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43rd IAH congress

# Assessments of groundwater recharge in the hyperarid Tarapaca alluvial fan (Northern Chile) at various scales of time and space


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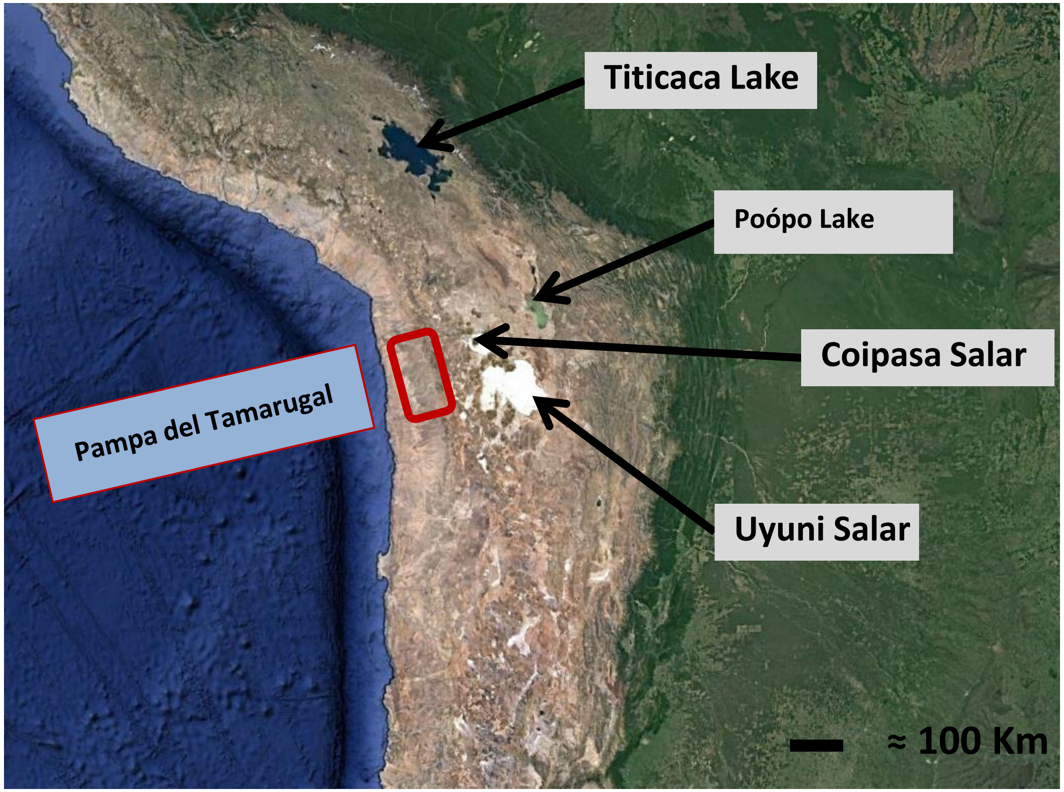
# Location of the study area

- South America, north of Atacama Desert
- Central depression of Northern Chile
- Pampa del Tamarugal: endorheic depression (~ 1000 m asl)

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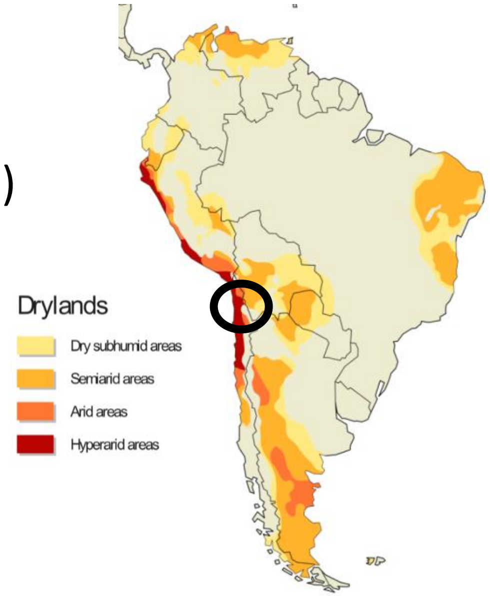
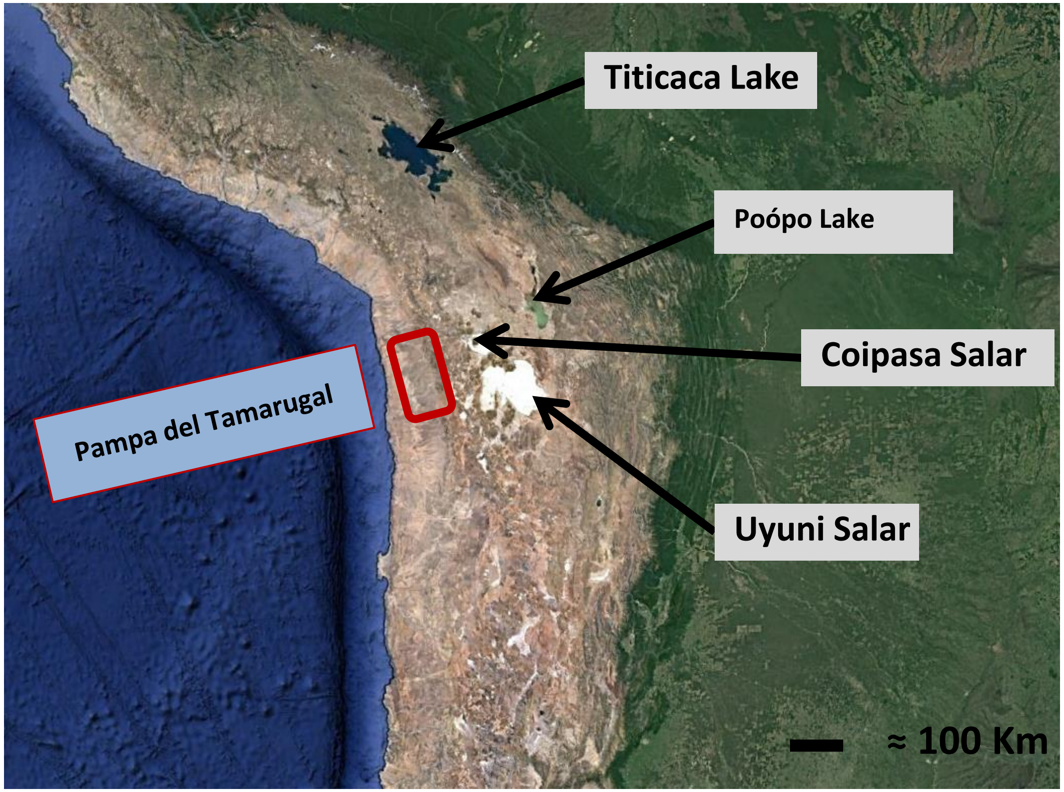
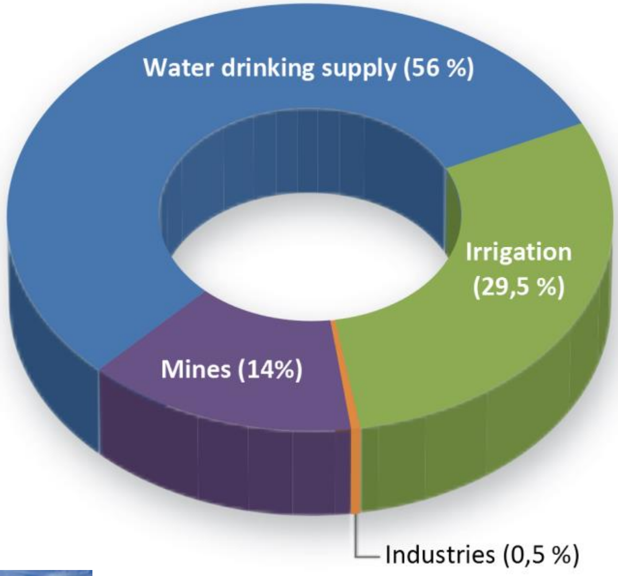



- Rainfall ~ 0 mm/year in Pampa del Tamarugal and < 2000 m asl
- Evapotranspiration ~ 2000 mm/year
- Precipitations up to 250 mm in the precordillera (> 3000m asl)

# Water Demand in Northern Chile

- Mainly covered by the extraction of groundwater from regional-scale aquifers
  → **Pampa del Tamarugal Aquifer** (present day water demand > 130 $Mm^3.year^{-1}$)




Water rights
*(Lictevout et al., 2013, modified)*

# Water Demand in Northern Chile

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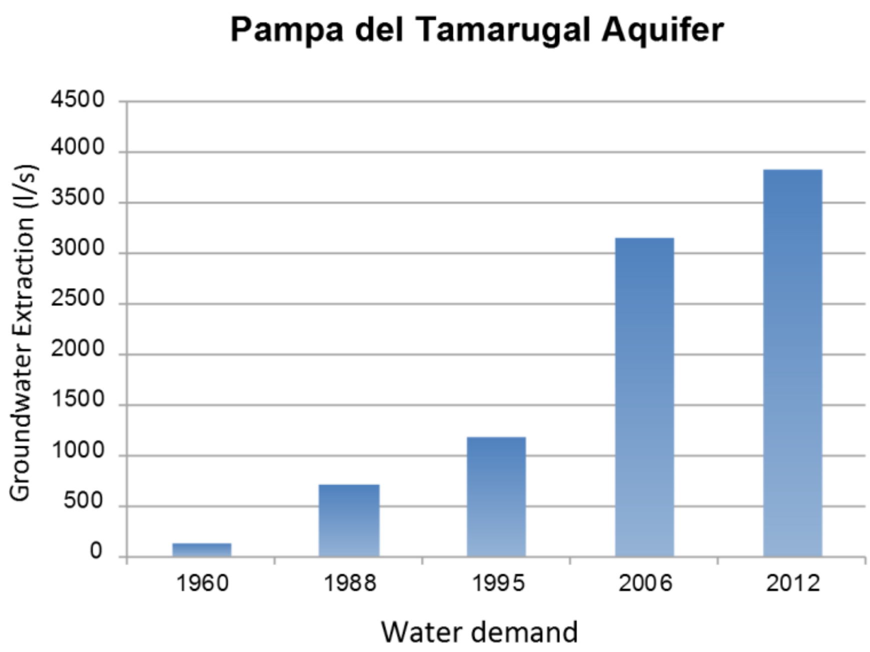
  → **Pampa del Tamarugal Aquifer** (present day water demand > 130 $Mm^3.year^{-1}$)

- Current and future water budgets highlight an important deficit that may attain 80% in 2025 for Northern Chile (*World Bank, 2011; Valdés-Pineda et al., 2014*)

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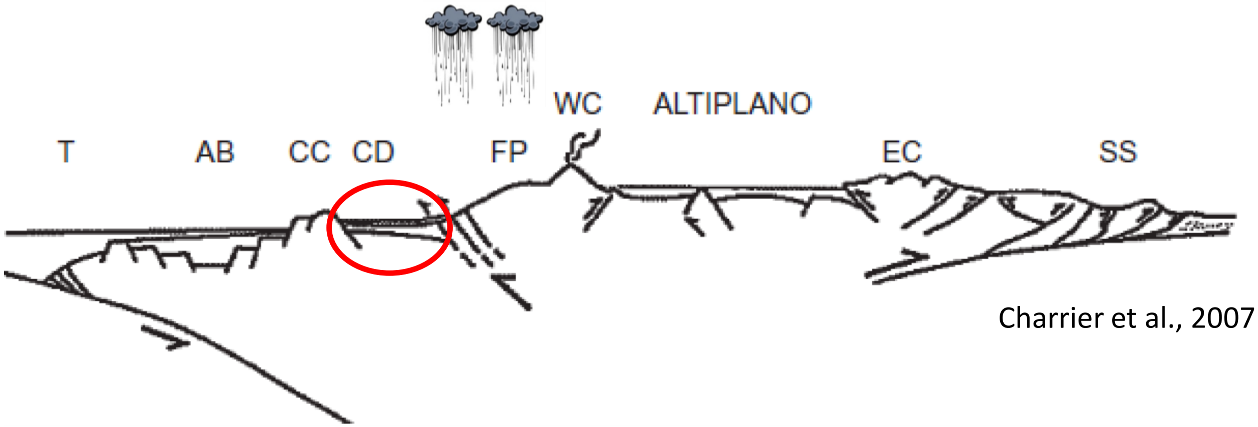
# Morphotectonic and climatic context

Morphotectonic cross-section of the Central Andes (Northern Chile)




Charrier et al., 2007

T : Trench ; AB : Arica Basin ; CC: Coastal Cordilera ; CD : Central Depression ;
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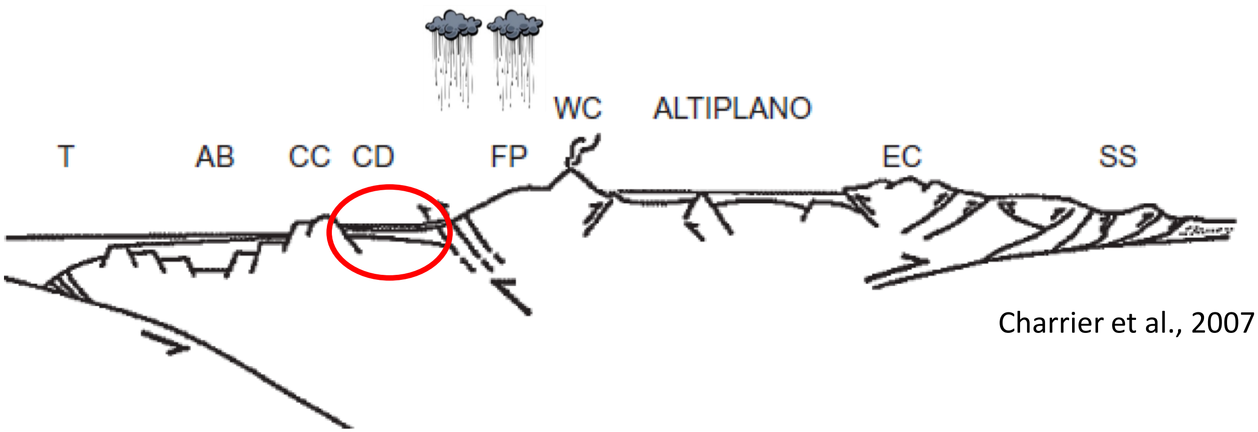


