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Groundwater-dependent wetlands

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From the biological point of view wetlands are highly productive areas. They are of growing interest not only for wildlife, scenic landscape and recreation, but as a source of income and as a bioreserve. The times when wetlands were considered unhealthy and undesirable areas are fortunately over. However, in Europe and other regions many of them have already been desiccated, often by public initiative. Many wetlands or parts of them depend on groundwater contribution. This means less fluctuating situations than when they depend only on surface water, and physico-chemical characteristics are more stable. Associated vegetation is resistant to drought conditions when there is groundwater available at shallow depth. Not only is groundwater discharge to land surface important, but underground discharge as well, since this plays an important role in the water balance and especially in salinity and solute concentrations of local water. Groundwater-dependent wetlands can vary from small spots to large, elongated areas, from vegetation-rich areas to impoundings of spring water, and they may contain water from fresh to briny and with precipitated salts. Aquifer development may interfere (and often does) with groundwater availability to wetlands. Then there is an environmental conflict. Its solution means a trade-off between development and conservation, which is often a difficult one. This requires compromises by initially very diverse interests, as well as overcoming deeply entrenched myths. Obtaining reliable data and adequate monitoring is a necessary step.

Key words: groundwater, wetlands, impact of development, role of groundwater, quality effects, delayed effects

Introduction

Wetlands are landscape features which can be found in almost all regions of the Earth. Surface areas vary from less than one hectare to many km^2. They are more frequent in flat areas, coastal zones and lowlands, especially if rainfall is relatively important and the terrain is poorly permeable, but they also appear in arid areas, where their relative importance is increased.

Wetlands may develop along valleys, in the central areas of geologic basins, in deltaic areas at places where foothills grade into low permeability flatlands, and in may other situations (Cowardin et al. 1979; González-Bernáldez 1988; Brinson 1993). The Ramsar Convention on wildlife and waterfowl classifies wetlands into marine, estuarine, lacustrine, riparian, paludial and artificial.

Wetlands have been defined as surface features which conform to some of the following conditions:

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a) areas with still water not forming lakes. That is, with a shallow water depth allowing waterfowl to feed and breed at least in a large part of them,
b) areas with a shallow water table which can be used most of the time by plant roots to get water from the aquifer or the capillary fringe,
c) areas in which evapotranspiration is greater than precipitation.

These definitions are not accepted by all scientists and water managers but they are useful to decide what a wetland is.

Wetlands may grade into lakes and into rivers. They can be more or less permanent or seasonal, or even something that fully develops only during and after wet years. Fluctuation is for some wetlands an important characteristic. Generally they contain fresh water, but saline water is found in coastal areas as well as in some continental situations in which salinity may grade from brackish to briny with associated precipitated salts.

Wetlands have been historically – and in some cases they still are – regarded as wasteland and unhealthy areas, a source of malaria and other water-borne diseases, a nuisance to human life and much wanted flatland for cultivation and human establishments. Thus, since old times they have been the subject of destruction by infilling and by drainage. In Europe and other developed regions a large fraction of existing surface area has already been destroyed and irreversibly transformed, up to 80% according to some figures. Regulations fostering this behavior still persist in some countries, especially in developing nations and in tropical areas, where health concerns are still real. Lay people are generally predisposed against wetlands. This is to some extent rooted in legends and myths, and derives from a poor understanding of the environment. In fact large surface areas of wetlands were destroyed and still continue to be in many areas of the world. The situation is being redressed, however, mostly in developed countries, where environmental concern is now part of daily life and where the economic value of wetlands begins to be widely recognized (Llamas et al. 1992; Barbier et al. 1997). Wetland study and evaluation is a current issue in many countries, such as the USA (Adams et al. 1991) and the European Union.

In Spain wetlands are now protected (at least in theory) by the Water Act. The River Basin Water Authorities, in charge of water management, have the duty of inventorying, monitoring and protecting wetlands, with objectives that must be included in the Plans for River Basin's Water Management.

Wetlands are important areas. This is because of the benefits they bring, from the natural, economic, and aesthetic points of view, and which are related to the:
a) very high organic matter production,
b) large diversity of plant and animal species,
c) beneficial effects on the water cycle, since they contribute significantly to regulate variability (e.g., smoothing floods), to retain nutrients, to foster water quality improvement and regularization, and to shape local climate and mitigate its fluctuation,

d) high economic interest for local as well as for downstream population, and also as a growing source of touristic income.

Many wetlands depend on local rainfall plus surface water contribution from a larger area, since they are maintained by river contributions and floods on the alluvial plain and in the flat areas into which they spread, or by contributions from tributaries barred by the main river banks.

Wetlands along the coast may be associated with sea tides, with or without continental contribution. These influences are easily recognized and have been extensively studied from the hydrological and ecological points of view, mostly because they are frequent in the temperate areas of developed countries.

However, groundwater-dependent wetlands are important as well. They present a large variety of patterns, circumstances, salinities (from fresh water to brine) and ecological values, although in many cases they have not been recognized as such until recently, especially when they are a part (often the most permanent one) of larger wetlands in which diverse hydrological circumstances are found.

Publications devoted to groundwater-dependent wetlands and papers focusing on their functioning and characteristics are scarce. A reference publication was edited by Winter and Llamas (1993).

Most examples and results presented hereafter will be taken from experience existing in Spain, which is the country of Western Europe with the largest number of groundwater-dependent wetlands covering a very varied climatic, geomorphologic and geologic range. A first attempt at synthesis was edited by Llamas (1987) and guidelines for restoration were compiled by Montes et al. (1995). The hydrogeologic knowledge is still sketchy.

Two main wetland areas in Spain which combine surface and groundwater-dependent circumstances are the Doñana National and Natural Parks in the SW, and the Las Tablas de Daimiel Natural Park and some other neighboring wetland areas in the Centre. They have been the subject of studies and argument due to the impact of poorly controlled (but to some extent successful) groundwater development for agricultural irrigation, and of some scientifically doubtful restoration undertakings, especially for the second wetland area (Llamas 1988; 1989; 1992). Some background on Doñana can be found in Llamas (1990); Suso and Llamas (1991, 1993); IGME, (1984); Custodio (1995a); Custodio and Palancar (1995); Custodio et al. (1999).

Groundwater-dependent wetlands

Groundwater-dependent wetlands are those in which the source of water is partly, dominantly or exclusively derived from groundwater. The different water contributions increase areal diversity and fluctuation pattern (water depth, surface area, salinity, and chemical conditions), which is important for biodiversity. Groundwater is the more permanent contribution and it secures the existence of permanent habitats, which are essential for a wide range of plants and non-migratory animals. These habitats are often less spectacular to the outsider, hunters, and Nature tourists, since they lack large waterfowl populations. Although they are less known and less protected, in spite of their key ecological and economic role, they are now being rediscovered, due to the large set of interesting aspects they involve.

Groundwater-dependent wetlands include typical ones in which water exists on the land surface and may grade into lagoons, lakes, and river courses. They also include as important features wet meadows and areas in which there is no continuous but patchy water at the surface. In such wetlands vegetation thrives on groundwater since the water table and the capillary fringe are at shallow depths and can be reached by the plants' roots. This vegetation often includes medium to large size trees which in some areas (as in the Doñana area in SW Spain) are called "monte negro" (black forest) in contrast to dominantly smaller-size xerophytic plants called "monte blanco" (white brush).

In other cases, especially in semi-arid and arid climates, the intense evaporation of water at or near the surface locally increases water salinity. This is more conspicuous when there is no surface water outflow and/or discharged groundwater is already rich in dissolved salts due to geologic conditions, such as the existence of soluble salts in the ground, concentration of airborne salts in the scarce groundwater recharge in arid areas (especially in areas which are close to the coast) and the mixing with relict or modern sea water in the ground (Bayó et al. 1996). Saline and brine water wetlands are in many cases highly interesting, as in Fuente de Piedra in SE Spain, which is a resting area for flamingo waterfowl (ITGE, 1998), or in the arid plains of the Monegros in NE Spain (García-Vera, 1994).

