Unis, a offert le cadre favorable pour la mise en œuvre des approches pluridisciplinaires. En effet, la ZC désigne la pellicule la plus externe de la planète qui permet la vie sur Terre. C'est un système ouvert qui s'étend depuis le haut de la canopée jusqu'au mur de l'aquifère. C'est un compartiment dans lequel ont lieu de nombreux processus bio- physico-chimiques en lien direct ou indirect avec les activités humaines.

Les principales questions hydrogéologiques au sein de la ZC, en vue d'une gestion durable de ses ressources en eau souterraines, concernent la compréhension de mécanismes et l'évolution de la recharge des aquifères en lien avec l'occupation de sols, la caractérisation et le suivi des flux (qualité et quantité) et l'estimation de la vulnérabilité, des risques à la pollution et le suivi de la pollution. Ces questions sont étroitement liées à la pression anthropique croissante sur les ressources en eau et le contexte du changement climatique. Ainsi l'augmentation des besoins sociétaux, la surexploitation des systèmes aquifères et leurs pollution, les changements de l'occupation de sols, l'intrusion saline, etc ont conduit les scientifiques qui travaillent sur l'ensemble de la Zone Critique à lever des verrous scientifiques tout en cherchant à développer/déployer des approches pluridisciplinaires et multiméthodes liant des outils avec une rapidité des mesures et une importante capacité de spatialisation. La caractérisation des interfaces ainsi que la caractérisation et le suivi des processus bio-physico-chimiques au sein de la ZC sont d'une importance cruciale pour la comprendre et la protéger.

En France, la création de l'Infrastructure de Recherche (IR) nationale OZCAR a mis en synergie des sites instrumentés en France (ex. SNO) et à l'étranger qui s'appuient sur des observations long-terme de l'eau, des glaces, des sols, des zones humides et de leur biodiversité. OZCAR est une plateforme communautaire qui s'intéresse à l'état et au devenir de la ressource en eau et en sol selon une vision scientifique intégrée de l'environnement et des territoires (Gaillardet *et al.*, 2018). OZCAR est dédiée à l'observation et à l'étude du fonctionnement des surfaces terrestres, des sous-sols à la basse atmosphère, depuis les hauts reliefs jusqu'aux régions côtières en couplant plusieurs disciplines environnementales (**Figure 4**). Clairement l'hydrogéophysique dispose un très large panel de méthodes qui sont adaptés pour étudier les interfaces et les processus au sein de la ZC.

En deuxième lieu mais presque en parallèle, la prise de conscience du besoin d'approches intégrées a conduit à la formation par la recherche d'une nouvelle génération de chercheurs, à cheval entre l'hydrogéologie et la géophysique, notamment via des thèses de doctorat et des travaux post-doctoraux. En France, ces travaux de recherche ont lieu grâce aux Services Nationaux d'Observations (SNO) de l'INSU qui d'abord offrent des observations long-terme sur les propriétés bio-physico-

chimiques des différents hydrosystèmes et ensuite réunissent des scientifiques autour des mêmes thématiques de recherche mais avec des approches différentes. Bien évidemment, cette pluridisciplinarité a également généré d'autres métissages comme la bio-géophysique ou l'éco-hydrologie.

Le monde industriel a démontré également un fort intérêt pour les approches hydrogéophysiques développées, tant sur le plan méthodologique que sur le plan technologique. Durant cette dernière décennie on constate en France une croissance des projets de recherche en hydrogéophysique incluant la formation doctorale (bourse CIFRE). La diminution regrettable de fonds publics dédiés à la recherche a peut-être précipité ce rapprochement entre le monde académique et le mode industriel dans ce discipline.

A titre d'exemple, représentatif à l'échelle européenne, le projet ENIGMA ITN (European training Network for in situ imaGing of dynaMic processes in heterogeneous subsurfAce environments - https://enigma-itn.eu/home/) auquel je participe, piloté par le SNO H+, réunissant 21 partenaires internationaux (15 académiques et 6 industriels), entre 2017 à 2020, a formé 15 doctorants en hydrogéophysique.

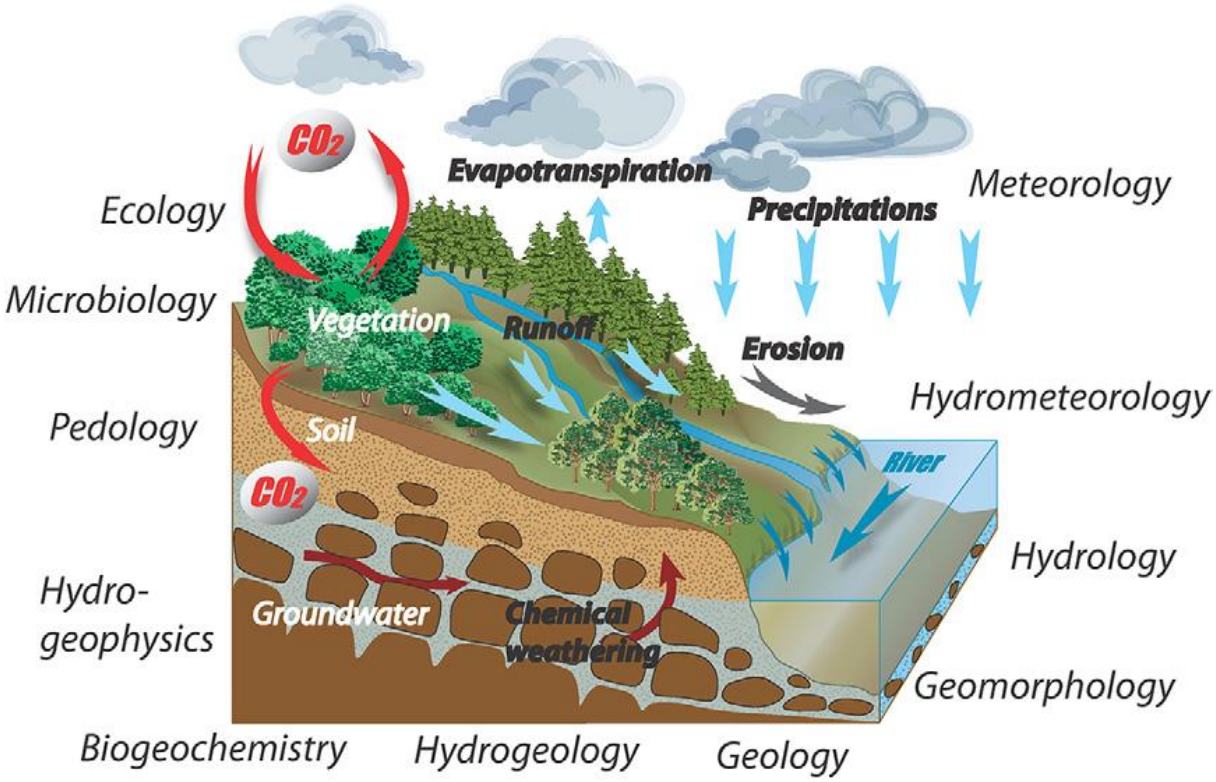

Figure 4 : *Schéma simplifié de la Zone Critique à l'échelle du bassin versant ; les disciplines environnementales associées (Gaillardet* et al.*, 2018)*

Finalement, la troisième évolution qui a permis l'émergence de l'hydrogéophysique concerne le développement des instruments géophysiques et des outils d'inversion. En effet, l'industrie des appareils géophysiques avait bien identifié les besoins en recherche et en ingénierie et les années 90 et 2000 sont marquées par une explosion du marché des outils géophysiques adaptés à la proche surface. Depuis les années 2000 on observe même une tendance d'accélération du progrès technologique des appareils pour le suivi environnemental offrant une rapidité de mesures toute en

proposant une résolution et une sensibilité (spatiale et temporelle) de plus en plus fines. A titre d'exemple, il y a actuellement plus de 15 équipements (issues des constructeurs différentes) capables de réaliser des mesures de tomographie électrique - ERT (Electrical Resistivity Tomography) en mode multivoies. Ceci permet d'abord d'optimiser la séquence d'acquisition afin d'acquérir des mesures simultanées sur plusieurs dipôles suite à une seule injection. Il y a ainsi un gain considérable sur le temps d'acquisition selon le dispositif de mesure employé et les propriétés du terrain étudié. Ainsi des enregistrements 3D ou encore 4D à mailles fins sont techniquement possibles (ex. Karaoulis *et al.*, 2014; Sawyer *et al.*, 2015; Xu *et al.*, 2016; Watlet *et al.*, 2018)

En parallèle du développement instrumental, l'amélioration des outils d'inversion de mesures géophysiques et le développement des approches théoriques sur la nature des phénomènes bio-physico-chimiques mesurés a été remarquable durant la dernière décennie. Portées principalement par les équipes académiques, l'amélioration des algorithmes d'inversion (ex. Günther *et al.*, 2006; Legchenko *et al.*, 2011; Pasquet and Bodet, 2017) et les capacités informatiques croissantes permettent une meilleure compréhension et interprétation de la nature des signaux géophysiques. Les inversions conjointes (ex. Behroozmand *et al.*, 2012; Doetsch *et al.*, 2012; Jiang *et al.*, 2020), l'analyse de sensibilité (ex. Descloitres *et al.*, 2000; Legchenko *et al.*, 2009; Xu *et al.*, 2017) ou encore la caractérisation des incertitudes (ex. Carrière *et al.*, 2017; Rembert *et al.*, 2020) n'en sont que quelques exemples.

L'ensemble de tous ces éléments a clairement accéléré le processus d'intégration des outils géophysiques dans les études hydrogéologiques.

2.3. La maturité : 1rst international conference on Hydrogeophysics – EAGE 2021

Jusqu'à présent des sessions spécifiques à l'hydrogéophysique ont été toujours organisées durant les conférences internationales organisées soit par la communauté géophysique soit par la communauté hydrogéologique. En 2019, la Near Surface Geosciences Division (NSGD - https://eage.org/en/about-eage/divisions/near-surface-geoscience-division) de l'EAGE (European Association of Geoscientists and Engineers - https://eage.org/) a identifié la nécessité de rassembler la communauté internationale qui travaille sur l'hydrogéophysique autour d'une conférence dédiée à cette sous-discipline de l'hydrogéologie.

Cette première conférence en Hydrogéophysique aura lieu en 2021 à Bordeaux (https://eage.eventsair.com/nsg2021/1st-conference-on-hydrogeophysics) en parallèle de la conférence annuelle de l'EAGE. En octobre 2019, j'ai été invité par la NSGD à coordonner cette conférence (chairman). Mes principales tâches étaient d'abord de former un comité scientifique (CS) rassemblant des scientifiques de rayonnement international en représentant le monde académique et le monde industriel. Ensuite, d'organiser et de piloter les réunions du CS afin de préparer l'introduction et l'annonce de la conférence en précisant ses objectifs tout en identifiant les thématiques les plus représentatives à l'échelle internationale. Il fallait également identifier les keynote speakers et les coordinateurs de chaque session. Par la suite le rôle du CS sera de sélectionner les travaux qui seront présentées durant la conférence et à la fin de choisir et inviter les meilleures présentations pour l'édition d'une issue spéciale dans un des journaux de l'EAGE.

En mai 2020, et après 3 mois d'échanges fructueuses avec le CS, nous avons finalisé l'annonce de la conférence (Annexe A) en proposant le contour général des thématiques d'actualité en hydrogéophysique. Ainsi ces premiers travaux du CS ont permis d'établir une cartographie de l'avancement de l'hydrogéophysique et donner les grandes lignes des perspectives affichées via les thématiques de la conférence. Outre le fait de rassembler la communauté internationale de chercheurs et d'ingénieurs, cette première conférence internationale en Hydrogéophysique permettra également de faire un état de lieu sur les avancées méthodologiques et technologiques ainsi que de proposer les perspectives en hydrogéophysique pour les années à venir.

3. Activités de recherche

Dans ce chapitre, je ferai une synthèse (non exhaustive) de ma contribution à la problématique générale autour de deux thèmes qui structurent aujourd'hui mes activités de recherche :

I. Apport de la mesure géophysique aux connaissances hydrogéologiques ; différentes échelles temporelles et spatiales à des milieux géologiques divers.
II. Approches méthodologiques intégrées pour la gestion durable de la ressource en eau en milieux complexes.

Compte tenu de la nature d'un mémoire d'HDR, cette synthèse est guidée, en partie, par mes encadrements de travaux de recherche.

3.1. Apport de la mesure géophysique aux connaissances hydrogéologiques

3.1.1. Les outils géophysiques sélectionnés

La géophysique dispose un très large panel de méthodes et de techniques de mesures associées. Elles peuvent être employées à partir de la surface – que ce soit sur le sol, sur l'eau (en mer et en rivière) ou dans les airs (par hélicoptère, avion, drone ou satellite) – et en forage (diagraphie). Le choix de la méthode ou de la combinaison des méthodes à mettre en œuvre est fonction des objectifs de la prospection et notamment de l'échelle à laquelle elle est entreprise, de la nature de la cible, de la résolution latérale et verticale recherchées, de la profondeur d'investigation, du milieu géologique, etc… Les mesures géophysiques sont réputées être non-invasives, moins coûteuses qu'un forage par exemple, et en général rapides. Je distingue encore deux principaux avantages qui, à mon sens, sont ceux qui représentent un intérêt majeur pour la recherche hydrogéologique :

A. la spatialisation de leurs résultats et
B. leur répétabilité

Mais les méthodes géophysiques sont également indirectes, c'est-à-dire qu'elles ne donnent pas accès directement à une image du sous-sol. C'est l'analyse des données collectées qui permet ensuite de proposer une image du sous-sol à partir des mesures. Elles sont également incertaines à cause de bruits provoqués par des structures géologiques, ou des activités anthropiques, qui peuvent induire un signal qui se superpose au signal cible, rendant sa détection plus compliquée. Des phénomènes d'équivalence peuvent également se produire lorsque plusieurs sous-sols différents provoquent des mesures identiques. Par ailleurs, des paradoxes peuvent avoir lieu lorsque des sous-sols proches provoquent des mesures très différentes. Enfin, ces méthodes sont limitées par la profondeur d'investigation, définie comme étant la profondeur jusqu'à laquelle une couche/structure peut se situer pour être détectée par les mesures géophysiques.

Parmi les outils géophysiques que j'ai utilisés durant mon parcours scientifique, je distingue 3 méthodes géophysiques de surface que j'ai privilégié pour les travaux hydrogéologiques : la méthode

électrique, la méthode électromagnétique basse fréquence (domaines temporel et fréquentiel) et la méthode de la Résonance Magnétique des Protons (RMP[11])

Ces méthodes ont été sélectionnées pour l'adéquation entre coût et rapidité de leur mise en œuvre ainsi que pour leur sensibilité à la présence de l'eau souterraine. Etant donné qu'il s'agit des méthodes très connues au sein de la communauté scientifique et bien documentées, je ne les présente pas dans ce manuscrit.

3.1.2. Représentativité spatiale des mesurables géophysiques

La représentativité spatiale de toute observation en hydrogéologie est critique. Les mesures géophysiques représentent des observations à une échelle intermédiaire entre les mesures en forages (échelle locale) et les mesures aux exutoires (échelle globale). Même si les mesures géophysiques sont de nature intégratrices, elles permettent de spatialiser les informations du sous-sol .

J'illustre mes apports de recherche en hydrogéophysique pour la caractérisation de la variabilité spatiale des observables hydrogéologiques via 3 exemples à des contextes géologiques et sociétales variés.

Aquifères glacio-sédimentaires du Danemark

Les ressources en eau potable au Danemark, dépendent essentiellement des aquifères souterrains. Prenant en considération tous les risques de contamination et de dégradation de ces ressources, l'agence danoise EPA (Environmental Protection Agency) a mis en place un programme national qui vise à cartographier et à évaluer les aquifères souterrains. Les informations primaires en géologie et en hydrogéologie au Danemark sont issues de forages (Thomsen, Søndergaard and Sørensen, 2004). Cependant, la cartographie et l'évaluation des ressources en eau souterraine (**Figure 5**), basées exclusivement sur les données de forages, même dans des zones avec une densité importante de forages, se montrent souvent inadéquates. Par conséquent la cartographie intensive par des méthodes géophysique est devenue une nécessité pour ce pays. Le sondage électromagnétique transitoire ou temporelle (TDEM – Time Domain ElectroMagnetic), depuis la surface ou les airs, est la méthode géophysique la plus employé à l'échelle du Danemark (Christiansen and Christensen, 2003).

[11] Plusieurs noms existent dans la littérature qui désignent toutefois la même méthode. En français : RMP (Résonance Magnétique des Protons), RMN (Résonance Magnétique Nucléaire). En anglaise: MRS (Magnetic Resonance Sounding), SNMR (Surface Nuclear Magnetic Resonance).

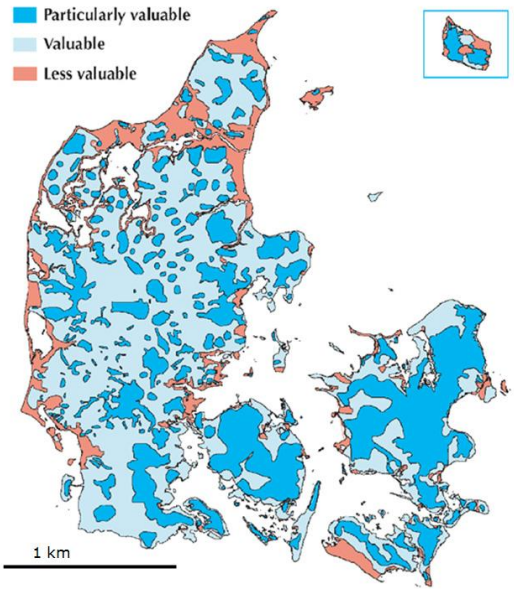

Figure 5 : *Subdivision du Danemark à trois catégories en fonction de l'importance de la ressource en eau souterraine*

(Thomsen, Søndergaard and Sørensen, 2004)

En collaboration avec la compagnie danoise Rambøll, j'ai travaillé entre 2006 et 2011 pour tester l'applicabilité et l'efficacité, puis l'utilisation à grande échelle de la méthode RMP au Danemark. Contrairement aux méthodes géophysiques dites « traditionnelles », la RMP mesure un signal directement généré par les molécules d'eau souterraine, et ainsi les paramètres obtenus peuvent être liés aux propriétés hydrogéologiques de l'aquifère (ex. Legchenko *et al.*, 2002; Behroozmand *et al.*, 2015).

Au cours de cette collaboration, nous avons pu démontrer l'efficacité de la méthode RMP pour le contexte danois. Malgré des conditions pas toujours favorables (bruit électromagnétique important, de nature anthropique, dans presque l'ensemble du territoire et temps de mesures très longs), nous avons pu adapter la méthode. Notamment, nous avons mis en évidence à l'échelle du pays, les limites de la méthode, telles que sa profondeur d'investigation (80-90 m) et le manque de résolution pour les fines couches aquifères, ainsi que ses avantages comme l'estimation adéquate du potentiel hydraulique de la zone aquifère et l'évaluation de sa transmissivité (Chalikakis, Nielsen and Legchenko, 2008; Chalikakis *et al.*, 2009; Ryom Nielsen *et al.*, 2011).

L'intensification des mesures RMP, par la compagnie Rambøll, dans le pays, nous a permis de mettre en évidence des liaisons entre les paramètres RMP obtenus (temps de décroissance et conductivité hydraulique) et les propriétés géologiques des aquifères sédimentaires (sablo-argileux) (**Figure 6**). En comparant les transmissivités obtenus par les forages et par la RMP, nous avons démontré l'efficacité de la méthode à spatialiser les informations hydrogéologiques (**Figure 7**).

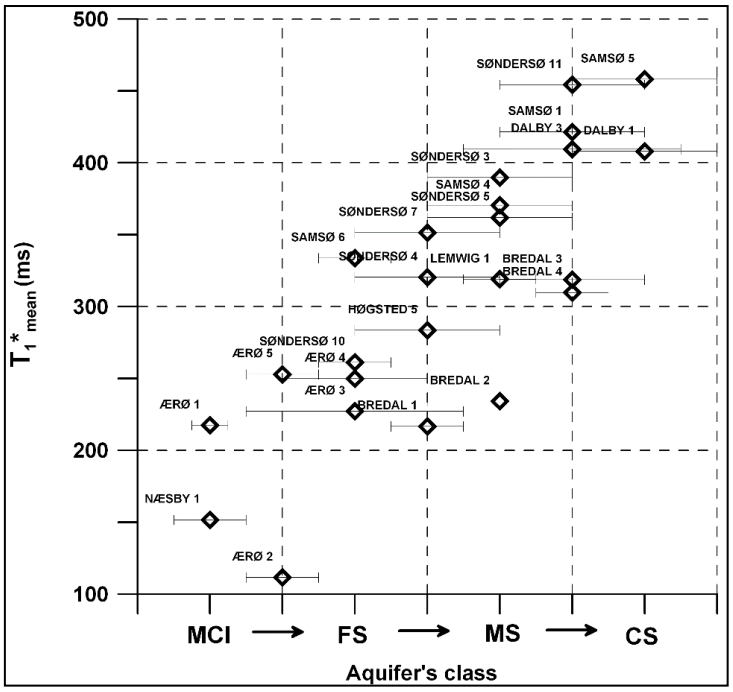

Figure 6 : Temps de décroissance RMP (T_{1mean}) en fonction de la classe de l'aquifère (d'après ses propriétés géologiques ; MCl = Morraine Clay, FS=fine sand, MS=Medium sand, CS=coarse sand) *(Chalikakis* et al.*, 2009)*

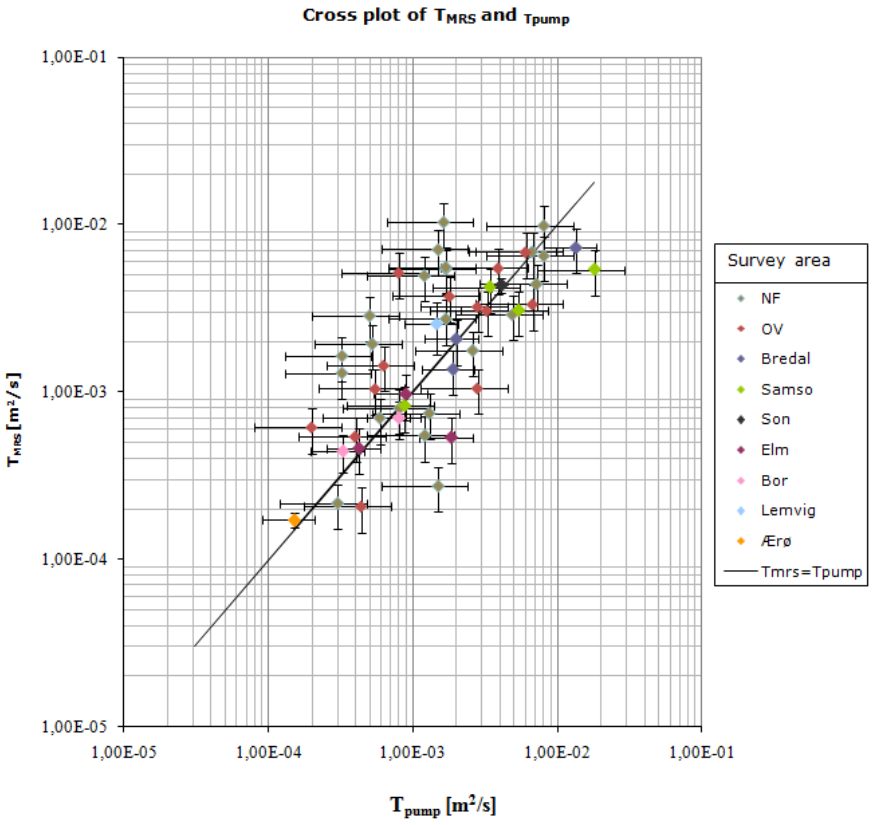

Figure 7 : *Comparaison des transmissivités obtenues par essais de pompage (T_{pump}) et par la RMP (T_{MRS})* (Ryom Nielsen *et al.*, 2011)

Je distingue deux autres impacts majeurs de mes travaux au Danemark :

1. La validation de la RMP en tant qu'outil opérationnel et sa mise en routine pour la cartographie des ressources en eau souterraines au Danemark. Actuellement toutes les données RMP collectées sont introduites dans la base de données du sous-sol nationale (https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/national-geofysisk-database-gerda).
2. Le réussite de l'adaptation de la méthode RMP aux conditions environnementaux et hydrogéologiques danoises, a incité Hydrogeophysics Group of Aarthus, un de leaders mondiaux en recherche hydrogéophysique, à s'intéresser à la méthode de la RMP. Depuis, cette équipe de recherche a réussi à améliorer et à développer de nouvelles approches méthodologiques ainsi que de nouveaux capteurs (ex. Behroozmand *et al.*, 2012, 2019; Liu *et al.*, 2019). Grâce à des nouvelles collaborations de recherche que j'ai mis en place avec Hydrogeophysics Group of Aarthus, nous allons tester l'applicabilité et l'efficacité de leur capteurs à nos sites expérimentaux en France.

Aquifères sédimentaires au Niger

Dans le cadre du projet PSP (Project Structurant Pilote) Lac Tchad (2008-2011), porté par l'IRD (Institut de Recherche pour le Développement) différentes mesures hydrogéophysiques couplant TDEM et RMP ont été réalisées dans la vallée de Komadougou au nord-est de Diffa (Niger de l'est). Komadougou Yobé est le principal affluent du Lac Tchad. Le bassin du Lac Tchad constitue une importante source d'eau douce qui fait vivre autour de 50 millions de personnes. Situé au carrefour du Cameroun, du Tchad, de la République centrafricaine, du Niger et du Nigeria, il regorge d'un potentiel important en terme de biodiversité et sur le plan du patrimoine naturel et culturel (Pham-Duc *et al.*, 2020).

L'objectifs de ses travaux de recherche était de documenter un aquifère très mal connu avec une pression anthropique croissante, notamment liée à l'agriculture. Ainsi il fallait d'abord préciser la répartition des formations lithologiques dans la vallée de Komadougou ainsi que leur rôle hydrogéologique vers et depuis la rivière ; d'autre part, il fallait étudier les propriétés de l'aquifère, dans des contextes d'utilisation de sols différentes (culture récente, culture ancienne au voisinage de la Komadougou) et sous des formes géomorphologiques diverses (bras inondés, bras mort, fans alluviales, zone désertiques). Les informations issues des mesures géophysiques devraient être intégrées au sein d'une modélisation hydrodynamique permettant d'améliorer la connaissance de la ressource en eau souterraine dans le cadre du changement climatique.

J'illustre ci-dessous une partie de résultats hydrogéophysiques majeurs (Descloitres *et al.*, 2013), le long d'un grand profil (12 km), perpendiculaire à l'axe de la vallée en recoupant un maximum de structures géomorphologiques (**Figure 8**), qui ont permis de démontrer les hétérogénéités latérales et verticales des propriétés hydrogéologiques de l'aquifère. En effet, le couplage des données TDEM et RMP (**Figure 9** et **Figure 10**) renseignent sur :

a) la structure subhorizontale du substratum argileux pliocène,

b) la forte hétérogénéité latérale des formations lithologiques entre 2 et 40 m,

c) les limites de l'aquifère, qui contrairement aux hypothèses hydrogéologiques de départ, ne coïncident pas avec le substratum argileux et

d) la géométrie de l'aquifère et ses propriétés hydrogéologiques assez variables le long du profil et qui ne sont pas directement liées aux hétérogénéités géomorphologiques observées à la surface.

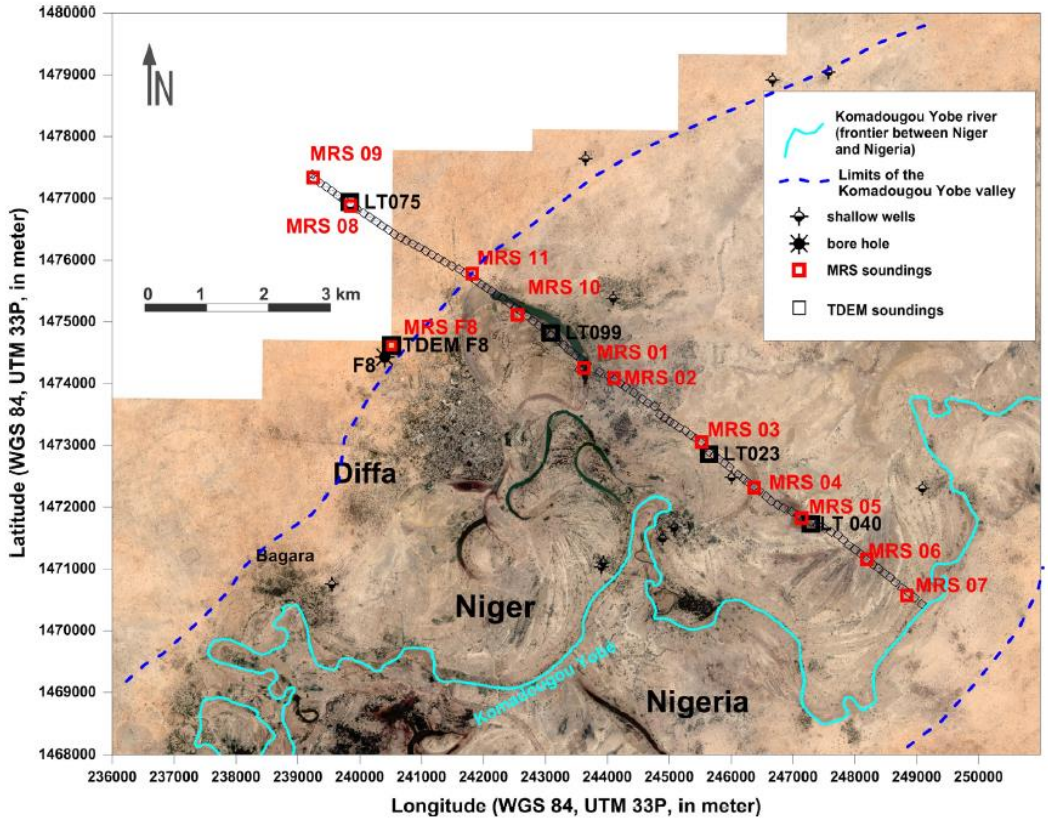

Figure 8 : *Localisation du 12km de long profil hydrogéophysique perpendiculaire à la vallée de Komadougou Yobé.*

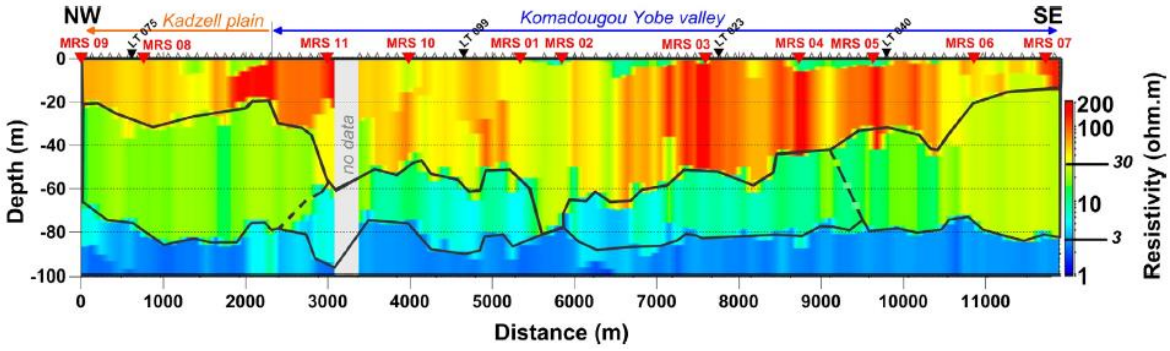

Figure 9 : *Les résultats TDEM (115 sondages) sur le profil nord-ouest sud-est* (Descloitres *et al.*, 2013).

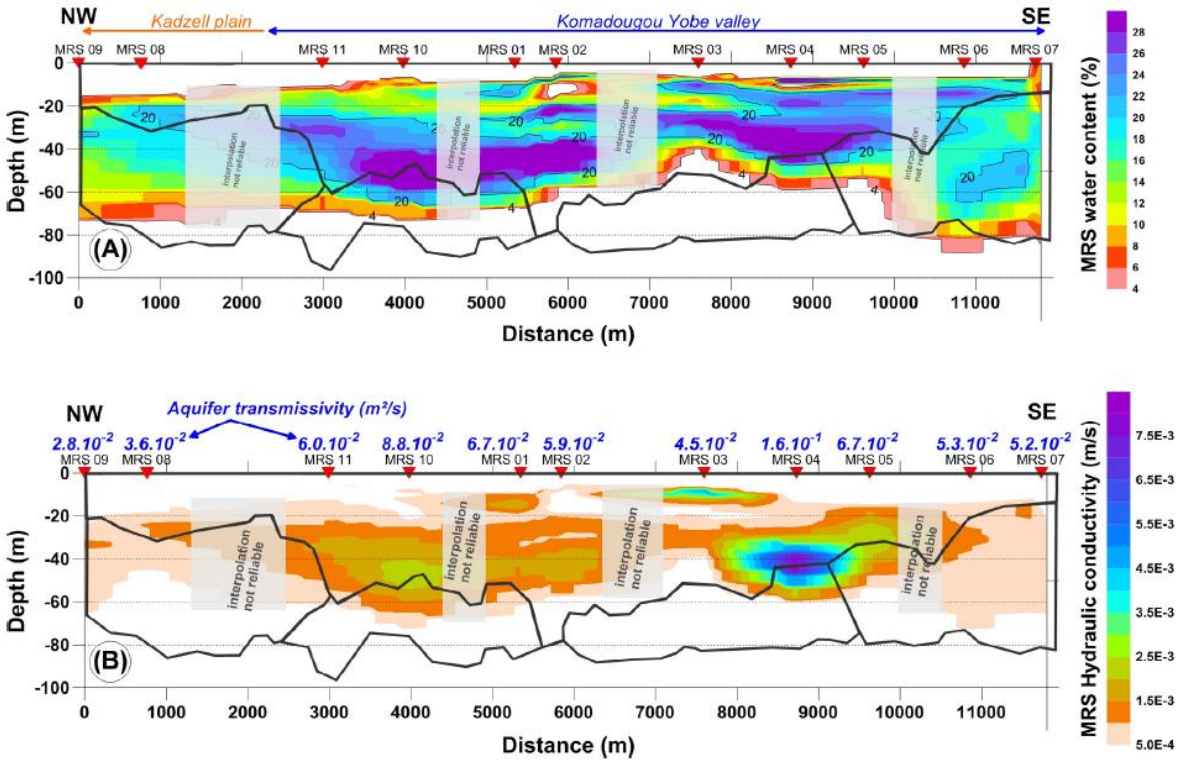

Figure 10 : *Les résultats RMP (11 sondages) sur le profil nord-ouest sud-est* (Descloitres *et al.*, 2013).

Aquifères karstiques en France – focus sur la zone non saturée (ZNS)

Dans le cadre des travaux de recherche post-doctorat de Naomi MAZZILLI (projet ANR HydrokarstG2 2009-2012) plusieurs campagnes de mesures RMP ont été réalisées afin de caractériser le stockage d'eau au sein de la ZNS de l'aquifère karstique du Durzon. Cet hydrosystème karstique d'environ 100 km^2 est situé sur le plateau du Larzac (sud de la France) et fait partie du Service National d'Observation (SNO) H+ qui est le réseau national des observatoires hydrogéologiques.

L'hydrosystème karstique de Durzon est composé des formations calcaires et dolomitiques du Jurassique moyen et supérieur, d'une épaisseur de l'ordre de 400 m. Ces formations reposent sur la série marneuse du Lias supérieur, de 200 m d'épaisseur. La signature hydrochimique des eaux de la source du Durzon indique un long temps de résidence au sein de la ZNS (Bondu-Grozel, 2012). En complément, les variations obtenues lors d'un suivi par micro-gravimétrie (Jacob *et al.*, 2008, 2009) indiquait de variations du stock d'eau dans la ZNS de l'ordre de 550 mm.

Au total 16 sites ont été sélectionnés pour les mesures RMP en prenant en compte d'abord la variété et la représentativité spatiale géologique et géomorphologique et ensuite le niveau du bruit électromagnétique ambient qui pourrait détériorer la qualité du signal RMP. La variété géologique et géomorphologique a été caractérisée par a) la lithologie – 3 types de formation géologique ont été identifiées (calcaire marneux, calcaire siliceux et dolomite ruiniforme), b) la présence de la fracturation/karstification qui pourrait favoriser l'infiltration rapide et c) la végétation, la pente et la couverture argileuse qui pourrait favoriser les écoulements superficiels.

Les résultats de ces travaux (Mazzilli *et al.*, 2016) ont démontré la faisabilité et le potentiel de la méthode RMP pour la caractérisation des stocks d'eau au sein de la ZNS de l'aquifère karstique de Durzon. Ils peuvent se résumer de la façon suivante :

A. Concernant la contribution méthodologique : **1.** La RMP détecte de l'eau au sein de la ZNS de l'aquifère karstique et **2.** La variation temporelle de l'eau est en dessous du seuil de la détectabilité au sein de cet hydrosystème karstique.
B. Concernant le stockage d'eau dans la ZNS : **1.** La teneur en eau détectée par la RMP varie selon la lithologie (moins de 0.5 % pour les calcaires marneux, entre 2.5 et 5% pour les calcaires siliceux et de 2 à 20% pour les dolomites ruiniformes) (**Figure 11**). **2.** Dans la plupart des sondages, la teneur en eau RMP est soit constante, soit croissante avec la profondeur. Des teneurs en eau en ZNS peuvent faciliter l'effet piston et ainsi accélérer les dynamiques de crues. **3.** Il n'y a pas, à l'échelle de ces travaux, un lien entre les teneurs en eau RMP et les formes géomorphologiques de surface.

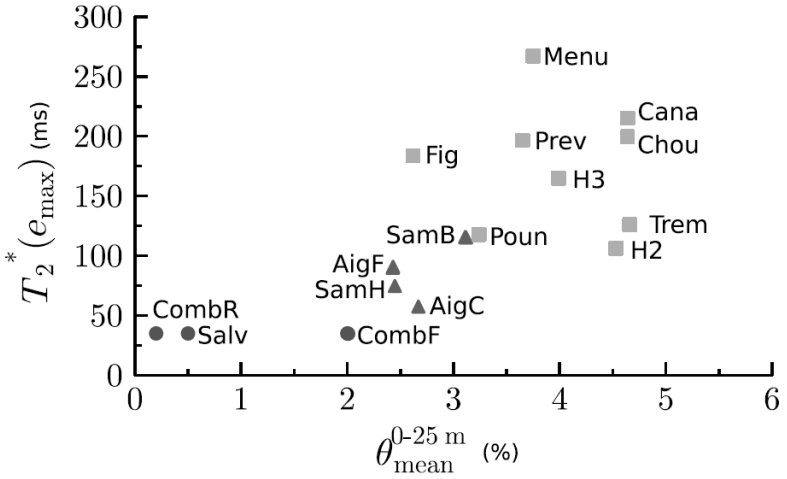

Figure 11 : *Le temps de décroissance T_2* du signal RMP en fonction de la teneur en eau (ϑ_{mean}) RMP (tranche de 0 à 25 m de profondeur) selon les différentes lithologies de l'hydrosystème karstique du Durzon (dolomites ruiniformes en rectangle, calcaires siliceux en triangle et calcaires marneux en rond)* (Mazzilli *et al.*, 2016).

3.1.3. Variabilité temporelle des mesurables géophysiques

Une des nouvelles frontières de l'hydrogéophysique est le suivi temporel (monitoring ou mesures en time-lapse). Selon l'amplitude et la fréquence temporelle de la variation recherchée ainsi que les contextes hydrogéologiques et environnementaux, le suivi hydrogéophysique peut prendre deux formes :

1. un suivi dite « basse-fréquence » qui correspond à des mesures mensuelles, trimestrielles ou même semestrielles et
2. un suivi dite « haute-fréquence » qui correspond à des mesures à l'échelle d'un évènement (ex. pluie intense, essai de pompage/injection) d'une durée qui varie de quelques jours à quelques semaines.

J'illustre les deux formes de suivi hydrogéophysique par des travaux que j'ai menés sur les sites de Draix Bléone (milieu marneux) et du LSBB (milieu karstique).

Suivi « basse-fréquence » temporelle

L'humidité des sols est un facteur déterminant dans le processus de mise en place des crues "éclair". L'observatoire Draix-Bléone a été créé en 1983 pour étudier les processus hydrologiques et érosifs en montagne. Il est situé dans les Alpes du Sud, sur un substrat de marnes noires très érodables, et caractérisé par un climat montagnard et méditerranéen. Sept bassins versants ont été équipés pour la mesure des flux solides et liquides. Ces bassins couvrent des surfaces allant de 0.1 ha à plusieurs dizaines de km2, avec des couvertures végétales, des lithologies et des topographies variées.

Dans le cadre de la thèse de Doctorat de Florian MALLET qui portait sur la problématique des écoulements torrentiels, nous avons cartographié la variabilité spatiale du sol sur un petit bassin versant (« le Laval ») (~0.86 km²) de l'observatoire (**Figure 12**).

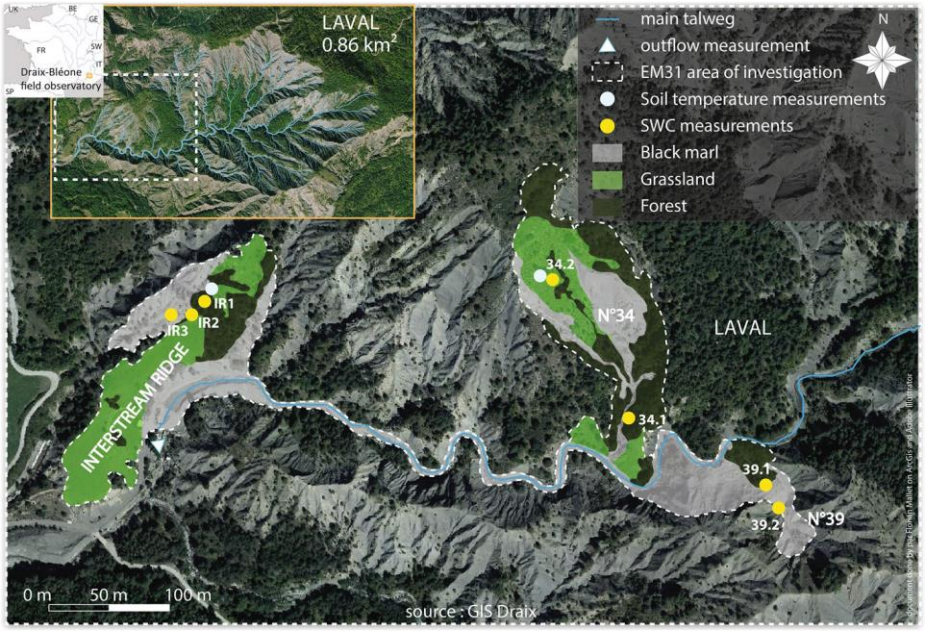

Figure 12 : *Localisation des zones d'investigation EM-31, des mesures de la température et du contenu en eau, et de l'occupation de sols* (Mallet *et al.*, 2018)

Quatre campagnes de mesures électromagnétiques basse fréquence de type Slingram (EM-31) ont été menées entre l'été 2015 et l'hiver 2016 sous des conditions d'humidité de sol variables. La cartographie électromagnétique en domaine fréquentiel de type Slingram offre une très grande rapidité de mesures avec une importante couverture spatiale. Nous avons ainsi combiné les données d'EM31 à des données topographiques, des mesures du contenu en eau dans le sol (par sondes capacitives) et d'occupation du sol selon une approche géostatistique. Ces travaux ont permis de spatialiser les mesures locales d'humidité du sol (**Figure 13**) pour produire des cartes d'humidité du sol tout en localisant les points présentant avec un potentiel de contribution hydrologique et ainsi à risques au sein du sous-bassin versant (**Figure 14**) (Mallet *et al.*, 2018).

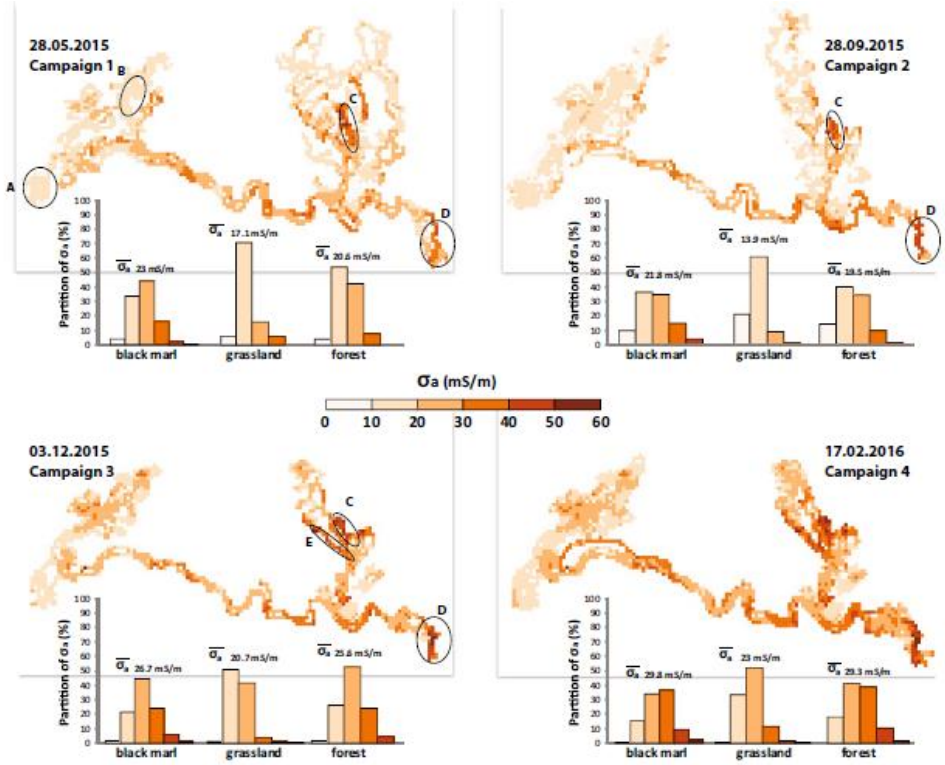

Figure 13 : *Conductivités électriques (non interpolées) et corrigées des effets de température obtenues avec l'EM-31 lors de 4 campagnes de mesures sur l'observatoire de Draix-Bléone* (Mallet *et al.*, 2018)

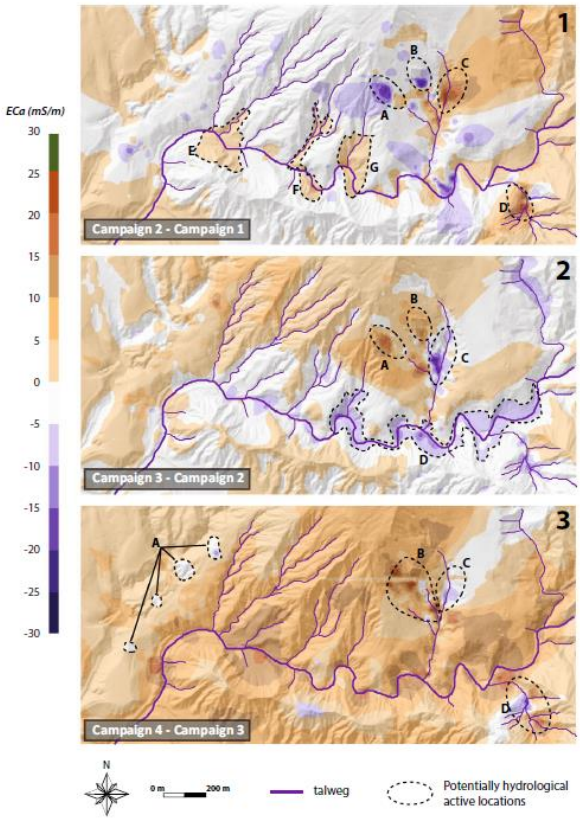

Figure 14 : *Soustraction de cartes de conductivités électriques (interpolées) obtenues avec l'EM-31 entre campagnes de mesures afin d'identifier de sites avec un potentiel de contribution hydrologique* (Mallet *et al.*, 2018)

Suivi « haute-fréquence » temporelle - ERT

Un des outils géophysiques les plus utilisés pour le suivi « haute-fréquence » est la tomographie électrique ou ERT (Electrical Resistivity Tomography) de la méthode électrique. Grâce à un développement instrumental en mode multivoies, on peut optimiser la séquence d'acquisition afin d'acquérir des mesures simultanées sur plusieurs dipôles suite à une seule injection. Ceci permet un gain considérable sur le temps d'acquisition.