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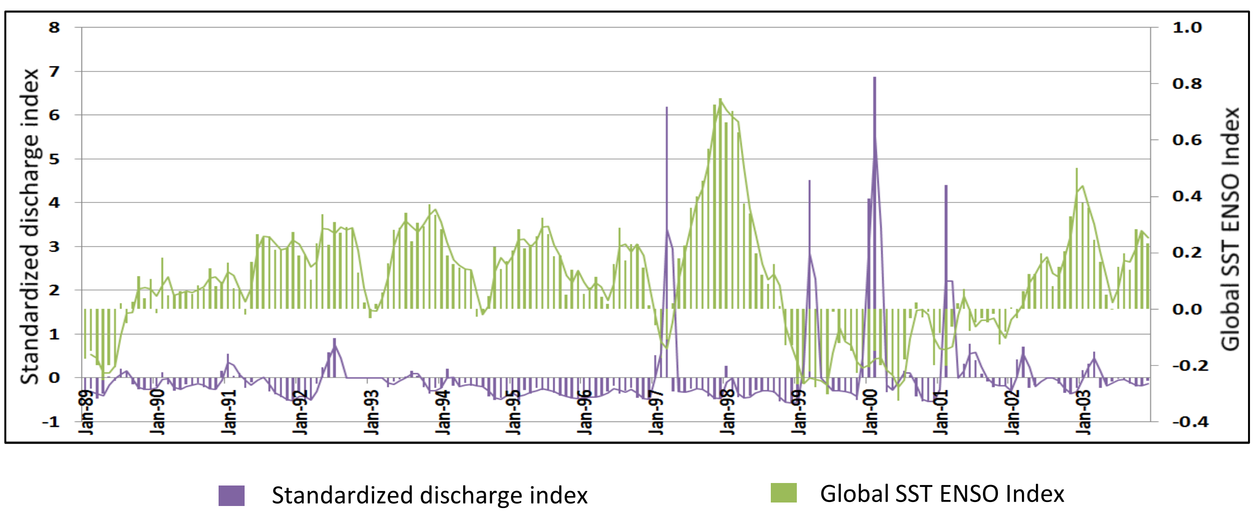


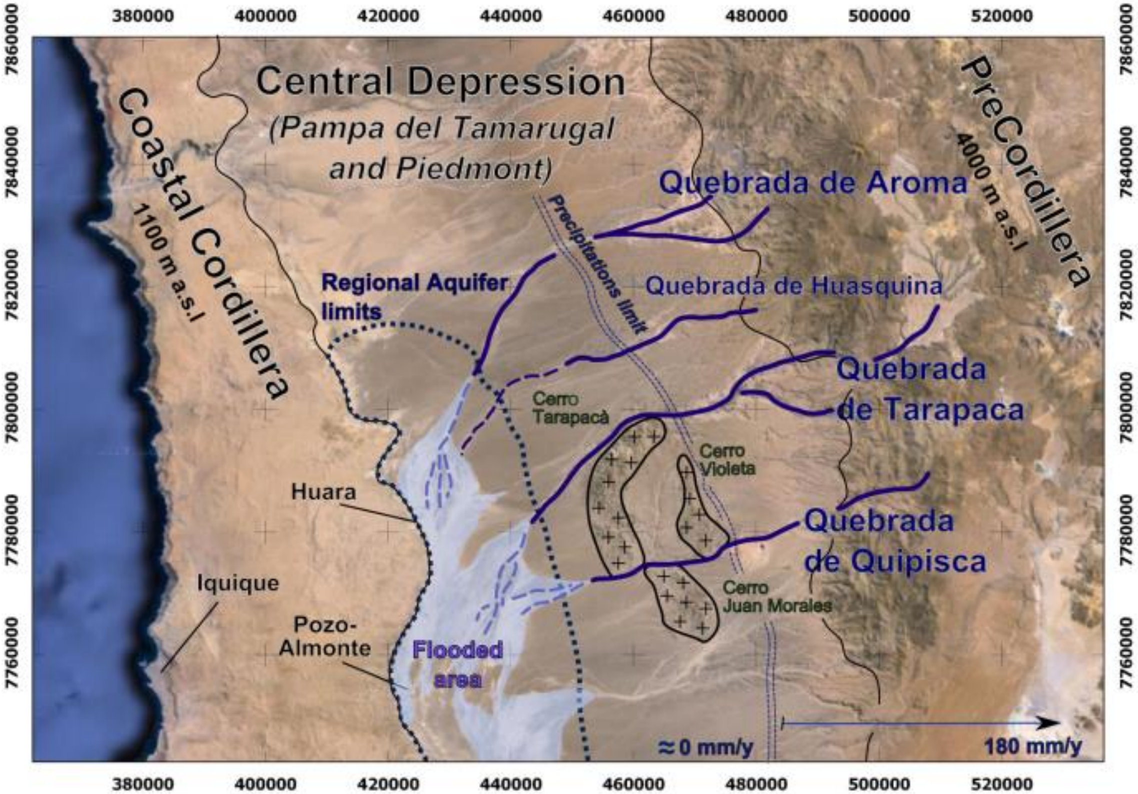

High precipitation between December and March in the Precordillera (>3000m)

High stream discharge correlated with ENSO index < 0 → La Nina events (Invierno Boliviano)

# Present day groundwater recharge ?

- No precipitation over the aquifer
- Floods during la Nina events

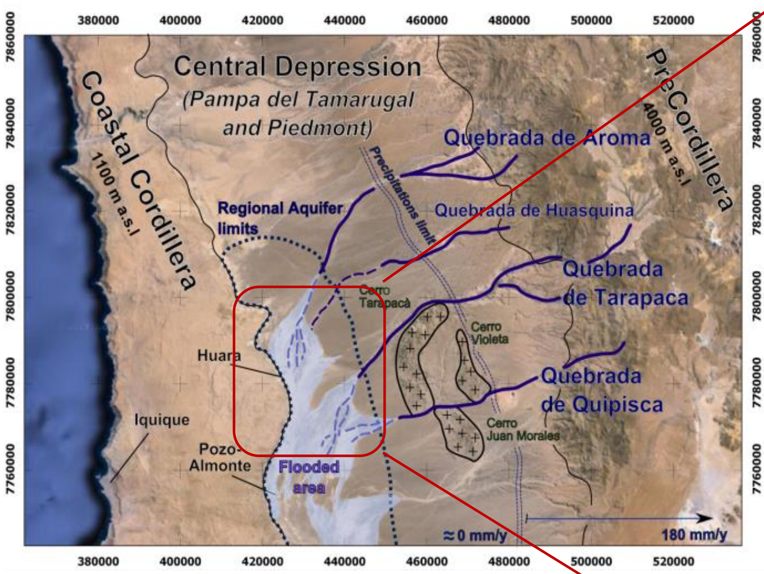
- Flooded area ?



# Location of potential groundwater recharge

**Alluvial Fans**

→ Zone of Heterogeneous deposits corresponding to complex sedimentary processes

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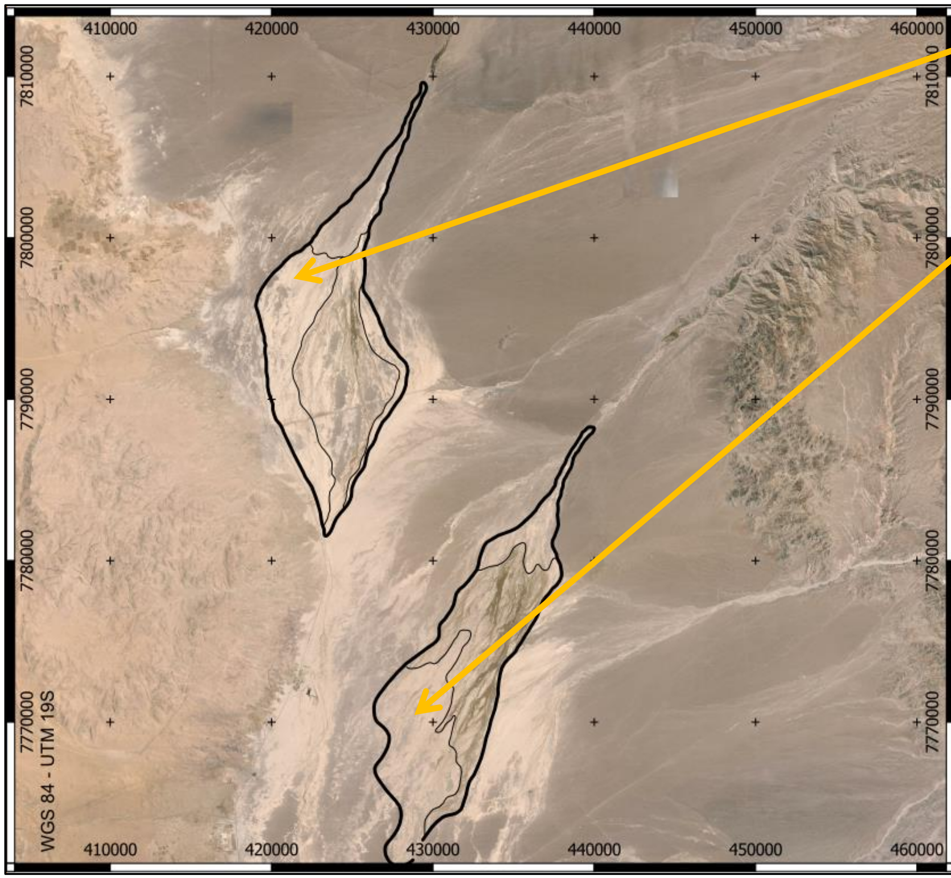


Flood Plain

Gullies and apex of alluvial fan

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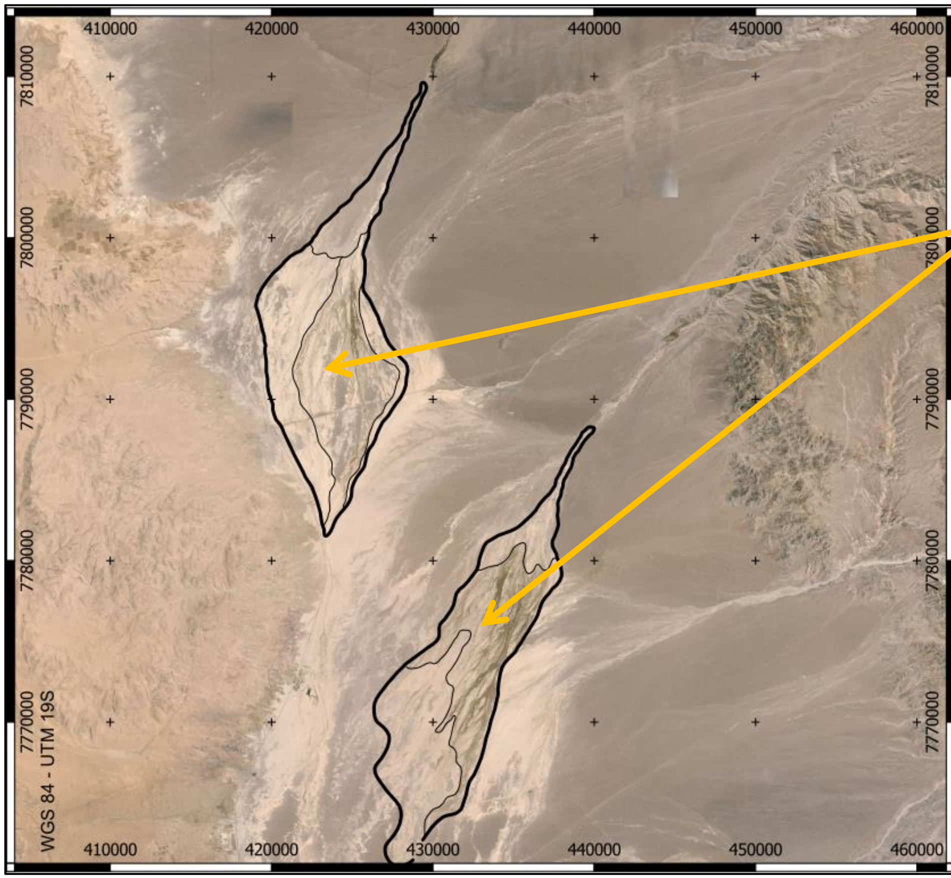


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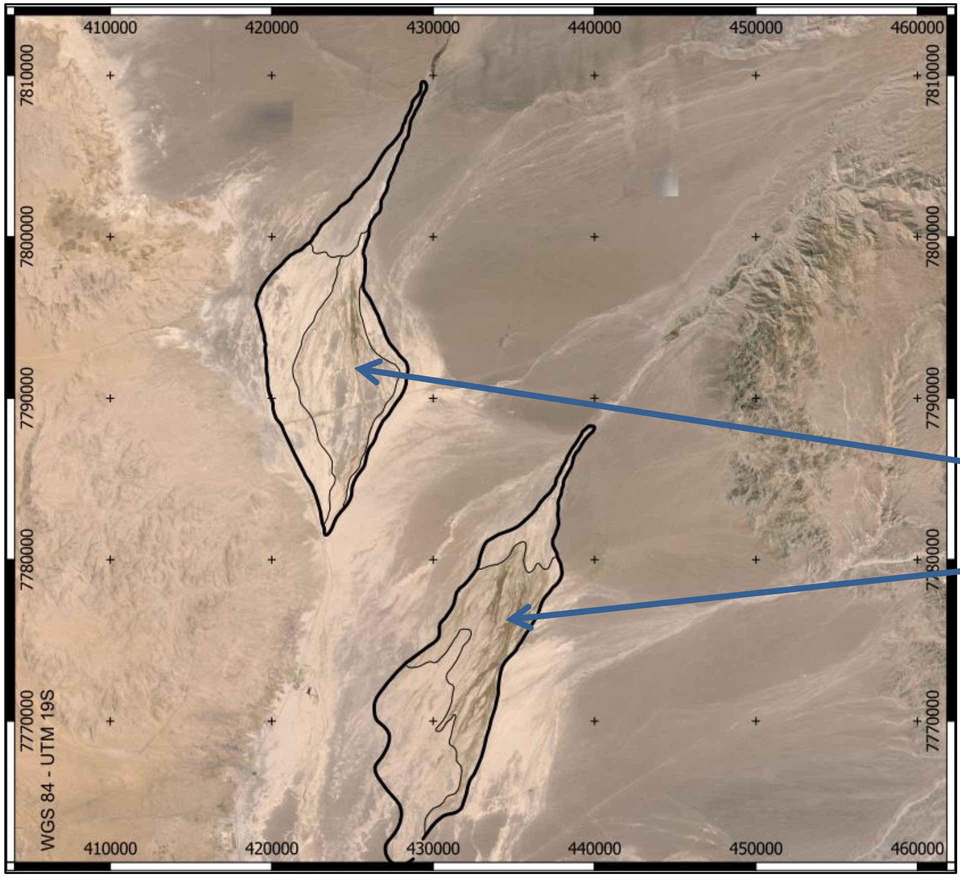


