

Projects XIBALBA and XIB_TCS

Extended Karst Studies integrating Citizen Science in Area of Tulum/Mexico

Aerogeophysics – hydr. Modeling – 3d Laserscanning – Laser Flux Imaging – Citizen Science-Monitoring



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2006 - 2008: Pilot ground surveys in the Tulum karst system: ERT, EM;
First (2007) and second (2008) aerogeophysical survey.

2008 - 2012: Project Xplore

Goals: Acquisition and advanced processing of geophysical data for input of **innovative hydro-geological modeling** approach (UNINE) / **advanced imaging** of the karst conduit system with **AEM**.

2009: Aerogeophysics near Cancun and Chetumal, Socorro, **extended ERT** in Tulum.

2010: Large ground geophysical campaign (ERT, GPR, borehole geophysics,
set up of **GWL logger network**, water analysis on site and in laboratory).

2011-2012: **d-GPS/piezometric GWL survey** with tides observation, retrieval of GWL/halocline loggers,
water analysis.

2012 – 2017: Project Xibalba

Goal: Medium/small scale acquisition of hydrogeological parameters with innovative methods (conduit geometry laser scanning, laser flux imaging) directly in the conduits, ERT, extended GWL observation, tracer tests. Water chemistry and hydrological model (UNINE).

Ongoing: Project Xib_TCS: Citizen supported ground water monitoring.

Partners



Geological Survey of Austria



Amigos de Sian Ka'an



Technical University of Denmark



Philippe Renard



Steffen Birk



Marco Philipponi



Wolfgang Kinzelbach



Secretaría de Marina
Armada de México



Sam Meacham



Robbie Schmittner



Mario Rebolledo-Vieyra



Bil Phillips



Project Funding



The Nature Conservancy, Unesco (AEM Surveys Tulum 2008/2009)



Austrian Science Fund (projects HIRISK, Xplore, Xibalba, Xib_TCS)



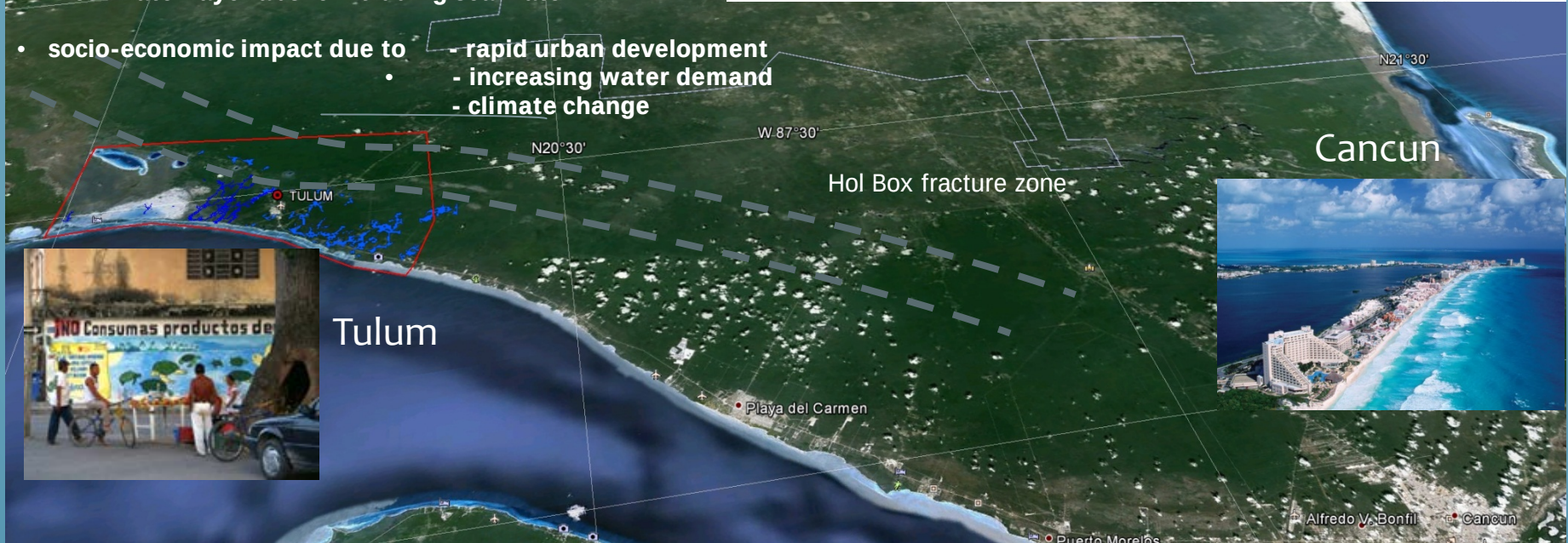
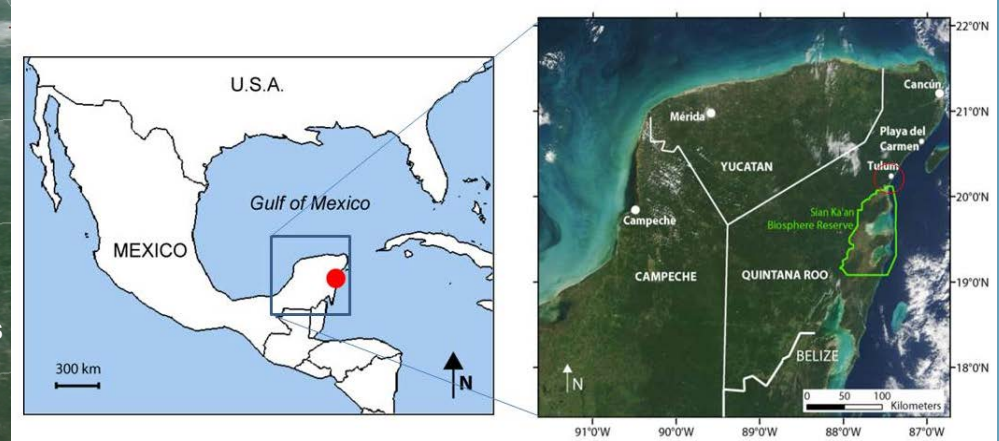
Austrian Academy of Sciences (programme 'Man and Biosphere')



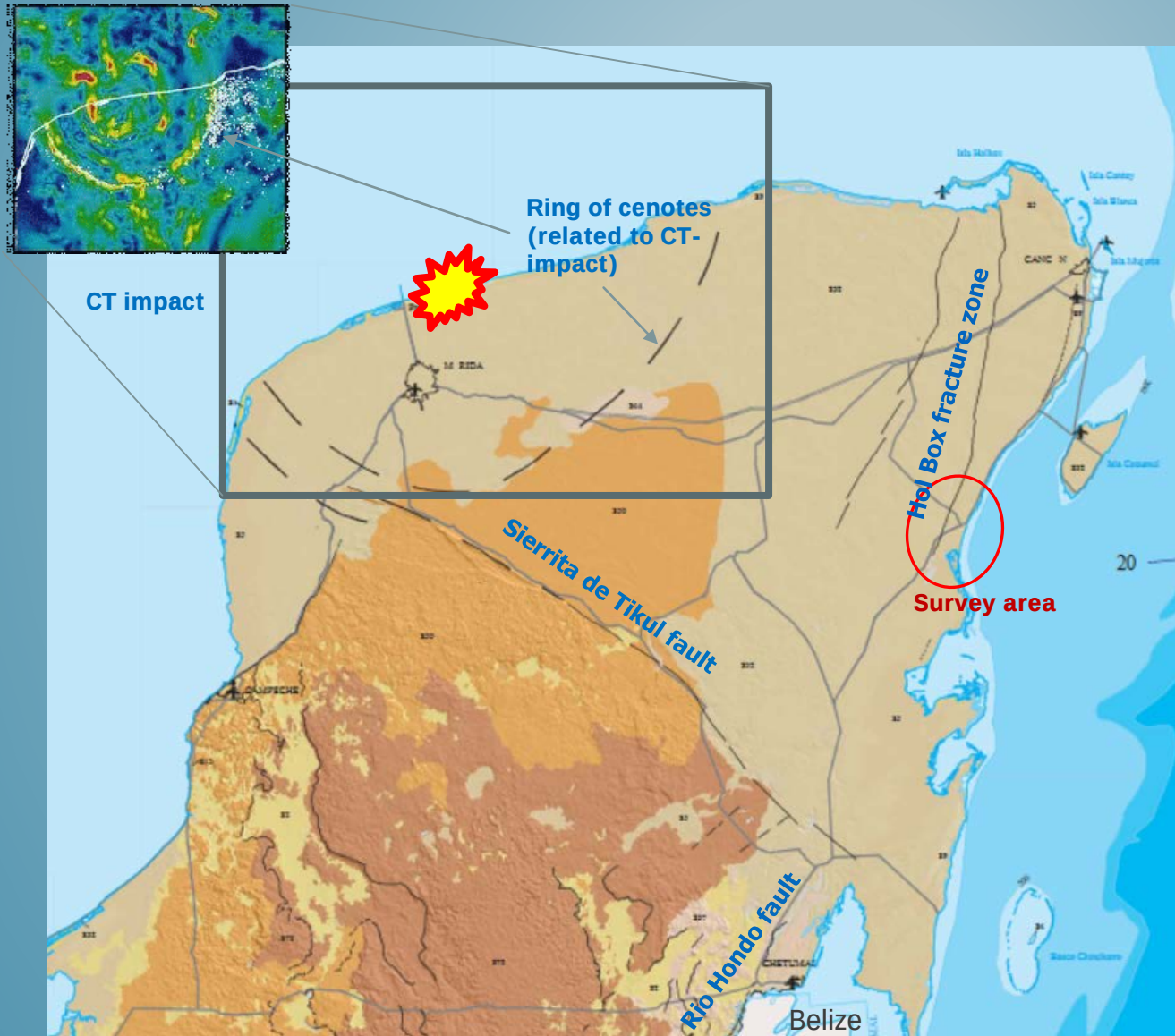
Swiss Science Fund (project Xibalba)

Survey Area – Tulum Karst Plain

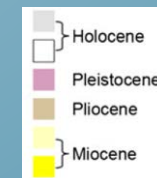
- huge and difficult accessible coastal karst plain covered by forests, mangroves and lagoons
- Thin soil cover – limestone exposed at the surface
- flat topography (0 - ~50 m above mean sea level)
- Main fresh water resource in the underground known conduit / cave network developed during ice ages explored by cave divers
- Freshwater layer above intruding sea water
- socio-economic impact due to
 - rapid urban development
 - increasing water demand
 - climate change



Yucatan carbonate platform



- 300.000 km² / 165.000 km² land
- Over 1500m thick
- Limestone, dolomite, evaporite
- Upper part of aquifer tertiary limestone, little deformation
- East Quintana Roo:
 - Pleistocene limestones, coral and reef units, caliche crusts
- Lagoon limestone (up to 2.6m)
- Dolomites in phreatic zone



Scientific challenges and Study methods

- Can **airborne geophysics (AEM)** image the underground conduit system?
- Can a combination of **aerogeophysical mapping** and statistical **hydrogeological modelling** methods provide **crucial information** about a **komplex Karst ground water regime** as in Tulum?

Methodology:

AEM-Survey → distribution of **electrical conductivity** in the subsurface due to lateral and vertical variation of **hydrogeological relevant domains and structures** as
 - rock porosity, water saturation, ion concentration, GWL, halocline, conduit (cave) network

Structural information from

AEM + **under water cave surveys** +
water level, water flow, tracer tests



hydrol. model

GBA, ASK
Divers
EECYTE, Divers, UNINE, ASK, GBA
UNINE, Switzerland

Hydrol. model

+

chemical water tests

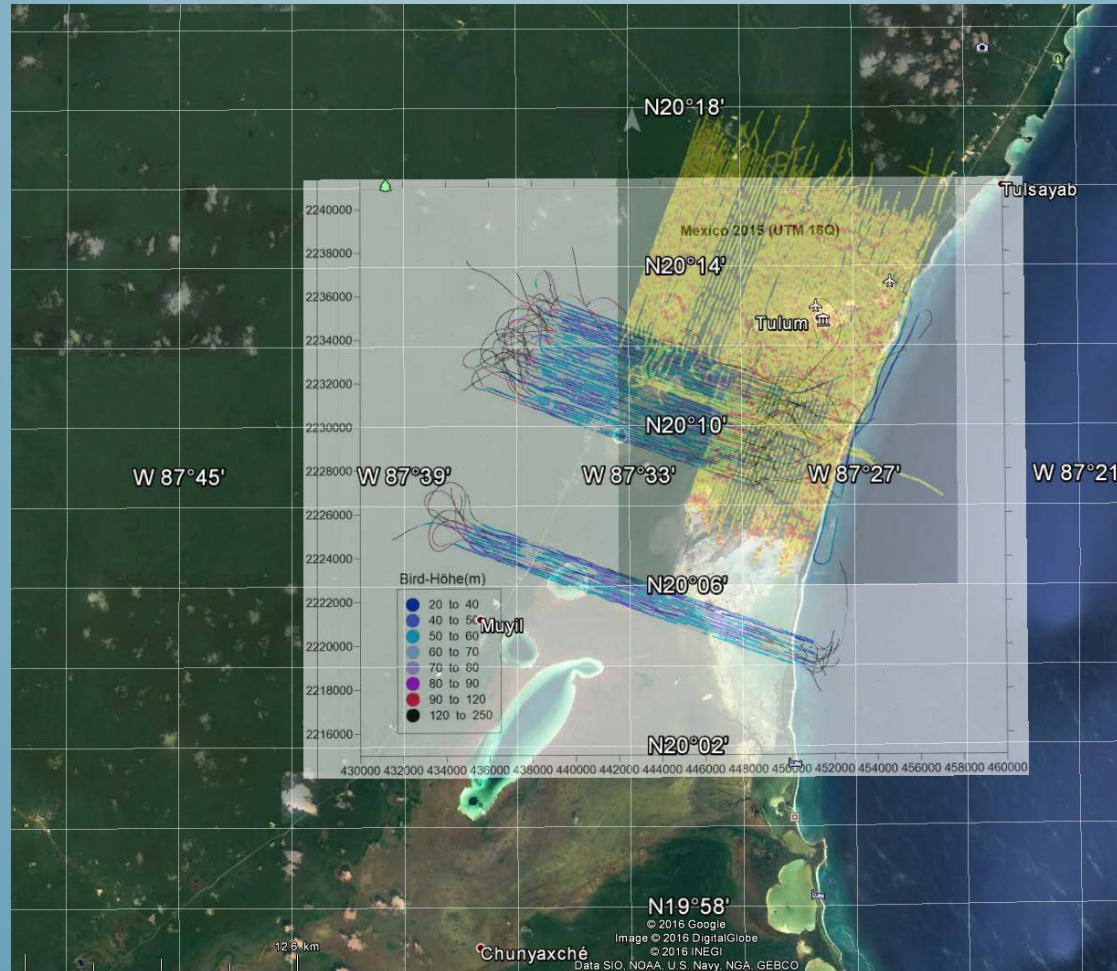


Capacity of fresh water, information about quality and sensitivity, pollutant storage and spreading, impact of climate change