Groundwater-dependent wetlands can be classified as groundwater discharge areas corresponding to local, intermediate and regional groundwater flow systems (Tóth 1971, 1972, 1999; Custodio and Llamas 1976, Sect. 24). González-Bernáldez (1992) attempted a first classification from the ecological point of view. A hydrological and geomorphologic classification has been prepared by a group of specialists led by Dr. C. Montes for the Ministry of the Environment of Spain, included in a still unpublished report, which however is being applied by the State and some Regional Administrations. They appear in a large variety of circumstances such as near valley bottoms, in interfluves, in lowlands, in coastal areas and along the shores of large lakes.

Discharge areas generally represent a small part of a groundwater basin and tend to be spotty or elongated, continuous or discontinuous areas. Even in the bottom area of small or large depressions, most groundwater outflow and availability to plants is along strips made up of a vadose zone, since the central part is often occupied by low permeability sediments, which are close to water saturation, and may contain brackish or saline water. However, upward vertical leakage of groundwater through these low-permeability sediments may also play the role of sustaining the wetlands, or of delaying their seasonal dry-up, or of creating local outflows where sediments are discontinuous or more permeable, forming scattered springs ("ullals" and "ojos" in Spain) and sometimes mud and quicksand pits.

As far as the water basin and the aquifer system are concerned, most groundwater-dependent wetlands correspond to some of the lowest areas, although not always. When ground permeability is relatively low and recharge is significant the water table is close to the ground surface everywhere except in the highest areas. Thus even in interfluves and headwater areas, flatlands and depressions may become wetlands. In this case fluctuation may be larger than in regionally depressed areas. In such areas groundwater contribution may be almost constant, independent of seasonal and year to year rainfall (recharge) fluctuation, due to the generally large turnover time of the system (many years to millennia).

Seasonal fluctuation in groundwater-dependent wetlands sometimes seems conspicuous and even the base flow of springs and rivers may disappear. This may not reflect a similar fluctuation of groundwater contribution to the area but the effect of seasonally changing evapotranspiration of the vegetation using groundwater. The total discharged quantity may be constant but the terms into which it is split fluctuate. This is the case of the La Rocina Basin, in the Doñana area (Trick 1998).

Conditions of groundwater-dependent wetlands

Hydrogeologic conditions in groundwater-dependent wetlands change dramatically from one place to another according to recharge area, rate of discharge, regional and local permeability pattern, topography and local sedimentary features around discharge areas. All of them, however, have in common a rather complex three-dimensional pattern of groundwater head potential around and close to the wetland, as well as changing physico-chemical characteristics, including environmental isotopic composition. Their understanding is necessary to explain groundwater behavior and pattern. See Figs 1 and 2 for two examples.

This is often neglected in simplifications. Horizontal, two-dimensional approaches are generally used, which may be enough to reproduce the regional behavior but not the wetland characteristics. It is not rare to consider water table and shallow well data together with some deep borehole water-level elevation information. Sometimes the piezometric levels of some deep, more productive layers, which are obtained from production wells, are the only ones to be considered. In this case the water table elevation may not be represented at all by the piezometric surface. Groundwater–wetland relationships may be greatly distorted. See Figs 3 and 4 for further explanation.

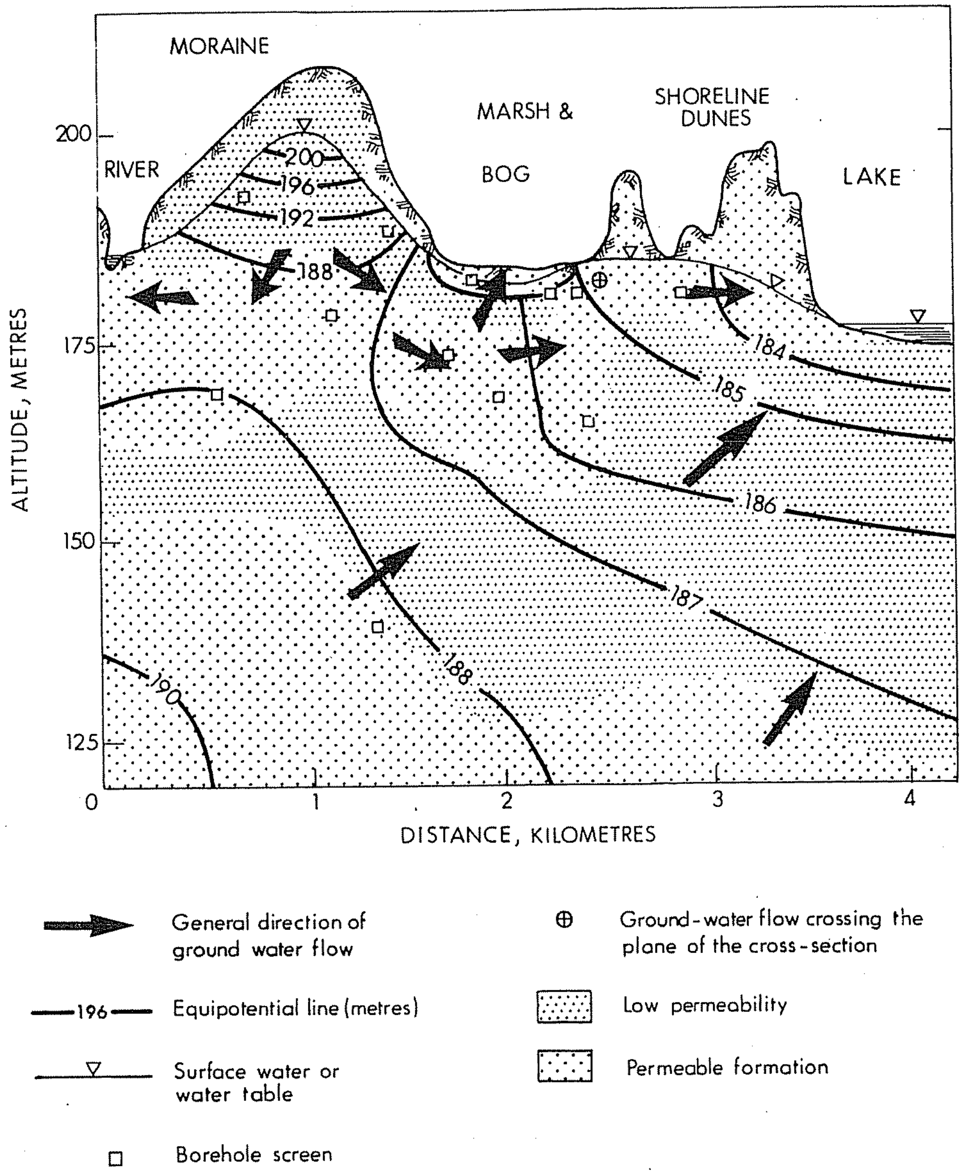


Fig. 1
Three-dimensional flow of groundwater towards Lake Michigan. Groundwater discharge, besides contributing to the lake, feeds an intermediate river and a marsh. Local recharge at the moraine and dune belt and regional groundwater discharge, and the pattern of permeable (dune sand, subtill, bedrock) and low permeability (till) material control the flow pattern (modified from Shedlock et al. 1993)

These types of problems are even more serious when interpreting water chemical and environmental isotope data. Relatively rapid changes in composition can be expected, especially in depth. The pattern of environmental radioactive isotopes show sharp changes from one place to another. If the three-dimensional flow pattern is not considered, data may be misleading and even appear as chaotic and seasonally variable.

