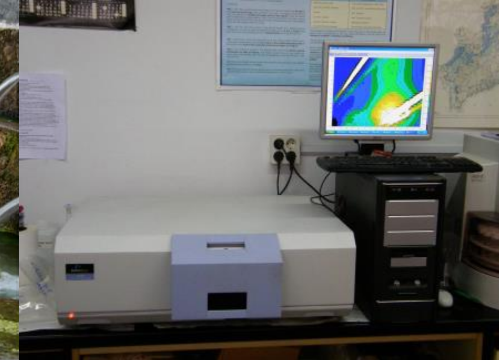

Karst flow system information from shape analysis and numerical modelling of tracer concentration curves

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43rd AIH Congress

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CONTENTS

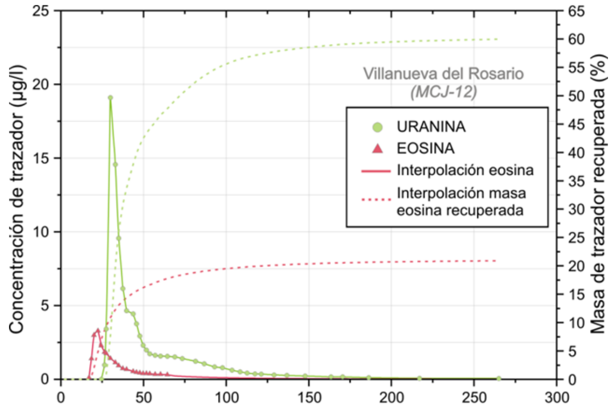
Justification of the research

- Numerous (dye) tracer test have been performed by the researcher of the CEHIUMA during the last years in carbonate karst aquifers of Málaga province (S Spain)

- The tracing experiments were done in a similar geological context but in distinctive hydrogeological frameworks

- An analysis of the tracer concentration curves (BTCs) has been yet conducted individually for karst connection assessment (among other purposes), <u>but not at regional scale</u>

- The application of modelling techniques to BTCs comprises an advanced step in the analysis of the data obtained from field tracer tests providing much more valuable information about tracer migration within karst media. A preliminar analysis on this way has been done



Main goals

The present research aims a preliminar **characterization the solute transport processes** of proved karst connections in carbonate aquifers of Málaga province (S Spain) by means of the application of transport models to tracer concentration data.

The work focuses on the following key topics:

- Hydraulic-hydrodynamic approach of karst connections
- Assessment of hydrodispersive parameters
- Comparative analysis of results from used transport equations

Location

- Four study sites widespread in Málaga province (S Spain)

Climate and physiographic characteristics

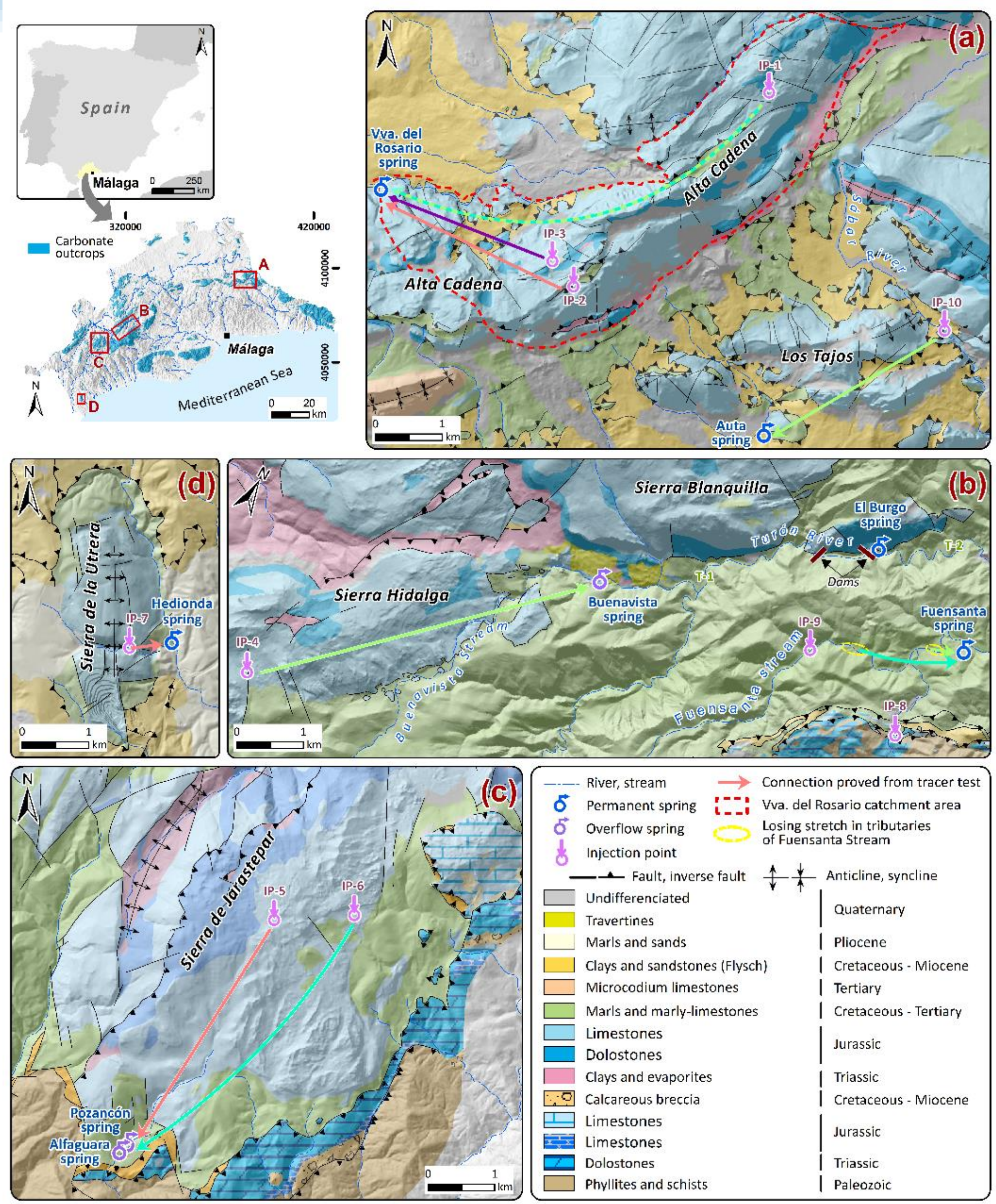
- Semi- to mild continental Mediterranean type
- Accumulated rainfall: from 680 to 1,000 mm
- Rugged land surface (altitude: 100-1,640 m a.s.l.)