Data basis and analytic tool for development of sustainable ground water management

AEM Surveys Tulum 2007, 2008 and 2015: approx. 250 km²



Helicopter provided by the Mexican Marina (MilMi - 8)







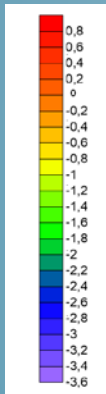
load specialist

Bird 30 m below the helicopter

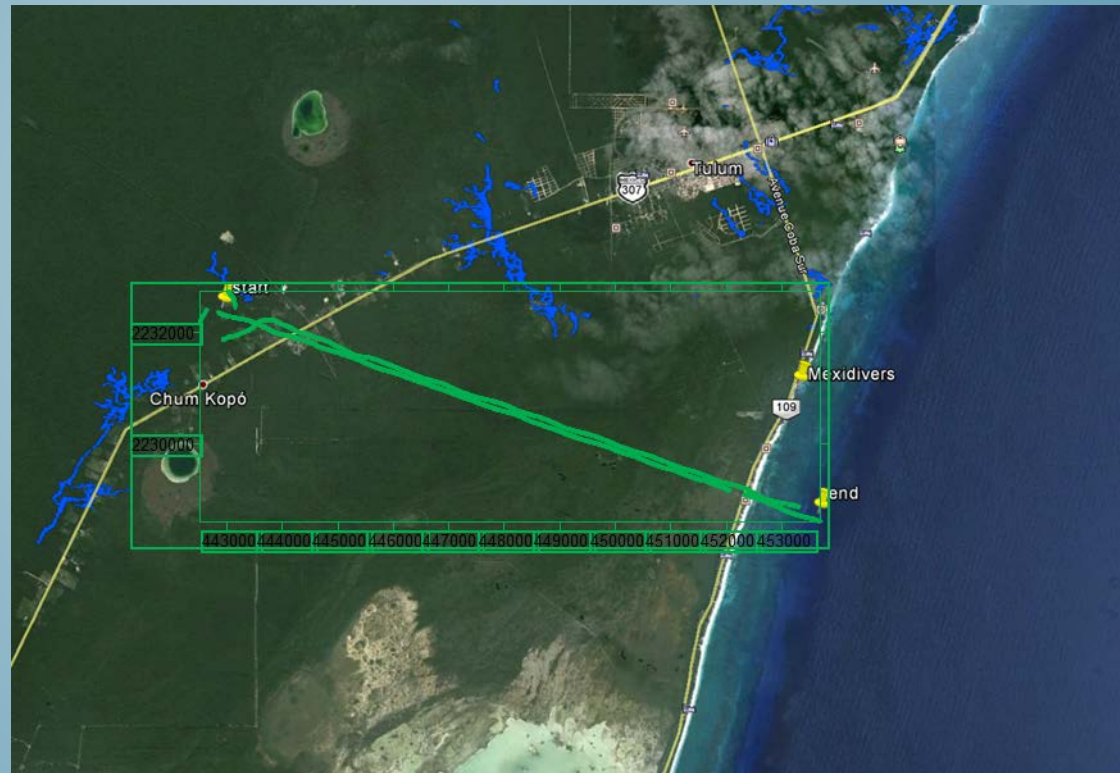


Sections beneath flight lines:

Detection of fresh water
layer, mixture zone and
salt water body



Electrical Conductivity $\text{Log}_{10}[\text{S/m}]$



Line YUK001, 2008-survey

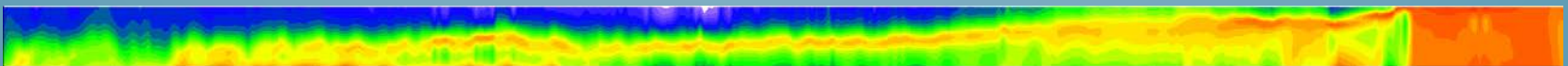
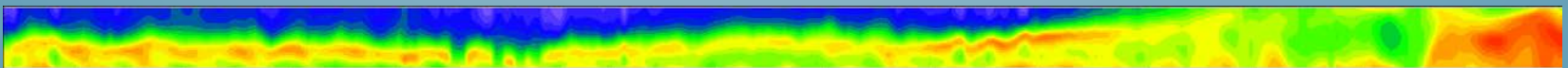
Fresh water layer (blue)

~ 10 km

Low wet land

reef

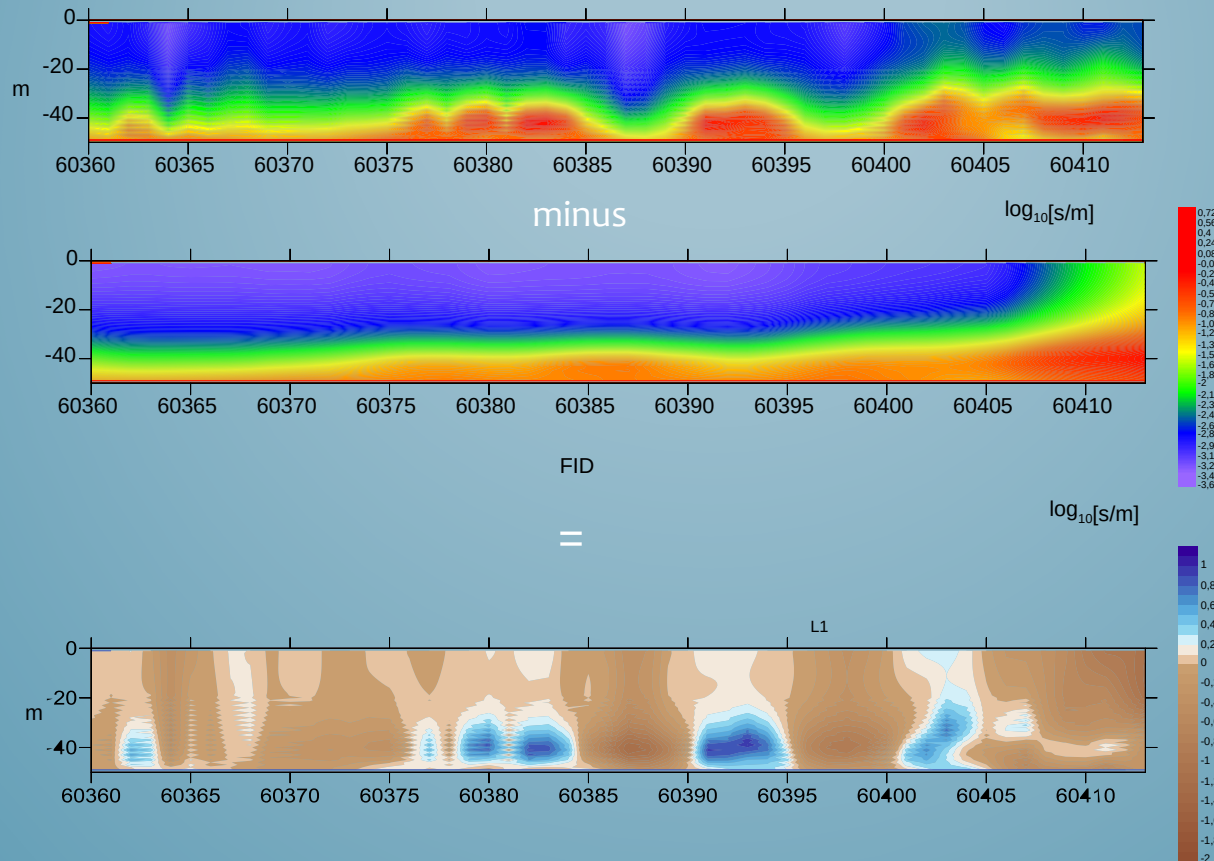
50 m
depth



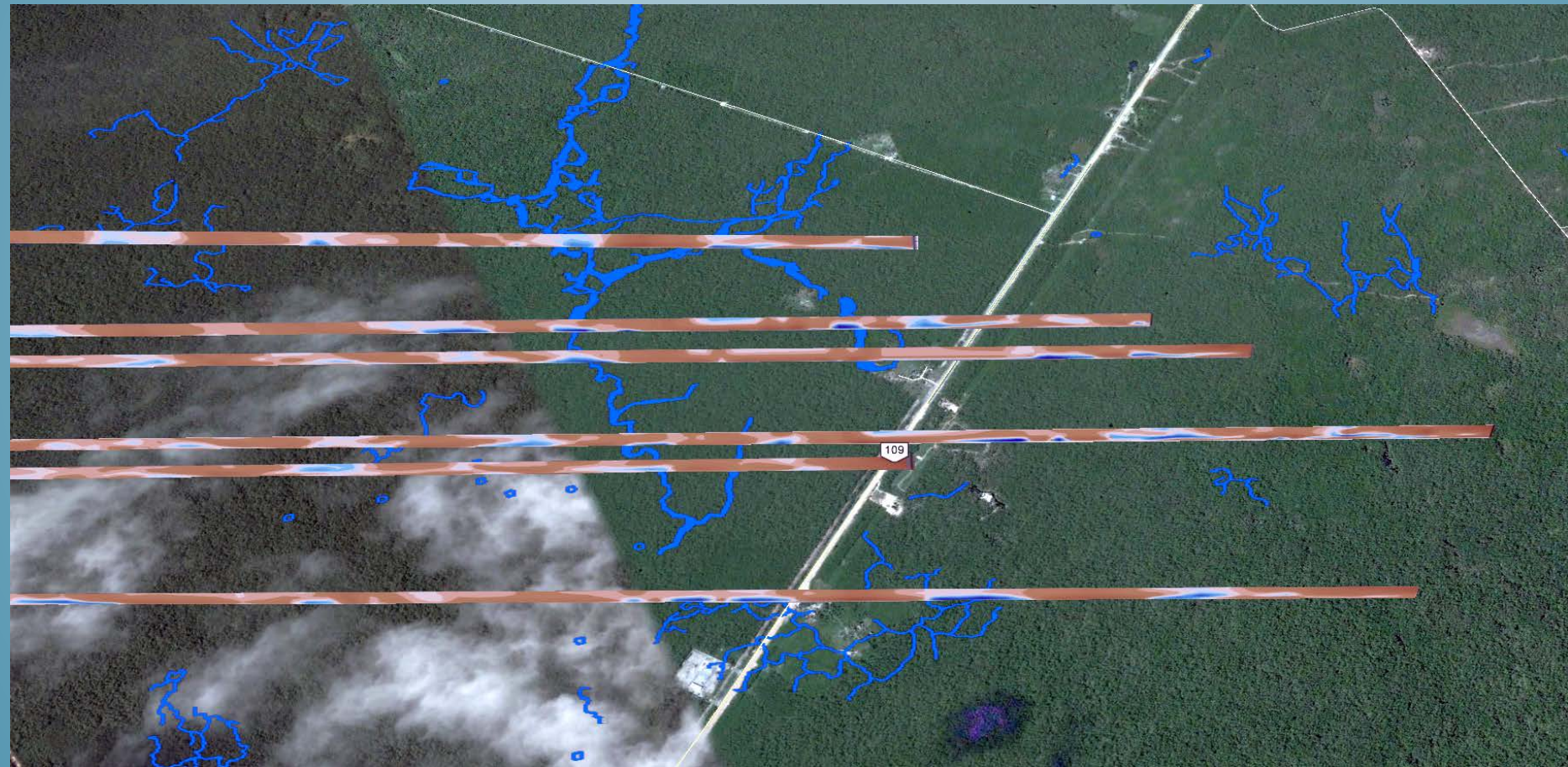
Salt water body (yellow-red)

Where are the caves? – background reduction of strong salt water response in line-inversion results.

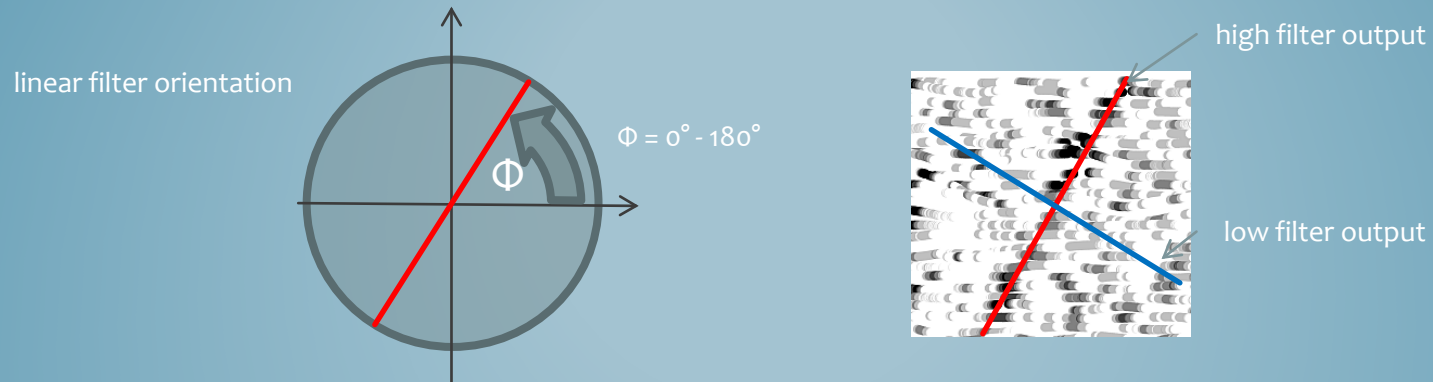
YUL054_detail



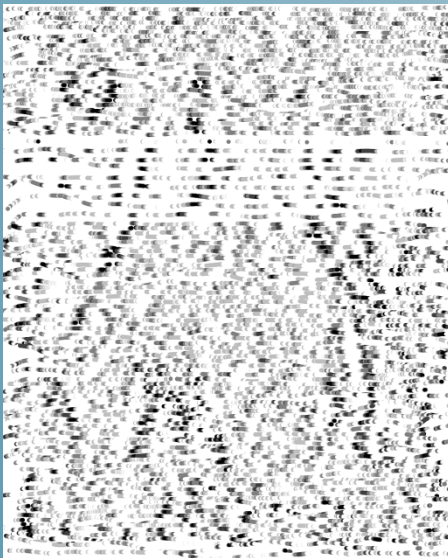
Background reduced sections crossing surveyed cave system