The salinity of wetland water depends on the salinity of discharging groundwater, on the contribution of surface water, on local evaporation and transpiration, and on the outflow of salts. This outflow of salts is an important salt balance term (total salinity or a given solute concentration or the isotopic composition) and can be split into several terms:

a) surface water outflow, perennial or seasonal. Generally it can be directly observed,

b) groundwater outflow, perennial or seasonal, depending on wetland water level and groundwater head conditions (Sacks et al. 1992; Novitzki 1982), which is not seen and requires an adequately-designed monitoring network and some seepage studies at the wetland site (Lee 1977; Lewis 1987; Carrera 1997; Hunt et al. 1996),

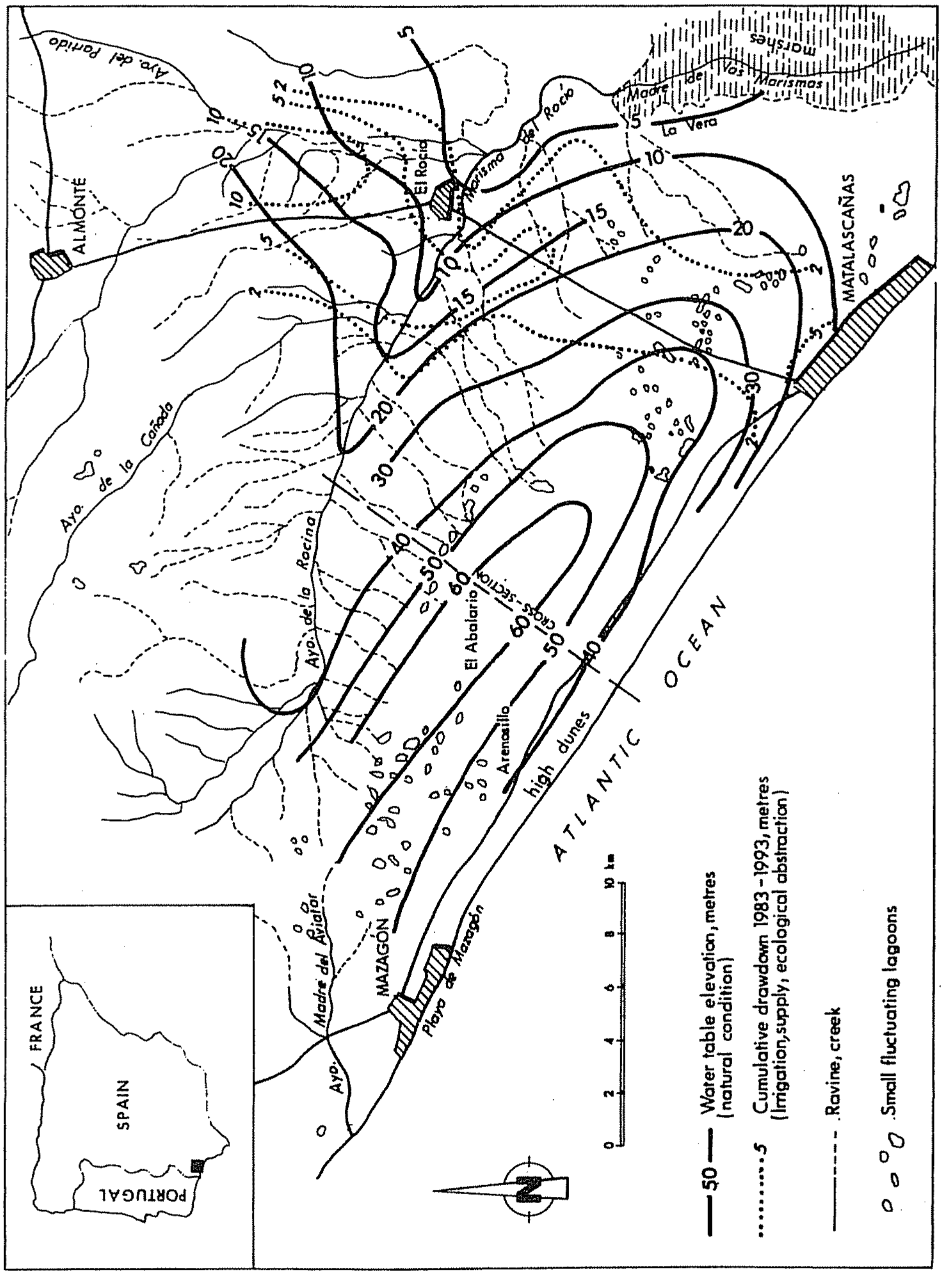
c) precipitation of some components when the solubility product is overcome due to evaporative concentration, co-precipitation with other solids or changes in pH and/or redox conditions. Some precipitates may be totally or partly redissolved in subsequent wet events or trapped with sediments. In some cases, instead of precipitation there occurs mass transfer to the atmosphere, such as happens for nitrogen from reduction or nitrate or carbon dioxide evolved from groundwater,

d) deflation by wind. Generally this is only important in some playa and sabkha-like wetlands; part of the wind-blown salts may be recycled to the wetland after incorporation by rainfall into the aquifer recharge.

Figure 5 shows a cartoon with different simplified conditions of groundwater-dependent wetlands and lagoons, which rely on surface and underground outflow conditions. Figure 6 refers to a chain of wetlands and lagoons in which inflow and outflow change from a wet to a dry period.

Even when the ground does not contribute directly soluble salts, the salinity of groundwater is generally higher than that of local runoff water. This is due to evaporative concentration, the incorporation of hydrolizable minerals after the passage through the soil due to the effect of soil CO_2, and to some extent to the oxidation capacity of dissolved oxygen (oxidation of organic matter, sulphides and nitrogen compounds). Carbonates are easily hydrolizable and given enough time also are many silicates. Silica (such as in siliceous beach and dune sands) does not contribute anions and its own solubility is low at ambient temperatures.

In some areas carbonate (as well as gypsum) dissolution may produce ground collapses, which may extend down to the water table, producing wetlands and lakes. In wetlands and lakes fed by calcium bicarbonate-rich groundwater, the


Ayo. del Partido
ALMONTE
El Rocio
Marisma del Rocio
Madre de las Marismas
marshes
La Vera
MATALASCAÑAS
Ayo. de la Cañada
Ayo. de la Rocina
El Abalario
CROSS-SECTION
Arenosillo
high dunes
ATLANTIC OCEAN
MAZAGON
Playa de Mazagón
Madre del Avitor
Ayo.
FRANCE
SPAIN
PORTUGAL
N
0 2 4 6 8 10 km
5
10
15
20
30
40
50
60
2
50 — Water table elevation, metres (natural condition)
........5 Cumulative drawdown 1983-1993, metres (Irrigation, supply, ecological abstraction)
- - - Ravine, creek
Small fluctuating lagoons