Le site expérimental du Laboratoire Souterrain à Bas Bruit (LSBB) à Rustrel se situe au sein de la ZNS de l'aquifère karstique de Fontaine de Vaucluse (sud-est de la France) et, à travers ses galeries, procure un accès privilégié et unique aux propriétés hydrogéologiques de l'hydrosystème. Le LSBB fait partie du Service National d'Observation (SNO) H+ qui est le réseau national des observatoires hydrogéologiques.

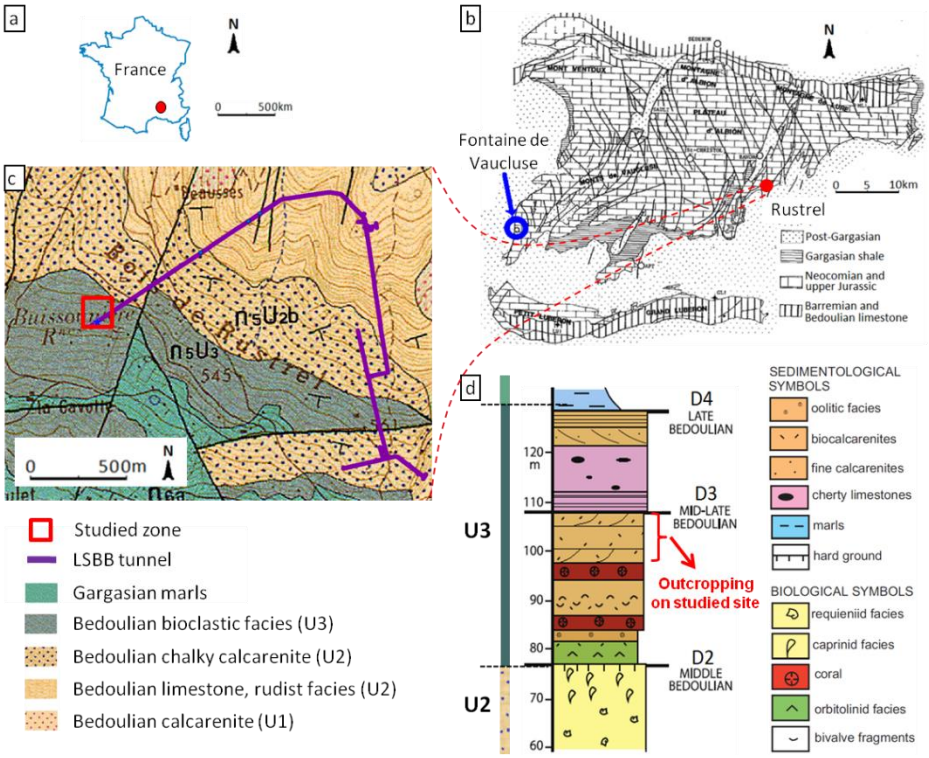

Figure 15 : *a. Localisation de l'hydrosystème karstique de la Fontaine de Vaucluse (FdV), b. Localisation du site expérimental du LSBB, c. le plan du LSBB et le site de Buissonnière sur la carte géologique et d. la colonne litho-stratigraphique.* (Carrière *et al.*, 2013)

Le site de Buissonnière du LSBB est situé à la surface, au-dessus de l'extrémité de la galerie de secours du LSBB (**Figure 15**). Il intègre un point d'écoulement d'eau permanent (nommé point « D ») au sein de la galerie de secours du LSBB.

Dans le cadre de la thèse de Simon CARRIERE (2010-2014), nous avons réalisé une expérience hydrogéophysique unique en milieu karstique et sous des conditions naturelles : une campagne de mesures ERT, haute-fréquence, depuis la surface, durant un évènement de pluie intense d'automne. Cet épisode naturel, typiquement méditerranéen, a duré 17 jours avec une pluie cumulée de 230 mm. Un total de 120 sections ERT a été enregistré sur le même profil durant et après l'événement pluvieux (30 jours).

Les résultats obtenus (Carriere, 2014; Carrière *et al.*, 2015; Carriere *et al.*, 2016) ont démontré :

A. sur l'approche méthodologique employée : **1.** l'efficacité de l'ERT à suivre les processus hétérogènes d'infiltration de l'eau dans la ZNS de l'hydrosystème karstique lors d'un événement pluvieux, **2.** la limitation des outils actuels d'inversion time-lapse en ERT pour identifier précisément les zones d'infiltration préférentielle dans un tel milieu hétérogène. En effet, le contraste de résistivité qui s'établit, au cours de la pluie, entre la roche calcaire électriquement résistante et l'horizon proche de la surface très conducteur rend l'identification des phénomènes profonds difficile, voire impossible, car les lignes de courant se concentrent près de la surface. Les résistivités inversées selon différentes stratégies permettent principalement d'imager le phénomène d'humectation de la sub-surface. **3.** L'étude des différences de résistivités apparentes brutes (**Figure 16**) permet toutefois de proposer de zones d'infiltration préférentielle sans pouvoir identifier précisément leur géométrie.

B. sur la connaissance du milieu : le suivi événementiel a permis d'étudier des phénomènes ponctuels et rapides qui s'opèrent au cours des événements pluvieux en milieux karstiques. Malgré les limitations technologiques qui ont été reconnues, l'ERT s'est avéré efficace pour identifier certains phénomènes en profondeur qui toutefois ne semblent pas se lier, au moins pas directement, avec les connaissances de la surface (ex. végétation, sol) et les résultats des précédents mesures géophysiques (ex. relevé de fracturation par Ground Penetrating Radar (GPR) - (Carrière *et al.*, 2013)).

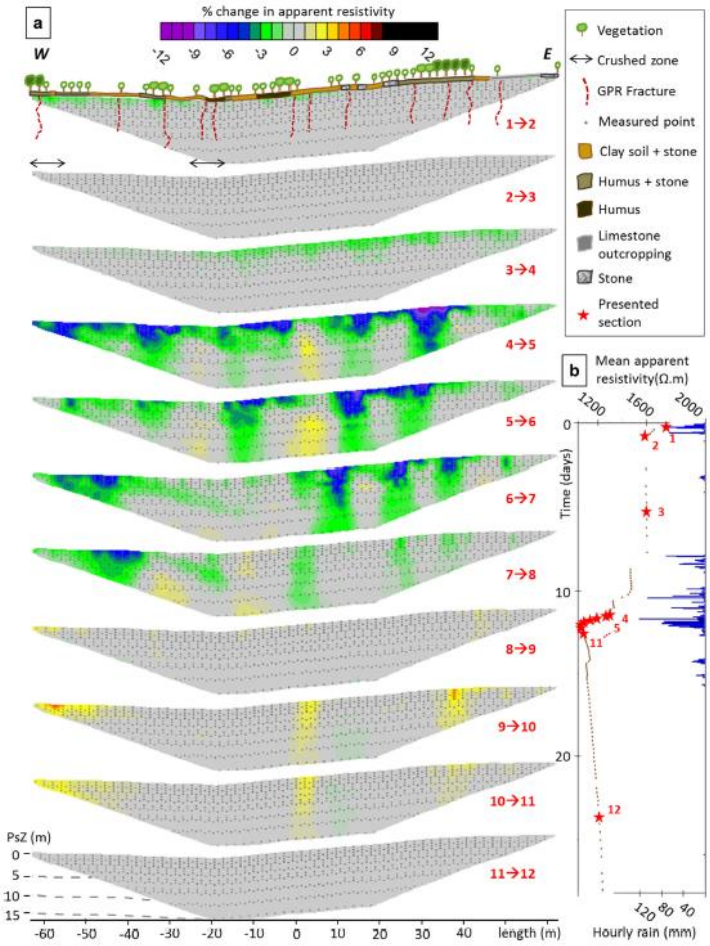

Figure 16 : *a. Variations horaires des résistivités apparentes par rapport au pas de temps précédent avec représentation simplifiée du couvert végétal et du sol ainsi que les fractures détectées avec le GPR* (Carrière *et al.*, 2013)*, b. Repérage temporel des sections dans le graphique pluie/moyenne arithmétique des résistivités apparentes.* (Carrière *et al.*, 2015)*.*

Suivi « haute-fréquence » temporelle – RMP

Dans la continuité des travaux précédents concernant le suivi haute fréquence en milieu karstique, nous avons mené une deuxième expérience hydrogéophysique unique aussi en milieu karstique et toujours sous conditions naturelles. Une campagne de mesures RMP, haute-fréquence, depuis la surface, durant un évènement de pluie intense d'automne a eu lieu sur le site de Buissonnière au sein du LSBB (**Figure 17**). Cet épisode, typiquement méditerranéen, a duré 5 jours avec une pluie cumulée de 168 mm. Un total de 8 sondages RMP ont été enregistrées sur le même profil avant, durant et après l'événement pluvieux (79 jours).

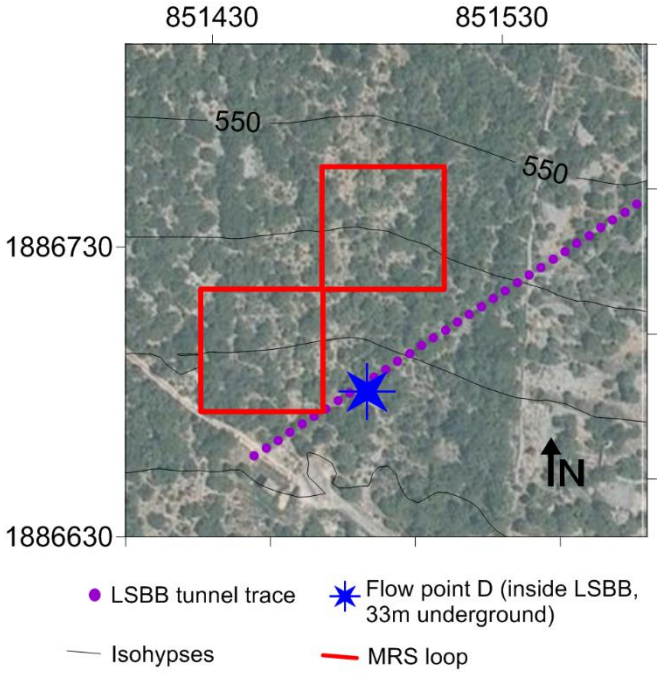

Figure 17 : *Localisation de la boucle RMP, du tunnel du LSBB et du point d'écoulement D sur le site de Buissonnière.*

Les résultats obtenus, non-inversés (développement du code d'inversion en time-lapse RMP en cours), démontrent (Mazzilli *et al.*, (accepted)) :

A. sur le plan méthodologique, l'applicabilité et l'efficacité de la RMP pour suivre des évènements pluvieux à haute-fréquence. En effet, les changements dans le contenu en eau de la ZNS de l'aquifère karstique génèrent des signaux RMP qui peuvent être mesurés depuis la surface. L'eau infiltrée a une forte influence sur les amplitudes des signaux RMP.
B. pour la compréhension de la dynamique de l'infiltration : **1.** même si l'évènement n'a duré que 5 jours, le maximum des signaux RMP a été observé entre 5 et 15 jours après (sondages 3, 4 et 5 - **Figure 18**). **2.** Le drainage du milieu semble démarrer environ 15 jours après l'événement (sondage 6 - **Figure 18**) et **3.** le retour à l'état initial du milieu a eu lieu environ 42 jours après la fin de l'épisode pluvial (**Figure 19**).

En faisant une inter-comparaison des hydrosystèmes karstiques, on constate que les mesures RMP réalisées sur le site du Larzac (**cf. Chapitre 3.1.2.**), mais en basse fréquence temporelle, n'ont pas pu identifier de changements sur la teneur en eau de la ZNS. Ceci est expliqué d'abord par la nature géologique des formations carbonatés et par la fréquence temporelle du suivi RMP.

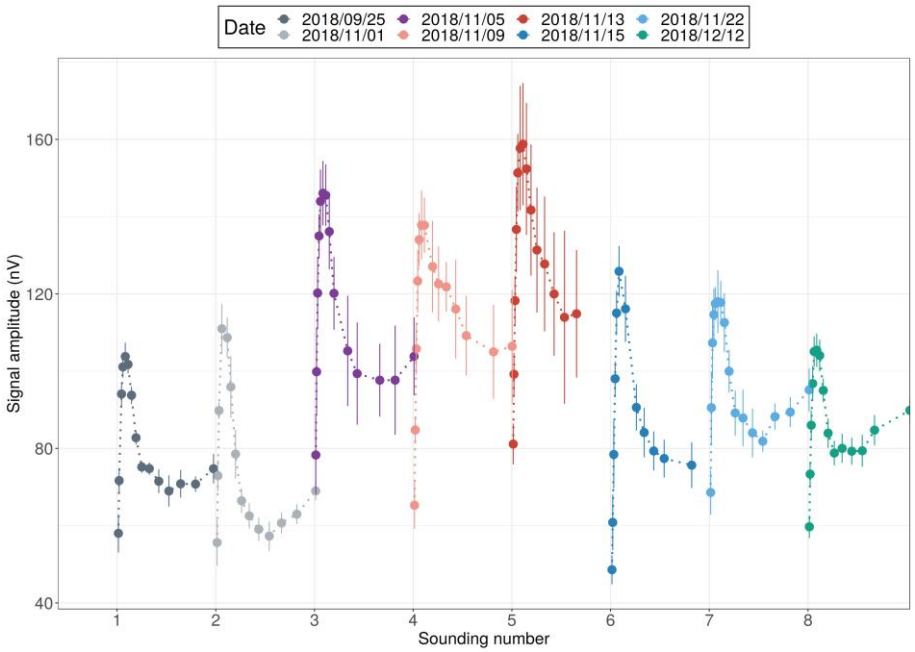

Figure 18 : *Variabilité temporelle du signal RMP. L'amplitude du signal RMP en fonction des impulsions pour toutes les sondages (Mazzilli* et al.*, (accepted))*

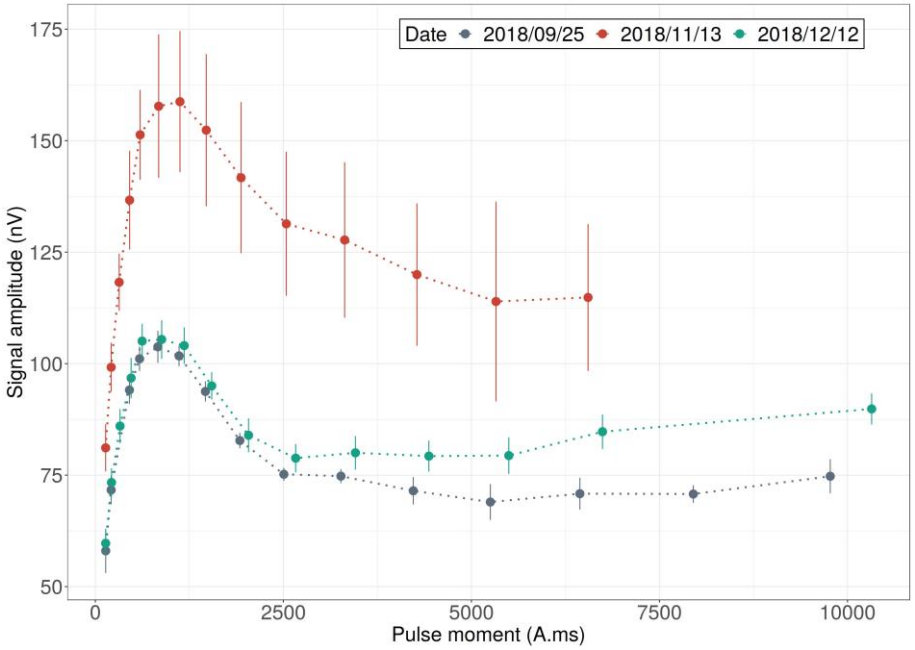

Figure 19 : *Variabilité temporelle du signal RMP. L'amplitude du signal RMP en fonction des impulsions pour trois sondages (1, 5 et 8) (Mazzilli* et al.*, (accepted)).*

3.1.4. Structure et fonctionnement des différents compartiments des hydrosystèmes

Hydrosystèmes karstiques

En 2011, j'ai évalué l'adéquation des méthodes et techniques géophysiques de surface pour la reconnaissance des différentes parties d'un système karstique, ainsi que leurs efficacité et rendement (Chalikakis *et al.*, 2011). Cette évaluation a été basée sur l'ensemble de mes travaux en hydrogéophysique appliquées à divers milieux karstiques sur le pourtour Méditerranéen, jusqu'à 2011, et une étude bibliographique exhaustive.

On peut résumer les principales problématiques que les hydrogéologues cherchent à résoudre en domaine karstique :

1. La définition des limites d'un système karstique affleurant ou sous couverture sédimentaire (toit du substratum carbonaté, contact avec les formations non carbonatées, présence de failles,…).
2. Localisation des zones de fracturation. Est-ce que la géophysique peut distinguer une formation carbonatée massive d'une zone plus fracturée ? Selon le contexte, les axes de fracturation peuvent correspondre à la direction préférentielle du développement de la karstification.
3. La détermination de la morphologie karstique quand le karst est sous couverture (dépressions, vallées,…).
4. Localisation de points d'infiltration préférentielle (gouffres, pertes,…) susceptibles d'être colmatés ou cachés sous des sédiments.
5. Localisation des cavités dites fossiles, localisées au-dessus du niveau de base (grottes, paléo drains éventuellement réutilisés en crue,…).
6. Localisation des cavités noyées.

En regard de ces problématiques, j'ai classé les méthodes et les appareils selon leurs performances, du point de vue de leur adéquation aux problèmes à résoudre, mais aussi du « rendement » et des coûts de mise en œuvre (**Figure 20**).

Ce tableau constitue un résultat important de mes travaux de recherche en hydrogéophysique sur les hydrosystèmes karstiques jusqu'à 2011 et peut être utilisé en première approche comme guide méthodologique. Toutes les méthodes à l'exception du magnétisme, sont recommandées pour au moins une problématique karstique. Leur combinaison est donc indispensable pour caractériser au mieux un site dans sa globalité.

Table 1 Adequacy of ground-based geophysics for karst-system exploration

Ground based geophysics		Adequacy of the method											Remarks	
		With sedimentary covering					Without sedimentary covering					Sedimentary covering			
Method	Measurement technique	Boundaries	Fractured zone	Preferential pathways	Cavities		Boundaries	Fractured zone	Preferential pathways	Cavities		Type	Thickness	Rent cost per week	Min number of operators
					Air-filled	Water-filled				Air-filled	Water-filled				
Electrical	ES	+++	++	+	0	0	+++	+	+	0	0	++	+++	II	3
	ERT	++	++	++	++	++	+++	++	++	+++	++	+++	++	III	2
	Mise-à-la-masse	0	0	++	0	++	0	+	++	0	++	0	0	II	2
	SP	0	++	+++	0	++	0	++	+++	0	++	+	0	I	2
EM	Slingram	++	++	++	+	+	++	++	++	++	++	+++	++	II	2
	TDEM	+++	+	0	0	0	+++	+	0	0	0	+++	+++	II	2
	GPR	0	+	+	+	+	+	+++	++	+++	++	+	0	II	3
	CSAMT	+++	++	++	+	+	+++	+++	++	+	+	+++	+++	IV	2
	VLF res.-RMT	++	++	++	+	+	+++	+++	+++	+	+	+++	+++	II	2
	VLF EM	+++	+++	+++	+	+	++	+++	+++	+	+	++	+	II	2
Seismic	Tomography	+++	++	++	++	++	+++	++	++	++	++	++	++	IV	2
	MASW	++	++	++	++	++	++	+++	++	++	++	++	++	IV	3
Microgravity	Profiling or mapping	0	++	+	+++	++	0	+	+	+++	++	0	0	III	2
Magnetic	Profiling or mapping	0	0	0	0	0	0	0	0	0	0	++	0	II	2
MRS	Sounding	0	0	0	0	+++	0	0	0	0	+++	+	0	V	2

+++ recommended; ++ appropriate but incomplete; + appropriate but limited; *0* not recommended

I <300 €; *II*301–600 €; *III*601–1000 €; *IV*1,001–2,000 €; *V*>2001 €—sources: ABEM France (2010), IRIS Instruments (2010), Expins (2010, Geomatrix (former Georental) (2010). Rental prices can vary depending on the geographical area, equipment type and model, time of rental etc.

CSAMT controlled source audio magnetotelluric; *EM* electromagnetic; *ERT* electrical resistivity tomography; *ES* electrical sounding; *GPR* ground penetrating radar; *MASW* multichannel analysis of surface waves; *MRS* magnetic resonance sounding; *RF-EM* radio frequency electromagnetic; *RMT* radio magnetotellurics (enhanced VLF-R); *SASW* spectral analysis of surface wave; *SP* self potential; *TDEM* time domain electromagnetic; *VLF* very low frequency; *VLF-R* very low frequency-resistivity

Figure 20 : *Adéquation des méthodes géophysiques de surface pour l'exploration des systèmes karstiques* (Chalikakis *et al.*, 2011)

Hydrosystèmes karstiques – focus sur la ZNS

La suite de mes travaux de recherche en milieux karstiques s'est orientée vers la caractérisation de la structure et du fonctionnement de la ZNS (Zone Non Saturée). La ZNS des hydrosystèmes karstiques peut jouer un rôle majeur en tant que réservoir avec un important soutien des débits, aussi bien en période de crue que d'étiage du système (ex. Emblanch *et al.*, 2003; Mudarra and Andreo, 2011).

Durant la thèse de Simon CARRIERE (2010-2014), nous avons menés plusieurs expériences hydrogéophysiques sur le site de Buissonnière du LSBB, situé eu sein de la ZNS de l'aquifère karstique de Fontaine de Vaucluse (**Figure 21**).

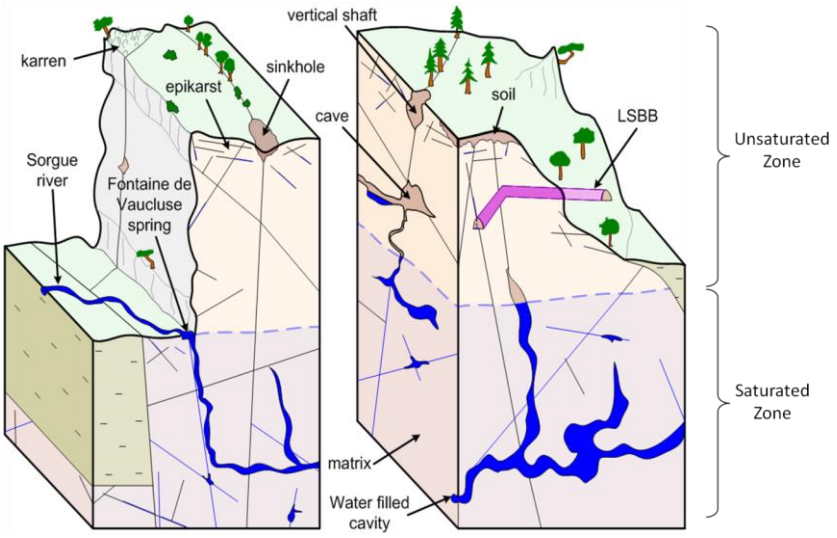

Figure 21 : *Schéma conceptuel de l'hydrosystème karstique de Fontaine de Vaucluse avec la localisation du LSBB* (Carriere *et al.*, 2016)

L'objectif de ces travaux était de comprendre le fonctionnement et l'origine de l'eau du point d'écoulement pérenne D, situé dans la galerie du LSBB et à 33 m de profondeur et ainsi améliorer la compréhension de la structure et du fonctionnement de la ZNS de l'aquifère karstique.

En combinant les informations géologiques, géomorphologiques et géotechniques avec un large panel de prospections hydrogéophysiques (ERT, GPR, EM-34, gravimétrie, sismique, RMP) nous avons identifié les structures géologiques sédimentaires qui gouvernent le stockage d'eau au sein de la ZNS (**Figure 22**). Nous avons synthétisé, ensuite, l'ensemble des connaissances acquises sur le site du LSBB en hydrogéophysique pour établir un modèle conceptuel du fonctionnement du point d'écoulement D (**Figure 23**). La présence d'eau pérenne au sein de la ZNS a été validé par l'implantation de trois forages sur la plateforme expérimentale de Buissonnière.

L'ensemble de ces résultats ont démontré que l'eau contenue dans la matrice poreuse au sein de la ZNS peut avoir un rôle important sur la régulation des écoulements lents pour l'hydrosystème karstique de Fontaine de Vaucluse (Carrière *et al.*, 2016).

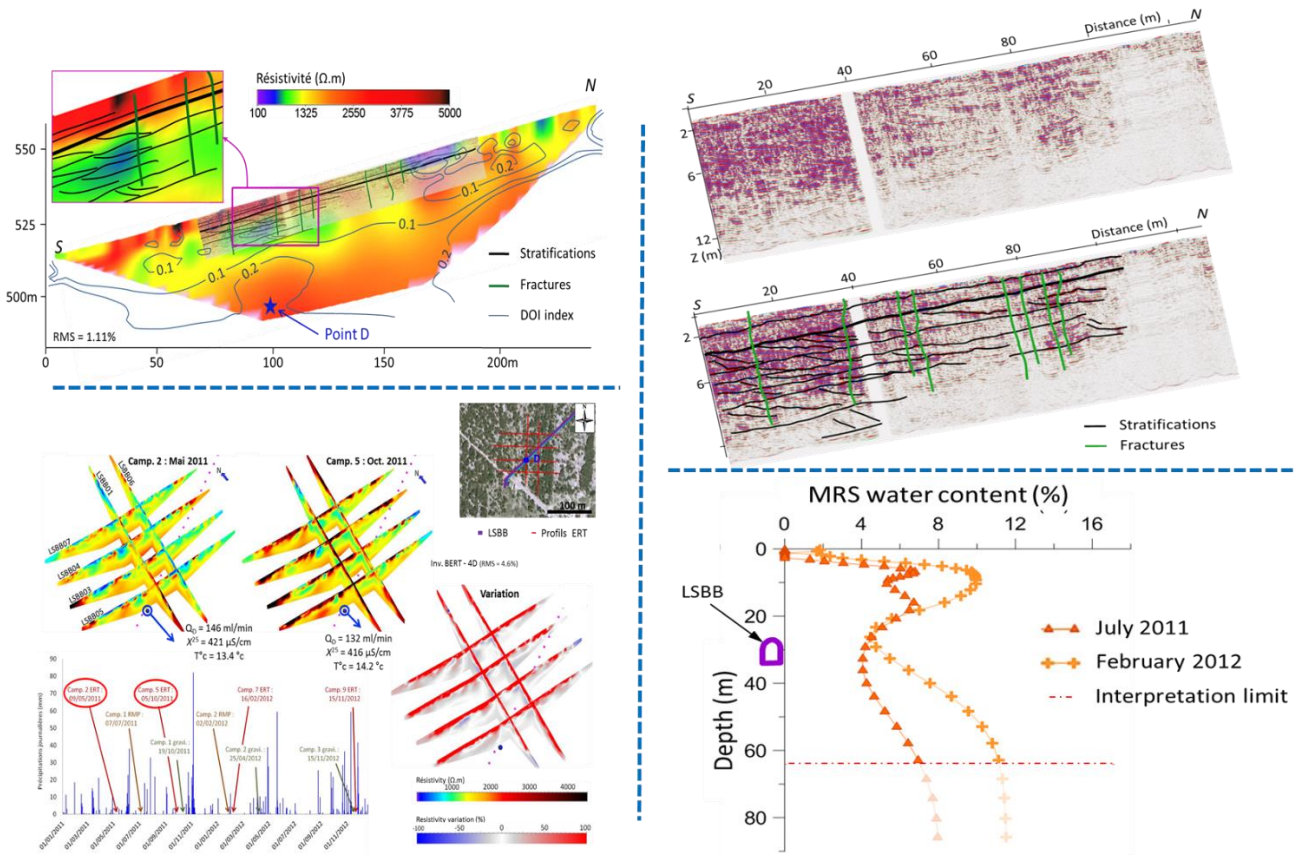

Figure 22 : *Synthèse des résultats de plusieurs campagnes hydrogéophysiques sur le site de Buissonnière (Carrière 2014, Carrière et al., 2013, 2016)*

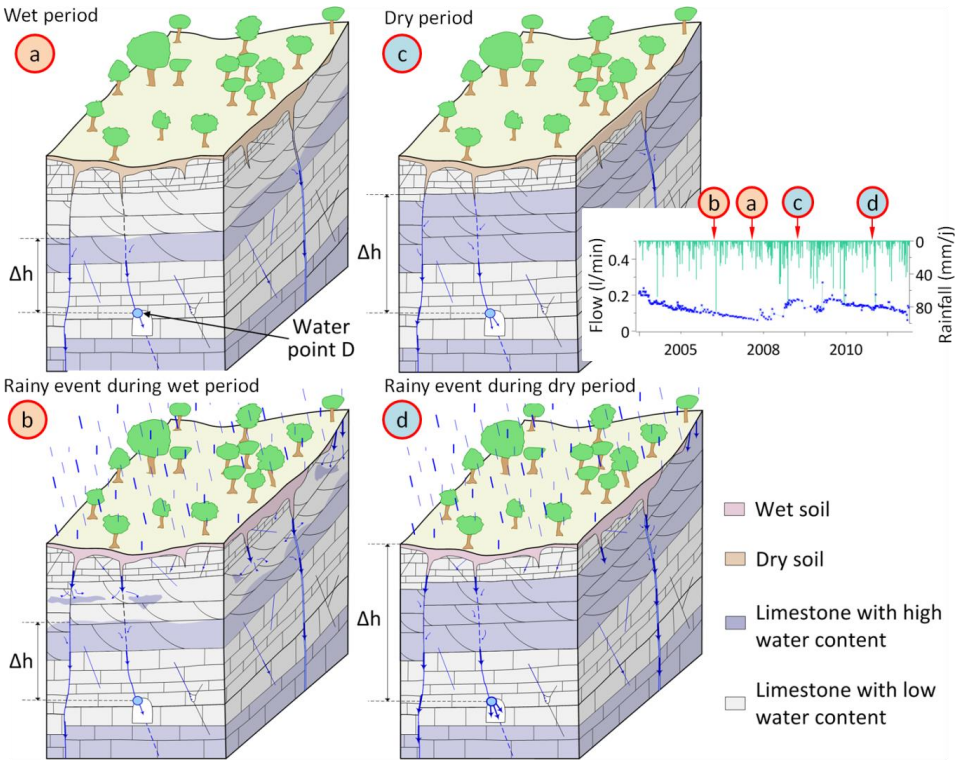

Figure 23 : *Modèle conceptuel du fonctionnement du point d'écoulement D sur le site de Buissonnière (Carrière et al., 2016)*

3.2. Approches intégrées pour une gestion durable des ressources en eau souterraines

Les exemples de travaux de recherche présentés dans les précédents chapitres démontrent que, malgré les limitations méthodologiques et instrumentales identifiées, l'hydrogéophysique permet de caractériser la structure des aquifères et d'améliorer les connaissances sur leur fonctionnement hydrodynamique. Toutefois, même si, grâce à l'hydrogéophysique, nous pouvons actuellement mieux localiser les ressources en eau souterraine, pour une optimisation de leur exploitation, nous devons, à tout prix, assurer leur durabilité.

La gestion durable des ressources en eau souterraine, établie en 1987 par la Commission pour l'Environnement et le Développement des Nations Unies, est un enjeu sociétal fort qui a des implications tant sur le plan environnemental que sur le plan économique. Cette notion, modifiée actuellement, suggère que la durabilité des eaux souterraines est le développement et l'utilisation des ressources afin de répondre à des utilisations actuelles et futures sans entraîner de conséquences environnementales ou socio-économiques inacceptables ou irréversibles.

Depuis 2014, et grâce à la pluridisciplinarité de l'UMR EMMAH et à plusieurs projets de recherche nationaux et internationaux, j'ai élargi une partie de mes travaux de recherche vers des approches plus intégrées visant à améliorer nos connaissances globales des hydrosystèmes afin d'assurer leur gestion durable.

3.2.1. De l'hydrogéophysique au suivi des ressources en eau souterraine en vue d'une gestion durable

Outre les suivis hydrogéologiques et hydrogéophysiques long-terme au sein de l'hydrosystème de la Fontaine de Vaucluse /LSBB, qui font partie de mes activités de recherche (**cf. Chapitre 3.3**) j'ai initié en partenariat avec l'ONG (Organisation Non Gouvernementale) Action Contre la Faim (ACF) l'implémentation d'un observatoire hydro-climatique au sud-ouest du Madagascar. J'y ai coordonné, entre 2014 et 2016 différents projets de recherche sur le plateau Mahafaly (sud-ouest de Madagascar) (**Figure 24**).

Le plateau Mahafaly est une région au climat semi-aride où l'eau souterraine représente la seule ressource en eau disponible et où la population, ainsi que la végétation, vivent en situation quasi-permanente de stress hydrique. En y associant les problèmes de malnutrition et de santé, le sud de Madagascar est souvent en état l'alerte humanitaire (https://fews.net/fr/southern-africa/madagascar). Les travaux menés visaient d'abord à assurer l'accès à l'eau potable pour la population et mais aussi à suivre et comprendre le fonctionnement et la recharge de l'aquifère exploité dans le cadre des changements globaux.

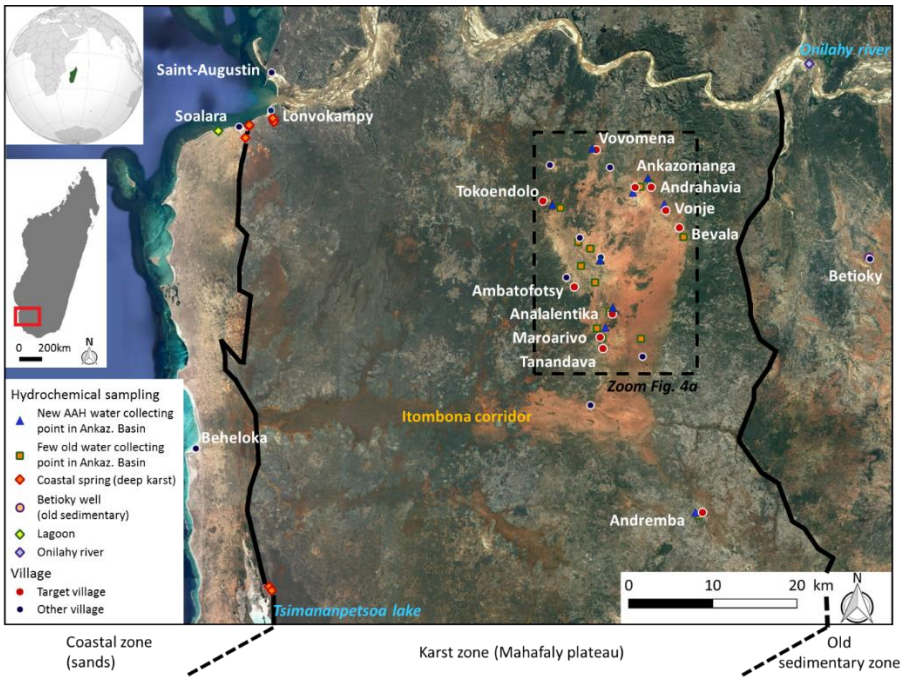

Figure 24 : *Localisation et caractéristiques générales du bassin d'Ankazomanga (Plateau Mahafaly).*

Dans le cadre des travaux post-doctoraux de Simon CARRIERE (2014), nous avons développé une approche méthodologique à quatre phases pour assurer l'exploitation durable de ressources en eau souterraine (**Figure 25**). Cette approche a été conçue pour s'adapter également aux contraintes des projets humanitaires (<40k€) (Carrière *et al.*, 2018).

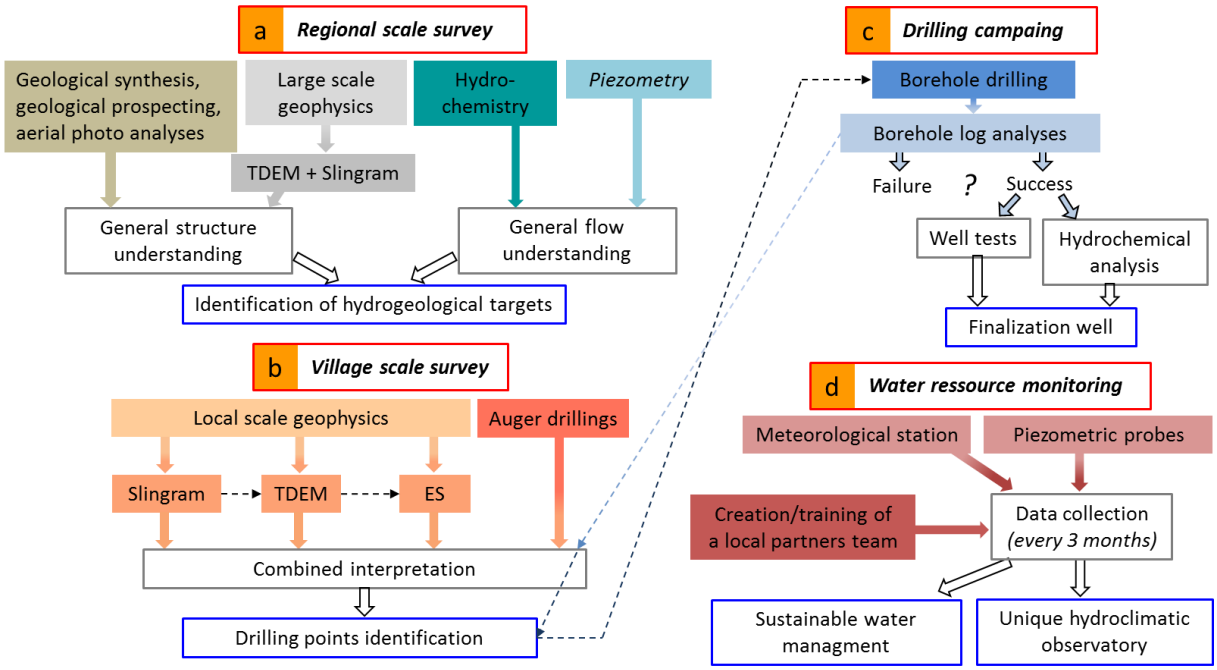

Figure 25 : *Approche méthodologique développé pour l'exploration, l'exploitation et la gestion durable des ressources en eau du plateau de Mahafaly (Carrière* et al.*, 2018).*

Nous avons combiné des mesures géophysiques (262 sondages TDEM, 2588 mesures EM-34 et 35 sondages électriques), des mesures hydrochimiques et isotopiques (112 échantillons d'eau) et des mesures piézométriques (127 points). Deux aquifères ont été identifiés, un profond (>150 m) et un superficiel (<20 m). Les résultats des analyses hydrochimiques ont montré un risque élevé de pollution, d'origine anthropique pour l'aquifère superficiel et d'origine naturelle (intrusion saline) pour l'aquifère profond.

Les résultats de cette approche hydrogéophysique intégrée ont permis d'optimiser l'implantation de 6 nouveaux forages et de 3 puits pour exploiter l'aquifère superficiel (**Figure 26**). Depuis la mise en place de ces nouveaux points d'eau nous avons mis en place un suivi piézométrique et météorologique pour suivre l'exploitation de la ressource, sa recharge en fonction du climat et identifier les périodes des fortes pressions anthropiques à la ressource en eau (**Figure 27**).

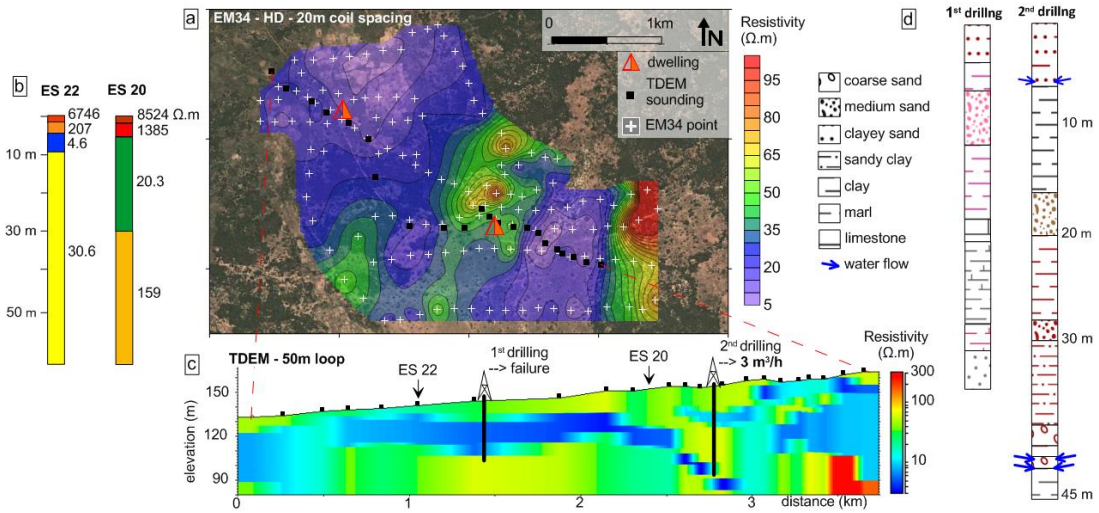

Figure 26 : *Exemple des résultats obtenus à l'échelle du village de Tokoendolo ; a. EM-34, b. sondage électrique, c. TDEM avec la position et les résultats de nouveaux forages et d. les logs simplifiés de ces forages (Carrière* et al.*, 2018).*

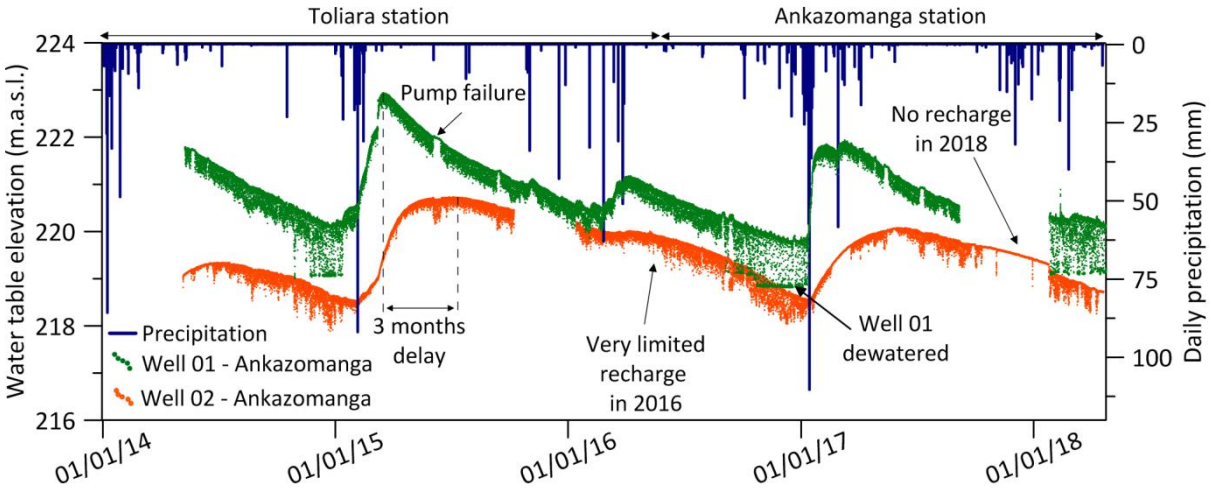

Figure 27 : *Résultats de l'observatoire hydroclimatique – exemple du village d'Ankazomanga ; les deux puits se situent à une distance de 500 m et ils ont 2 m de différence d'altitude (Carrière* et al.*, 2018).*

Depuis 2016 jusqu'à aujourd'hui, d'autres sites ont été instrumentés au sud de Madagascar dans le cadre d'une collaboration plus large, entre ONG et universités (locales et françaises), menant au développement du Groundwater Resource Observatory for Southwestern Madagascar (GROSoM).

Les observations hydroclimatiques montrent une forte variabilité inter annuelle des précipitations qui induisent une forte variabilité sur la recharge. Les travaux préliminaires des études transdisciplinaires (avec notamment des épidémiologistes et des spécialistes en sous-nutrition) soulignent un lien direct entre les ressources en eau et la santé des populations.

GROSoM est actuellement piloté par Simon CARRIERE et je reste toujours activement impliqué.

3.2.2. Vulnérabilité, recharge et modélisation des hydrosystèmes karstiques

La recharge des hydrosystèmes karstiques dépend des conditions climatiques, de la transpiration de la végétation, de l'évaporation des sols, des propriétés du sol et de l'hétérogénéité du karst (**Figure 28**).

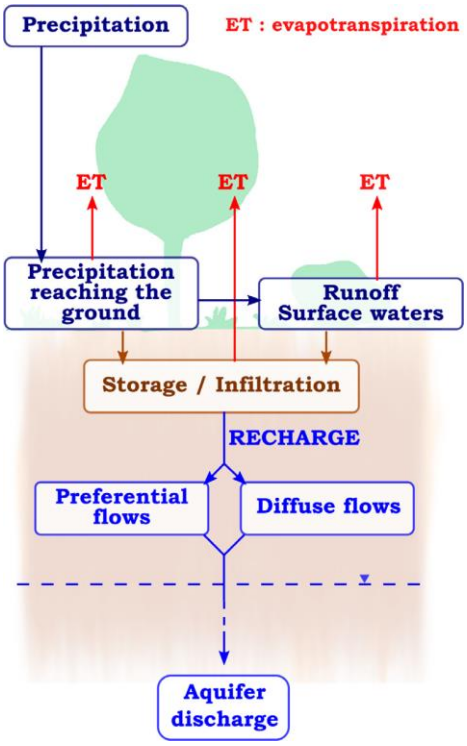

Figure 28 : *Schéma des processus de recharge des aquifères karstiques (Ollivier et al., 2020)*

Le modèle conceptuel semi-distribué KaRaMel (**Ka**rst **R**echarge and disch**a**rge **M**od**el**) (Ollivier *et al.*, 2020), développé dans le cadre de la thèse de Chloé OLLIVIER (2014-2019), permet de simuler la variabilité spatiale et temporelle de la recharge des hydrosystèmes karstiques.

Pour contraindre la répartition entre flux lents et flux rapides (**Figure 28**) du modèle KaRaMel, dans l'étude de l'aquifère karstique de la Fontaine de Vaucluse, nous avons employés les indices de vulnérabilité intrinsèque (Ollivier, Chalikakis, *et al.*, 2019) identifiés par la méthode PaPRIKa (Dörfliger and Plagnes, 2009; Kavouri *et al.*, 2011) (**Figure 29**).

