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Managing drought and scarcity in semi–arid lands:
The cases of California and Spain17 January 2015

Botín Foundation / Rosenberg International Forum on Water Policy
Madrid, January 29, 2015

Session 4: Responding to drought

The role of groundwater in Spain in coping with scarcity

Contents

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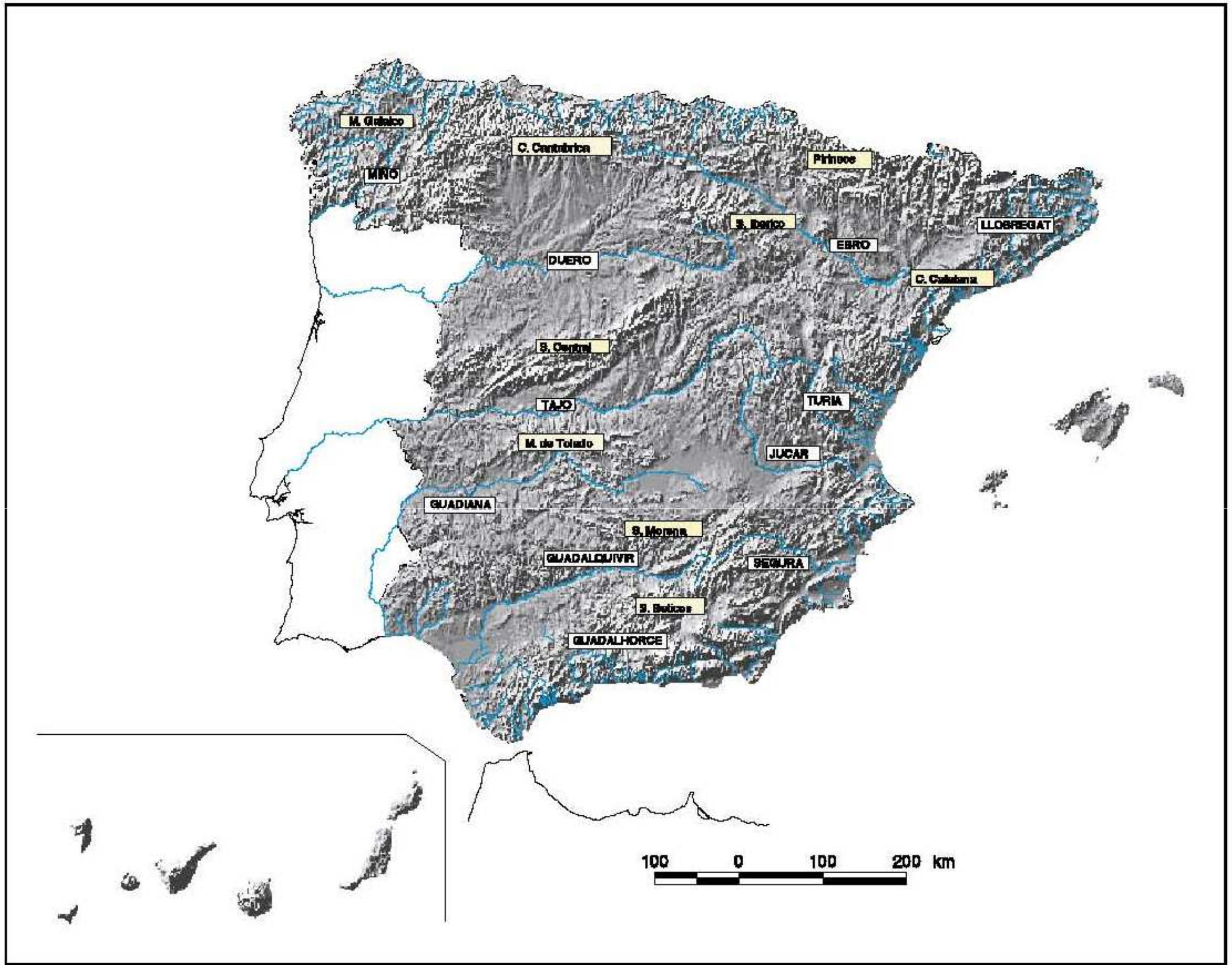
River basins in Spain and relief



About 1000 km to the SW,
in front of the Sahara coast

Territories:
- The Iberian Peninsula
- The archipelagos { Balearic Is. / Canary Is. }

About 500,000 km^2

Mountaineus
Small plains

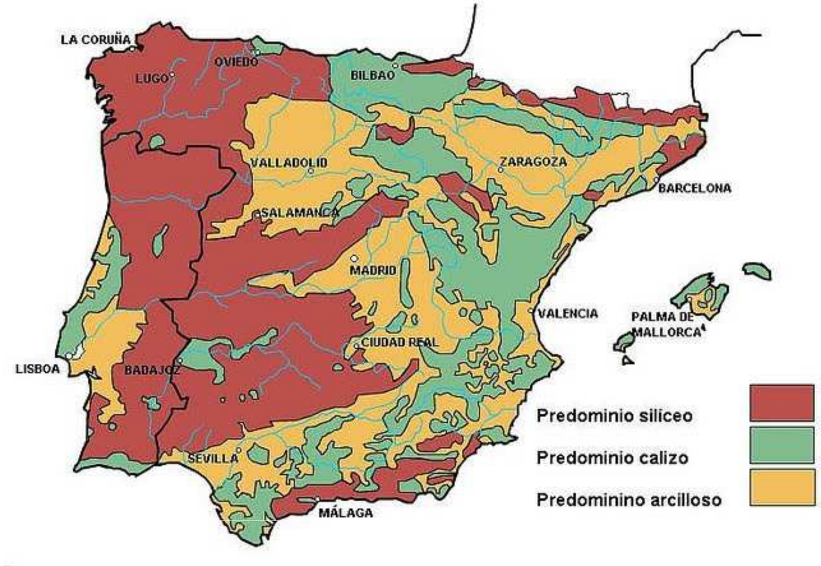
2/3 to the Atlantic Ocean
1/3 to the Mediterranean Sea

Rivers:
- effluent and influent
- effemeral in some tracts
- high slope

Water administration
- → river basins
- → islands

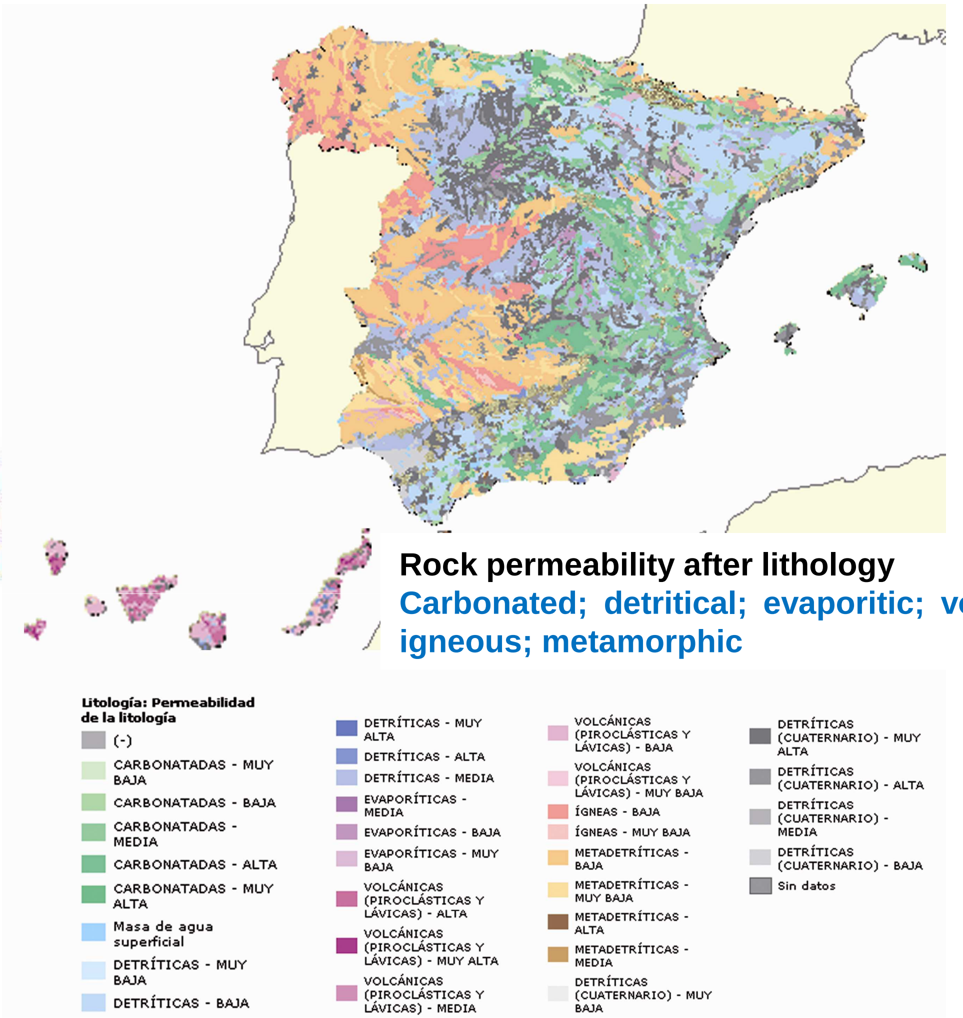
Irrigation, Population, Tourism, Industy } **Mostly in: Center, Med. Area**

Aquifers in Spain. Main lithologies



Main dominant rock types

Siliceous; carbonated; clayish/detrital



Rock permeability after lithology

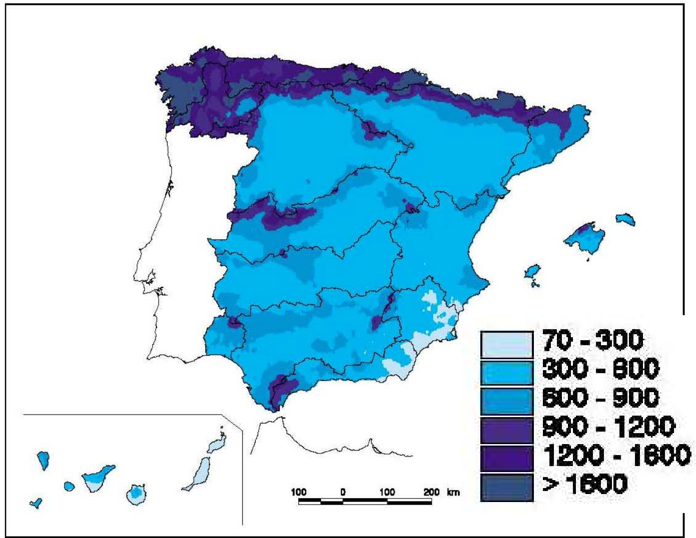
Carbonated; detritical; evaporitic; volcanic; igneous; metamorphic

Intensive geologic disturbance

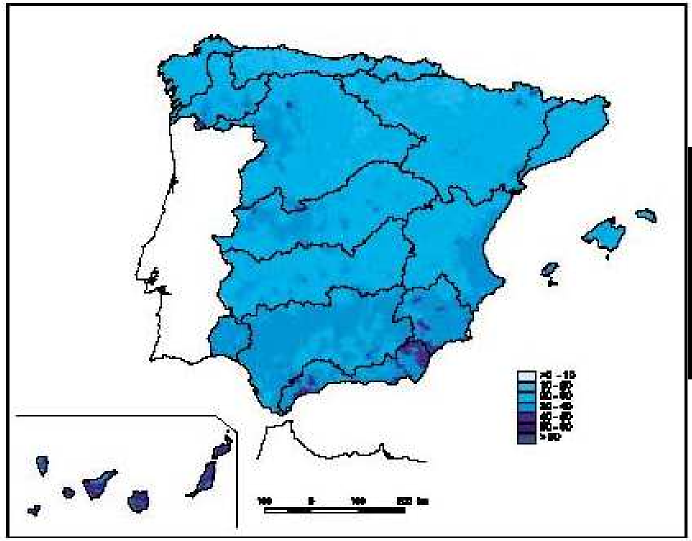
Few large aquifers
Small, moderate size, unconsolidated aquifers (100–600 km²)
Small–size thick, highly productive, low storage carbonate aquifers, in the E and S
Volcanic aquifers in the Canaries

→ 50.000 km² in the Central Valley of California

Rainfall and groundwater recharge in Spain

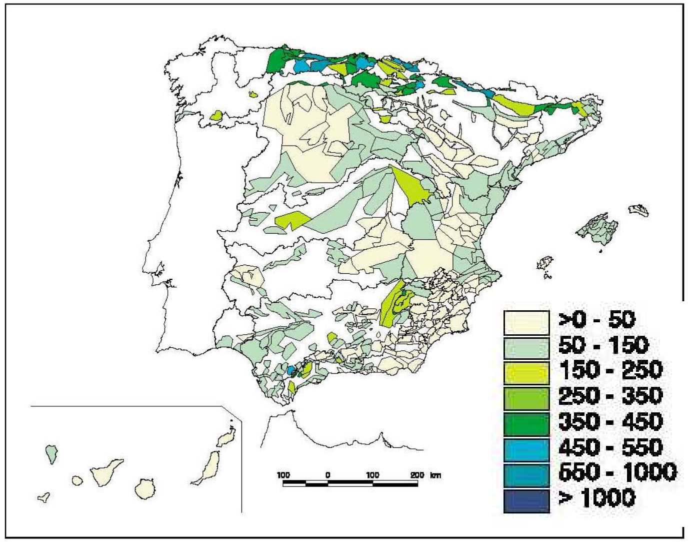


Average rainfall in mm/yr
LBA 2000



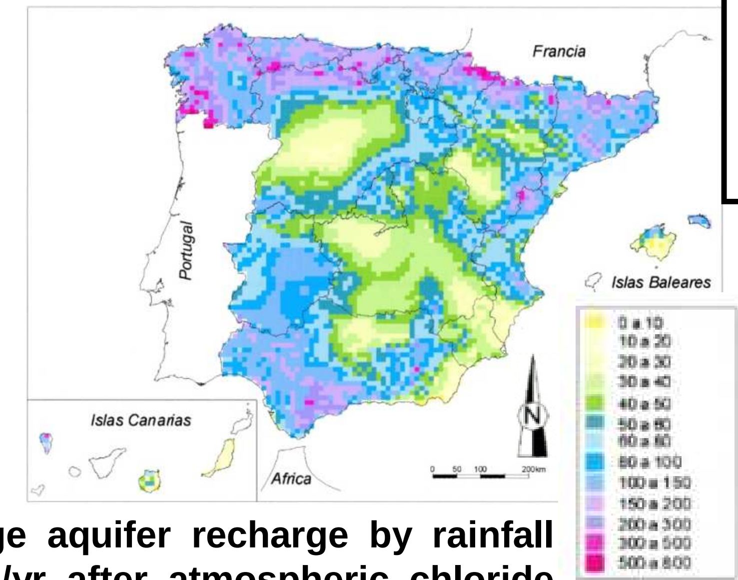
Coefficient of variation of yearly rainfall (%)
LBA 2000