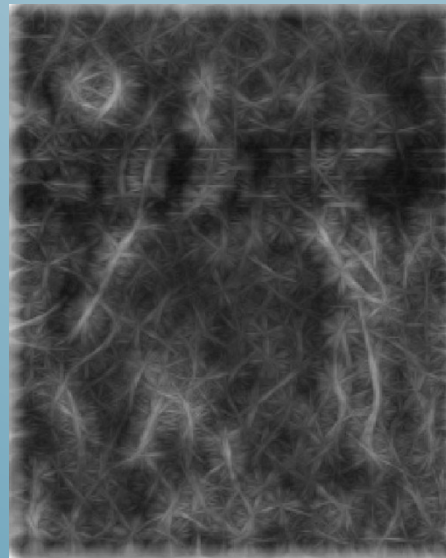
Advanced AEM processing – enhancement of linear structures



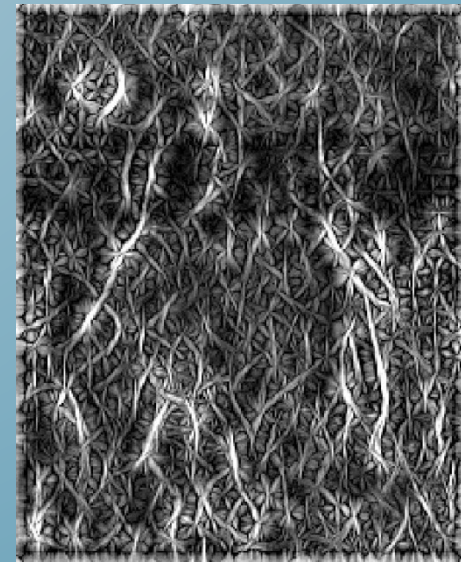
Height reduced and
mean free ppm-signal
(f3_in, part of 2008-survey)



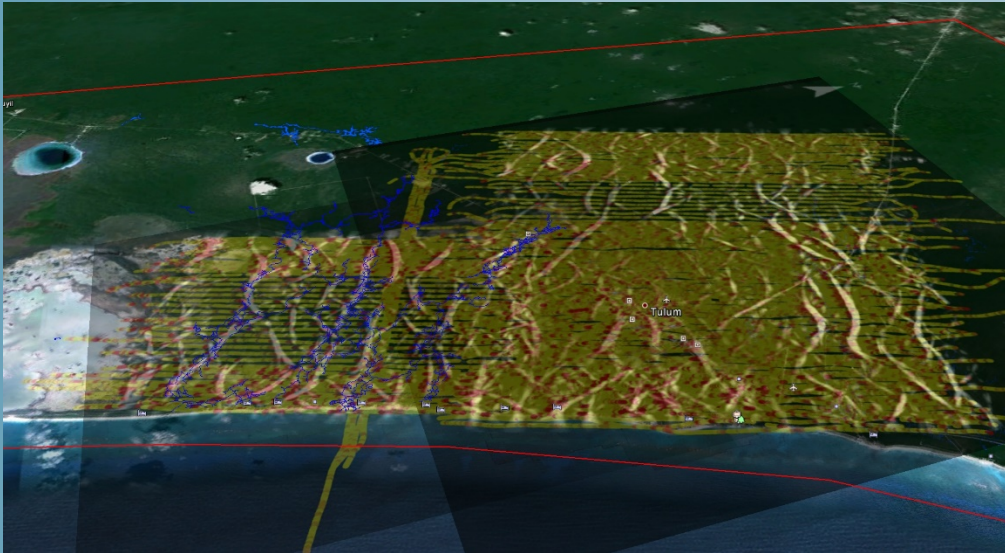
Linear structures enhanced



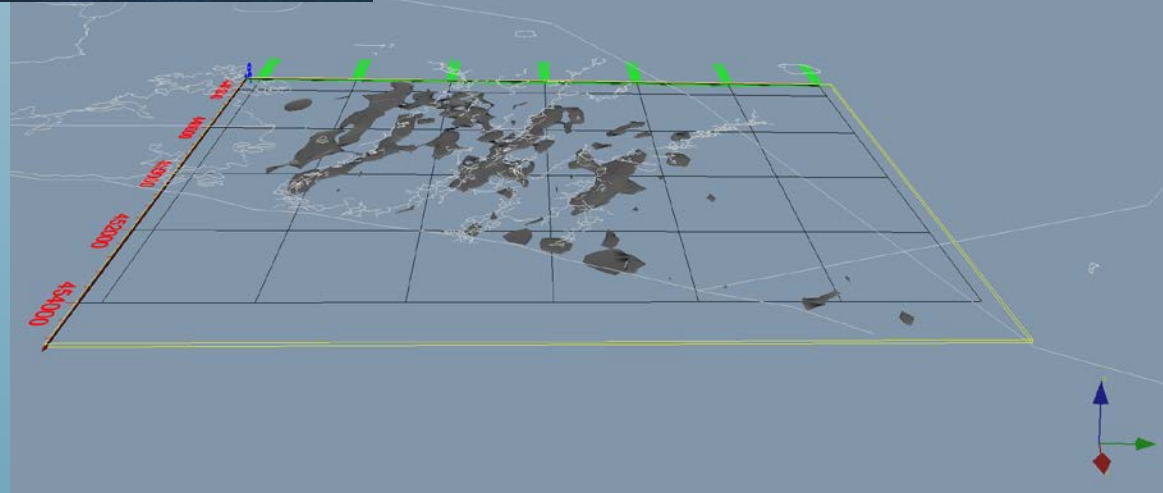
edge filtered

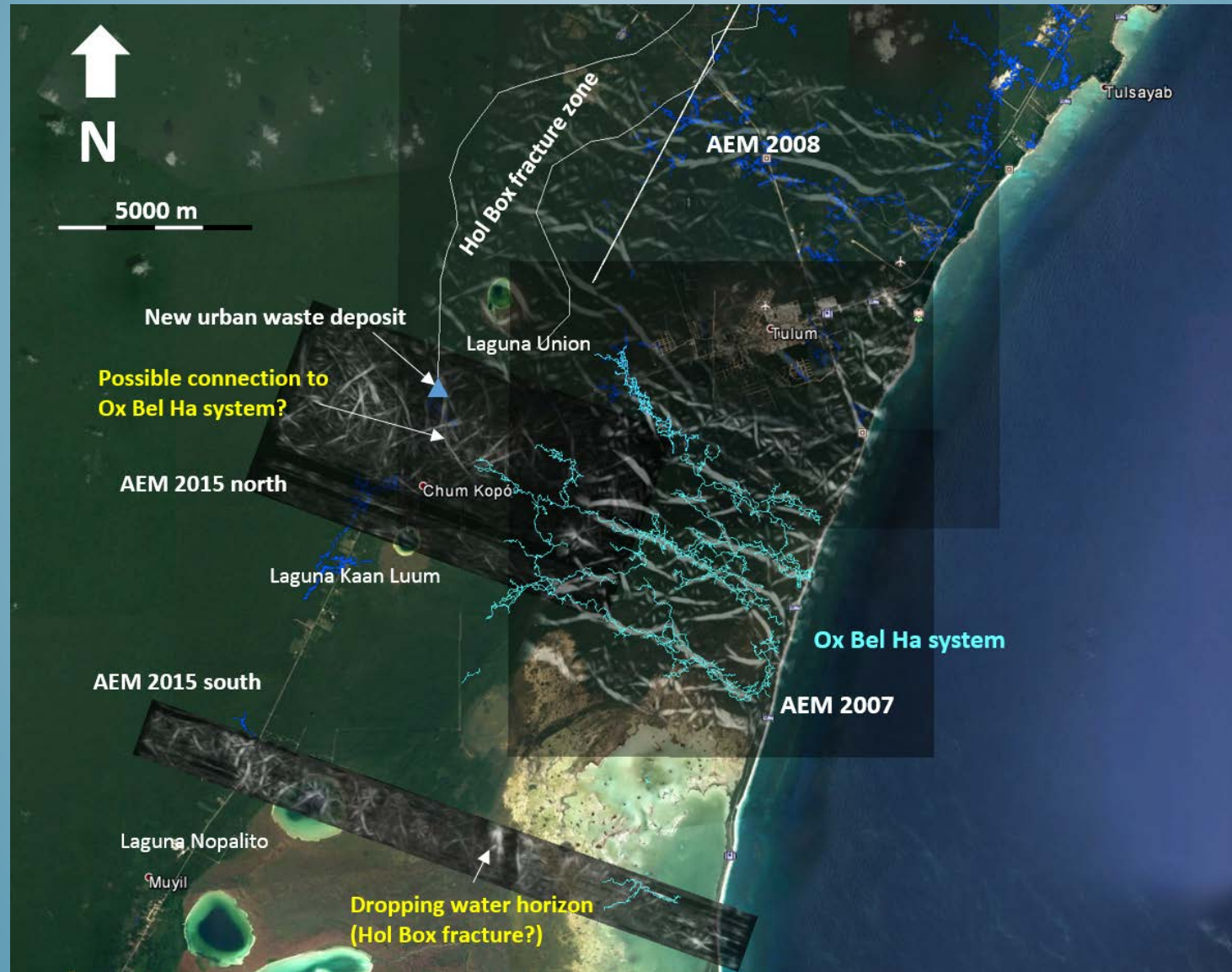


Results: Overview of conduit network (from 2007 and 2008 AEM data)



Left: map of conduits lineament enhanced.
Below: 3d-model el. conductivity indicating
concentration of water.





Project Xibalba/Xib_TCS:

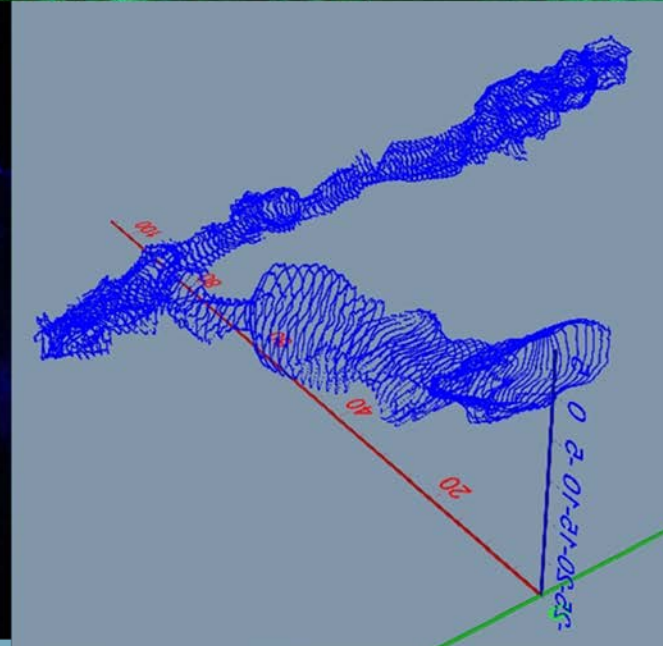
Acquisition of medium scale parameters for hydro-modelling
- 3D geometry laser scanning in underwater karst tunnels



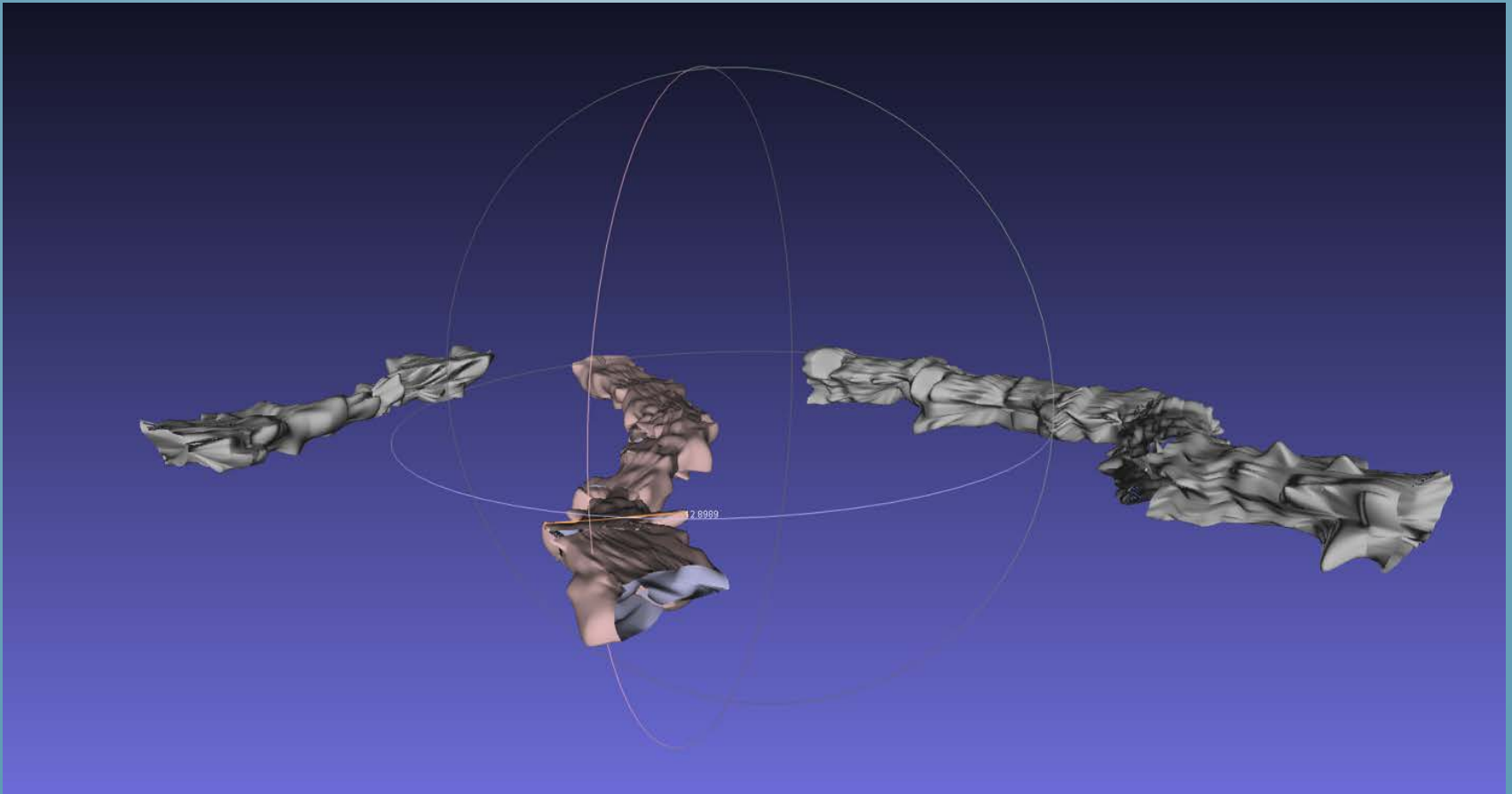
arnulf.schiller@geologie.ac.at

Cenotes





Scans Cenote Cristal, Jailhouse, Tercier Cielo (2015)