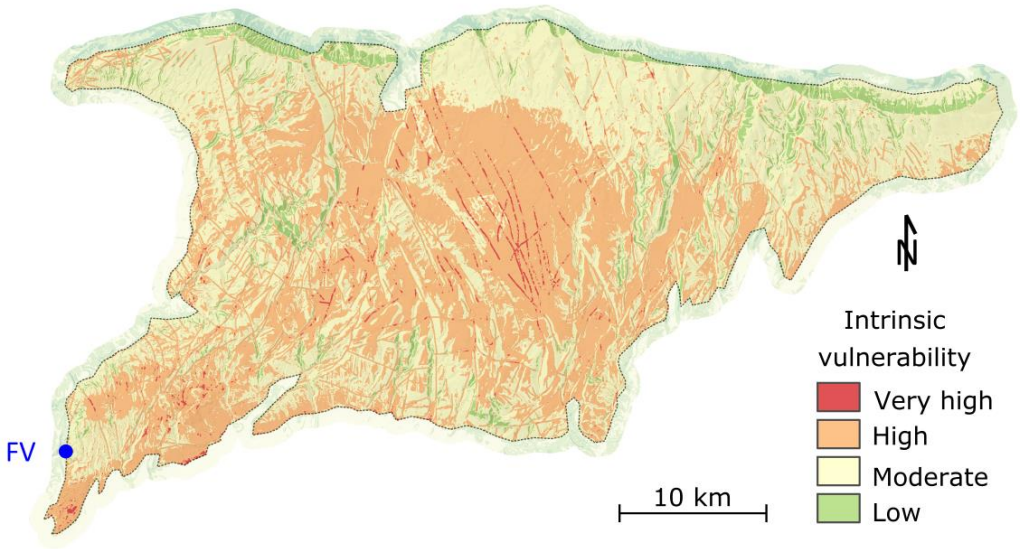

Figure 29 : *La carte de la vulnérabilité intrinsèque de l'hydrosystème karstique de Fontaine de Vaucluse (Ollivier, Chalikakis,* et al.*, 2019)*

Les parties les plus vulnérables (en rouge) de l'hydrosystème de Fontaine de Vaucluse ne représentent que 2 % de la superficie du bassin. Il s'agit de zones avec un exokarst bien développé ou des zones avec des importantes structures tectoniques. 45 % du territoire du bassin présente un index de vulnérabilité élevé (en orange) où les plateaux et les formes karstiques permettent une infiltration rapide. 48 % présente un index de vulnérabilité modérée correspondant aux pentes montagneuses abruptes tandis que 5 % présente un faible index de vulnérabilité où grâce aux fortes pentes du versant le ruissellement est dominant.

Un module d'extension (plugin) pour le système open-source d'information géographique (QGIS Quantum Geographic Information System) a été développée (Ollivier, Lecomte, *et al.*, 2019) afin de faciliter la cartographie de la vulnérabilité intrinsèque des aquifères karstiques avec la méthode (**Figure 30**). Ce module, développé avec le support du SNO KARST, a été mis à disposition à l'ensemble de la communauté hydrogéologique internationale. Depuis sa dernière mise à jour le module d'extension a été téléchargé plus de 1000 fois.

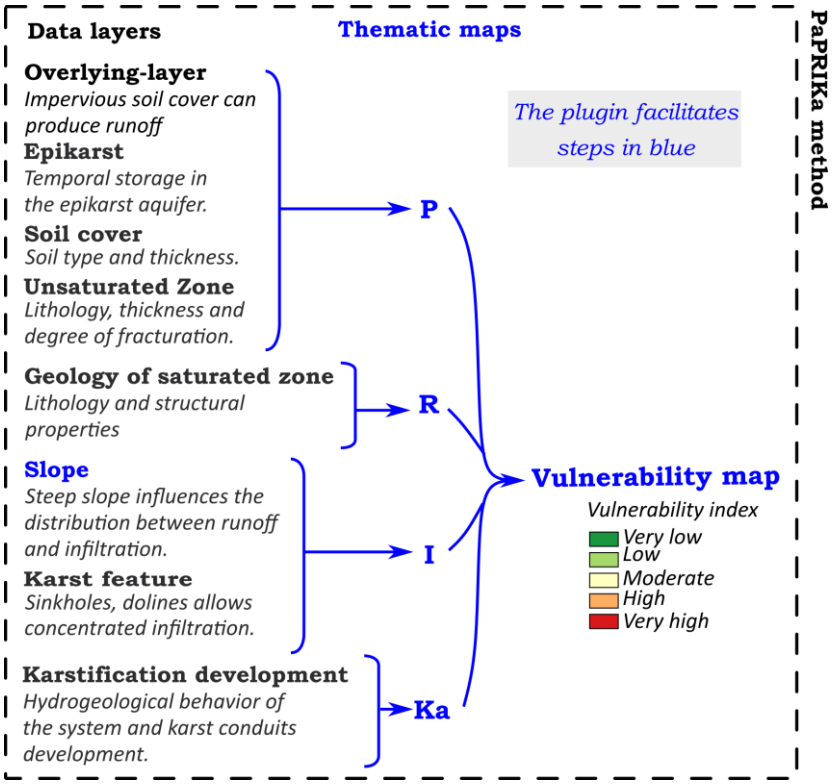

Figure 30 : *Module d'extension de la méthode PaPRIKa (Ollivier, Lecomte,* et al.*, 2019)*

La thèse de Chloé OLLIVIER est une belle illustration de la pluridisciplinarité, du potentiel des collaborations thématiques transversales et de la synergie qui peut se créer au sein de l'UMR EMMAH.

3.2.3. Approche intégrée pour la gestion des ressources en eau des hydrosystèmes karstiques en Grèce

Les travaux de recherche post-doctoraux de Nerantzis KAZAKIS visaient à appliquer les approches méthodologiques développées au sein de l'équipe HYDRO de l'UMR EMMAH aux hydrosystèmes karstiques en Grèce. Ces derniers représentent environ 35% du territoire grec (Daskalaki and Voudouris, 2008), avec un rôle central sur le plan environnemental et économique.

Nous avons mené un travail de synthèse concernant les aquifères karstiques en Grèce. Ceci incluait d'abord un bilan bibliographique exhaustif des travaux de recherches appliquées aux hydrosystèmes grecs et ensuite, la mise en place d'une approche méthodologique intégrée à un aquifère stratégique du pays. En effet, l'hydrosystème karstique de Damasi-Titanos (Grèce centrale) présente un intérêt socio-économique majeur avec des importants enjeux environnementaux liés à la complexité de sa structure et de son fonctionnement. Nous avons combiné les outils, précédemment présentés, pour l'estimation de la vulnérabilité intrinsèque et le risques à la pollution avec des analyses statistiques et hydrodynamiques (Kazakis *et al.*, 2018).

La **Figure 31** (Kazakis *et al.*, 2018) présente un résultat central de ces travaux : une feuille de route proposée pour l'exploration et la gestion durable des aquifères karstiques en Grèce. Elle contient 4 étapes indispensables :

1. Les observations hydrogéologiques (données spatiales et temporelles)

2. L’application des méthodes statistiques avancées pour l’analyse des séries de données
3. L’application des modèles intégrées selon les caractéristiques de l’aquifère
4. L’évaluation de la vulnérabilité et des risques à la pollution

Les observations hydrogéologiques doivent s’étendre au-delà de l’aquifère karstique pour pouvoir comprendre les interactions avec les hydrosystèmes avoisinants. En complément la fréquence temporelle des données acquises est critique pour les étapes suivantes. Par exemple, les analyses hydrochimiques et isotopiques peuvent fournir des résultats fiables même si leur acquisition n’est pas continue. Au contraire les données climatiques, piézométriques et hydrodynamiques à l’exutoire doivent être continues avec une haute fréquence temporelle (ex. journalière ou horaire). Il est également important de mettre régulièrement à jour l’usage du territoire de l’hydrosystème car il est étroitement lié à la demande de l’eau. Si ces données (a minima) sont limitées, le passage à l’autre étape n’est pas recommandé car l’analyse statistique, nécessaire pour la modélisation, présentera un grand nombre d’incertitudes. Ainsi l’hydrogéologue doit revenir en arrière et assurer en amont l’efficacité et la fiabilité de ses données.

La troisième étape vise à quantifier l’eau dans l’hydrosystème et la quatrième étape concerne la protection de la qualité de la ressource. En effet, l’évaluation de la vulnérabilité et du risque à la pollution sont des outils qui permettent de délimiter des zones de protection et proposer des changements sur l’usage du territoire. Dans tous les cas, il est important de maintenir la circularité de ces étapes qui seront soutenues mutuellement pour pouvoir supporter cette approche intégrée en vue d’une gestion durable de la ressource en eau.

Certainement cette feuille de route peut être applicable à d’autres hydrosystèmes karstiques mais des adaptations concernant les particularités structurales et fonctionnelles seront nécessaires.

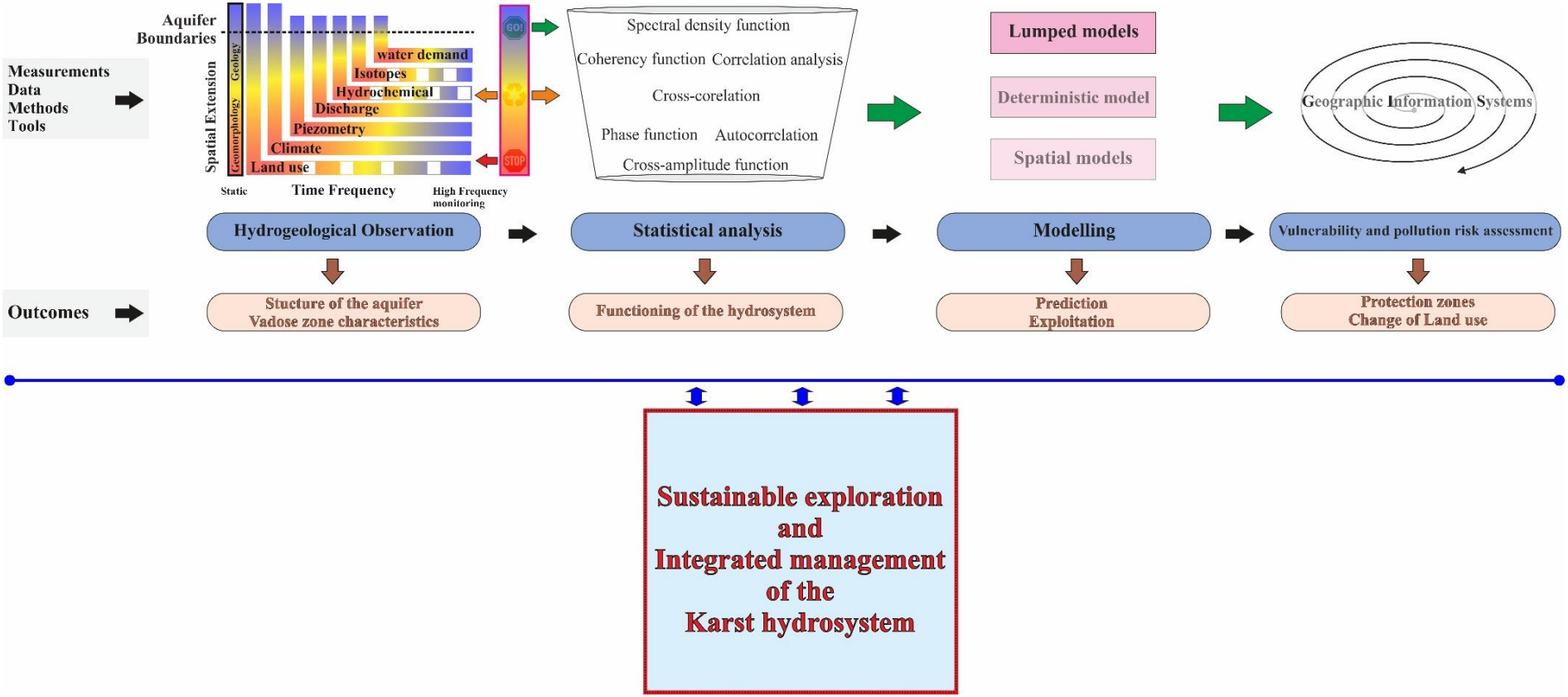

Figure 31 : *Feuille de route pour l'exploration et la gestion durable des ressources en eau des hydrosystèmes karstiques en Grèce (Kazakis* et al.*, 2018).*

3.3. Dispositifs de mesures et d'observations

Mes travaux en hydrogéophysique en France sont liées à trois dispositifs d'observations scientifiques. Les SNO H+, KARST et l'IR OZCAR. Ces derniers jouent un rôle majeur pour la recherche hydrogéologique en France, pour mes travaux et ainsi j'y ai une forte implication. Mes activités de recherche ont également permis de développer au sein de l'UMR EMMAH une plateforme d'instrumentation hydrogéophysique, unique en région PACA.

3.3.1. Services Nationaux d'Observations (SNO) : H+ et KARST

Une importante partie de mes activités de recherche sur les hydrosystèmes karstiques est basée sur les observations hydrogéologiques et hydrogéophysiques, temporaires ou permanentes au sein du bassin d'expérimentation de la Fontaine de Vaucluse / LSBB (Laboratoire Souterraine à Bas Bruit) sur deux échelles d'investigation imbriquées: le bassin d'alimentation de la Fontaine de Vaucluse (avec des travaux principalement à l'échelle de l'hydrosystème) et le LSBB (avec des travaux des échelles locale à méso échelle). Ces activités de recherche, à ces deux échelles, font partie de deux SNO[12] : le SNO H+ et le SNO KARST.

Le site du LSBB à Rustrel fait partie du SNO H+ qui est le réseau national des observatoires hydrogéologiques (http://hplus.ore.fr/) regroupant 6 sites hautement instrumentés en France et à l'international. Le SNO H+ fait partie de l'infrastructure de recherche OZCAR (Observatoires de la Zone Critique: Applications et Recherches). Le LSBB se situe au sein de la zone non saturée de l'aquifère karstique de Fontaine de Vaucluse et, à travers ses galeries, procure un accès privilégié et unique aux propriétés hydrogéologiques de l'hydrosystème. Par ses infrastructures et les observations associées, il s'agit d'un site unique pour la compréhension de la structure et du fonctionnement de la zone non saturée des aquifères karstiques. Le suivi hydrologique long-terme des écoulements souterrains au sein du LSBB, quasi ininterrompu depuis plus de 15 ans pour le volet hydrochimique, a été récemment enrichi grâce à des mesures hydrodynamiques et hydrogéophysiques et constitue un atout scientifique majeur pour la compréhension de la réponse des systèmes hydrologiques aux changements globaux. Les nouvelles infrastructures du LSBB (plateformes de forage depuis la surface et nouveau tunnel) permettront de nouvelles avancées tant sur le développement métrologique et méthodologique que sur la compréhension des mécanismes de la recharge des hydrosystèmes karstiques en vue d'une exploitation durable de leurs ressources en eau. Une compréhension qui est fortement dépendante de la caractérisation des flux au sein de la zone non saturée. Depuis 2015, je suis le responsable du site du LSBB et je coordonne toutes les actions hydrogéologiques qui y sont menés pour le SNO H+.

Le bassin d'alimentation de la fontaine de Vaucluse, au sein duquel se situe le site du LSBB, est le support de l'un des 9 sites-ateliers du SNO KARST (https://sokarst.org/) qui fait également partie de l'infrastructure de recherche OZCAR. Fontaine de Vaucluse est l'exutoire quasi-unique d'un système karstique exceptionnel tant par la surface de son bassin d'alimentation (1160 km²) que par l'épaisseur de ses zones non saturée (en moyenne 800 m) et saturée (> 300 m). L'ampleur du système permet d'appréhender l'impact de la variabilité latérale des environnements de dépôt sur les faciès

[12] les SNO labelisés par l'INSU (Institut National des Sciences de l'Univers) visent à documenter sur le long terme la formation, l'évolution et la variabilité des milieux naturels.

carbonatés, sur les processus de fracturation et karstification et sur la dynamique des écoulements. Les travaux menés au sein de l'observatoire (suivis hydrodynamiques, hydrochimiques et isotopiques à l'exutoire de l'hydrosystème karstique qui sont enrichis récemment avec des suivis hydrogéologiques à l'exutoire de sous-systèmes au sein du bassin) visent à améliorer la compréhension et la modélisation conceptuelle et numérique du fonctionnement hydrodynamique et hydrochimique des différents compartiments des hydrosystèmes karstiques, en contexte de changements globaux.

3.3.2. Plateforme d'instrumentation hydrogéophysique

Un des résultats, majeur mais indirect, de mes travaux de recherche est le développement d'une plateforme d'instrumentation hydrogéophysique au sein de l'UMR EMMAH. En effet, depuis ma prise de fonction en décembre 2009, et en étroite collaboration avec les collègues des équipes HYDRO et SWIFT de l'UMR, j'ai incité et coordonné l'achat de plusieurs équipements géophysiques. Cette plateforme est actuellement dotée de plusieurs outils de mesure (méthodes électrique, électromagnétique en domaine fréquentiel et RMP) et d'une importante variété d'accessoires liés aux différents dispositifs qui peuvent être mis en place sur le terrain. La création de cette plateforme d'instrumentation hydrogéophysique, unique pour le sud de la France et notamment dans la région PACA, a pu être mise en place grâce à plusieurs financements issus de divers projets de recherche (thèses, post-doc, partenariats industriels et socio-économiques, projets région).

Complémentaire à la plateforme du laboratoire analytique (hydrochimie et isotopie) qui existe depuis plus de 30 ans et piloté par l'équipe HYDRO, la plateforme d'instrumentation hydrogéophysique a une double importance pour les activités de l'UMR EMMAH :

1. **Recherche** : Elle permet d'abord une multitude d'expériences (à différentes échelles spatiales et temporelles) que nous pouvons mener de façon autonome sur les sites expérimentaux de l'UMR. Ensuite, elle est un atout majeur pour les travaux de recherche en cours et pour le montage de nouveaux projets. Finalement, la plateforme d'instrumentation hydrogéophysique est un pôle d'attractivité qui permet le rayonnement de nos activités de recherche tout en attirant de nouveaux partenariats de recherche.
2. **Enseignement** : Elle permet la mise en place des TD et des TP spécifiques pour chaque méthode hydrogéophysique et pour leur combinaison dans des contextes hydrogéologiques variés. Ainsi, elle permet une adaptation et une mise à jour des enseignements en hydrogéophysique en lien avec les avancées technologiques et méthodologiques du domaine. En effet, nous pouvons démontrer les avantages, la complémentarité, les limites et les avancées de la recherche pour chacune de méthodes, permettant ainsi d'améliorer constamment notre offre de formation.

Actuellement, la stratégie du développement mise en place pour la plateforme d'instrumentation hydrogéophysique prévoit des nouvelles acquisitions d'équipements (ex. TDEM). Suite à la reconnaissance institutionnelle très récente de cette plateforme instrumentale je focalise actuellement mes efforts sur la pérennisation du support en ressources humaines.

4. Conclusions et perspectives

Dans ce mémoire d'HDR, j'ai fait une sélection de travaux proposant de nouvelles avancées tant sur le plan méthodologique en hydrogéophysique que sur la caractérisation et la compréhension des processus hydrogéologiques au sein de la Zone Critique en vue d'une gestion durable de ses ressources en eau souterraine. Afin de garder un fil conducteur simple j'ai fait le choix de ne pas être exhaustif. Un grand nombre de travaux de recherche, que j'ai pilotés ou auxquels j'ai activement participé, ne sont donc pas présentés dans ce mémoire. Malgré cela, ils ont à mes yeux une valeur scientifique ou opérationnelle importante. Parmi ceux-ci, il y a aussi des travaux toujours en cours ou en voie de finalisation, des travaux pas encore valorisés ou pas (encore) concluants, parfois des pistes sans issues ou des idées de recherche en suspension !

La sélection des travaux présentés, représentatifs de mes activités de recherche, était également guidée par mon encadrement de la recherche. Un encadrement auquel je crois avec conviction. En tant qu'enseignant-chercheur et responsable depuis 2012 du CMI (Cursus Master en Ingénierie) R2E (Ressources en Eau et Environnement), une grande partie de mes activités porte sur l'enseignement par la recherche et l'innovation. Hélas, dans notre corps de métier, le temps proprement dédié à la recherche se limite de plus en plus. Il est fortement contraint par les tâches pédagogiques et administratives qu'il faut assurer mais qui sont toutefois nécessaires pour le bon fonctionnement de l'université. Néanmoins, ces contraintes m'ont permis de mieux m'organiser afin de garder actif le volet recherche de mon activité. Elles m'ont permis de moins me disperser et ainsi d'apprendre à prioriser les actions de recherche à mener. J'aborde cette nouvelle étape de ma carrière scientifique avec les idées plus claires à ce sujet (ou du moins, je l'espère).

Vue d'ensemble et projet global de recherches

Les deux enjeux sociétaux et environnementaux qui forment le fil conducteur de mon parcours scientifique sont **l'accès** et la **durabilité** des ressources en eau souterraine au sein de la Zone Critique. Pour assurer l'accès à l'eau j'ai investi une importante partie de mes recherches en hydrogéophysique. Un autre volet de mes activités a visé l'exploitation optimisée des ressources en eau des hydrosystèmes en déployant des approches méthodologiques intégrées. Dans cette continuité, les deux grandes questions scientifiques qui vont guider la suite de ma carrière sont résumés en :

1. **Comment peut-on mieux caractériser et comprendre les processus de recharge des hydrosystèmes ?**
2. **Quels sont les impacts anthropiques et naturels sur les ressources en eau souterraine ? Peut-on les quantifier ? Peut-on les anticiper ?**

Les observations sur le long terme sont, à mon sens, le moyen le plus adéquat pour essayer de répondre à ces deux questions.

Pour répondre à la première question l'hydrogéophysique jouera un rôle central. En fait, la recherche en hydrogéophysique s'articule autour de trois composantes de nature interconnectées : le volet métrologique/instrumental, le volet codes de calculs/inversion des mesurables et le volet choix et application de méthodes/optimisation des dispositifs. Mes activités ainsi que mes perspectives de recherche en hydrogéophysique se positionnent dans cette dernière. Elles sont/seront alimentées par

les avancées sur les deux autres composantes et réciproquement elles identifient/identifieront les nouveaux verrous à lever grâce aussi aux résultats de mes travaux. Je donne dans la section « Perspectives à courts et moyens termes » ci-dessous un éclairage sur le rôle que peut jouer l'hydrogéophysique pour apporter des éléments de réponse à cette première question en précisant plusieurs pistes de recherche spécifiques.

Les observatoires scientifiques constituent la colonne vertébrale de l'approche que nous devons mener pour répondre à la deuxième question. Le rapprochement effectif entre sciences de l'eau, agronomie-foresterie, économie et gestion est aussi une condition indispensable. La gestion durable des ressources en eau est de nature transdisciplinaire. Le couplage des méthodes développées par les disciplines associées ne sera que bénéfique. Des métissages ont déjà eu lieu avec l'émergence des nouvelles sous-disciplines (ex. hydroecophysiologie, hydrobiophysique, hydroéconomie, hydrosociology). Outre les observatoires institutionnels déjà en place, il faut promouvoir la création de nouveaux observatoires à différentes échelles. Le rôle et l'implication du monde opérationnel et des gestionnaires territoriaux est central. L'observatoire GROSoM à Madagascar (**cf. Chapitre 3.2.1.**) est un bel exemple de la compréhension par le monde opérationnel de la nécessité d'une mise en place des observations long-termes. Mes travaux continueront dans la lignée de cette dynamique.

En déformant, un peu, les propos de Monique Toublanc (Projets de paysage 02/07/2009), on constate que les recherches conduites ces dernières décennies, nombreuses, diversifiées et de natures pluridisciplinaires, ont montré combien les hydrosystèmes sont des objets complexes, aux multiples facettes situées entre nature, technique et société.

Perspectives à court et moyen termes

Même si l'hydrogéophysique dispose d'un très large panel de méthodes adaptées pour étudier les interfaces et les processus au sein de la Zone Critique et alors que son potentiel intéresse de plus de plus la communauté scientifique, des limites méthodologiques et instrumentales ont été identifiées. Elles sont les nouveaux défis à relever en hydrogéophysique tant sur le plan méthodologique pour ce qui concerne la complémentarité et l'intégration de ses résultats aux autres disciplines qui étudient la Zone Critique.

Ces nouveaux défis guident mes perspectives de recherche à court et moyen termes. Celles-ci s'inscrivent dans la dynamique de projets de recherche en cours que je pilote ou auxquels je participe.

1. Caractérisation des mécanismes de recharge des hydrosystèmes karstiques

Les formations carbonatés karstiques contiennent 25% de la ressource en eau à l'échelle globale et plus qu'un quart de la population globale est totalement ou partiellement dépendante de l'eau potable issue de ces aquifères (ex. Chen *et al.*, 2017). Mais les ressources en eau des hydrosystèmes karstiques sont mal connues, vulnérables à la pollution et sensibles aux aléas climatiques et aux changements globaux (Jourde *et al.*, 2018; Liu *et al.*, 2018). Même si le développement des outils de modélisation améliore actuellement notre connaissance globale sur leur recharge (ex. Mudarra *et al.*, 2019; Berthelin *et al.*, 2020; Ollivier *et al.*, 2020), les processus dominants demeurent mal identifiées.

A l'échelle locale - LSBB

Comme déjà présenté dans les précédentes parties, le LSBB et notamment la plateforme expérimentale de Buissonnière procure d'excellentes conditions pour les études hydrogéophysiques de la ZNS des hydrosystèmes karstiques. Nous disposons actuellement d'une base de données très importante, en nombre et en valeur scientifique. En complément des mesures déjà réalisées dans le cadre de la thèse de Simon CARRIERE et de son post-doctorat à INRAE (S.D. Carrière *et al.*, 2020; Simon Damien Carrière, Martin-StPaul, *et al.*, 2020; Simon Damien Carrière, Ruffault, *et al.*, 2020), depuis 2018, dans le cadre du projet Interwells 4D (en partenariat avec TOTAL SA), nous avons mis en place, un suivi hydrogéophysique RMP mensuel à bimensuel. Grâce à SNO H+ et OZCAR, ce suivi RMP, qui sera pérennisé, a été doté ponctuellement par un suivi haute-fréquence (**cf. Chapirte 3.1.3.**) et enrichi avec d'autres mesures géophysiques ponctuelles (électriques, sismiques et muons) (post-doctorat de Sylvain PASQUET) ou permanentes (gravimétrie, GPS). Les trois forages implantés en 2015, qui recoupent la ZNS, sont équipés de sondes qui permettent de suivre le niveau piézométrique, la température et la conductivité de l'eau présente. Des essais de pompages/injections y ont été effectués avec des suivis hydrochimiques et isotopiques en continu. Une série complète de mesures diagraphiques a eu lieu. Depuis 2016, nous avons également installé une station météorologique pour un suivi climatique à une échelle plus fine. En profondeur, plusieurs stations automatiques ont été mises en place pour un suivi (hydrodynamique et hydrochimique) des points d'écoulements d'eau au sein des galeries du LSBB dont le point D qui se trouve à l'aplomb de Buissonnière.

Du point de vue technologique et instrumental, grâce à de divers partenariats, notamment l'UMR IGE, le Hydrogeophysics Group of Aarthus (Danemark) et IRIS Instruments (France), nous allons :

A. Améliorer l'interprétation de l'important jeux de données RMP, déjà acquises et en cours d'acquisition, en employant les nouveaux outils d'inversion en time-lapse en cours de développement (Legchenko, Baltassat, *et al.*, 2020).
B. Employer des nouveaux capteurs RMP en surface (Liu *et al.*, 2019) et en forage (Legchenko, Texier, *et al.*, 2020) pour compléter nos observations.
C. Améliorer, via de nouvelles avancées technologiques, notre compréhension du bruit électromagnétique afin d'améliorer la qualité et le temps d'acquisition de la RMP.

Du point de vue méthodologique et de la compréhension des processus, et compte tenu du caractère multi-physiques et multi-échelles de toutes les mesures acquises sur le site (depuis la surface et en profondeur), en étroite collaboration avec Géosciences et Hydrosciences Montpellier, ISTERRE et IGE à Grenoble, nous allons :

A. Etablir une stratégie d'interprétation commune de l'ensemble des observations.
B. Synthétiser les avancées sur la compréhension des processus de recharge au sein de la ZNS.
C. Identifier la ou les combinaisons des outils/méthodes les plus adéquates.
D. Identifier les nouvelles limitations et lever les défis associés.

A l'échelle de l'hydrosystème – Fontaine de Vaucluse

Les travaux menés à l'exutoire de l'hydrosystème karstique de Fontaine de Vaucluse (suivis hydrodynamiques, hydrochimiques et isotopiques) visent à améliorer la compréhension et la modélisation conceptuelle et numérique du fonctionnement hydrodynamique et hydrochimique des

différents compartiments des hydrosystèmes karstiques, en contexte de changement global. Depuis 2019, ces travaux sont enrichis avec des suivis hydrogéologiques à l'exutoire de sous-systèmes au sein du bassin de la Fontaine de Vaucluse.

Suite aux travaux de la thèse de Chloé OLLIVIER et aux résultats à l'échelle du LSBB, nous allons réaliser plusieurs campagnes hydrogéophysiques à l'échelle du bassin de Fontaine de Vaucluse avec deux objectifs scientifiques interconnectées :

A. **L'amélioration des modèles conceptuel et numérique de fonctionnement**. Des suivis hydrogéophysiques long-termes seront mis en place à l'échelle de sous-systèmes récemment équipés. L'objectif sera d'abord d'améliorer le modèle conceptuel de fonctionnement de ces sous-systèmes de l'aquifère de Fontaine de Vaucluse, en couplant les observations hydrodynamiques, hydrochimiques et hydrogéophysiques. Nous allons ensuite contraindre la modélisation numérique avec des observables hydrogéophysiques à l'échelle de sous-systèmes. Leur dimension réduite, et malgré la complexité du karst, offre un cadre adéquat à cette expérimentation. En effet, même si l'intérêt de l'insertion de données hydrogéophysiques dans les modèles hydrodynamiques a été reconnu par la communauté scientifique (ex. Comte *et al.*, 2010; Legchenko *et al.*, 2020a; Lesparre *et al.*, 2020), son potentiel reste très largement sous-exploité et d'autant plus pour les aquifères karstiques.
B. **La validation/confirmation des résultats du modèle semi-distribué de recharge de l'hydrosystème de Fontaine de Vaucluse.** En effet, des mesures hydrogéophysiques, permanentes ou temporaires, seront implantées dans des zones identifiées présentant de fortes variations de recharge par le modèle KaRaMel (Ollivier *et al.*, 2020). Cela va nous permettre d'abord une validation/confirmation des résultats du modèle semi-distribué de recharge et dans un deuxième temps, une meilleure cartographie de la vulnérabilité à la pollution de l'aquifère de Fontaine de Vaucluse qui conduira, in fine, à une gestion optimisé du territoire.

2. Développement d'un modèle conceptuel de fonctionnement via un couplage de suivis hydrochimique et hydrogéophysique (Thèse de Doctorat de Mathieu BERTRAND - ANDRA).

L'ANDRA est chargée en France de la gestion des déchets radioactifs et effectue des recherches de solutions de stockage pour l'ensemble des déchets radioactifs ultimes. Elle est notamment chargée des études de faisabilité d'un stockage de déchets de haute et moyenne activité en couche géologique profonde. Ce projet, appelé Cigéo, devrait voir le jour sur la zone interdépartementale de Meuse - Haute Marne à proximité du Laboratoire souterrain de l'ANDRA situé sur la commune de Bure. Les formations superficielles présentes sur cette zone sont les Calcaires du Barrois, formation carbonatée d'âge Tithonien (Jurassique terminal).

Cigéo sera composé d'installations de surface, notamment pour accueillir et préparer les colis de déchets (bâtiments nucléaires). Ces installations permettront également la réalisation des travaux de creusement et de construction des ouvrages souterrains (puits d'accès et descenderies). Les déchets seront stockés dans des installations souterraines, situées à environ 500 m de profondeur, dans une couche de roche argileuse imperméable choisie pour ses propriétés de confinement sur de très longues échelles de temps.

Le projet de thèse de Mathieu BERTRAND (2019-2022), que je co-dirige (collaboration UFC, AU et ANDRA), a pour objectif de caractériser et appréhender les circulations au sein de l'hydrosystème des calcaires du Barrois, la formation géologique la plus superficielle qui sera directement impactée par les installations de CIGEO (bâtiments, descenderies, puits d'accès) et concernée par les études d'impact environnemental. L'intégration des méthodes non invasives (hydrogéophysiques et hydrochimiques) dans une approche méthodologique globale pour compléter et spatialiser les connaissances géologiques et les connaissances hydrogéologiques acquises en forages, est un enjeu important dans la surveillance de l'environnement d'installations industrielles de grande envergure telles que le projet CIGEO. Un des enjeux scientifiques se situe également dans la connaissance fondamentale du processus de karstification en climat continental.

La finalité de la thèse sera l'intégration des différentes approches d'investigation (hydrogéophysique, hydrochimique et hydrogéologie) au sein d'un modèle conceptuel d'écoulement, préalable indispensable au développement d'un outil de modélisation spatialement distribué qui permettra la prédiction du comportement hydrodynamique de l'hydrosystème avant, durant et après la mise en place des infrastructures du projet CIGEO.

3. ***Impact de la crise économique aux suivis et à la gestion des ressources en eau en Grèce.***

La Grèce a été très lourdement impactée par la crise économique récente, tous domaines confondus. En 2020, j'ai mis en place et je coordonne un projet de recherche avec l'Université de Thessaloniki (Grèce) qui vise à évaluer et à mesurer l'impact de la crise économique sur les ressources en eau souterraine du pays à court, moyen et long termes.

Suivis de la qualité et de la quantité d'eau souterraine interrompus pour plusieurs années et parfois non redémarrés, règlementations nationales ou européennes non respectées (ex. usage des pesticides incontrôlé, surexploitation des aquifères), changements d'occupation de sols désordonnés (ex. déforestations anarchiques liées à l'agriculture ou à l'élevage intensifs, feux de forêts), dissolution des organismes de contrôle et de gestion, transferts de responsabilités à des nouvelles instances sans compétences et formations préalables, ne sont qu'une partie des impacts liés aux conséquences directes et indirectes de la crise économique sur les ressources en eau souterraine de la Grèce. La pression touristique croissante et les changements globaux ne font qu'accélérer ces impacts. Les aquifères insulaires et les aquifères côtiers se situent en première ligne. Projet de nature transdisciplinaire entre sciences de l'eau, économie et gestion, il s'inscrit dans une dynamique de collaboration de long terme avec l'Université de Thessaloniki.

4. ***FuseGI – Erasmus+***: ***Cooperation for fusing skills on Cloud-based Open Geoinformatics: Innovative Environmental Management.***

Le projet européen FuseGI (2019-2022), que je coordonne, financé par l'Agence ERASMUS+, se situe au carrefour entre la recherche et la pédagogie innovante (https://ec.europa.eu/programmes/erasmus-plus/projects/eplus-project-details/#project/2019-1-FR01-KA203-062767). Le projet FuseGI vise à développer les compétences en Système d'Information Géographique (SIG) en adaptant la formation académique à la demande professionnelle pour 3 secteurs clés : Eau, Agronomie et Santé. Le consortium comprend 3 Universités (en France et en Grèce) associés à 4 partenaires socio-professionnels (en France, Grèce, Bulgarie et Belgique) dont 2 PME

(Grèce et Belgique), un institut de recherche (Bulgarie) et une ONG (France). La production au cœur du projet est une plate-forme d'apprentissage virtuel dédiée à l'apprentissage des compétences-clés professionnelles dans le domaine des SIG.

De quoi l'Habilitation à Diriger des Recherches est-elle le nom ? (2/2)

En avant-propos de ce mémoire d'HDR j'avais présenté, et de façon très informelle (voire détendue) – via une métaphore, ma vision de l'encadrement des jeunes chercheurs.

Le deuxième volet concerne la structuration, la coordination et l'animation des recherches.

Structuration, coordination et animation de la recherche.

Diriger des recherches signifie :

- Identifier les Ithaques ! c'est-à-dire identifier les enjeux sociétaux, environnementaux,…
- Identifier et structurer les questions de recherche associées aux enjeux ainsi que les moyens pour y répondre.
- Structurer et organiser le(s) groupe(s) de recherche.
- Animer le(s) groupe(s) de recherche, assurer leur bon fonctionnement.
- Les intégrer dans les réseaux/instances nationaux et internationaux.
- Programmer, coordonner et prioriser les travaux menés.
- Faciliter les mobilités thématiques et géographiques.
- Encadrer, protéger mais aussi mettre en avant les plus jeunes, les moins expérimentés, ceux en début de carrière.

5. Références bibliographiques

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6. Annexe A

1st Conference on Hydrogeophysics

Contribution to Exploration and Management of Groundwater, Land-Use and Natural Hazards under a Changing Climate

EAGE / Near Surface Geoscience Bordeaux 2021

Over the last three decades, hydrogeophysics has emerged as an important sub-discipline in hydrogeology and ecohydrology. It involves investigations of the structure and processes of the subsurface environment, at different spatio-temporal scales, by identifying key properties and state variables related to water flow and solute transport.

The first EAGE conference on Hydrogeophysics, in Bordeaux, 2021, will bring together geoscientists from academia, research institutes, industry, service and engineering companies to present and discuss the state-of-art in the latest research and advances on hydrogeophysics.

The objective is to provide a comprehensive overview of the state of hydrogeophysical research (tools and theoretical advances) for investigating dynamic processes in subsurface settings regarding various environmental issues such as water resources management, remediation, natural and anthropogenic hazards as well shallow geothermal energy. It will allow identification of challenges and ways forward within an integrated cross disciplinary framework.

The technical program of this first EAGE conference on Hydrogeophysics will cover the widest range of topics on geophysics (airborne/satellite, surface based and logging) applied in all types of hydrosystems of the Critical Zone (fractured, karstified and porous aquifers, volcanic and complex aquifers, island aquifers, wetlands, saltwater intrusion, permafrost, …) and at different temporal (from seasonal to high frequency monitoring) and spatial scales (from sample to the catchment scale).

We cordially invite you to participate actively in this leading-edge event in the frame of the Near Surface Geoscience Conference & Exhibition 2021 in Bordeaux, France.

The Scientific Committee of the 1st Conference on Hydrogeophysics

Topics

We are pleased to welcome extended abstracts on the following topics:

- Characterization and Monitoring (water content and flux) of the Critical Zone Interfaces:
    - soil – plant – atmosphere
    - unsaturated – saturated zones
    - groundwater – surface water
    - freshwater – saltwater
    - Cryosphere interfaces
- Groundwater resources and recharge under a changing climate
- Characterization and monitoring of natural and anthropogenic hazards
- Environmental characterization and remediation:
    - Biogeophysical signals at contaminated sites
    - Remediation monitoring and assessment
- Land-use, forestry and agricultural geophysics
- Shallow geothermal energy
- Advances in methods from monitoring, modeling to processes:
    - Spatio-temporal monitoring (time lapse approaches)
    - Petrophysics in support of hydrogeological process characterization
    - Reactive transport: from pore scales to field scales processes
    - Data integration, inverse methods and machine learning

Special Topics

We are pleased to welcome extended abstracts on the following two special topics aiming presentation and promotion of:

- Hydrogeophysical Observatories (highly instrumented sites) and cross disciplinary national and international Networks
- Novel sensors and systems for hydrogeophysics

7. Sélection de publications

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7.1. Chalikakis et al., 2011

Contribution of geophysical methods to karst-system exploration: an overview

Konstantinos Chalikakis · Valérie Plagnes · Roger Guerin · Rémi Valois · Frank P. Bosch

Abstract The karst environment is one of the most challenging in terms of groundwater, engineering and environmental issues. Geophysical methods can provide useful subsurface information in karst regions concerning, for instance, hazard estimation or groundwater exploration and vulnerability assessment. However, a karst area remains a very difficult environment for any geophysical exploration; selection of the best-suited geophysical method is not always straightforward, due to the highly variable and unpredictable target characteristics. The state of the art is presented, in terms of the contributions made by geophysical methods to karst-system exploration, based on extensive analysis of the published scientific results. This report is an overview and should be used as a preliminary methodological approach, rather than a guideline.

Keywords Karst · Geophysical methods · Overview

Introduction

Karst areas are characterised by a specific type of morphology that is formed in carbonate and evaporitic rocks, primarily by dissolution. The structure of karst systems is complex and the related functioning mechanism of aquifers can be highly heterogeneous (Mangin 1975; Bakalowicz 1995; Ford and Williams 2007; White 2007). Therefore, karst areas are the subject of many geomorphological, geological, hydrogeological, geotechnical, environmental, archaeological, etc. explorations. Typical geological, hydrogeological and geomorphological studies provide partial information on the degree of karstification development, but cannot determine the internal structure of the karst system. The knowledge of the geometry and the structure of the different parts of a karst system (epikarst, infiltration zones, karst conduits, cavities, etc.) involve many uncertainties because of the complex nature of karst systems. Furthermore, vulnerability mapping of karst aquifers is based on infiltration-property distribution over the catchment area of a karst system (e.g. thickness and internal structure, presence and type of overlying sediments). Infiltration can be slower and diffuse if overlying sediments cover the karst system or can be fast and concentrated in areas that lack overlying sediments through karst features such as swallow holes or dolines (Andreo et al. 2009; Daly et al. 2002; Davis et al. 2002; Dörfliger and Plagnes 2009; Kavouri et al. 2011; Ravbar and Goldscheider 2009; Zwahlen 2004).

However, suitable characterisation of heterogeneities in the karst environment is challenging for ground-based geophysical methods. Depending on climatic conditions, the drainage, saturation and physical or geochemical characteristics of the system can vary. Conduits, for instance, may or may not be water-saturated, and some parts of the network may either be filled with unconsolidated sediments or even be empty. This complexity produces multiple and time-variable geophysical signatures.

This report is a forward-looking evaluation of the surface-based geophysical methods applied to karst-system exploration. First it describes the most common issues in karst exploration. Second, for each issue, it provides an overview of the most relevant geophysical research studies published over the last 20 years in international journals. Some research results presented exclusively at national and international conferences have been excluded because they could not be accessed. Finally, it evaluates the adequacy of all surface-based geophysical methods used for karst-system exploration

Received: 3 July 2010 / Accepted: 30 April 2011
Published online: 18 May 2011

© Springer-Verlag 2011

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DOI 10.1007/s10040-011-0746-x

with respect to the most common of these issues. Proposals are given for future geophysical works in karst terrains.

Background: geophysical methods in karst-system investigation

Since the 1960s, geophysical methods have been applied in the investigation and evaluation of geotechnical problems related mainly to voids, sinkhole detection or epikarst structures. Until the early 1990s, only a few published studies were well documented. Electrical resistivity techniques were used in cave detection (Cook and Nostrand 1954; Vincenz 1968; Dutta et al. 1970; Greenfield 1979; Militzer et al. 1979; Smith 1986). Very few studies focused on the use of geophysical microgravimetric and gravity gradient techniques to target subsurface cavities and karst features (Colley 1963; Neumann 1965; Arzi 1975; Blizkovsky 1979; Butler 1984). Cook (1965) applied a seismic method to map underground cavities using reflection amplitudes. Kaspar and Pecen (1975) used an electromagnetic (EM) method for tracing karst features in eastern Slovakia by means of differences in electrical properties between limestone and karst features. Greenfield (1979) investigated several geophysical methods for the detection of voids, caves and hazards. Moore and Stewart (1983) used seismic refraction, electrical resistivity tomography (ERT) and microgravity to delineate zones of increased fracture density. Steeples et al. (1986) mapped salt-dissolution subsidence features in Kansas (USA) utilising the seismic reflection technique. Vogelsang (1987) tested EM methods to map karst features. The results of all these studies revealed the value and the potential of using geophysics for karst-system exploration.

Since the early 1990s, geophysical investigations in karst regions have increased rapidly due to technological developments, lower costs, simpler field procedures and more rapid inversion and interpretation of data. Moreover, delineation of subsurface cavities and abandoned tunnels using geophysical methods has gained wide interest because their discovery is relevant for environmental, engineering and even archaeological studies.

During the last few years, several studies were undertaken in order to provide guidelines for geophysical methods in karst system exploration. Benderitter (1997) was the first to attempt to evaluate the possibilities of using geophysics in karst systems. Doolittle and Collins (1998) compared EM methods with ground penetrating radar (GRP) techniques. Thomas and Roth (1999) presented a comparison study between 12 methods (including four geophysical techniques) for sinkhole and void detection in eastern Pennsylvania and north New Jersey in the USA. Hutchinson et al. (2002) provided a useful comparison of various geophysical approaches for void detection. Fauchard and Pothérat (2004) established a guide for air-filled cave detection using geophysical methods. Bechtel et al. (2007) described geophysical methods adapted to karst study in a general book on karst hydrogeology. Gutiérrez et al. (2008) presented an evaluation of geophysical methods for sinkhole detection in evaporate areas based on the general use of the geophysical methods for karst exploration proposed by Hoover (2003). Finally, every few years ASTM International (2006) provides a standard guide for selecting geophysical tools. A restraint part of this guidebook evaluates the geophysical tools used for karst-system exploration.

Karst systems: the main challenges

Taking into consideration the complexity of a karst system, the main challenges related to environmental, geotechnical and hydrogeological exploration of karst systems were identified. Although the list presented herein may be oversimplified, it is based on the most frequent issues geophysicists have reported in the literature.

At this point, it is important to mention the inconsistency in the use of terms for karst-feature description within the different studies included in this report. For instance, many authors using the term "void" in fact refer to sinkholes (collapse hazards with no water movement). To homogenise the terms used for this review, Field's (2002) lexicon of cave and karst terminology was employed. Accordingly, five main issues can be delineated.

The limits and extent of a karst system

The extent of the catchment area will provide the geometry and the volume of the karst reservoir. Consequently, an estimation of the available water resources can be provided. How can geophysics help define the boundaries of a karst system? For example, can geophysical methods define vertical or lateral limits of an outcropping karst system or of a sedimentary buried karst system? Is it possible to locate the karst substratum or the contact with other non-karst formations as well as the presence of faults?

Structural discontinuities

The presence of fractures as well as their orientation and intensity are important knowledge to decipher karst functioning because the drainage network of the karst system depends highly upon them. Combined with the hydraulic gradient, this information is very useful to evaluate the lateral underground flow and the vertical recharge. When epikarst is present, it constitutes a highly fractured zone above the massive carbonate rocks with high water-stock capacities. Can geophysical methods distinguish more fractured zones of a karst system from the massive part of the same formation? Can it define the orientation of the fractures?

 DOI 10.1007/s10040-011-0746-x

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Preferential pathways and/or concentrated infiltration

Sinkholes are near-surface indicators of deep underground active karst features such as cavities, conduits and dissolution-enlarged fractures. Often, sinkholes are also points of recharge to the karst groundwater system and generally the most vulnerable points of a karst system. These features often do not have a surface expression, and their presence may go unrecorded. Can geophysical methods help localise such preferential pathways?

Cavities

Cavities dependent on their location inside the karst system (i.e. above or below the piezometric level) can be partially or entirely air- or water-filled.

Empty cavities

Locating cavities in the ground is an important task in drawing geohazard maps, particularly in populated areas. Detecting underground cavities beneath construction sites and urban areas is a key task for many engineering projects. Every year, subsidence and surface soil failure due to underground voids causes substantial damage around the world. In what conditions can geophysical methods help to localise air filled cavities?