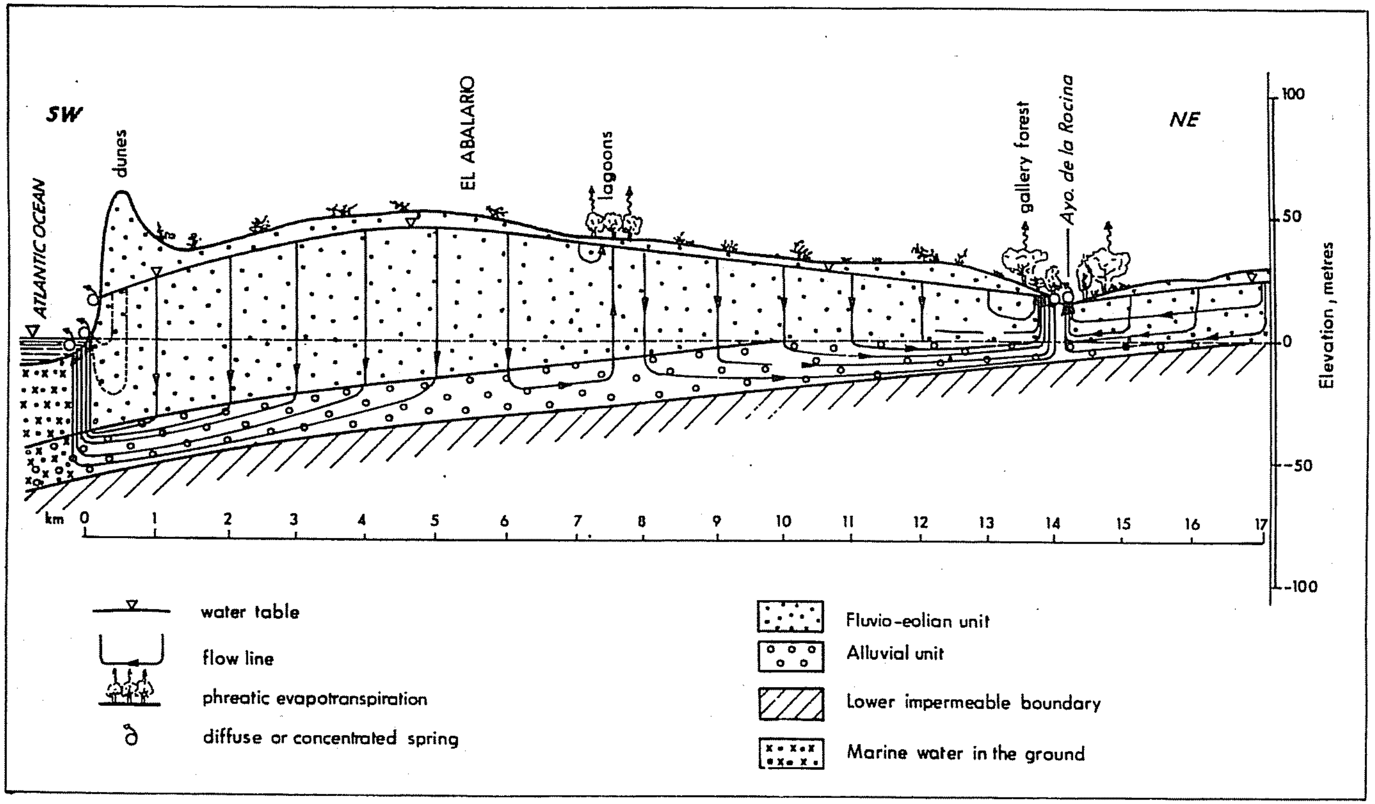


Fig. 2
Schematic representation of the water table elevation of the El Abalario sandy area, to the W of the Doñana wetland area, in SW Spain. The cross-section shows the simplified groundwater flow pattern between La Rocina ravine and the sea. It has a clear three-dimensional pattern due to the existence of a permeable alluvial unit below the sand formation. This last is one to two orders of magnitude less permeable. Equipotencial surfaces are almost horizontal in the sands and close to vertical in the alluvial unit. Beside groundwater discharge at the coast and to the ravine, groundwater sustains the riparian gallery forest and an intermediate area with forest and fluctuating lagoons (after Custodio and Palancar 1995). Model interpretation and chemical and environmental isotope studies confirm these conclusions (Trick et al. 1995; Trick 1998; Iglesias 1999)

loss of CO_2 to the atmosphere and pH changes favors calcium carbonate precipitation. Under favorable water turnover time in the lagoon and biochemical conditions precipitation may be concentrated in the surface water outflow area, thus forming travertine that may partly clog the outlet, and raise the water level in the wetland, lagoon or lake. This is the case of the Lagunas de Ruidera, in Central Spain. This situation differs from the ponding effect

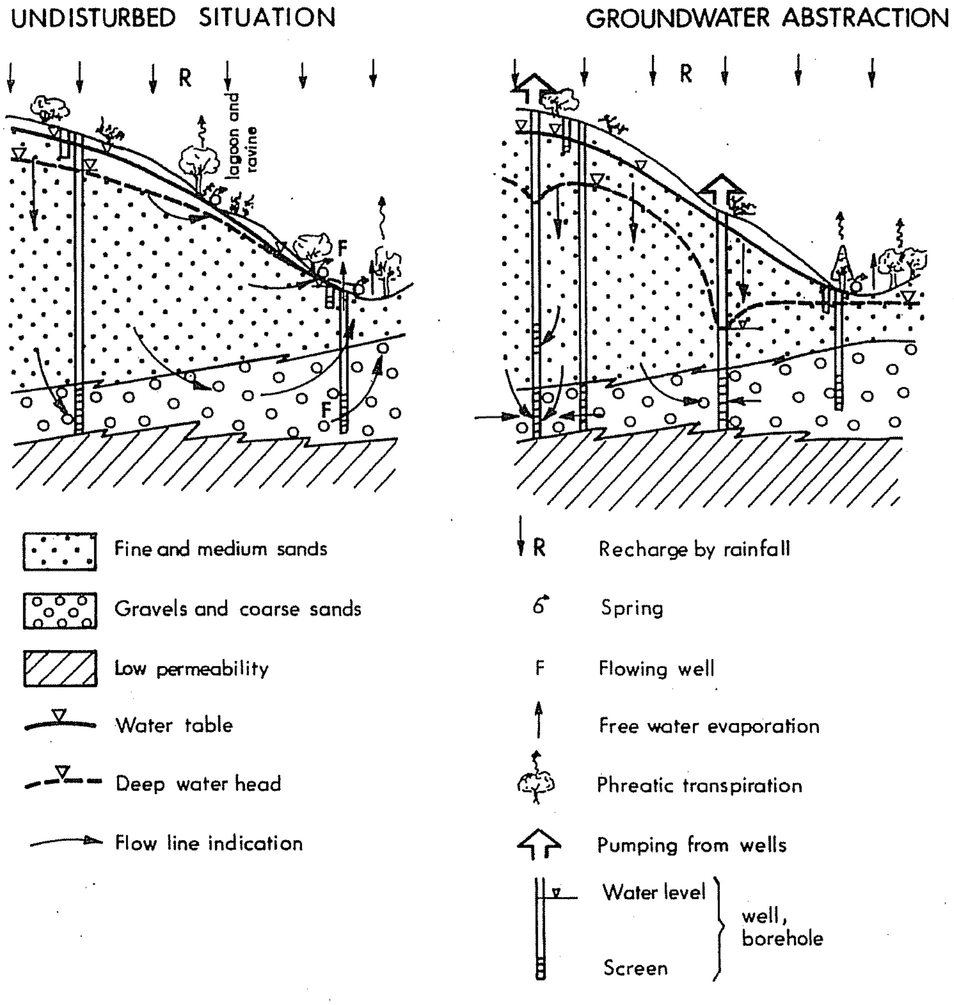


Fig. 3
Idealized cross-sections based on data around the La Rocina ravine from an area close to El Rocío, in Doñana, SW Spain, showing the difference between the water table and the deep water head of the preferentially permeable bottom layer, under undisturbed conditions and with wells abstracting groundwater from the bottom layer