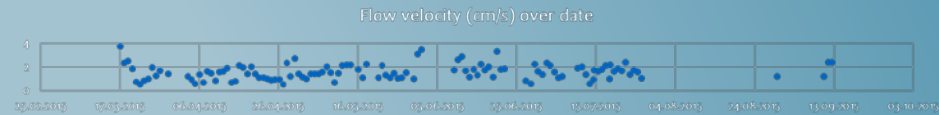
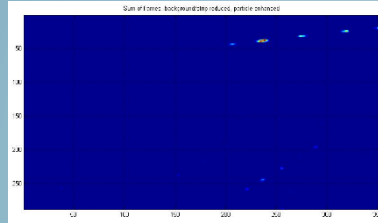
Flux Imager

Flux Imager Jailhouse station

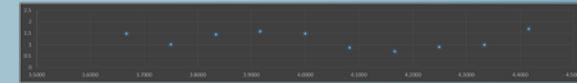
Long term series



$t_1=0.595$



Short term variations – time interval 2 hours



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73

tunnel cross section

levelled aluminium structure

camera

cm/s



measurement area

laser head

total cross section

Flux through area:

Total volumes by: cm^3/s

Trapezoidal Rule: 20160.1

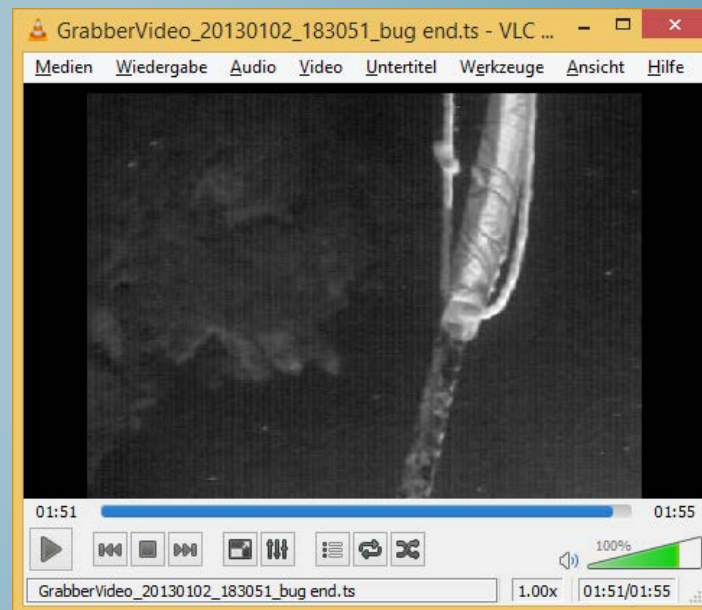
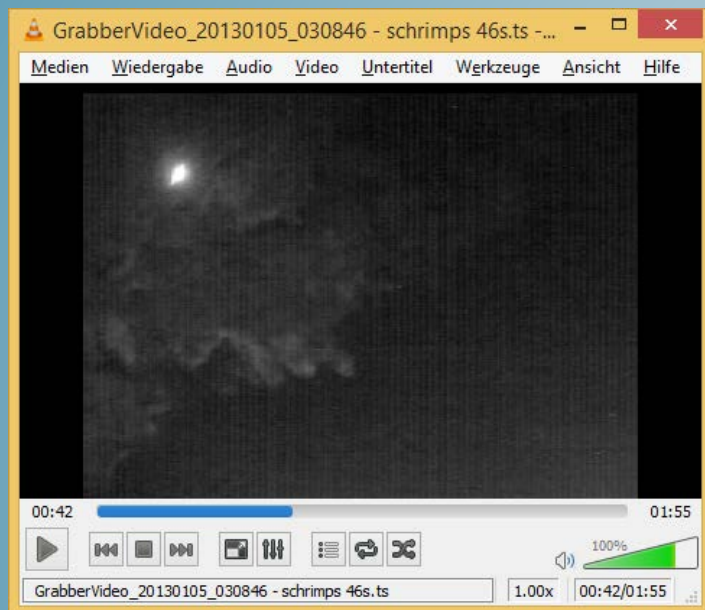
Simpson's Rule: 20133.8

Simpson's 3/8 Rule: 20159.1

Flux: 20.15 liters/s

(extrapolated to whole cross section up to 200l/s)

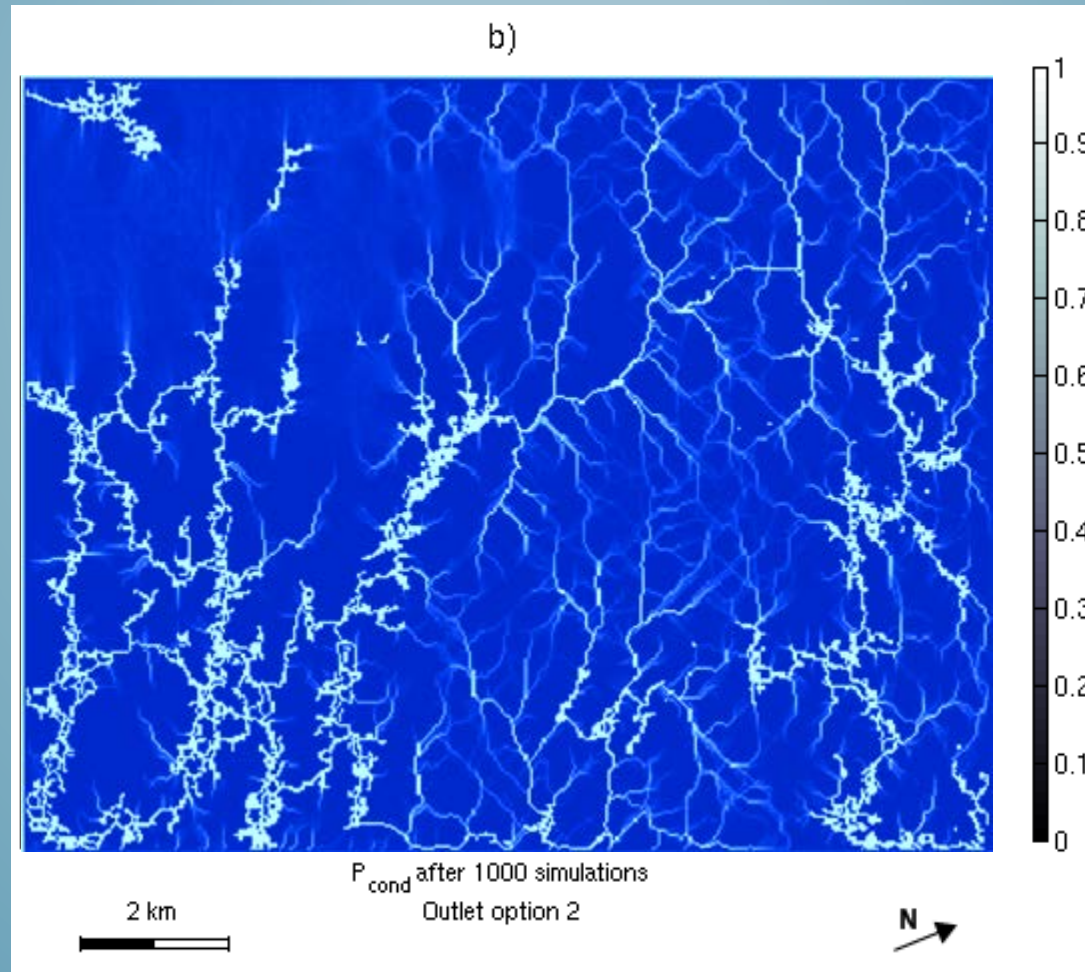
INTERFERING PHENOMENA - STYGIOBIONTS



Right: *Niphargus ictus* (<http://en.wikipedia.org/wiki/Niphargus>)

Left: *Proasellus cavaticus* (<http://www.karstforschung.at/H%F6hlenfauna.htm>).

Hydrological modeling – conduit probability map



Plot from: C Vuilleumier et al. A method for the stochastic modeling of karstic systems accounting for geophysical data: an example of application in the region of Tulum, Yucatan Peninsula (Mexico), Hydrogeology Journal 21 (3)

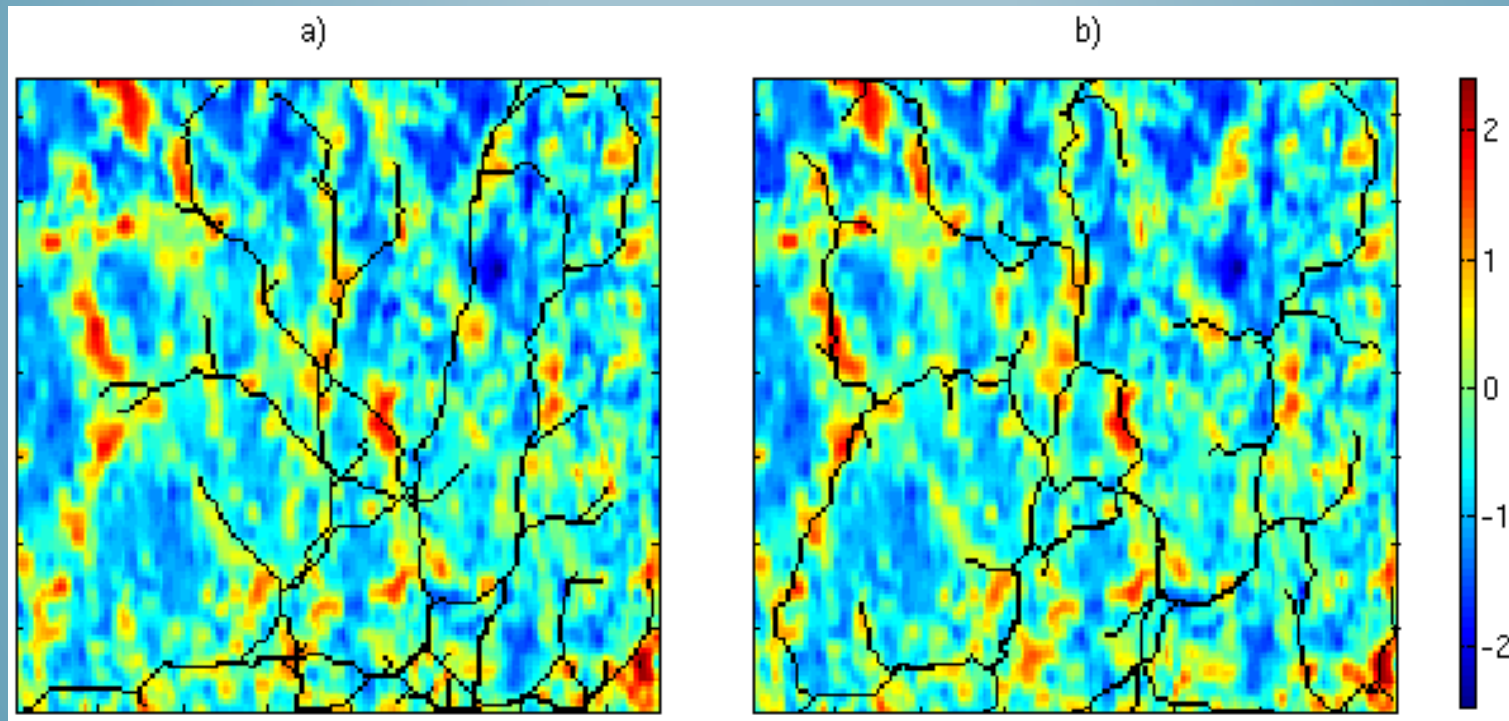
What for? => Input for Hydrological Modeling/Karst Simulator

30/11/2018

Stochastic Modelling Group (Philippe Renard), Center for Hydrogeology and Geothermics, University of Neuchâtel, Switzerland.



Realisations of conduit nets governed by AEM and cave survey data.



Weak weighting of AEM data

Strong weighting of AEM data

Plot from: C Vuilleumier et al. A method for stochastic modeling of karstic systems accounting for geophysical data: an example of application in the region of Tulum, Yucatan Peninsula (Mexico), Hydrogeology Journal 21 (3)

Hydrological modeling – simulation results

30/11/2018

(P. Renard, C. Vuilleumeier, G. Kaeser, University of Neuchatel)

Simulated flow velocities through conduits: 0.03-0.93 m/s.

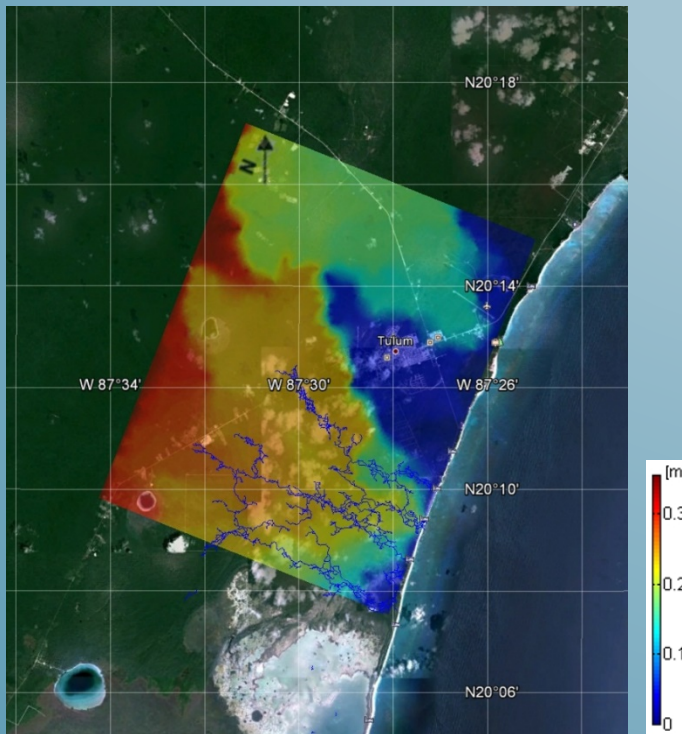
Major part of the flow passes through the conduits.

=> Flow traveltime from Tulum town to the sea 5-15 days.