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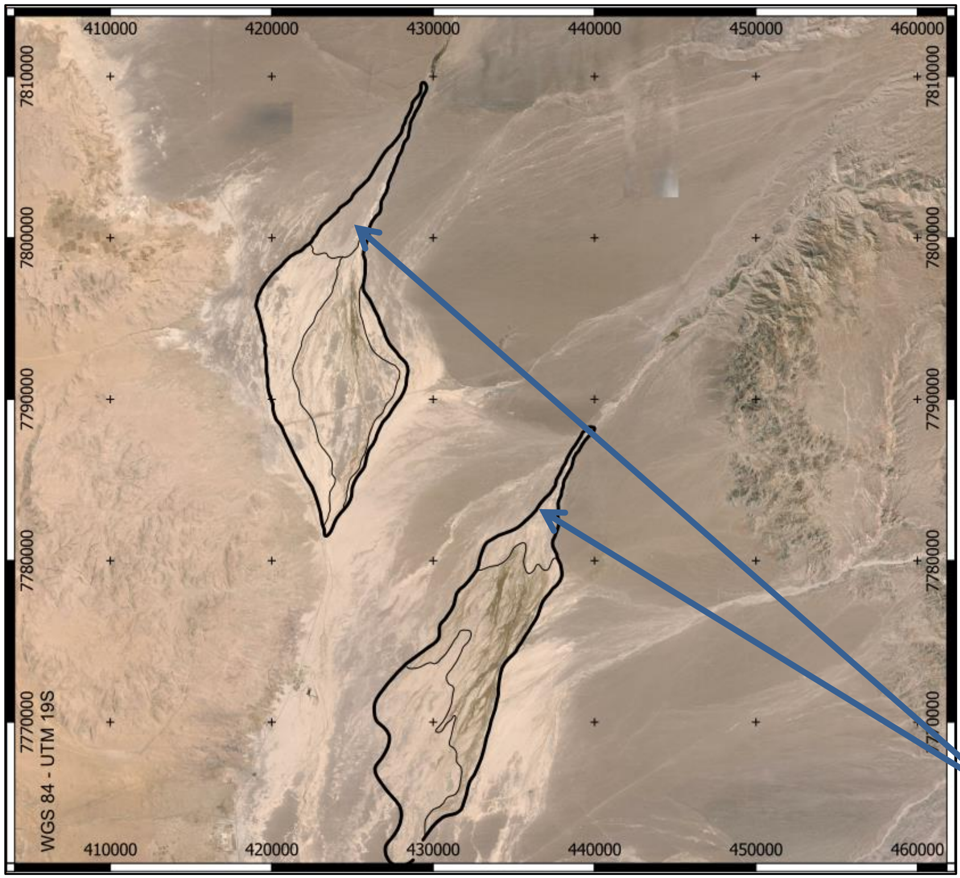


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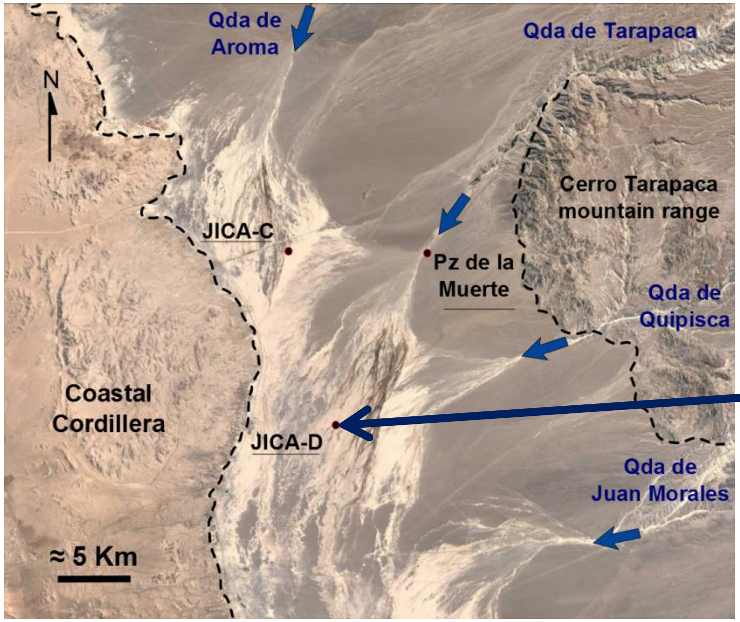
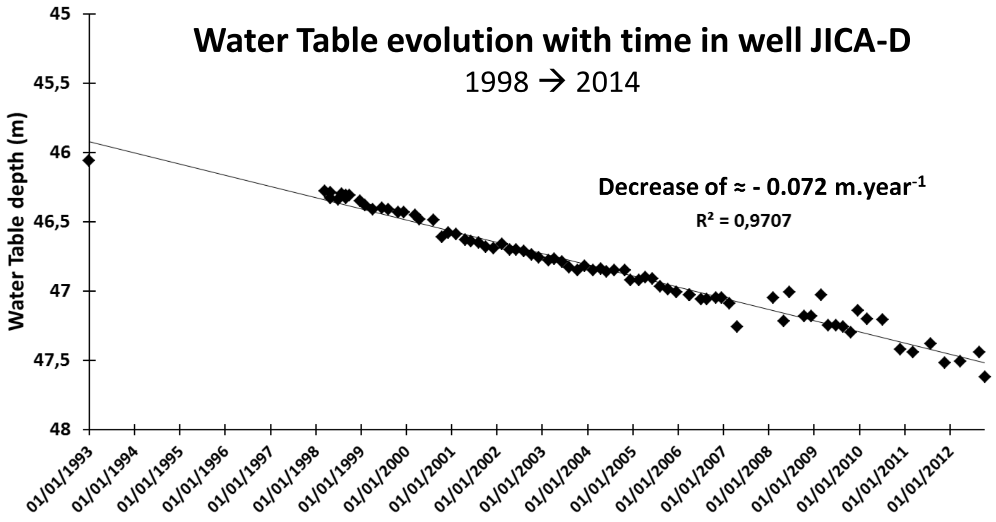
# Surface water / groundwater interaction

- **Well JICA-D** : General decrease of groundwater level of ~ 0.072 $m.year^{-1}$ during the last 15 years



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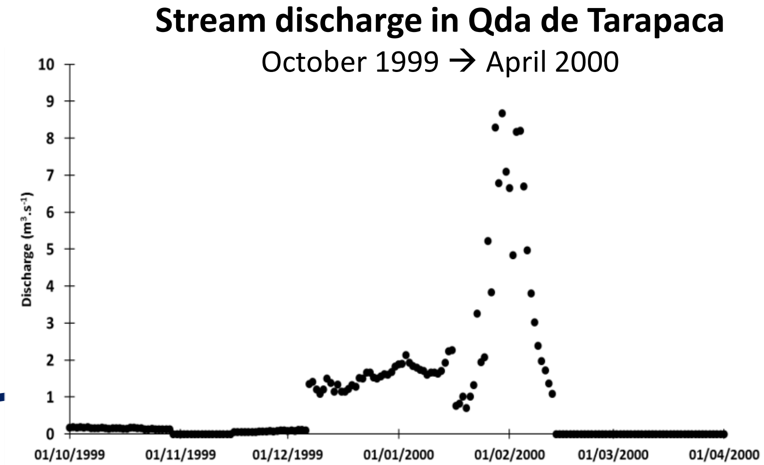


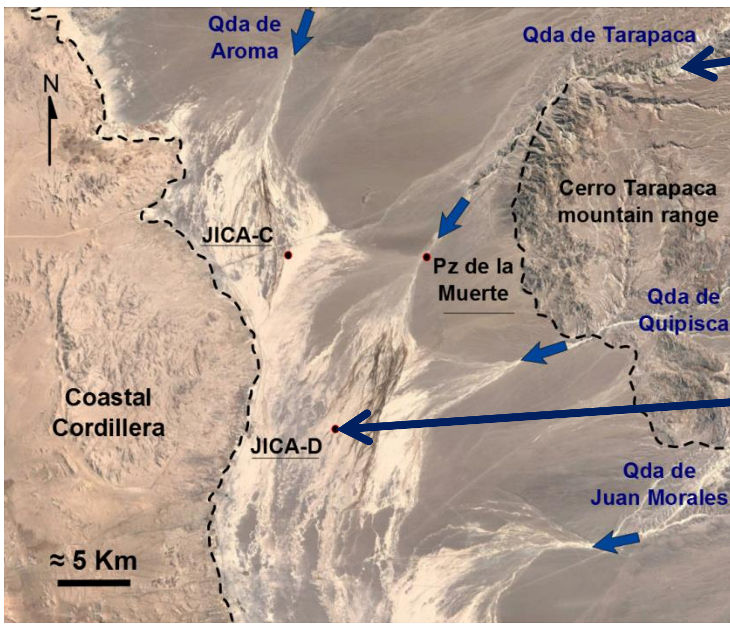


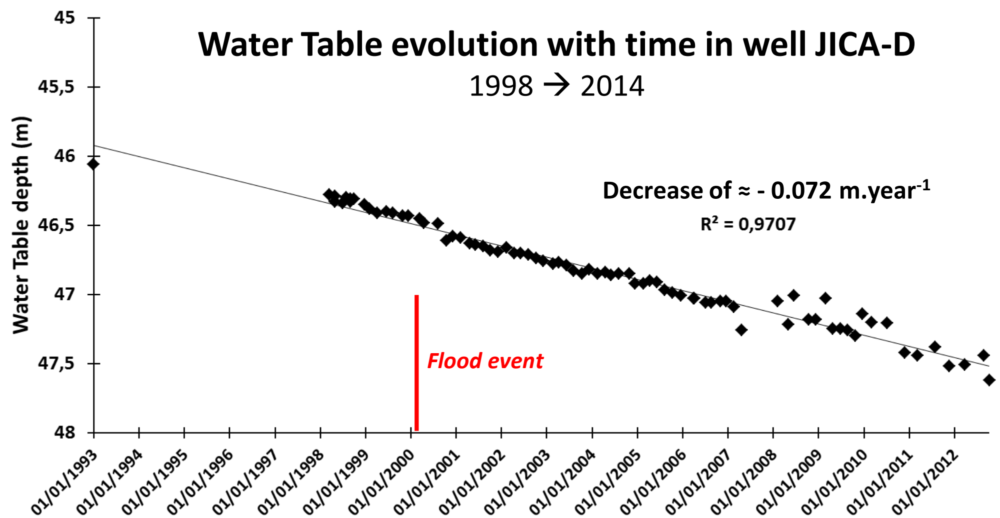

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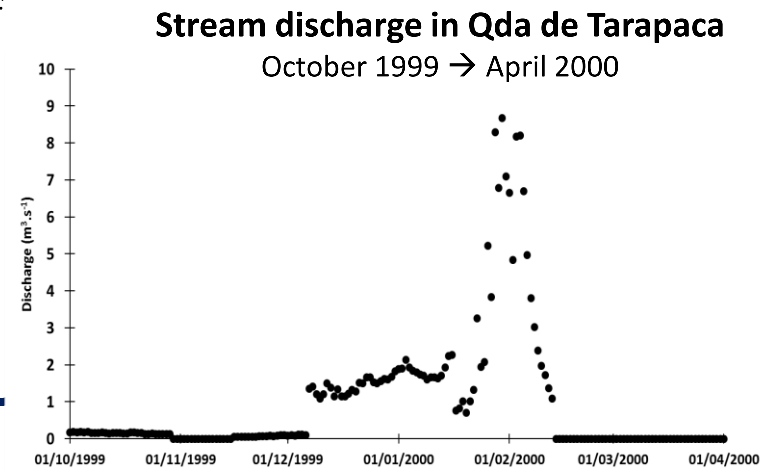