Semi–arid conditions: Centre Mediterranean side



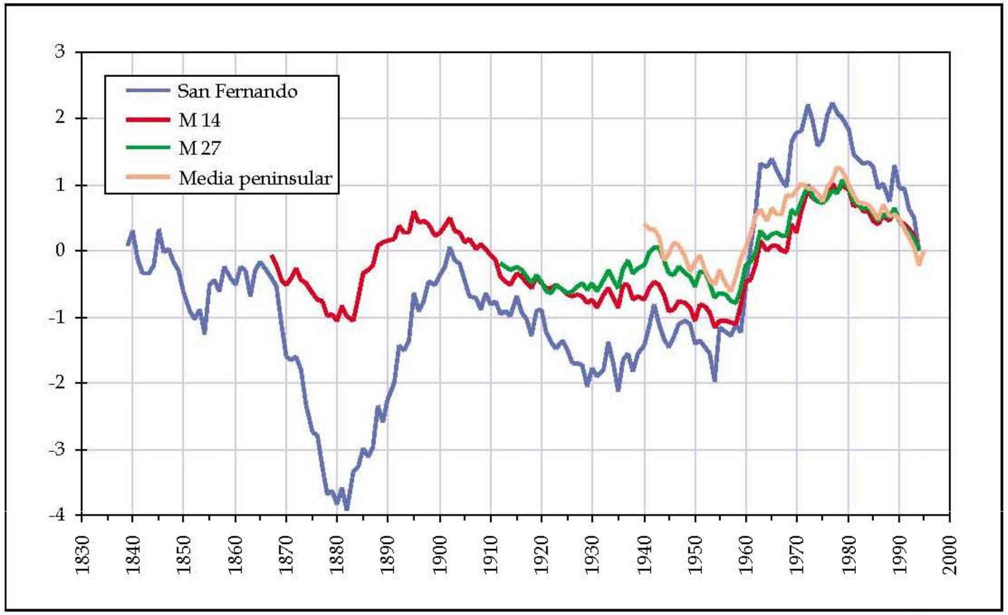
Average aquifer recharge by rainfall in mm/yr
LBA 2000

Arid conditions: part of the Canary Islands



Average aquifer recharge by rainfall in mm/yr after atmospheric chloride deposition balance
(Alcalá and Custodio, 2010)

Rainfall and water resources variability

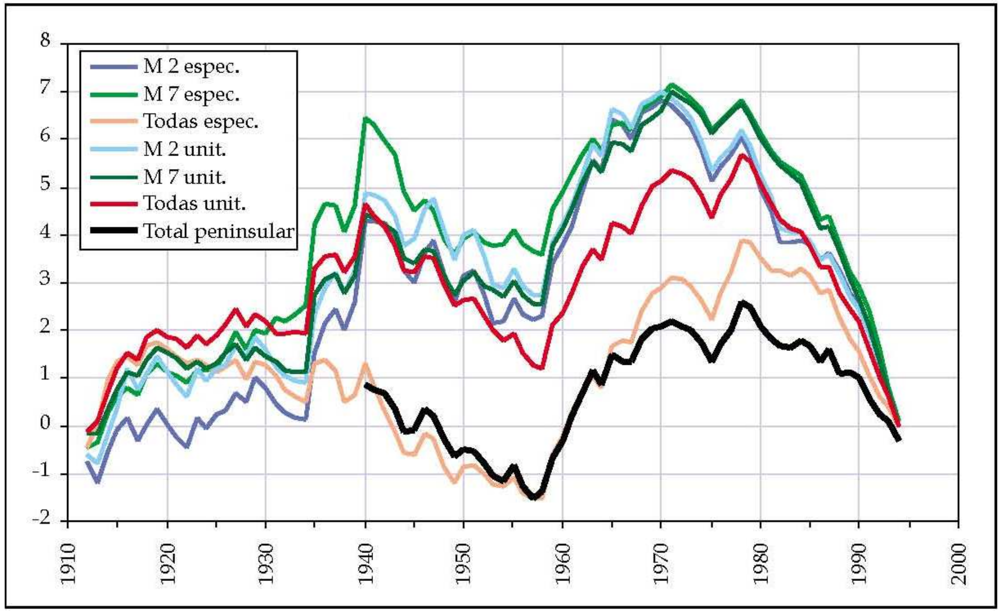


Cumulative deviation from the mean of the period

Values in metres

Annual precipitation. Various total periods. The longuest period 1840–1995

Annual water resources. Period 1910–1995



High irregularity **Cyclic behaviour of 10 and 20 years** **3–5 years** **Long dry/wet periods**

LBA, 2000

Some approximate definitions applied to groundwater

Reserves: aquifer volume x drainable porosity

Intensive development: a significant fraction of recharge is abstracted
important changes in the aquifer flow system
in its relation with other water bodies
drawdown may be large and increasing along time

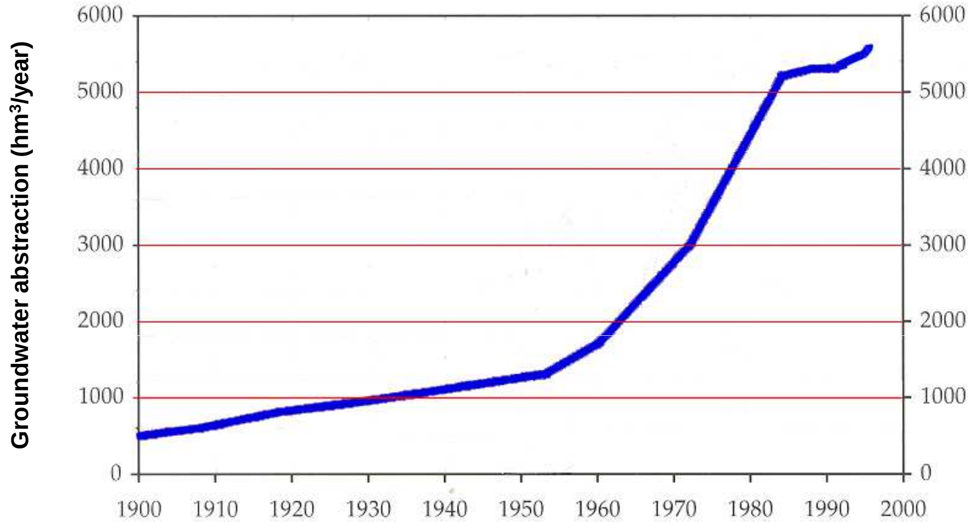
Overexploitation: Negative effects observed on groundwater quantity and quality
Subjective
Hydrodynamic effects not considered
A legal term in Spain
Its use should be discouraged

Renewable resources: ~ total net recharge
Variable according to circumstances: specify them

Exploitable resources: Those that can be abstracted with bearable consequences
Depends on **what is bearable**
economically, environmental, socially and politically
This is not a true technical result but a social and political decision

Groundwater mining ≡ sustained use of groundwater reserves
It implies: abstraction > recharge → steady state not possible
It is a long–term evaluation
When recovery needs > 50 years after abstraction ceases
When freshwater storage is changed into saline water

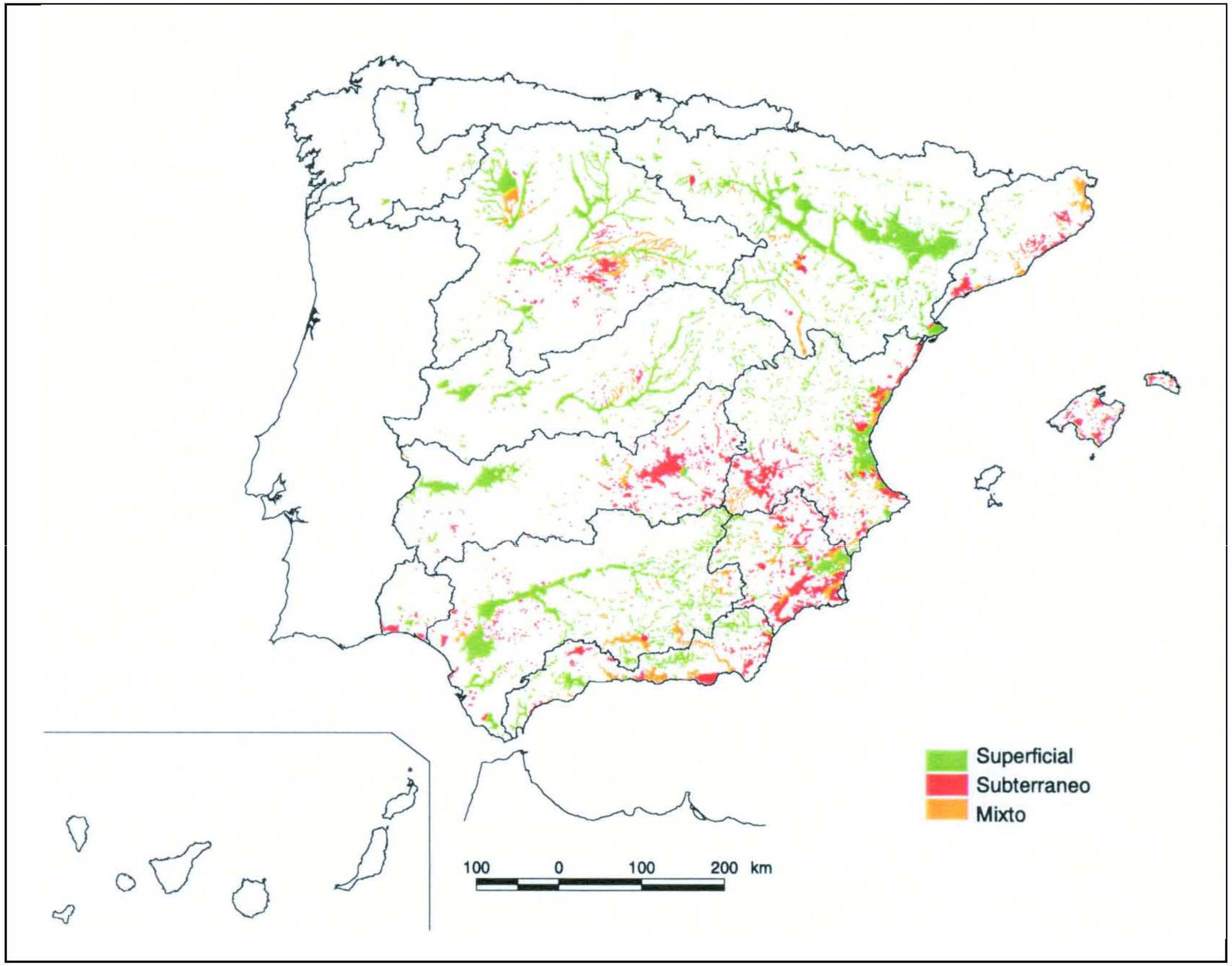
Groundwater development in Spain



Groundwater abstraction in Spain in hm^3/year

Current value is 7 km^3/year
Start of intensive groundwater development in the 1950s
Trend to stabilization after the 1980s

Groundwater use in agriculture in Spain



Map of irrigated zones with indication of water origin LBA, 2000

Agriculture uses 80% of GW resources in the Peninsula
50–60% in the archipelagos:
Mallorca, Gran Canaria, Tenerife, La Palma and Gomera

Legal conditions of groundwater in Spain

Water Act 1866 → all water in the public domain
1879 → groundwater in the private domain
1985 → **all water is a public domain**
→ to avoid expropriation of existing groundwater rights: legal options
- right holders • get public protection (?) by giving their rights
  maintain the rights for 50 years
  preference for a concession
  go to a registry
- preserve their rights forever
  without changing well characteristics (??)
  go to a catalogue
- reality → few owners have changed their status
  pre–law development was already intensive

→ **most groundwater is private in practice**

→ the inventory of groundwater rights is very incomplete

→ overexploitation areas can be declared by water authorities

owners in overexploited areas have to { adapt their abstraction / form an users' association

→ mostly a failure

→ **groundwater users associations** →public entities→some existing

2001 → incorporation of the European Water Framework Directive of year 2000
→ successive modifications → European "Groundwater Directive" of year 2006
→ the main problems are not properly addressed

The water law may condition groundwater use in droughts

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Administrative framework of groundwater in Spain