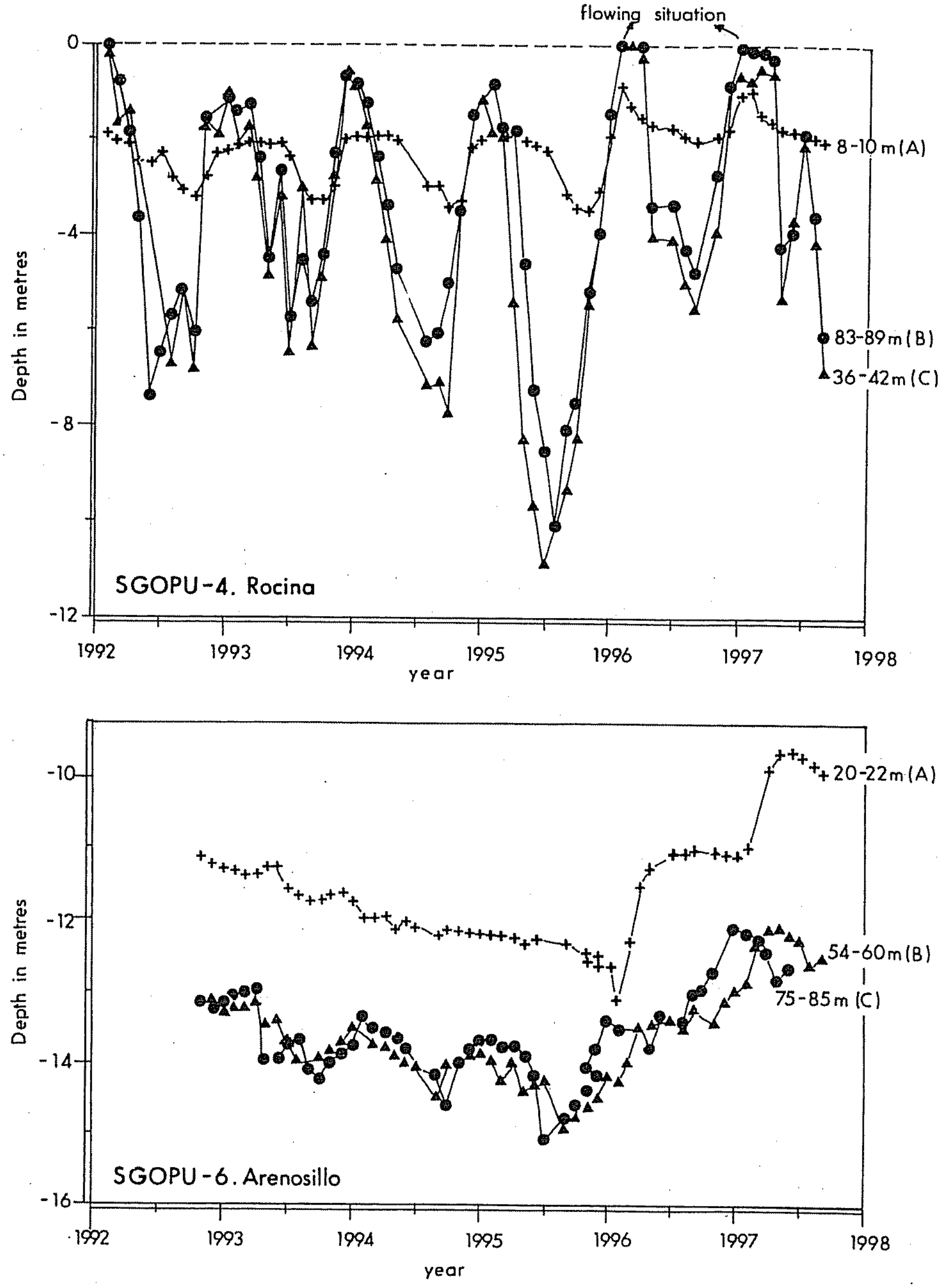


Fig. 4
Different water level records at different depths in El Abalario area, Doñana, SW Spain. See Fig. 2 for the situation. Borehole A represents the water table position and boreholes B and C the water head in the deep, more permeable layers. Note the influence of seasonal deep groundwater development

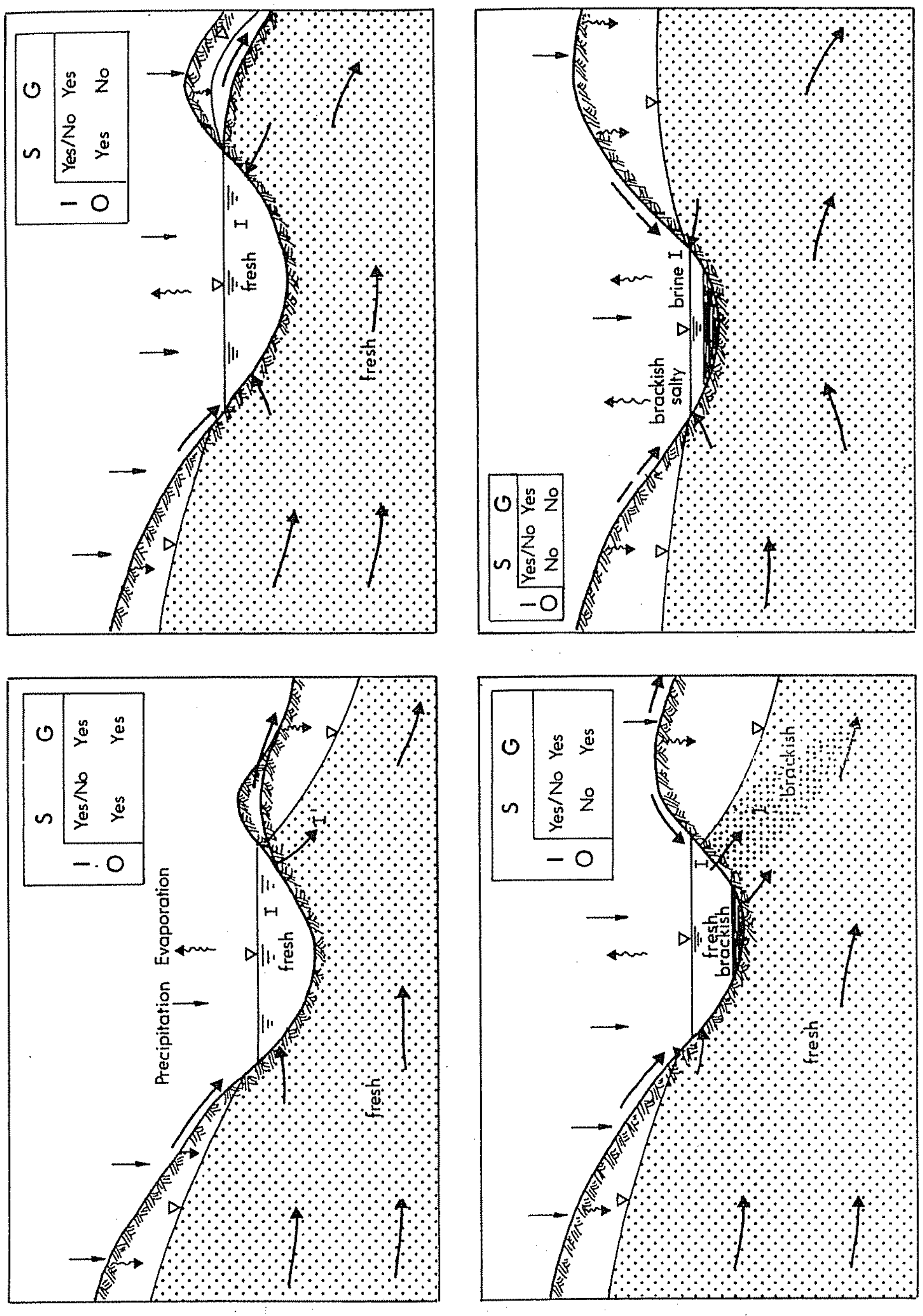


Fig. 5
Cartoons depicting surface water (S) and groundwater (G) inflow (I) and outflow (O) to a wetland, and the salt budget effect on the lagoon and groundwater, assuming that inflow is fresh water. It is assumed that the wetland (or the lagoon) has low permeability bottom sediments that restrict surface-groundwater recharge to the boundaries. "I'" means that water has a heavier isotope composition, means water table and water level. The undotted parts below ground level correspond to the unsaturated zone