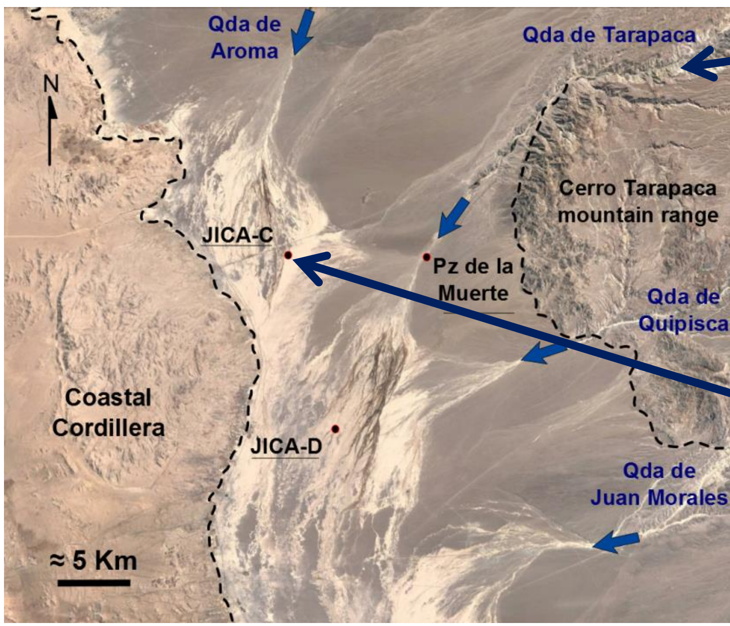


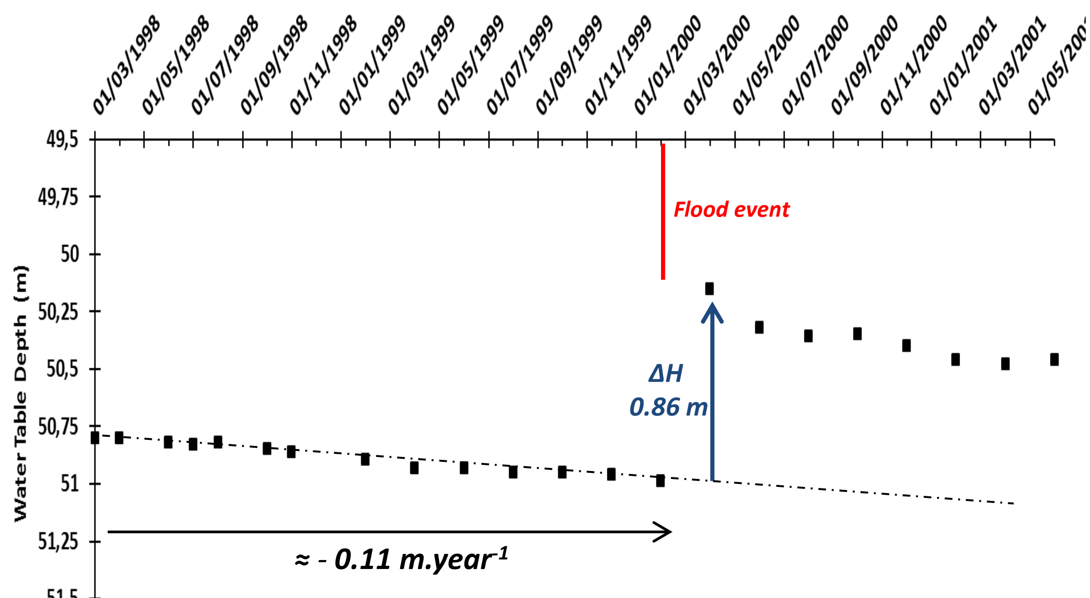

Water Table evolution with time in well JICA-C

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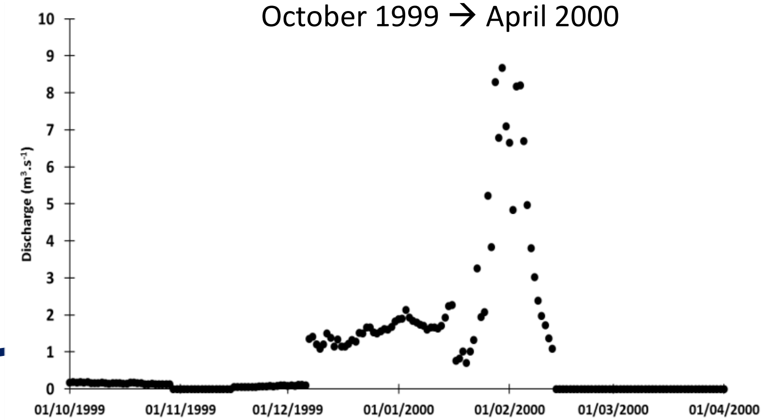
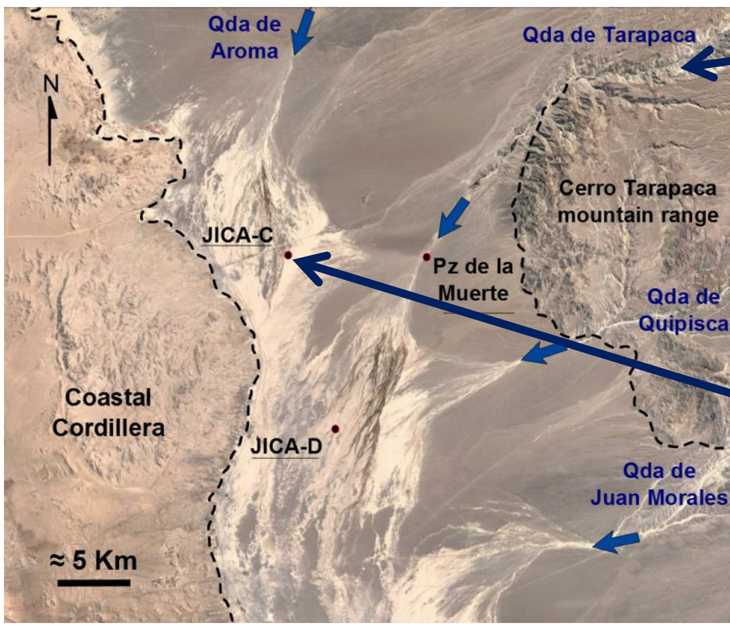
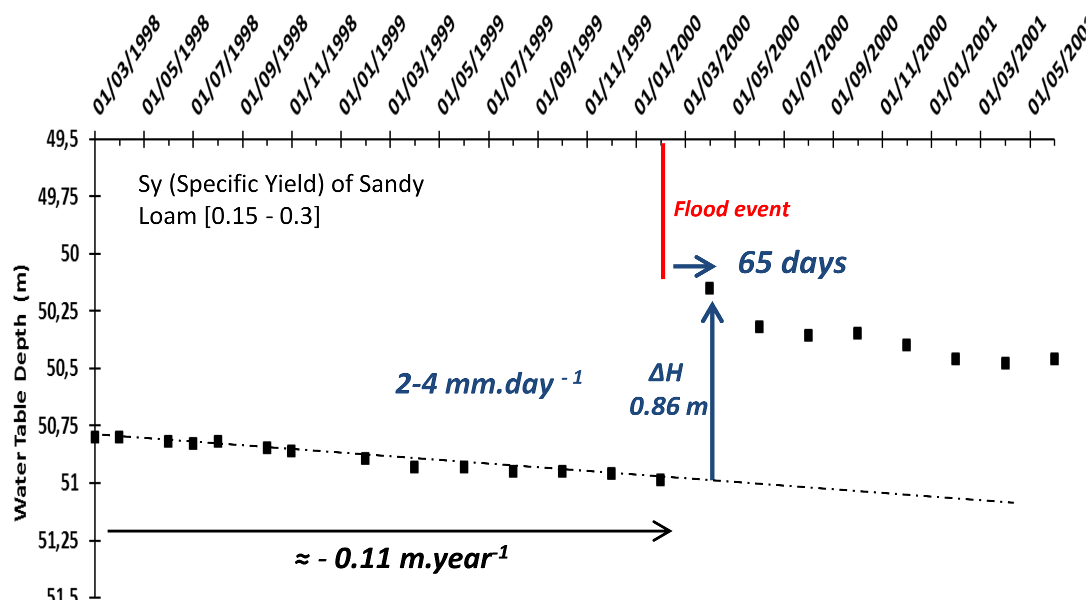
**Stream discharge in Qda de Tarapaca**

October 1999 → April 2000




**Water Table evolution with time in well JICA-C**

**Recharge estimation** with the *water table fluctuation method* $R = \frac{Sy * \Delta H}{\Delta t}$

(Healy and Scanlon, 2010)

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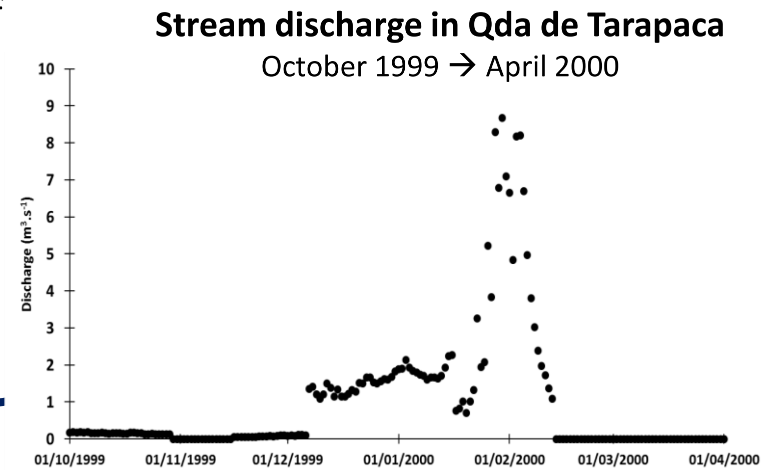


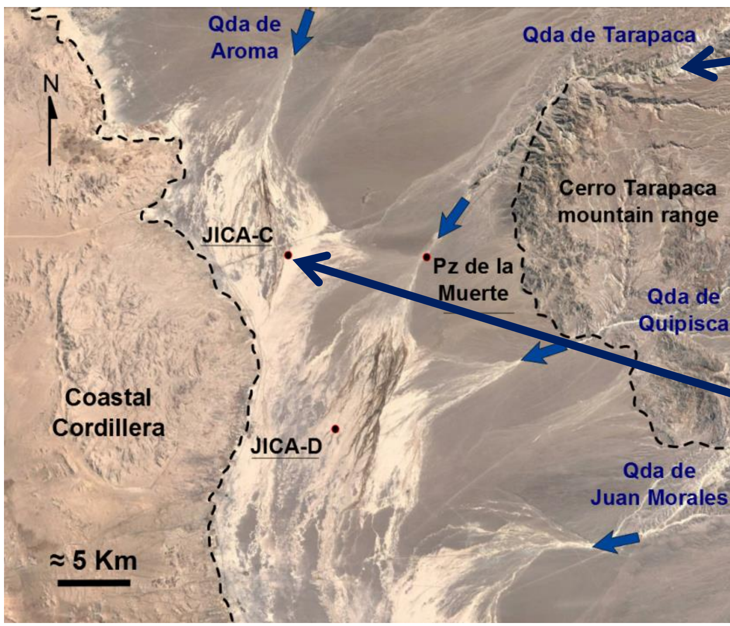


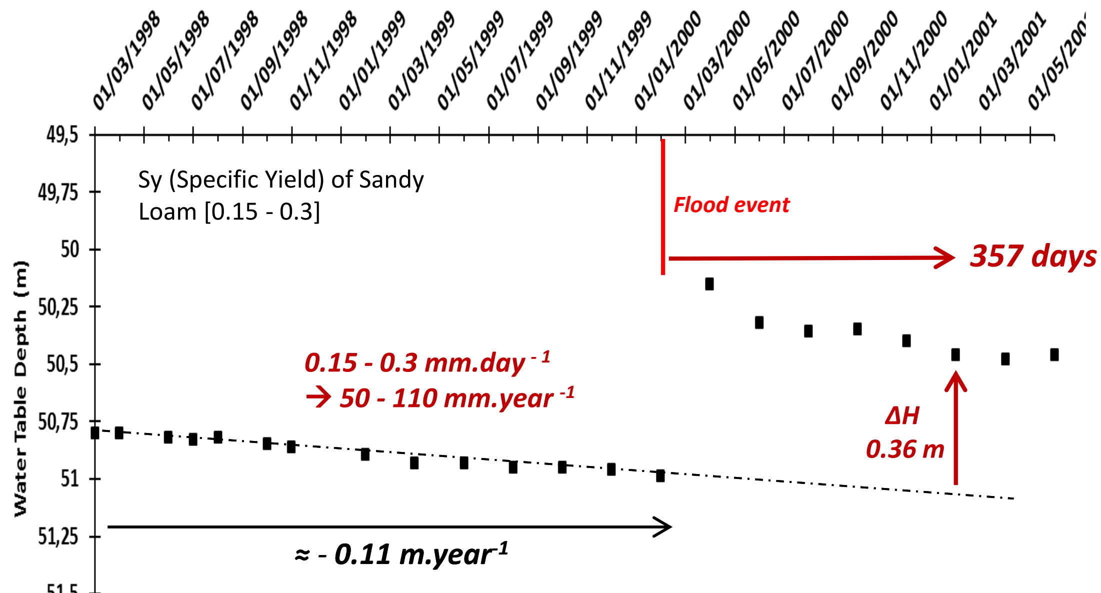

Water Table evolution with time in well JICA-C

**Recharge estimation** with the *water table fluctuation method*

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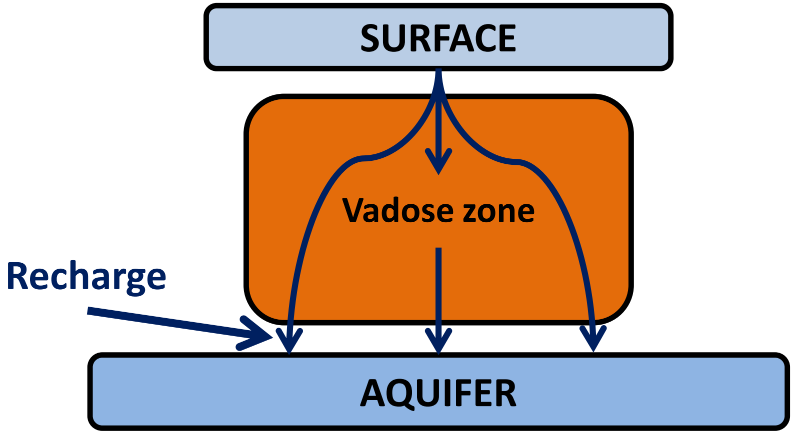
# Flow modeling in the vadose zone

**Recharge of the aquifer depends on :**

- Hydroclimatic forcing (Flood duration, return period of floods, ET, …)
- Heterogeneity of sedimentary layers within the unsaturated zone → Control of water-retention parameters and hydraulic conductivity



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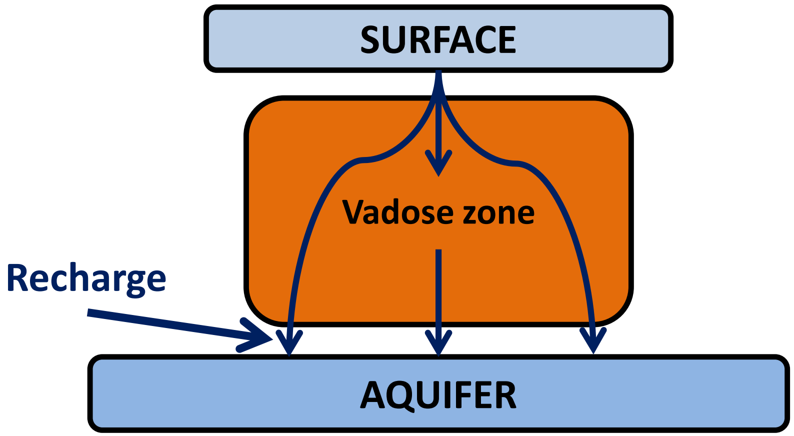


**Numerical solution of Richards equation - Hydrus-1D**

- **Sampling in gullies and floodplain** → Pedotransfer function (Rosetta Model) to estimate the van Genuchten (1980) water-retention parameters (Schaap et al., 2001)
  → Comparison with in situ measurement of Ks

- **Analysis of various scenarios** (Flooding duration, Surface water depth, ET)