Geology

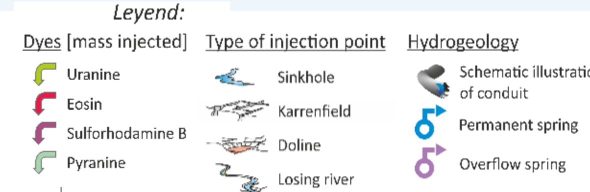
- Betic orogen
- Dolostones and limestones of Jurassic age (~500 m thick)
- Box-type folds with almost vertical and fractured flanks

Hydrogeology

- Recharge mainly by rainfall infiltration
- Natural discharge through karst springs
- Conduit-dominated systems (*Alta Cadena-Los Tajos, Hidalga-Turón, Jarastepar and Utrera*) with distinctive hydrogeological functioning
- Highly developed karst landscapes: wide range of exokarst features

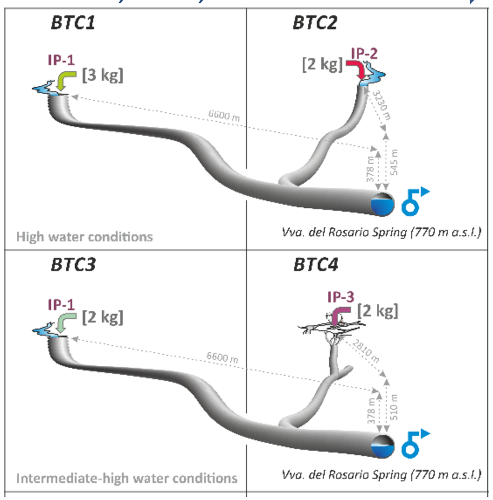


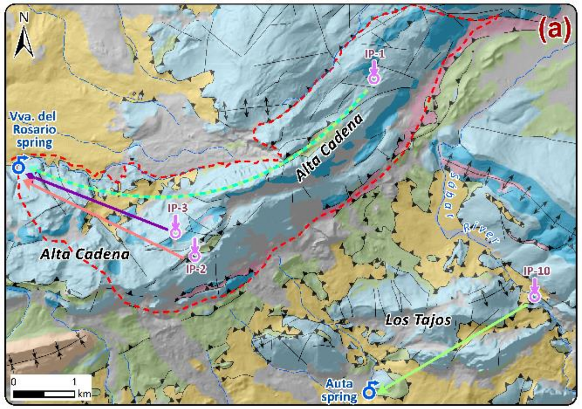
Simplified schemes of studied karst connections