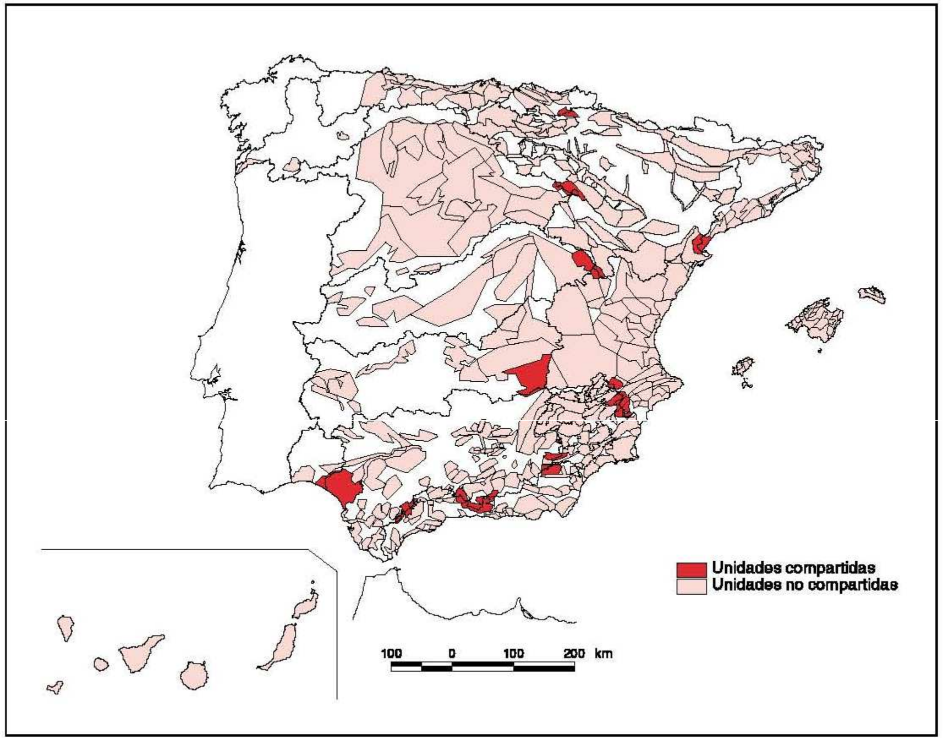
Political division in Autonomous Regions

Responsible of water resources and the environment but not of water management in shared basins

Administrative framework of water and groundwater in Spain

Often Regions and River Basins do not coincide

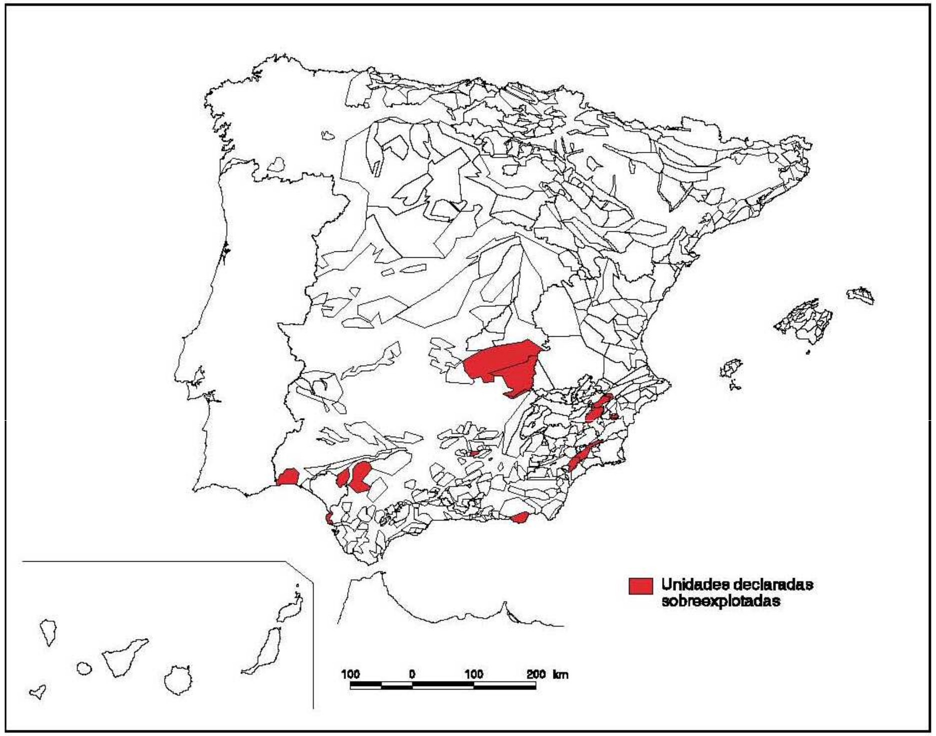
Map of hydrogeological units with shared units between water administrations



In pink → non–shared units
In red → shared units
LBA, 2000

Some shared units are intensively exploited
→ dificult management

Map of hydrogeological units with a some declaration of "overexploitation" in 1996

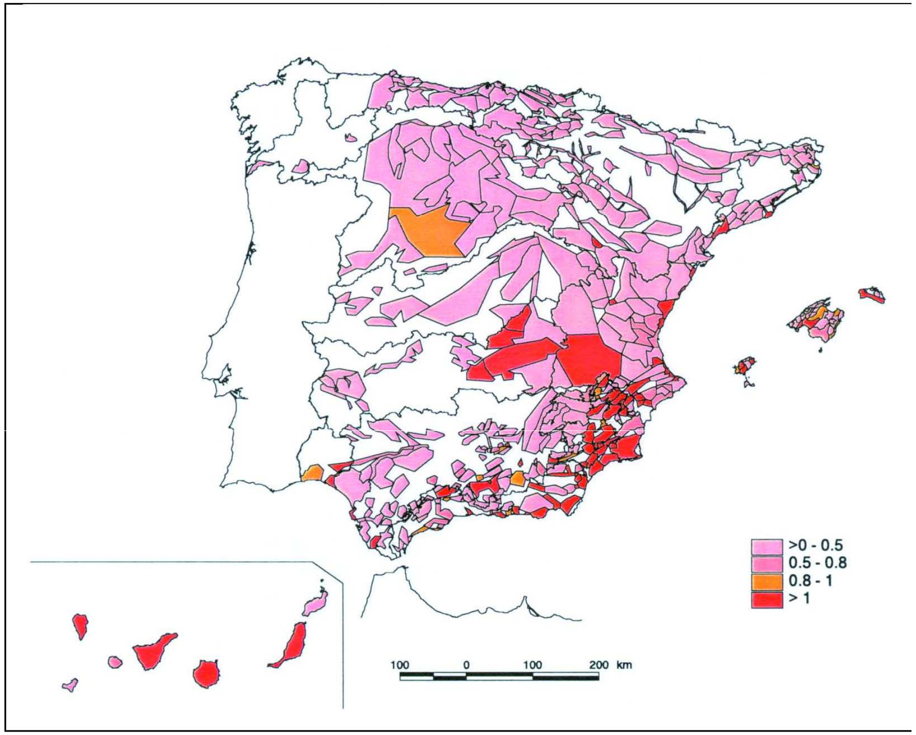


In red : official «overexploited units»
LBA, 2000

There are many more
After 25 years only a few have completed the procedure

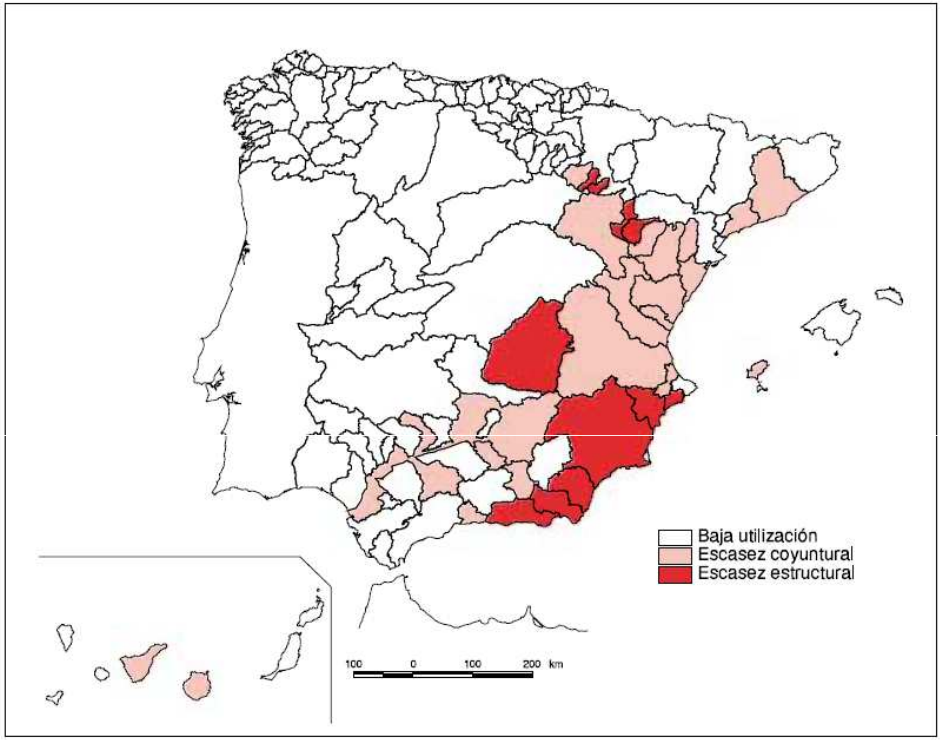
Groundwater scarcity

Ratio of groundwater abstraction to recharge by hydrogeological units



LBA, 2000

Excess of groundwater exploitation in hydrogeological units



LBA, 2000

Great intensity of groundwater exploitation in { the South–east / the Canaries }
Recharge is exceeded in some areas

Legend: low use
occasional scarcity
«structural» scarcity

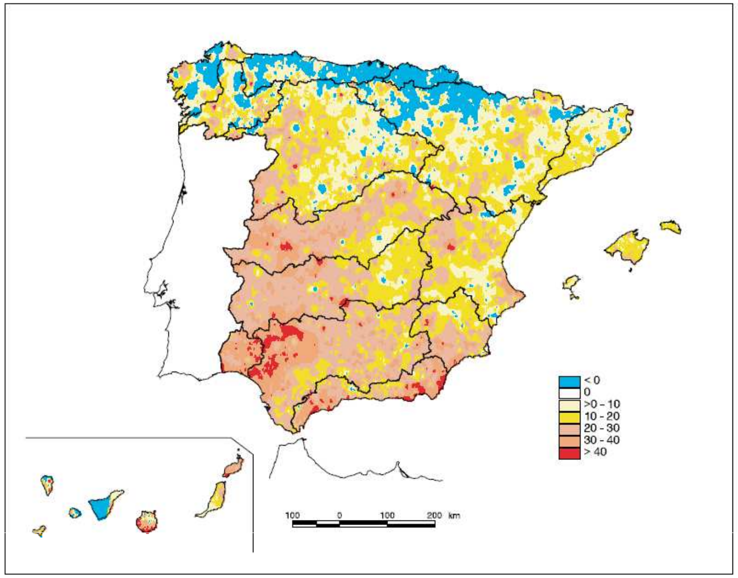
Total GW values in km³/year

	Península	Islands
Recharge	31	1,2
GW abstraction	7	0,6

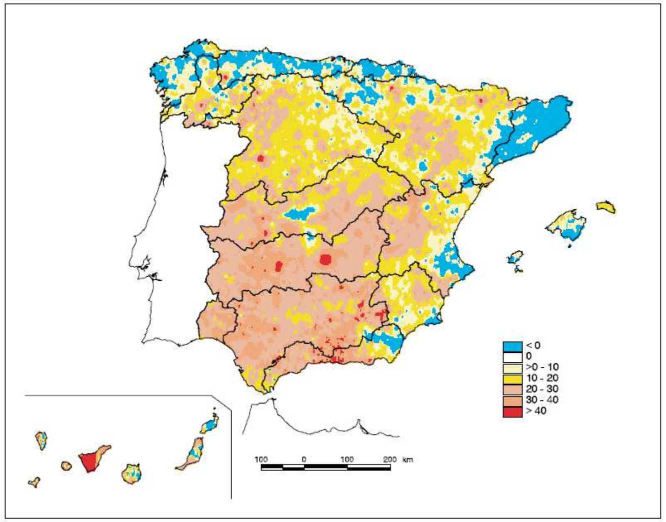
LBA, 2000

Changes in water resources in drought periods

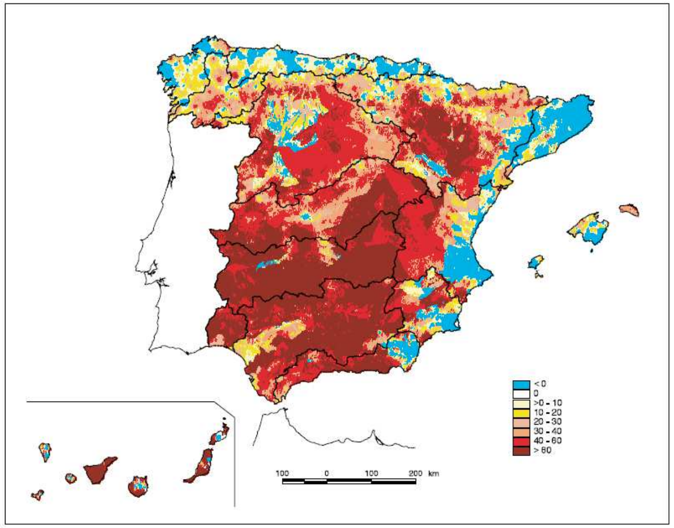
Percent reduction relative to the 1940–41/1995–96 period



Average rainfall decrease
1979–80/1982–83 period



Average rainfall decrease
1990–91/1994–95 period



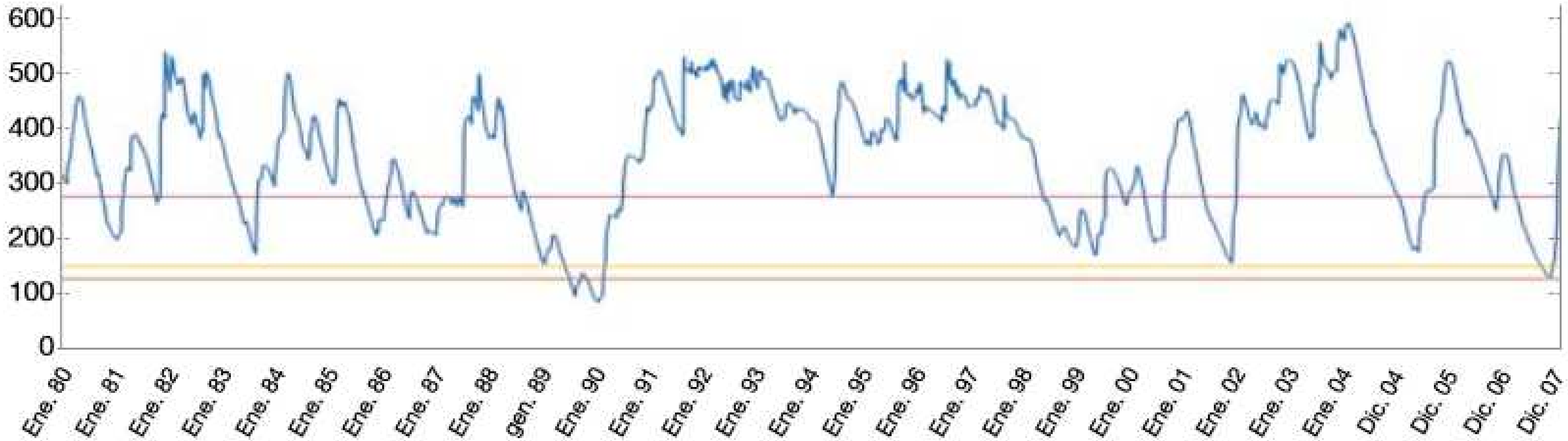
Average water resources decrease
1990–91/1994–95 period