Water-filled cavities

Cavities can be partially or completely water-filled and, depending on the composition of the water, can have a resulting electrical conductivity ranging from very conductive to relatively resistive, compared to host rock. In addition, water-filled karst conduits play a crucial role for water supply in many parts of the world. Can geophysical methods accurately provide the position, in three-dimensions (3D), of a water-filled cavity? What about clay-filled cavities?

Finally, sedimentary covering, when it exists, plays a very important role for karst hydrogeology, and its characteristics (thickness and consistency) can significantly change the geophysical response of the underlying karst-related target. Moreover, sedimentary covering of a karst system can often also be a specific target for geophysical investigation in order to evaluate vulnerability issues of the karst aquifer and to contribute towards a protection strategy.

Contribution of geophysical methods to karst-system exploration

Geophysical methods aim to characterise the variations of the physical parameters of underground formations. Geophysical measurements produce a set of data in which various parameters are measured (observed). Each of these parameters is related to one or more physical properties of the subsurface and to their spatial distribution. These methods are widely used for hydrogeological, environmental and engineering explorations throughout the world in various geological formations. However, geophysical methods are not systematically used for karst-system exploration.

In recent years, several geophysical methods and assessment techniques have been rapidly developed. In general, the investigation depth for karst exploration of the subsurface is between 2 and 200 m. For most studies, several methods are combined to compare the benefits of each method.

For an accurate presentation of the geophysical methods used, the terminology was standardised for the present report. For example, the term ERT is used even though in the original papers the authors employed several terms such as 'resistivity imaging', 'resistivity 2D profiling' (two-dimensional profiling), etc. In the following section, geophysical results will be listed according to the five main issues previously recognised and discussed. For all these studies, geophysical results provided information for more than one karst-related issue.

Limits and extent of a karst system

Lange (1999) mapped the karst structure and groundwater channels beneath sediments using three techniques: EM, gravity, and self-potential (SP). The EM method defined the boundary between carbonate rock and alluvium. Zhou et al. (2000) demonstrated the advantage of using resistivity methods, and mainly ERT, to define the depth to carbonate bedrock in sedimentary, shallow, covered karst terrains. Combining 2D ERT, seismic refraction and the high-resolution reflection seismic methods, Šumanovac and Weisser (2001) mapped the vertical boundaries of a karst system in Croatia. He et al. (2006) used integrated passive source EM and the controlled source audio magnetotelluric (CSAMT) method for mapping the deeply buried geological structures in karst terrains in China. Chalikakis (2006) used the time domain electromagnetic (TDEM) method to map covered deep karst in a sedimentary basin in north Peloponnisos in Greece. Mari et al. (2009), from a 3D seismic data set and wells, obtained a 3D porosity model of a near-surface karst aquifer. These results helped locate highly productive zones and could be useful for flow modelling.

Most of these published studies involved the upper limits of the karst systems under sedimentary covering. However, their results also provide important information concerning the thickness and the consistency of the overlying sediments.

Structural discontinuities

Grandjean and Gourry (1996) successfully used GPR data to obtain a 3D near-surface feature map in a marble quarry. Seismic reflection profiling was combined with microgravimetry and borehole data by Benson (1995) to identify karst near-surface highly fractured zones and to assess their impact upon a proposed bridge design in

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Florida (USA). Turberg and Barker (1996) used a combination of ERT and radio magnetotellurics—RMT, enhanced very low frequency resistivity mode (VLF-R)—to describe the near-surface epikarst zone on a test site in Switzerland. The seismic refraction method was employed to evaluate subsurface fracturing by Johnston and Carpenter (1998) above a coal-mine panel on the southern portion of the Illinois coal basin (USA). Busby (2000) tested the effectiveness of azimuthal apparent-resistivity measurements as a method for determining fracture strike orientations. Bosch and Müller (2001) developed and tested a very low frequency electromagnetic (VLF-EM) gradient technique to map near-surface heterogeneities in a karst area in Switzerland. A few years later, a comparison of the VLF-gradient array with ERT, RMT and continuous VLF-EM, methods was successfully carried out in the same area to identify and map karst near-surface heterogeneities also as the epikarst zone (Bosch and Müller 2005). Sheehan et al. (2005) examined and discussed three commercial refraction tomography codes with respect to karst applications. They demonstrated that refraction tomography can assess many of the 3D features observed in these environments such as epikarst, where fracture density is important. Elawadi et al. (2006) employed a combination of ERT with a dipole-dipole array, GPR and VLF-EM methods in southern Cairo, Egypt. Integrated interpretation led to the delineation of hazard zones that were rich with vertical and sub-vertical faults, fracture zones, and geological contacts. Rey (2007) successfully mapped the near-surface fracture density and extent of a karst system in southern France with the Slingram type EM method (EM-31 device). Time-lapse microgravity measurements have been carried out for over 40 sites in the Larzac karst plateau (southern France), complemented by absolute gravity measurements, by Jacob et al. (2008, 2009, 2010). These measurements provide valuable information about the water-storage temporal dynamics of the epikarst zone.

Preferential pathways and concentrated infiltration

Witten et al. (1997) noted that the broadband EM induction technique holds promise for the detection and location of underground structures in the Anacostia metro station, Washington (USA), and in Nye County, Nevada (USA). EM conductivity mapping was combined with gravity, GPR, seismic refraction and electrical sounding (ES) by Carpenter et al. (1998) to identify sinkholes in the Oak Ridge reservations in Tennessee (USA).

An integrated microgravity and ERT geophysical survey was successfully conducted by McGrath et al. (2002) to detect underground voids in south Wales (UK). The results were integrated in groundwater vulnerability mapping. Kaufmann and Quinif (2001) used an ERT system and cone penetration tests to delineate cover-collapse sinkhole areas. Batayneh et al. (2002) employed GPR to delineate buried sinkholes in the Dead Sea Basin in Jordan. That study tested the usefulness of GPR to identify and locate buried sinkholes as a means of interpreting the existence of these sub-surface hydraulically active karst features. Van Shoor (2002) demonstrated that ERT was a geophysical tool that was well suited for the detection and mapping of sinkholes in dolomitic areas. Moreover, Zhou et al. (2002) used and compared several ERT arrays in order to detect a cover-collapsed sinkhole in Maryland (USA); a mixed array was preferred. Ahmed and Carpenter (2003) combined electrical tomography and electromagnetic techniques to map high-conductivity anomalies linked to filled sinkholes in east-central Illinois (USA). Time-lapse microgravity was used by Branston and Styles (2003) to investigate and monitor sinkholes in England (UK). Ezersky et al. (2006) combined TDEM, GPR, ERT and magnetic methods to study sinkhole development in the Dead Sea area (Middle East). Jardani et al. (2006) developed SP tomography in order to detect cavities related to sinkholes. Vertical flow of water is necessary for this method. A year later, preferential infiltration pathways were detected with joint inversion of SP and Slingram EM source (EM-34 device) conductivity data (Jardani et al. 2007). ES and hydrogeological investigations were carried out to characterise an unusual, from the hydrogeological point of view, epikarst in southern Italy by Petrella et al. (2007). Because of the high fracture density and good interconnection of openings within the underlying limestone, the percolation water was found to be diffused below the epikarst zone also. Kruse et al. (2006) successfully used GPR and ERT to map a large developing sinkhole in a covered karst terrain in west-central Florida (USA). Pueyo-Anchuela et al. (2009a, b) employed GPR to characterise processes involved in karst hazards and they propose a number of associated geomorphologic sections. Geomorphologic interpretations were also made from ERT and seismic refraction tomography data in karst depressions by Siart et al. (2009). Valois et al. (2010, 2011) combined Slingram, ERT and seismic refraction methods to identify buried or hidden preferential pathways, characterize dolines geometry and provide information about doline fillings.

Cavities

The drainage phenomena of karst systems are related to generally irregular cavities, fractures and fault zones, which decrease seismic velocities. In spite of successful case histories, void detection is still a challenge because of the lack of a standard, quantitative void-detection technique. In addition, existing nondestructive techniques do not consider the effect of lateral inhomogeneities, i.e. cavities, in the wave propagation. Thus, the detection of underground cavities needs further study.

Detection of cavities seems to be the most popular target for geophysical methods. The rock surrounding natural cavities is often disturbed, particularly in carbonate karst environments where a cave is formed by the chemical and physical interaction of groundwater with the rock. In such an environment, fractures and the dissolution of rock surrounding a karst cavity creates a larger bulk anomalous volume than the cave itself. Fortunately, this helps geophysical methods detect such

 DOI 10.1007/s10040-011-0746-x

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caves more easily. Also the air-filled cavities have a near-infinite electrical resistance compared to the damp limestone and readily produce recognisable anomalies. However, their detection is controlled by the volume and the depth of the cave. Consequently, it was found that the effective geophysical size of each cavity varies with the geologic environment, but it is usually larger than the true size of the cavity. A variety of geophysical techniques can be used to detect the presence of caves and voids below the surface. All of them are based on a physical contrast between the cave or the conduit and the surrounding rocks.

Air-filled cavities

The resistivity of air-filled caves is always significantly higher than the bulk rock. Ogilvy et al. (1991) managed to detect air-filled cavities using the VLF resistivity method and Noel and Xu (1992) experimented with ERT for cave detection. Camacho et al. (1994) developed a gravimetric 3D inversion approach to detect air-filled cavities. Robert and de Bosset (1994) successfully conducted experiments in laboratory concrete structures for cavity detection with GPR. Guérin and Benderitter (1995) explored a near-surface karst system using a combination of VLF resistivity and electrical methods. McMechan et al. (1998) tested GPR to map cavities in a paleokarst system in Texas (USA). Cavity detection within other similar geophysical targets, by combining refracted and diffracted seismic waves, was demonstrated by Belfer et al. (1998). Batayneh et al. (1999) and Batayneh and Al-Zoubi (2000) presented ERT results for cave detection inside salt formations in Jordan. Gautam et al. (2000) attempted to map subsurface cavities by combining electrical sounding (ES) and electrical profiling (EP) and gamma ray measurements. Leparoux et al. (2000) demonstrated the potential of the seismic Rayleigh wave method for cavity detection and Chamberlain et al. (2000) successfully used GPR to delineate karst cavities. Several years later, Leparoux and Grandjean (2004) compared several seismic techniques for cavity detection at an experimental test site.

Beres et al. (2001) combined GPR and microgravimetric methods to map shallow subsurface cavities in western Switzerland. Rybacov et al. (2001) used microgravity to detect and monitor cavities in the Dead Sea area. Gibson et al. (2004) used ERT to locate an unknown 210-m-long, 70-m-wide and 25-m-deep collapse feature in eastern Ireland beneath sediments. A magnetic investigation of an unfilled paleokarst collapse structure produced a 40-nT (nano Tesla) anomaly, illustrating that the technique can be employed in Ireland to locate unknown caves. El-Qady et al. (2005) combined ERT using a dipole-dipole array and GPR to the east of Kattamya at Al-Amal Town, Cairo, to image shallow subsurface cavities. Three-dimensional interpretations of GPR have been used to identify burials and other archaeological features. Nasseri-Moghaddam et al. (2005) used the multi-channel analysis of surface waves (MASW) and presented the results of computer simulations of surface-wave propagation for a homogeneous medium containing a void. The numerical results of this study do not include other situations that may be encountered in natural settings such as inclined layers, reflecting boundaries and 3D conditions. Thierry et al. (2005) and Debeglia et al. (2006) took microgravity measurements in conjunction with MASW to detect and characterise karst structures in an urban environment, in Orléans (France). Kofman et al. (2006) demonstrated the value of reverberation phenomena in GPR records to detect near-surface air-filled cavities. Detecting air-filled cavities, within other geophysical targets, with P-wave seismic tomography was demonstrated by Grandjean (2006). Cardarelli et al. (2006) successfully mapped buried cavities with ERT under the city of Rome (Italy) and Piscitelli et al. (2007) used a combination of GPR and microwave tomography to detect shallow cavities in an archaeological site in southern Italy. Gravimetric, magnetic and GPR surveys led to successful detection of karst cavities in the Zaragoza area in north-eastern Spain (Mochales et al. 2008).

Water-filled cavities

Holub and Dumitresku (1994) conducted pioneering experiments for water-filled cavity detection using GPR and ERT methods. Zhou et al. (1999) found evidence of a water-filled conduit using the SP method. The absence of electrically conductive sediments at the surface allowed Al-Fares et al. (2002) to detect a known partially water-filled cavity 20 m deep at the Lamalou site in southern France with GPR. At the same site, Vouillamoz et al. (2003) combined magnetic resonance sounding (MRS) and ERT to map the partially water-filled cave. MRS proved to be a useful tool for water-filled conduits as soon as the quantity of water was sufficient to be detected. A new methodology for MRS data acquisition and interpretation was developed for locating water-filled karst cavities (Boucher et al. 2006). This methodology was used to investigate a wide, shallow, water-filled conduit in the Ouysse karst system in the Poumeyssens shaft (France). A 2D numerical MRS response model was designed to improve accuracy over the previous 1D MRS approach. In a further improvement, Girard et al. (2007) made use of magnetic resonance tomography (MRT). This work emphasises the gain in resolution for 2D and 3D imagery of MRT versus the interpolation of 1D inversion MRS results along the same profile. Numerical modelling results show that the MRT response is sensitive to the size and location of the 2D target in the subsurface. For the same test site in the Poumeyssen shaft, Guérin et al. (2009) demonstrated the efficiency of combining MRS, ERT, mise-à-la-masse and seismic methods to accurately characterise the shallow water-filled conduit.

Legchenko et al. (2008a) applied the MRS method to estimate the volume of a water-filled cave formed by salt dissolution in the Nahal-Hever area of the Dead Sea coastline. A quantitative verification of the accuracy of karst-volume estimates in Nahal Hever with MRS was not possible, but in a qualitative sense MRS results are found to be in good agreement with all other available data.

DOI 10.1007/s10040-011-0746-x

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Numerical modelling of the accuracy of the 1D MRS estimation of different 3D-target volumes (Legchenko et al. 2008b) shows that, under Nahal Hever conditions, this type of volume can be estimated. The results of this field study can help to estimate the risk of the development of new sinkholes related to water-filled cavities.

Overview of the geophysical results

The geophysical response depends on the size of the target in relation to its depth and on the contrast between the physical properties of the target and the surrounding rock. The size of karst features is usually small, except for caves, which have a larger size but are often located at greater depth. The amplitude of geophysical anomalies is, moreover, an inverse function of the distance between the measurement point and the structure. In addition, the lateral limits of geophysical methods are linked to the measurement sampling (investigation step) and the vertical limits correspond to the investigation depth, which is also related to the equipment, configuration array and the physical properties of the carbonate matrix.

It is important to point out that the goal of this present report was not to review all the previously described scientific publications but mainly to collect the geophysical studies, standardize the main karst issues and summarize the usefulness of all available surface-based geophysical methods. Methodology and results are considered of a good quality and their publication in high-standard scientific magazines is the guarantee of this statement. However, studies cannot be compared or criticised because, firstly, the different investigated karst systems were highly variable from the geological and hydrogeological point of view and, secondly, all geophysical methods are in constant development. Certainly some studies were undertaken several years before the methods could provide better results with the use of new equipment or inversion software.

Electrical methods

Conventional resistivity techniques (ES and EP) cannot give satisfactory results in areas with very complex subsurface geology such as karst areas. One of the theoretical assumptions for ES is a horizontal stratified earth model, which is rare in karst areas. However these techniques can be used for exploration of the limits of buried karst under sedimentary covering. The use of the mise-à-la-masse method should give indications on water-filled cavity orientation, as it does with conductive bodies in mining exploration. The use of 2D and 3D ERT has considerably increased in the last 10 years. Resistivities increase if the karst features are filled with air and decrease if they are filled with clay and/or water. The presence of clay generally decreases resistivities more than water (valid for fresh water, but not for salt water). In real exploration, their influence cannot be determined because of the unknown and irregular shape of the features and the fact that the degree of the filling is unknown most of the time. Electrical resistivity methods can, in any case, give more information on the lithology of the host rock because they engage the entire rock mass, but some structural features can be resolved by using 3D electrical tomography (even if such measurements are rare), which is sensitive to rock discontinuities. However, for all resistivity methods, how to implement the electrodes properly in the ground and secure adequate contact remains a major practical issue to be resolved. This can be extremely difficult for outcropping limestone, for instance.

The SP technique seems to be a suitable low-cost geophysical tool to detect preferential pathways when water flow is included. New algorithms are being developed to improve the accuracy of the technique. Although electrofiltration is a very attractive phenomenon to track the flow of water in water-filled cavities, most often signals recorded with SP measurements on such structures do not have only one source (i.e. telluric currents due to induction of ionosphere and electromagnetic storms, bioelectric effect of tree roots) and therefore cannot often get conclusive results on the water flow. In addition, electrofiltration is strongest for fluid flow in a permeable matrix.

Electromagnetic (EM) methods

Electromagnetic (EM) geophysical methods have proved useful in identifying and locating several karst features.

Slingram sources (EM at low induction number)

For the most part, two pieces of equipment have been used for the studies presented: the EM-31 and EM-34. Both can provide important information on the lateral variations of the near-surface karst features such as filled fractures and lateral contacts with other geological formations. While addressing the ground's electrical resistivity, these EM techniques provide light-weight equipment with high resolution and fast measurement progress, which is well appreciated mainly during preliminary geophysical studies.

Time domain electromagnetic (TDEM) and controlled source audio magnetotelluric (CSAMT) methods

These techniques have been used successfully only a few times, mainly to locate the upper part of a sedimentary-buried karst system and to characterize the overlying sedimentary covering. However, CSAMT can also be employed in an outcropping karst, where TDEM seems not to be working correctly.

Very low frequency (VLF) techniques

Enhanced VLF techniques (e.g. with broadened frequency range or continuous measuring capabilities) such as RMT (enhanced VLF-R), radiofrequency electromagnetics (RF-EM) and VLF gradient (both enhanced VLF techniques)

 DOI 10.1007/s10040-011-0746-x

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have proved particularly useful for near-surface karst structure detection and imaging. Combined application provides quick detection of preferential vertical water flow paths as fractures, faults and sinkholes as well as the investigation of sediment-cover layer thickness. However, published case studies using enhanced VLF techniques have mainly been carried out with academic prototype equipment. Currently, there are only a few types of equipment commercially available. All these equipment types are using VLF and low frequency (30–300 kHz) radio transmitters, which are located at several positions around the world and are used principally for navigation and submarine communication. The frequency and the orientation of these transmitters play an important role in the geophysical surveys. Consequently another practical issue during a geophysical campaign that uses this type of equipment can be the reception of the appropriate radio transmitter towards the investigation depth and the orientation of the transmitters.

Ground penetrating radar

Ground penetrating radar (GPR) is very efficient for describing the epikarst in detail (i.e. the shallow part of karst systems) and the infiltration zone of karst aquifers, where limestone crops out at the surface. In recent years, GPR techniques appear to be the most popular geophysical tools for identifying and locating subsurface karst features such as cavities, conduits and solutionally enlarged fractures. GPR is extremely limited when the overburden is electrically conductive (as it commonly is in temperate lowland karst where there is a thick residual clay soil cover). The absence of electrically conducting sediments such as clays and the use of low frequencies (less than 100 MHz) make the application of GPR to limestone formations efficient and useful because of the weak attenuation of the radar waves.

Seismic methods

Structural information could be extracted from reflections in seismic data. Indeed, reflections help to determine vertical and sub-vertical boundaries such as faults and geologic contacts. Horizontal limits can be expected as well if there is a velocity contrast at the top or the bottom of the karst medium, for example. However, seismic reflections could be weak in karst terrains, due to uneven reflectors and a high level of noise such as when the refraction energy is dominant in recordings. Seismic refraction techniques can provide important knowledge of the near-surface karst heterogeneities such as preferential pathways and near-surface cavities. Nevertheless, the seismic velocity has to increase with depth for a sufficient investigation depth and a near-surface fast layer could hide underground structures.

The spectral analysis of surface wave (SASW) method has been used to assess near-surface soil conditions as well as to detect underground voids. Advancing the SASW method, the multi-channel analysis of the surface wave (MASW) method is based on the use of several transducers. The MASW method removes noise more effectively and identifies higher modes of Rayleigh waves better. MASW, sensitive to the soil stiffness profile, helps to reduce these ambiguities by characterising the mechanical behaviour of the gravity anomalous zones, and thereby minimising the extent and cost of mechanical controls.

Microgravity

Successful application of the gravity method for the detection of sinkholes depends on a density contrast between the material filling the sinkhole and its surroundings. Gravimetry requires high-density contrast between the cavity and the surrounding matrix. This method detects only large sinkholes or those located close to the ground surface but cannot be used to track the presence of buried sinkholes, because the presence of open conduits does not provide a strong perturbation of the gravity field. Microgravity, conducted with close spacing and careful implementation in order to ensure high resolution and accuracy, remains one of the methods best suited to the detection of voids in the uppermost 20 m, even when these voids are relatively small. Microgravity can also be accurate in delineating near-surface zones of increased fracture density and also in revealing major fractures with important gravity anomaly amplitude. The combination of microgravity with absolute gravity measurements seems promising in providing information at large lateral scales about water storage and the dynamics of the epikarst zone.

Magnetic resonance sounding

Magnetic resonance sounding (MRS) is a geophysical technique developed for groundwater exploration. This technique can be used for investigating karst aquifers. Generally, the study of a karst water-filled feature requires a 3D field setup and corresponding multichannel data-acquisition instruments. Now only single-channel MRS equipment is available; thus, the time needed for a 3D MRS field survey is multiplied by a factor of four or five. Moreover ambient EM noise greatly influences MRS measurements. At the current stage of instrument development, the method is limited to detecting large water-filled near-surface targets in areas with low ambient EM noise. Multi-channel data acquisition instruments and 2D and 3D numerical approaches seem promising for hydrogeological karst investigations.

Discussion

The adequacy of ground-based geophysical methods and their measuring techniques for the most common issues in karst formations are presented in Table 1. The notation—recommended (+++), appropriate but incomplete (++), appropriate but limited (+), and not recommended (0)—is based on the results of the previously described scientific

 DOI 10.1007/s10040-011-0746-x

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Table 1 Adequacy of ground-based geophysics for karst-system exploration

Ground based geophysics		Adequacy of the method												Remarks	
		With sedimentary covering					Without sedimentary covering					Sedimentary covering			
Method	Measurement technique	Boundaries	Fractured zone	Preferential pathways	Cavities		Boundaries	Fractured zone	Preferential pathways	Cavities		Type	Thickness	Rent cost per week	Min number of operators
					Air-filled	Water-filled				Air-filled	Water-filled				
Electrical	ES	+++	++	+	0	0	+++	+	+	0	0	++	+++	II	3
	ERT	++	++	++	++	++	+++	++	++	+++	++	+++	++	III	2
	Mise-à-la-masse	0	0	++	0	++	0	+	++	0	++	0	0	II	2
	SP	0	++	+++	0	++	0	++	+++	0	++	+	0	I	2
EM	Slingram	++	++	++	+	+	++	++	++	++	++	+++	++	II	2
	TDEM	+++	+	0	0	0	+++	+	0	0	0	+++	+++	II	2
	GPR	0	+	+	+	+	+	+++	++	+++	++	+	0	II	3
	CSAMT	+++	++	++	+	+	+++	+++	++	+	+	+++	+++	IV	2
	VLF res.-RMT	++	++	++	+	+	+++	+++	+++	+	+	+++	+++	II	2
	VLF EM	+++	+++	+++	+	+	++	+++	+++	+	+	++	+	II	2
Seismic	Tomography	+++	++	++	++	++	+++	++	++	++	++	++	++	IV	2
	MASW	++	++	++	++	++	++	+++	++	++	++	++	++	IV	3
Microgravity	Profiling or mapping	0	++	+	+++	++	0	+	+	+++	++	0	0	III	2
Magnetic	Profiling or mapping	0	0	0	0	0	0	0	0	0	0	++	0	II	2
MRS	Sounding	0	0	0	0	+++	0	0	0	0	+++	+	0	V	2

+++ recommended; ++ appropriate but incomplete; + appropriate but limited; *0* not recommended

I <300 €; *II*301–600 €; *III*601–1000 €; *IV*1,001–2,000 €; *V*>2001 €—sources: ABEM France (2010), IRIS Instruments (2010), Expins (2010, Geomatrix (former Georental) (2010). Rental prices can vary depending on the geographical area, equipment type and model, time of rental etc.

CSAMT controlled source audio magnetotelluric; *EM* electromagnetic; *ERT* electrical resistivity tomography; *ES* electrical sounding; *GPR* ground penetrating radar; *MASW* multichannel analysis of surface waves; *MRS* magnetic resonance sounding; *RF-EM* radio frequency electromagnetic; *RMT* radio magnetotellurics (enhanced VLF-R); *SASW* spectral analysis of surface wave; *SP* self potential; *TDEM* time domain electromagnetic; *VLF* very low frequency; *VLF-R* very low frequency-resistivity

DOI 10.1007/s10040-011-0746-x

studies. A method stands as: (1) *recommended* when, in many studies, results for the corresponding issue are relevant and even, in several cases, the method can stand alone to characterise the karst-specific target; (2) *appropriate but incomplete* when, for the specific karst issue, results are good but are mostly combined with other methods to provide concrete interpretation of the data; (3) *appropriate but limited* when only a few studies show the usefulness of the method even when combined with other methods; and (4) *not recommended* when the method is not adapted to the geometry and physical properties of the specific target. The optimum number of operators and weekly rental cost (rough value) of each one is also presented in Table 1.

However, it is important to remember that the response of each geophysical method is highly dependent on overburden sediments. Their thickness and consistency (percentage of clay, density, presence of water, etc.) can significantly change the geophysical signature of the target also as its depth is increasing. The presence, the thickness and the structure of the epikarst zone is also extremely important.

Table 1 presents the state of the art in terms of the contribution made by geophysical methods to karst-system exploration, based on published scientific results. It should be used as an overview and as a preliminary methodological approach rather than a guideline. For each karst-related issue, at least one geophysical method is recommended. However, the use of a combination of geophysical tools is always preferable to obtain a better-constrained model of karst features. Due to the specificities of each karst system, the suitability of each geophysical method can be site-related. Consequently preliminary experiments in the study area, before a survey, are highly recommended in order to check the adequacy of the chosen methods or measuring techniques.

Conclusions

Each karst system is unique, and the geometry of its different parts can be rather complex. Due to very strong lateral and vertical changes of the physical and lithological properties in karst regions, the main goal of exploration is to acquire a precise 3D geological model of the underground. Geophysical methods can play an important role in building such a model for two main reasons. Firstly, on the basis of geophysical results, the optimum locations and quantities of exploration boreholes can be defined which can have great implications on the total exploration cost. Secondly, geophysical methods can provide for continuous coverage over an exploration area, connecting data from boreholes to build a complete 3D model. Wide spatial covering and rapid sampling (dense spatial coverage), low cost and fast data interpretation are the main advantages of geophysical methods compared to traditional geological, hydrogeological and geomorphological studies. Finally, 3D-data-acquisition development for many geophysical methods holds great promise for karst-system exploration.

Acknowledgements The authors wish to thank Peter Huggenberger, Arthur Batte, Kristine Walraevens and Timothy Bechtel for their comments and suggestions, which helped to improve this technical report.

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Hydrogeol J (2016) 24:1905–1918
DOI 10.1007/s10040-016-1425-8

REPORT

The role of porous matrix in water flow regulation within a karst unsaturated zone: an integrated hydrogeophysical approach

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Received: 2 August 2015 / Accepted: 25 April 2016 / Published online: 7 May 2016
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Abstract Some portions of the porous rock matrix in the karst unsaturated zone (UZ) can contain large volumes of water and play a major role in water flow regulation. The essential results are presented of a local-scale study conducted in 2011 and 2012 above the Low Noise Underground Laboratory (LSBB – Laboratoire Souterrain à Bas Bruit) at Rustrel, southeastern France. Previous research revealed the geological structure and water-related features of the study site and illustrated the feasibility of specific hydrogeophysical measurements. In this study, the focus is on hydrodynamics at the seasonal and event timescales. Magnetic resonance sounding (MRS) measured a high water content (more than 10 %) in a large volume of rock. This large volume of water cannot be stored in fractures and conduits within the UZ. MRS was also used to measure the seasonal variation of water stored in the karst UZ. A process-based model was developed to simulate the effect of vegetation on groundwater recharge dynamics. In addition, electrical resistivity tomography (ERT) monitoring was used to assess preferential water pathways during a rain event. This study demonstrates the major influence of water flow within the porous rock matrix on the UZ hydrogeological functioning at both the local (LSBB) and regional (Fontaine de Vaucluse) scales. By taking into account the role of the porous matrix in water flow regulation, these findings may significantly improve karst groundwater hydrodynamic modelling, exploitation, and sustainable management.

Keywords Karst · France · Hydrogeophysics · Carbonate rocks · Matrix porosity

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Introduction

Karstified rocks cover a large portion of the world's surface (Gunn 2004), particularly around the Mediterranean Sea (Bakalowicz and Dörfliger 2005). Unfortunately the complexity of karst hydrosystems continues to impede sustainable water exploitation and management (e.g. Mangin 1975; Bakalowicz 1995; Ford and Williams 2007; Goldscheider and Drew 2007; White 2007). In the context of climate change, additional stress on water resources may require more intense exploitation of karst hydrosystem water resources. These factors and sustainable management require improved knowledge about how karst hydrosystems function.

Karst is a complex medium with multi-scale heterogeneity. Water flow pathways are present throughout the entire medium, from rock matrix to fractures and karst features (Fig. 1). The hydrodynamic role of these water pathways is still poorly understood (e.g. Bailly-Comte et al. 2010) and water flow regulation within karst hydrosystems remains an important issue. On one hand, karst hydrosystems have high permeability because a large amount of water moves quickly through karst conduits and rapid pressure transfer occurs. On the other hand, karst hydrosystems provide an important buffer effect because spring discharge remains high even during long dry periods, as at the Fontaine de Vaucluse spring in France. Several hypotheses have been advanced to explain the important water flow regulation capacity of karst hydrosystems: (1) significant water storage within the saturated zone in karst

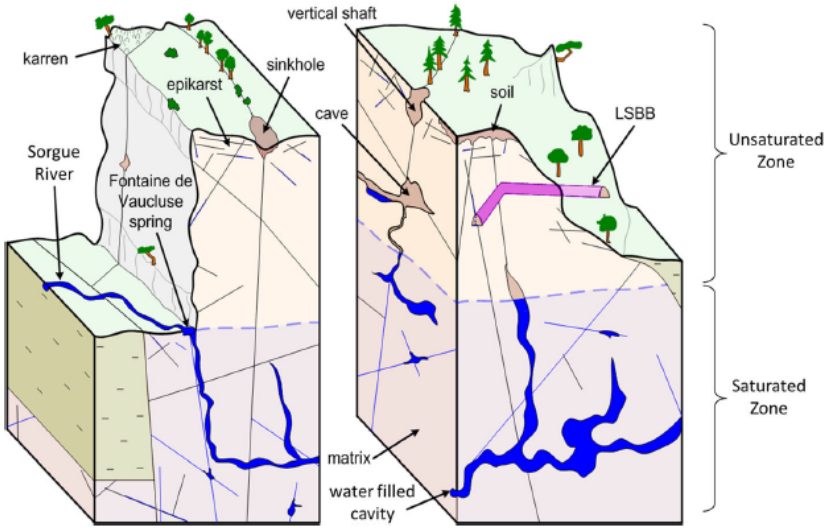

Fig. 1 Karst system model showing the Fontaine de Vaucluse hydrosystem and the Low Noise Underground Laboratory of Rustrel (*LSBB*)

conduits (e.g. Mangin 1975; Marsaud 1996); (2) water storage in the epikarst (fractured and weathered near-surface karst; e.g. Aquilina et al. 2006; Ford and Williams 2007); and (3) delayed infiltration or travel time within the entire unsaturated zone (UZ; e.g. Celle-Jeanton et al. 2003; Emblanch et al. 2003; Mudarra and Andreo 2010; Mudarra et al. 2012). However, this regulation capacity within the UZ is not related to identified geological features (e.g. fractures, matrix). Finally, few researchers consider water storage in the UZ zone to be significant enough to play a role in water flow regulation and the capacitive function of karst.

Due to these complexities, distributed hydrogeological modeling of karst systems remains difficult to implement and is not often done (e.g. Kiraly 1998; Larocque et al. 1999; Scanlon et al. 2003; Worthington 2009; Worthington and Ford 2009). The usual approach to karst hydrosystems is the so-called "black box" model (e.g. Mangin 1975; Marsaud 1996; Labat et al. 2000a, b; Rimmer and Salingar 2006; Fleury et al. 2007; Moussu et al. 2011; Hartmann et al. 2012). However, "black box" models are site-specific. The lack of physics and geology in such models makes their transfer difficult from one karst system to another. Moreover, "black-box" modeling (e.g. Fleury et al. 2007) and hydrochemical estimates (e.g. Batiot et al. 2003) have indicated large residence time differences within a single karst hydrosystem.

Most techniques traditionally used in hydrogeology are of limited success in a complex and heterogeneous media such as karst (Bakalowicz 2005). Hydrogeologists often apply techniques commonly used in surface hydrology such as natural and artificial tracers or rainfall/runoff models. In recent years, surface-based geophysics was added to the methodological suite to improve the analysis of spatial and temporal variability of underground properties (Berkowitz 2002). Numerous techniques are available, each with its strengths and weaknesses. Chalikakis et al. (2011) proposed a general overview of geophysical methods for karst media and more recently Kaufmann and Deceuster (2014) published an overview on the use of geophysical surveys to detect ghost rock. In recent years, an increasing number of hydrogeophysical projects aimed at studies of karst hydrogeological functioning have appeared (e.g. Jacob et al. 2008, 2009, 2010; Gondwe et al. 2010; Zhu et al. 2011; Deville 2013; Mazzilli et al. 2013).

This report presents an integrated hydrogeophysical approach based on several ground-based geophysical methods combined with geological and hydrogeological techniques. This integrated approach provides additional insight into karst UZ structure and functioning. It also proposes a conceptual hydrogeological model to explain the multi-annual dynamics of the studied karst hydrosystem. This conceptual model will likely promote additional and more accurate hydrodynamic modeling. The methodological approach was developed and tested in a typical Mediterranean karst hydrosystem observatory: The Fontaine de Vaucluse – Low Noise Underground Laboratory (LSBB) karst watershed.

Experimental site

General geological and hydrogeological context

The LSBB, a nearly horizontal underground passageway originally dug for military purposes, was converted to a research laboratory in 1997 (Figs. 1 and 2c). It is situated in the Fontaine de Vaucluse hydrosystem karst UZ, in the village of Rustrel. The rock cover over the passageway ranges in thickness from 0 to 519 m depending on the topography.

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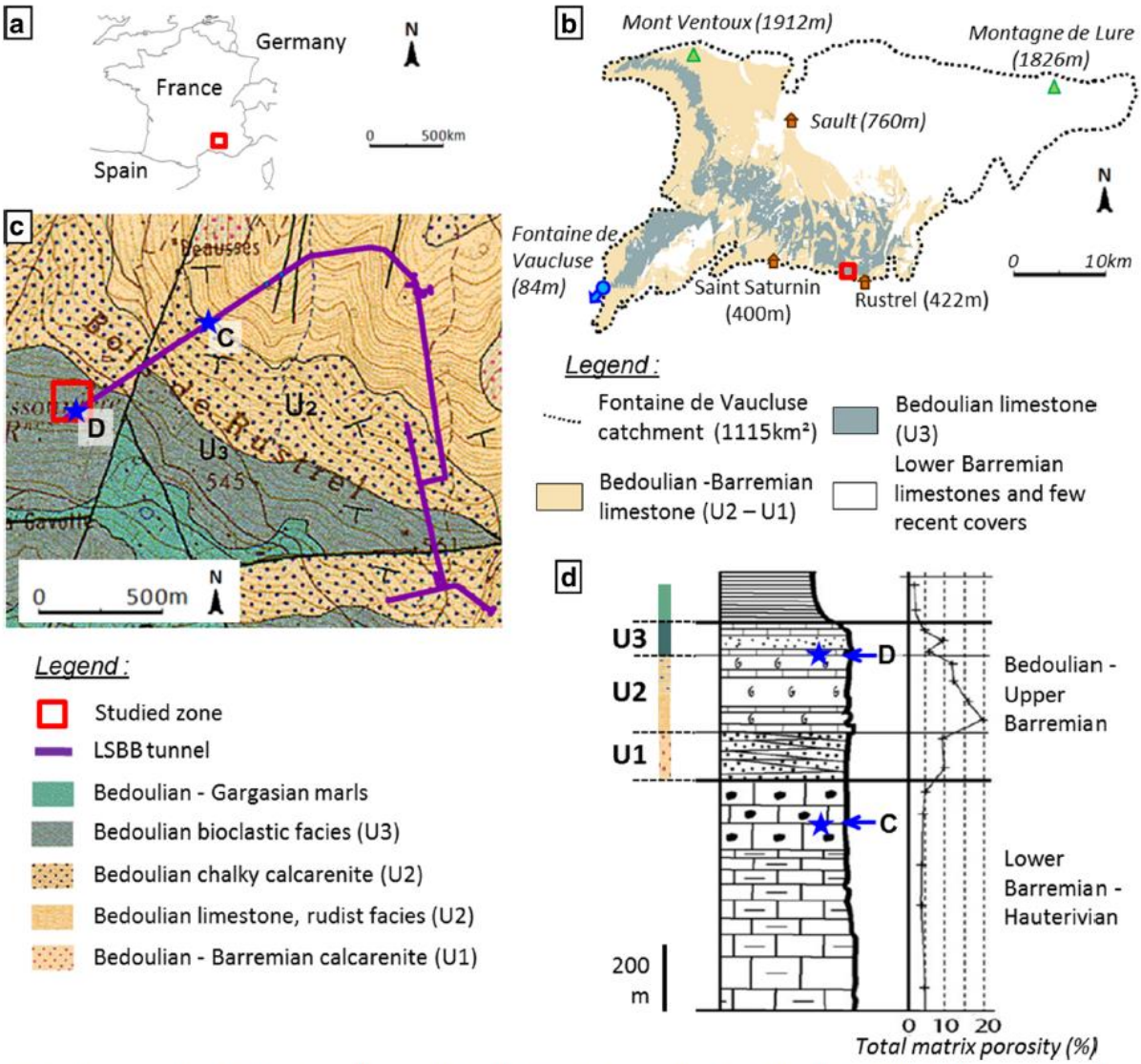

Fig. 2 **a** The Fontaine de Vaucluse basin located in France; **b** The Rustrel experimental site located in the Fontaine de Vaucluse basin; **c** Excerpt of local geological map, No. 942 (after Blanc et al. 1973); **d** Total porosity of limestone outcropping on Fontaine de Vaucluse hydrosystem measured in a small sample (after Guglielmi 2010)

The general saturated zone of the karst system is approximately 400 m beneath the LSBB. The 3.8-km-long passageway traverses the karst medium and arbitrarily intersects faults and karst networks. As a result, the passageway also intersects some flow paths in the UZ. Since 2003, more than 61 flow points have been identified and studied within the laboratory. Three of the flow points are permanent and 58 are temporary; they are located between approximate depths of 33 and 440 m (Garry 2007; Blondel 2008; Barbel-Perineau 2013).

One permanent flow point is located 33 m below the surface at the western extremity of the LSBB passageway (Fig. 2c). This point, called "point D," has an average discharge of approximately 130 ml/min (Perineau et al. 2011). The flow at point D is of great hydrogeological interest because it occurs in a featureless zone in a karst environment: no major fault, no apparent karstification (in both surface, exokarst, and at depth). Furthermore, it is located several tens of meters below the so-called "epikarst" zone—according to Mangin's schema (Mangin 1975); however, it presents surprisingly smooth water dynamics compared to other flow points in the LSBB. The flow at D has sometimes increased after a rain event, while at other times flow has remained unchanged after a similar amount of rain (Barbel-Perineau 2013). The geological context associated with this puzzling

hydrogeological behavior led to a research focus on the area located above point D.

The study site is located within the Fontaine de Vaucluse karst hydrosystem in southeastern France. The Fontaine de Vaucluse is the largest karst spring in Europe; between 1877 and 2004 it produced an average daily outlet discharge of 19 m^3/s (Cognard-Plancq et al. 2006). The catchment area is approximately 1,115 km^2 (Fig. 2b) and the karst UZ is particularly thick; its average thickness is approximately 800 m (Puig 1987). The large size is due to the presence of a nearly 1,500-m-thick massive and continuous limestone (Masse 1969, 1976) comprising Necomanian marls to upper Aptian marls. A part of this carbonate platform is composed of reef limestone, which may reach a thickness of approximately 450 m in the region (Fig. 2d). This reef limestone contains Urgonian facies that are traditionally divided into three subdivisions: U1, U2, and U3 (Leenhardt 1883). A part of this Urgonian limestone has exceptionally high total matrix porosity for a limestone and it covers at least half of the Fontaine de Vaucluse catchment (e.g. Masse 1969; Léonide et al. 2014); however, the role of this porosity in water dynamics is still unknown.

Local geological structure investigated in previous studies

The geological structure of the study site was investigated using geophysical and geological surveys (Carrière et al. 2013) and geological modeling (Ollivier et al. 2013). To detect geological structure, a combination of ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) were used to identify geological features that may impact groundwater dynamics. The GPR results provide near-surface high-resolution imaging, and thus can provide relevant geological information such as stratification and fractures (Fig. 3b, c). Despite the exceptional quality of the results, GPR's investigational depth remains limited to around 12 m. ERT is able to

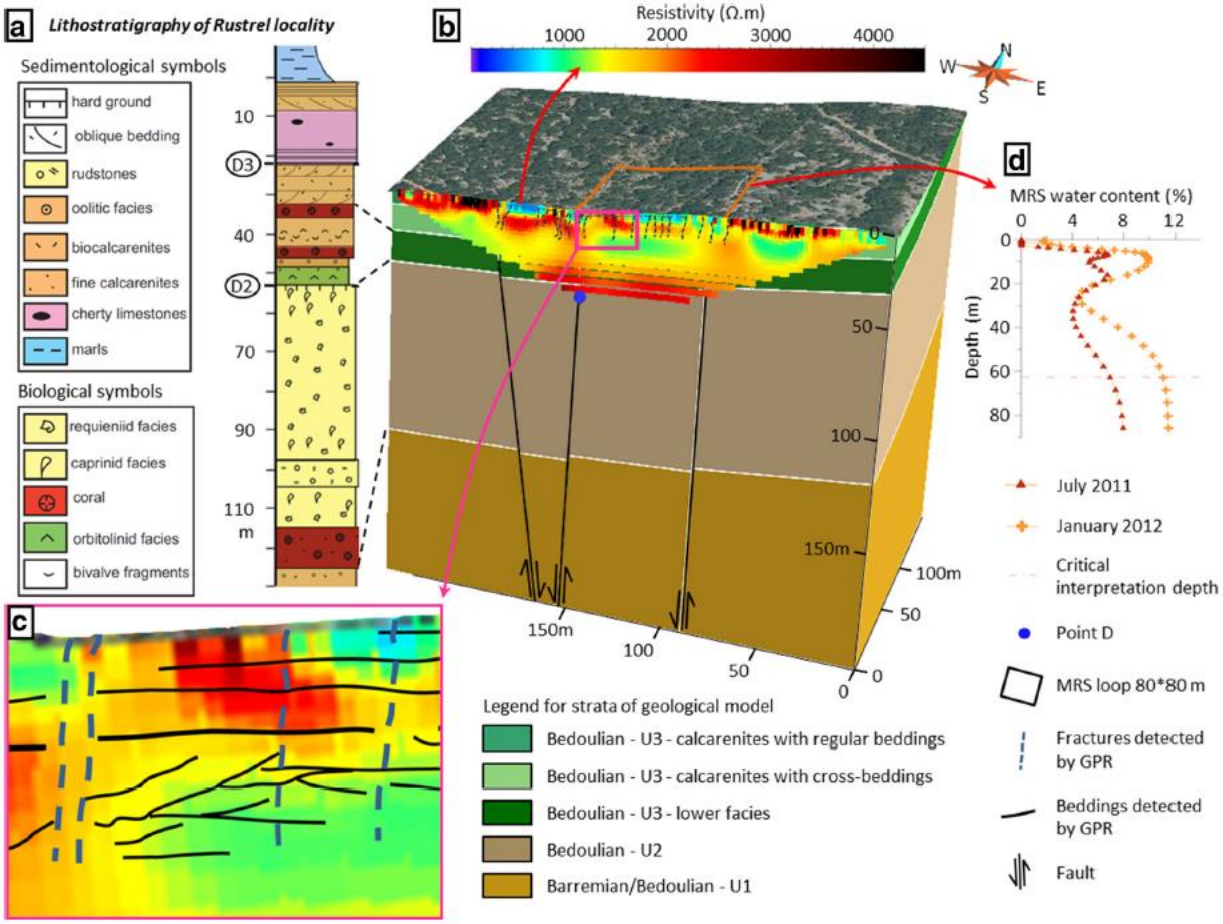

Fig. 3 Comparison between different types of geological and geophysical information: **a** regional lithostratigraphic log (Masse and Fenerci-Masse 2011, modified); **b** 3D geological model (Ollivier et al. 2013) with 252-m-long electrical resistivity tomography (ERT) section LSBB03, inverted in three iterations; **c** zoom on ERT section LSBB03 with bedding and fractures detected by ground-penetrating radar (GPR); **d** Magnetic resonance soundings (*MRS*) of July 2011 and January 2012 (Carrière 2014)

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investigate down to 40 m, but it is an integrative technique that has lower resolution than GPR. In the study area, the investigated limestone is commonly an electrically resistive formation (more than 2,000 Ω.m). However, below a depth of 5–7 m, the ERT profiles reveal several zones of moderate resistivity (around 900 Ω.m). In these zones, cross-stratifications were clearly identified by GPR. The combination of both GPR and ERT results, in addition to field geological studies and geotechnical observations (recorded during underground passageway construction), lead to a well-founded geological interpretation (Fig. 3). Cross-stratifications formed under certain sedimentation conditions (high energy, for example) may have produced a more porous limestone; however, during the first phase of the study, it was impossible to determine the exact role of the identified geological features. What are the respective roles of the detected faults, fractures, or crushed zones? Is it possible to monitor water recharge dynamics in the moderate resistivity zone? These questions were answered during the second phase of the study presented in this report.

Ollivier et al. (2013) performed geological modeling (Fig. 3b) using GOCAD software to combine all available geophysical, geological, and geotechnical information. This geological modeling made it possible to propose a well-founded interpretation for geological structures and to extend the analysis of the site below the depth investigated by geophysics.

An integrated hydrogeophysical approach: methods and tools

The approach used in this study combines several tools (surface based geophysics, geology and tectonics, geotechnical information, hydrodynamics, and infiltration modeling) to explain the functioning of the local hydrosystem.

Effective infiltration assessment

To assess as accurately as possible the effective infiltration entering locally into the karst hydrosystem, exchanges between soil/plant/atmosphere were modeled using CASTANEA (Davi et al. 2005; Dufrêne et al. 2005). This model calculates the effective infiltration by taking into account the following processes: canopy water interception, tree transpiration, soil and litter evaporation, dynamics of soil water content and drainage. This model is based on the Penmann-Monteith equation for calculating evapo-transpiration. The model includes the downregulation of soil drought on transpiration via stomata closure. CASTANEA is a species-specific model that considers features of the forest environment in the study area. CASTANEA was validated in a similar environment (Mediterranean shrubby forest with holm oak) at the Puéchabon site (southern France) using eddy-covariance measurements (Davi et al. 2006; Martin 2012). A requisite inventory of forest species was conducted for a representative zone measuring 120 m × 20 m to define stand-specific input parameters; it included a tree inventory to assess the standing biomass, hemispherical photographs to assess the canopy leaf area index (Davi et al. 2008), and soil pits to estimate soil water content.