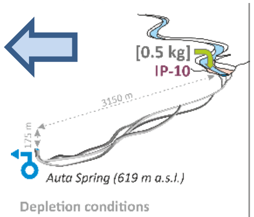


Alta Cadena system

BTC1, BTC2, BTC3 and BTC4

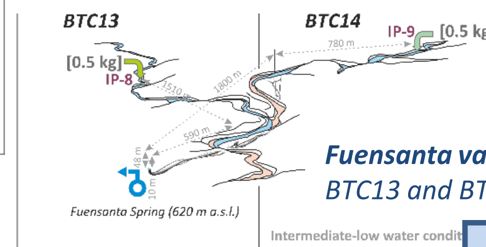






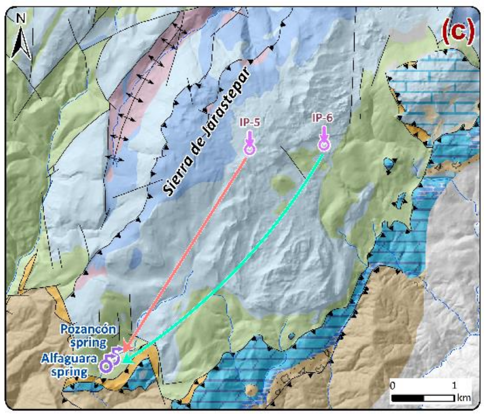
Los Tajos system

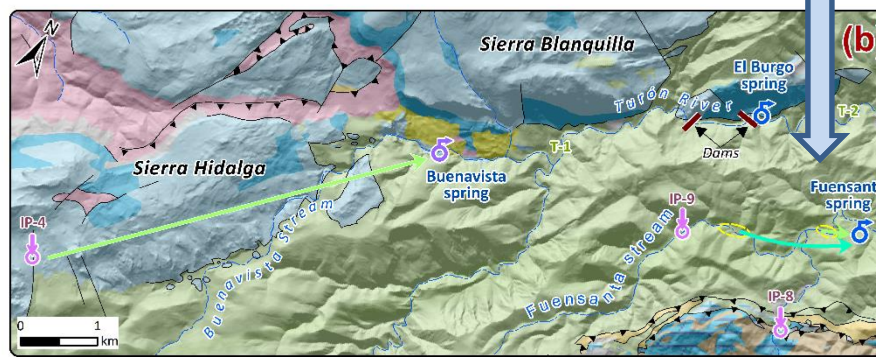
BTC15



Fuensanta valley

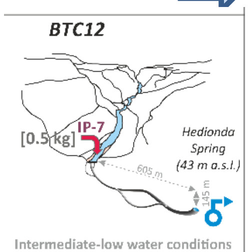
BTC13 and BTC14

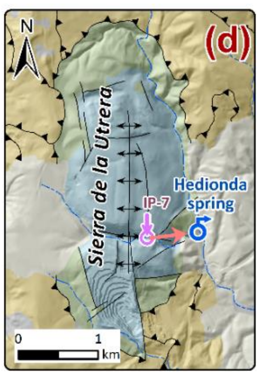


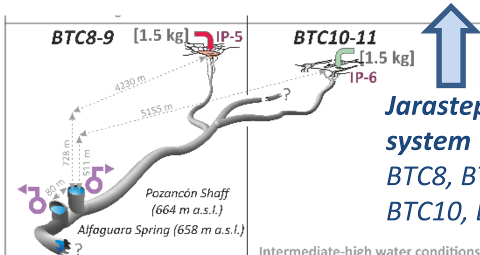


Utrera system

BTC12





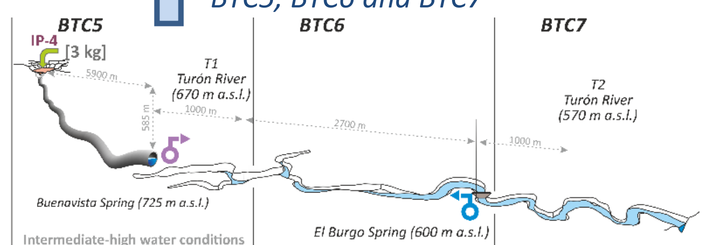


Jarastepar system

BTC8, BTC9, BTC10, BTC11

Hidalga-Turón system

BTC5, BTC6 and BTC7



Field work

- 7 single/multitracer tests (similar logistic for each one)
- 4 tracer used: uranine, eosine, pyranine and sulphorodamine B
- Injection sites: sinkhole, karrenfield, doline and losing stretch in river/streams
- Monitoring points:
- Sampling mode: m 2002)
- Sample/measurem hours (discrete san
- Fluorescence analy LS55 luminiscence

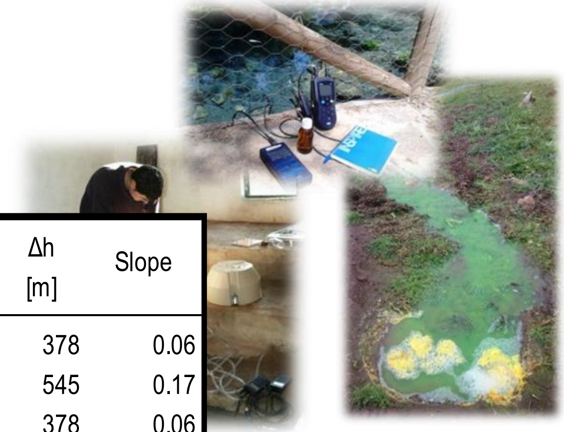
Graphical analysis o

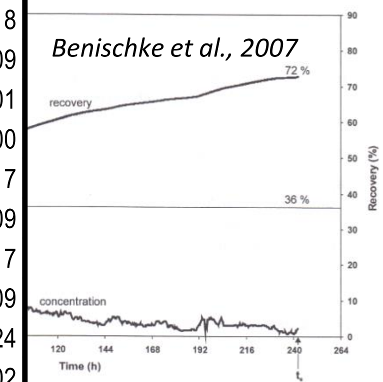
- 15 tracer concentra
- Quantification of t tracer concentratio