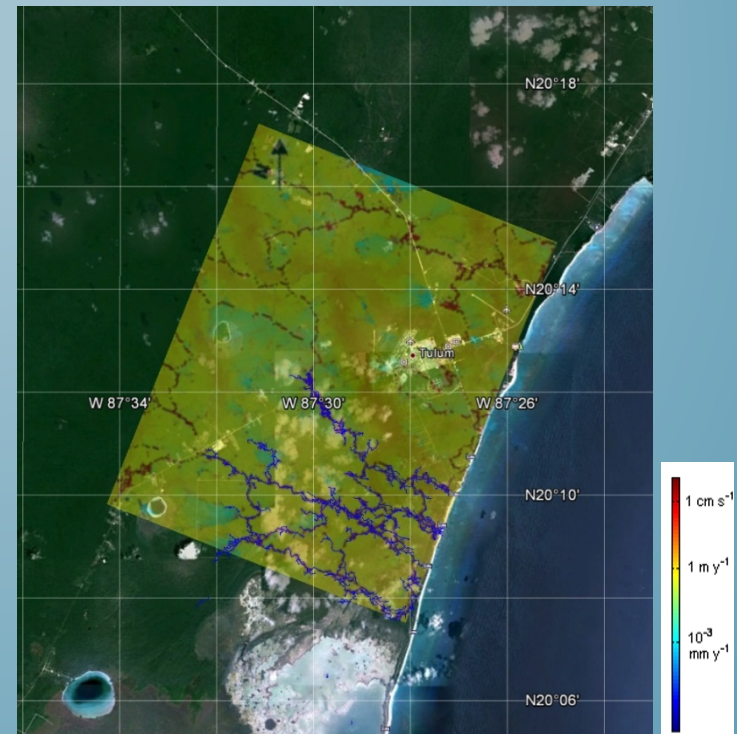
Piezometric map

$h_{\max} = 0.36 \text{ m}$



Velocity map

$v_{\max} = 0.75 \text{ m/s}$



Plots from: C Vuilleumier et al. A method for the stochastic modeling of karstic systems accounting for geophysical data: an example of application in the region of Tulum, Yucatan Peninsula (Mexico), Hydrogeology Journal 21 (3)

Xibalba _ Top Citizen Science



- Citizen supported groundwater monitoring in Tulum
- Add-on to project ,Xibalba' (2013-2017)



Goals

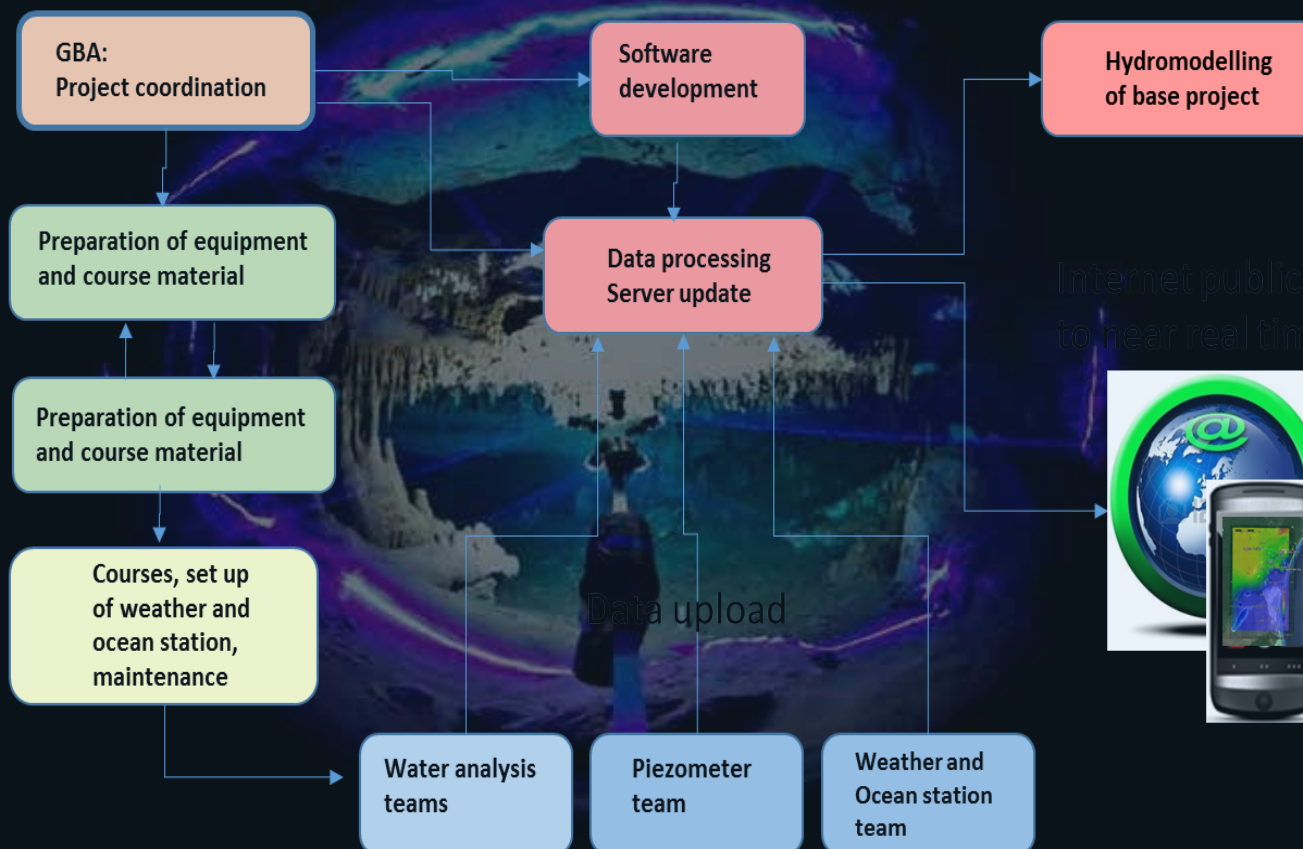
- Monitoring of the Tulum groundwater with the support of citizen science teams 2017-2019
- 20 to 30 selected locations in/around Tulum
- Minimum 1 measurement a week per location, period 1 year
- Parameters: water chemistry (nitrates, CO₂, KH, phosphates, O₂, Mg/Ca), pH, salinity, water levels, velocity data read out, weather stations)
- publication of results on project website www.tulum-water.net
- Increasing public awareness about vital water resource
- Generation of data/information about karst groundwater regime for hydrological model and decision makers

Work Flow

Vienna

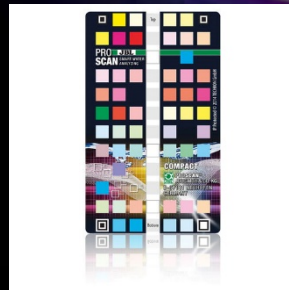
Cancun

Tulum



Methods

- A) Students** – surface water sampling
ProScan strip test on site, temperature, water level, other waterchem. parameters in high school laboratory
- B) Divers** - samples from inside conduits, ProScan on site, laboratory
- C) UNINE/GBA/ASK:** more elaborated kation/anion and E.-Coli analysis, d-GPS, piezometers, flux, weather station, tunnel scanning



Parameters significance :

Water chemistry:

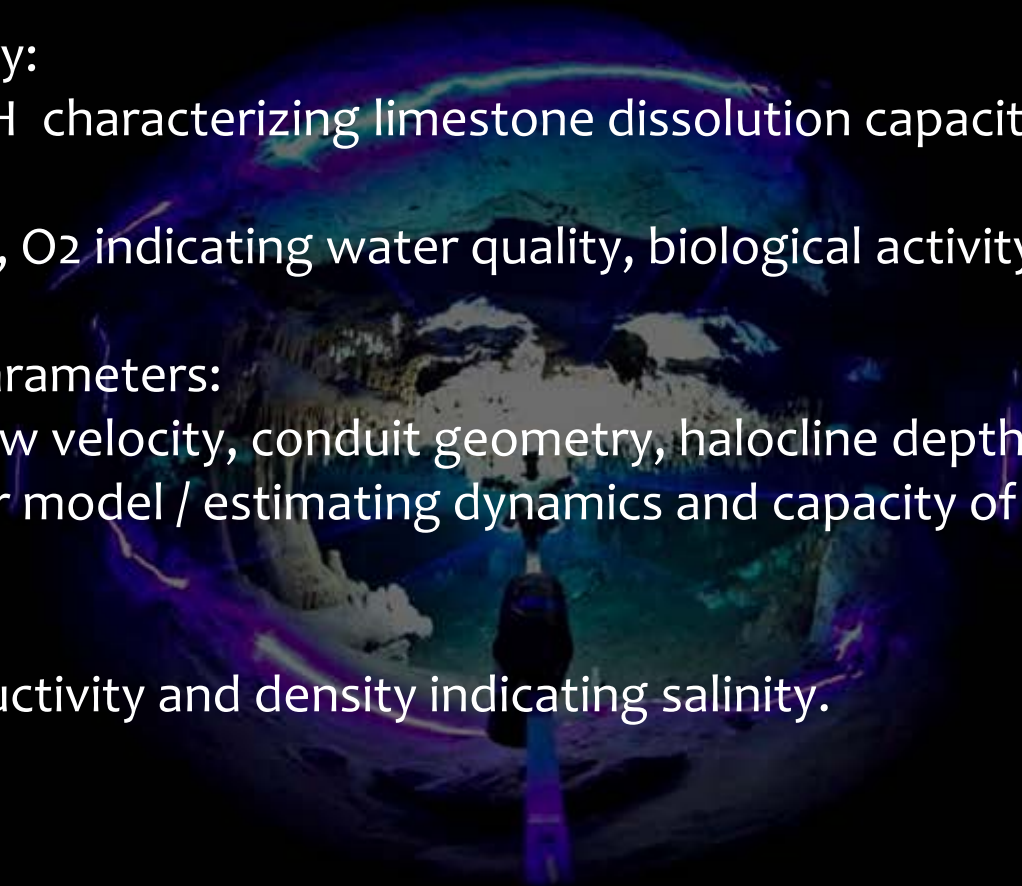
KH, GH, CO₂, pH characterizing limestone dissolution capacity

NO₂, NO₃, PO₄, O₂ indicating water quality, biological activity

Hydrological parameters:

water table, flow velocity, conduit geometry, halocline depth for calibration of groundwater model / estimating dynamics and capacity of ground water regime.

Electrical conductivity and density indicating salinity.

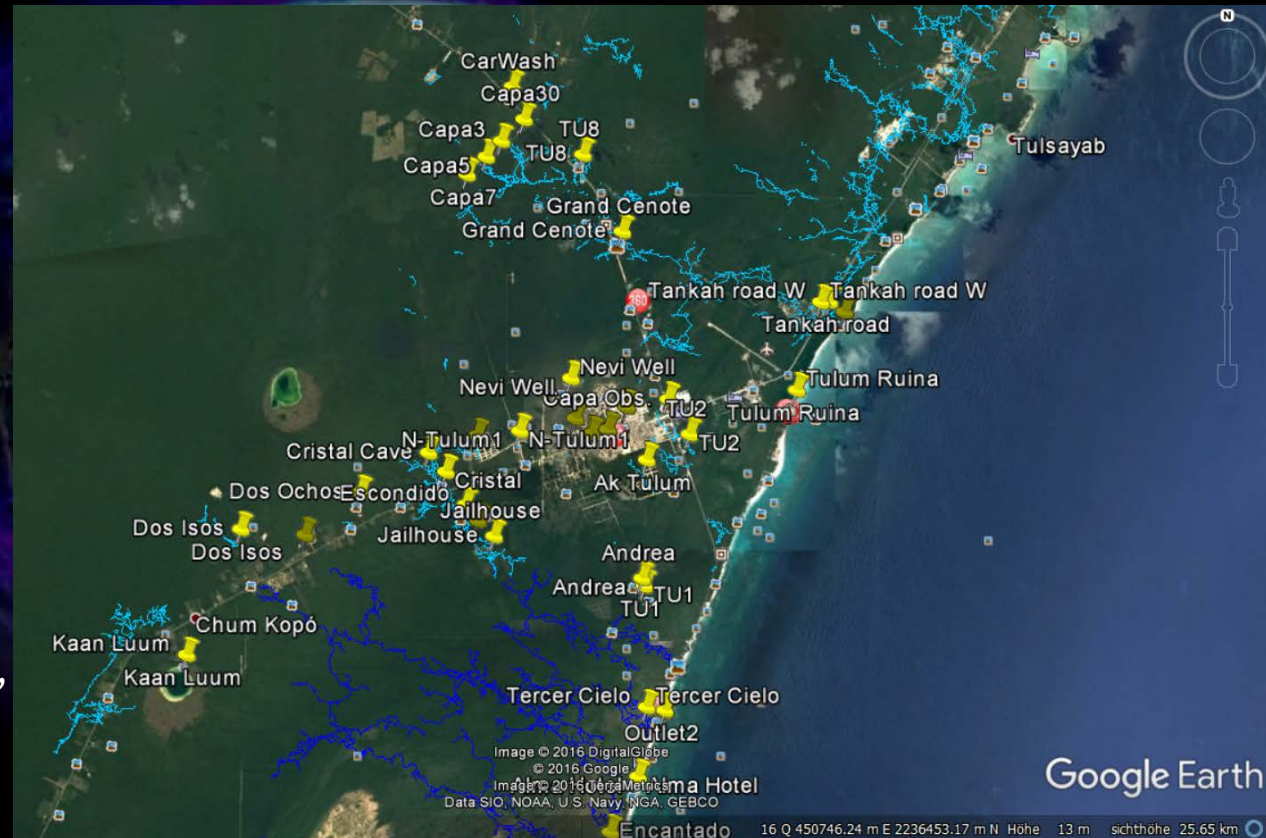


Locations

(UNINE, Xplore/Xibalba, Xib_TCS)

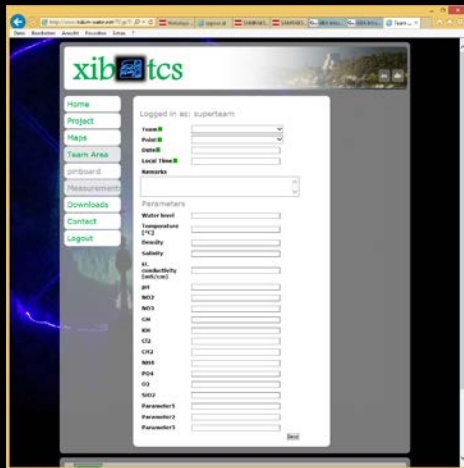


- Wells, cenotes, sea
- Spatial distribution, accessibility
- Integrating and complementing locations of former and on-going projects (continuing time series)
- Sampling surface water or within conduits (by divers)
- Piezometres (incl. ocean station), weather station, flux imaging, d-GPS, tunnel scanning