Changes }
Severity } not coincident in the territory

Surface water systems suffer the more
→ even in wet areas

Groundwater systems are resilient

Current groundwater use in Spain in droughts



Water volume stored in the Ter–Llobregat system for the water supply of Barcelona

Thresholds for situations of: emergency; exceptionality; high exceptionality

They are often attained

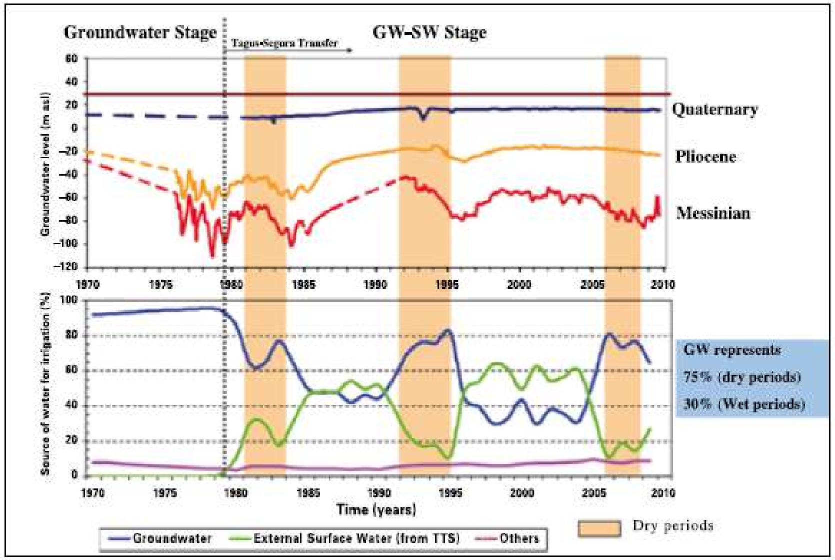
Solutions: lower Llobregat aquifer storage depletion + others

Campo de Cartagena area (Murcia)

Groundwater is intensively used in droughts

when { imported/industrially produced water
fails/is scarce/is too expensive

In the Mediterranean area "drought wells" are used for town and agriculture supply during droughts



The MASE project

MASE = Minería del agua subterránea en España
Groundwater mining in Spain

Executed: Department of Geo–Engineering, Technical University of Catalonia (UPC)

Prepared by : E. Custodio

Finantial support: AQUALOGY

Supervision: CETaqua

Considered aspects:
- hydrology / hydrogeology
- environment
- economics
- social issues
- administrative issues
- ethic issues

Use of data in:
- in existing reports and studies (non–exhaustive)
- from information from experts
  - contributions
  - questionnaire

No specific studies.

Areas considered: South–eastern Spain (Levante): southern Alacant, Murcia and Almeria
The Canary Islands: Gran Canaria, Tenerife

The MASE project

Results

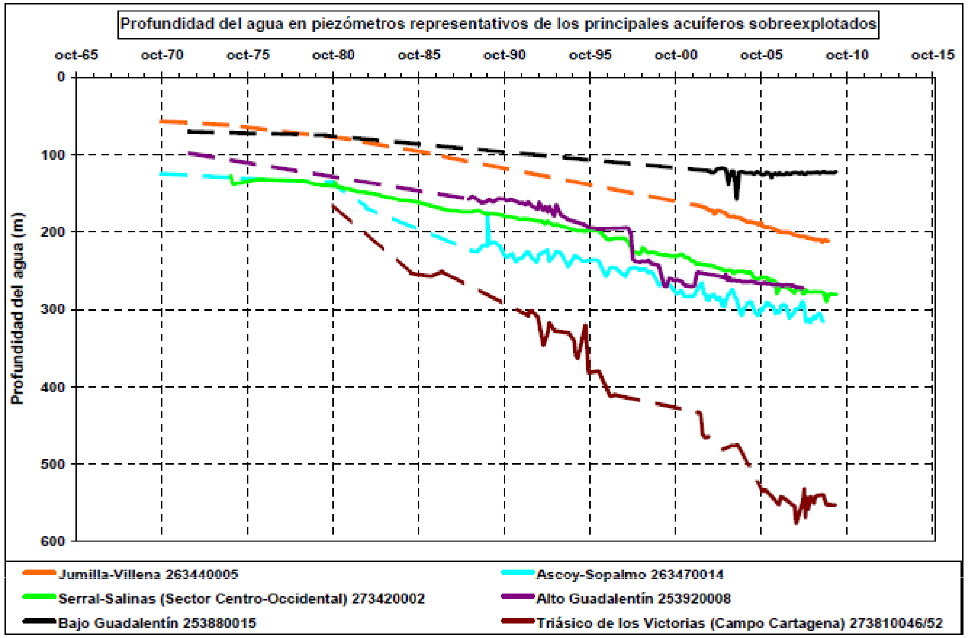
evaluation of groundwater intensive use and its consequences

importance for development and prospective

estimated groundwater mining: 15 km^3 in south–eastern Spain
0.3–0.5 km^3 in Gran Canaria Island
2 km^3 in Tenerife Island

partial volume recovery is possible after ceasing abstraction
- there is some significant recharge
- from some decades to some centuries (?)
- in Tenerife a part of the mid–to–top island is permanently drained by water galleries (long water tunnels)

Intensive groundwater use and mining in the Segura basin

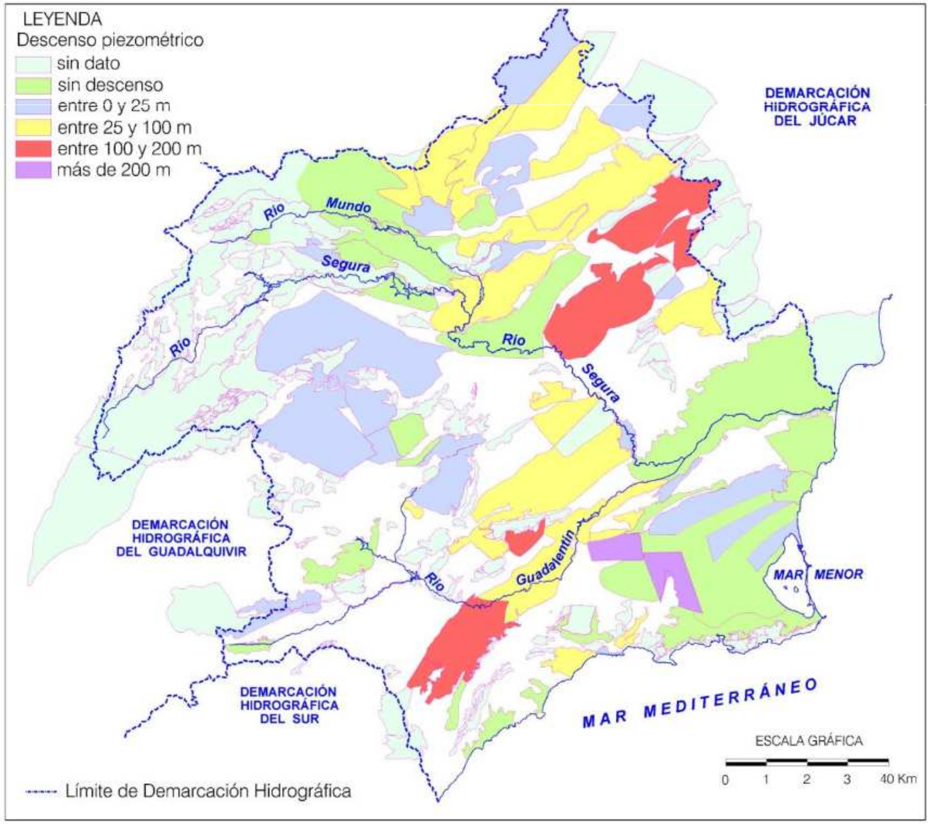


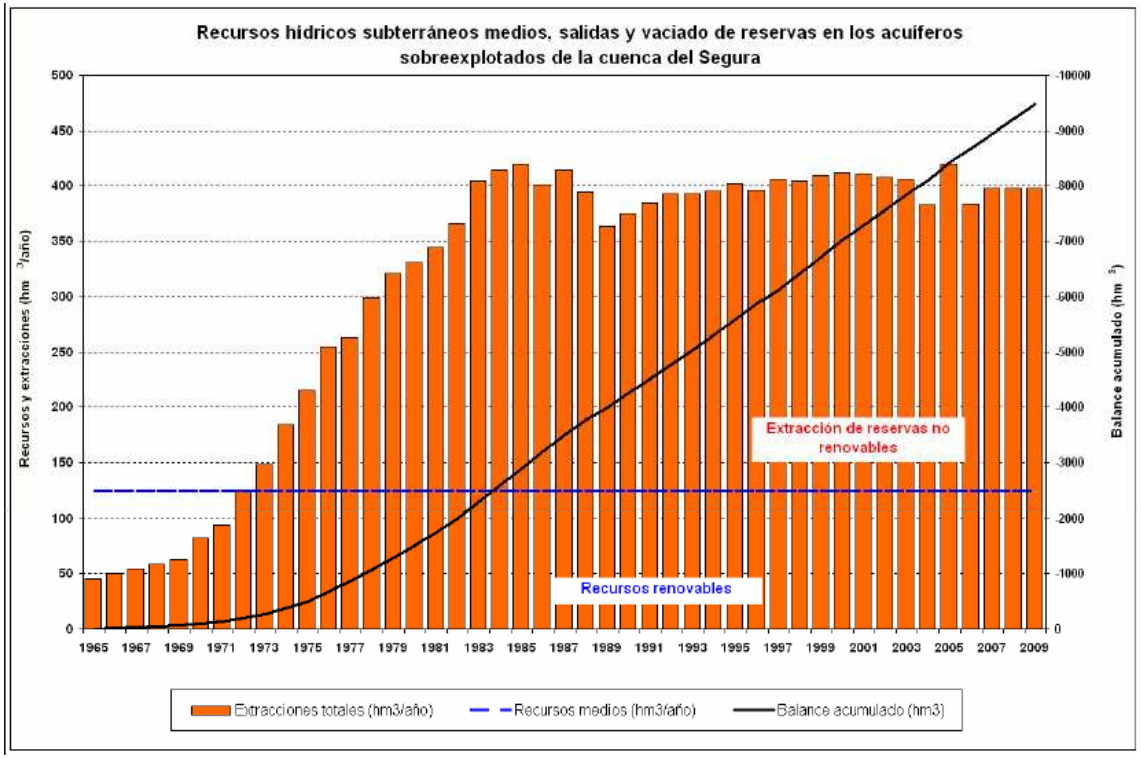
Piezometric level evolution in some of the more intensively exploited aquifers

(Cabezas, 2011, García–Aróstegui, 2013)

Total piezometric drawdown

(PHS, 2013)





Cabezas, 2011; Senent et al. 2013

Segura River Basin

Available water resources, hm³/a

Surface water	**500**
Imported water	**400**
«Azarbes» (river drains)	**40**
Reuse	**80**
Groundwater	
• renewable	**240**
• non–renewable	**170**
	1330

South–eastern Spain and the Canary Islands

Main water streams, desalinization plants, and aquifers in South–eastern Spain

Groundwater use

(modified from De Stephano et al., 2013)

Área	hm^3/year				
	Spain	Xúquer	Segura	CMA	Canaries
Urban	1500	320	---	140	125
Irrigation (C)	5000	1180	450	377	210
Industry	300	100	---	3	8
Recreation	65	10	---	20	12
Total groundwater(A)	7000	1610	485	540	355
Total water (B)	31500	3156	1850	1225	510
A/B groundw/total	0,22	0,51	0,26	0,44	0,70
C/A irrig/groundwater	0,71	0,73	0,93	0,70	0,59

South–eastern Spain and the Canary Islands

Use and economic value of groundwater for agriculture
(modified from De Stephano et al., 2013)

Área	Spain	Xúquer	Segura	CMA	Canaries
Total irrigated surface, 10^3ha	3345	490	200	210	25
Groundwater irrigated surface, 10^3ha	945	160	70	85	25
Total use, hm^3/a	12000	1655	800	755	170
GW use hm^3/a	3220	535	270	310	170
Production, M€/yr, for total	15300	2260	1450	2460	340
Production, M€/yr, for GW	4730	410	585	1385	340
GW / total use	0,31	0,18	0,40	0,56	1,0
Prod. / surface for total €/ha	4600	4600	7200	11700	13600
Prod. / surface for GW €/ha	5000	2600	8400	16300	13600
Prod. / use for total €/m^3	1.3	1.4	1.8	3.3	2.0
Prod. / use GW €/m^3	1.5	0.8	2.2	4.5	2.0
Endowment for total m^3/ha/a	3590	3380	4000	3600	6800
Endowment for GW m^3/ha/a	3410	3345	3860	3650	6800

Preliminary estimation of groundwater reserve consumption.
South–eastern Spain.
Period 1980–1995

Área	Groundwater reserves, hm^3			Consumption rate hm^3/a	Time to depletion, years
	Consumed, 1980–1995	Existing	Usable		
Almería	800	1100	750	50	15 (10–75)
Murcia	2000	10000	7100	125	60 (10–80)
Alacant	1000	7000	6000	50	120 (10–400)
Valencia	100	2500	200	15	130 (20–350)

(DOGH–ITGE, 1997)