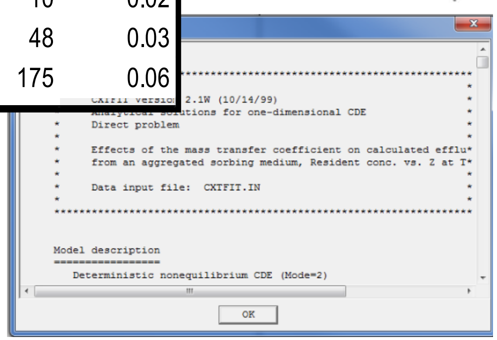
Study site	Karst connection	BTC	Tracer used	Flowpath lenght [m]	Flow conditions	Δh [m]	Slope
Alta Cadena	IP1-Vva. Rosario sp.	BTC1	URN	6,600	High	378	0.06
Alta Cadena	IP2-Vva. Rosario sp.	BTC2	EOS	3,230	High	545	0.17
Alta Cadena	IP1-Vva. Rosario sp.	BTC3	PYR	6,600	High-intermediate	378	0.06
Alta Cadena	IP3-Vva. Rosario sp.	BTC4	SRB	2,810	High-intermediate	510	0.18
Hidalga-Turón	IP4-Turón river (T1)	BTC5	URN	6,900	High-intermediate	640	0.09
Hidalga-Turón	IP4-El Burgo spring	BTC6	URN	9,600	High-intermediate	70	0.01
Hidalga-Turón	IP4-Turón river (T2)	BTC7	URN	10,600	High-intermediate	30	0.00
Jarastepar	IP5-Pozancón shaft	BTC8	EOS	4,230	High-intermediate	728	0.17
Jarastepar	IP6-Alfaguara spring	BTC9	PYR	5,155	High-intermediate	511	0.09
Jarastepar	IP5-Pozancón shaft	BTC10	EOS	4,300	High-intermediate	734	0.17
Jarastepar	IP6-Alfaguara spring	BTC11	PYR	5,230	High-intermediate	517	0.09
Utrera	IP7-Hedionda spring	BTC12	URN	606	Intermediate-low	145	0.24
Fuensanta valley	IP8-Fuensanta spring	BTC13	URN	590	Intermediate-low	10	0.02
Fuensanta valley	IP9-Fuensanta spring	BTC14	PIR	1,650	Intermediate-low	48	0.03
Los Tajos	IP10-Auta spring	BTC15	URN	3,150	Low	175	0.06

Tentative of solute

- Simulation of BTCs Genuchten *et al.*, 2
- Application of advection-dispersion (ADM) and two-region non equilibrium models (2RNE; Field and Pinsky, 2000)
- Assessment of simulation result by means of Nash-Sutcliffe efficiencies (Nash and Sutcliffe, 1970)