Meteorological data were recorded at the Centre d'Information Régional Agro-Météorologique et Economique (CIRAME) station at Saint Saturnin-les-Apt (Fig. 2). Between 2004 and 2012, average daily temperatures ranged between –7.2 and 28.7 °C. The average annual temperature was 13.5 °C and the average annual rainfall was 660 mm.

Flow measurement

The discharge rate at point D has been monitored since 2003 to study the response of the UZ to natural rainfall events (Garry 2007; Blondel 2008; Barbel-Perineau 2013). Flow point D shows smooth hydrodynamic behavior even though it is located at a depth of 33 m (Figs. 4 and 5).

Within the LSBB passageway, 42 other flow points have also been monitored since 2003. In this report, a comparison of point D to point C is given; these two points show the maximum difference in terms of hydrodynamics. The measurement frequency was almost weekly (349 measurement campaigns at the end of 2012). Discharges are measured by collecting water in a graduated cylinder over a period of time.

Geophysics implementation, acquisition strategy, and field constraints

After extensive testing with a large array of geophysical methods (electromagnetic, electric, gravimetric, and nuclear magnetic resonance; Carrière 2014), two efficient and accurate techniques were selected to study hydrodynamics at the local scale (a few hundred meters squared): ERT and magnetic resonance sounding (MRS). These geophysical techniques make it possible to image temporal variation in complementary physical properties of the subsurface (until 90 m). This variation may be related to variation in water content and thus may shed light on hydrodynamic behavior.

Measurements at the study site were conducted at two timescales: (1) with a seasonal time step to detect rough variations, and (2) with a short time step during a large rain event to detect fast water flows. At the experimental site (Fig. 4), the slope, the vegetation, and the gravel cover required extensive preparation prior to measurements. The exact position of all geophysical measurements was calculated via the real time

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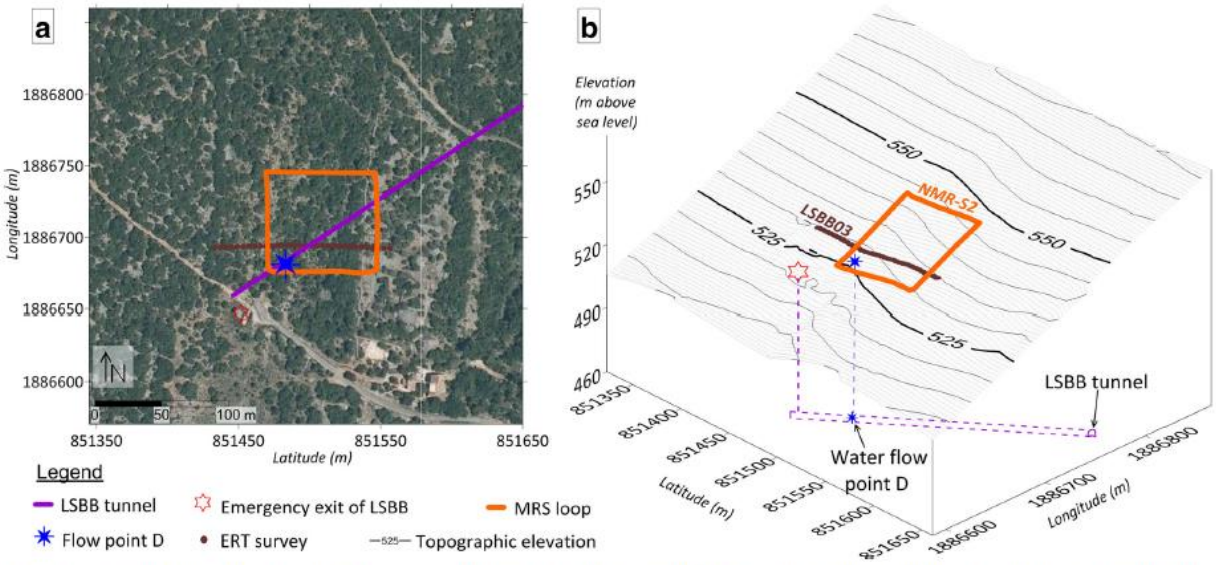

Fig. 4 Experimental site of the Low Noise Underground Laboratory (*LSBB*): a location of geophysical measurements on aerial photo; b pseudo 3D location of geophysical measurements discussed in this report

kinematic (RTK) acquisition method every 2 m using the differential global positioning system (GPS) TRIMBLE 5800.

MRS

MRS is the only ground-based geophysical method that can obtain a signal directly related to the presence of water to a depth of several meters. MRS, which is designed for a quantitative description of aquifer formations, is based on the phenomenon of hydrogen proton magnetic resonance. The MRS array generates a signal with a specific frequency to excite the hydrogen protons in water molecules, and the MRS signal received is specifically related to groundwater (e.g. Legchenko et al. 2002; Vouillamoz et al. 2003).

The minimal amount of time necessary to conduct an MRS survey (approximately one day per sounding) and the high cost of the equipment led to the use of this geophysical technique at the seasonal time step for imaging seasonal variations in water content. Only two MRS surveys were repeated at the seasonal time step and the results of both show the same

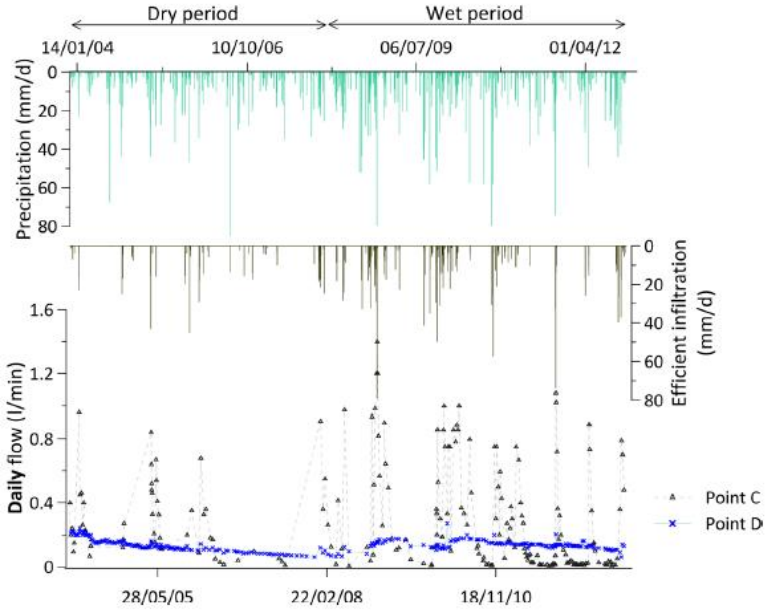

Fig. 5 Precipitation and effective infiltration calculated using CASTANEA compared with flow dynamics at points *C* and *D* between 2004 and 2012

dynamics. In this report, the temporal variability of only one MRS sounding, MRS S2, is presented and discussed. This sounding was chosen because it is located above the moderate resistivity zone detected with ERT.

The acquisition system used is a Numis Plus by IRIS instruments. The measurements were collected in summer (July 2011) and in winter (January 2012). To integrate a large area above water point D, a wide MRS array (80 × 80 m) was chosen for these surveys. It is important to mention that for both MRS surveys, electromagnetic noise was low compared to signal amplitude (ratio signal to noise >1.5), ensuring interpretability and comparability between measurements (e.g. Legchenko et al. 2002).

The details of MRS results from this site were discussed and presented by Mazzilli et al. (2012) and Chalikakis et al. (2014). These results indicated the presence of a significant amount of water in the UZ karst to a depth of 90 m (MRS sometimes indicated a water content greater than 10 %). Eight MRS were conducted at the experimental site to study the spatial variability of MRS signals. All soundings exhibit similar forms; however, significant lateral variation in water content was observed between soundings (Mazzilli et al. 2012), revealing that the karst UZ is also a heterogeneous environment in terms of water content.

ERT

The ERT technique has been widely used in karst areas because it is robust and reliable (e.g. Cardarelli et al. 2006; Robert et al. 2012). The sensitivity of electrical resistivity to moisture variations and the rapidity of ERT measurements (approximately 1 h per section) led to the selection of this geophysical technique to image rapid resistivity variation during heavy rainfall. During the 30-day campaign, ERT time-lapse acquisition ranged from every 3 h during the rain event (17 days) to one section a day after the rain event.

The acquisition system used is an ABEM Terrameter SAS 4000 (Dahlin 2001) with four channels and 64 electrodes. Implantation of the ERT electrodes, mainly at limestone outcrops, required holes that were mechanically dug into the rock; saltwater and mud were added to ensure a good quality ground contact. The ERT section LSBB03 acquired with Gradient array is presented in this report (Fig. 4). The section is oriented east–west. This direction is perpendicular to the general slope, is sub-perpendicular to one of the main fault and lineament directions, and is the most heterogeneous direction in terms of apparent resistivity spatial distribution (Carrière et al. 2013). The Gradient array was chosen for this survey because of its robustness and its rapidity (Dahlin and Zhou 2004).

A portion of the first ERT results were presented by Carrière et al. (2015) to evaluate the effectiveness and technical limits of ERT to monitor water infiltration via previously recognized karst features under natural conditions. Apparent (directly measured) resistivity (ρ_α) analysis is not usually considered in ERT surveys; however, Carrière et al. (2015) demonstrate that with the current technology, in this kind of complicated media, existing inversion schemes are not adequate. It was hoped that raw results with no artifacts related to inversion schemes could provide relevant information. If one analyzes variation in resistivity of inverted sections, it is only possible to observe general evolution of the near surface. Due to its integrative character, the inversion process smooths any fine variation even if one tries to observe only inverted resistivity variation between two consecutive time steps. In this context, apparent resistivity variations ($\Delta\rho_\alpha$) between two consecutive time steps were analyzed. These variations were normalized by the delay (Δ_T) between consecutive measurements (ρ_n and ρ_{n-11}) using the following equation.

$$\Delta\rho_\alpha = \left(\frac{\rho_{n-1}}{\rho_n} - 1\right)\frac{100}{\Delta_T} \quad (1)$$

Results and interpretation

The hydrodynamics of flow points C and D as a function of recharge (rain and effective infiltration) is presented first, followed by the results of geophysical monitoring at both seasonal and event timescales.

Flow dynamics versus rain and effective infiltration

Two hydrological periods can be observed: a dry period from 2004 to 2007 and a rainy period from 2008 to 2013 (Fig. 5; Barbel-Perineau 2013). Effective infiltration modeling using CASTANEA (Fig. 5) confirms this alternation of wet and dry periods. One notes that effective infiltration is quite limited between 2004 and 2007. Rigorous modeling of effective infiltration is essential in supporting subsequent interpretations because the difference between rain and effective infiltration can be quite large and can lead to misinterpretation.

During the first dry period, the water discharge at point D generally decreases and there is no clear reaction during rain events. On the contrary, during the second rainy period, this water discharge increases and responses to rain events are more apparent. The regularity of point D is obvious when comparing variation ranges between points D and C.

Point C discharge is highly reactive to rainfall; it shows typical karstic dynamics even though it is located at a depth of 256 m (Fig. 5). Note that the reactivity of flow point D to a rain event differs from dry period (no variation) to wet period (rapid discharge increases for strong rainy events); however,

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the flow rate at point C increases proportionally with effective infiltration in both dry and wet periods. Without more arguments, it is difficult to explain the difference between D and C. One can only point out that point D is located within porous Urgonian limestone and C is located within lower Barremian limestone (Fig. 2d).

Hydrogeophysical monitoring

Seasonal dynamics

MRS was used to detect the seasonal variation in storage in the karst UZ between summer 2011 and winter 2012. In processed MRS results (Fig. 3d), two layers reveal unusual water contents for karst UZ. The first interval with high water content (10 % water content according to MRS) is at a depth of approximately 15 m (above low point D); the other high water content interval (12 % water content according to MRS) is deeper than 40 m.

Although these elevated water contents are surprising for a karst hydrosystem UZ, these values agree with the high porosity estimated by other geophysical methods used at the LSBB (Maufroy 2010; Bereš 2013) and total matrix porosity measured in plugs in the region (e.g. Masse 1969; Léonide et al. 2014; Fig. 2d).

Significant temporal variations in MRS water content are observed at several depth levels (Fig. 3d). The measured variations are as high as 3 % water content, indicating that these storage variations could participate in seasonal water flow regulation in the karst UZ.

It is difficult to conceive that such a large volume of water could be stored in fracture and conduit porosity of karst UZ. For this reason, in this geological context where limestone can be very porous, the majority of the water content can be attributed to the porous matrix.

The high water content level detected by MRS near the depth of 15 m corresponds to location of the cross-stratifications and a moderate resistivity zone detected by GPR and ERT (Fig. 3b, c). This feature probably contains a stock of water located above point D, and supplies this water to point D. Its hydrogeological role will be discussed in the next section.

Event dynamics

This unique large-scale ERT surface-based experiment was conducted during a typical Mediterranean autumn rain event (17 days). A total of 230 mm of rain were recorded and 120 ERT time-lapse sections were measured over the same profile (LSBB03) during and after the rain event (a total of 30 days).

Apparent resistivity values have been arithmetically averaged for each section. Apparent resistivity decreased sharply during the rain event from 1,750 to 1,050 Ω.m (Fig. 6b). These variations do not seem to be related to temperature variations because air temperature and water temperature (at point D) remained stable during the experiment (Carrière 2014); thus, these electrical resistivity variations can be reasonably related to variation in water content in the subsurface. Analysis of this mean apparent resistivity indicator made it possible to select the 12 critical time steps presented in Fig. 6a: before, during, and after the rain event. These results are presented (Fig. 6a) as hourly percentage changes in ρ_α with a basic representation of vegetation and soil cover around the profile. Previously recognized karst features (Carrière et al. 2013) are also represented.

At the beginning of the rain event (Fig. 6a, section 1 → 2), ρ_α decreased moderately and homogeneously along the section. This resistivity decrease could be related to moistening of near surface horizons; however, after the first rain event (Fig. 6a, section 2 → 3), ρ_α stabilized quickly. During the following heavy rain episode (Fig. 6a, sections 4 → 5 to 7 → 8), the moistening process appeared to be quite heterogeneous and some zones resembled water pathways or preferential infiltration zones; nevertheless, it would be unwise to link observed ρ_α variations at depth with deep moistening processes. The observed variations can also be directly influenced by near surface variations. Immediately after the rain (Fig. 6a, sections 9 → 10 and 10 → 11), ρ_α increased in some zones. This result may be related to drainage processes. These zones correlate well with zones previously identified as preferential pathways. This second observation reinforced the hypothesis of preferential pathways playing a hydraulic role that can be traced with ERT monitoring; however, it is still not possible to specify properties such as the geometry of these pathways. Other zones where such drainage processes are not identifiable may be related to zones where soil is thicker and remains moist after rainfall.

The assumed water pathways identified on the basis of apparent resistivity do not seem to be related to vegetation density or soil cover variations (Fig. 6); however, these zones appear related to fractures or fault zones previously detected by GPR (Carrière et al. 2013). Note also that resistivity variations in fractures are different from those measured in the crushed zone located in the western part of the profile. A crushed zone may provide a larger water pathway than a fracture. It is important to emphasize that the methods used in this study do not image the pathways with certainty.

Fig. 6 **a** Hourly change in apparent resistivity between two consecutive time steps. Positions of fractures previously detected by ground penetrating radar (*GPR*) and basic representation of vegetation and soil cover; **b** Evolution of mean apparent resistivity during monitoring versus rain. Each *brown point* represents one electrical resistivity tomography section (Carrière et al. 2015). *PsZ* is pseudo depth

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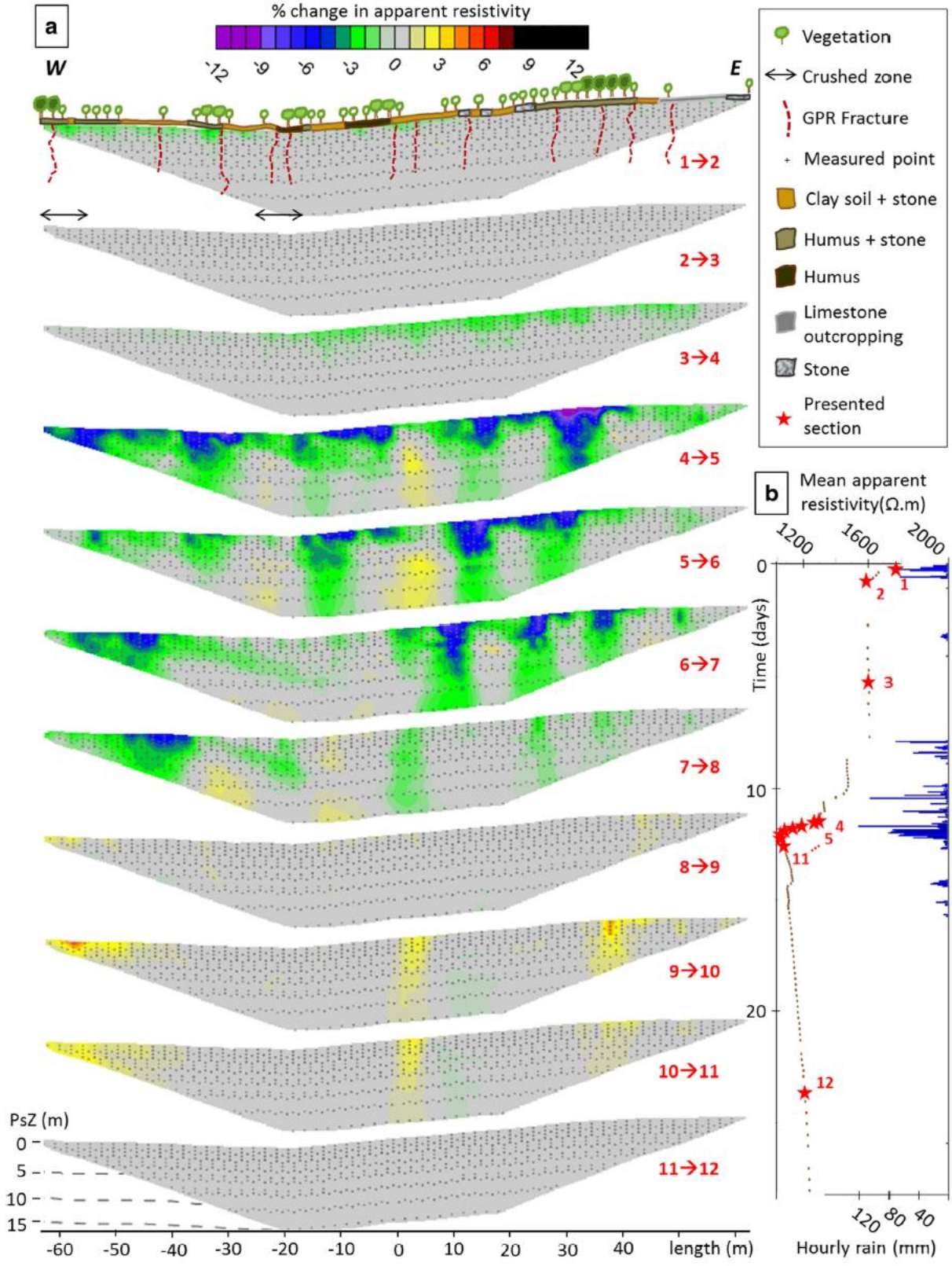
a
% change in apparent resistivity
-12 -9 -6 -3 0 3 6 9 12
W
E
1→2
2→3
3→4
4→5
5→6
6→7
7→8
8→9
9→10
10→11
11→12
PsZ (m)
0
5
10
15
-60 -50 -40 -30 -20 -10 0 10 20 30 40 length (m)
Vegetation
Crushed zone
GPR Fracture
Measured point
Clay soil + stone
Humus + stone
Humus
Limestone outcropping
Stone
Presented section
b
Mean apparent resistivity(Ω.m)
1200 1600 2000
Time (days)
0
10
20
1
2
3
4
5
11
12
120 80 40
Hourly rain (mm)

Discussion

Local scale: study area

This integrated hydrogeophysical approach at two different timescales has improved the current understanding knowledge of the hydrogeological functioning of study site. At the seasonal time step, MRS made it possible to identify water storage variation above and below flow point D. These variations are related to slow water dynamics within matrix porosity. This hypothesis is consistent with the regular flow dynamics at point D, which were observed during both dry and recharge periods (Fig. 5). Moreover, it is consistent with the large total matrix porosity within Urgonian limestone, which may reach 20 % (Fig. 2d). At the rain event timescale, ERT monitoring revealed heterogeneity in infiltration (Fig. 6). Some fractures or faulted zones previously detected by GPR (Fig. 3) were identified as probable preferential water pathways (Fig. 7b, d).

During wet periods, when water fills these vertical structures, hydraulic head (Δh) increases above flow point D, which induces a prompt increase in flow at D as in October 2011 (Fig. 7d) during ERT monitoring (Fig. 6). During this type of rain event, this increased flow may push forward older, less mobile water according to the water schema proposed by Barbel-Perineau (2013) who studied hydrochemistry within the LSBB.

During long dry periods, as for example, between 2004 and 2007 (Fig. 7a), flow point D did not respond to rain pulses even during extreme events (Fig. 7b). Thus, there is probably no significant hydraulic continuity between near-surface water-filled fractures and the deeper porous matrix reservoir; therefore, there is no transmission of a pressure pulse to cause increased flow at point D. This absence of connection is probably due to partial drying of the porous matrix reservoir above point D. The evolution of the dry porous matrix to water-filled matrix may take several years. This timeframe can explain the multi-annual inertia to recharge the stock that supplies point D, as was observed between 2007 and 2010 (Fig. 5).

To confirm this interpretation, three 50 m boreholes were dug around flow point D at the end of 2014, at a distance of approximately 20 m. In each borehole, the water level was measured at a depth of approximately 40 m. Another hydrogeological study is currently in progress to examine borehole dynamics and water circulation.

Regional scale: Fontaine de Vaucluse hydrosystem

How can this knowledge about the local hydrosystem at point D help explain karst hydrodynamics at a larger scale such as the entire Fontaine de Vaucluse hydrosystem? It is particularly relevant to study the relationship between rainfall and water discharge during the period from 2004 to 2012 because recharge was highly variable during this period. A long dry period between 2004 and 2007 was followed by a more rainy period between 2008 and 2012. The annual dynamics of rainfall, effective infiltration, and water discharge presented in Fig. 8 illustrate these dry and wet periods.

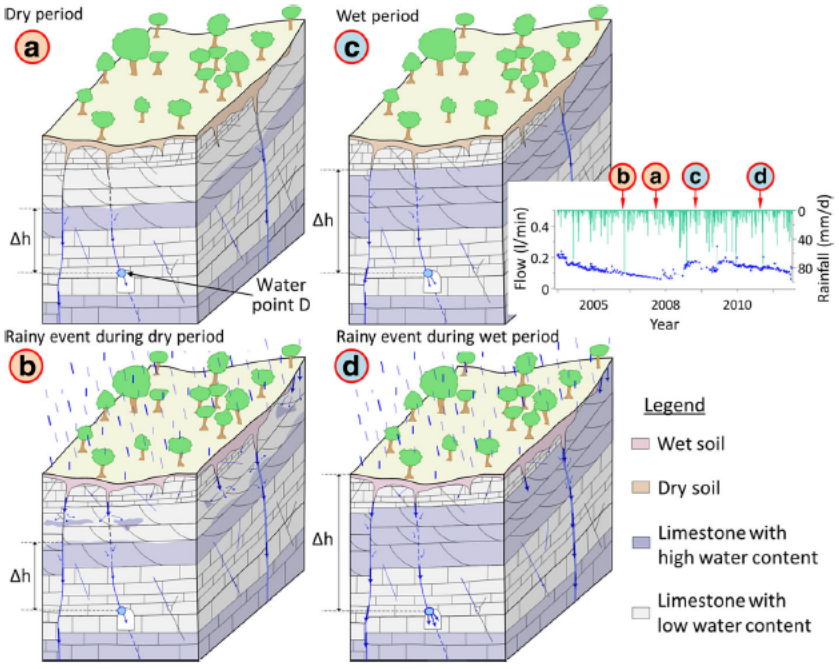

Fig. 7 a–d Synthetic functioning model of the local hydrosystem that supplies flow *point D*. D flow variation depends on rain conditions

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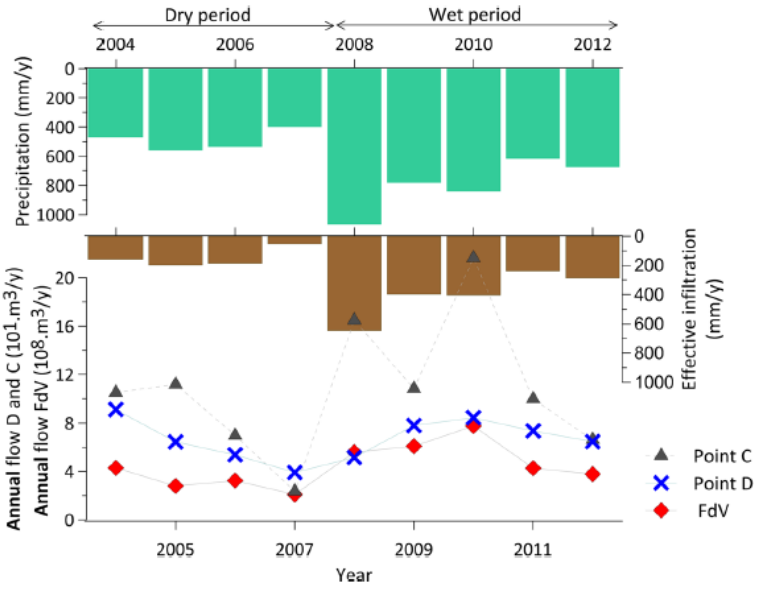

Fig. 8 Comparison of annual water discharge for Fontaine de Vaucluse (*FdV*) and flow points *D* and *C* with annual precipitation and effective infiltration modeled for the period of 2004 to 2012 by CASTANEA

Although these results are applicable to a discussion of the relationship between rainfall and output flow at LSBB flow points, the relationship with spring discharge at the Fontaine de Vaucluse should be approached with caution. However, the total annual rainfall in Saint Saturnin-les-Apt (Fig. 2b) is representative enough of inter-annual rainfall variation in the region to allow the following discussion.

These inter-annual recharge variations cause changes in discharge rates at the outlet of the karst system as a whole (Fontaine de Vaucluse spring) and at local outlets of karst sub-systems such as water points C and D in the LSBB. However, these variations are highly variable between the Fontaine de Vaucluse and water points C and D, and are summarized as follows:

- Water point C exhibits typical karst dynamics with large flow range (a factor of 10) depending on the quantity of annual effective infiltration. This relationship was clearly demonstrated in 2007 when effective infiltration was at a minimum and water flow at C was very low.
- The water point D has different dynamics because its water discharge is quite regular; the range of its annual discharge variation is only a factor of 2. The flow rate at point D decreased continuously between 2004 and 2007, after which its flow increased regularly until 2010. However, effective infiltration decreased significantly between 2008 and 2010; thus, there is a kind of delayed dynamic. The results highlight the importance of porous matrix on water flow, even in a karst limestone aquifer system.
- The annual water discharge of the Fontaine de Vaucluse exhibits dynamics similar to those at point D (Fig. 8), although its flow variation range is slightly larger than point D, a factor of 3.5. Similar to point D, the flow rate at the Fontaine de Vaucluse also increased between 2007 and 2010; however, effective infiltration decreased significantly from 2008 to 2010. This observation suggests that water flow regulation mechanisms observed at point D are site-specific. Similar mechanisms of water flow regulation through the porous matrix may play an important role in the entire Fontaine de Vaucluse hydrosystem (Fig. 8). Considering the large volume of Urgonian porous formations in the hydrosystem (Fig. 2b), this assumption is a plausible explanation of part of the multi-annual dynamics of the Fontaine de Vaucluse spring.

Even so, at a daily time step, the Fontaine de Vaucluse spring can be highly reactive, similar to flow point C; however, even if floods at the Fontaine de Vaucluse can be impressive, they represent only a limited part of the annual water discharge. The annual flow dynamics of the Fontaine de Vaucluse seem to be predominantly influenced by slow water flow within a porous matrix, as is the case at point D.

Conclusions

This study was conducted at a local scale around the LSBB underground laboratory to improve the current understanding of the local karst hydrosystem. The results presented in this report demonstrate that a considerable volume of water can be stored within matrix rock in the karst UZ. Masse (1969) measured exceptional matrix porosity for limestone (up to 20 %) on the Urgonian platform around Fontaine de Vaucluse

catchment area; however, the hydrodynamic role of this matrix porosity was not yet known.

MRS surveys confirmed high free water content (5–10 %) within the karst UZ. This high water content indicates a large volume of water that cannot be stored within fractures or karst conduits in the UZ. This water is stored within limestone layers that were also identified by previous ERT and GPR surveys; moreover, MRS surveys identified seasonal variations in stored water (around 3 %), which indicates that this water reserve is active. The ERT monitoring at the event scale made it possible to demonstrate that despite the presence of porous limestone, the study site has characteristics of a fractured/karstified area in which recharge processes are highly heterogeneous. Rapid water circulation can occur through preferential water pathways and cause flow peaks at point D.

Without additional measurements, the geophysical survey cannot be used to extend the hydrodynamic properties observed at the LSBB site to the Fontaine de Vaucluse hydrosystem, either wholly or in part. That is why it is not reasonable to try to quantify the consequences of the presence of porous limestone on the Fontaine de Vaucluse spring flows; however, considering that Urgonian limestone covers more than half the surface area of the Fontaine de Vaucluse basin (Fig. 2b) and that Masse (1969) measured high matrix porosity on the entire Urgonian platform, there are necessarily repercussions in Fontaine de Vaucluse outlet flow that may explain the multi-annual dynamics of water flow (Fig. 8).

If Urgonian limestones play an important role in Fontaine de Vaucluse hydrodynamics, similar geological formations can impact the hydrodynamics of other karst hydrosystems in comparable ways, including areas far from the Mediterranean Sea where the sedimentary conditions are almost identical—for example, Cenozoic carbonate rocks in the Gulf of Mexico and the Caribbean are highly porous (Halley and Schmoker 1983). Therefore, on the basis of these results presented, it is essential to consider the role of the porous matrix in water flow regulation within a karst UZ. Hydrodynamic modelling should be adjusted accordingly to properly assess the groundwater resource potential and improve sustainable management and exploitation of karst hydrosystems.

Acknowledgements The authors would like to express their gratitude to CIRAME, to ORE H+ and to all the LSBB team for their technical and logistic help. This study was funded by a French ministry of education and research PhD grant. This work was performed within the framework of the FDV/LSBB observation site, part of the KARST observatory network (www.sokarst.org) initiative of INSU/CNRS, which seeks to support knowledge sharing and promote cross-disciplinary research on karst systems. We also thank the editorial board of *Hydrogeology Journal*, S. White, M. Saribudak and an anonymous reviewer for helping us improve this report.

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7.3. Carrière et al., 2018

Environmental Earth Sciences (2018) 77:734
https://doi.org/10.1007/s12665-018-7909-1

THEMATIC ISSUE

Sustainable groundwater resources exploration and management in a complex geological setting as part of a humanitarian project (Mahafaly Plateau, Madagascar)

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Received: 11 April 2018 / Accepted: 15 October 2018
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Abstract
Southwestern Madagascar is a semi-arid region and a hot-spot of global change. On the Mahafaly plateau, people live with quasi-permanent water stress and groundwater, the only available resource, is difficult to exploit due to a complex hydrogeological environment. A methodology (suitable for humanitarian projects; < 40 k€) was developed in four phases to assess the sustainable exploitation of the water resource: (A) regional scale exploration, (B) village scale exploration, (C) drilling campaign, and (D) hydro-climatic monitoring. This integrated hydrogeophysical approach involves geophysical measurements (262 TEM-fast soundings, 2588 Slingram measurements, 35 electrical soundings), hydrochemical analyses (112 samples), and a piezometric survey (127 measurements). Two groundwater resources were identified, one deep (below 150 m) and one shallow (< 20 m). Hydrochemical results highlighted the vulnerability of both resources: anthropic contamination for the shallower and seawater intrusion for the deeper. Therefore, subsequent geophysical surveys supported the siting of six boreholes and three wells in the shallow aquifer. This methodological approach was successful in this complex geological setting and requires testing at other sites in and outside Madagascar. The study demonstrates that geophysical results should be used in addition to drilling campaigns and to help monitor the water resource. In fact, to prevent over-exploitation, piezometric and meteorological sensors were installed to monitor the water resource. This unique hydro-climatic observatory may help (1) non-governmental organization and local institutions prevent future water shortages and (2) scientists to understand better how global change will affect this region of the world.

Keywords Humanitarian project · Groundwater resources · Mahafaly plateau · Hydrogeophysics · Saline intrusion · Water access

Introduction

Characterizing aquifer systems and identifying groundwater resources are of primary importance for sustainable groundwater management. Disorderly groundwater resource extraction can lead to ecological, economic, and humanitarian disasters (e.g. Leduc et al. 2007; Re et al. 2011; Lee

This article is a part of Topical Collection in Environmental Earth Sciences on Water Sustainability: A Spectrum of Innovative Technology and Remediation Methods, edited by Dr. Derek Kim, Dr. Kwang-Ho Choo, and Dr. Jeonghwan Kim.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12665-018-7909-1) contains supplementary material, which is available to authorized users.

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Published online: 31 October 2018

et al. 2015). Facing global warming (IPCC 2014), intensive pastoralism, and deforestation (e.g. Lavee et al. 1998), numerous regions around the world are suffering and will continue to undergo intense changes. For these reasons, the scientific community must seek to limit these effects (e.g. Wilkinson 1996; Moustadraf et al. 2008; Dai 2013; Taylor and Scanlon 2013).

Southwestern Madagascar is a global warming hot spot (Dai 2013). Since 2016, El Nino conditions resulted in reduced rainfall. Widespread charcoal production results in deforestation and spread overgrazing which amplifies desertification process. Fifty percent of the population of southern Madagascar (850,000 people) required humanitarian assistance in 2016. The study site is known as, the Ankazomanga basin, the name comes from one of the main villages of the region in the northern part of the Ankazomanga basin. The basin is a depression covered by red sand, overlying a karstified carbonate formation in the middle of the Mahafaly plateau where 14,000 people were living in 2013 (Lazzarini and Ratsimbazafy 2013). Since 2013, 11 villages have been targeted as a humanitarian priority by the Non-Governmental Organization (NGO) Action Against Hunger (AAH). In this basin, rains are weak and scattered and scarce, the ground is highly permeable, and there are no rivers. In this setting, groundwater is the unique source of water supply. An AAH survey (Lazzarini and Ratsimbazafy 2013) reported that 66% of households use less than 15 L/capita/day. According to the same assessment report, many villages do not have perennial water sources; during the dry period, the 20 existing water collecting points are constantly surrounded by crowds of people seeking water. Despite poor water quality the waiting lines are very long, a water "trading center" is installed at the expense of the poor, and small conflicts related to the difficulty of obtaining water are also observed. Women have to walk several kilometers for water and traditional water collecting points are of poor quality. The population has limited coping capacity and drought evolves rapidly into humanitarian crises. Between 2012 and 2016, AAH implemented a 4-year integrated project linked to the alarming rate of food insecurity in the area. The project aimed to prevent chronic malnutrition in children under age 5 and included the construction of water collecting points and installation of new boreholes.

During humanitarian crises, whether for camps or for people in place, NGOs and local institutions look for quick solutions to urgent water needs (Carter 2007). However, in many developing countries, interim solutions become definitive and unsuitable facilities or modes of exploitation can create other problems (e.g. sewage treatment, over-exploitation of the resource). There is often a gap between hydrogeology and humanitarian goals. Groundwater dynamics are slow, droughts or pollution may be related to old environmental conditions or human activities, while humanitarian interventions are often linked to emergencies that require rapid responses (Villholth and Neupane 2011). However, it is often difficult to exploit an underground resource sustainably if the environment is not well known and if historical water records are not available. In this context, it is essential to associate each humanitarian Water Sanitation and Hygiene (WASH) action with an integrated hydrogeological study of the area to promote sustainable groundwater management. Sustainable groundwater management requires an understanding of the following three components: aquifer structure and limits, resource exploitation, and recharge monitoring. This is clearly understood by researchers (e.g. Carter 2007; Lytton and Bolger 2010) but is not always prioritized by local authorities and decision makers (politicians, NGOs, donors). It is therefore necessary that NGOs share the activities they conduct worldwide and communicate related data. This communication will allow humanitarian teams to conduct their activities more efficiently when they arrive at a new site, a priori poorly known (e.g. Jackson et al. 2009; Skokan and Munoz 2010) and to propose sustainable water resource exploitation and management.

The carbonate Mahafaly plateau (3600 km^2), which is poorly documented, is particularly complex from a hydrogeological point of view. The Ankazomanga basin is covered by Quaternary red sand and geological outcrops are scarce (Besairie 1970). Limestone outcrops can be found at the margins of the study area at distances of a few kilometers from the target villages. Moreover, the study area is located on the karstified Mahafaly plateau (Fig. 1) where karst morphologies can be highly developed. In the southern part of the Mahafaly plateau, numerous large sinkholes (20–500 m wide) are present; they have a cauldron shape, as identified by De Saint-Ours (1959) and Karche (1961, 1963). In this setting, traditional hydrogeological tools such as photographic interpretation or field cartography are not very useful for borehole siting. However, geophysics offers a wide range of techniques to improve successful borehole implementation (Vouillamoz et al. 2002). Numerous studies have shown the significant contribution of geophysics in zones of limited geological outcrops (e.g. Edet and Okereke 2002; Lachaal et al. 2011; Descloitres et al. 2013).

This paper presents the main results of an integrated hydrogeophysical approach undertaken in Madagascar since 2013. The paper includes: (1) the methodological approach specifically developed for the study; (2) results at both regional and local scales and the validity of the approach through the drilling campaigns; (3) the first results from the newly established hydro-climatic observatory.

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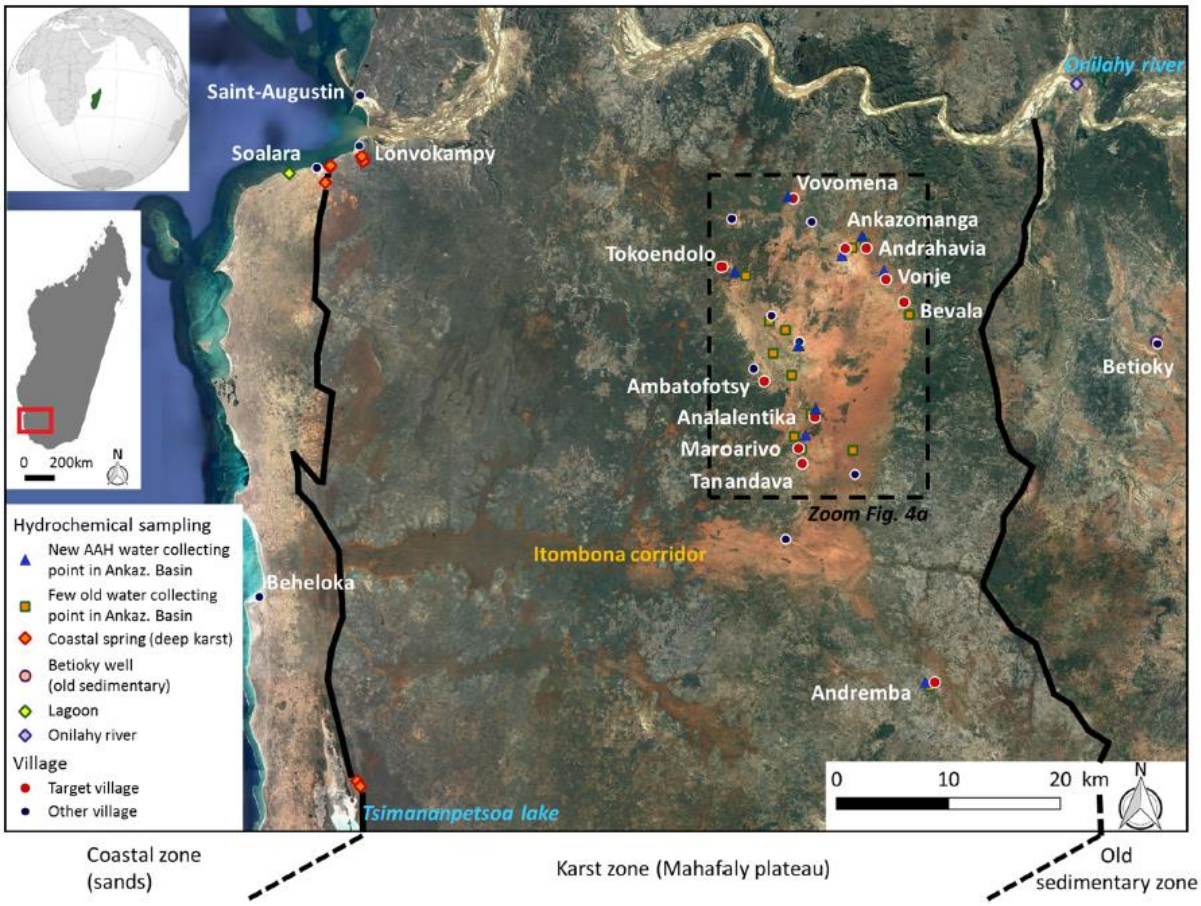

Fig. 1 General setting of the study zone. Additional geological setting is presented in Fig. 3

Background information and site constraints

Geographic and climatic setting

The study area is located 55 km southeast of the city of Toliara and south of the Onilahy River, between 160 and 230 m above sea level. Ankazomanga is quite isolated (a 7–10 h drive from Toliara and 2 to 3 h from Betioky). The study area has no electricity and all material supplies come from Toliara. Logistical constraints were a major challenge during the hydrogeological study.

Southwestern Madagascar is semi-arid; annual rainfall is the lowest in the country (Chaperon et al. 1993; Ferry et al. 1998). Annual rainfall distribution follows a bi-seasonal cycle; the wet season lasts from December to March, and generally reaches maximum precipitation in January. However, precipitation shows very strong spatial and temporal irregularities. Annual precipitation may vary by a factor of five from 1 year to the next (De Haut de Sigy 1965; Guyot 2002). By extrapolation, precipitation should be around 500–600 mm/year at Ankazomanga, with increasing rainfall inland (Guyot 2002). Unfortunately, weather records are not continuous and weather recording stations are located 20–55 km from Ankazomanga.

Hydric stress and humanitarian background

The semi-arid climate causes high water stress for vegetation and populations. The Mahafaly carbonate plateau is a large area that lacks permanent rivers because rainwater infiltrates quickly (because of lapiazed limestones or permeable sands), or rainfall flows towards the bottom of depressions to create temporary ponds. Therefore, runoff from the Ankazomanga basin and Itombona corridor does not reach the ocean. The villages on the Mahafaly plateau are located exclusively in depression areas, such as the Ankazomanga basin or Itombona corridor, where people can access water from temporary ponds or perched aquifers.

In the 1950s, following a severe famine in the Great South of Madagascar, research on water resources intensified and

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the first hydrogeological map was published at a scale of 1/500,000 (Besairie and Pavlovsky 1950; Aurouze 1957). Numerous local hydrogeological studies have been carried out in the Mahafaly (Aurouze 1957; Karche 1961), which led to drilling campaigns that were not very successful (Guyot 2002). In such a hydrogeological setting, water is more valued than in other areas. A 2013 AAH survey (Lazzarini and Ratsimbazafy 2013) reported that 66% of households use less than 15 L/capita/day, the minimum required quantity is 15 L/capita/day to ensure basic personal and food hygiene (Sphere 2015), while 92% use less than 30 L/capita/day. In the drought season, the humanitarian situation becomes critical and limited access to water results in extremely poor hygiene practices and very high pressure on functioning water collecting points. A vast number of inhabitants have to queue for hours to fill their jericans. As a result, a water market develops in which water transporters sell expensive water and water conflicts arise.

In the Ankazomanga basin 74% of the population expressed dissatisfaction with its water access (Lazzarini and Ratsimbazafy 2013). 28% of the surveyed population lacks water, 26% suffer from poor quality, and 14% report a too great distance to water collecting points. When temporary ponds dry out, women in some villages, such as Vovomeena, must walk 10 km daily to fetch water. In addition to the problem of distance, water is mostly drawn from traditional wells where water quality is poor and promotes water-related diseases. Only 40% of the population of the Ankazomanga basin has access to wells equipped with pumps. During drought periods, malnutrition severely affects the population and 37.5% of children under 5 years of age are undernourished (Lazzarini and Ratsimbazafy 2013).

Methodological approach

A four-stage methodological approach was developed in accordance with the objectives and constraints of the project. The cost was adjusted to the realities of humanitarian projects and was keeping below 40 k€. The Mahafaly plateau was studied at different scales due to the scant available knowledge concerning geology and hydrogeology.

Phase A: regional scale survey

This stage began with standard field geological exploration and analysis of available aerial photos (Fig. 2a). 42 water collecting points were sampled for hydrochemical analyzes in the Ankazomanga basin and its surroundings. Regional scale geophysics was applied to image the general geological structure of the filling of the Ankazomanga basin. The main hydrogeological targets and a conceptual hydrogeological schema were identified. All water collecting points in the Ankazomanga basin were surveyed to produce a piezometric map of the near surface water table.

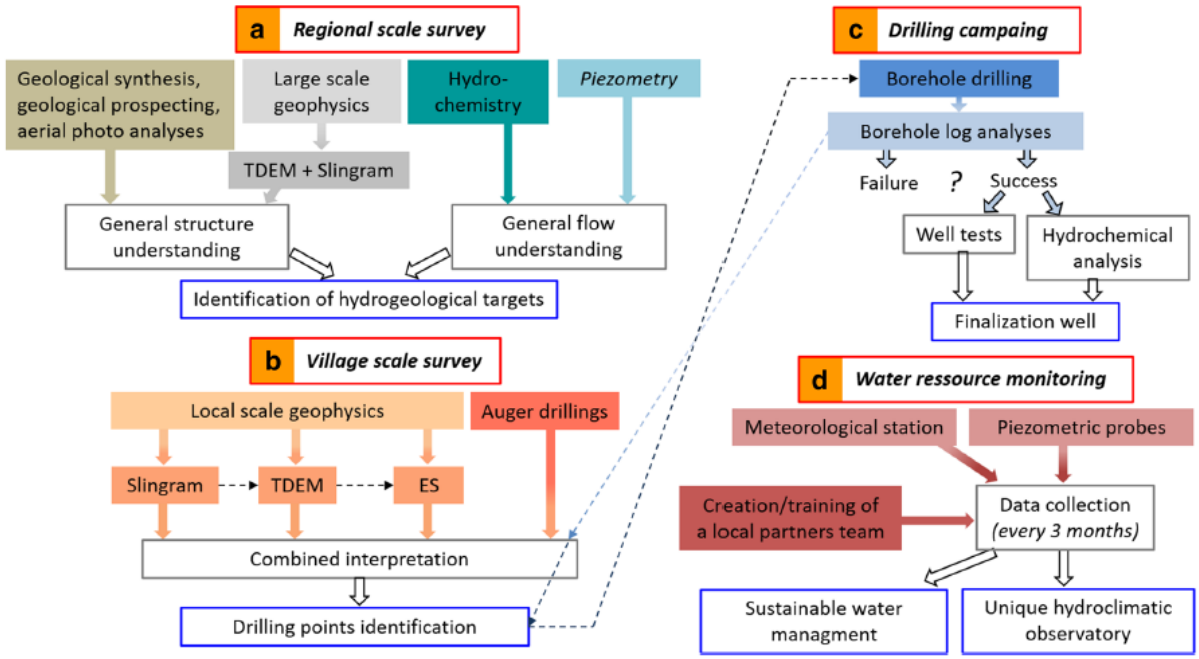

Fig. 2 Methodological approach of the project

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Phase B: village scale survey

At the village scale, a multi-method geophysical survey was used to determine the location for drilling water collecting points in 11 target villages. The village scale survey (Fig. 2b) began with a Slingram survey to detect geological heterogeneities at the local scale and to determine the location of Time Domain Electromagnetism (TDEM) profiling. Electrical soundings were conducted near the TDEM surveys to compare results. Auger drillings to a depth of 8 m aided in the interpretation of the first meters of geophysical results.