Current estimated total groundwater mining: 15 km^3

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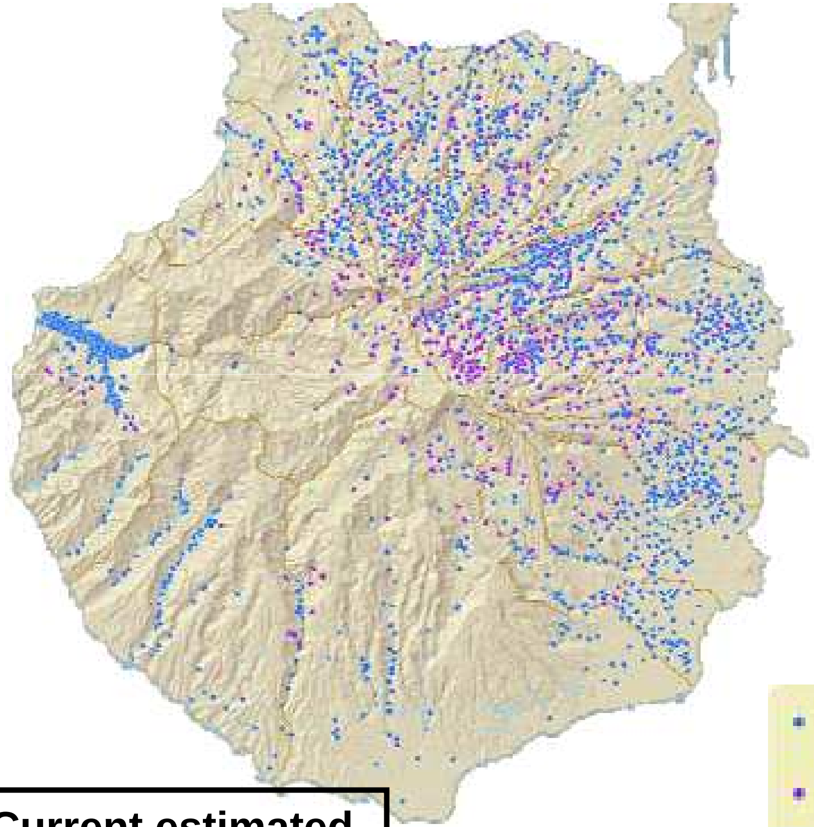
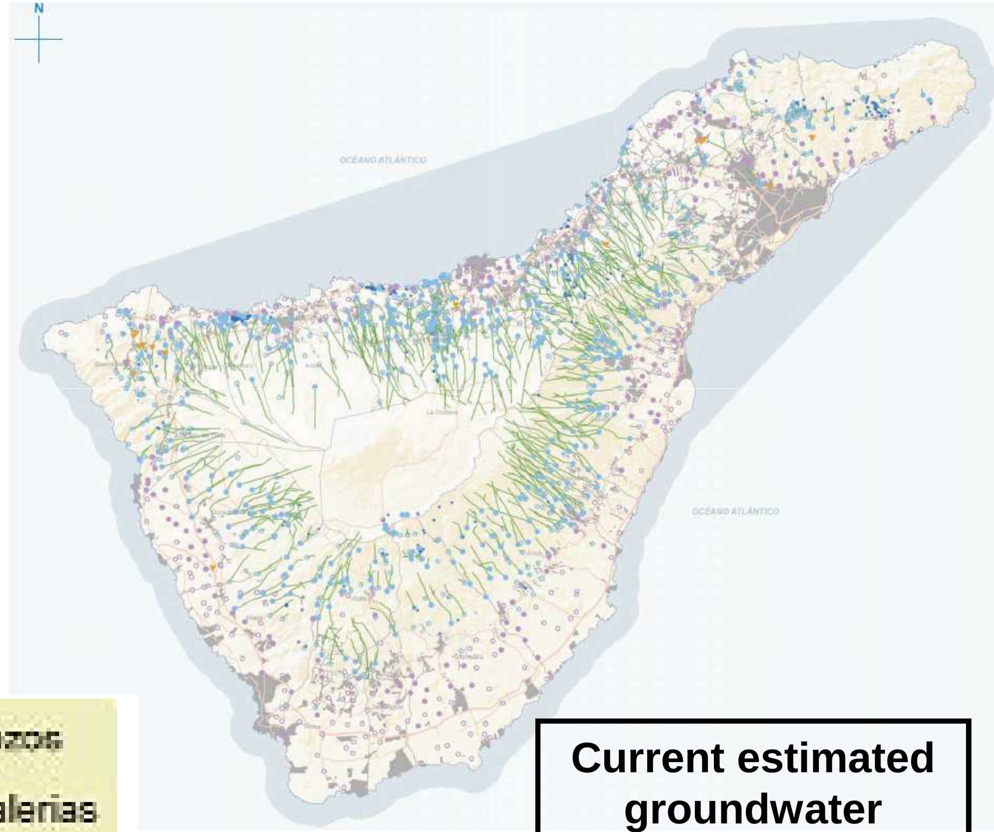
Groundwater in Gran Canaria and Tenerife: Canary Islands





Current estimated groundwater mining 0.3–0.5 km^3

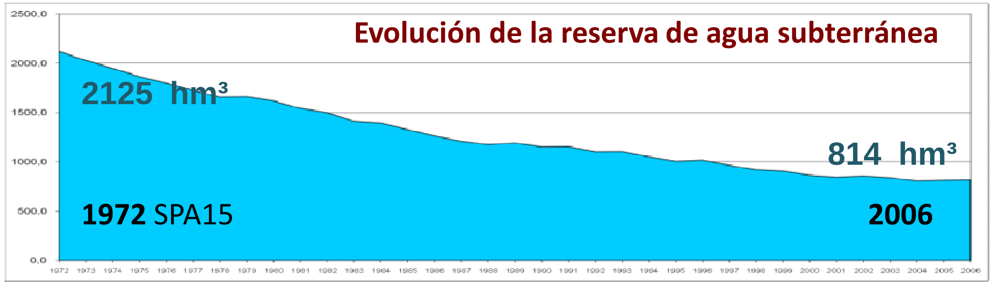
Gran Canaria

Tenerife

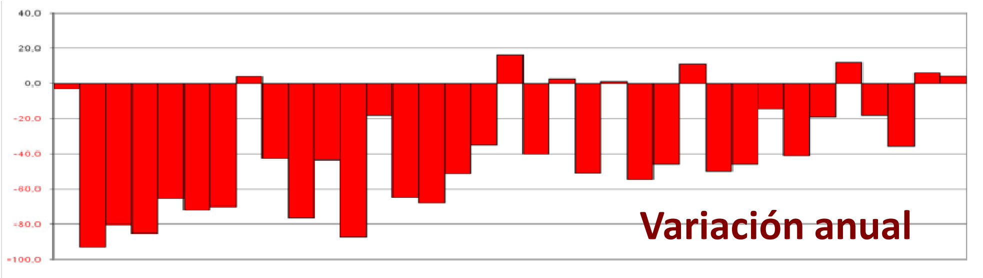
Current estimated groundwater mining 2 km^3

Wells and well–shafts; Water galleries (water tunnels); Boreholes

Groundwater reserve evolution inGran Canaria Island aquifer



Evolution of groundwater reserves



Annual changes of groundwater reserves

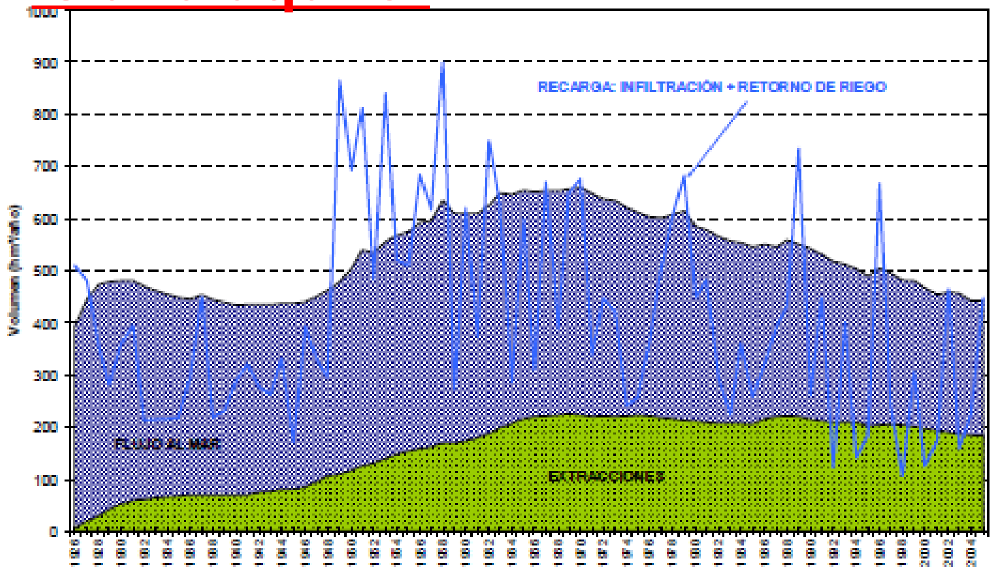
Water table depth in a high– altitude, deep borehole →

Consejo Insular de Aguas de Gran Canaria, 2009

Groundwater abstraction reduction due to the high cost pumping

Groundwater evolution of Tenerife Island aquifer

(PHTF, 2010)



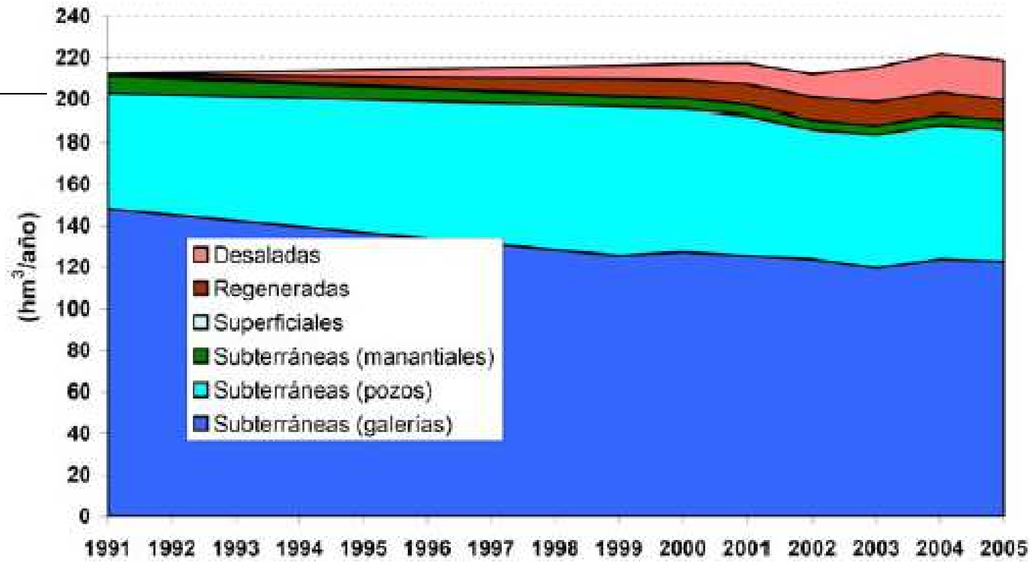
Evolution of groundwater balance components

(ETITF, 2008)

Decade	1971–1980	1981–1990	1991–2000	2001–2005
Input, hm³/a				
Recharge	338	321	235	279
Irrig. return flows	93	55	38	27
TOTAL	431	376	273	306
Output, hm³/a				
Abstraction	218	213	205	188
To the sea	399	342	294	266
TOTAL	617	555	498	456
Reserve decrease	186	179	225	148

Large water table drawdown
Important groundwater outflow to the ocean
Large rock volume drained
by mid– and high–altitude water galleries
→ non–recoverable

Groundwater balances



Desalination; Wastewater reclamation; Surface water; Springs; Wells; Water galleries

Groundwater quality issues

Salinity problems
- Climatic effects in the southern areas of the Canary Islands
- Coastal effects (seawater contamination) along the Mediterranean coast
- Return irrigation flows in many areas (poor irrigation water)

Other natural groundwater quality problems:

gypsum and halite dissolution from sediments in the Mediterranean area and the Ebre River basin

high Na–HCO_3 in Tenerife and Gran Canaria Islands

high F in Tenerife Island

Anthropogenic groundwater quality problems: high NO_3, up to several 100s mg/L

De–brackishing of groundwater and others:

practiced in Barcelona, Campo de Cartagena and Gran Canaria

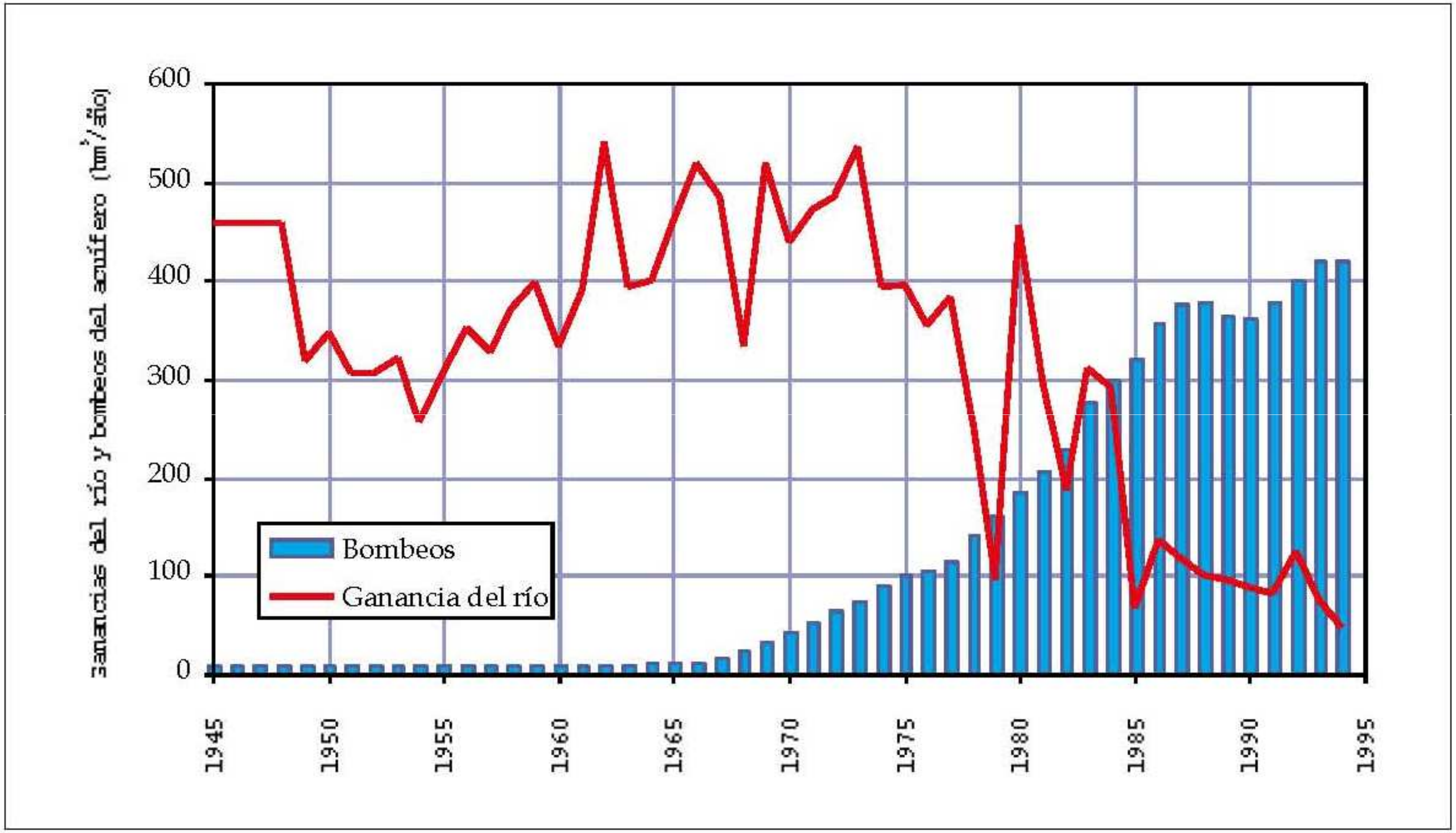
Groundwater quality in droughts: In some cases deterioration due to deep groundwater mobilisation

Until present poor attention → water quantity usues dominate
→ water mixing is common
except for same large water supply systems: Barcelona
Treatment for groundwater quality is costly → more attention is paid
- debrackishing
- nitrate reduction

Prospect for improvement
- when the aquifer functioning is known
- by improving the current poor well construction technology

2015 Botín/Rosenberg–25

Environmental effects: on rivers



Júcar River flow decrease due to development of the La Mancha Oriental aquifer for agricultural irrigation at the upstream part of the basin.

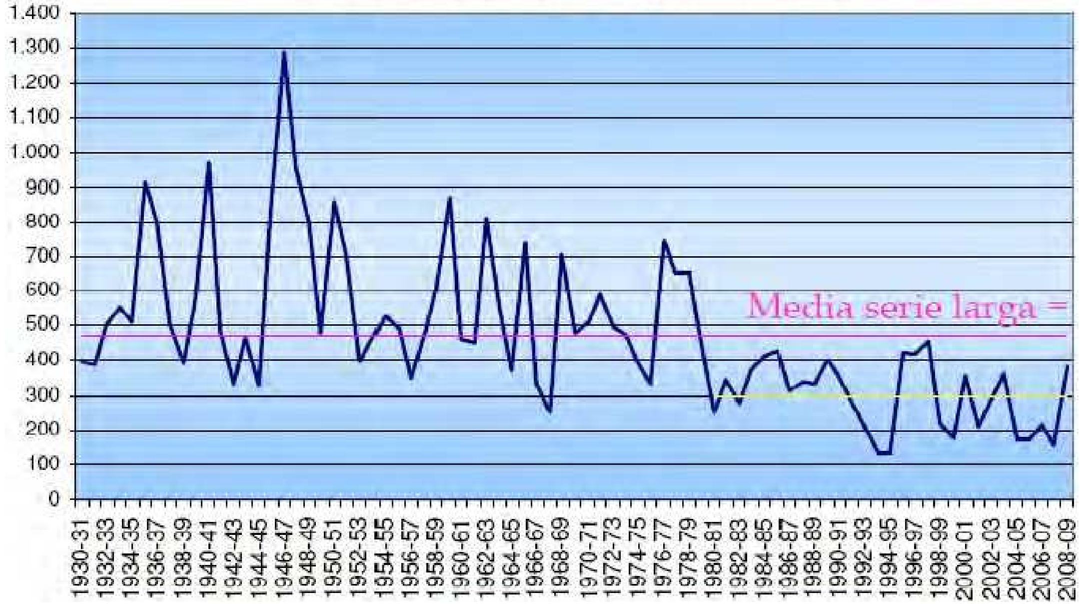
MIMAM, 2000

Environmental issues related with intensive groundwater use development

Segura River flow decrease

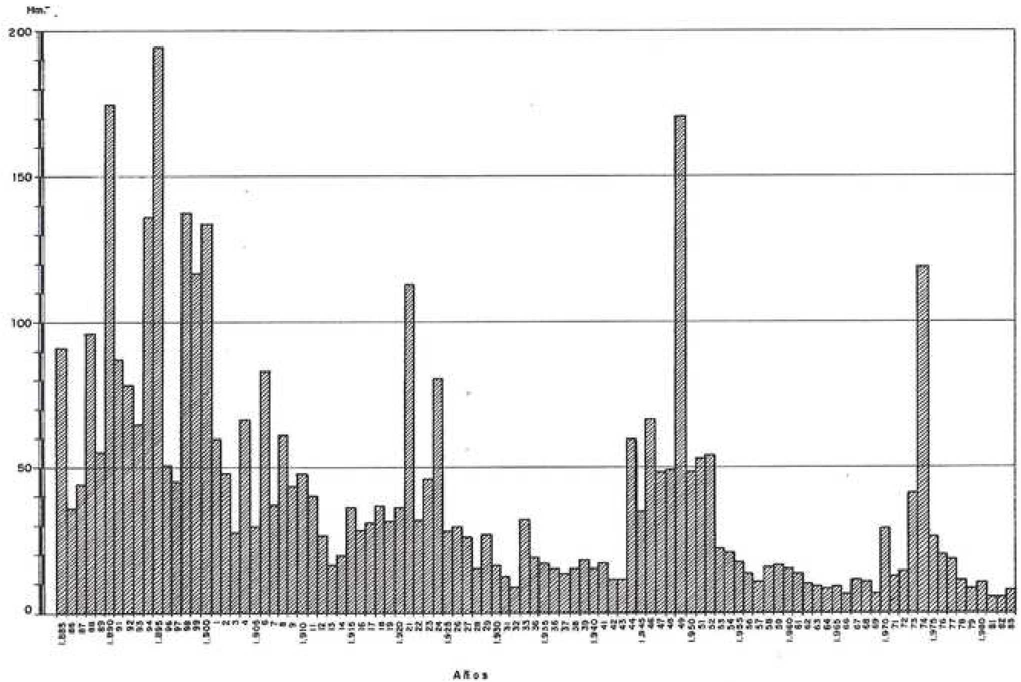
Partly explained by increasing upstream groundwater development

Most of depletion is due to surface water use



Upper Guadalentín River flow decrease

Not explained by upstream groundwater development



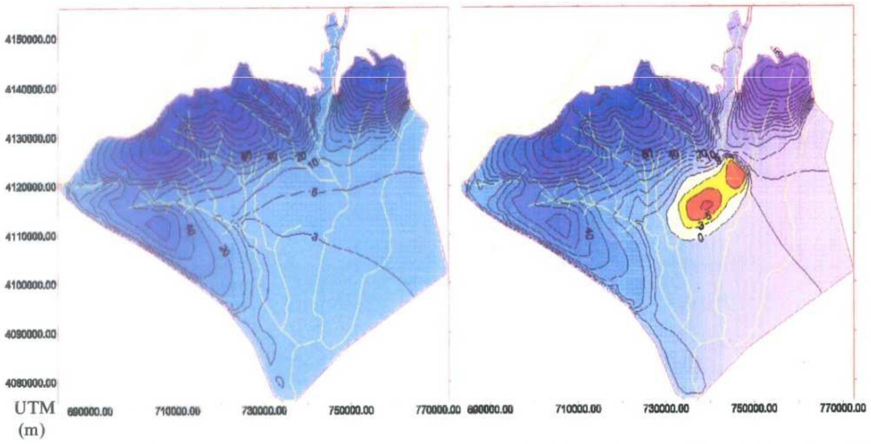
Causes of river flow decrease are not always well explained

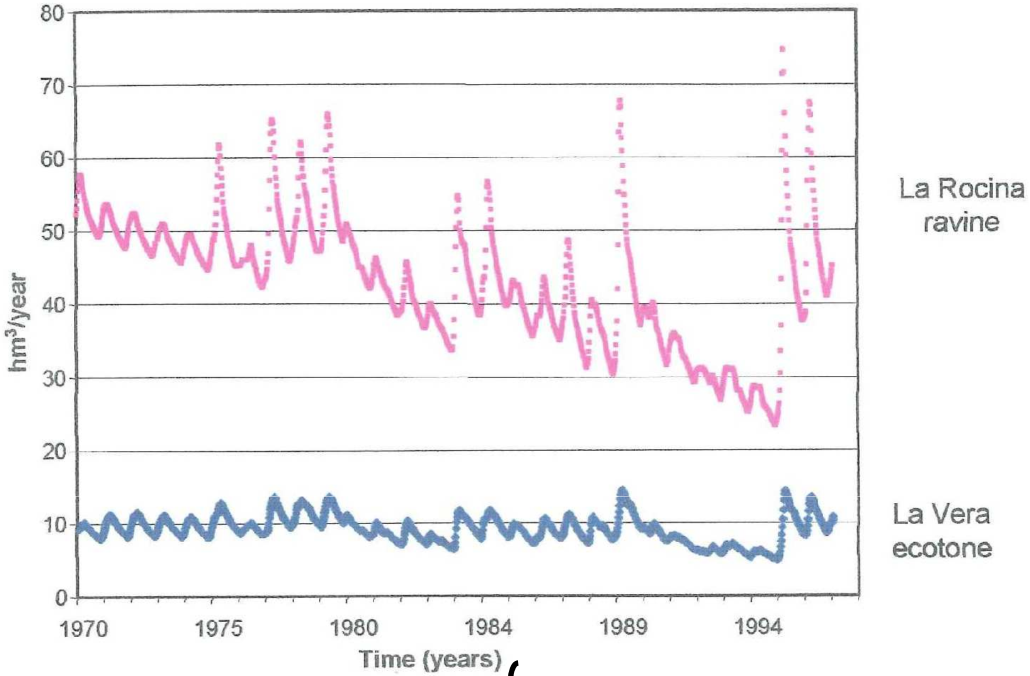
Environmental effects: Doñana National Park

The largest natural park in Western Europe
A Ramsar site and UNESCO protected area

Groundwater level above mean sea level (m)

Natural conditions October 1992	Disturbed conditions October 1996





Groundwater discharge to { La Rocina ravine / La Vera ecotone

Dramatic situation of 1994 → combined effect of:

- cumulated water level lowering due to pumping,
- a 4 years–long drought

modified from UPC, 1999

Large irrigated area with local groundwater.
Developed mainly in the 1980s

Conflict between { social development / nature preservation

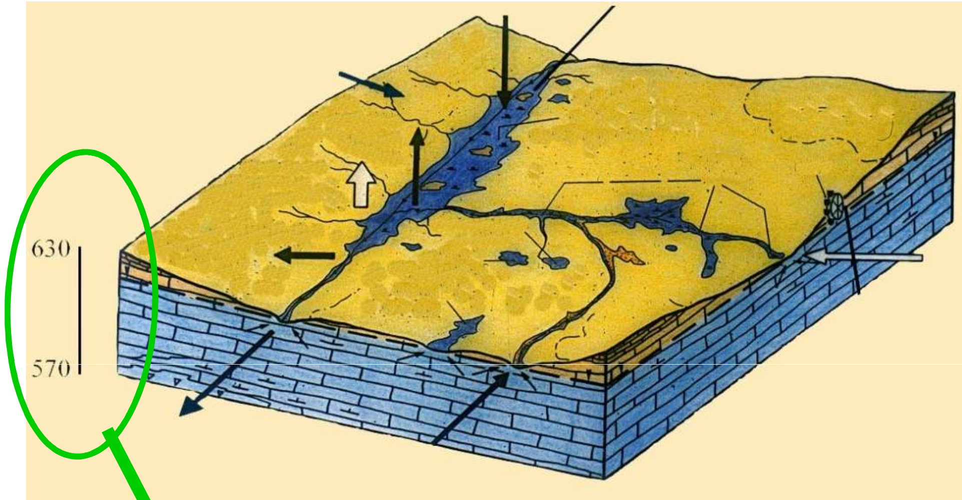
Complex governance

Results: northern ecotone dried up
western and southern ecotone reduced
decreased / more irregular stream flow
impairment of lagoons

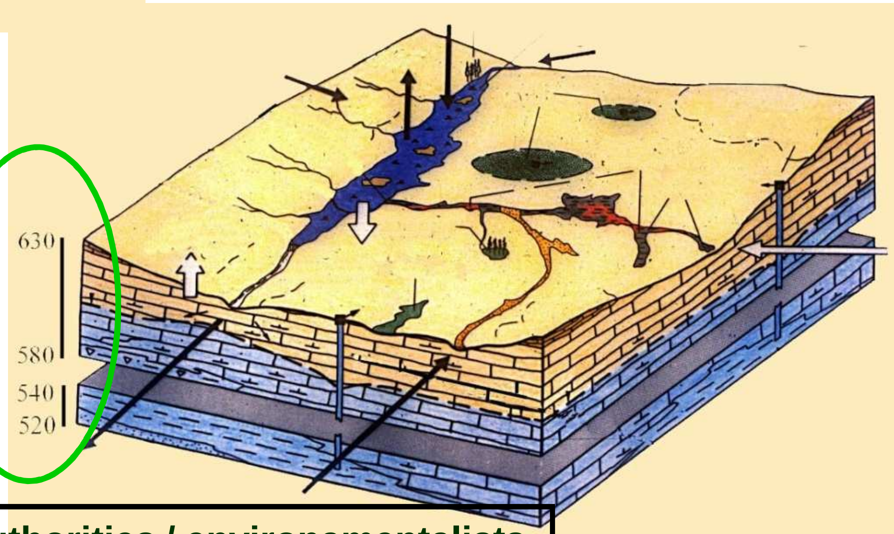
Environmental impacts: Las Tablas de Daimiel wetlands