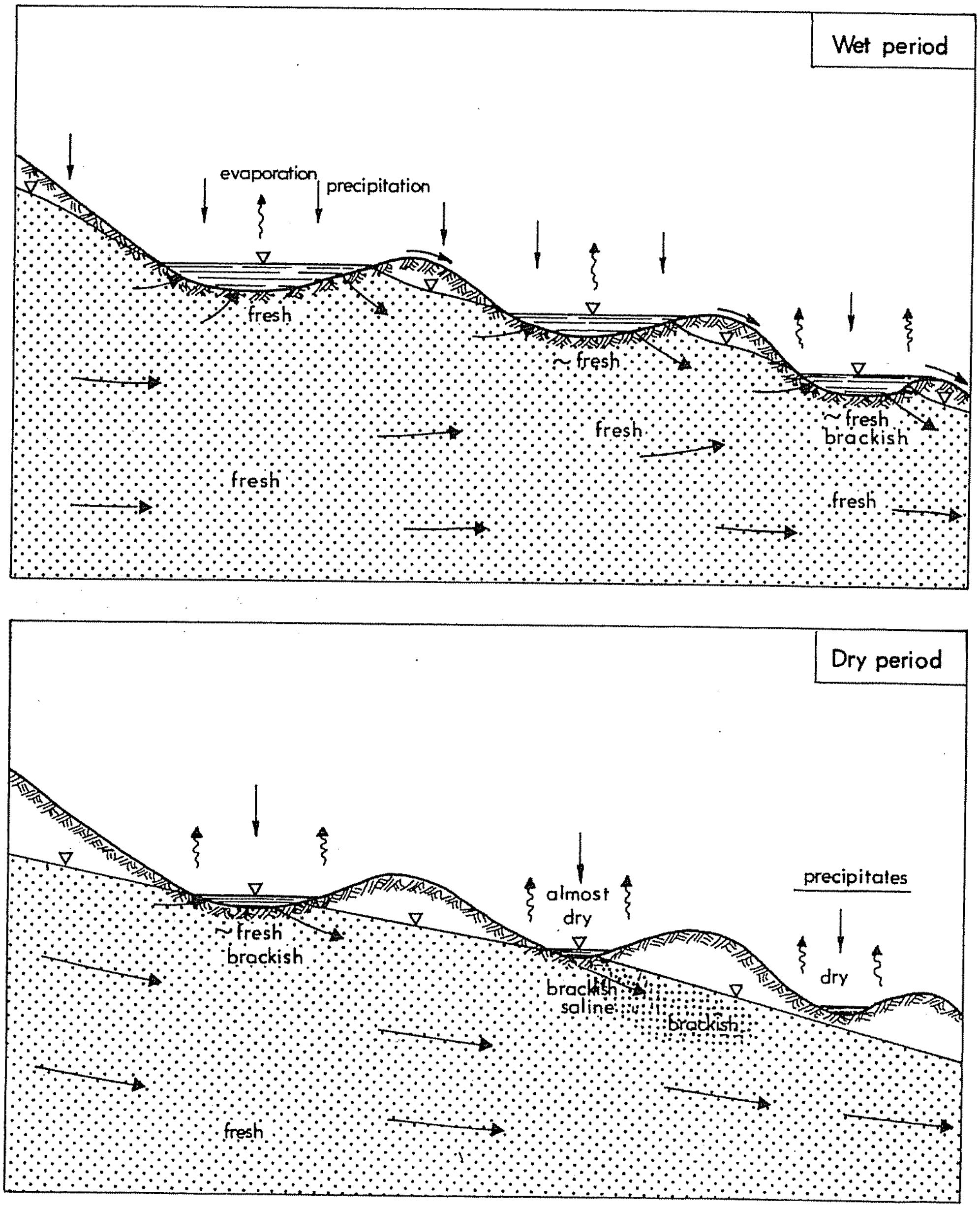


Fig. 6
Cartoon of a series of surface and underground related wetlands and lagoons along a flow path in a wet and in a dry period

produced by tectonics or by obstruction by volcanic outflows or landslides, as can be seen in the Canary Islands, especially in the arid southern Gran Canaria, in the form of oases at the bottom of the deeply-incised creeks (barrancos).

Groundwater salinity in semi-arid environments may be changed if the vegetation cover is changed. This has a delayed but sometimes definitive effect on wetlands and river base flow. An example is the Murray Basin in South Australia (Barnett 1984; Simpson and Herczeg 1991) after eliminating the highly efficient rain water use of eucalyptus forest. This is what probably happened in the arid Monegros area (NE Spain) a few centuries ago, when similarly effective brush forest was destroyed.

As mentioned above, groundwater-dependent wetlands can be found in:

a) areas close to rivers and creeks, in flat lands and alluvial plains, in areas associated with obstructions by landslides or volcanic sediments, and as lateral groundwater discharges from old, elevated terraces,

b) depressions and flats at the foot of slope changes, at dune edges or at inter-dune positions ("corrales" in SW Spain),

c) depressions formed by ground dissolution, such as dolines, poljes and collapse structures, in carbonate rocks but also in gypsum and halite formations. In these karstic features the normal evolution implies a decreasing water table. In this case depressions generally do not reach the water table except if the area is affected by a rise of the regional discharge base level due to tectonics, Holocene sea level rise, obstruction of the river valley, or other effects. Dissolving formations may be shallow or deep ones, acting as a confined aquifer,

d) areas in which spring flow, creeks and rivers are ponded by calcium bicarbonate rich groundwater, which clog and dam the outflow channel by calcium carbonate precipitation, in the form of travertine,

e) areas in which forced, confined aquifer outflow through the confining layers (following tectonic faults or sedimentary discontinuities). In such cases the wetland may form even in elevated areas which are surrounded by highlands where the aquifer recharge is produced (Fig. 7),

f) places where the aquifer flow is forced to discharge due to lateral transmissivity decrease of sedimentary origin or due to coastal sedimentation. Such is the case of aquifers that are bounded laterally or which become confined by recent, low-permeability coastal marine sediments in deltas. It is not rare that discharging water becomes brackish in some areas when there is flow along the fresh groundwater–seawater mixing zone (see Fig. 8).

When the wetland is at the end of an aquifer system its characteristics are rather permanent, the more permanent the larger the system. But there are wetlands receiving only a part of the groundwater flow (the regional discharge being at other place), like an overflow. These show the most large fluctuation and may change dramatically after natural or artificial hydrologic changes (climatic change, vegetal cover modification, and groundwater development).

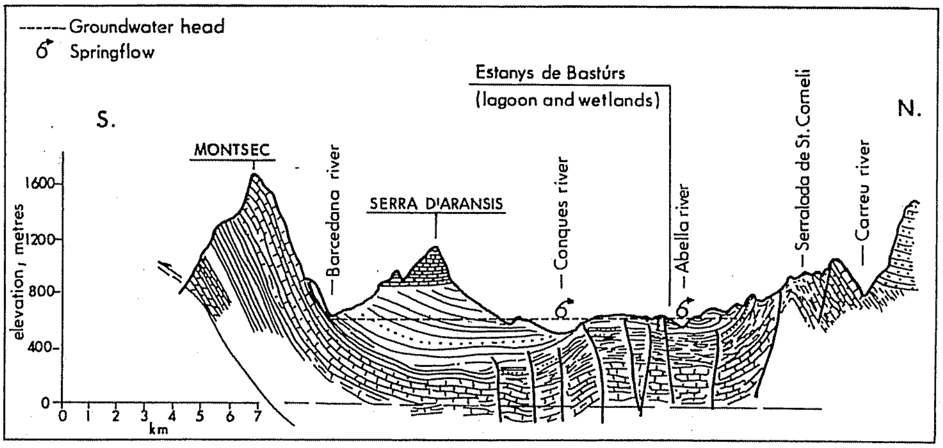


Fig. 7
Basturs lagoon and surrounding wetlands, in central Catalonia, NE Spain (after Pascual 1992). The cross-section shows that they are due to the discharge of a deep limestone aquifer, recharged in the surrounding highlands and discharging to other rivers and artificial reservoirs. Groundwater outflow is through tectonic discontinuities, which connect the deep limestone and sandstone layers with the surface through the marly formations

Groundwater exploitation effects

Aquifers which feed wetlands may also be interesting potential sources for abstracting freshwater. Actually many of them are intensively developed. Groundwater resource development has a clear set of advantages linked to the reliability derived from the associated large water reserve, the generally good chemical and biological water quality, the possibility of direct use as drinking water, the large surface area which allows for direct access from many points (thus avoiding large water transportation networks), the relative security against natural hazards, human failures and criminal actions, and some resilience against rapid, accidental pollution. Groundwater resources and aquifer system characteristics are relatively easy to evaluate, and knowledge improves as development progresses if there is a monitoring network and complementary studies are added. Future behavior can be forecast with some confidence if reasonable future scenarios are used.