Phase C: drilling campaign

Due to the lack of geological knowledge, borehole logs provide valuable information for reinterpreting geophysical results and possibly refining borehole positioning (Fig. 2c). Well productivity and hydrochemical quality were tested before the wells were completed. Consequently, the third stage of the project was the drilling campaign, which enabled validation or reinterpretation of results from previous stages.

Phase D: water resource monitoring

Due to the limited geological and hydrogeological knowledge of the study area and considering its extent, it was necessary to study the exploitation and recharge of the water resource using meteorological and piezometric monitoring (Fig. 2d). Considering the remoteness of the study area, maintenance and data collection is done by teamwork with local partners. The sensor network installed constitutes a unique hydro-climatic observatory and it improves the ability of authorities and NGOs to anticipate water stress and associated humanitarian crises due to water stress.

The results presented in the next chapters follow the same stages as the methodological approach (Fig. 2).

Equipment and tools

Geophysical methods

Slingram (EM 34)

The Slingram device used to conduct electromagnetic induction measurements (EMI) (McNeill 1980) was the EM34-3, developed by Geonics (Ontario, Canada). 2588 EMI points were measured with an approximate spacing of 20–30 m between each point. After preliminary testing and taking into account the hydrogeological target, the decision was made to conduct the survey with a spacing of 20 m between coils. This coil spacing provides a theoretical investigation depth of 15 m (McNeill 1986). The measurements were carried out in both horizontal (HD) and vertical dipole (VD). The EM34 was mainly used for village scale exploration so as to detect general structuring and to find a judicious positioning for the TDEM profile.

Time domain electromagnetism (TDEM)

The TEM-Fast 48 HPC device was used; specifications of the system can be found in the TEM-Fast manual (AEMR 2005a). The principles of the method are described by Barsukov et al. (2006). In brief, an electromagnetic signal is sent and then recorded from a cable loop deployed on the ground allow to estimate the rocks resistivity. The TDEM measurements were interpreted using a commercially available 1D inversion software packages. TEM-Researcher is designed for modeling and inversions of large TDEM sounding data sets (AEMR 2005b). TDEM was used in profiling at both the regional and village scale and a total of 262 soundings were done. At the regional scale a single square loop (100 × 100 m) was used. The profiles are sub-perpendicular to the regional faulting direction N10° (André et al. 2005) and had a reach of 15 km long. At the village scale a 50 × 50 m loop was used. The profiles are perpendicular to the general geological structures detected by EM34 and reach no more than 2 km.

Electrical sounding (ES)

The "Geo-Instruments" device developed by CNRS-Garchy (France) was used. 35 electrical soundings were conducted at the same place as or in the vicinity of TDEM soundings to compare the two techniques and to give more robustness to geological data and hydrogeological interpretation. TDEM is very sensitive to electrically conductive targets and ES is more accurate for electrically-resistive targets. TDEM data interpretation is also significantly less ambiguous as compared to the direct current method, and it is less sensitive to lateral heterogeneities than vertical electrical sounding (Goldman et al. 1988; Goldman and Neubauer 1994). The Schlumberger array was used with a maximum spacing of current electrodes of 200 m and maximal injected intensity was 0.3 A. IPI2Win 3.0.1 software was used to invert apparent resistivity (ρ_a) values into geo-electrical models (Bobachev 2002).

Auger drillings

The auger soundings made it possible to (1) investigate under the omnipresent red sand and (2) reach the phreatic water table to provide more points for the piezometric map. Many auger drillings were conducted during the 2 months of geophysical investigation because the near-surface

underground is generally soft in the Ankazomanga basin. A hand auger 8 m in length and 10 cm in diameter was used. These hand augers were used for 79 holes with a cumulative length of 280 m and the penetrated horizons were summarily described.

Hydrochemistry

Seven sampling campaigns were carried out between 2013 and 2016 and 112 samples were collected in several water points (wells, sea, river, springs) that can be located in Fig. 1 "Hydrochemical sampling". Major ions and total organic carbon were analyzed to obtain information about geological formations present under the red sand cover and about possible anthropic pollution. The sampling was done at both old and new water collecting points in the Ankazomanga basin. Samplings were carried out beyond the Ankazomanga basin to characterize possible interactions with other water resources in the area. Sampling was also done at karst system outlets near the sea (springs, wells, and sinkholes), in the Onilahy river, and in two wells in the town of Betioky that was dug in Old Sedimentary terrains.

Piezometric survey

Piezometry and GPS survey

The study area is very flat and it has no functional topographical landmark. Differential GPS was used to obtain enough accuracy (less than 10 cm in z) to produce a piezometric map of this huge area from 135 measured water points (wells, traditional wells, and auger drillings). The Trimble GPS R10/TSC3 was used with real time correction by RTX satellite.

Piezometric probes

Ten Mini-Diver automatic piezometric probes, developed by Schlumberger, have been installed as part of this project. These devices can obtain results to a depth of 20 m under water, with an accuracy of 1 cm H_2O and a resolution of 0.4 cm. Two barometric probes (Baro) were installed in Ankazomanga and Maroarivo villages for atmospheric pressure variation compensation. In 2014, three Mini-Divers and two Baro probes were installed in already existing built wells. The remaining seven Mini-Divers were installed in the AAH wells in 2016. The measurement interval is hourly and they can acquire 1030 days of data.

Meteorological station

A BWS200 weather station developed by Campbell Scientific has been installed in the Ankazomanga Basin. The weather station is composed of four sensors that measure wind speed and direction, air relative humidity, air temperature, and rainfall. The chosen time step is 1 h. The station is commercially available with a rechargeable battery connected to a solar panel. Taking into account local security conditions it was decided to create a battery box to reduce theft risk to the solar panel and to facilitate battery replacement. The equipment is connected to a CR200X control unit. The control unit receives a scan from each sensor every minute. The autonomy of the system is 1000 days.

Results and interpretation

Regional scale survey

Geological synthesis and field exploration

The study area is at the heart of the Mahafaly plateau, which is composed of Eocene carbonate formations (Besairie 1946). Contrary to the "limestone" terminology used by André et al. (2005), the term "carbonate formation" is preferred in this document because the plateau is composed of other rock types in addition to limestone. Marl, sandstone with calcareous cement, and poorly consolidated lumachelle can be observed at the margins of the Ankazomanga basin. The Eocene formations are divided into three units (Aurouze 1957):

- E1, 300 m thick, nummulitic limestone, calcareous sandstone, and oolitic limestone,
- E2, 150 m thick, clayey limestone with orbitolinids,
- E3, 150 m thick, marly limestone, oyster marl, and gypsum marl.

Although the geological Map of Besairie (1970) showed the Ankazomanga Basin to be filled exclusively with red sand, Aurouze (1957) found some isolated metric-size blocks of black ferruginous sandstone in the field, which confirms the presence of continental Neogene (N) formation. Our geological survey and our drillings confirmed this second hypothesis. In a region more to the south, Besairie (1946) described the continental Neogene as a discontinuous and heterogeneous formation reaching a maximum thickness of 150 m and composed of:

- Compact ferruginous sandstone,
- Red sandstone with cross-bedded stratifications,
- White to pink clayey sandstone and purple clay,
- Kaolin levels 3 to 4 m thick.

According to Besairie (1946) two terrains can be distinguished surrounding the carbonate terrain of the Mahafaly

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plateau (Figs. 1, 3). The Old Sedimentary terrains (Cretaceous, Jurassic, and Karoo) crop out to the east and plunge under the Eocene plateau (Fig. 3). The name "Old Sedimentary" is the local term given to these rocks by geologists who have worked in the area 60 years ago. To the west, the coastal strip, composed of Quaternary sand and sandstone, is separated from the Eocene plateau by the Toliara fault. The Quaternary, 6–10 km wide, overlies on Eocene carbonate formations.

Finally, aerial photographs made it possible to identify faults inside the Ankazomanga basin. These faults are oriented approximately N°10 at the Mahafaly scale, as described by André et al. (2005). These observations will aid in the geophysical results interpretation later in this document.

Hydrogeological synthesis and piezometric mapping

Within the Mahafaly plateau two aquifers can be distinguished: (1) a near-surface water resource (< 20 m) within the sedimentary fill in the Ankazomanga depression, and (2) a deeper water resource (> 150 m) within karstified Eocene formations. The majority of water collecting points are traditional wells (Fig. 4b) (the so-called "vovo"), exploiting the near-surface aquifer at a depth of 2–4 m, through open holes in the ground, to which livestock have easy access. Certain wells exceed a depth of 10 m but they are not the most productive. The deepest well of the region reaches 19 m but is dry most of the year. The deep karst aquifer is not exploited due to its depth (more than 150 m). Near the coast, karstification features such as caves and sinkholes (Fig. 4d), or shallow wells make it possible to access the karst resource at the boundary between the coastal strip and the Mahafaly plateau (De Saint-Ours 1959; Karche 1961, 1963). In the South of Mahafaly plateau, Guyot (2002) demonstrated a strong connectivity between these wells or sinkholes and the lagoon. Several coastal discharges (Fig. 4c) are identified south of the Onilahy River (Solara and Lonvokampy). These karst discharges are highly mineralized (1000–5000 µS/cm) even at a distance of more than 1 km from the coast (Antsiliky spring near Lonvokampy). To the south, André et al. (2005) measured higher mineralization (10,000 µS/cm) in the coastal strip. Exokarst features and the presence of cave fish in some wells (Guyot 2002) indicate that the karst system is well developed.

After the rainy season of 2014, an inventory of water collecting points was carried out in the Ankazomanga basin. 127 water collecting points were inventoried (Fig. 4a), but the majority are temporary. The study area is very flat and devoid of geodetic reference. The use of a differential GPS was therefore necessary. The resulting piezometric map (Fig. 4a) shows that the general flow of the near surface aquifer is towards the west, in the same direction as topographic slope. However, when measurement point density is high enough, it can be seen that at the village scale underground flows are more complex. North of Ankazomanga, flows are directed towards the east. This reflects heterogeneity and a complex morphology of the aquifer wall, which can be explained by either: (1) karst morphologies under Ankazomanga basin fill, or (2) geomorphology of sedimentary formations that fill the basin.

Connectivity between the near surface aquifer of Ankazomanga and the deeper karst hydrosystem remains completely unknown, as are the hydrogeological relationships between Eocene carbonate formations and the Old Sedimentary terrains in the east. The hydrogeological boundaries of the aquifers are poorly known and must be clarified to propose sustainable exploitation and management solutions.

Natural tracing Natural tracing made it possible to identify water masses present in the region. Five groups can be distinguished (Fig. 5):

1. The mineralization of the Ankazomanga basin water (old and new) is low [electrical conductivity is less than 300 µS/cm (see Online Appendix)]. The hydrochemi-

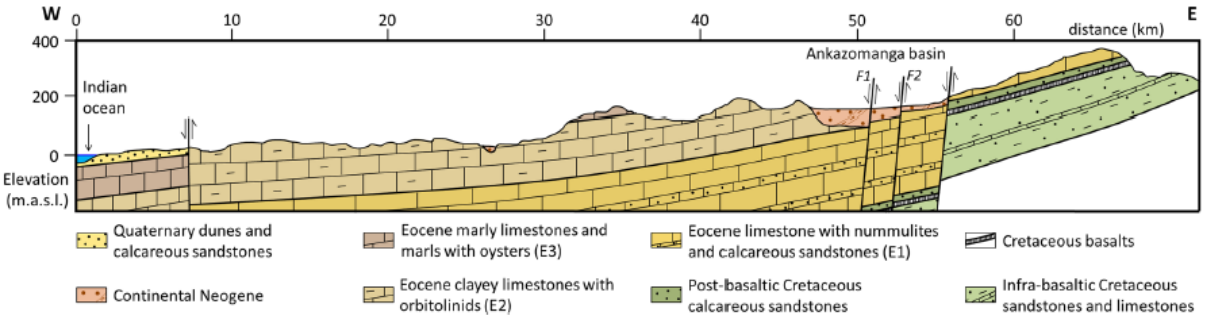

Fig. 3 Simplified geological cross-section of the study area (at latitude 23°47′00″; between Analalentika and Maroarivo villages in Fig. 1) after Aurouze (1957) modified. F_1 and F_2 are the fault identified by geophysics in Fig. 6

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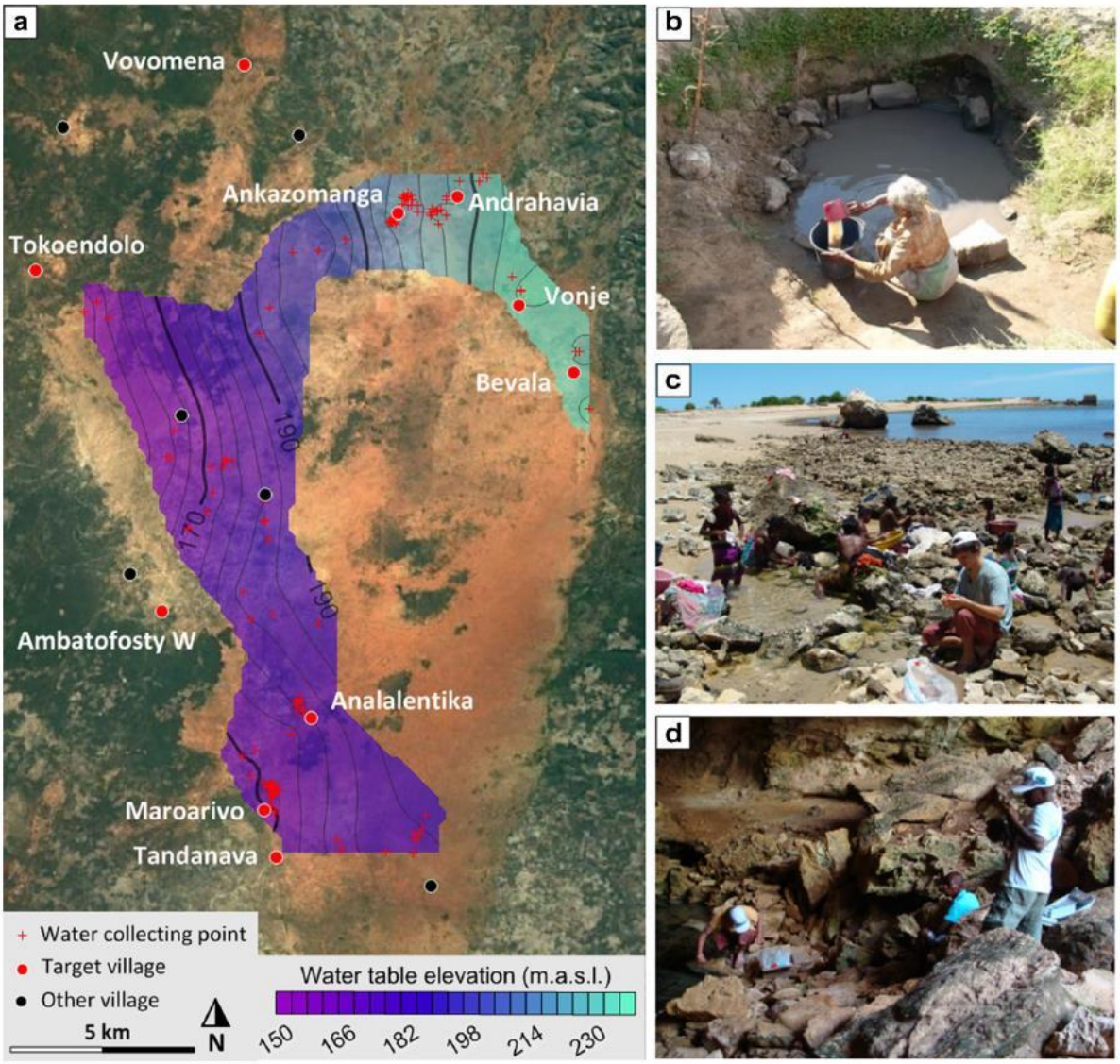

Fig. 4 **a** Piezometric map of the phreatic water table, based on 127 measurements with differential GPS after the 2014 rainy period. **b** Traditional well (so called "vovo") makes it possible to exploit water under tedious and unsanitary conditions. **c** Coastal spring, a natural karst system discharge, near Solara. **d** Hydrochemical sampling in a cave near Tsimanampetsotsa Lake at 8 km from the coast (southwestern of Fig. 1)

cal facies are variable with dominance of bicarbonates, calcium, and sodium. Some waters are affected by anthropic pollution with strong concentrations of NO_3^-, and Cl^-. The chemical variability of these waters reflects the complex and multiple geological facies of Neogene formations. Most Ankazomanga basin waters have Br^-/Cl^- ratios close to seawater, which is probably due to the influence of sea spray.

2. Water from coastal sources, wells, or sinkholes are highly mineralized (electrical conductivity is more than 3000 µS/cm); they reflect hydrochemical characteristics of the deep karst. This strong mineralization of coastal karst waters is consistent with the results of André et al. (2005). The Br^-/Cl^- ratio (Fig. 5b), commonly used in coastal hydrogeology (e.g. Alcalá and Custodio 2008; Katz et al. 2011) confirms that this salinization is due to sea water intrusion, despite the distance to the coast which may be as much as 9 km.
3. Obviously, lagoon water is highly mineralized. Figure 5 shows that this water does not have the exact composi-

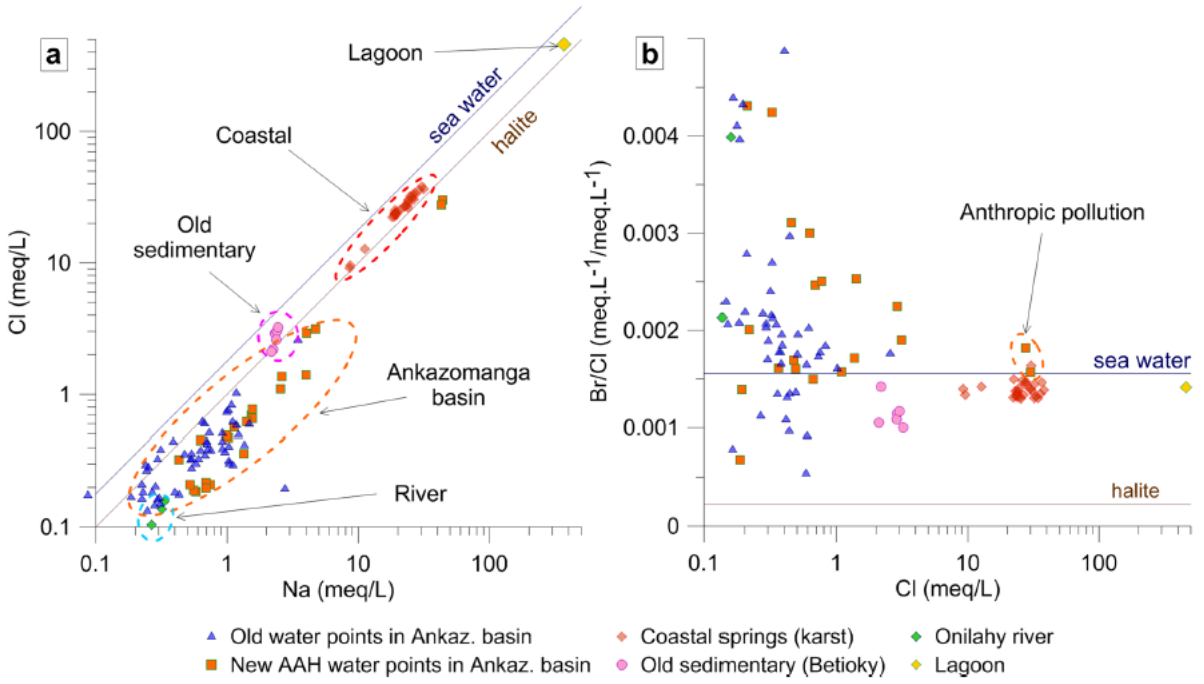

Fig. 5 Hydrochemical results for the 112 waters sampled between 2013 and 2016 (sampling points are located in Fig. 1). **a** Na vs. Cl relationship with identification of water masses. **b** Relationship Cl vs. Br/Cl. Ratio of seawater and halite lines from Fudge (1974), Fontes and Matray (1993), Copin-Montegut (1997)

tion expected for seawater. This composition is probably due to chemical reactions occurring in the lagoon. Dilution of lagoon water by the Onilahy River was suspected but the Br^-/Cl^- ratio (Fig. 5b) invalidates this hypothesis.

4. The Betioky boreholes are in Old Sedimentary terrains and the water has moderate mineralization (≈ 600 µS/cm). Betioky water was sampled from only two boreholes, so these points cannot be considered representative of all Old Sedimentary terrains. However, they are more highly mineralized than the Ankazomanga basin water collecting points, which is consistent with Rabemanana et al. (2005) in the south and measurement obtained by AAH east of the town of Betioky.
5. The Onilahy River has the lowest mineralization (≈ 100 µS/cm). This was expected for surface water. Moreover, slow interactions between water and the crystalline basement where the rainiest area of the Onilahy watershed is located (in central Madagascar) may also be responsible for this low mineralization.

The hydrochemical results point to a strong marine influence on deep karst waters. Any natural tracer (e.g. Br^-/Cl^-, SO_4^{2-}, Br^-/SO_4^{2-}, K^+) would make it possible to identify another source of salinity (evaporites, thermal waters) for these karst waters. However, the tracers used do not reveal any connection between deep karst waters and waters from Old Sedimentary terrains or the Onilahy River. Therefore, it does not seem advisable to exploit the deep karst resource because the distance where sea water intrusions occur remains unknown. Guyot (2002) has shown that further south, the tides have an effect on piezometry and salinity 20 km inland from the coast. Thus, deep karst water can potentially be contaminated under the basin of Ankazomanga. In addition, two more issues need to be taken in to account: (a) exploiting this resource would probably require boreholes to depths of more than 150 m and the related manual exploitation of the water resource would not be possible, and (b) although the Mahafaly karst is highly developed (André et al. 2005) and the risk of borehole siting failure would be high because there is no way to guide a successful borehole to a cavity at such depth. Therefore, the decision was made to focus local scale exploration in the Ankazomanga basin on the near surface aquifer within the Neogene formations.

Regional scale geophysics

Slingram EM34 exploration made it possible to highlight considerable underground spatial variability (Fig. 6a). In

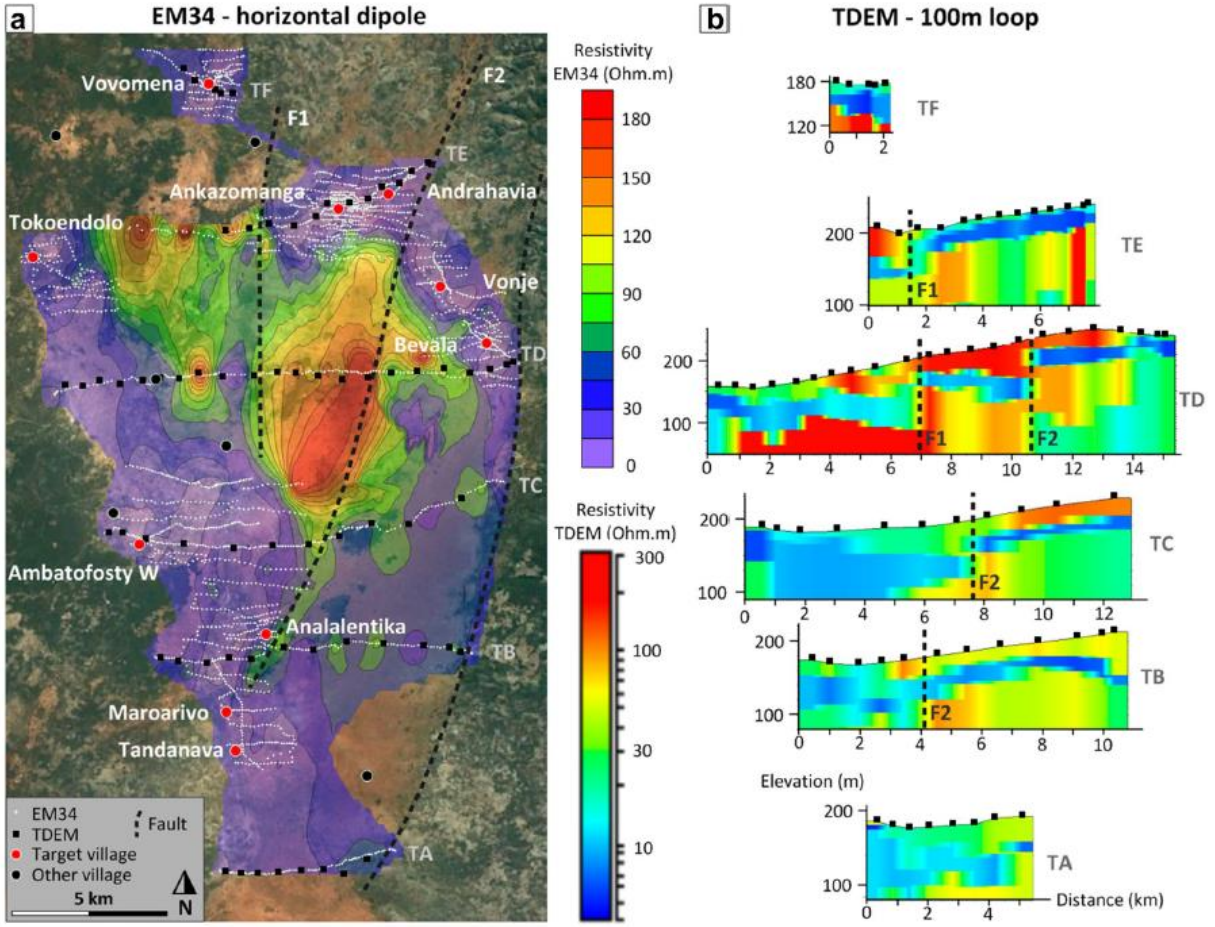

Fig. 6 Geophysical regional scale results and interpretation. **a** Slingram map for horizontal dipole and 20 m inter-coil spacing. **b** Inverted TDEM cross-section obtained by 100 × 100 m square loop

particular, in the heart of the Ankazomanga basin, a more resistant zone (> 150 Ω m) extends in the north–south direction. This direction is consistent with the major regional fracturing direction N°10 (André et al. 2005). Auger drillings revealed a significant consistency between sediment found under red sand covering and Slingram measurements. The most resistive zones correspond to coarse sand whereas more conductive zones coincide with clayey sediments. Following the example of Vouillamoz et al. (2002), different scales are used in Figs. 6 and 7 for each geophysical technique because the measurements do not exploit the same physical principles. For the same geological formation, the two techniques measure different resistivity. However, the spatial variability of a geological formation is accurately detected by both techniques.

TDEM profiles were therefore oriented east–west so as to intersect: (1) the resistive anomaly observed on the Slingram results, and (2) primary regional fracturing. The TDEM results made it possible to produce 2D vertical imagery (Fig. 6b) with remarkable coherence between cross-sections, from both stratigraphical and tectonic points of view. The TDEM cross-section made it possible to locate two major faults (F_1 and F_2, Fig. 6) with overall N°10 orientation. These faults involved vertical movements of several tens of meters. They are visible on TDEM cross-sections and the Slingram map, and they are cross validated by aerial photo interpretation. Stratigraphically, the TDEM cross-sections make it possible to distinguish systematically three geological entities:

- Upper horizon with variable resistivity (between 20 and 300 Ω m),
- Intermediate horizon, highly conductive (between 3 and 10 Ω m),

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- Lower horizon with variable resistivity but overall more resistive than the upper horizon (between 30 and 300 Ω m).

At this second stage of the study, without hard geological data from drilling, it was not possible to interpret these geophysical results with certainty. It was assumed that the upper horizon corresponds to loose sandy sediment, more or less clayey. It was also assumed that the lower and more resistive horizon would correspond to the Eocene carbonate formations. Eocene formations contain limestone and sandstone levels that should be resistive. The nature of the intermediate horizon remained unknown until drilling campaign results were obtained. Given the geological setting, such resistivity levels (3 and 10 Ω m) could correspond to:

- Clay,
- Salt clay,
- Sand or sandstone saturated with salt water,
- Sand or sandstone containing conductive elements (e.g. oxide, magnetite).

The nature of the intermediate geological formation was a crucial issue for the design of the drilling campaign. It was not known if the formation was an aquifer or aquiclude. This is why close cooperation was maintained during the drilling campaign (Fig. 2). Hydrogeophysical interpretations were updated daily, which led to adjustments of drilling locations and depth of the investigation targets. During the drilling campaign, it was discovered that the conductive intermediate formation is composed of a variety of lithologies dominated by marl and clay with sand and sandstone intercalations.

It should be noted that in the study area magnetic viscosity could disturb TDEM measurements. This well-known effect distorts signals for long reception times (more than 3 ms), (e.g. Krivochieva 2002; Hoareau et al. 2010). Magnetic viscosity is due to presence of magnetic materials in the vicinity of the coil. Extremely high conductivity and unrealistic values were obtained for long reception times in this study. Every time this problem was encountered, it was solved by adjusting the intensity of the injected current and the measurement was repeated until this undesirable effect disappeared.

Village scale survey: Tokoendolo example

The Tokoendolo example illustrates the strategy that was followed during this project. This example demonstrates the geological complexity and the uncertainties that persisted despite the number of measurements conducted.

At the village scale, exploration began with EM34 mapping that produced a preliminary characterization of a large area around the village (≈ 8 km^2). The general structure detected is oriented north–south overall (Fig. 7a) with alternation of conductive (10 Ω m) and resistive (more than 50 Ω m) bands. This pattern agreed with the EM34 results obtained at the regional scale (Fig. 6).

The TDEM profile was positioned as perpendicularly as possible to the structure detected by the EM34. Field conditions do not always allow for straight tracings, which is

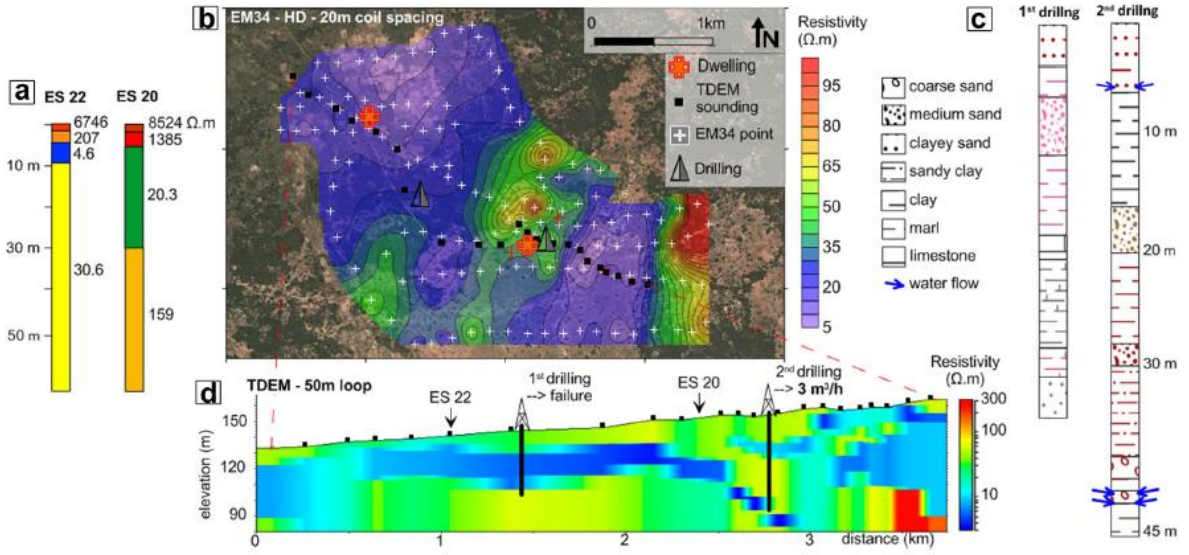

Fig. 7 Results obtained at the village scale for Tokoendolo; **a** electrical sounding (ES); **b** Slingram EM34 in horizon dipole (HD) with 20 m coil spacing; **c** borehole log with a simplified representation of colors observed on cuttings; **d** TDEM with 50 × 50 m loop

especially true when the ideal linear transect crosses a dense spiny forest. The temporal constraints of this humanitarian project did not allow for bush clearing. The village scale TDEM profile (Fig. 7c) detected the three horizons found at the regional scale. The highly conductive intermediate formation is always present but its thickness is quite variable, from a few meters to tens of meters. Moreover, this conductive formation is not tabular in shape. On the right side of the profile, there appears to be a kind of large scale cross-stratification and the conductive formation appears to be discontinuous. These observations are consistent with the presence of continental Neogene formations because continental formations often have a limited lateral continuity.

ES surveys (Fig. 7b) confirm the presence of the three horizons imaged by TDEM. In the near surface (1–2 m) a very resistive horizon (6500–8500 Ω m) is present. This result was consistent with red sand cover, which is not identified by TDEM due to instrumental cut-off time and because this very resistive horizon does not produce electromagnetic induction current. The resistive horizon described by TDEM is present under the sand cover. Below the resistive horizon, the highly conductive formation is present but its thickness can vary considerably compared to TDEM results (5 m for ES-22 vs. 20 m for the nearest TDEM sounding, and 15 m for ES-20 level vs. 25 m). This variability results from the fact that ES and TDEM provide estimates and not exact measurements because measurements are indirect and the raw signal needs to be inverted. The techniques are not based on the same physical principle and the investigated volumes are quite different.

Two boreholes were drilled around Tokoendolo village (Fig. 7d). The first drilling was aimed at exploiting water that could be collected within the conductive formation where the formation was thickest. During borehole drilling it was discovered that the conductive formation consisted mainly of clays and marls. This led to the failure of the first drill-hole and a second drill-hole was installed aiming at the aquifer above the marly conductive formation in a zone where this formation is deeper (43 m). This second borehole was successful and yielded around 3 m^3/h.

Drilling campaign

The drilling campaign ended with six positive and six negative boreholes. Three of the six negative boreholes reached water but aquifer thickness was not sufficient to allow the installation of a pump. For these three cases, wells were installed as replacements. The drilling campaign result is positive given the geological complexity and the lack of existing knowledge of the study area when the project began.

In such a complex and poorly understood environment, it is imperative to maintain a close cooperation between the hydrogeological team and the drilling team so as to reinterpret the data every day with new drilling information and in this way improve drillings siting.

Drilling made it possible to characterize the geology of the Ankazomanga basin and to find geological formations that are not easily found in outcrop. Drilling showed that continental Neogene formations are mainly composed of marl and clay with thin intercalations of sands and limestones. It is not possible to establish clear consistency between drilling logs because Neogene formations are of variable composition, discontinuous, and not always tabular. In addition, these discontinuous formations overlie the Eocene series, which are potentially affected by advanced karstification phenomena.

Water resource monitoring

To ensure the sustainability of the Ankazomanga basin hydro-climatic observatory, a partnership was created with local institutions (Toliara University, Regional of Meteorological Service, and Regional Direction of Water). A team was trained to maintain equipment and collect data every 3 months. The hydro-climatic observatory is composed of ten piezometric probes (distributed throughout the Ankazomanga basin) and a weather station (located in a secure area in the village of Ankazomanga). The piezometric sensors were installed to monitor zones of dissimilar conditions, so as to be as representative as possible of hydrogeological diversity.

The example of two wells monitored since 2014 near the Ankazomanga well illustrates the diversity of hydrogeological functioning (Fig. 8). These two wells are about 500 m apart and are located at similar altitude (Well 01: 225 m and Well 02: 227 m) on a flat area, however their hydraulic behavior is significantly different. First, their water levels are different, water in Well 02 is 1–4 m lower than water in Well 01 depending on the season. The recharge of Well 01 is much more reactive to rain events. Well 02 reaches its recharge peak 3 months later and in a smoother way than Well 01. This temporal shift can be explained by lateral water transfer toward the east from Well 01 to Well 02. This water movement, which is contrary to the general direction of underground flow (Fig. 4a), is probably explained by complex morphology of the base of the aquifer, which may be affected by karst morphologies in Eocene formations.

During the wet seasons 2015/2016 and 2017/2018, El Nino conditions resulted in weak rainfall. Despite 6 rainy episodes of more than 30 mm in 2015/2016, recharge was very limited. During the next dry season (autumn 2016), the well water level was very low. Extracting water for human consumption caused Well 01 to be pumped dry every day for about 2 months (green dots reaches a plateau—Fig. 8). Because Well 01 went dry, extraction for human consumption increased in Well 02. In the same way, it is always

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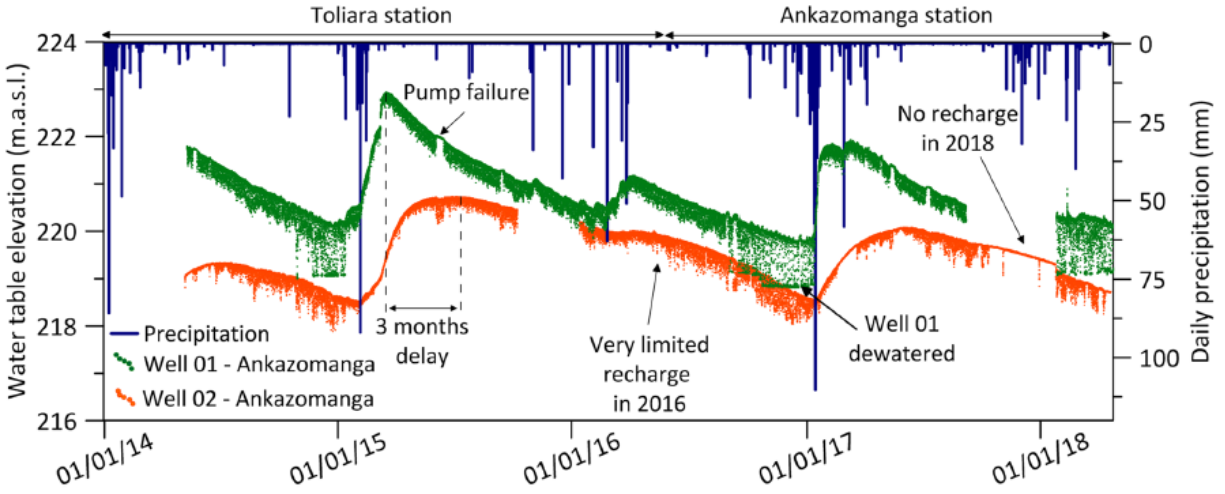

Fig. 8 Results of the hydro-climatic observatory with the example of Ankazomanga. The weather station and Well 01 (elevation 225 m) and Well 02 (elevation 227 m) are about 500 m apart

observed that when the pump of the Well 01 is broken, water extraction is more intense in Well 02. The wet season 2017/2018 is the driest year ever since 1982/1983 in Toliara region (Fews-Net 2018). Unfortunately, a failure of the Well 01 probe generates a gap in the data. But Well 02 shows that there was no recharge for this year. Currently, rainfall records are insufficient to determine what type of rainfall is most favorable for near-surface aquifer recharge. However, it seems that an accumulation of several rainy days is necessary to favor recharge.

At present, the piezometric and meteorological data record of Ankazomanga is still too short to conduct statistical analyses on the evolution of water resources in a climate change context. This is particularly true in a setting where climatic inter-annual variability is very strong. In a few years, the record will be sufficient to work on sustainable management scenarios of water resources for the medium and long term.

Discussion and perspectives

Geophysical measurements and drillings have shown that the Ankazomanga basin is filled with Neogene deposits whose heterogeneity and discontinuity make it a complex environment. The Neogene formations are highly diverse (sand, clay, marl, limestone, sandstone) and have weak lateral continuity. Moreover, karst morphologies (e.g. sinkholes, karren) at the base of Neogene fill impose complex constraints on flows that occur within the Neogene formations. Despite numerous investigations, the Ankazomanga basin remains poorly characterized in relation to its size and heterogeneity. At the current state of knowledge, hydrogeological modeling is impossible at the basin scale. It has been demonstrated that the Ankazomanga basin cannot be considered to contain a single aquifer, but rather many smaller aquifers that are more or less connected. For this reason, the piezometric map (Fig. 4a) needs to be interpreted cautiously at the basin scale. Indeed, at the village scale the underground hydrodynamics may be more complex, for example near Ankazomanga village where water flows locally towards the east.

If the project were extended, it would make sense to try to construct a local hydrogeological model around Ankazomanga village because the weather station and two piezometric probes there could be used to calibrate and validate the model. In addition to developing a model, it would be necessary to carry out aquifer tests to determine properties of the exploited aquifers (transmissivity, permeability). From a budgetary and temporal organization point of view, it was not possible to conduct aquifer tests during this humanitarian project. Geophysical measurements (TDEM) around the village should also be made with fairly close profiles (a few hundred meters of separation) to determine aquifer morphology with more accuracy. In this project, only 1 day of exploration was possible around each village with the three working groups (TDEM, electrical sounding, and EM34).

Several water collecting points in the Ankazomanga basin have high levels of tracers that mark anthropogenic pollution (NO_3^-, Br^-, NH_4^+). The new AAH borehole in Andrahavia exploits an aquifer at a depth of 19 m with a high NO_3^- content (≈ 3000 mg/L, see Online Appendix). It is thought that a zebu park was formerly located upstream of this borehole. This water is currently used for agriculture and livestock and renewal of aquifer water could reduce its salinity. In the future, it would be useful to evaluate the connectivity between surface and groundwater by analyzing ^3H and

possibly ^{14}C if ^{3}H activity is zero. Parameters such as pH and dissolved oxygen should also be measured. This monitoring would aid in pollution prevention (protection perimeter around wells) and in estimation of water resource renewal.

The hydro-climatic observatory that has been created with a weather station and a network of piezometric sensors, makes it possible to produce a unique dataset. In an extremely remote area, it is essential to collaborate with a local institution (University, Water Direction, Meteorological Direction) to ensure the durability of the monitoring system and knowledge transfer. It is now possible to assess the evolution of seasonal water storage and to estimate aquifer recharge. It was decided not to over-instrument this site to be able to adhere to a limited maintenance budget and in this way maintain it over time. However, a problem of spatial representativeness could arise in future interpretations, given the subsoil and precipitation heterogeneity and the size of the study area. The rainfall amount in Ankazomanga is not necessarily the same as in Andremba (Fig. 1), depending on weather conditions. This uncertainty should not be overlooked in future hydrogeological interpretations.

Conclusions

From an operational point of view, this integrated hydrogeological study successfully determined locations for nine borings at a cost of 40 k€. However, the contributions of this study do not stop there.

The methodological approach developed in this paper is not site specific. At the regional level, this approach will promote implementation of new wells across the Eocene Mahafaly plateau and its geological equivalent that continues into northern Onilahy. Many inhabited areas are present in the same geological setting on the west coast of Madagascar and maybe elsewhere in the world.

The geophysical knowledge acquired was essential for working in sustainable resource management scenarios. The geophysical results made it possible to implement the piezometric probe network in a judicious manner. This information aids in the selection of wells that are representative of study area heterogeneity. Moreover, the previously acquired hydrogeological knowledge is essential for interpreting piezometric monitoring of each water collecting point because different geological settings result in widely varying piezometric responses.

The network of piezometric sensors and the meteorological station make the Ankazomanga basin a unique hydro-climatic observatory that should produce data for at least 10 years. Industrial or urban pollution is non-existent because inhabitants have a very low per capita water consumption. The hydrogeological comparison with the urban area of Toliara, which is in a similar geological setting and is currently experiencing a serious water shortage, would be very relevant. Because southwestern Madagascar is a global change hotspot (Dai 2013), this hydrogeological observatory will be unique for studying the effects of global change on groundwater resources. Operationally, this observatory will be an early-warning network for monitoring groundwater shortage. It will make it possible to work on scenarios of sustainable water resource management with local partners. As an example, the year 2018 promises to be extremely dry as early as March. This situation allows more time prior to the beginning of a humanitarian crisis to mobilize authorities to implement preventive actions and to seek funds to install additional and deeper drillings, to advise inhabitants to use less irrigation on their crops, and to organize water trucking.

Acknowledgements The authors would like to express their gratitude to: the donors (Sustainable Initiatives for Water (SIWA), DG International Cooperation and Development (DEVCO), Agence de l'Eau Loire-Bretagne (AELB), Agence de l'Eau Adour-Garonne (AEAG), Syndicat Intercommunal Garrigues Campagne, Ville de la Rochelle, Conseil Régional Midi Pyrénées, Action Contre la Faim (ACF)); the local partners (the Malagasy Water Direction (DREAH), the Malagasy Meteorological Direction (SMR)); the AAH members who work on this project (Aude Lazzarini, Esteban Vallejo, Karl Lellouche, Nicolas Guibert).

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7.4. Kazakis et al., 2018

Science of the Total Environment 643 (2018) 592–609

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Management and research strategies of karst aquifers in Greece: Literature overview and exemplification based on hydrodynamic modelling and vulnerability assessment of a strategic karst aquifer

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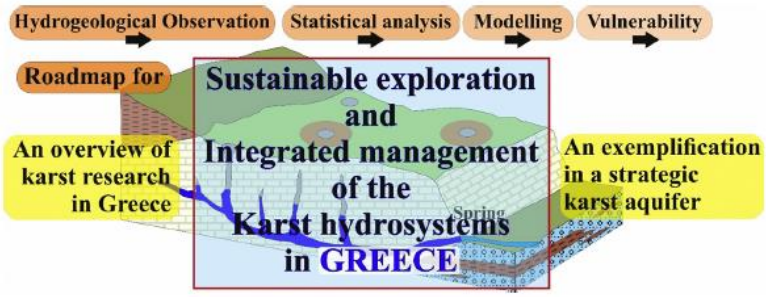
HIGHLIGHTS

- An overview of Karst aquifer researches in Greece was obtained.
- Hydrodynamic analysis was coupled with vulnerability assessment.
- The novel PaPRIKa plugin was used for the vulnerability assessment.
- The importance of allogenic Rivers was highlighted.
- A road map for sustainable exploration and integrated management was developed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 April 2018
Received in revised form 14 June 2018
Accepted 14 June 2018
Available online 24 June 2018

Editor: D. Barcelo

Keywords:
Groundwater depletion
Allogenic recharge
Damasi-Titanos
KarstMod
PaPRIKa
Road map

ABSTRACT

Karst aquifers are valuable water resources in terms of quantity and quality, hence, their protection and rational management is of utmost importance to sustain water supply. An overview of research articles regarding Karst aquifers in Greece was obtained revealing that progressively the initial simple statistical analysis was replaced from advanced tools but rarely coupled. Additionally, a combined approach including the concept of groundwater vulnerability and pollution risk in conjunction with statistical and hydrodynamic analysis was performed in the complex karst aquifer of Damasi-Titanos in Thessaly Central Greece.