A key permanent wetland area in Western Europe
Ramsar site
UNESCO protecte area

NATURAL STATE



DISTURBED STATE

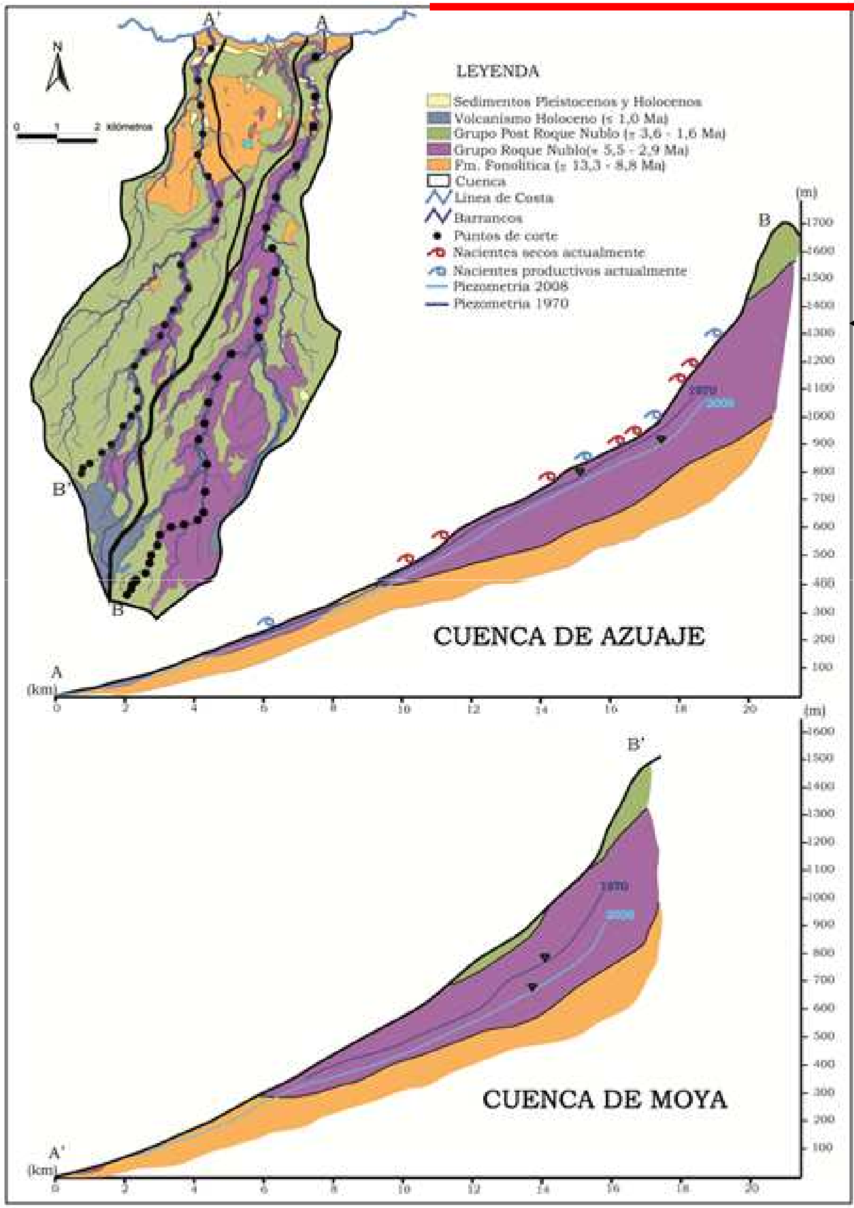


Significant decrease in piezometric levels; more than 30 m

25 years of conflict between farmers and water authorities / environamentalists
A partial solution has been agreed

Effects of intensive groundwater exploitation in northern Gran Canaria Island

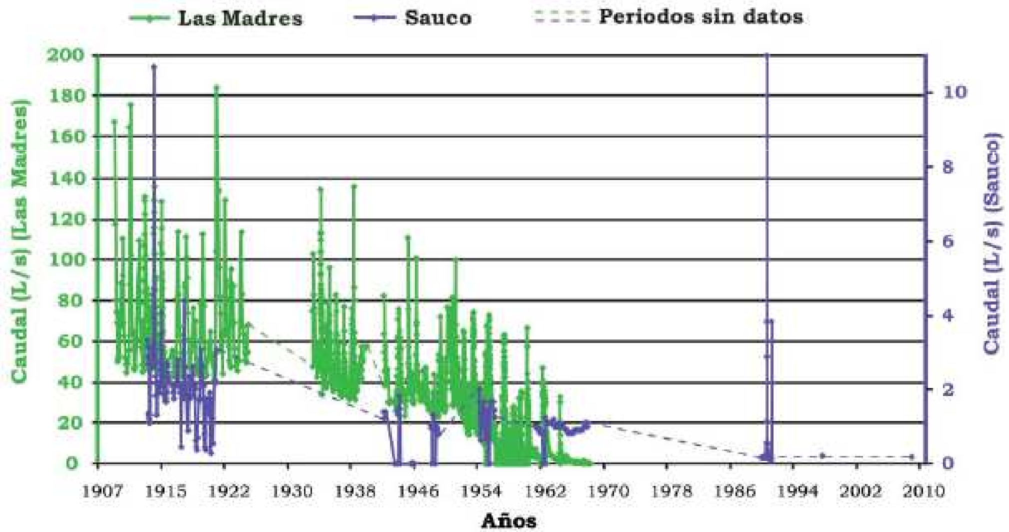
Large effects in
- spring flow
- environment
- other GW developers



Evolution between 1970 y 2008

Barrancos (gullies) de Moya and Azuaje
Water–table drawdown. Reserve depletion

Hernández–Quesada et al., 2011
Cabrera et al., 2014

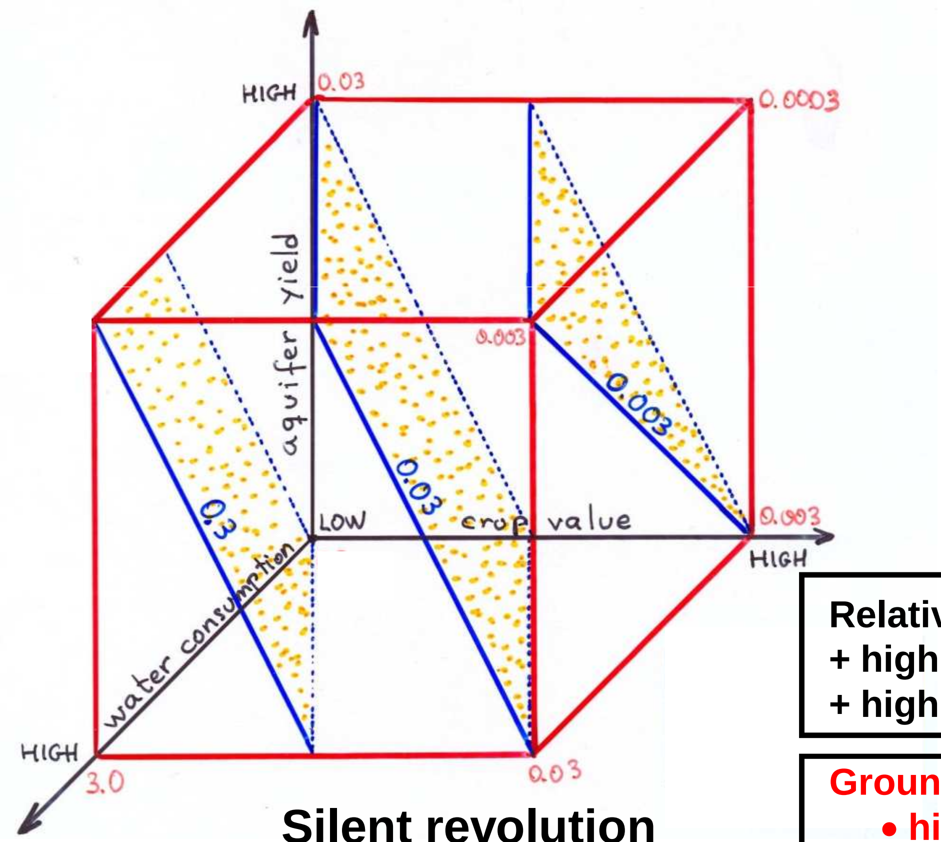


Springflow decrease, Bco. Azuaje

Permanent surface water has almost dissappeared
Few people keep memory of old conditions
Some present recovery due to high pumping cost

Economic issues related to groundwater intensive use

Groundwater costs and prices
Groundwater as a security investment to cope with drought
Groundwater versus other water sources



Silent revolution

(Custodio, 2004)

Idealized representation of

- agricultural production
- water consumption
- crop value

Shadowed plans: surfaces of equal ratio

$$\frac{\text{water cost}}{\text{crop value}}$$

Relatively cheap groundwater + high priced crops + high yielding aquifers	→	• almost non–stopable GW development • silent revolution

Groundwater abstraction costs in stressed areas

- high → 0,4 to 0,5 €/m³ → up to 1,0 €/m³
- still cheaper than water from other sources in the site
- subsidies distort the concurrence
- important role in droughts

Socio–economical issues related to groundwater intensive use

Taxation → early attempts failed

even to get resources for monitoring / administration

Trading of public water rights → just starting in the South–east
short experience
some reluctancy of water right holders
close control by water authorities

Trading of private water rights

- common in some areas of Peninsular Spain, especially in the South–east
  - bilateral agreements
  - poorly known
  - limited importance
- well established in Gran Canaria and Tenerife, and to some extent in La Palma Islands
  - old tradition in water markets
  - trade of { galleries and wells shares for construction; groundwater + transportation }
  - water produced by public entitites is sold in the markets
    - partly subsidized → control of prices
      → less incentive for private investment

Increase of water offer by public entities is partly subsidized

- to respond to social and political pressure
- to try to { reduce groundwater mining; increase environmental water flows }

Still poor action to manage water / groundwater demand

Groundwater institutions

Large and old experience in water users' institutions to manage their water

- mostly for surface water
- rarely involved in resource management and protection

Scarce institutions for groundwater resources management

- 10 groundwater user's association already exist
- the first one started in 1975, when groundwater was in the private domain
- it is the most effective → town suppliers and industrialists
  difficult to form when farmers dominate
- existing ones have been highly effective in { monitoring, control, agreeing with authorities }
- created bottom–up
- poor results if top–down to comply with legal requirements in areas declared "overexploited"
- key institutions to cope / tame drought effects

Poorly structured civil society

- partly displaced by political action
- lack of experience in using their { vision, capabilities }

Variable degree of transparency in public water institutions

unclear action during droughts

→ large and costly failures due to lack of transparency (case of Barcelona)

Some considerations related to grundwater mining

- Groundwater mining is a fact and will continue unless subsidized water is not provided
- The main deterrent to groundwater mining are not regulations but
  - the increasing weight of energy cost
  - in some cases groundwater quality deterioration
- Environmental effects
  - are poorly known and valued
  - mostly happened decades ago

  recovery
  - is difficult
  - it may be at a disproportionated cost
  - it may produce damage in some areas

- Ethical aspects

  some slow recovery is possible

  need of a change of paradigm → a difficult task

  need of groundwater users involvement in
  - monitoring
  - surveyance
  - decision making

  civil society should
  - recover from current poor activity
  - be more concerned

  politicians should not overcontrol groundwater affairs

Prospective

Enactment of a more flexible Water Act

→ **solve the stiffness of water rights and concessions**

Agreement on a water pact { **among all interested actors** / **especially among political parties** }

→ **the seed is on the mind**

→ **this is large ignored by present government**

→ **its interest centers on water planning (WFD required)**

Consideration that groundwater mining { **is not necessarily evil** / **in some cases it is good** }

control it
keep benefits to compensate for current and future damage
consider it as a transient situation with a dead end

Improvement of groundwater mining experience

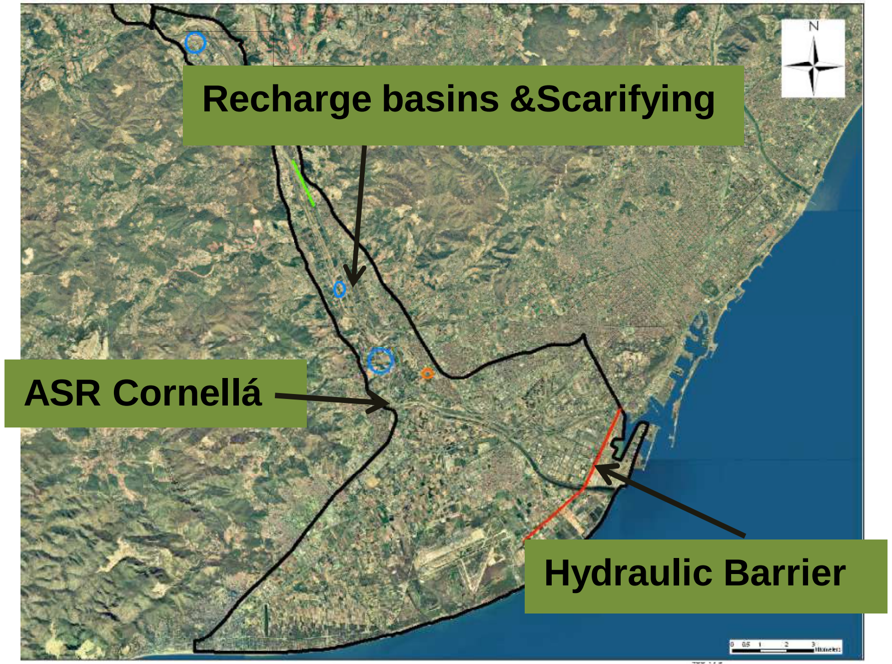
→ **study the experience in other parts of the World**