However, aquifer development also has negative consequences, most of which can be anticipated if development is carried out rationally. Consequently they are susceptible to correction and economic internalization. These negative consequences are often called problems and/or overexploitation (Custodio 1992, 2000) but are really effects which have not been taken into account beforehand, mostly due to development without adequate knowledge of the aquifer.

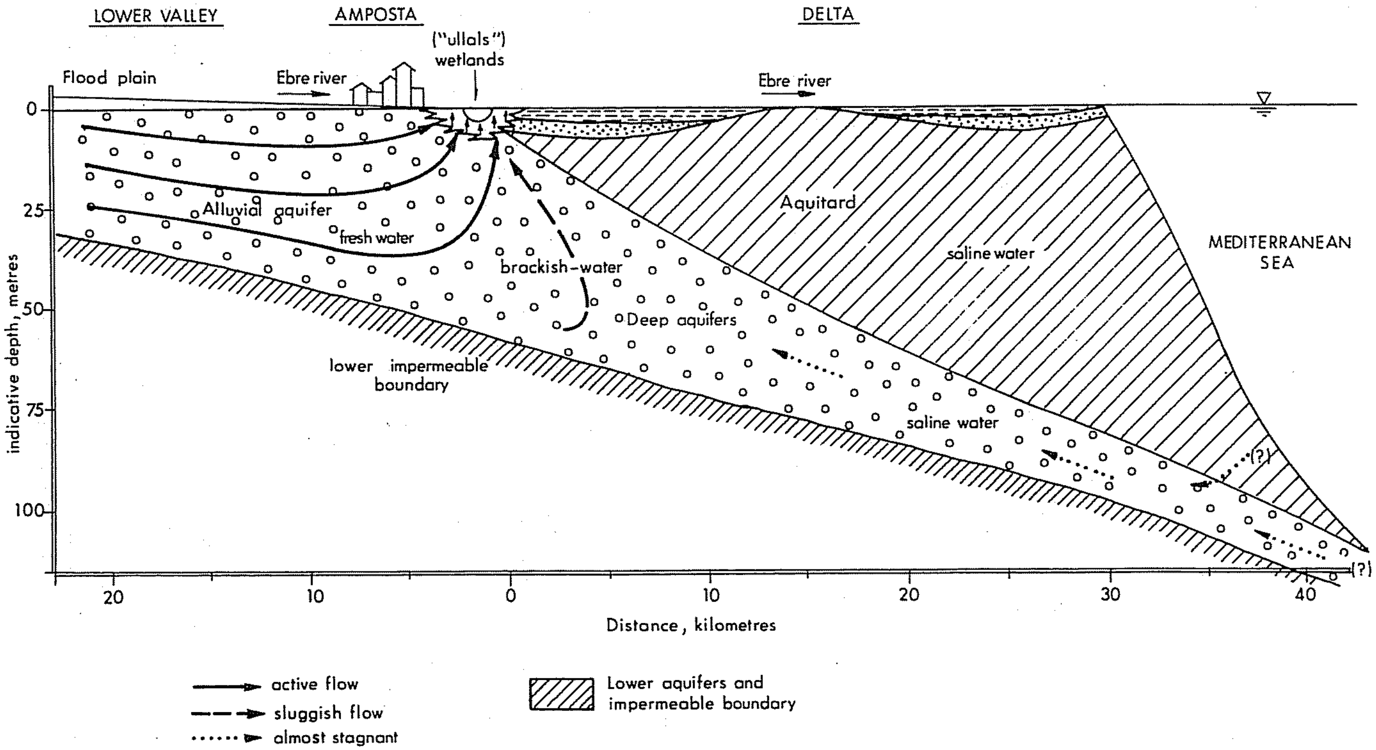


Fig. 8
Schematic representation of groundwater conditions in the lower Ebre river valley and delta, southern Catalonia, NE Spain (after Bayó et al. 1996). Flow of fresh groundwater, recharged at the river terraces and surrounding carbonate mountains, is forced to discharge at the delta apex because the low permeability Holocene sediments confine the Pleistocene aquifer. The higher density of marine water produces a fresh water head at the submarine outcrop of the Pleistocene aquifer, which is higher than the river elevation at the delta apex. This produces a sluggish flow of salt water moving towards the fresh water discharge area in the wetland by means of springs ("ullals"). The result is brackish water by mixing fresh and saline water. Saline water flow is also enhanced by deltaic sediment compaction

Negative groundwater effects refer to the groundwater level drawdown associated to well abstraction, which is hydraulically needed to create the head conditions to convert natural aquifer discharge into well production (see Figs 3, 4 and 9). The associated use of water reserves as water level decrease delays the