The karst aquifer discharges via three springs and it is in dynamic interaction with one of the two rivers that cross the system. The water demands of the area are mainly met with groundwater from the karst aquifer rendering its protection fundamental priority for the sustainability of the area. The hydrodynamic analysis of the karst system was performed by pairing statistical techniques and KarstMod. The analysis revealed a high correlation between the springs that highlights the karstification maturity of the aquifer. Additionally, spring discharge is mainly controlled by the percolation of River Titarisios rather than precipitation. Following the hydrodynamic analysis, the PaPRIKa method was applied and validated using sensitivity analysis in order to assess the intrinsic vulnerability. The vulnerability and hazard maps were combined to produce the pollution risk map of the karst aquifer. The majority of the karst aquifer is characterized by high to very high vulnerability as well as pollution risk.

The case study and the obtained overview revealed that a holistic approach can provide mutually supported results increasing their reliability. In this base, a four-step road map including hydrogeological observation,

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https://doi.org/10.1016/j.scitotenv.2018.06.184
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statistical analysis, modelling and vulnerability assessment is suggested in order to obtain the sustainable exploration and integrated management of karst aquifers in Greece.

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1. Introduction

Karst aquifers constitute the drinking water source for almost a quarter of the world's population (Ford and Williams, 2007). Ford and Williams (1989) estimated that carbonate rocks cover 12% of the Earth's continental area, while karst regions occupy about 7–10% of the planet. Despite their low surface coverage, karst aquifers are usually positioned underneath a thick sediment cover and hence can be considered one of the most important aquifer types (Bakalowicz, 2005). Karst aquifers are the result of the karstification process which involves the solution of carbonate minerals (calcite and/or dolomite) due to the acidity of water that contains dissolved CO_2. The process is driven by climatic conditions because dissolved CO_2 concentrations are controlled by temperature and atmospheric CO_2 partial pressure (Bakalowicz, 1992). Knowledge of the hydrogeological and hydrodynamic characteristic of a karst aquifer is essential to adapt exploitation management practices and protection measurements. When these characteristics are neglected the productivity of karst aquifer may be over/underestimated and the system can be depleted by over/underexploitation. Additionally, when protectiveness is taken for granted groundwater quality deterioration occurs. The internal structure of a karst aquifer can be studied by analyzing spring hydrograph shape (ex. White, 2002). However, discharge of karst springs is strongly dependent on rainfall events and/or diffuse river recharge (ex. Manga, 1999). According to future climate projections, a large decrease in precipitation is predicted in the Mediterranean region and this may cause a reduction in the quality and quantity of karst water resources (Christensen et al., 2007).

Karst aquifers of Greece include the aquifers developed in carbonate rocks: sedimentary (limestones and dolomites) and metamorphic rocks (marbles). Carbonate rocks occupy about 35% of the surface area of Greece and are mainly located in the western, central and southern parts of the country (Daskalaki and Voudouris, 2008). Carbonate rocks in Greece mainly date from the Triassic to the Cretaceous periods, whereas marbles have a Paleozoic-Mesozoic age.

According to Katsanou and Lambrakis (2017), karstification of Hellenic karst can be distinguished into three stages: a) Upper Cretaceous to upper Miocene/early Pleiocene period during which the warm and humid conditions of a savanna climate type drove the karstification process of palaeokarst, b) Mid-glacial to the mid Pliocene/Holocene period where younger karst developed under warmer conditions with higher humidity than the recent ones, and c) late karstification stage that occurred under recent climatic conditions and formed younger karst. The majority of karst hydrosystems in Greece were formed during the second karstification stage, while the majority of the country's karst aquifers have a holokarst type shape. Karst aquifers are more abundant in the western part of Greece. This region receives high amounts of precipitation that can reach up to 1800 mm/year. In contrast, significantly lower precipitation of up to 600 mm/year occurs in the eastern part of the country (Mimikou, 2005). Nevertheless, water demands are geographically opposed to precipitation distribution because the main agricultural activities are located in the lowlands of eastern Greece.

The prefecture of Larissa is a representative example of where excessively irrigated agriculture in conjunction with relatively low groundwater recharge rates has led to groundwater depletion and quality deterioration. The karst system of Damasi-Titanos is located in this region and is the main drinking water source for the cities of Larissa and Tyrnavos which house a total population of 175,000. Additionally, numerous wells exploit this karst aquifer and supply water for local agricultural and livestock activities. Indisputably, the karst system constitutes a strategic resource of water in the region and preserving its quantity and quality is of the utmost importance for the sustainability of the wider area. The complexity of the site's hydrogeological and hydrodynamic regime also stipulates wider scientific interest for this karst aquifer. Three springs discharge the aquifer, two rivers cross the system, and agricultural activities cover a significant part of its surface.

Considering the strategic importance of the Damasi-Titanos karst aquifer in terms of quantity and quality, the aims of this study were to a) determine the hydrodynamic interactions between the system's allogenic rivers and springs, and b) assess resource vulnerability and groundwater pollution risk.

First an overview based on the published scientific results (included in Scopus platform) was performed to present the applied tools and approaches in karst hydrosystem research in Greece. Second, a two steps methodological approach was developed to meet the aims of Damasi-Titanos karst aquifer study: 1) Hydrodynamic analysis of the karst system was performed by pairing statistical techniques and KarstMod, 2) Following the hydrodynamic analysis, the PaPRIKa method was applied with the novel QGIS-environment plugin and validated using sensitivity analysis in order to assess the intrinsic vulnerability. The vulnerability and hazard maps were combined to produce the pollution risk map of the karst aquifer.

Finally, in addition to our case study limitations the overview was the base to develop a road map suggesting mandatory steps from field survey to modelling and protection to achieve the sustainable exploration and integrated management of Greek karst aquifers.

2. Overview of karst system research in Greece

The research interest of karst aquifers in Greece was significantly increased during the period of 1970 due to the increasingly water demands for agricultural, livestock, domestic and industrial use. During that period, the exploitation of karst aquifers was mainly limited to the discharge of springs. Additionally, there was no significant pollution stressors to karst aquifers due to their location at hilly and mountainous parts of Greece. Nevertheless, the socioeconomic development of Greece in conjunction with the population rise resulted in the expansion of agricultural land and industrial activities also in the karst aquifers boundaries. Similarly, to Damasi-Titanos karst system, the first studies were performed with National founding while the research groups consisted of mixed hydrogeological groups with researchers from Greece, France, Germany and other countries (SOGREAH, 1974). The boundaries of the karst systems were initially defined according to the geological maps, while spring discharge was measured during that studies. Additionally, groundwater quality was monitored in the majority of the karst systems mainly in spring's discharge. The Greek Institute of Geological and Mineral Exploration (IGME) conducted numerous studies (unpublished reports) for the characterization of karst aquifer systems including works such as: geological mapping, construction of boreholes, pumping tests, chemical analysis, meteorological analysis and discharge measurements of karst springs. In many cases the collected data from the agencies where the basis for further analysis and karst aquifers characterization. The first research included four karst systems – Korissos-Militsa, Voula and Xerovouni – aiming to determine the effective infiltration based on empirical methods such as Turc's, Countagne's and Thornthwaite's and Mather's (Soulios, 1984). Drogue and Soulios (1988) studied the salt water flow into the natural cavities of karst aquifers along the coast of Kefalonia Island. The first attempt for the characterization of karst systems based on hydrographs analysis was obtained at the early 1990s (Soulios, 1991). After the decade of 2000, groundwater depletion and quality deterioration of

porous aquifers in Greece has turned the interest to karst aquifers for further exploitation. Hence, the discussion was focused on the sustainable management, while new tools and approaches were applied for the characterization of the karst systems. Petalas et al. (2005) suggested a sustainable management approach based on quantitative assessment of hydrological and hydrochemical data of the karst system in the mountainous part of Nestos River. Panagopoulos et al. (2005) applied factor analysis for the determination of the hydrochemical processes occurring in the karst system of Trifilia. The hydrodynamic behavior of the same system was evaluated applying time series analysis (Panagopoulos and Lambrakis, 2006). Later, the hydrochemical status of the Trifilia karst system was re-evaluated using isotopic analysis (Panagopoulos, 2009). The deterministic model named MODKARST was applied in the Almyros and Makaria brackish karst springs of Crete for the determination of seawater intrusion mechanism (Maramathas et al., 2006). The aforementioned model was also used for the characterization of the Almyros/Heraklion coastal karst spring and its management under climate change (Maramathas, 2011; Maramathas and Gialamas, 2011). Arfib and de Marsily (2004) applied the SWIKAC model to delineate the quantitative status of the seawater intrusion inside the karst conduit. Additionally, the MODKARST was applied in the Louros karst system (Epirus) so as to determine its behavior (Katsanou et al., 2011; Katsanou et al., 2015a). The function of the system was also evaluated using the Sacramento Soil Moisture Accounting model (Katsanou and Lambrakis, 2017). The evolution of this karst system was evaluated using statistical analysis of discharge values (Katsanou et al., 2015b), while it was characterized analyzing hydrochemical and isotopic data (Katsanou et al., 2017). Microstructural analysis has been successfully used for the determination of Aggitis karst system structure, while statistical analysis and hydrochemical evaluation used for the understanding of the system's function (Novel et al., 2007). The basic hydrogeological research was used for the exploitation and function characterization of the Coastal karst aquifer system of Zarakas–Parnon (Southeastern Peloponnesus) (Lappas et al., 2011). Deligianni et al. (2013) performed geomorphological analysis aiming to further exploitation of the karst aquifer in Ksiromero Region. The spatial models have been lately introduced in the study of karst systems of Greece. Panagopoulos (2012) simulated the flow of Trifilia karst aquifer using the MODFLOW code. Thereinafter, spatial models were applied in several karst systems aiming in sustainable management. Archontelis and Ganoulis (2015) applied the MODFLOW code in Almyros coastal aquifer (Heraklion, Crete). Similarly, the MODFLOW code was applied in the Agyia karstic aquifer of Crete (Steiakakis et al., 2015). Steiakakis et al. (2016) used MODFLOW and SEAWAT codes in conjunction with climate model in Malia's coastal karst aquifer (Crete) in order to manage groundwater quality deterioration. FEFLOW was used for the delineation of recharge zones in the karst aquifer of Palaikastro-Chochlakies (Crete) (Kavouri and Karatzas, 2016). Nevertheless, the spatial models require the knowledge of aquifer and conduits' geometry and location as well as the hydraulic properties of the matrix and the karst conduits. Hence, in literature the application of spatial model in karst aquifers are skeptically evaluated because the required data are generally not available (Hartmann et al., 2014). Prediction of spring discharge was attempted in Rouva karst Aquifer (Crete) using a neural network model (Paleologos et al., 2013), while Manakos et al. (2011) applied SARIMA models in Damasi-Titanos karst system. Kallioras and Marinos (2015) contributed to karst aquifers sustainable management in Greece providing the characteristics of karst aquifers in Greece. Statistical analysis and hydrochemical characterization was performed in the karst aquifer in Philippi (Northern Greece) (Petalas, 2017) and Paradisos karst aquifer (Petalas et al., 2018) aiming the sustainability of the system. It is worth mentioning that karst aquifer's sustainability and integrated management require the protection of the aquifer which has less been discussed until 2015. Kazakis et al. (2015) assessed groundwater vulnerability and pollution risk for the protection of the karst aquifer of Anthemountas basin applying the EPIK method. The PaPRIKa method was applied for the assessment of Palaikastro-Chochlakies karst system's vulnerability, while the method was the base for the application of a spatial model using FEFLOW (Kavouri et al., 2017). Nanou and Zagana (2018) applied the COP method for the assessment of groundwater vulnerability of the Ziria karst aquifer in Southern Greece.

Obviously, the last decade in Greece an increasingly number of studies have been applied in karst aquifer aiming to contribute in the characterization, protection and sustainable exploration and management. Indisputably, karst aquifers are in-valuable sources of water in Greece, considering the overexploitation and groundwater quality deterioration of porous aquifers. Hence, an holistic management plan should be precede based on integrated research approaches including characterization, hydrodynamic analysis and protection. In Table 1 are presented the methodological approaches and perspective of the obtained research articles of karst aquifers in Greece, while the system locations are shown in Fig. 1.

The presented overview arose the following questions regarding the management of the karst aquifers:

- Can we manage a karst aquifer based only on the knowledge of the system's functioning?
- Should the hydrogeological observation should be limited within the boundaries of the aquifer?
- Which data in time and space are mandatory to supply integrated modelling and statistical analysis?
- Is it necessary the hydrodynamic analysis for the implementation of vulnerability and pollution risk assessment in karst aquifers?

The experience of the case study application might help to answer these questions and suggest a mandatory time step research approach for integrated management of karst aquifers in Greece.

3. Hydrogeological setting of the Damasi-Titanos area

The karst aquifer of Damasi-Titanos is located in eastern central Greece in the prefecture of Larissa (Fig. 2). It covers an area of 320 km^2 with a mean altitude of 292 m ASL and a perimeter of 111 km. The system lies between the mountains of Zarkos and Titanos and its minimum and maximum altitudes are 73.5 and 735 m, respectively. The karst system is well defined by schist outcrops located in the south and west and a gneiss outcrop on its northern border. In the east, the aquifer is in contact with Pleistocene, Pliocene and alluvial sediments due to normal faults with NE-SW orientations. The study area is characterized by a typical Mediterranean (Csa) semi-arid climate with dry summers and wet winters with heavy rains. According to data obtained from the nearest meteorological station in Larissa, the area's mean annual temperature and precipitation values are 15 °C and 450 mm, respectively. Agriculture constitutes the primary economic activity of the area and the main crops are vegetables, wine grapes and cereals.

Geologically, the study area comprises formations of the Pelagonian geotectonic zone. The karst aquifer is hosted in crystalline limestones of mid-Triassic to Jurassic age. The crystalline limestones constitute the normal upward evolution of the Paleozoic-mid-Triassic formations with a mean thickness of 500 m in the wider region. The limestones are thick-bedded to massive, coarse-crystalline and strongly tectonized of white-blue to white-grey color, while in the lower members are bituminous and dolomitic (IGME, 1985, 1987, 1998). The base of the karst aquifer comprises Paleozoic to mid-Triassic schists and gneisses. A quarter of the karst aquifer underlies sedimentary formations. An eluvial mantle is located in the northern part with a mean thickness of 20 m. In the center of the aquifer Pleistocene deposits of sand, clay and gravel occur as well as talus cones and scree of variable thicknesses consisting of cobbles mixed with fine-grained material. Alluvial deposits are

Table 1
Methodological approaches and perspectives in research of karst aquifers in Greece.

A/A	Authors	Methodology	Location	Perspectives
1	Soulios (1984)	Empirical methods (Turc, Countagne, Thornthwaite and Mather)	Korissos-Militsa, Voula and Xerovouni	Calculation of effective infiltration.
2	Drogue and Soulios (1988)	Analyzing flows and hydrochemical data	Kephalonia (Ionian Islands)	Determination of brackish water process outflow
3	Soulios (1991)	Statistical - study of the recession curves	Korissos, Militsa, Mara, Micro Vouno, Agios Nicolaos, Stylos-Armeni	Classification of the systems
4	Arfib and de Marsily (2004)	SWIKAC model	Almyros/Heraklion Coastal spring	Determination of the salinity process
5	Petalas et al. (2005)	Quantitative assessment of hydrological and hydrochemical data	Mountainous part of Nestos River (Thrace)	Sustainable management
6	Panagopoulos et al. (2005)	Statistical analysis (Factor analysis)	Trifilia (Peloponnesus)	Determination of hydrogeochemical process
7	Panagopoulos and Lambrakis (2006)	Time series analysis	Trifilia (Peloponnesus), Almyros (Crete)	Function and hydrodynamic behavior
8	Mandilaras et al. (2006)	Pumping test analyses	Greek karst aquifer systems	Hydraulic parameters
8	Maramathas et al. (2006)	Deterministic model (MODKARST)	Almyros and Makaria brackish karst springs (Crete)	Determination of seawater intrusion mechanism
9	Novel et al. (2007)	Statistical, hydrochemical, microstructural measurements	Aggitis karst system (Central Macedonia)	Function and structure
10	Panagopoulos (2009)	Hydrochemical and boron isotopes analysis	Trifilia (Peloponnesus)	Determination of hydrochemical status
33	Voudouris et al. (2010)	Stochastic models (SARIMA model)	SARIMA model (Crete)	Sustainable management
11	Maramathas and Gialamas (2011)	Deterministic model (MODKARST)	Almyros/Heraklion coastal spring	Management of the spring under climate change
12	Katsanou et al. (2011)	Deterministic model (MODKARST)	Louros karst system (Epirus)	Function of the system
13	Maramathas (2011)	Deterministic model (MODKARST)	Almiros brackish karst spring (Crete)	Determination of operation mechanisms for sustainable development
14	Manakos et al. (2011)	**10** Stochastic models (SARIMA)	Damasi Titanos (Thessaly)	Sustainable management
15	Lappas et al. (2011)	Classic hydrogeological research and isotopes analysis	Coastal karst aquifer system of Zarakas–Parnon (Southeastern Peloponnesus)	Exploitation and function characterization
16	Panagopoulos (2012)	Spatial simulation (MODFLOW)	Trifilia (Peloponnesus)	Planning water management
17	Paleologos et al. (2013)	Neural network model	Rouva karst aquifer (Crete)	Prediction of spring discharge
18	Deligianni et al. (2013)	Geomorphological analysis	Ksiromero Region (Western Greece)	Increase water yield, groundwater protection
19	Kallioras and Marinos (2015)	Review/Stress analysis	Greece/Asopos	Contribution to sustainability
20	Kazakis et al. (2015)	Vulnerability assessment (EPIK method)	Anthemountas basin	Protection
21	Archontelis and Ganoulis (2015)	Spatial simulation (MODFLOW)	Almyros/Heraklion coastal aquifer	Sustainable management
22	Steiakakis et al. (2015)	Spatial simulation (MODFLOW)	Agyia karst aquifer (Crete)	Sustainable management
23	Steiakakis et al. (2016)	Spatial simulation (MODFLOW – SEAWAT-Climate model)	Malia's coastal aquifer (Crete)	Management of the groundwater quality deterioration
24	Kavouri and Karatzas (2016)	Spatial simulation (FEFLOW)	Palaikastro-Chochlakies (Crete)	Determination of recharge zones
25	Katsanou et al. (2017)	Hydrochemical and stable isotopes analysis	Louros karst system (Epirus)	Determination of hydrochemical status and verifying the structure of the system
26	Katsanou and Lambrakis (2017)	hydrodynamic modelling (Sacramento Soil Moisture Accounting model)	Louros karst system (Epirus)	Function and hydrodynamic behavior
27	Katsanou et al. (2015b)	Statistical analysis	Louros karst system (Epirus)	Describing karst evolution
28	Katsanou et al. (2015a)	Deterministic model (MODKARST)	Louros karst system (Epirus)	Function and hydrodynamic behavior using incomplete time series
29	Kavouri et al. (2017)	Spatial simulation (FEFLOW) vulnerability assessment (PaPRIKa method)	Palaikastro-Chochlakies (Crete)	Sustainable management
30	Petalas (2017)	Statistical (Time Series Analysis) and Hydrochemical analysis	Philippi aquifer system (Eastern Macedonia)	Sustainable management
31	Nanou and Zagana (2018)	COP method	Ziria karst System, Southern Greece	Protection, vulnerability assessment
32	Petalas et al. (2018)	Statistical and Hydrochemical analysis	Paradisos karst aquifer (Northern Greece)	Function and hydrodynamic behavior

mainly observed in the south and these consist of clays and sand of varying thicknesses. The structure and morphology of the karst aquifer has been determined by the several deformation phases that defined the tectonic architecture of Thessaly Basin. Understanding of the region's tectonic deformation is critically important because this caused the fracturing of the aquifer in question and determined the present paths of the rivers Titarisios and Pinios that flow across the system. Therefore, a brief description is presented below. The present-day morphology of Thessaly is mainly related to the Neogene tectonic inversion (Caputo and Pavlides, 1993). The late Miocene–early Pleistocene NE–SW extension in Thessaly formed horsts and grabens bordered by NW–SE trending faults (Caputo, 1990), while fluvial and mainly lacustrine conditions characterized the palaeogeography of the Larissa plain in that period (Caputo, 1994). The permanent hydrographic network of the basin was formed after the generation of the permanent water outpouring in the Pinios delta (Faugeres, 1977). During the mid to late Pleistocene the extensional regime changed to N-S orientation (Mercier et al., 1989) generating normal faults trending from E-W and

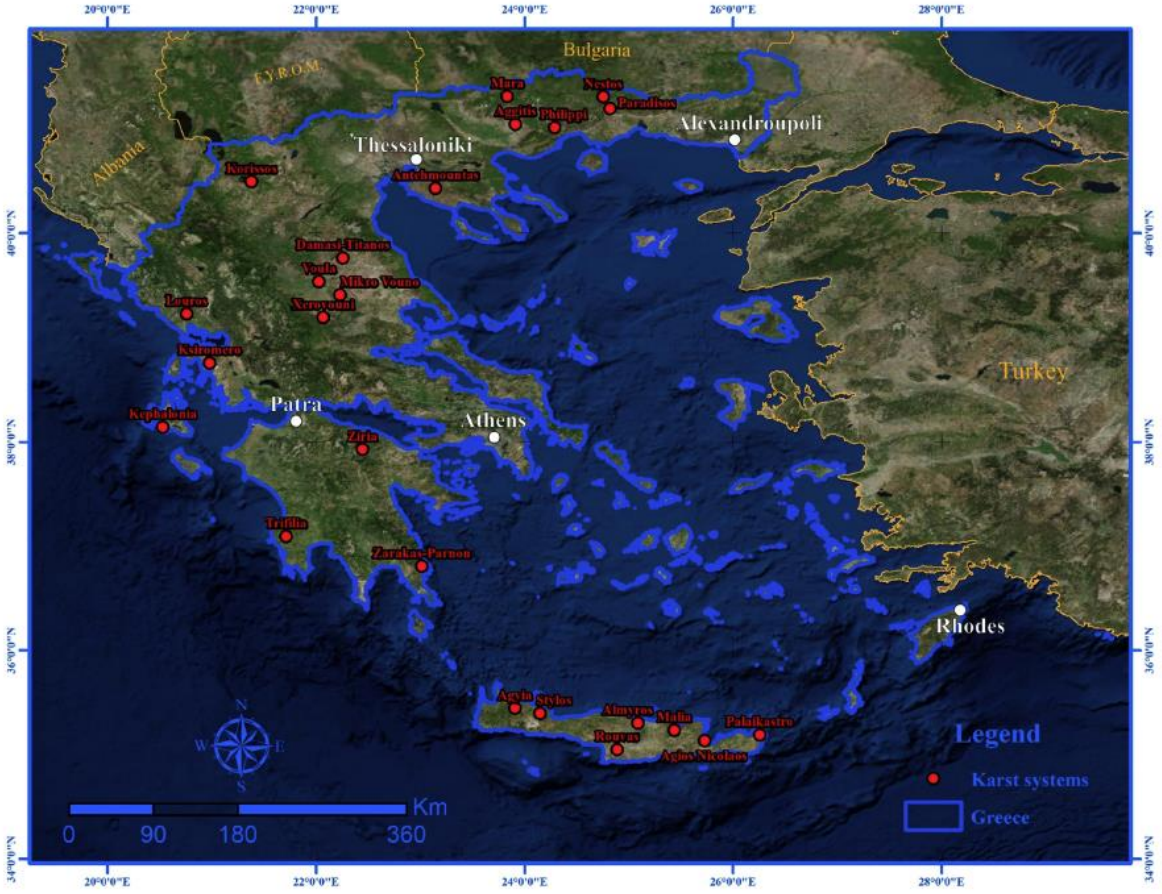

Fig. 1. Location of the studied karst aquifers in Greece.

ESE-WNW. Hence, the normal faults of Tyrnavos and Larissa developed in the area crossing the karst system and formed E-W orientated gorges (Caputo et al., 2004; Caputo et al., 2006).

The karst system of Titanos-Damasi can be characterized as holokarst due to its vast exokarstic and endokarstic features such as ponors, dolines, poljes, caves, gorges and karst springs. The overlying alluvial and Plio-Pleistocene deposits host negligible amounts of water and therefore the wells exploit only the underlying karst system. The thickness of the karst aquifer varies but has a mean value of 90 m. The rivers of Titarisios and Pinios have perennial flow and cross the karst aquifer through the tectonic gorges. The system is recharged mainly through precipitation, while diffuse allogenic recharge occurs only from River Titarisios (Manakos, 2010). The system is discharged by three karst springs named Mati, Agia Anna and Kalamaki, with elevations of 73.5, 75 and 76 m, respectively. The discharge of the Mati spring reaches 7.3 m^3/s, while the discharge recorded in Agia Anna and Kalamaki reaches 1.6 and 0.9 m^3/s, respectively. During the last 40 years overexploitation of the karst aquifer via numerous wells has resulted in a 15 m decrease in water level and this caused the Kalamaki spring to dry up and therefore only seasonal discharge occurs here (Fig. 3). Outflows outweigh inflows and hence the negative groundwater balance occurs in the Titanos-Damasi system. The direction of the aquifer's groundwater flow is mainly from SW to NE, while lateral flow to the alluvial deposits has been reported in previous studies (SOGREAH, 1974). The dominant water type of the aquifer is Ca-Mg-HCO_3 and is suitable for domestic and drinking use. However, elevated concentrations of NO_3 (up to 40 mg/L) have been recorded in the springs mainly during dry periods (Manakos, 2010). Protection of the karst aquifer is critically important to ensure the sustainability of the water supply in the wider area. Beyond the systematic monitoring of the quantity and quality of the karst springs no protection measures have been taken for the karst aquifer of Titanos-Damasi.

4. Methodological approach

4.1. Hydrodynamic behavior

Four meteorological stations are located in the wider area of the karst system: Tyrnavos, Farkadas, Elassona and Larissa. The only station with available daily precipitation data was Larissa with a time series dating from 1958 to 2016. Monthly data for a shorter time period were available from the other three stations and therefore they were excluded from the statistical and hydrodynamic analysis of the system. Monthly water level measurements were available for the three springs (Mati, Agia Anna, Kalamaki) from 1972 to 2016, however after 2005 many measurements were missing. Piezometric data (in total 400 measurement) from boreholes were available for the period 1972 to 2016 and, similar to the spring flow, measurements had been taken once per month. In total 470, 400 and 360 measurements of spring flow were analyzed for Mati, Agia Anna and Kalamaki springs, respectively.

4.1.1. Statistical analysis

The time series data for precipitation, spring discharge, piezometric head and river percolation were analyzed descriptively. Auto-

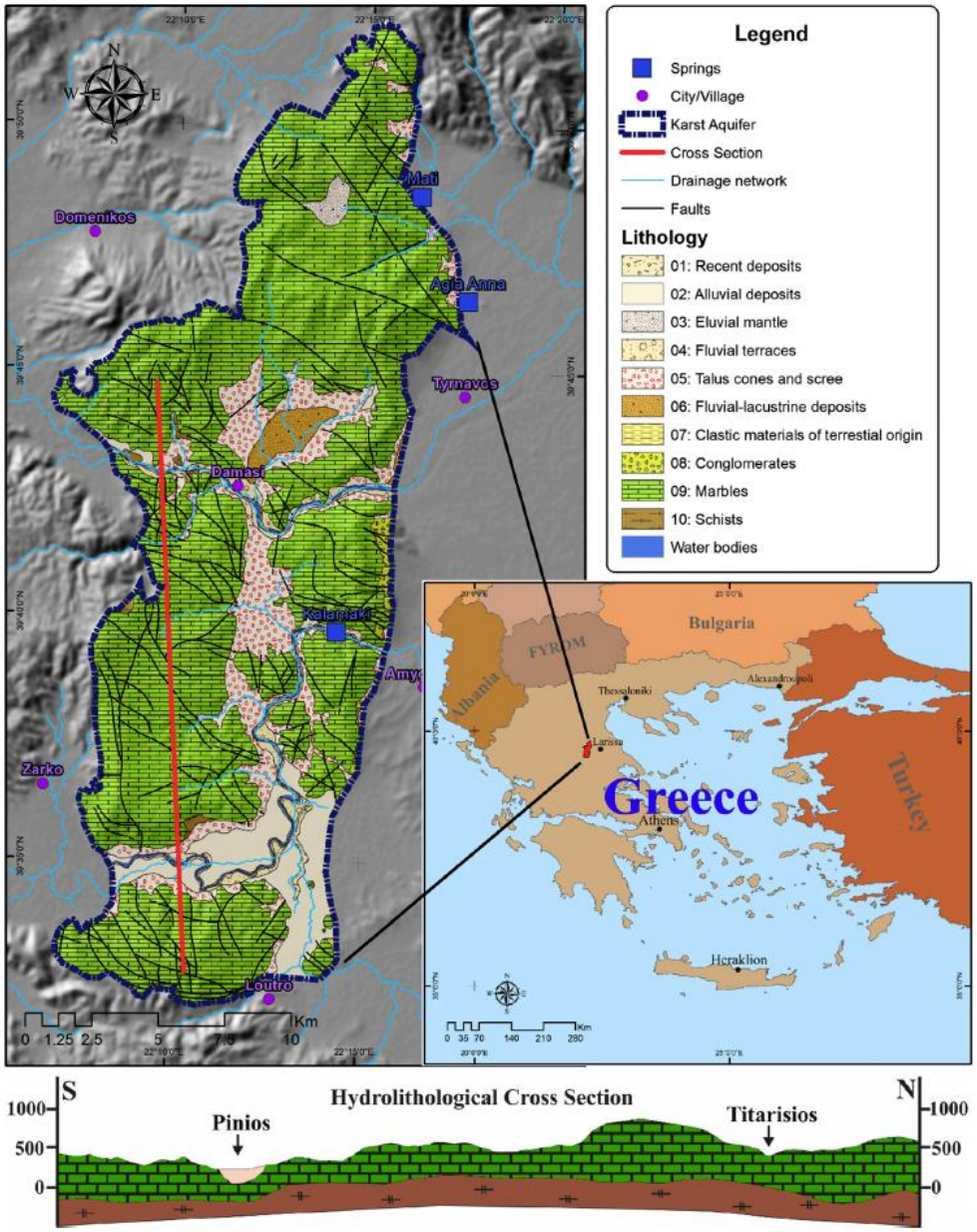

Fig. 2. Geological map of Damasi-Titanos karst aquifer.

covariance could not be assessed due to the monthly sampling of discharge values. Cross-correlation was used to assess the average delay between inflows (precipitation and percolation) and outflows (springs discharge). The Pearson correlation coefficient (ρ) was used to determine the linear relationship between the variables (Mangin, 1984).

4.1.2. Evapotranspiration estimation

Evapotranspiration was estimated using the Thornthwaite method (Thornthwaite and Mather, 1957) and data from the meteorological station of Larissa (Manakos, 2010). The original method was available for a monthly step and was therefore down-scaled to a daily step in order to estimate the percentage of actual evapotranspiration in regard to potential evapotranspiration for all data sets. Hence, the evapotranspiration was estimated for each month and a daily value was assigned. The data set obtained was then used for the hydrodynamic analysis in the KarstMod platform.

4.1.3. KarstMod

The KarstMod platform was chosen for the hydrodynamic modelling of the Damasi-Titanos karst system due to its high flexibility in complex systems. KarstMod can simulate the spring discharge at karst outlets and analyze the hydrodynamics of the compartments included in the model (Mazzilli et al., 2017). The daily precipitation data used was that available only from the meteorological station of Larissa for the period 1958 to 2016. Monthly spring discharge and River Titarisios percolation data were available for the period 1972–2016 (Manakos, 2010).

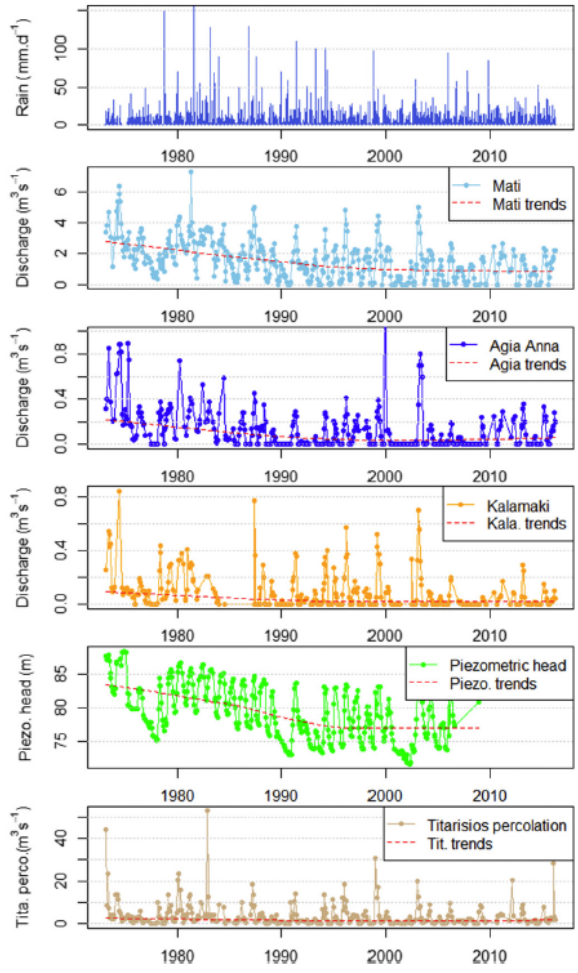

Fig. 3. Rainfall, percolation and discharge time series for the Damasi-Titanos (period 1972–2016).

The total data inputted into the model were: the discharge of all springs, percolation values of River Titarisios, lateral outflow of the karst system to the sedimentary aquifers, and well abstractions. Both lateral outflow (20×10^6 m^3/year) and well abstractions (10×10^6 and 15×10^6 m^3/year in 80s and 90s respectively) are average estimations based on previous studies (Manakos, 2010). The aquifer system was simulated for a twenty-year period (1980 to 1999). The chosen time period is characterized by consistency in the available measurements. The warm up started from the beginning, the calibration stage was set to between 1300 and 4000 (days from the beginning of the simulation, using 100 measurements Titarisios flow and 87 for spring flow and piezometric head) and the validation stage followed (days 4001 to 7304 using 138 measurements Titarisios flow and 102 for spring flow and piezometric head). The sum of River Titarisios inflow (as a negative value), lateral outflows, and well abstraction values comprise the total outflows of the system (Q_{Mpump}). The model also included data on the variation of the system's piezometric head that was obtained from a representative well.

4.2. Vulnerability and risk assessment

4.2.1. PaPRIKa

The assessment of intrinsic groundwater vulnerability within a karst aquifer presupposes detailed field measurements and thorough hydrogeological knowledge of the system. One well-known vulnerability assessment method is PaPRIKa which was developed in 2005 by a French research team headed by the BRGM (Dörfliger et al., 2009a, 2009b) and has since been successfully applied to karst systems (Plagnes et al., 2010). The method is in accordance with French legislation which is based on the European Water Framework Directive (WFD, 2000). PaPRIKa is an index method based on the structure and function of an aquifer system utilized in a geographic information systems (GIS) environment. Aquifer structure includes two factors, protection (P) and rock type (R), while aquifer function is based on infiltration (I) and karstification (Ka). The protection (P) factor includes four sub-factors which are: a) the catchment areas of sinking streams (Ca), b) soil cover (S), c) the unsaturated zone (UZ), and d) behavior of the epikarstic aquifer (E). The infiltration (I) factor is the combination of slope and karst features. The karstification (Ka) factor considers the hydrogeological behavior of the system and endokarst development. Factor R (rock type) considers the lithology and structure of the saturated zone. The method is flexible and can also be applied also to non-karst, principally sinkhole, catchments in allogenic karst systems. The four factors are mapped independently and classified into the five qualitative vulnerability categories of: very low, low, moderate, high, and very high (0–79, 80–159, 160–239, 240–319, 320–400). The final vulnerability map is generated by overlying the four parameters and their corresponding weights (p, r, i, k) following Eq. (1).

$$Pa = pP + rR + iI + kKa \quad (1)$$

Detailed guidelines and tables of the method can be found in Dörfliger and Plagnes (2009) and Kavouri et al. (2011). In this study the PaPRIKa method was applied using the QGIS PaPRIKa plugin. The plugin was developed in 2017 by the HYDRO team of the UMR EMMAH to standardize the application of the method (http://plugins.qgis.org/plugins/Paprika/).

4.2.2. PaPRiKa's method validation

The single-parameter sensitivity analysis was applied to evaluate the impact of each parameter on the final vulnerability map according to PaPRIKa method. This technique was initially applied by Napolitano and Fabbri (1996) to estimate vulnerability of aquifers to pollution. Since then the analysis has been used in numerous studies to validate the weights of index methods (e.g., Napolitano, 1997; Gogu et al., 2003; Pacheco et al., 2015; Kazakis et al., 2015). In the sensitivity analysis the initial arbitrary weights are replaced with some derivative indices; the "effective weights" calculated from Eq. (2):

$$W = \frac{Pr \times Pw}{V \times 100} \quad (2)$$

where:

W = the effective weight of each parameter
P_r = parameter rating
P_w = parameter weight
V = the aggregated value of the applied index.

4.2.3. Pollution risk assessment

The groundwater pollution risk map was evaluated by combining the vulnerability and hazard maps with the following Eq. (3) (Uricchio et al., 2004).

$$Risk = Vulnerability \times Hazard \quad (3)$$

The hazard map corresponds to the probability that a detrimental event will occur in a given area in a given period of time (Passarella et al., 2002). In this study, the hazard map was obtained by combining a Corine land cover map and pollution sources based on field research and rated according to the literature on a scale of 0 to 4 to ensure compatibility with the PaPRIKa method. The rating of the Hazard map

assigned according to previous relative studies (Zwahlen, 2004; Werz and Hötzl, 2007; Kazakis et al., 2015). Finally, the vulnerability map and hazard map were overlaid thus producing the risk map of PaPRIKaRa indices.

5. Results

5.1. Hydrodynamic behavior

Thorough comprehension of the hydrodynamic regime of the Damasi-Titanos karst aquifer is crucial for the effective management and protection of the system. Hence, time series of karst springs discharge rate, precipitations and percolation of river Titarisios were analyzed descriptively (Mangin, 1984).

Visual analysis of the time series (Fig. 3) shows a long-term decreasing trend of karst springs discharge and piezometric head. The same trend is not observed in the rainfall and river percolation dataset, which indicates that overexploitation of the aquifer for domestic and agricultural use via numerous boreholes is probably the main cause for the groundwater depletion in Damasi-Titanos.

Linear correlation between the discharge time series of Mati, Agia Anna and Kalamaki springs is strong which verifies the high karstification degree of the studied aquifer (Fig. 4). However, these three springs have different average lag times as shown by autocorrelation and rainfall-discharge cross-correlation analysis (Fig. 5).

Springs discharge values also correlate well with the percolation rate of River Titarisios (Fig. 3), thus verifying the interaction between the river and the aquifer.

Rainfall-discharge cross-correlation is highest when cumulative rainfall is considered instead of daily (even lagged) values, in particular for Mati which shows the most important memory effect from the three studied springs (Fig. 5a).

Further analysis was essential to understand the system and hence we confronted our conceptual model to the dataset using 1D KarstMod platform for rainfall - Mati discharge modelling at daily time step (Mazzilli et al., 2017).

We tested several configurations of reservoirs and flows. The most appropriate configuration was selected based on model performance and equifinality assessment and is commented hereafter. The proposed model structure is composed of two reservoirs E and C (Fig. 6). The upper reservoir E represents the soil and epikarst compartments.

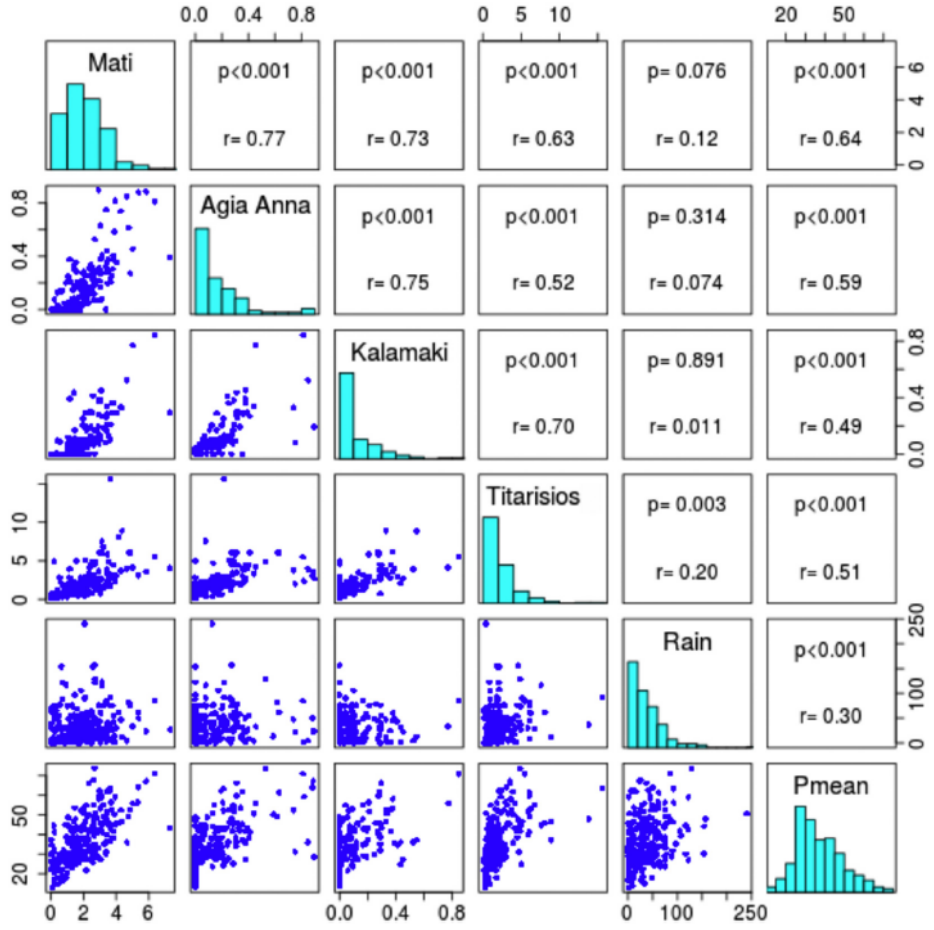

Fig. 4. Pairwise correlation plot for discharge at Mati, Agia Anna, Kalamaki karst springs, percolation from Titarisios, daily rainfall (Rain) and averaged rainfall over the last 8 days (Pmean). The graph should be read as follows: 1) distribution of each variable on the diagonal, 2) bivariate scatter plots on the bottom of the diagonal, 3) significance level and correlation on the top of the diagonal.

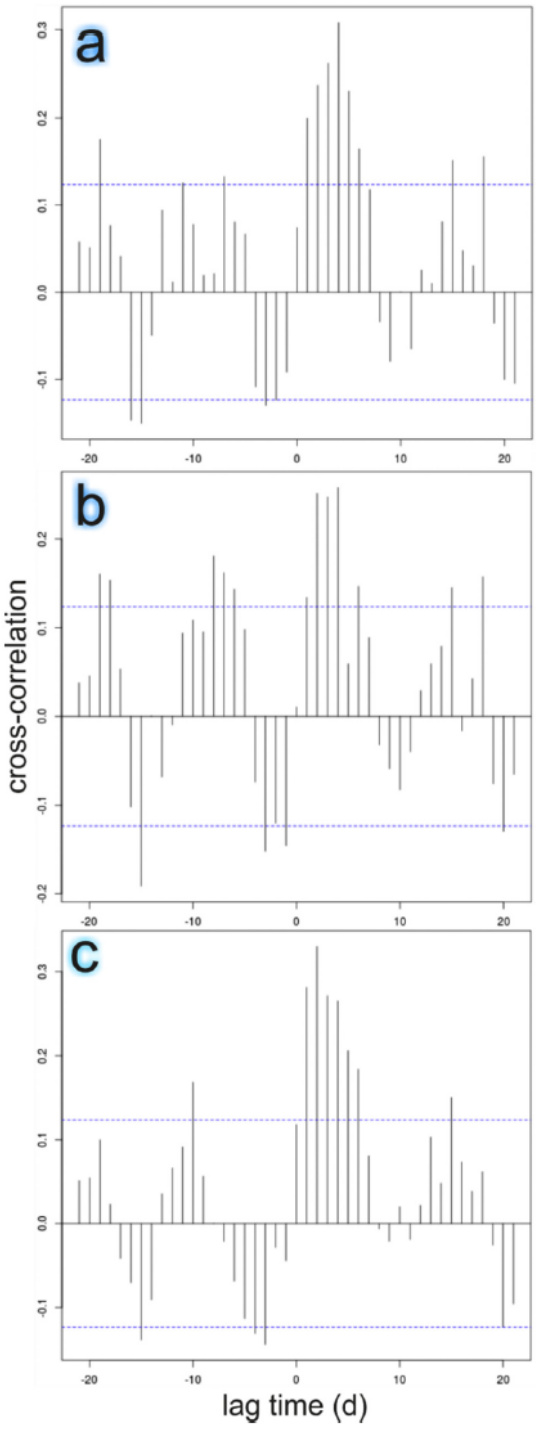

Fig. 5. Rainfall-discharge cross correlation for (a) Mati, (b) Agia Anna (b), (c) Kalamaki springs. The average lag time over the 1972–2016 time series ranges from 3 to 5 days.

When sufficient saturation is reached, infiltration (flux Qhy) occurs from the upper reservoir towards 1) the slow flow volumes from the fissured and fractured matrix of the unsaturated and saturated zones (flux QhyEC), and also 2) directly to the spring through piston flow effect (flux QhyES). QhyEC and QhyES are defined as a proportion of the Qhy flow.

$$QhyEC = p * Qhy$$
$$QhyES = (1-p) * Qhy$$

Extractions from boreholes and percolation from Titarisios result in a net inflow value to reservoir C (QpumpC). Reservoir C also discharges to the spring. All model equations are detailed in Annex 1.

Recharge area is set equal to 220 km^2 based on hydrogeological knowledge of the system. Simulation results for the calibrated dataset are shown in Fig. 6 (nash index 0.55). Dotty plot of simulated versus observed discharge values confirm that the overall dynamics of the springs is adequately reproduced by the model (Fig. 7). Better fit would probably be difficult to achieve due to dataset limitations: 1) lack of representativity of single raingauge data during high-intensity convective rainfall events, 2) monthly measurements of Titarisos losses.

Spring discharge is mainly due to QCS (internal discharge rates of compartment C) flux (1:10 ratio). However, most of the inflow to reservoir C is due to Titarisios losses as QhyEC amounts to only 3 to 10% of the total infiltration from reservoir E. This result confirms that intercatchment flow (lateral outflow and Titarisios inflow) and "hidden" flow (undocumented pumping) dominate the hydrodynamics of the Damaris-Titanos system. The values of the K_{hy} (specific discharge coefficient of the hysteretic discharge) and K_{CS} (specific discharge coefficients of compartment C) coefficients were determined to be 0.008 and 0.001 mm/day, respectively. The calibrated parameters of the model are shown in Annex 2.