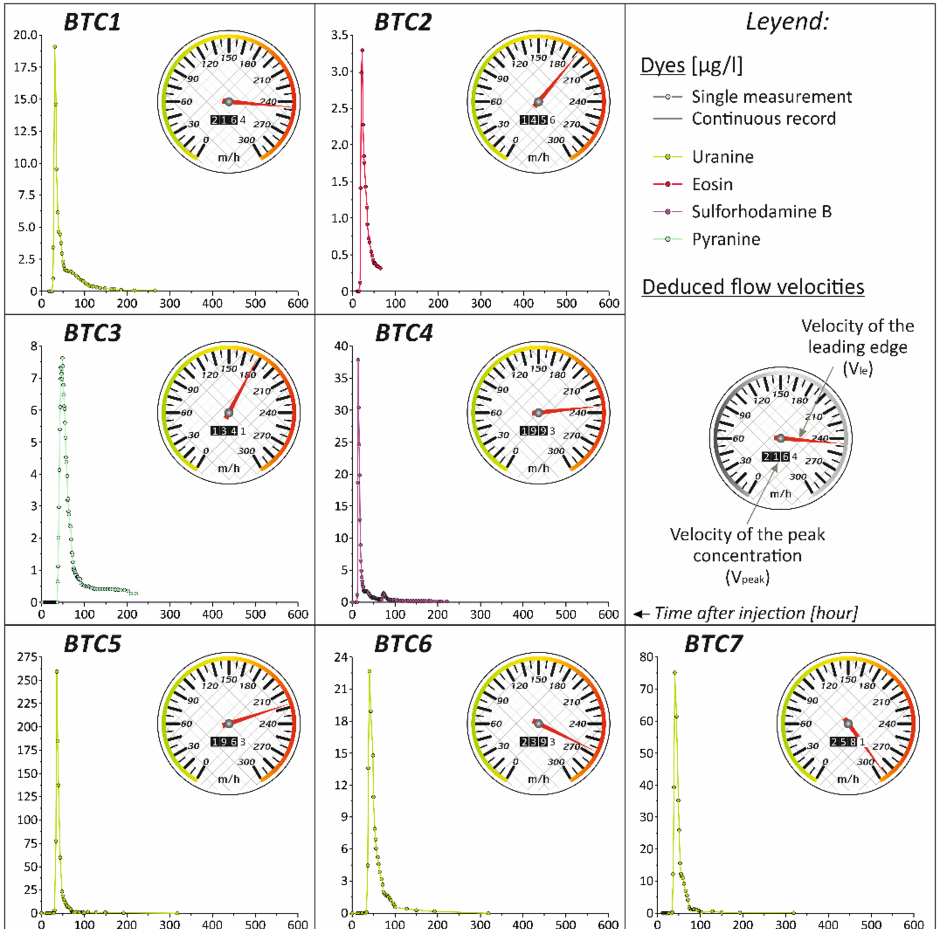




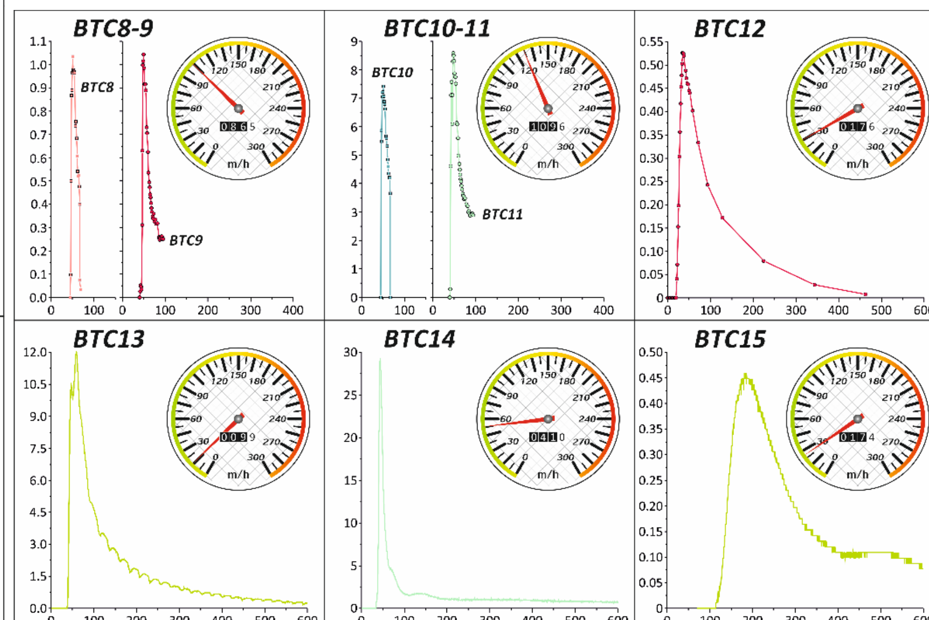
An overview of some karst connections…

Morphological analysis of BTCs

Wide range of shapes (single-peaked and narrow, multi-peaked, with positive skewness, long-tailed curves, etc.) and magnitude in studied BTCs



Main factors that control the evolution in the time of the tracer concentration are the **flow conditions**, the **mass of tracer injected** and the **morphology of the conduit** system



Quantification of BTCs key parameters (graphical analysis)

- Estimation of **travel time, concentration and velocity data** of the 15 BTCs
- Travel time of the leading edge: 12.1 h (BTC4) to 114.3 h (BTC15)
- Travel time of the peak concentration: 14.1 h (BTC4) to 180.8 h (BTC15)
- Average delayed time leading edge-peak concentration was 11.9 h
- Maximum peak concentration: 0.46 µg/l (BTC15) to 258.9 µg/l (BTC5)
- **Recovery rates** of injected tracers were **generally higher in** the experiments performed under **high flow** than that of conducted during low flow
- Modal flow velocities (peak concentration): 9.9 m/h (BTC13) to 258.5 m/h (BTC7)
- A **persistent skewness** is observed **in most of BTCs**
- **Tailing effect** (BTC12, BTC13 and BTC15) and **multi-peaked curves** (BTC4, BTC14 and BTC15) are also observed

The analysis of key parameters and the shape of BTCs are coherent with tracer transport **dominated mainly by advection and dispersion** processes in **high flow,** while in those corresponding to **low flow retardation processes** also participates