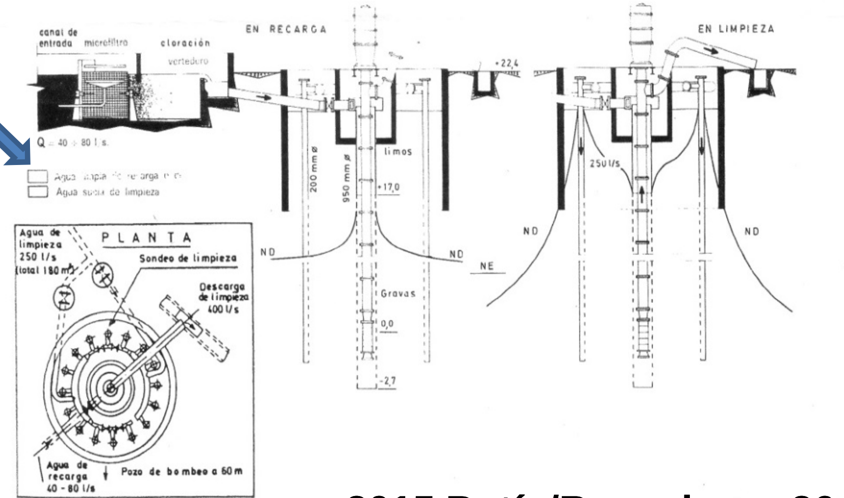
→ **develop the GWM project to compile worldwide existing experience**

Incorporation of groundwater reserves into drought management

CONJUNCTIVE USE IN SPAIN

- Artificial Recharge
  - Supply of the Metropolitan Area of Barcelona
    - Llobregat river
      - » Sea water intrusion Barrier
      - » 12 dual recharge–pumping wells ASR
      - » Recharge basins
      - » River bed scarification
    - Besós river
      - » 2 ASR wells (1954 and 1955). Pumping and injection well ø 1m and 16 ø 0.2 m to help cleaning
  - Others
    - Belcaire river (Castellon)
    - Algar dam. Purposely leaking dam in limestone
    - Canal de Isabel II (Madrid)





ALTERNATE CONJUNCTIVE USE

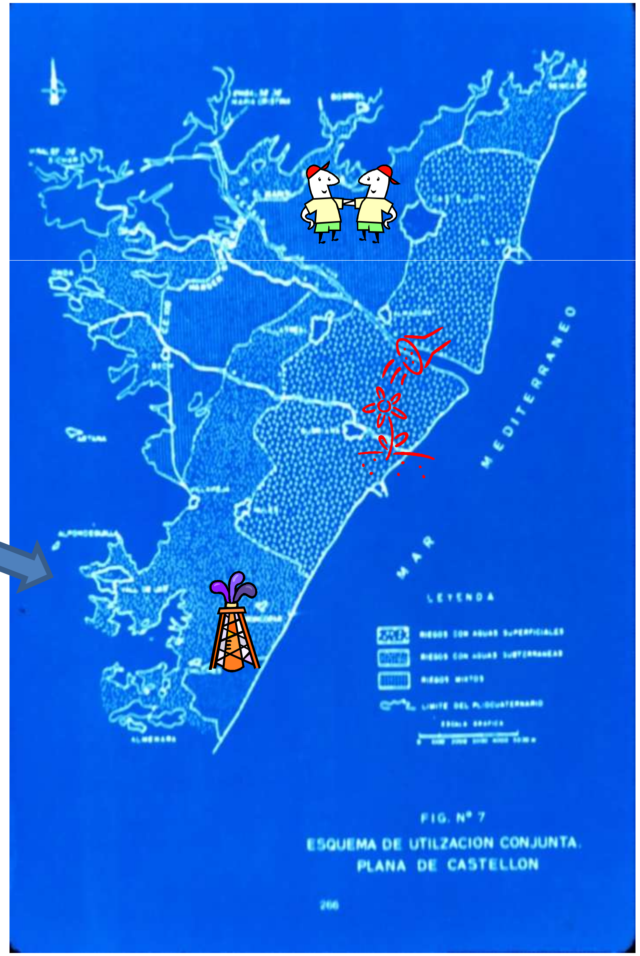
Mijares river Plana de Castellón

- Water needs part with surface water
- Part with groundwater
- Remaining parts alternate ways; more g.w in dry years and more s.w in wet

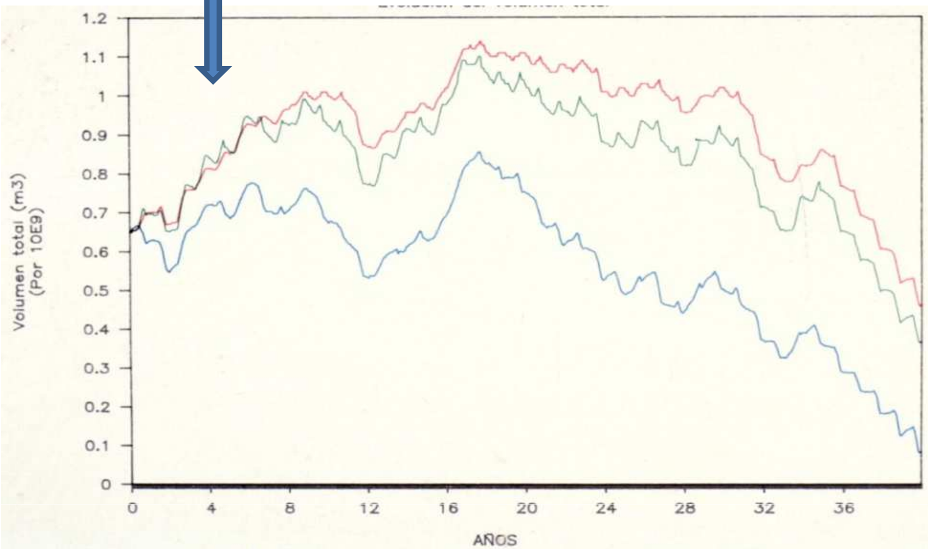
COMPONENTS

- – 1 big upstream dam 100 hm^3 of storage
- – 2 leaking dams in limestone, Sichar Dam 60 hm^3 and Mª Cristina Dam 28 hm^3
- – River losses in Mijares and Rambla de la Viuda
- – Irrigation return flows
- – Sea water encroachment in the South

- Strategy strategy suggested by users accepted by the Basin Authority in 1973.
- Replaces groundwater extraction with surface water releases
  - Strategy proposed in the CWP 1957, (in–lieu recharge)



Use of storage in the L P de Castellón aquifer



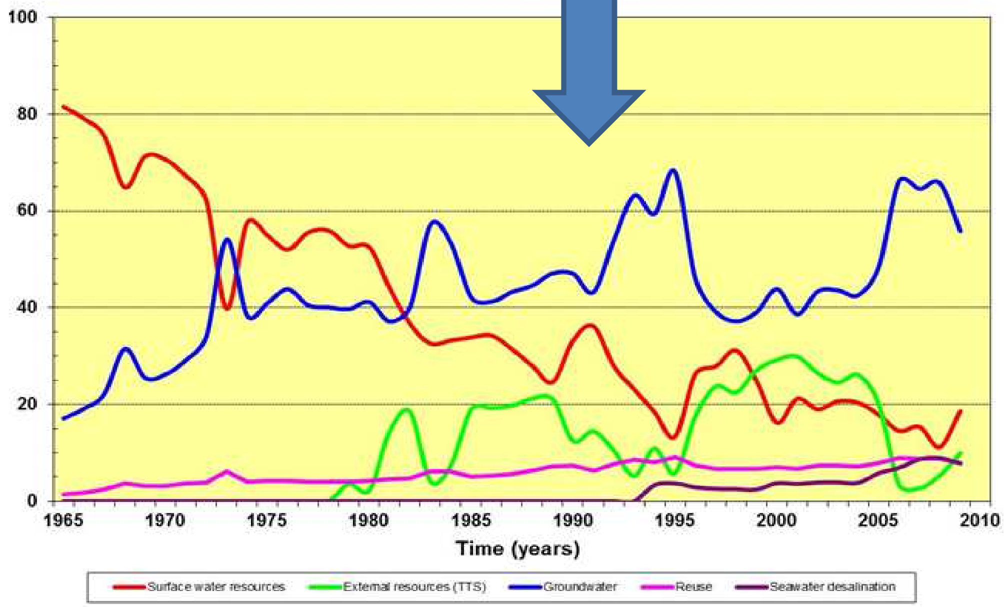
- Aquifer storage used was about 700 hm³ (4 times the storage of dams)
- Increment in the last 2 decades
  – drip irrigation has augmented
  – irrigation with reused treated water.
- Alternate use strategy in several areas of the Júcar Basin
  – In the Palancia Basin started alternate conjunctive use at the first quarter of the last century

- In most aquifers, mainly in droughts, pumping increases

Water supply of Madrid wells, up to 80 hm³/yr. Used mainly in droughts or low storage in dams

2007 drought in the aquifer Plana de Valencia Sur, pumped 50 hm³ from wells given to farmers previously drilled by the Basin Authority

Similarly CH Segura pumped 50 MCM in the alluvial aquifer of the Segura river



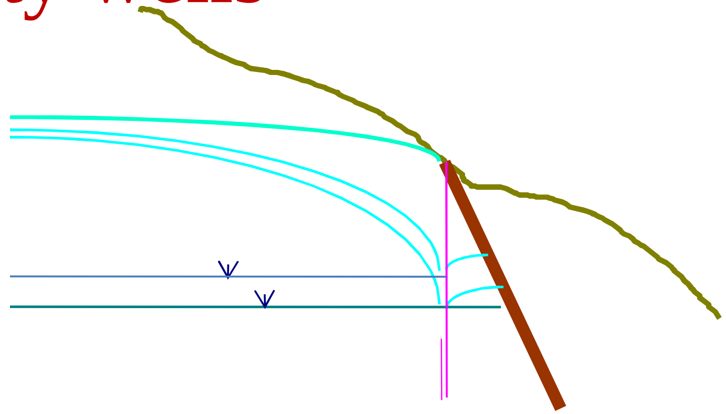
Regulation of karstic springs with nearby high capacity wells

- Abundant carbonate aquifers.
  - Specific yield 1–3%. Low storage capacity, high water level oscillation
  - Quicker impact on surface flows and wetlands
  - Recharge from dams and channel infiltration

Flow of some karstic springs in Spain fluctuates between 0,1–100 m^3/s

Topographical conditions often preclude drilling wells away from the spring

- Proximity of canals or conduits allows the transport of pumped water.
- Frequent high flows
  - (850+350)L/s in Los Santos
  - 2,250 L/s in Deifontes (Granada) 5 wells
  - (400+400) L/s in El Algar spring (Benidorm)
  - Arteta spring. Navarra



Conjunctive use in La Marina Baja

2 dams + 2 well fields + 1 pumping station + water reuse (interchange)

THE EIGENVALUE SOLUTION

An explicit solution that makes conjunctive use modeling easier

- Classical g.w. modeling:
  - in sequential time steps
  - Water heads are obtained in each step by solving a big algebraic linear system of equations.
- But there are other solutions. The continuous in time g.w. flow equation is reduced to a well known Sturn–Louiville problem. It is only valid for N parameters (eigenvalues). Each one has its corresponding eigenvector.
- The solution is given by a vector $\bar{L}$ of the intensities of each eigenvector.
- $\bar{L}$ is a complete solution in a different basis

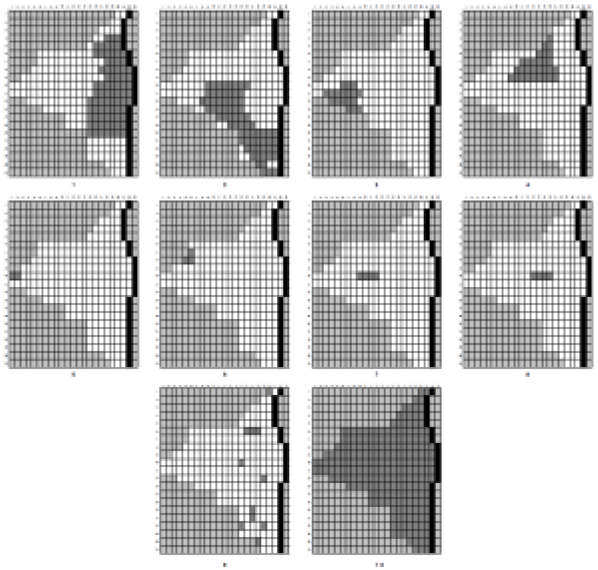
  0, 0, 0, ….0, 1, 0 …0, 0, 0
  0, 0, 0, ….0, 0, 1 …0, 0, 0, for the Cartesian
  0, 0, 0, … 0, 0,1, 0 ….

The orthogonal set of eigenvalues for the eigenv

- From the previous $\bar{L}$ situation and the action in the new period a new $\bar{L}$ is obtained easily and explicitly. Instead of heads in the nodes.

- Surface and subsurface components of conjunctive use schemes should be simultaneously simulated.
- When many alternatives must be evaluated, an explicit tool for aquifer simulation would be advantageous.

Modelling process always uses a limited number of unitary elementary actions



Eigenvalues II

- An N&P invariant matrix previously computed multiplied by $\overline{L}$ can provide the following P control parameters
  - Aquifer and river flow interchange in different zones
  - Groundwater heads in different points
  - Groundwater stored in different areas of the aquifer
  - Flows between two zones of the aquifer
- Once computed the eigenproblem and the matrix, it is easy to incorporate to most surface water models and able to simulate jointly and explicitly numerous alternatives
- The complete solution of the eigen–problem is the most demanding task, but it must be done only once
- A very reduced set of $\overline{L}$'s components is needed to simulate with the same precision as FD or FE
- Oscar Alvarez Villa is his dissertation tested the methodology to a 22.000 cells aquifer that were reduced to a number of linear deposits, 200 to 600
- **<u>Adequate for complex systems, multiple alternatives and climate change uncertainties</u>**