# Estimation of water-retention parameters

**Sampling**

Particle size analysis

Pedotransfer Function Model Rosetta

Gullies and apex of alluvial fan - Coarse sediments zones

# Estimation of water-retention parameters

**Sampling** | Particle size analysis | Pedotransfer Function Model Rosetta

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# Estimation of water-retention parameters

Sampling

**Particle size analysis**

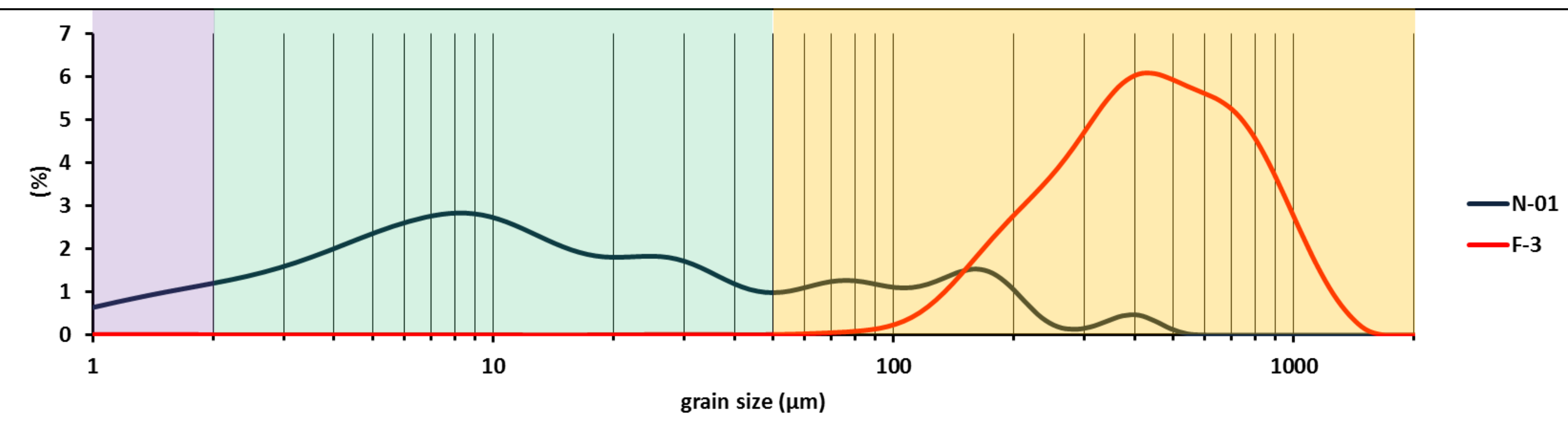
Pedotransfer Function Model Rosetta

**Particle size analysis by laser diffraction** (courtesy of L. Dezileau, GM)

**1.5 mm sieving pretreatment**

**USDA** (US Department of Agriculture)Textural Classification

**Sand** (2000 µm => 50 µm)
**Silt** (50 µm => 2 µm)
**Clay** (2 µm => …)



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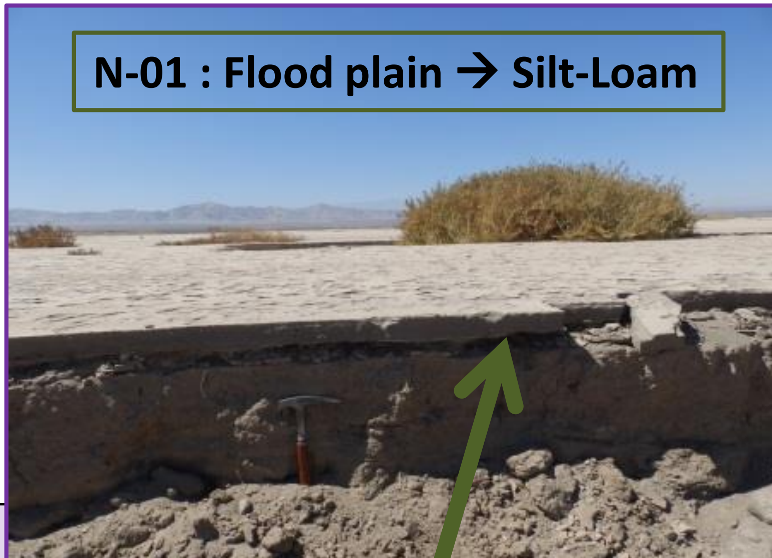
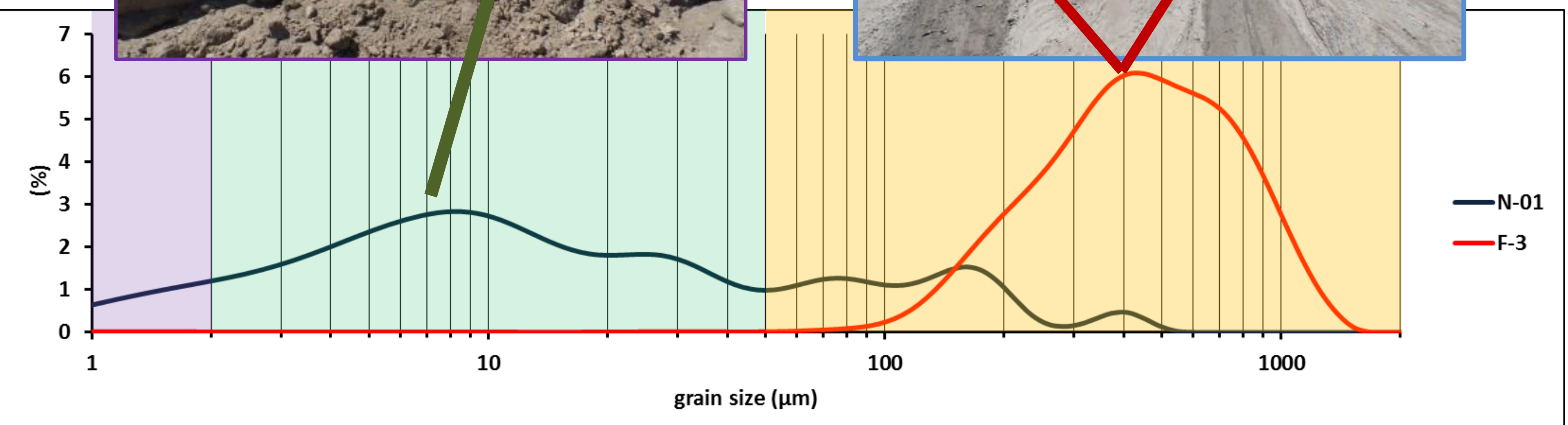






# Estimation of water-retention parameters

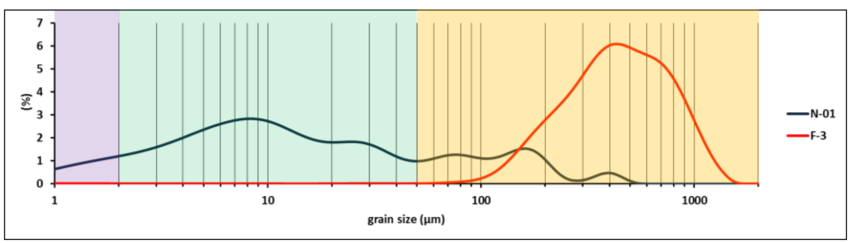
Sampling

Particle size analysis

**Pedotransfer function Model Rosetta**

Pedotransfer Function (PTFs) : **Rosetta Model** (Schaap et al., 2001)

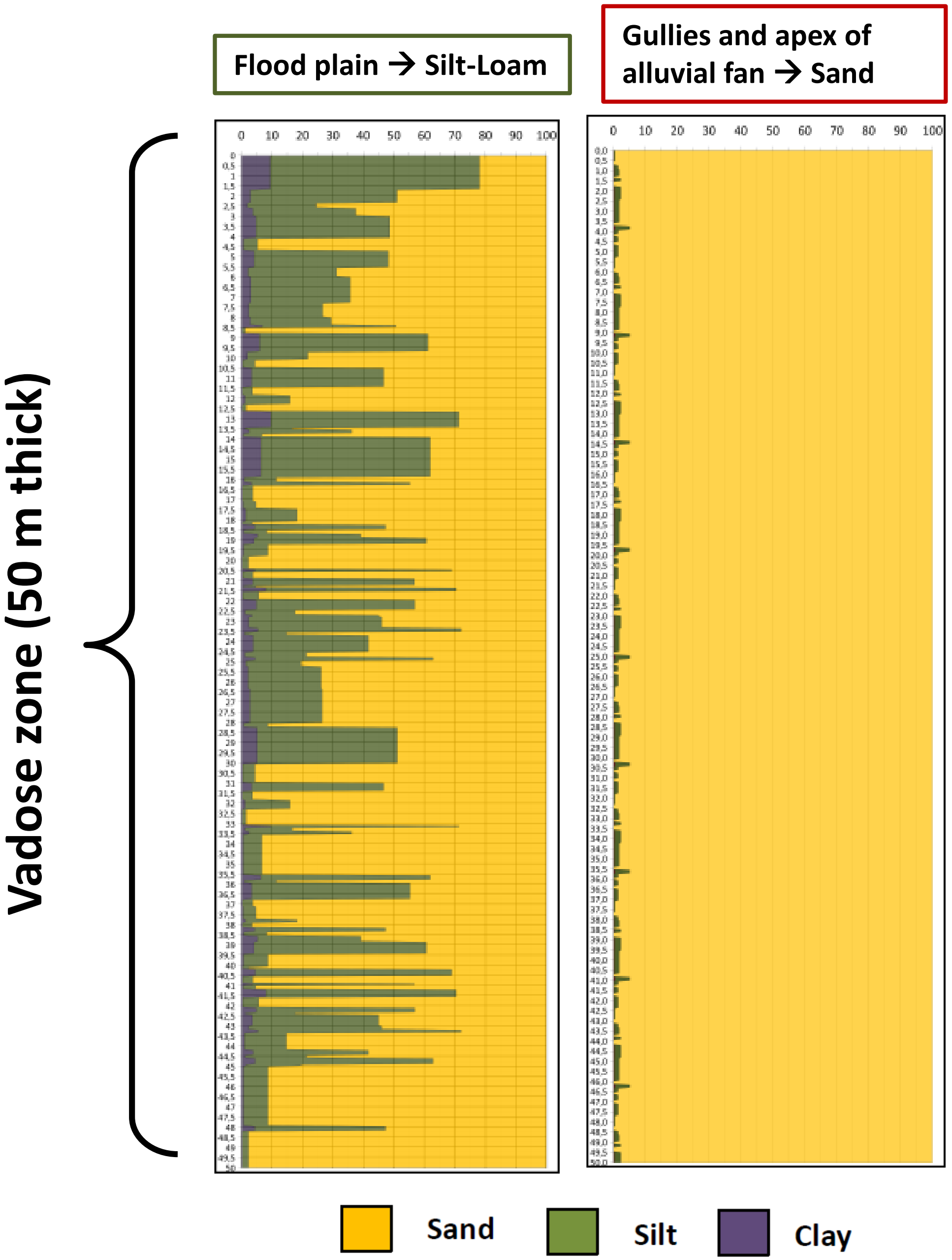
**Modèle H2 : % clay, % silt, % sand**




| Echantillon | | F-3 | N-01 |
|---|---|---|---|
| %Clay | (0-2 µm) | 0,13 | 9,43 |
| %Silt | (2-50 µm) | 0,34 | 68,64 |
| %Sand | (50-2000 µm) | 99,53 | 21,93 |
| ROSETTA MODEL CSS% (H2) | $\theta$r [cm3/cm3] | 0,0507 | 0,0517 |
| | $\theta$s [cm3/cm3] | 0,3766 | 0,4433 |
| | $\alpha$ [cm-1] | 0,0345 | 0,0044 |
| | hg [cm] | 28,98551 | 227,2727 |
| | n [-] | 4,3247 | 1,7178 |
| | Ks [cm/day] | 1352,29 | 38,53 |
| | *Ks (m/s)* | *1,57E-04* | *4,46E-06* |

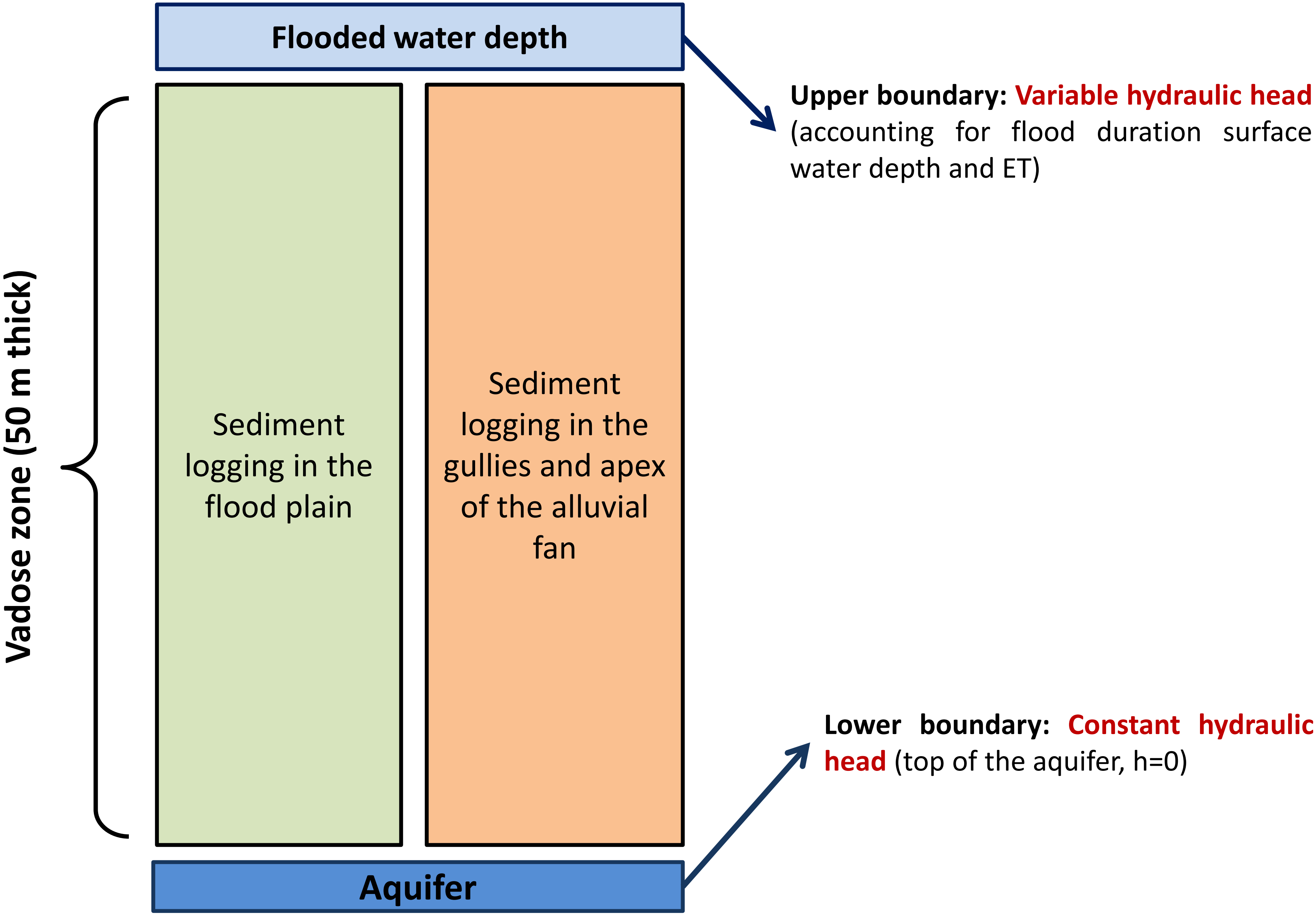
**Θ [-] : water content ; Θr [-] : residual water content ; Θs [-] : saturated water content ; h [cm] : pressure head ; K [cm/day] : hydraulic conductivity ; Ks [cm/day] saturated hydraulic conductivity ; hg [cm] : capillary fringe depth ; m [-] shape parameter = 1-1/n**