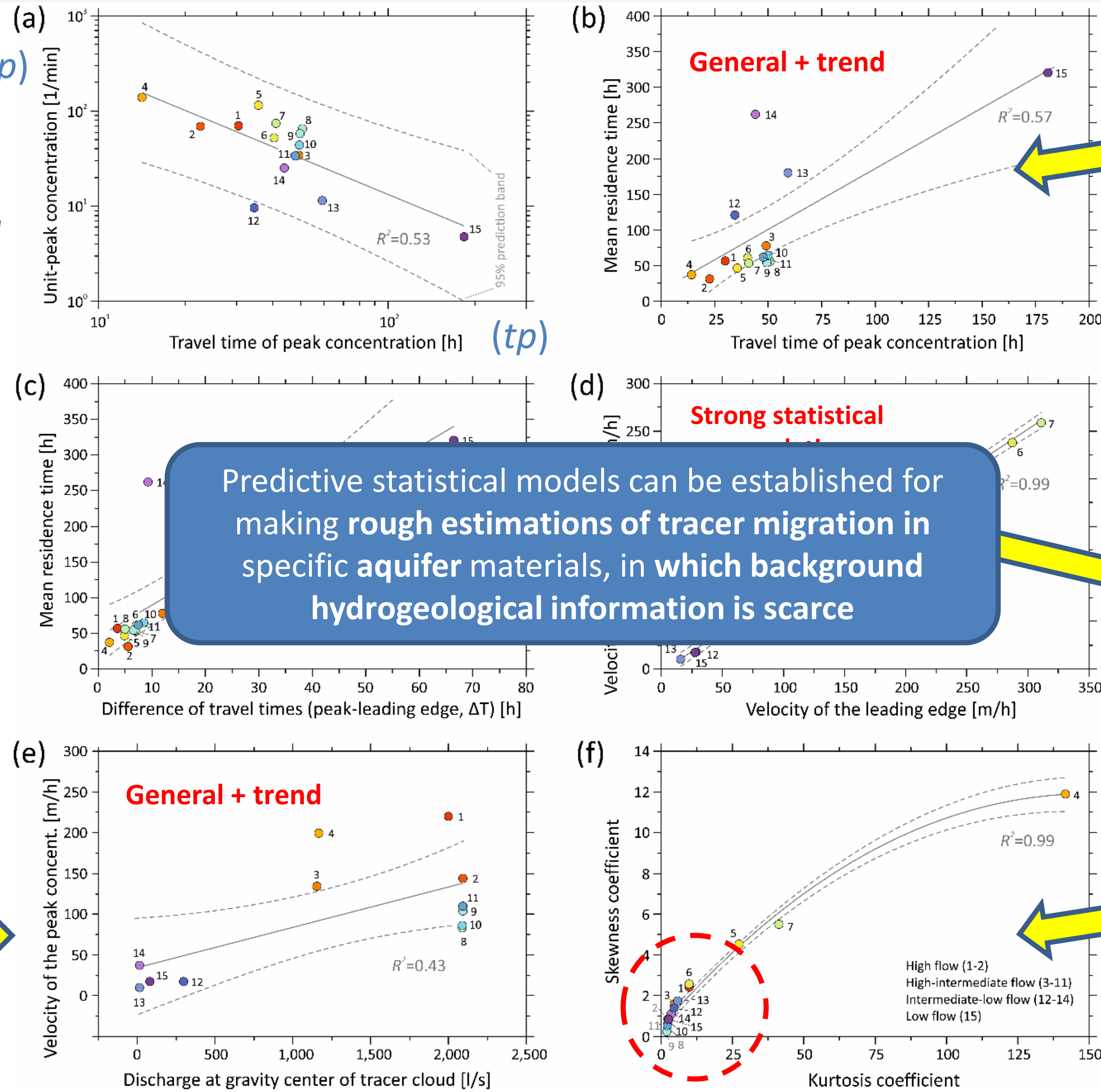
BTC	T_{le} [h]	T_{peak} [h]	ΔT [h]	Duration [h]	V_{le} [m/h]	V_{peak} [m/h]	Inflow rate [l/s]	Q_{50} [l/s]	Q_{test} [l/s]	$Q_{historic}$ [l/s]	Mass injected [kg]	Tracer recovery [%]	Mean resid. time [h]	Mean velocity [m/h]	Variance [$10E^6$ min^2]	Skewness coeff.	Kurtosis coeff.	Maximum concentr. [µg/l]	Unit-peak concentr. [1/s]
BTC1	26.5	30	3.5	238.5	249.1	220.0	10	1,999	1,330	226	3	60	56.5	153	5.72	2.4	9.7	19.1	0.0012
BTC2	17	22.5	5.5	47.5	190.0	143.6	25	2,091	1,330	226	2	21	31.4	115.2	0.50	1.1	3.3	3.3	0.0012
BTC3	37.2	49.2	12	184	177.4	134.1	7.5	1,154	925	226	2	42.4	77.7	106.2	7.45	1.6	4.4	7.6	0.0006
BTC4	12.1	14.1	2	209.2	232.2	199.3	1	1,167	925	226	2	54.2	37.4	135.6	1.16	11.9	141.8	37.8	0.0023
BTC5	30.8	35.6	4.8	287	224.0	193.8	2	-	-	238	3	-	46.9	168.6	3.29	4.5	27.3	258.9	0.0019
BTC6	33.4	40.4	7	285.4	287.4	237.6	2	-	-	79	3	-	60.6	184.8	3.83	2.6	9.7	22.7	0.0009
BTC7	34.1	41	6.9	285.2	310.9	258.5	2	-	-	733	3	-	53.2	222	3.21	5.5	41.2	75.1	0.0012
BTC8	45.6	50.7	5	23.9	92.6	83.5	1	2,087	1,393	-	1.5	9.9	55.5	76.8	0.12	0.3	2.1	1.04	0.0011
BTC9	43	49.5	6.5	25.4	119.9	104.1	2	2,093	1,393	-	1.5	91.9	53.9	96.6	0.13	0.2	2.0	8.5	0.0009
BTC10	41.4	49.9	8.5	53.8	103.8	86.1	1	2,087	1,393	-	1.5	9.9	64.0	70.2	0.68	0.6	2.3	1.1	0.0007
BTC11	40.3	47.8	7.5	53.7	129.9	109.5	2	2,093	1,393	-	1.5	91.9	62.0	89.4	0.80	0.5	2.1	8.6	0.0006
BTC12	21	34.5	13.5	442	28.9	17.6	3.5	295	295	97	0.5	8.4	121.0	8.4	28.94	1.4	4.5	0.5	0.0002
BTC13	37.4	59.3	21.9	797.5	15.8	9.9	7.5	12	11	50	0.5	9.1	179.8	4.8	92.48	1.7	5.7	12.0	0.0002
BTC14	34.6	43.9	9.3	798.7	47.7	37.6	3.5	12	11	50	0.5	9.9	262.4	16.8	209.83	0.9	2.4	29.3	0.0004
BTC15	114.3	180.8	66.5	602.6	27.6	17.4	3.5	81	77	97	0.5	7.4	320.3	12	83.13	0.8	2.6	0.5	0.0001