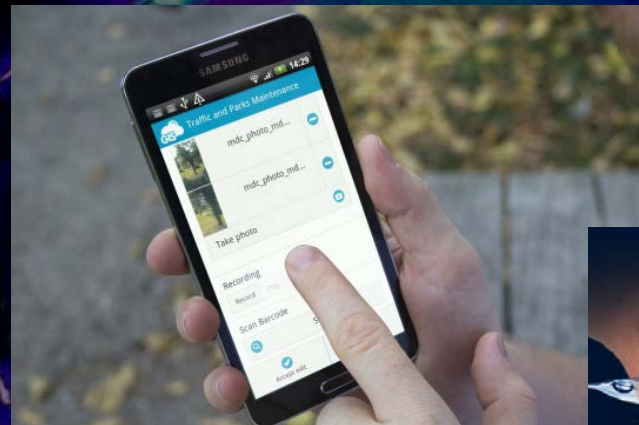


Data input for citizens

via website



Open data kit App - ODK-collect
(android based, open source)



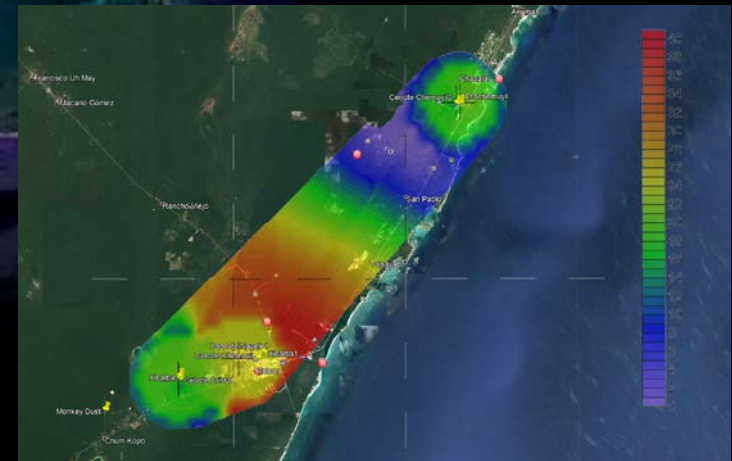
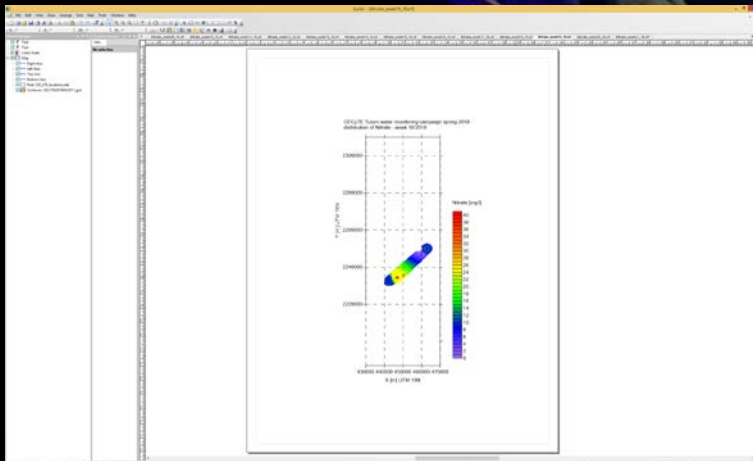
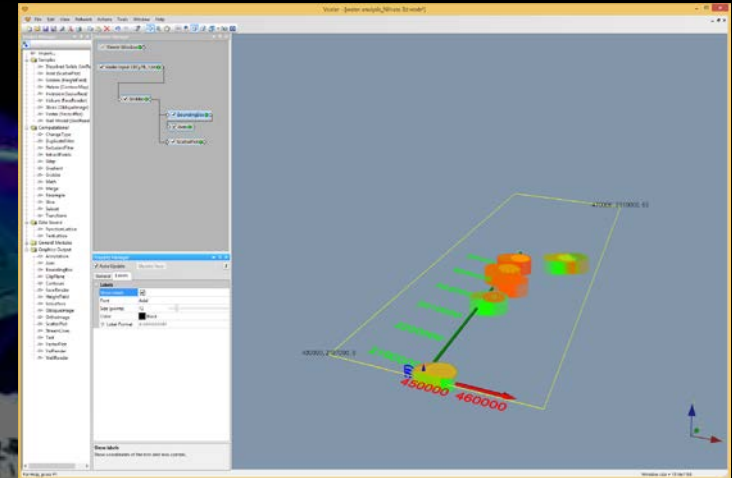
... or directly via
whatsapp



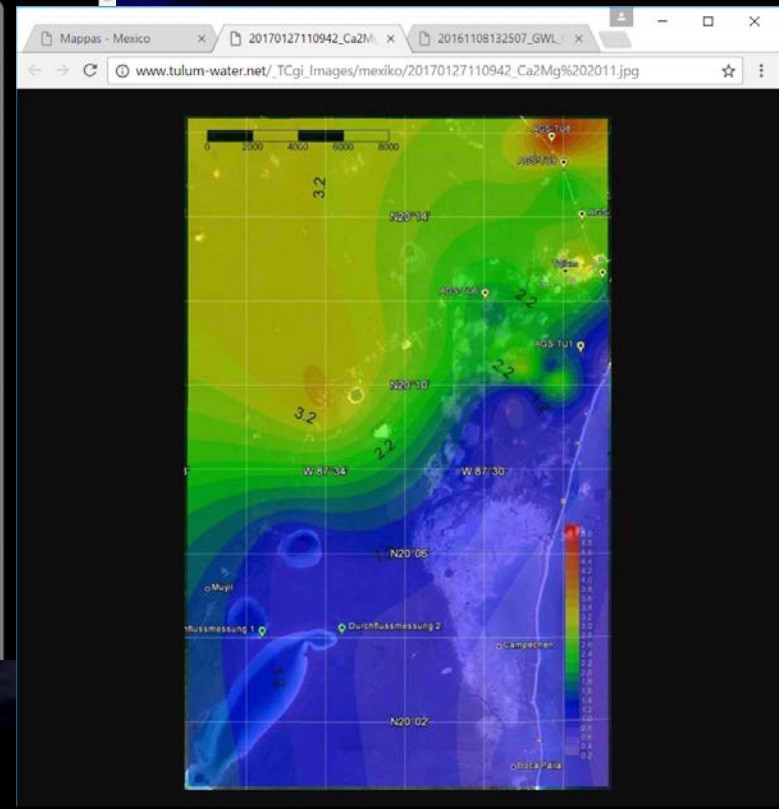
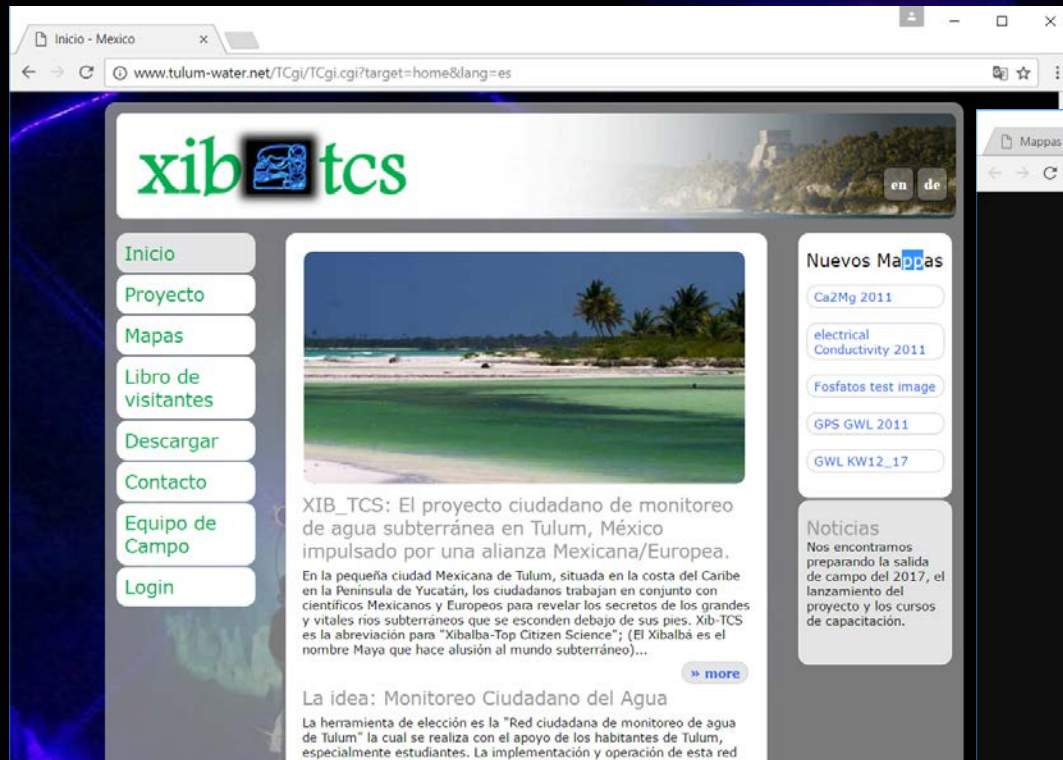
back up on paper

DATA PROCESSING

1. Quality control
2. 3d - time-space interpolation of irregularly distributed data (3d-gridding
Voxler => x,y,t-dataset)
3. Time slices gridding (Surfer)
4. Visualization in GIS



Publication of results on website



Opening Event and Workshops



Tulum water chemistry monitoring in spring 2017



Fig. 1

Fig. 1: The teams equipped with team dresses.

Fig. 2,3: Testing at well

Fig. 4,5,6: The students of the CECyTE Tulum high school at work.



Fig. 2



Fig. 3



Fig. 4

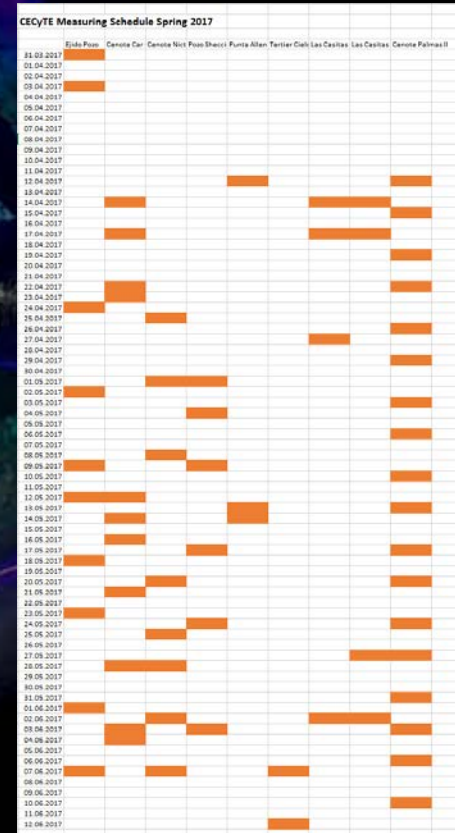


Fig. 5



Fig. 6

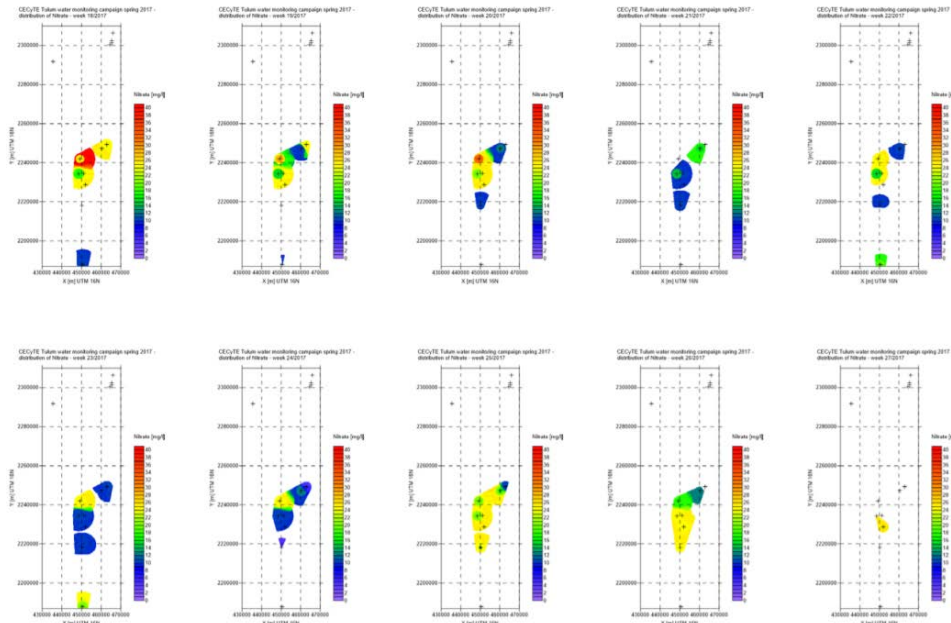
March- July 2017 ; NO₂,NO₃, GH, KH, pH,CL₂, CO₂; 80 measurements at 12 locations; ~ 25 students, 2 teachers, 2 assistants (ASK); surface water samples