# Hydrus 1D - model set up



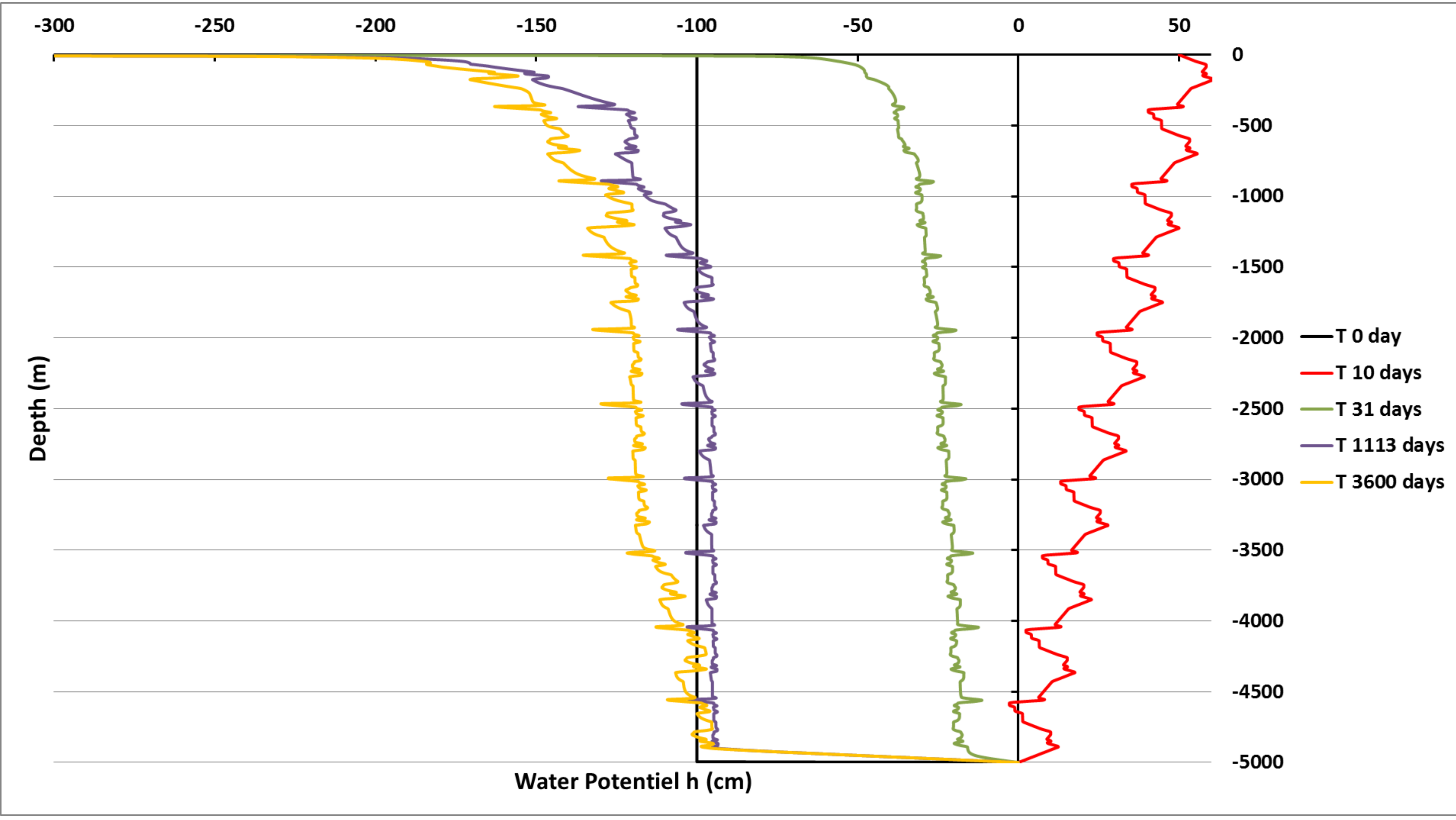

96 nodes and up to 18 types of sedimentary layer classified on the basis of the shape parameter (n) and Ks (Wang et al, 2009)

# Boundary conditions



# Model initialisation

## ET = 5mm/day during 10 years after flooding



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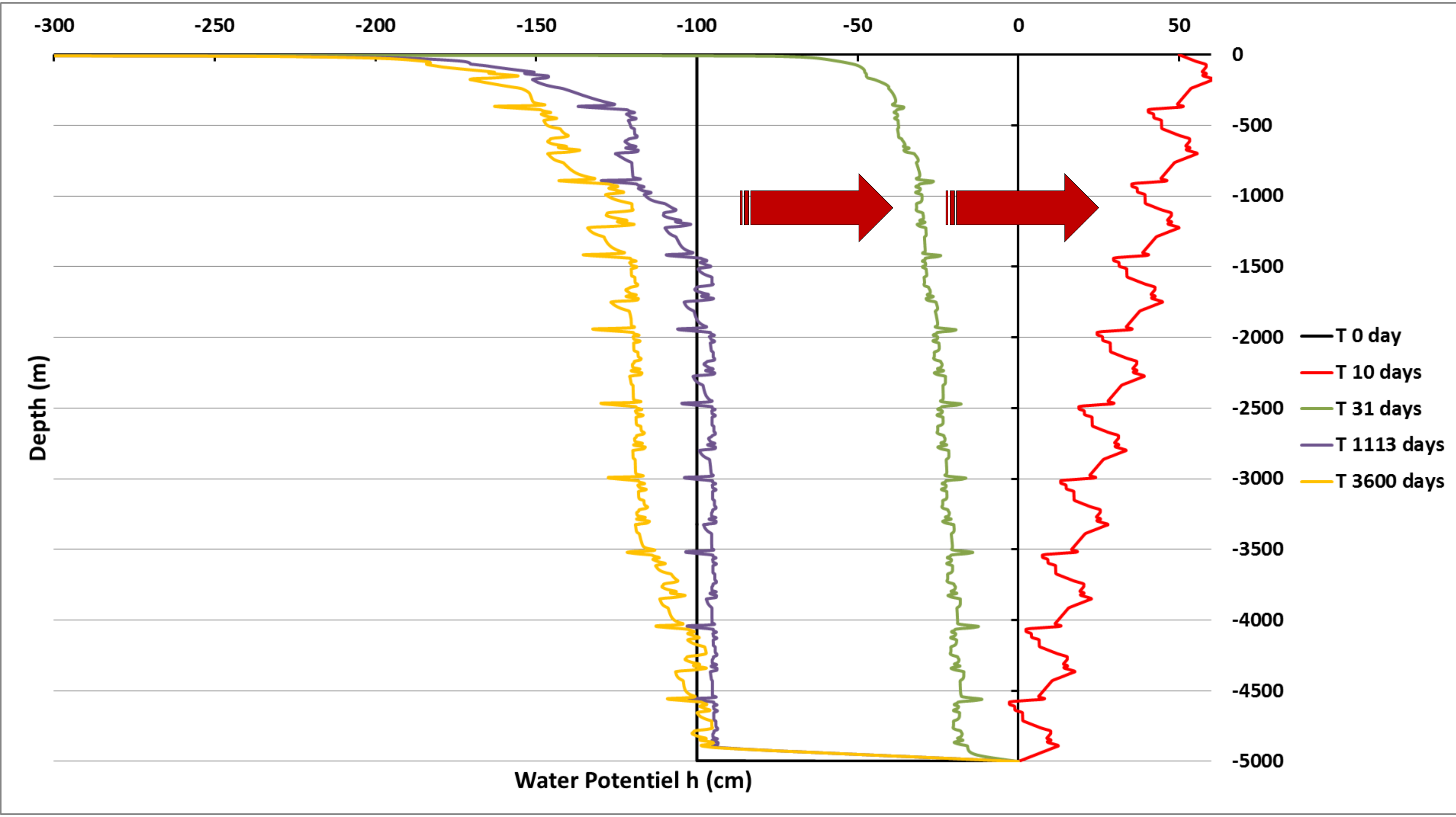

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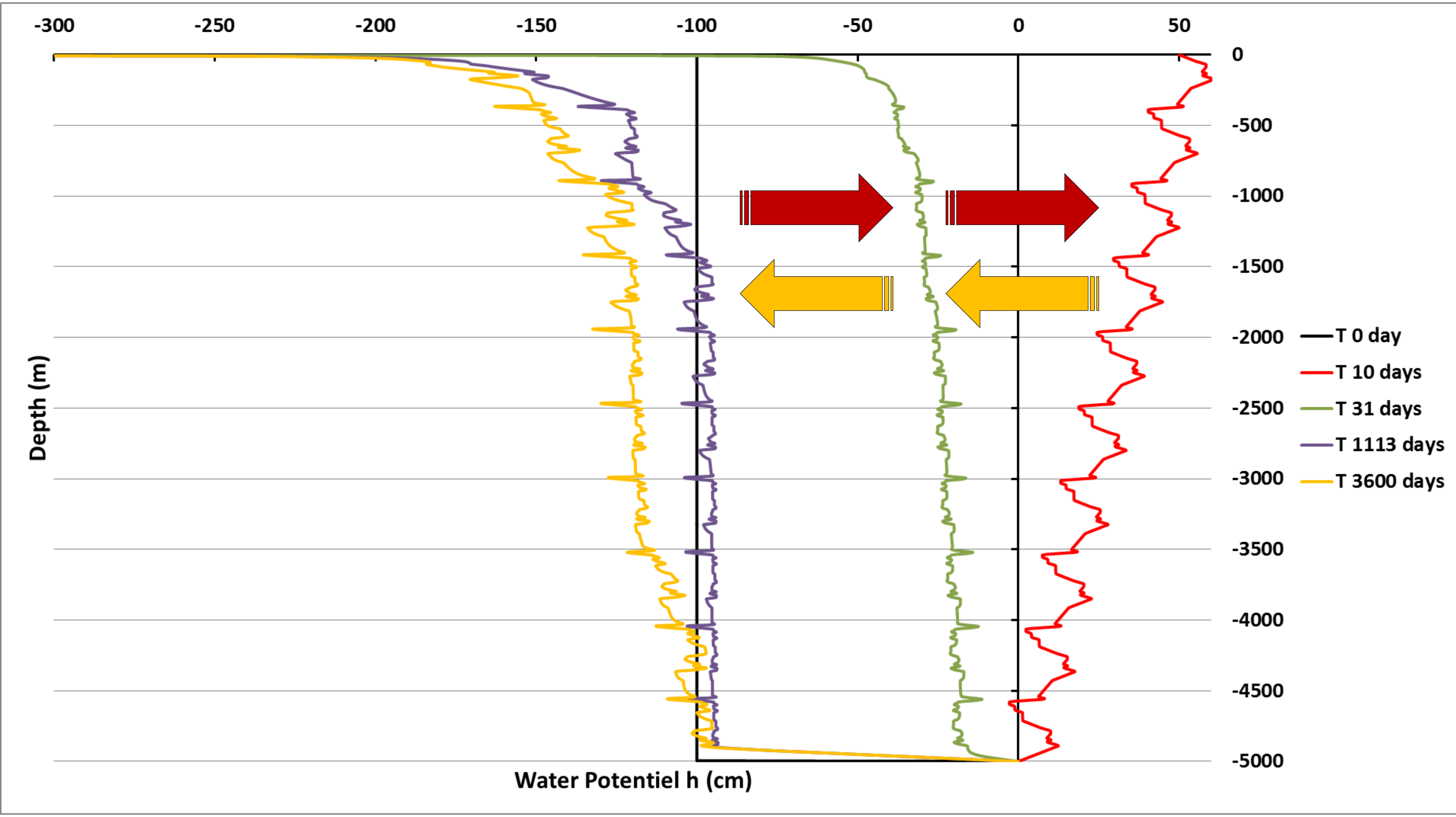
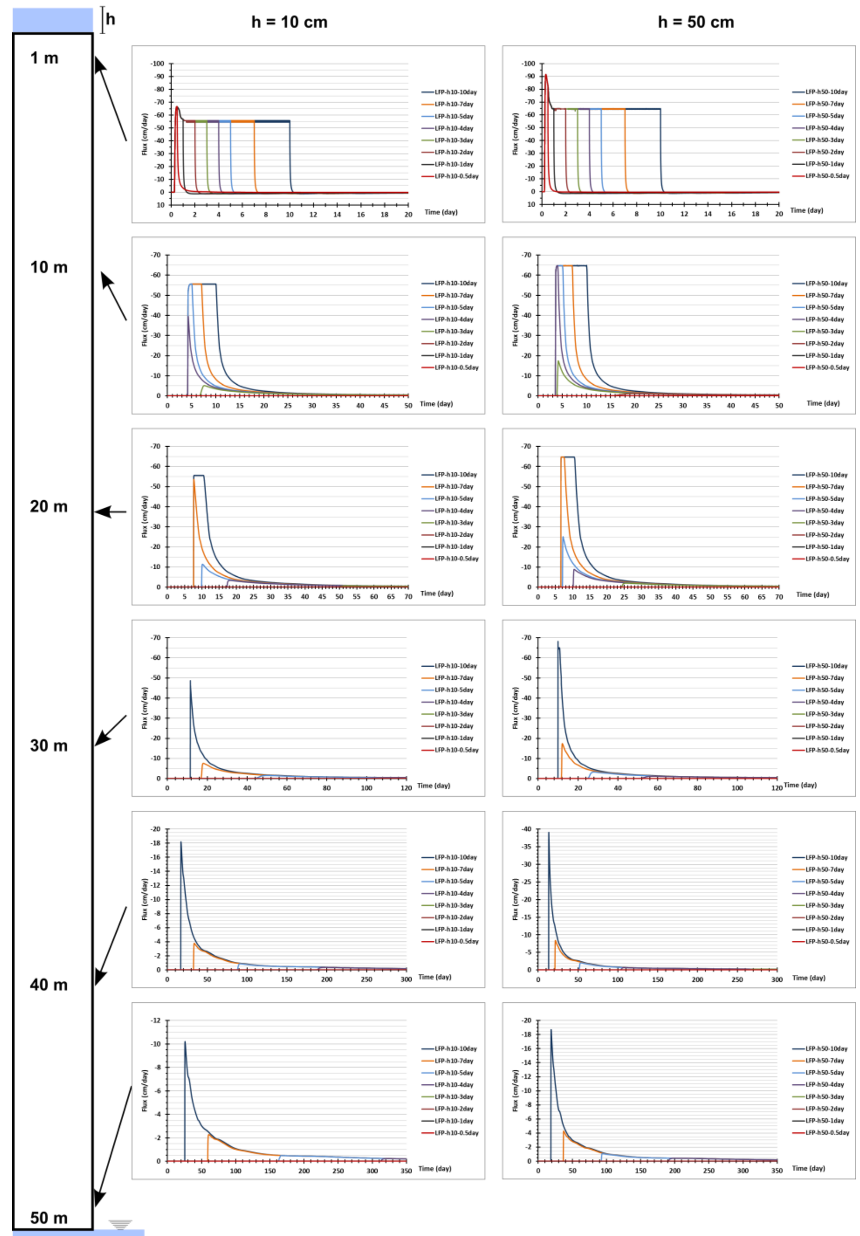