Characteristic relationships among hydrodispersive parameters

$$C_{up} = 242.9 \cdot t_p^{-1.263}$$

Transport in considered karst connections is generally characterized by highly efficient longitudinal mixing

Flow conditions strongly influence the *Vpeak* in all examined BTCs



Predictive statistical models can be established for making **rough estimations of tracer migration in** specific **aquifer** materials, in **which background hydrogeological information is scarce**

The more the travel time of BTCs, the more the *Mean Residence Time* in the aquifer

Predictive capability for its application in karst groundwater management, but also in logistical issues (e.g. sampling strategies in tracer tests)

Most of BTCs are positively skewed and peaked-like curves

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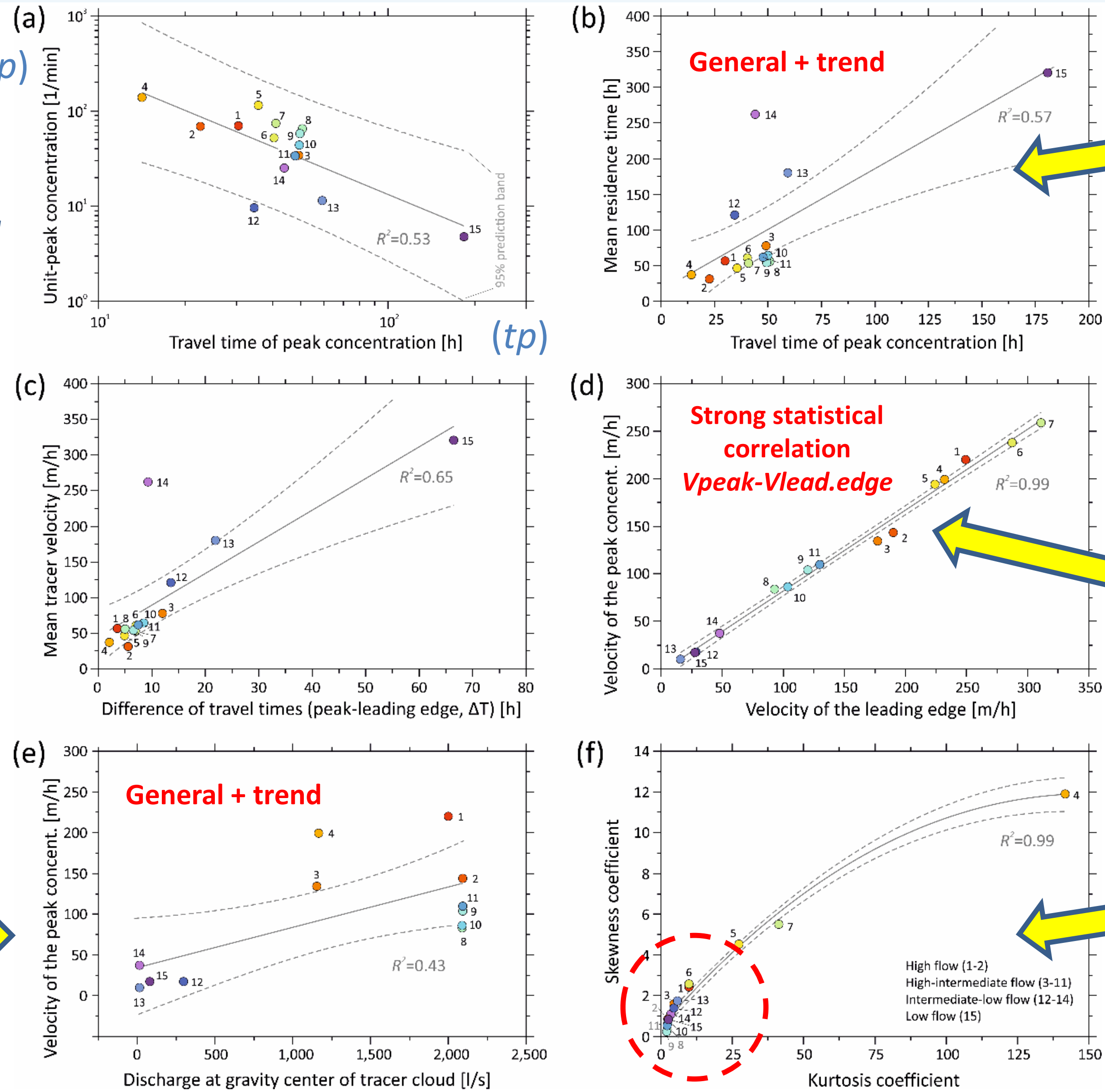

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Tentative of Solute transport modelling

- Computed transport velocities and dispersion using ADE are, on average, higher than that of 2RNE model
- Hydrodispersive parameter estimated from ADE are similar to those provided by the analytical solution (graphical analysis of BTCs)
- Better BTCs simulation results using 2RNE due to the general long-tailed and positive skewed shapes of the tracer curves
- This is confirmed by the generally higher Nash-Sutcliffe efficiencies calculated for the 2RNE modelling results

- **1-D General advection-dispersion equation (ADE):** (Parker and van Genuchten, 1984b)