5.2. Vulnerability and risk assessment

Following the statistical analysis and simulation, the PaPRIKa method was applied in the karst aquifer of Damasi-Titanos to assess source vulnerability. The final vulnerability map was obtained from the combination of four factors: protectiveness (P), rock type (R), infiltration (I) and karstification (Ka). The QGIS-based plugin of PaPRIKa was used for data elaboration and method application. The P factor derives from the combination of the catchment areas of sinking streams (Ca), the soil cover (S), the unsaturated zone (UZ), and the epikarstic aquifer (E). In the case of Titarisios-Damasi system the Pinios and Titarisios rivers cross the aquifer without sinking into sinkholes. Therefore, the Ca parameter was not included in the estimation of the protectiveness factor. The protectiveness of the soil cover factor was produced by combining field surveys, a geological map and satellite images. High protectiveness corresponds to soils with significant thickness and fine grain material, while low thickness and coarse-grained soils afford lower aquifer protection. The final sub-parameter of protectiveness considers the lithology, thickness, and fracturing of the unsaturated zone. It is a critical parameter, while the process to be developed is also complicated. The final map of protectiveness (P) is shown in Fig. 8 where high vulnerability corresponds to low protectiveness and is related to the highly fractured zone and low thickness of the vadose zone. Low values of P parameter occur in lowlands in the central part of the aquifer, while very high values are related to fracture zones. The R map was produced based on the field experience during the drilling of wells in the study area. The entire aquifer is strongly affected by intense fracturing and hence vulnerability was attributed R3, while in high fracture zones the aquifer was characterized by very high vulnerability (R4) (Fig. 8). The majority of the karst aquifer is characterized by high vulnerability according to R factor. The I map is the conjunction of karst features and slope. The slope inclination values were obtained from the digital elevation model (DEM). The vulnerability categories of I range from low to very high and are shown in Fig. 8. Very low values are related with the part of the aquifer which is covered with sediments and no vertical recharge occur. The final parameter is the karstification degree of the aquifer (Ka). Based on field experience, lithological

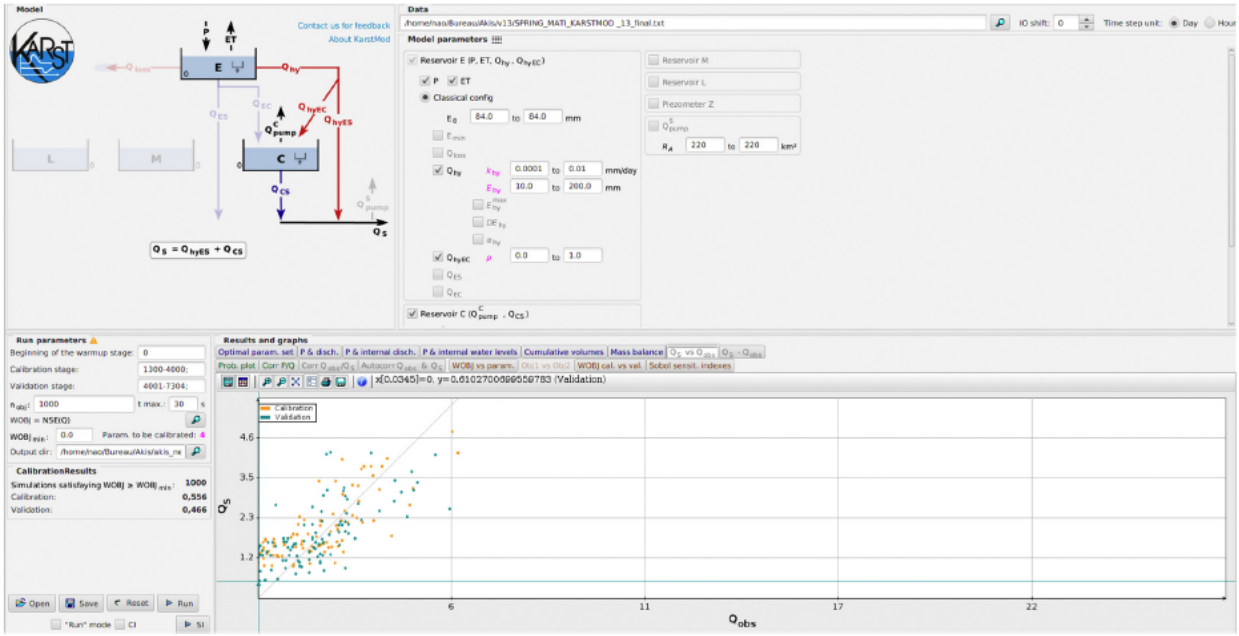

Fig. 6. Conceptual model of Damasi-Titanos karst aquifer and simulation results using KarstMod.

profiles, pumping tests and estimation of groundwater velocity (up to 20 m/h), the vulnerability of Ka is moderate to high (Fig. 8). Table 2 shows the vulnerability class coverage of each factor in the study area. The intrinsic vulnerability of the karst aquifer was calculated using the following weights for each factor: 30% for P, 20% for R, 30% for I, and 20% for Ka.

Hence, the final map was produced and is presented in Fig. 9. According to PaPRIKa (9a), the majority of the study area is characterized with high (70.9%) to very high vulnerability (20.3%) (Table 2). Moderate vulnerability characterizes about 9% of the area, while the very low and low vulnerability categories are not observed in the studied aquifer. The PaPRIKa method was then validated using the sensitivity analysis process. This helps to better understand the role of each factor and overcome the subjectivity of the individual weights. The effective weights (Table 3) were then used to map vulnerability using the validated PaPRIKa-V index (Fig. 9b). Nevertheless, the modified vulnerability map presents insignificant differences with the initial one.

The next step was to assess the risk of the karst aquifer to external pollution. Initially, ratings on a scale of 0 to 4 were assigned to land use and pollution sources so as to create the hazard map (Table 4). The rating scale is in agreement with the concept of PaPRIKa and corresponds to hazard degrees from very low to very high. The hazard map of the Damasi-Titanos karst aquifer is presented in Fig. 10. Agricultural land and industrial activities correspond to very high hazard and forest areas correspond to very low hazard. Agricultural land, mineral extraction sites and industrial activities mainly occur in the lowlands, while the mountainous part of the basin is covered with forest vegetation. The risk map was created by overlaying the hazard and the validated vulnerability maps and the resulting index was named PaPRIKaRa (Fig. 10). In Fig. 10a is shown the pollution risk map in crossing zone of Titarisios which is characterized by very high pollution risk, while the crossing zone of Pinios rivers correspond to low pollution risk (Fig. 10b).

The highest risk of pollution exists when a hazard is placed in zones high vulnerability. Hence the risk map shows areas where groundwater is highly likely to be polluted by human activities. The majority of the aquifer has high (47.4%) to very high (11.9%) pollution probability (Table 5). The PaPRIKaRa index also showed that a significant part of

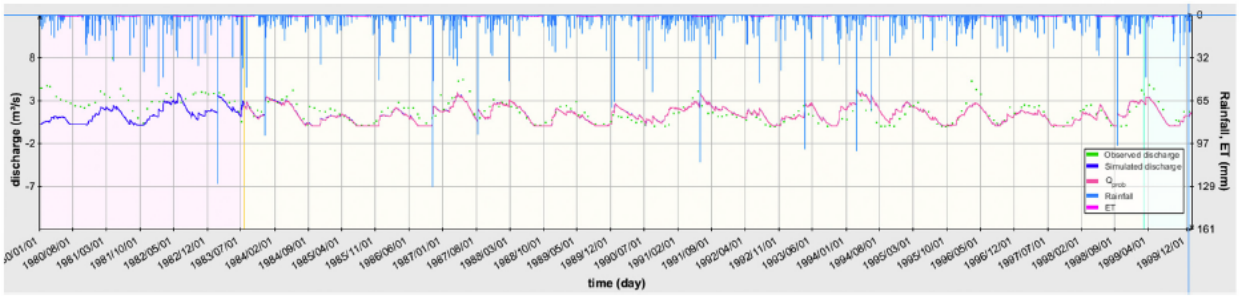

Fig. 7. Simulation results for the Damasi-Titanos karst system using KarstMod.

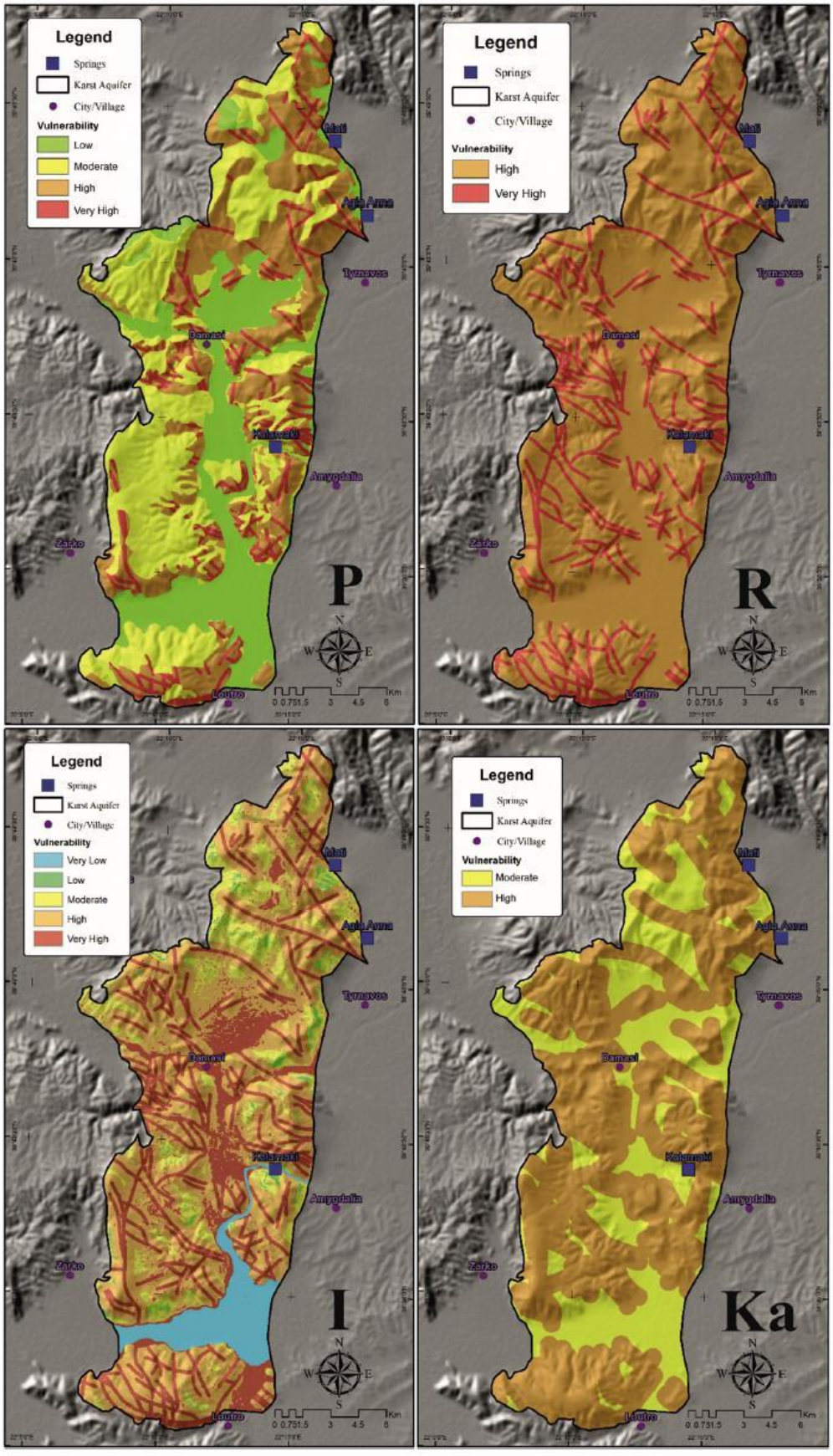

Fig. 8. P, R, I and Ka maps of the intrinsic vulnerability of Damasi-Titanos karst aquifer.

Table 2
Vulnerability class areas of factors and PaPRIKa method of Damasi-Titanos karst aquifer.

Vulnerability	PaPRIKa		P		R		I		Ka	
	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)
Very low	0.0	0.0	0.0	0.0	0.0	0.0	22.1	6.9	0.0	0.0
Low	21.5	6.6	77.5	24.2	0.0	0.0	4.4	1.4	0.0	0.0
Moderate	28.4	8.9	111.4	34.8	0.0	0.0	36.1	11.3	90.6	28.3
High	201.0	62.8	95.4	29.8	254.5	79.5	164.6	51.4	229.4	71.7
Very high	65.0	21.7	35.7	11.2	65.5	20.5	92.8	29.0	0.0	0.0

the aquifer, mainly its mountainous part, is characterized by low risk (25.5%).

6. Discussion

6.1. Damasi-Titanos karst hydrosystem

In this study the QGIS-based plugin of PaPRIKa was used to estimate the resource vulnerability of the karst aquifer of Damasi-Titanos in Greece. The plugin proved sufficiently flexible and powerful to develop the four thematic maps and the final vulnerability map. It should be noted that the application of the PaPRIKa method using the plugin cannot replace a standard hydrogeological field survey. Additionally, thorough hydrogeological analysis of a karst system is essential to avoid their misinterpretation. PaPRIKa is robust and can provide a reliable tool for karst aquifer protection. Sensitivity analysis was used to overcome the subjectivity of the factor weights and has been successfully used in other studies to estimate aquifer vulnerability (Dixon, 2005; Gontara et al., 2016). This technique was successfully applied using the PaPRIKa method in the Damasi-Titanos karst system. However, significant changes in the vulnerability mapping were not observed when the modified weights were applied. The majority of the karst aquifer was characterized by high to very high vulnerability, while the low and very low vulnerability categories were not observed. The absence of very low and low vulnerability characterization has also been referred in a karst aquifer of the western Pyrenees (Huneau et al., 2013). This can be considered logical because the PaPRIKa method considers the worst-case scenario in terms of vulnerability. The method has been applied extensively in France and has recently been applied in Spain (Jimenez-Madrid et al., 2012; Marin et al., 2012) and Cuba (Farfan-Gonzalez and Plagnes, 2013) and in all cases has provided high reliability in the vulnerability assessment. PaPRIKa has been compared to other methods of karst aquifer vulnerability assessment (Ivan and Madl-Szonyi, 2017), the most well-known of these being EPIK (Dörfliger, 1996), the European Approach (Daly et al., 2002; Zwahlen, 2004), PI (Goldscheider et al., 2000), VULK (Jeannin et al., 2001), and COP (Vias et al., 2006). Marin et al. (2012) highlighted that one of the strong points of PaPRIKa is that it focuses on infiltration-related parameters. The application of the PaPRIKa method in the complex aquifer of Damasi-Titanos showed coherent results based on the known

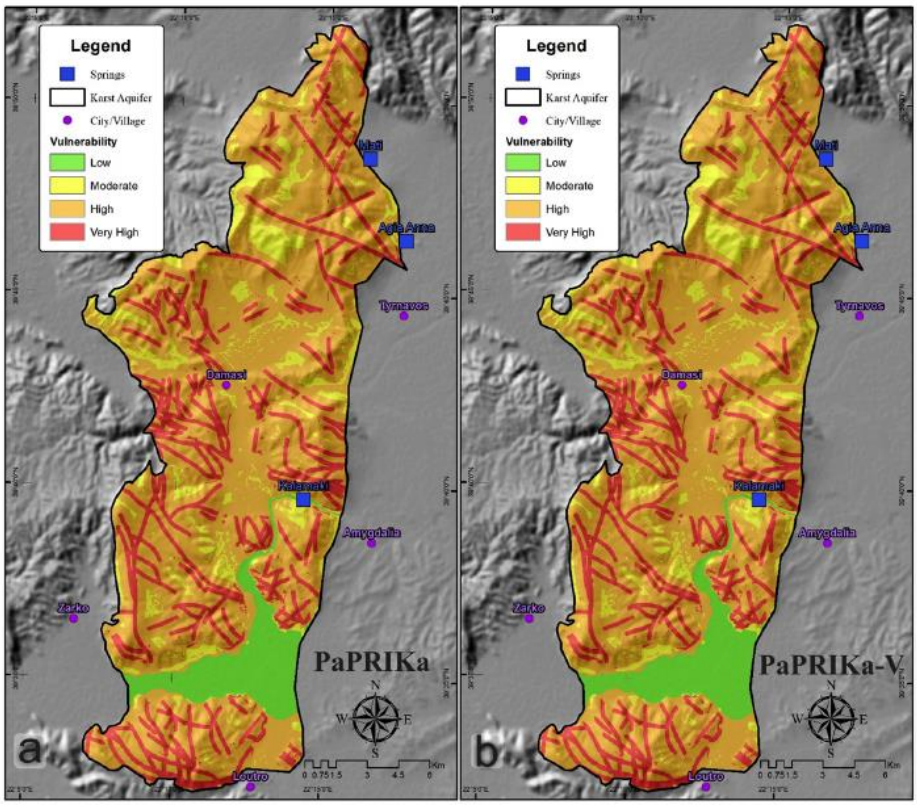

Fig. 9. Vulnerability maps of the karst aquifer Damasi-Titanos using PaPRIKa (a) and PaPRIKa-V (b) methods.

Table 3
Statistics of the single-parameter sensitivity analysis.

Factors	Min	Max	Mean	SD	Weight (%)
P	10	44.9	24.8	7.8	25.9
R	15	60	23.1	10.2	24.1
I	0	44.9	28.3	9.3	29.5
Ka	13	60	19.7	7.5	20.5

characteristics and behavior of the aquifer. Additionally, the novel plugin renders the application of PaPRIKa user-friendly and affordable even in complex karst systems.

The pollution risk assessment of the Damasi-Titanos aquifer provides a protection tool for this valuable groundwater resource. The aquifer is the main source of drinking water for the city of Larissa and its surrounding towns and villages. If permanent groundwater deterioration or drying of springs occurred, the cost of restoring the water supply would be unbearable for the local community. Indisputably, land use changes, protection measures, and the use of suitable alternative crops in the area should be enforced in order to retain the sustainability of the aquifer system. Gutiérrez et al. (2014) listed numerous human activities that can impact karst systems. Hence the assessment of pollution risk is essential to protect karst aquifers. Pollution risk of karst aquifers has also been estimated in other cases by combining hazard and vulnerability maps (Laimer, 2005; Andreo et al., 2006). Nguyet and Goldscheider (2006) estimated contamination risk in a tropical karst area of Vietnam and produced a land-use planning and sustainable groundwater management tool for the Tam Duong area. In Slovenia a pollution risk map was based on the Slovene Approach for groundwater vulnerability assessment and a hazard map (Ravbar and Goldscheider, 2007). In northern Greece pollution of a karst aquifer was estimated by combining the EPIK method and a hazard map (Kazakis et al., 2015). In this study, the PaPRIKa method was successfully combined with a hazard map to produce a risk map of the aquifer. The hazard map could be updated performing statistical in order to define the pollution hazard probabilities of the study area. Considering that varying nitrate concentrations (up to 40 mg/L) were observed in the springs, it is essential to define protection zones for the aquifer's three springs. Additionally, the pollution risk assessment provided discrimination in the River crossing zones driven from the interaction between the karst aquifer and the allogenic Rivers. Titarisios River constitutes a valuable source for Damasi-Titanos karst aquifer recharge. However, the protection of the River's water quality and quantity is of utmost importance to preserve the quantitative and qualitative status of the karst aquifer. Although groundwater velocity was estimated in previous studies, the source vulnerability of the springs had not been previously estimated. Undoubtedly, the complexity of the aquifer system presupposes a holistic and simultaneous systematic tracing test on the system that focuses on the interaction between the springs and River Titarisios. This test would increase the reliability of the source vulnerability map and help delineate protection zones.

Table 4
Land use ratings for the Hazard map.

Land uses	Hazard	Rating
Water courses	Very high	4
Vineyards		
Permanently irrigated land		
Olive groves		
Mineral extraction sites		
Land principally occupied by agriculture, with significant areas of natural vegetation		
Industrial or commercial units		
Discontinuous urban fabric		
Complex cultivation patterns		
Non-irrigated arable land	High	3
Fruit trees and berry plantations		
Natural grasslands	Moderate	2
Transitional woodland-shrub	Low	1
Sparsely vegetated areas		
Pastures		
Inland marshes		
Sclerophyllous vegetation	Very low	0
Coniferous forest		
Broad-leaved forest		
Pinios		

This study also illustrates the necessity of hydrodynamic analysis and system simulation before the assessment of vulnerability and pollution risk in complex karst systems. Knowledge of the interactions between rivers and the karst system is essential for vulnerability assessment as a significant part of recharge can originate from surface waters. In this study the correlation analysis verified the field measurements and showed a strong interaction between River Titarisios and the aquifer. According to previous studies, River Pinios does not contribute to the recharge of the studied aquifer (Manakos, 2010). It is worth mentioning that a limitation of the cross-correlation analysis was the gap in the time series. A future challenge is the establishment of daily or hourly-measurements of springs and Titarisios flow. This can allow to simulate discharge and hydrochemical data similar to other studies (Manakos, 1999; Manakos and Dimopoulos, 2004; Voudouris et al., 2010), while statistical analysis can contribute in the determination of hydraulic parameters (Mandilaras et al., 2006). The necessity of climate data spatialisation is also underlined.

The Damasi-Titanos aquifer was simulated in KarstMod to better understand the system. The model has proved effective and useful in areas where knowledge of the geometry of the karst environment is lacking. Despite the non-complete data series, the KarstMod simulation can be characterized as successful as it confirmed the conceptual model produced in previous studies of the area. More specifically, the simulation confirmed the existence of two compartments in the aquifer and the direct fast flow of groundwater from compartment E to the springs. Despite the lack of available climate and spring discharge data the simulation did indicate aquifer mis-management. For instance, there are limited information regarding hidden flow (undocumented pumping) and inter-catchment flow (lateral outflow and Titarisios inflow). The available data did serve the scopes of this study however it is insufficient to allow the prediction of future trends and/or management scenarios of the springs and boreholes. Nevertheless, the flow of the River Titarisios must be preserved as it is a valuable source of recharge for the Damasi-Titanos system.

6.2. A road map towards sustainable exploration and integrated management of Greek karst hydrosystems

The obtained overview showed the evolution of research approaches for the characterization, protection and management of karst aquifers in Greece. The statistical analysis dominated for the characterization of the aquifers, while in less cases was evaluated in conjunction with field measurements such as microstructural measurements and geological mapping. The boundaries of the aquifer in the majority of the studies were obtained from the existing geological maps. In many studies highlighted the necessity of a sustainable management plan mainly in terms of exploitation. The neglection of karst aquifers protection research is obvious from the overview. This fact is depicted in the assessment of karst aquifers vulnerability only in two cases and is mainly attributed in the lack of data. Vulnerability assessment of karst aquifers requires a deep hydrogeological knowledge of the system including the detailed structure of the aquifer, the hydraulic characteristics of the vadose zone and the aquifer, the infiltration regime as well as the function of the system.

The study of the Damasi-Titanos system also highlighted the importance of the interaction between the karst aquifers and allogenic Rivers. This fact has been remarkably neglected in other cases. Additionally, tools such as hydrogeophysical research have been less used although

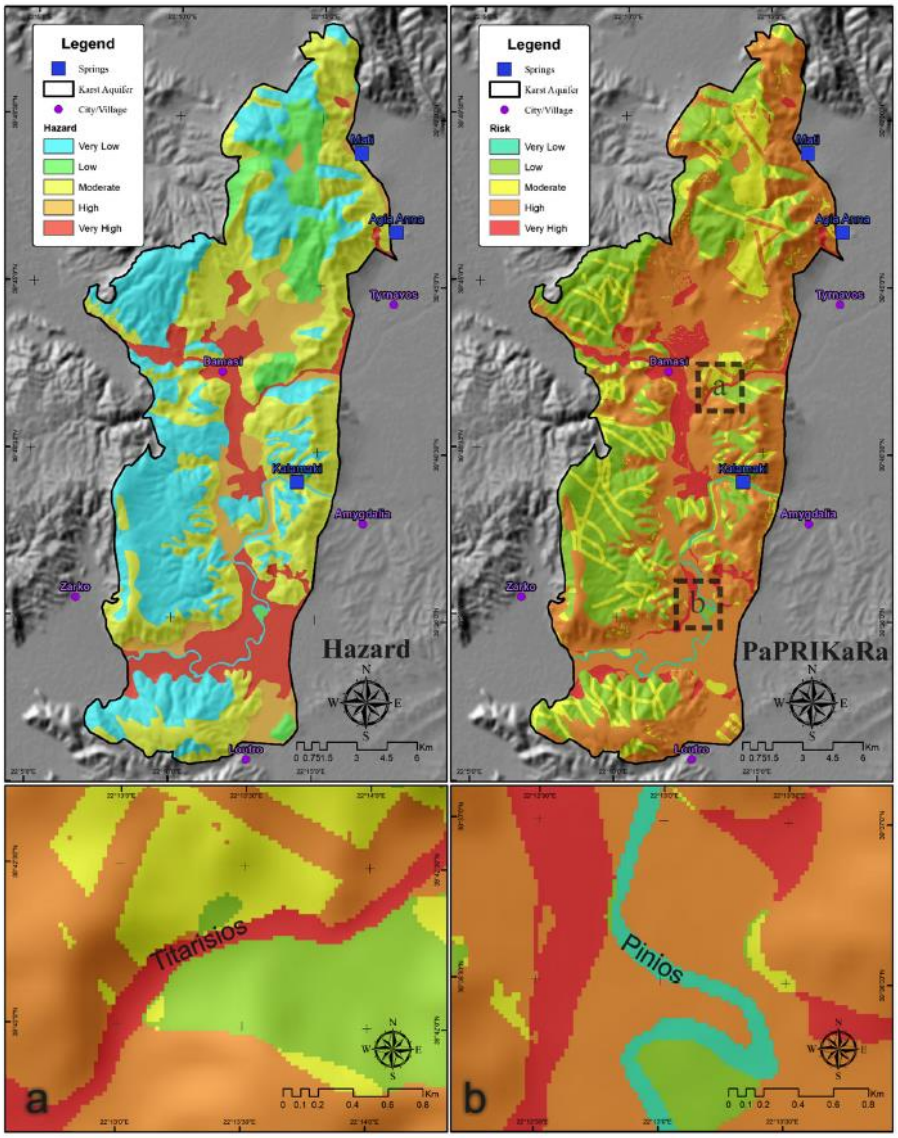

Fig. 10. Hazard and Pollution Risk maps of the karst aquifer Damasi-Titanos using PaPRIKaRa method. Focused areas on River Titarisios (a) and River Pinios (b).

they can contribute in the characterization of karst aquifers with various methods (Chalikakis et al., 2011). Spatial models were preferred in the research approaches despite the chosen assumptions and their high uncertainty. Contrarywise, lump models have been less used although they can provide valuable information. In the case of Damasi-Titanos system the conjunction of KarstMod and Vulnerability assessment increased the robustness of the applications and contributed in the better characterization of the aquifer. The study of the Damasi-Titanos system lead us to conclude that only the knowledge of the aquifers function cannot ensure sustainable management of the aquifer. Additionally, the interaction with the surface waters should be considered in the assessment of vulnerability and pollution risk of the aquifers. A key point of this study was the application of a lump model with low degree of uncertainty. Nevertheless, the necessity of a detailed monitoring plan was emphatically suggested. In Fig. 11 a road map is presented suggesting the mandatory steps including:

1) the hydrogeological observations (temporal and spatial data),
2) the application of advanced statistical methods to analyze the data

Table 5
Pollution Risk class areas of factors and PaPRIKa method of Damasi-Titanos karst aquifer.

Vulnerability	PaPRIKa-V		RISK	PaPRIKaRa	
	Area (km^2)	Percent (%)		Area (km^2)	Percent (%)
Very low	0.0	0.0	Very low	2.4	0.8
Low	21.5	6.7	Low	80.2	25.1
Moderate	28.4	8.9	Moderate	49.8	15.6
High	205.1	64.1	High	167.9	52.5
Very high	65.0	20.3	Very high	19.6	6.1

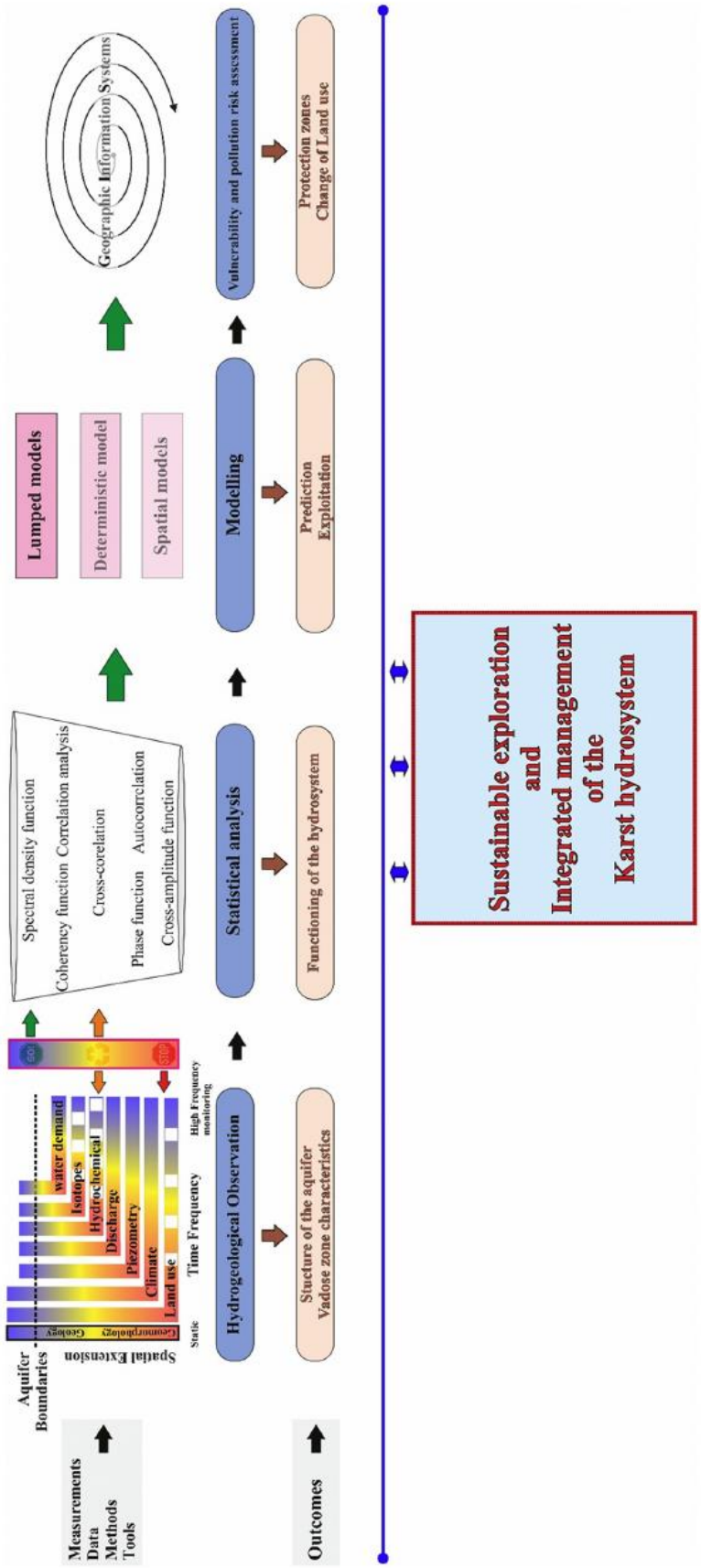

Fig. 11. Road map for sustainable management of karst aquifers in Greece.

3) the application of integrated models depending of the aquifer's characteristics
4) the vulnerability and risk assessments

The hydrogeological observation should be spatially extended beyond the boundaries of the aquifers in order to understand the interaction with nearby aquifers and hydrological catchments. Additionally, the time frequency of the data collection is critically important for the next steps. For instance, the hydrochemical and isotope analysis can provide reliable results even in periodically analysis. Contrarywise, climate, piezometric and discharge data should follow a high frequency time step (e.g. daily or hourly). It is also important to update the land use of the aquifer which is closely related to the water demand of the region. In the case of limited collection moving to the next step is not suggested, while moderate quantity of the data sets can lead to uncertainties and the hydrogeologist has to move back to the first step for reevaluation of the data set. Statistical analysis is suggested as the second step in order to understand the functioning of the hydrosystem, which is required before modelling. Prediction and exploitation are mainly focused on the quantities of the system, while the final step deals with the groundwater quality protection of the aquifer. The vulnerability and pollution risk assessment are tools to delineate protection zones and suggest land use changes. On condition that all steps in terms of circularity are adopted and mutually supported then an integrated management can be achieved.

The suggested road map aims to a sustainable management plan in terms of protection, preservation and exploitation of Greek karst aquifers. Additionally, the application of this approach can answer the posed questions of this study regarding karst aquifers management in Greece.

7. Conclusions

The management of karst aquifer resources in Greece is a very difficult and challenging task however careful and interconnected steps are required. An overview of research application in combination with a case study application in Greece provided a four-step road map for integrated karst aquifer management. The mandatory steps are hydrogeological observations, statistical analysis, modelling, vulnerability and risk assessments. Beyond the road map this study verified the flexibility and adaptability of the PaPRIKa method for the assessment of intrinsic vulnerability in a complex karst aquifer of Greece. The novel plugin in QGIS was used to assess the final vulnerability map. The sensitivity analysis was used to validate the PaPRIKa method by overcoming the subjectivity of the initial weights. However, the characterization of the aquifer remained high to very high without significant changes in the spatial distribution of the vulnerability zones. The pollution risk map was produced by overlaying the hazard and validated vulnerability maps. The aquifer was characterized by low to very high risk, but high risk dominates. The hydrodynamic analysis of the aquifer showed a low correlation between spring discharge and precipitation. In contrast, high correlation was observed between percolation from River Titarisios and spring discharge. The strong correlation recorded between the discharges of the three springs verified the high karstification degree of the Damasi-Titanos system. Additionally, KarstMod verified the conceptual model of the karst system despite the absence of a detailed data series. Considering that the karst aquifer is the main source of drinking water for the entire area it is of utmost importance to establish a protection plan that includes land use changes in order to sustain the quality of the aquifer's groundwater. Additionally, it is critically important to preserve the streamflow of R. Titarisios in order to sustain the quantitative regime of the Damasi-Titanos karst system. Effective, thorough, monitoring should also be included in an optimal management plan of the karst system. Additionally, the study of Damasi-Titanos karst system highlights the necessity to couple hydrodynamic analysis and vulnerability assessment acting complementary so as to increase the robustness and reliability of the results.

On balance, the proposed road map can contribute in the sustainable management of karst aquifers in Greece establishing a research process based on feedback and re-evaluation of the systems function and protection.

Acknowledgement

This research was carried out within the framework of the Post Doc of Dr. Nerantzis Kazakis in Avignon University (UMR 1114 EMMAH) and has been funded by the French Embassy in Greece (Séjours Scientifiques de Haut Niveau). Additionally, this work benefited from fruitful discussions within the KARST observatory network (SNO KARST) initiative from the INSU/CNRS, which aims to strenghten knowledge-sharing and promote cross-disciplinary reasearch on karst systems at the national scale.

Annex 1. Model equations

Mass balance equations of the model are the following:

$$dE/dt = P - ET - Qhy$$

$$dC/dt = QhyEC - QpumpC - QCS$$

where E and C are the water levels in reservoirs E and C respectively, P is the precipitation rate, ET is the evapotranspiration rate, Qhy is the infiltration rate, QhyEC is the portion of Qhy which flows through reservoir C, QpumpC is the overall outtake (algebraic value) from reservoir C, QCS is the discharge rate from reservoir C to the spring. Evapotranspiration stops when the water level reaches the minimum zero value.

Internal fluxes are assumed to obey the following relationships

$$Qhy = khy * (E - Ehy) \text{ if } E \geq Ehy \ (Qhy = 0 \text{ otherwise})$$

$$QhyEC = p * Qhy$$

$$QhyES = (1 - p) * Qhy$$

$$QCS = kC * C$$

where khy, kEC are specific discharge coefficients and Ehy is the activation threshold for Qhy. Discharge QS at the outlet of the catchment is defined as

$$QS = A * (QhyES + QEC)$$

where A is the total area of the catchment.

Annex 2. Table of calibrated values

Model parameter	Value	Unit
K_{hy}	0.007	mm/day
E_{hy}	122	mm
p	0.032	
K_{cs}	0.001	mm/day

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7.5. Ollivier et al., 2018

Groundwater

Technology Spotlight/ Technology Editor / M. Gefell

A QGIS Plugin Based on the PaPRIKa Method for Karst Aquifer Vulnerability Mapping

by Chloé Ollivier[1], Yoann Lecomte[2], Konstantinos Chalikakis[3], Naomi Mazzilli[3], Charles Danquigny[3], and Christophe Emblanch[3]

Introduction

Intrinsic vulnerability is an expression of geological and hydrogeological properties of an aquifer that govern its susceptibility to pollution, regardless of the nature of the contaminant and the contamination scenario (Vrba and Zaporozec 1994). It can be understood as a qualitative indexing of the flow pathway through a geological sequence, from a contaminant release point to potential target. The target might be either an aquifer (resource protection), or an outlet (spring protection). In what follows, we will use "vulnerability" to refer to the intrinsic vulnerability. Aquifer vulnerability maps are a key element for improving groundwater management and allowing sustainable development of karst aquifers. Since vulnerability index is a relative measure, vulnerability assessment methods depend on the conceptual model of transport that was used for their development. The latest method proposed for karst aquifer vulnerability mapping is the PaPRIKa method (Dörfliger and Plagnes 2009). This method is currently widely used by the scientific and engineering communities (e.g., Kavouri et al. 2011). PaPRIKa stands for Protection of aquifers from the assessment of four criteria: the Protectiveness provided by vadose zone (considering the most protective aspects among parameters related to soil cover, unsaturated zone and epikarst behavior), the Rock type of the saturated zone, the Infiltration and the Karstification degree. This multicriteria assessment method uses a weighting system whose criteria are selected according to the aquifer under study.

We proposed a Quantum Geographic Information System (QGIS) plugin based on the PaPRIKa method that facilitates the vulnerability mapping of karst aquifers. This toolbox standardizes the application of the PaPRIKa method with a clear workflow, thus saving time and preventing user omissions. Using the PaPRIKa QGIS plugin, hydrogeologists can more easily handle the different types of spatial data required to generate the four thematic maps relative to the criteria of protection (P), rock type (R), infiltration (I), and karst development (Ka). The plugin expedites the weighting system test and generates the vulnerability map that is most relevant for groundwater managers and decision-makers, allowing faster sensitivity analysis to the weighting system.

Outline of the PaPRIKa Method

The PaPRIKa method for mapping intrinsic vulnerability is based on an analysis of geological and hydrological aquifer properties. The main concepts of the method are summarized as follows; for more details the reader is invited to read the PaPRIKa method guide (Dörfliger and Plagnes 2009) and useful application cases (e.g., Kavouri et al. 2011; Kazakis et al. 2018). The method consists of analyzing aquifer properties in terms of four thematic criteria: P, R, I, and Ka. The complete workflow of the method is illustrated in Figure 1.

Protectiveness of the vadose zone (P) refers to aquifer properties that delay infiltration. It is determined on the basis of three components: (1) soil cover, (2) unsaturated zone properties (thickness, fracturing . . .), and (3) presence of perched aquifers (epikarst). In the case of allogenic water source, their catchment area should be considered to determine its ability to limit (or produce) runoff and thus to store (or transport) a potential pollutant.

Rock type of the saturated zone (R) describes flows within the saturated zone based on analyses of aquifer geology and fracturing. A qualitative lithological classification ranging from the most to the least draining lithology is applied. The highest vulnerability index is assigned to the most draining lithology because it carries the pollutant to the target faster.

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Received December 2018, accepted December 2018.

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doi: 10.1111/gwat.12855

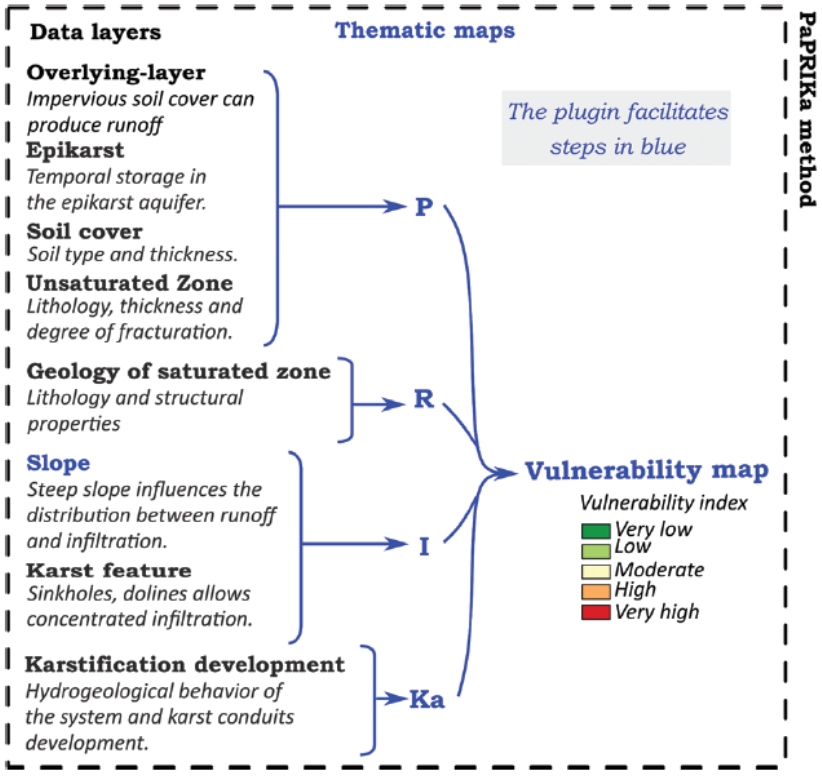

Figure 1. PaPRIKa plugin with detailed data sets.

Infiltration (I) depends first on slope because it controls the runoff/infiltration ratio, and secondly on surface karst features (aven, sinkhole, polje, dry valley) which are preferential infiltration points.

Karstification degree (Ka) represents the functionality of the karst, based on karst network organization and development. Development and functionality of the karst network can be defined by analysis of outlet recession curves using the classification of Mangin (1975) (modified by El-Hakim and Bakalowicz 2007). This analysis defines the Ka index for the entire aquifer. This index is weighted more highly in the presence of karst features (doline, cave, polje), particularly if a tracer test has proven their connection to the main groundwater resource.

Criteria P and R are related to aquifer structure and criteria I and Ka represent hydrosystem functioning. These four criteria are mapped independently and categorized into five classes, from the least to the most likely to promote vulnerability. The vulnerability index is defined as the weighted average from the P, I, R, and Ka criteria:

$$V = p^*P + i^*I + r^*R + k^*Ka$$

where V is the vulnerability index, p, r, i, and k are weights of criteria P, R, I and Ka, respectively. This weighting relationship is specific to each study site. The exact values of p, r, i, k, are thus defined by the user. However, Dörfliger and Plagnes (2009) advise that the sum of i and k should range between 50 and 65%, the sum of p and r should range between 35 and 50%.

QGIS Plugin Workflow

The PaPRIKa QGIS toolbox plugin provides an intuitive workflow for producing P, R, I, Ka maps and computing a vulnerability index (Figure 1). The plugin interface (Figure 2) can be summarized as follows.

(a) The user defines a dedicated folder for the vulnerability mapping work, in which data produced by the toolbox will be stored.

(b) The study area polygon called the catchment area and the expected map resolution are used to generate the guide. The guide is an empty rectangular raster whose spatial extent and resolution enable data standardization for all toolbox data processing. The expected resolution should be consistent with data resolution; the standard value may be set equal to the digital elevation model resolution.

(c) Each of the four criteria (or factors) P, R, I, and Ka has a dedicated tab. Each criteria tab specifies the expected information to generate the thematic map. The calculation method used to compute a thematic index is underlined at the bottom of each tab. Figure 2 shows the contents of the P factor tab.

(d) The PaPRIKa vulnerability mapping method provides a framework that can be adapted to each study

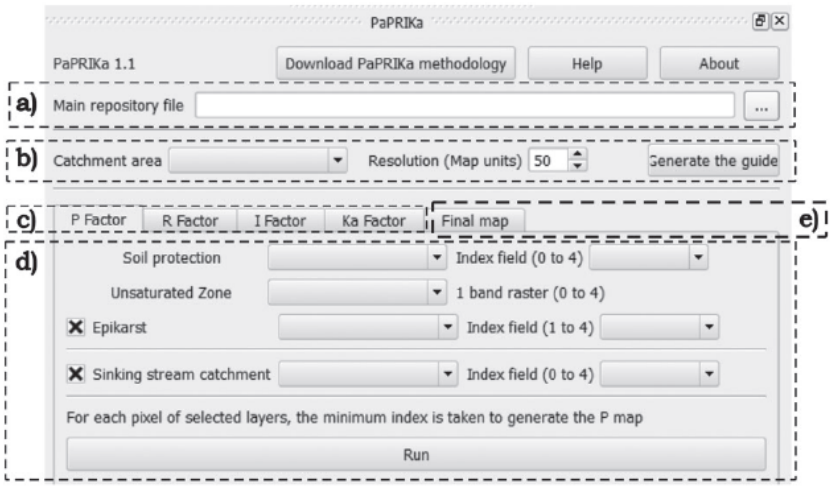

Figure 2. QGIS PaPrika plugin. a, b, c, d, and e are ordered steps to generate the final vulnerability map.

case. Nonmandatory data layers can be either selected or discarded from the analysis. For instance, if the studied aquifer does not have clear proof of the presence of epikarst that might delay infiltration, the epikarst layer checkbox should be unchecked (Figure 2d). The plugin proposes a list of currently available data with the expected format (shapefile or raster). Once the input data set is complete, pressing the run button generates the thematic map.

(e) The final map tab drives the vulnerability map creation. Thematic factor weighting ratio (p, r, I, k) should be determined by the user and range from 0 to 100. The sum of the four weights is 100.

The plugin helps the hydrogeologist combine and crosscheck spatial data to compute the vulnerability index. However, it does not substitute for hydrogeologic expertise. Expected inputs for the plugin are shapefile or raster layers with attribute vulnerability indexes derived from the PaPRIKA classification guidelines. No-value (NA) attributes do not stop the process, but generate a NA in associated cells.

Conclusion and Perspectives

The QGIS plugin that has been developed with the aim to provide a fast and secure way for creating thematic maps and vulnerability map based on the PaPRIKa method. The toolbox minimizes time spent on technical problems; this time can then be devoted to hydrogeological issues, which are the core of vulnerability mapping. Using this plugin, the operator can easily share data and decision rules used for vulnerability mapping and obtain repeatable results. Since it avoids most GIS-related, technical problems and thus possible errors, use of the plugin is a first step toward intercomparability of vulnerability maps. Testing several weighting scenarios is also made easier by the plugin. Such sensitivity analysis may support the operator's subjectivity and provides more evidence to managers.

This free plugin is developed in an open access environment (github.com/Paprika-plugins/PaPRIKa); since its upload in November 2017 onto the QGIS platform (plugins.qgis.org/plugins/Paprika) it has been widely downloaded and used by the engineering and scientific community (Kazakis et al. 2018). Feedback and discussions from users are expected to enrich future developments, in particular: (1) vulnerability assessment validation tools and (2) sensitivity analysis of criteria. In addition, standardization of vulnerability assessment in this complex geological medium will also make it possible to improve pollution risk assessment.

Acknowledgments

Led by the EMMAH, UMR INRA-Avignon University research team, PaPRIKa plugin development was supported by a consortium of French public organizations including: the Provence Alpes Côtes d'Azur region, the Syndicat Mixte de Bassin des Sorgues (www.lasorgue.com), and the KARST Observatory Network (www.sokarst.org) initiative from the INSU/CNRS, which aims to strengthen knowledge-sharing and promote cross-disciplinary research on karst systems. The authors thank the reviewer Dr. P. Renard from University of Neuchâtel.

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