# Flow modeling in the flood plain

Various flooding durations (0.5 → 10 days)

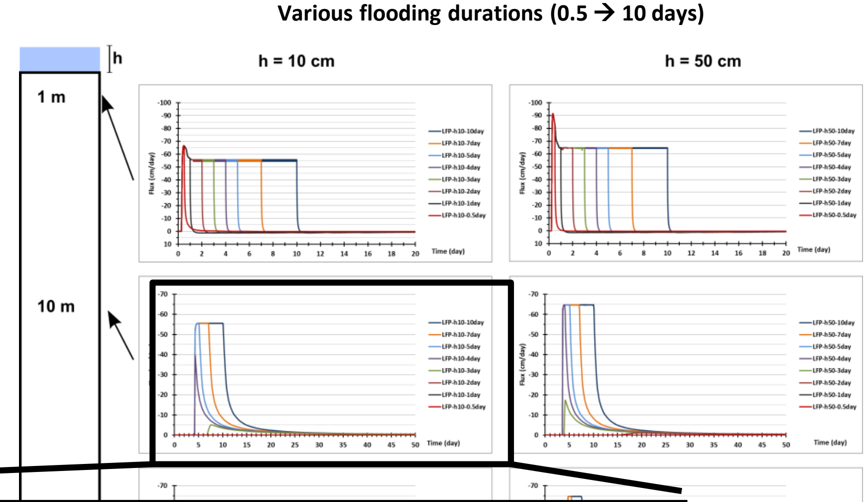


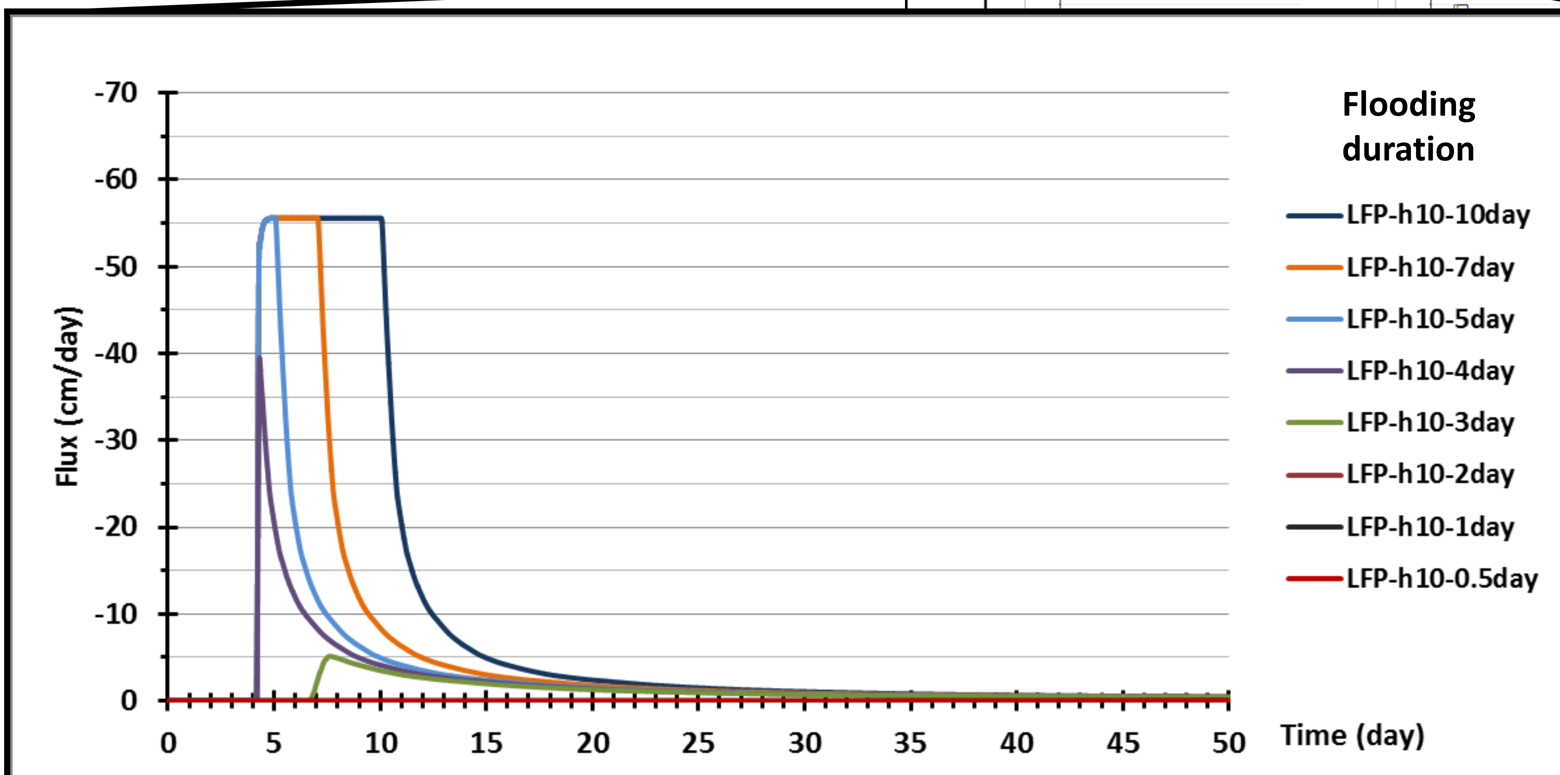

Slight increase of cumulated fluxes (recharge) for higher surface water depth

Recharge increases with flood duration

# Flow modeling in the flood plain

at 10 m depth



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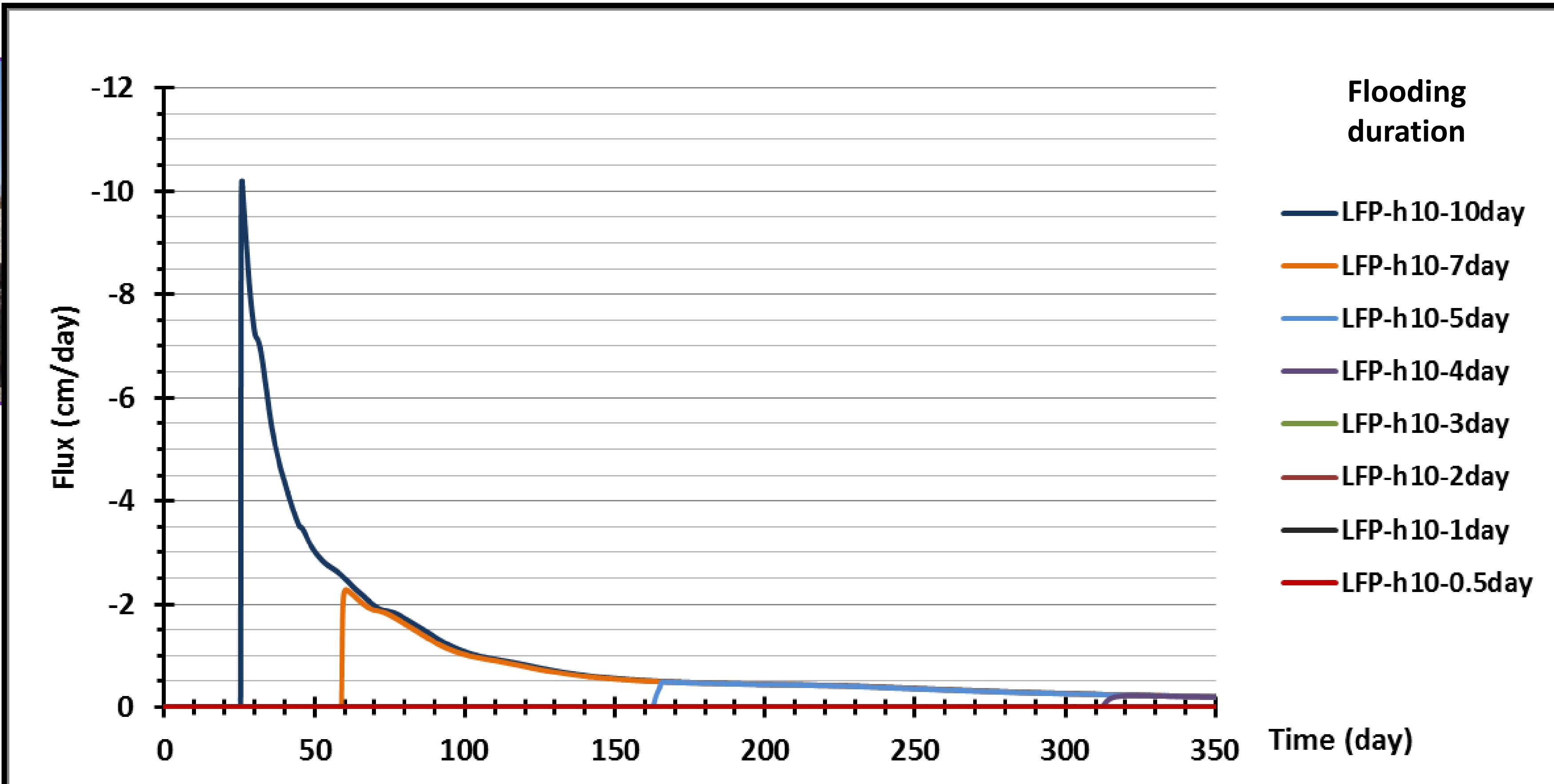


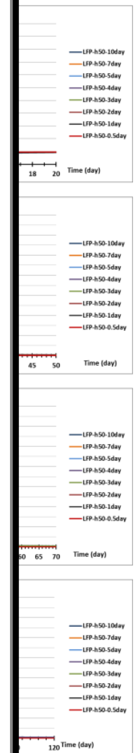

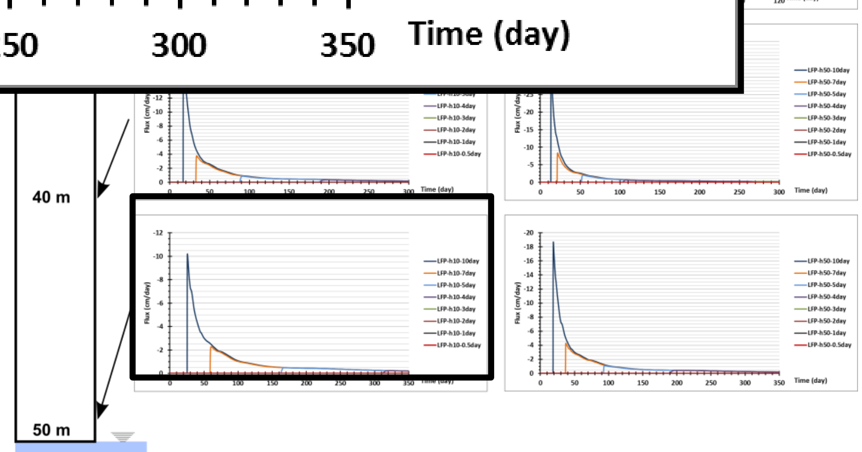


**Flooding duration of 5 to 7 days**

→ Flux of ~ 2- 4 mm.day$^{-1}$ and response time of ~65 day in agreement with previously estimated recharge

**at 50 m depth**

# Groundwater residence time

Apparent groundwater age based on $^{14}C$ activities

(pmc= percent of modern carbon)

- Well Pz de la Muerte > 1950
- Well JICA-C ≈ 3500 – 4000 year BP
- Well JICA-D ≈ 14500 – 15000 year BP