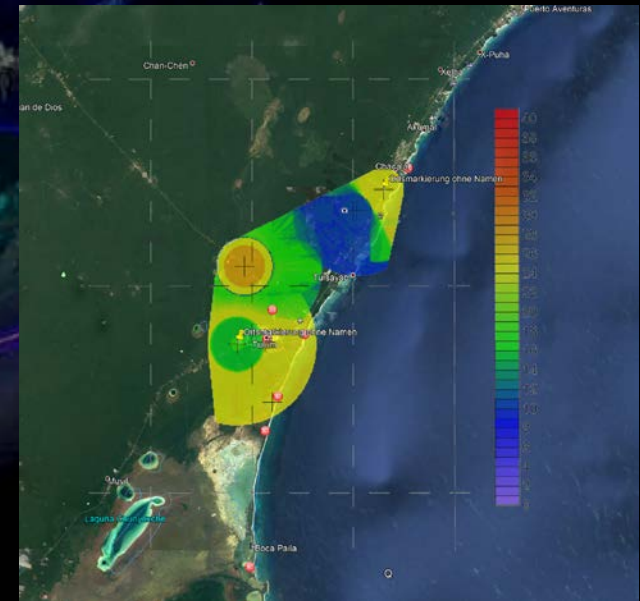
Example: NO₃ – maps 2017

30/11/2018
xib  tcs

CECyTE Tulum March-July 2017: Distribution of Nitrate



Above: Week 18-27. Right: Week 19 detail



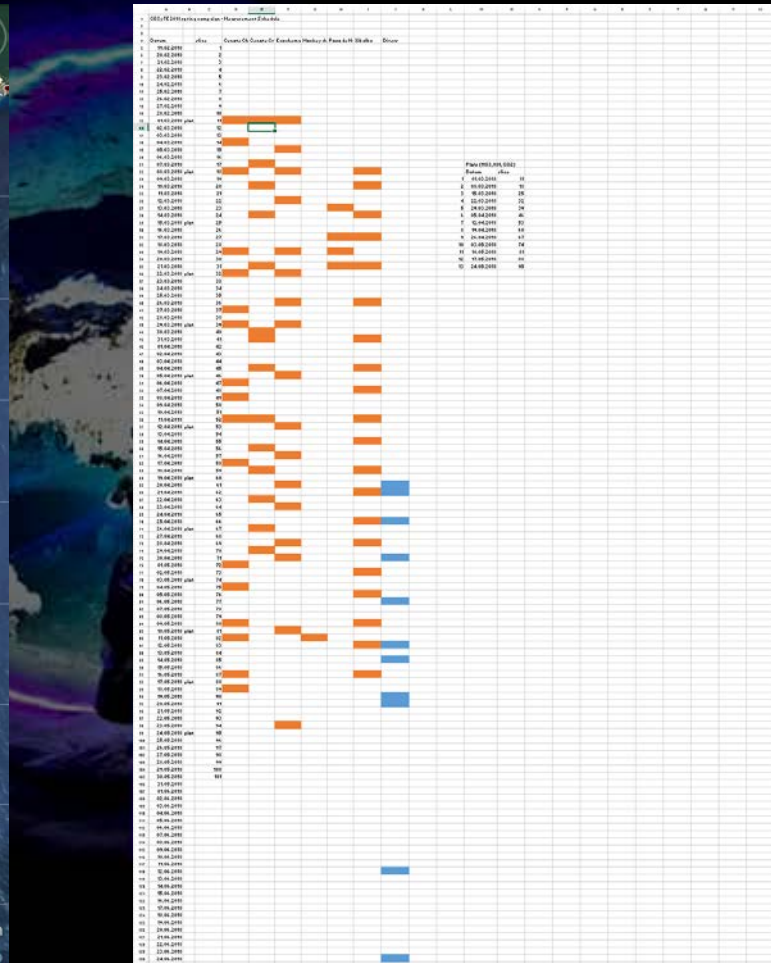
Citizen Science Campaign Spring 2018

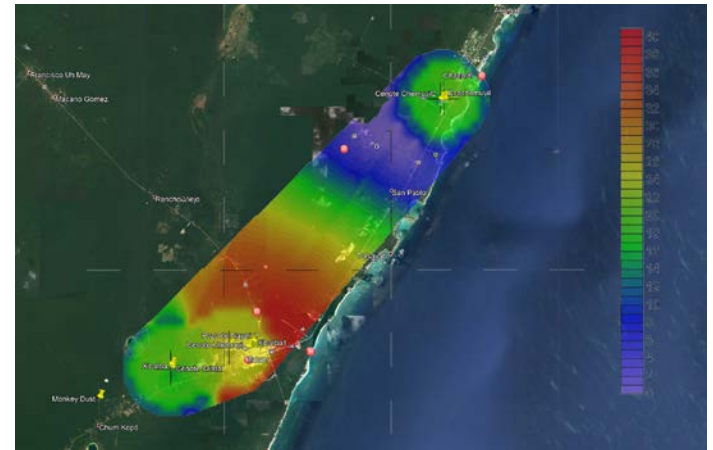
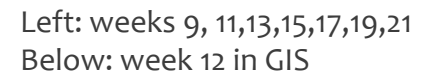
30/11/2018 30/11/2018
8

March 1st –May 23rd, ~30 pupils, 2 teachers, 3 divers, 2 assistants of ASK

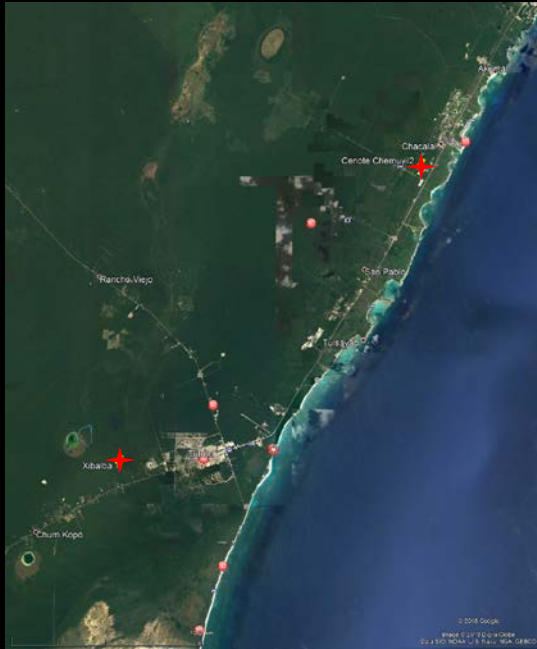
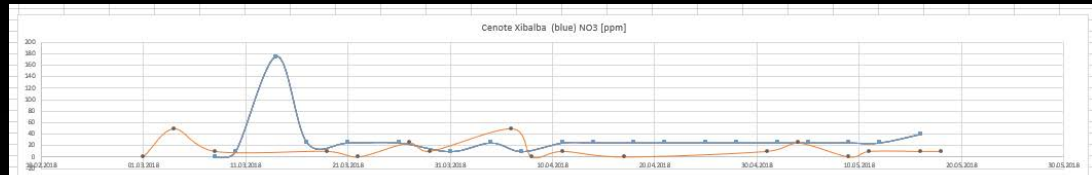
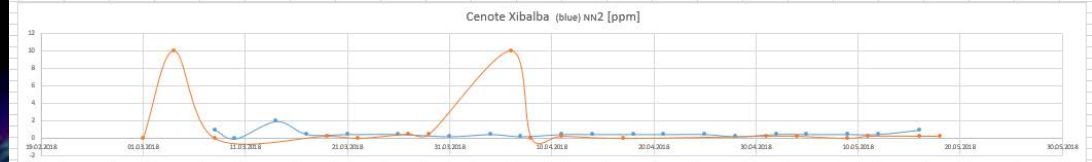
Spatial distribution (16 locations)

Temporal distribution distribution (98 measurements)

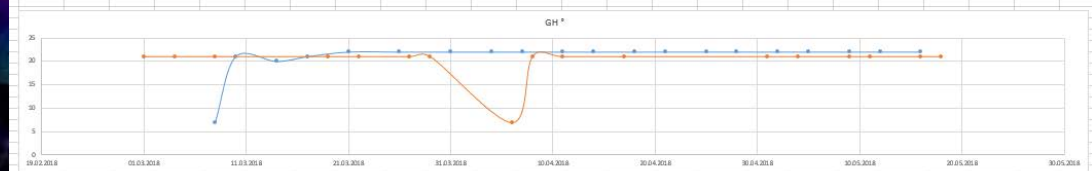




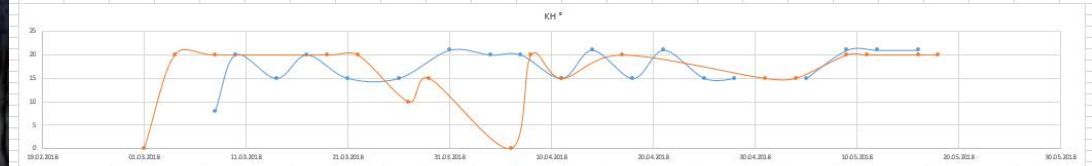
Time series: Comparison Cenotes
Xibalba (north, blue)
Chemuyil (south, orange)
8.3. – 16.5. 2018

NO₃NO₂

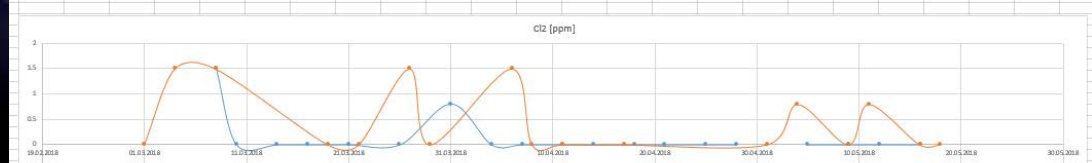
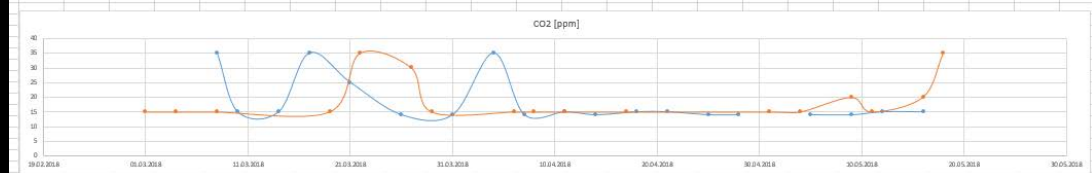
GH

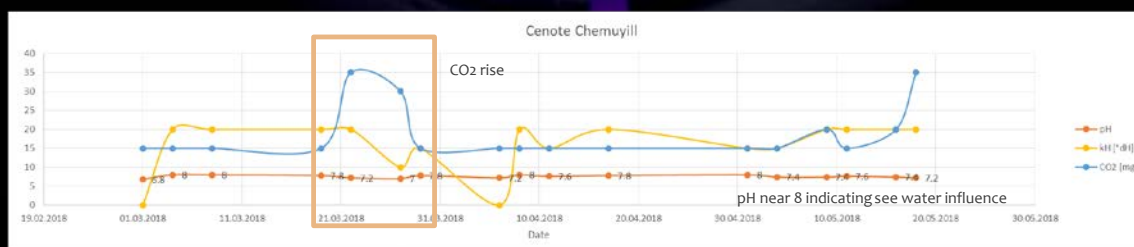
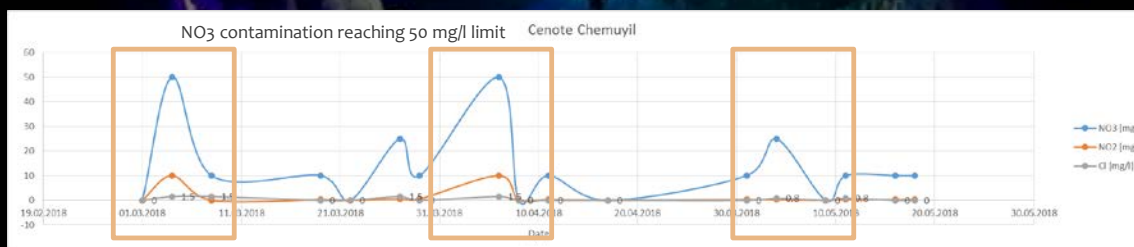
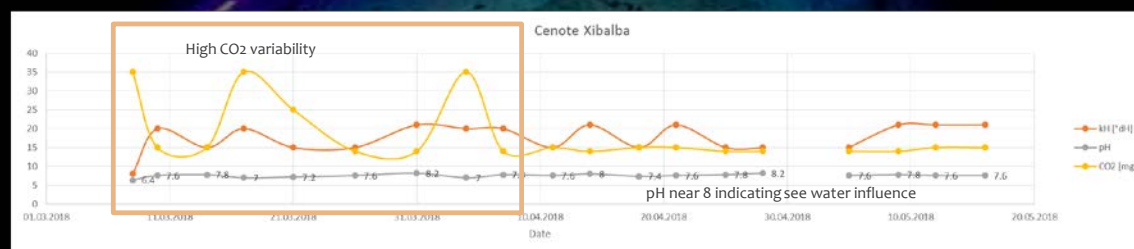
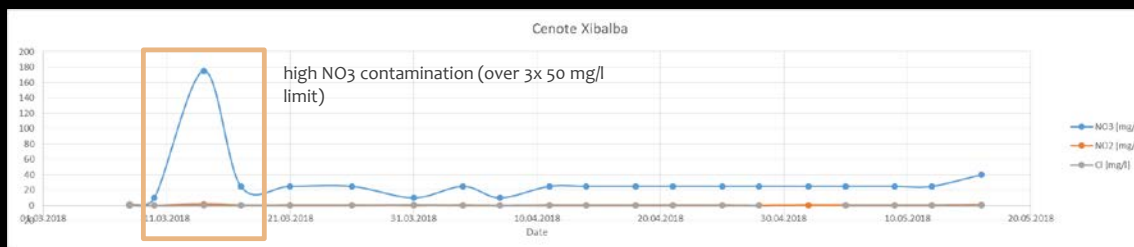


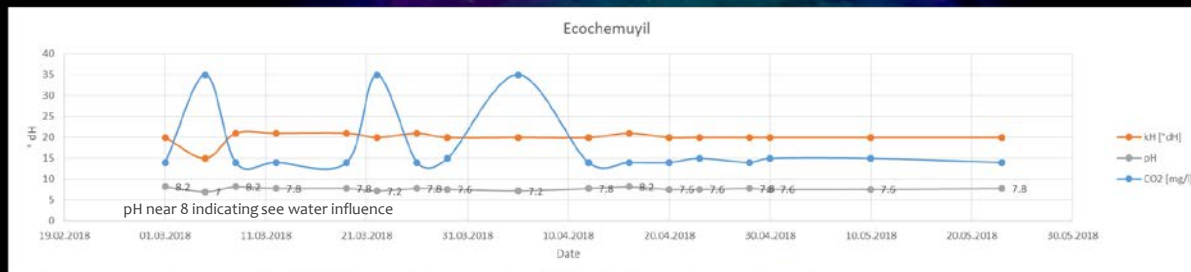
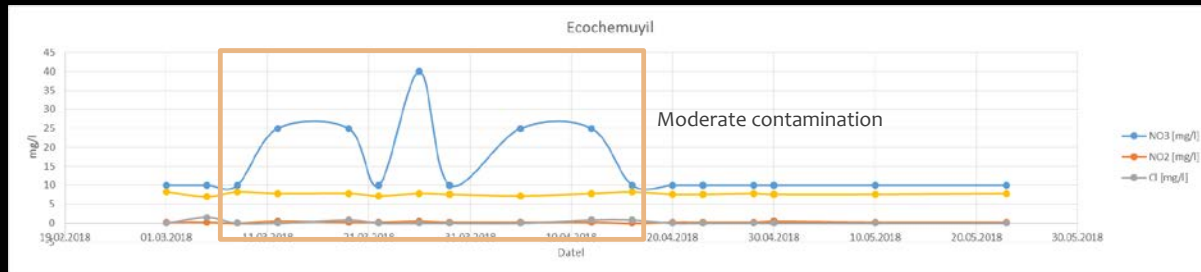
KH