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x}$$

- **1-D Two region non-equilibrium equation (2RNE):** (Toride et al., 1995; Field and Pinsky, 2000)

$$\beta R\frac{\partial C_m}{\partial t} = \frac{1}{P}\frac{\partial^2 C_m}{\partial x^2} - \frac{\partial C_m}{\partial x} - \omega(C_m - C_{im}) - \mu_m C_m$$

$$(1-\beta)R\frac{\partial C_{im}}{\partial_t} = \omega(C_m - C_{im}) - \mu_{im} C_{im}$$

BTC	AD model				2RNE model					
	v [m/h]	D [m²/h]	d [m]	$E_{j=1}$	v [m/h]	D [m²/h]	d [m]	β	ω	$E_{j=1}$
BTC1	206	5,880	29	0.52	158	2,020	13	0.74	0.99	0.86
BTC2	127	10,600	83	0.54	101	1,420	14	1.34	0.99	0.92
BTC3	127	12,400	98	0.77	119	3,720	31	0.82	1.44	0.89
BTC4	181	4,510	25	0.63	170	668	4	0.84	1.70	0.76
BTC5	188	2,560	14	0.67	178	1,010	0	0.92	2.53	0.76
BTC6	213	20,300	95	0.66	44	3,230	74	0.21	1.21	0.76
BTC7	241	14,900	62	0.76	224	6,160	28	0.88	0.8	0.92
BTC8	77	2,200	29	0.76	75	2,680	36	0.99	0.07	0.78
BTC9	95	4,600	48	0.64	92	26	0	0.80	0.00	0.78
BTC10	75	4,290	57	0.29	53	574	11	0.63	0.00	0.80
BTC11	87	19,500	225	0.45	83	184	221	0.93	0.35	0.78
BTC12	10	669	66	0.79	7	859	116	0.99	2.00	0.77
BTC13	5	354	68	0.76	3	47	14	0.42	1.14	0.93
BTC14	35	445	13	0.04	9	80	9	0.26	1.15	0.77
BTC15	11	3,430	301	0.52	7	602	81	0.49	1.08	0.89

Final remarks and future perspectives

Conclusions

- A conjunctive analysis of tracer tests results from 15 BTCs (dual analytical solution and modelling approach) has permitted a first step to **characterize solute transport** and **get deeper hydrodynamic insights in karst connections** of several carbonate aquifers in S Spain.
- Predictive capability of statistical approaches using characteristic relationships among hydrodispersive parameters can be **useful for tracer migration estimations** of similar hydrogeological systems **at regional scale**.
- Tracer migration is generally controlled by longitudinal advection and dispersion along flow path length.
- **Retardation or stagnant processes, although less influent, promote marked tailing effect in a good number of tracer concentration curves.**
- The application of advection-dispersion equation (**ADE**) allows for a **reasonable quantification of mean flow velocity and dispersion** (according to analytical solution results) while the two regions non-equilibrium transport model (**2RNE**) is able to **fairly reproduce the** generally long-tailed and positive skewed **BTCs**.

Future perspectives

- New data from tracing experiments in specific and well known karst conduit systems (performed in variable flow conditions) using intermediate sampling locations along the traced flowpath.
- Advances in the formulation of modified 2RNE for explaining the general skewness (even multipeaked) of BTCs.


Thanks for your atention

CONGRESS ON GROUNDWATER AND GLOBAL CHANGE IN THE WESTERN MEDITERRANEAN

Granada, 11-13 September 2017

Organized by
International Association of Hydrogeologists
(Spanish Group, French Group, Moroccan Group)

Participation from Tunisia and Algeria is expected

The congress

Major drivers of global change include population growth and migration, climate change, urbanization and expansion of infrastructures, changes in land use and pollution. Western Mediterranean countries of both southern Europe and North Africa are expected to experience impacts on the sustainability, quantity, quality, and management of water resources. Future scenarios in this region forecast the decline in streamflow and in reservoir capacity. In this context the groundwater becomes an increasingly strategic resource to meet the water demand from irrigated and urban areas. Particularly, coastal areas are threatened by water depletion, groundwater reduction and saline water intrusion.

Dealing with this situation makes necessary to address regional needs through global coordination, so the IHP-UNESCO recommends facilitating the country/regional groundwater assessment and exchange of information via seminars, workshops and conferences, like the one that is presented here.

The topics that are expected to be covered by this conference include:

- Defining **growing population pressure** on groundwater resources
- **Evaluating changes** in groundwater quality, storage and fluxes by way of monitoring and modelling approaches
- Predicting **global warming impacts** on groundwater recharge rates and saltwater intrusion
- Assessing steps for the **protection and sustainable use** of groundwater in quantity and quality

Granada

Granada is a city that will captivate all your senses: your sense of **sight** with its impressive monuments such as the Alhambra, the Cathedral and the stunning landscapes seen from the viewpoint of San Nicolás; your sense of **smell** with its jasmine blossom scented streets in the Albaicín district; your sense of **hearing** with the flamenco celebrations of the Sacromonte; your sense of **touch** when you cast your hand over the ancient stones of the buildings; your sense of **taste** when you try the delicious local dishes. Granada is a city of kings, which has to be experienced.

More information: www.aih-ge.org
calvache@ugr.es

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CENTER OF HYDROGEOLOGY OF UNIVERSITY OF MALAGA