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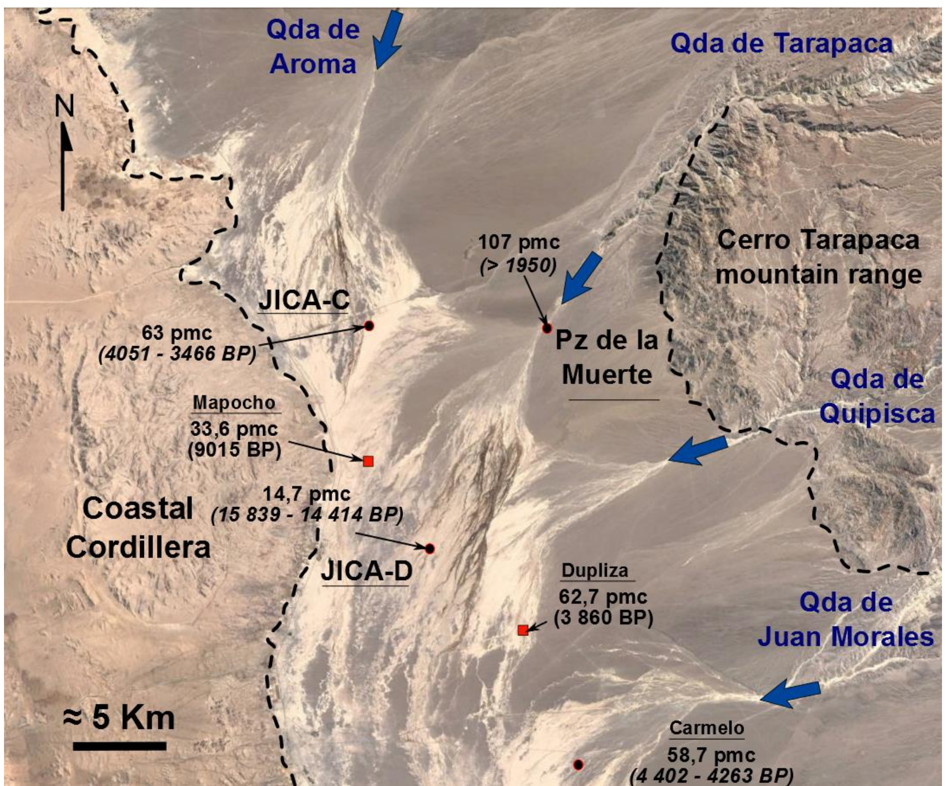
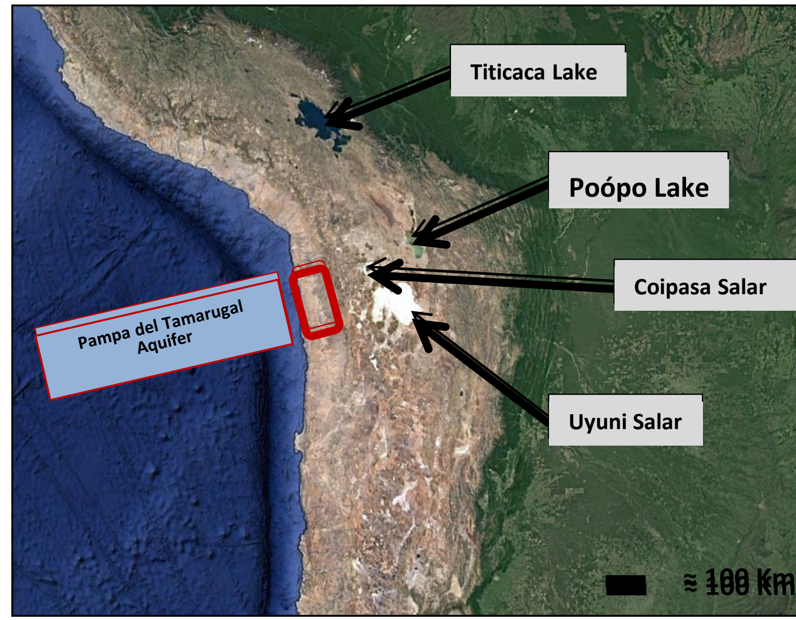



In agreement with paleoclimatic variation and wet phases influenced by high altitude lakes




Placzek et al., 2011; *Sáez et al., 2016 ; Google Earth view*

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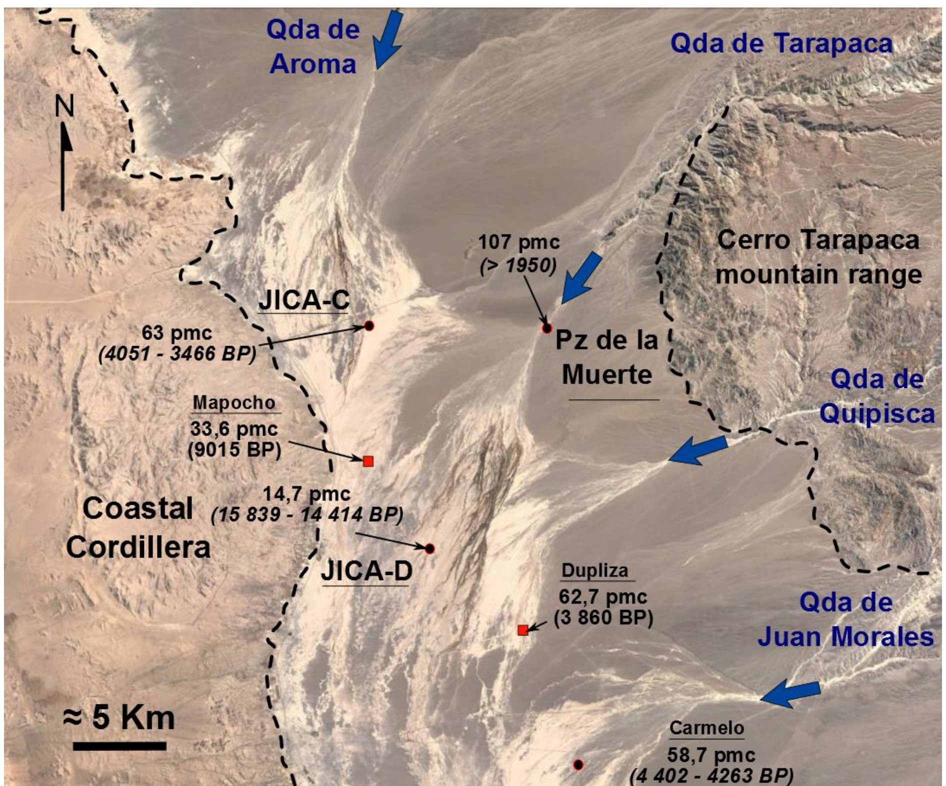
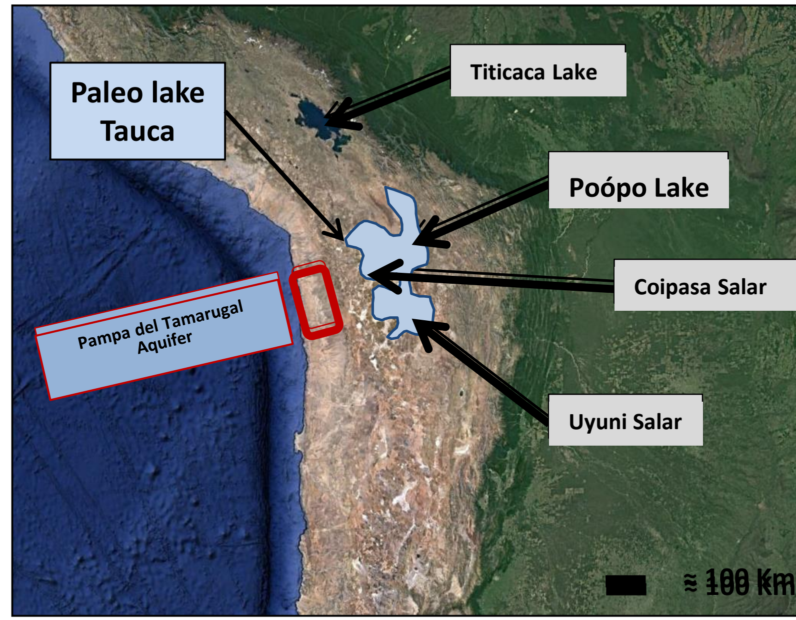



In agreement with paleoclimatic variation and wet phases influenced by high altitude lakes




Placzek et al., 2011; *Sáez et al., 2016 ; Google Earth view*

Wet phases during the last 20000 years:

- Tauca phase ≈ 18 000 - 14 000 years BP
- Coipasa phase ≈ 13 000 - 10 000 years BP
- Early Holocene ≈ 8 500 - 9 700 years BP
- Late Holocene ≈ 4 700 years up to present day?

Return to dry conditions since 700 years BP

# Groundwater residence time

Apparent groundwater age based on $^{14}C$ activities
(pmc= percent of modern carbon)

- Well Pz de la Muerte > 1950
- Well JICA-C ≈ 3500 – 4000 year BP
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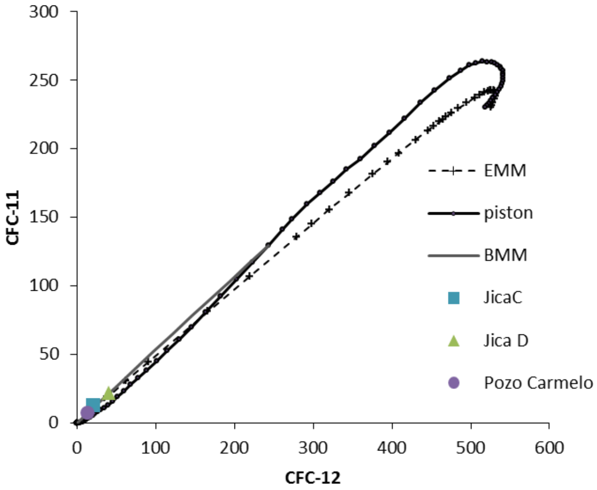
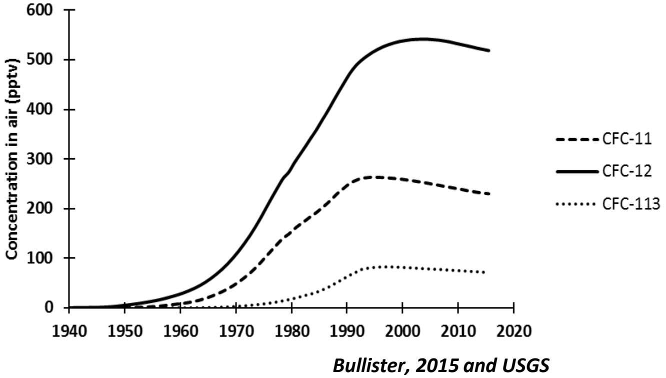
Positive concentrations of CFC-11 and CFC-12 measured in groundwater → Recent recharge




Low concentration → Low proportion of recent infiltrated water (1940 - present day) mixed with older groundwater




→ Confirmed by $^{3}H$ measurements in JICA-C and JICA-D

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→ Paleorecharge and present day mountain front recharge


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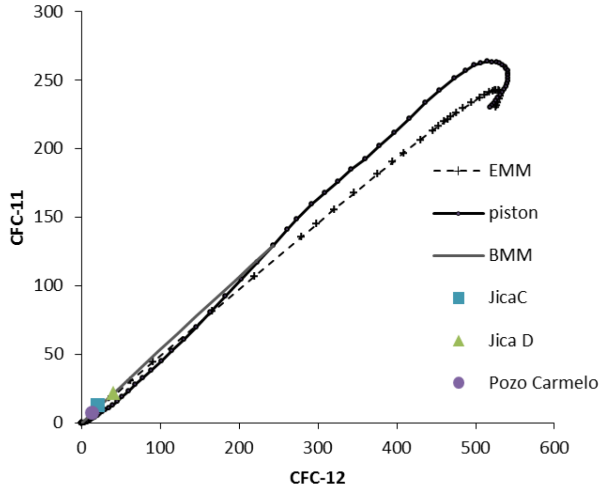


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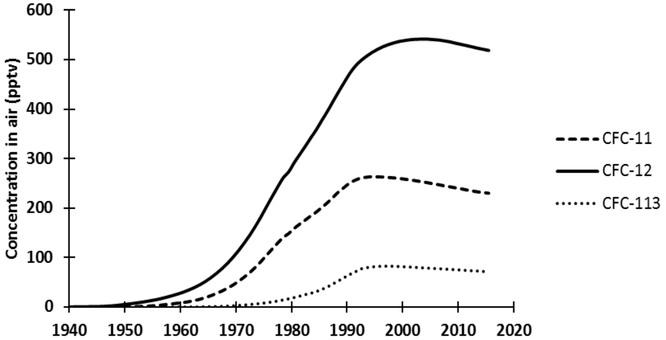


*Bullister, 2015 and USGS*

→ Confirmed by $^{3}H$ measurements in JICA-C and JICA-D

# Conclusion

**Groundwater recharge at various scale of time**

- **Paleo recharge :** Pleistocene and Late Holocene periods → **Fossil groundwater**
- **Event scale** : floods events → localized mountain front recharge evidenced by hydrodynamic analyses and environmental tracers
- **Steady state recharge** (surface flow losses)

**Groundwater recharge at various scale of space**

- **High** recharge at the **apex** areas (>> cm up to $m.day^{-1}$)
- **Low or nil** recharge in **flood plain** at the alluvial fan's end
- **Medium to significant** recharge in the alluvial fan close to **network of gullies** (a few $mm.year^{-1}$)

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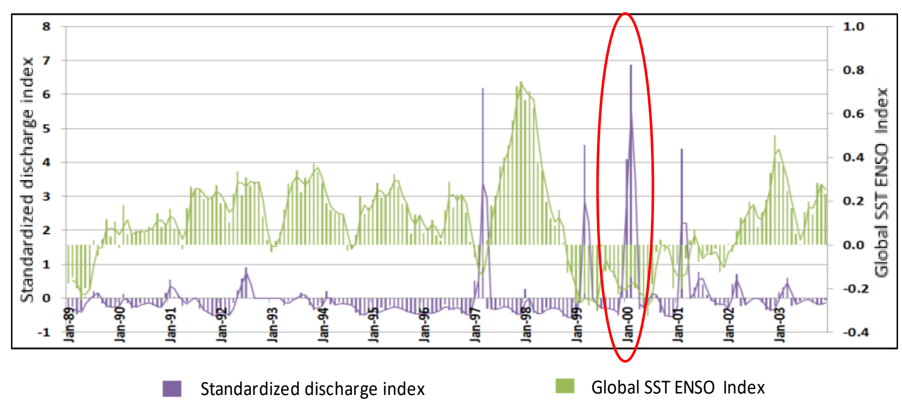
# Remaining questions

- **Flooding duration ?**
- **Size of flooded area ?**
- **4 events in 15 years, only one "efficient flood" ?**



Thanks !

Come and meet Benoit at 4.40 p.m → E-poster session 6.03