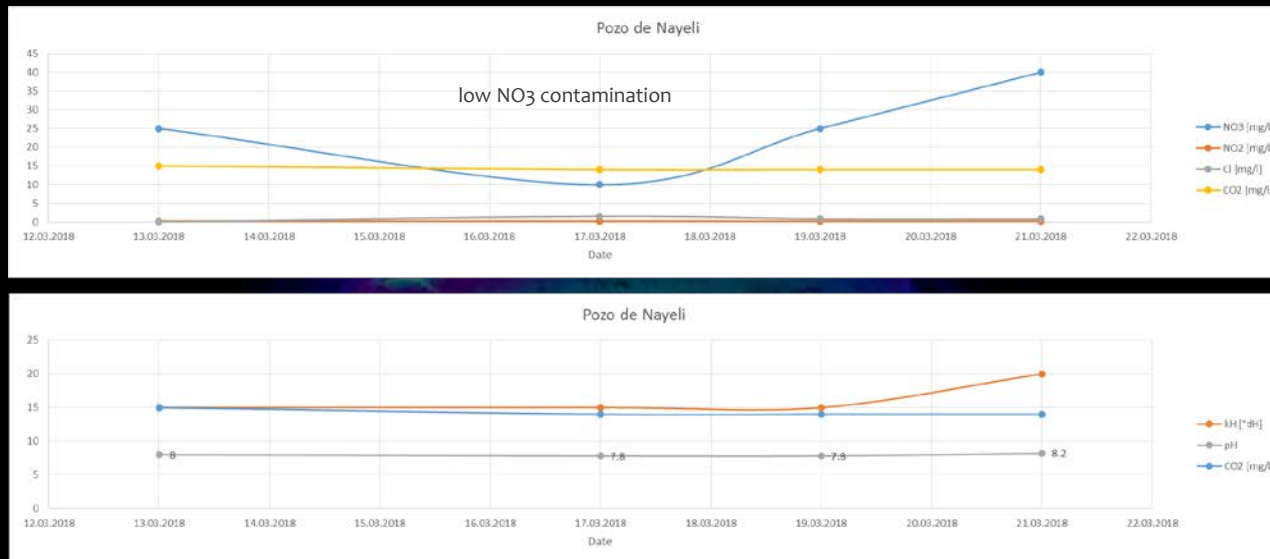


pH

Cl₂CO₂



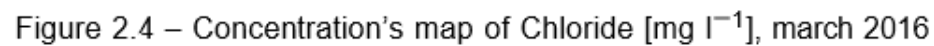




Interpretation spring campaign 2018:

- temporally moderate to high NO₃-contamination in Cenotes Xibalba, Chemuyil, Cristal
- Simultaneous Cl₂-rise indicates water originating from public water supply => waste water input, NO₃ rise without Cl₂ rise indicates direct input of organic matter.
- Pozo de Nayeli: Higher pH => salt water influence.
- pH temporally also high at other locations which may also be a consequence of saltwater presence.
- High CO₂ variation at locations Xibalba and Chemuyil, constant CO₂ at Ecochemuyil and Cristal – reasons to be analysed.

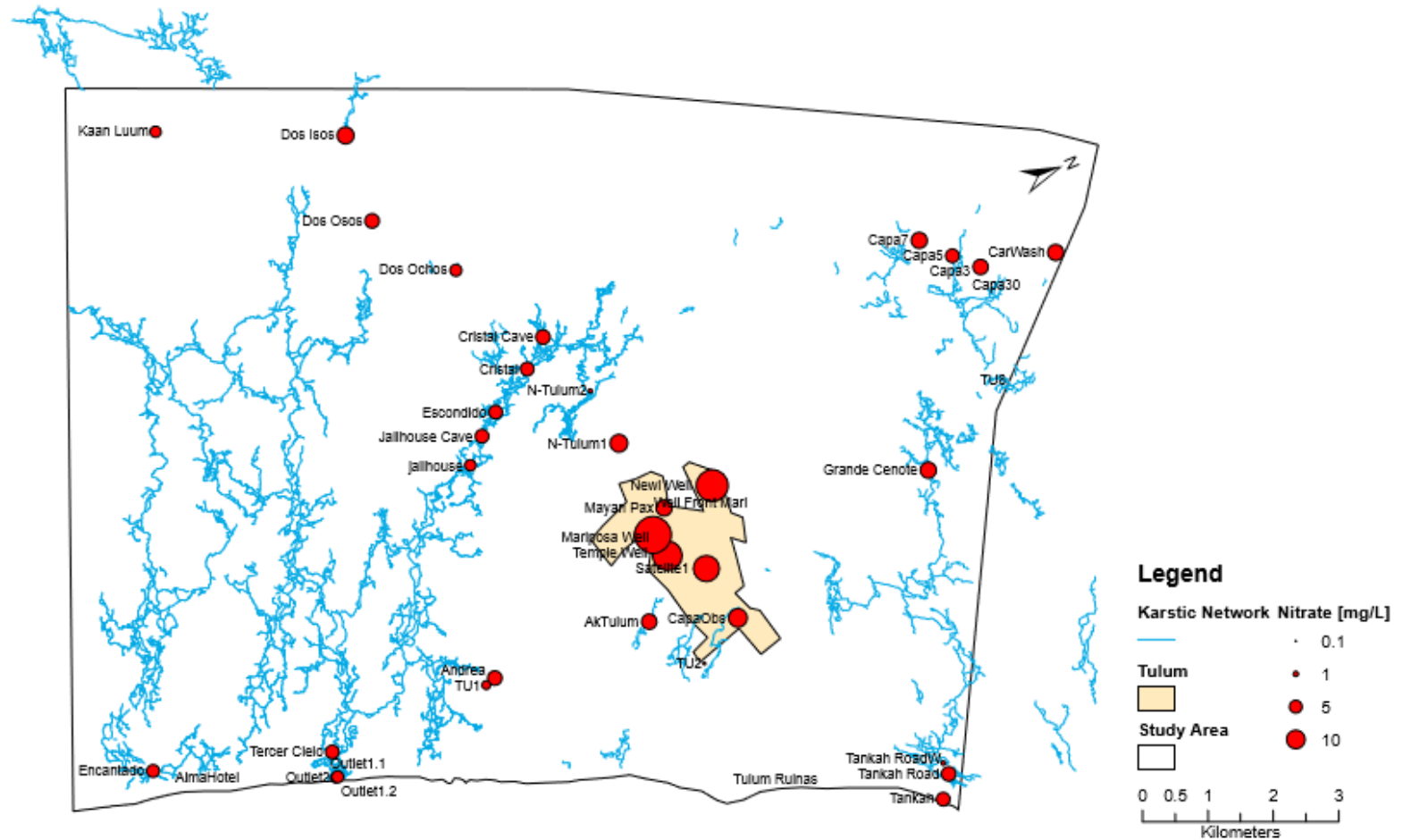
(from Kaeser, 2016, Saint-Loup et al., 2018)



WATER ANALYSIS - UNINE

(from Kaeser, 2016, Saint-Loup et al., 2018)

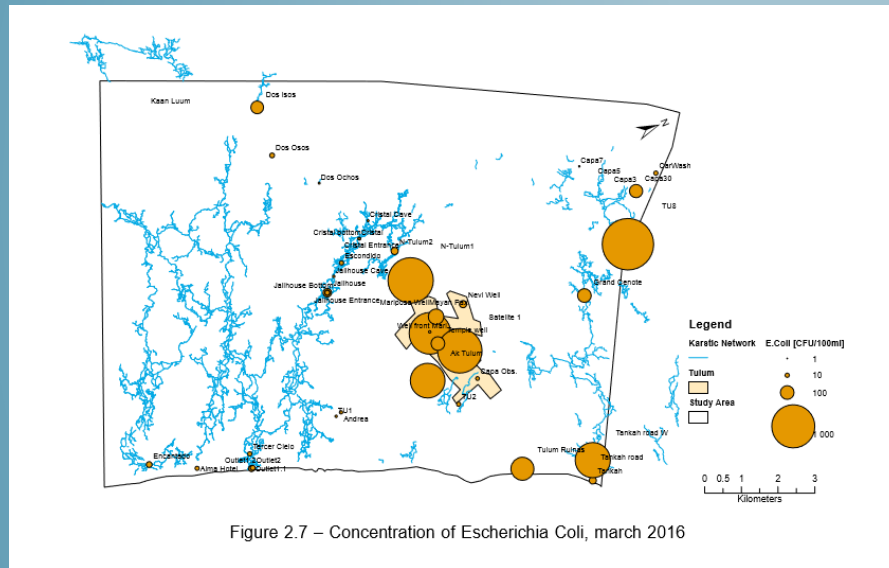
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WATER ANALYSIS - UNINE

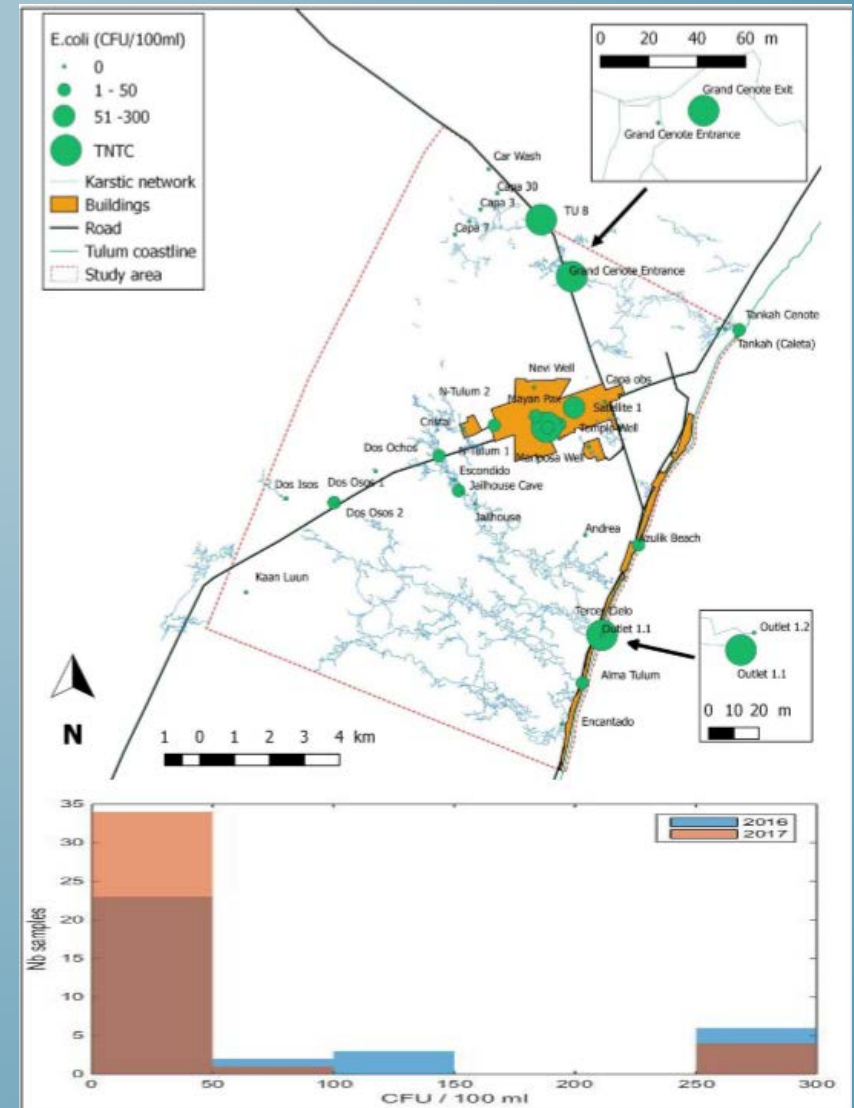
(from Kaeser, 2016, Saint-Loup et al., 2018)

Escherichia Coli 2016, 2017



References:

Kaeser Gregory: *Groundwater Flow and Solute Transport Modeling in the Karst System Ox Bel Ha, Tulum (Mex)*. Diploma Thesis, University of Neuchatel (2016)
 Renaud, Saint-Loup, Théo, Felix, Axaycatl, Maqueda, Arnulf, Schiller, Philippe, Renard, A survey of groundwater quality in Tulum region, Yucatan Peninsula, Mexico, Environmental Earth Sciences (2018) 77:644, <https://doi.org/10.1007/s12665-018-7747-1>



Citizen Science –Summary of experience:

- Xib_TCS = test of a new method (,complex sensor network‘, capturing dynamics)
- Reaching citizen scientists (Internet↓, direct contact, events, schools↑)
- Significant organizational and social effort (local mobilizer, cont. support)
- Data quality control
- Feed back (communicating significance of results, successes, problems,...)
- Transmission/publication of data and results considering stakeholders => sensitive (population, tourism, community, education, preservation of nature and culture)
- Slow start but interest and problem awarress accelerating (schools are doors to community, CS projects need ,warm up‘)
- High potential in optimizing integration of classic, automatic and citizen science monitoring

Future challenges for Tulum Karst research

Combining **classic** and **automatic monitoring network** with **citizen science monitoring** => improved spatial and temporal distribution for capturing dynamics.

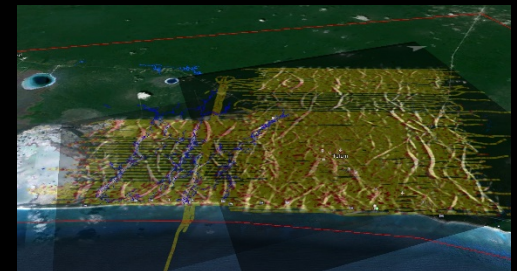
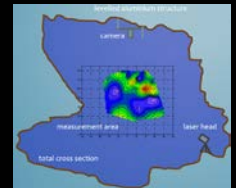
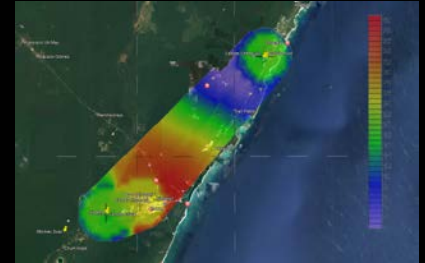
Inclusion of the **barrier reef** (modeling pollution spreading from conduit network to reef, deeper conduit network)

ROV-conduit geometry measurement - 3d scanning of smaller caves and deeper cave system horizons for extending conduit model

Low velocity water flow sensor network based upon laser sensor technology for capturing slow but significant flow (turbulence analysis)

Numerical 3d model addressing climate induced varying fresh/saltwater levels affecting Tulum population and ecosystem.

Further airborne AEM-survey (filling gaps)?



CONCLUSION

Aero-geophysics and ground measurements can image underground water systems and provide significant information for water management

Stochastic Karst network modeling delivers realistic estimation for karst structure, fresh water capacity and pollutant transport.

New instrumental and Citizen Science methods are in the state of introduction and show big potential for extended monitoring.

Tulum Karst ground water regime could evolve to one of the best studied in the world enabling sustainable water management preserving water quality, controlling urban development, and preparing citizens, culture and nature for consequences of climate change.

Gracias!