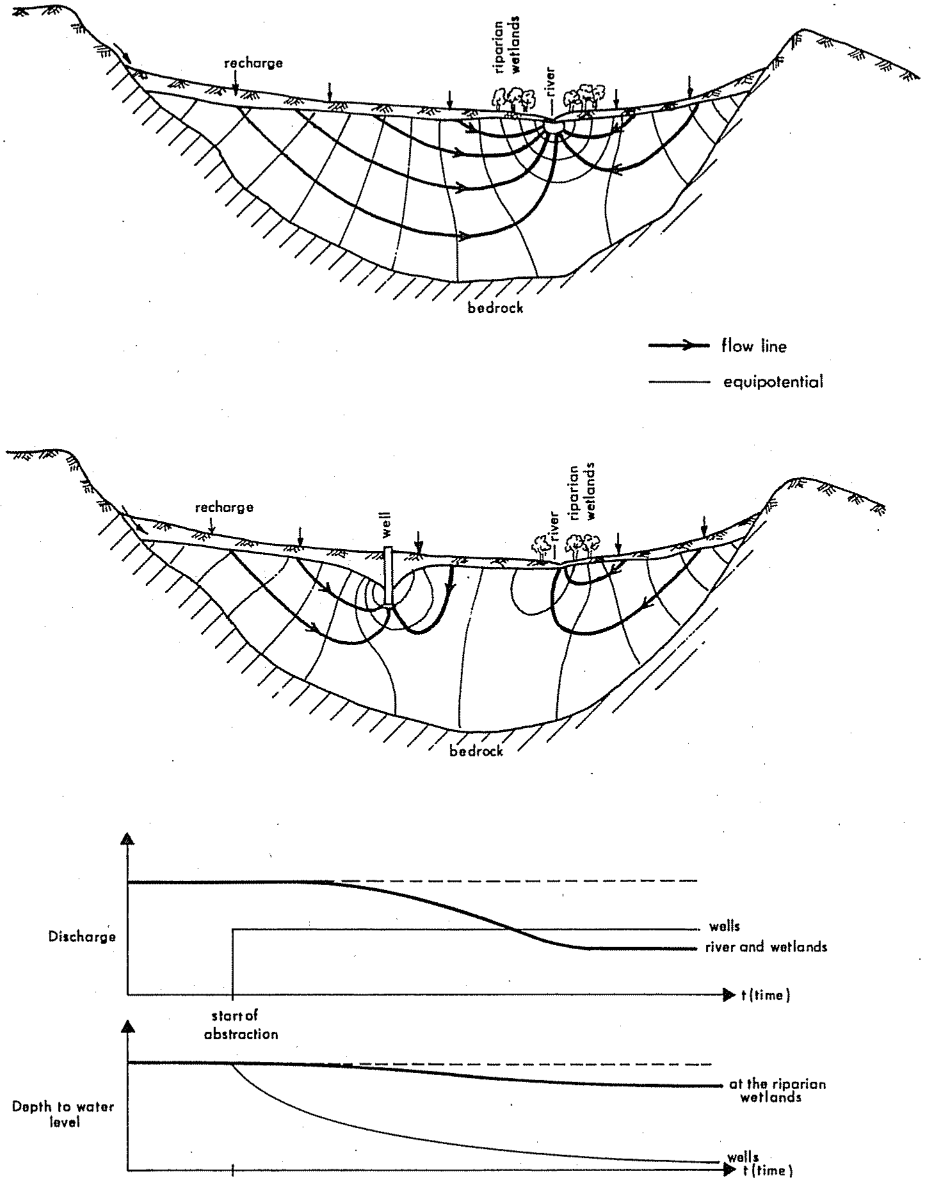


Fig. 9
Effect of groundwater development in the sediments of a river valley or a depression, on riparian wetlands dependent on groundwater

effect from months to millennia, depending on aquifer size and characteristics. The result, however, besides increasing exploitation costs, is the progressive reduction of spring and river base flow and, in general, a decreasing discharge rate at the natural outflow points and surface areas.

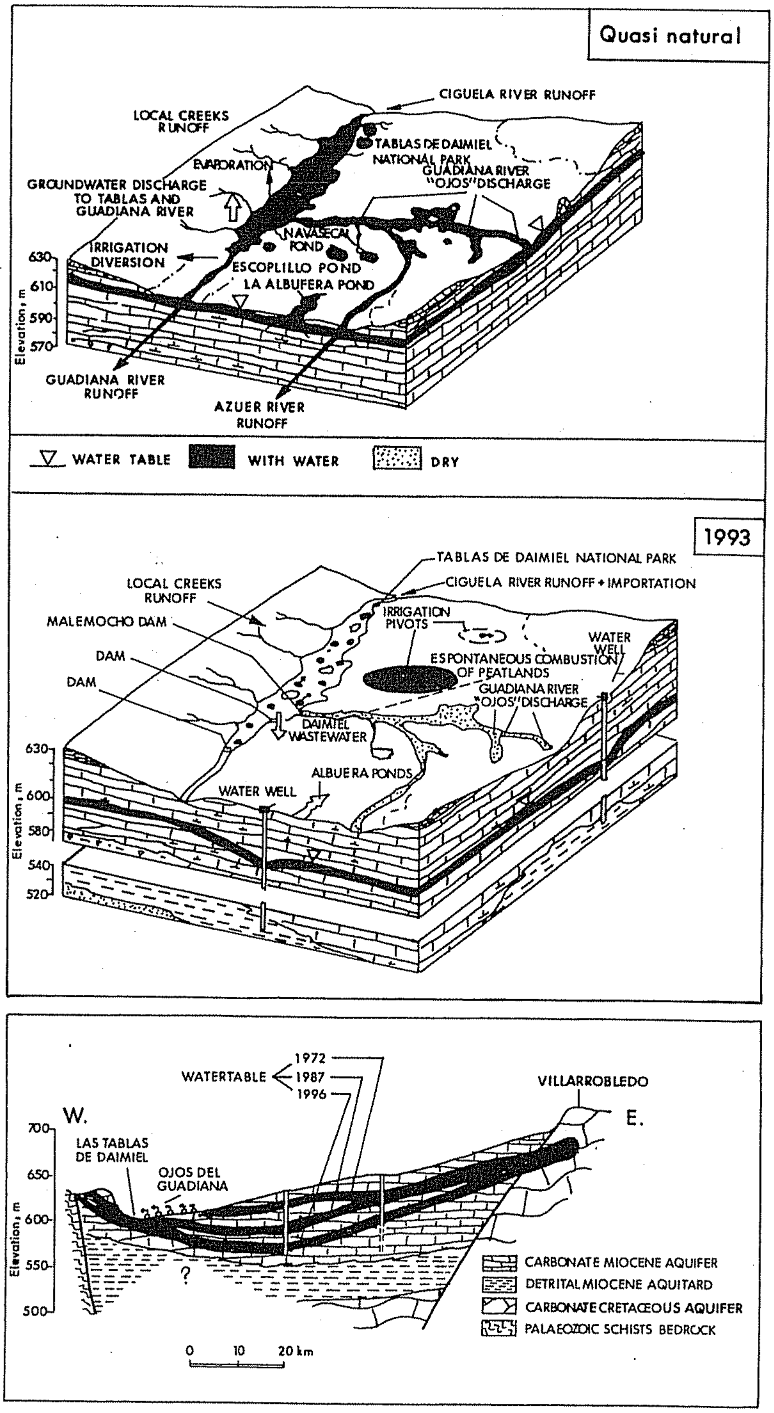
Associated to groundwater flow pattern changes, some slow groundwater quality modification may happen due to changes in the water-mixing pattern. This appears when different aquifers and subaquifers are developed at the same time (long screen or multiscreen wells), when different (often poorer) quality groundwater bodies are displaced – recent or relict sea water encroachment in coastal areas is one example – and when surface water infiltration is induced or increased.

Another class of negative consequences is land subsidence due to sediment compaction as pore water pressure decreases, as well as increased collapse rate in karstic areas (carbonates and gypsum), mostly but not exclusively at shallow depths.

The related economic, social and political consequences must be added to these negative technical consequences. The impact on wetlands will be considered below. However, it must be stressed that these negative consequences must be compared with the advantages of groundwater development. Part of the benefits should be applied to compensate physically, economically, and socially for the drawbacks. Often aquifer development, if rationally carried out, has a net economic and social benefit, even if environmental values are affected to some extent. There is a trade-off to be considered between satisfying reasonable human needs and Nature preservation. Not only technical and economical evaluation but also social acceptance and political decisions are needed. This is something not specifically linked to groundwater development, as some argue, mostly to discredit it in order to foster other water resource development projects, which are often more expensive, put a heavy economic burden on the population and may be less environmentally friendly.

From what has been previously explained, the primary impact of groundwater exploitation on wetlands is the decrease of groundwater discharge and the lowering of the water table. This reduces water input to the wetland and in some areas the water table and the capillary fringe are brought down beyond the root depth of plants whose roots cannot follow the deepening of their water source. The result is the reduction of the wetland and phreatophyte surface area. In severe cases they will completely disappear (Fig. 10). All these processes are slow and delayed. The time scale is measured by L2/D, where L is the linear dimension of the affected aquifer and D is hydraulic diffusivity, which is the ratio of

Fig. 10 →
Decline of groundwater contribution to the Las Tablas de Daimiel National Park wetlands, in Central Spain, as a consequence of intensive groundwater development for irrigation. The wetlands are now fed only by surface water and imported water from other river basins. The tail part of the Guadiana river and the main springs ("ojos") feeding it are now dry except for occasional runoff. Some dewatered peatlands may start spontaneous combustion (modified from Llamas 1988, 1989, 1992)


Quasi natural
CIGUELA RIVER RUNOFF
LOCAL CREEKS RUNOFF
TABLAS DE DAIMIEL NATIONAL PARK
EVAPORATION
GUADIANA RIVER "OJOS" DISCHARGE
GROUNDWATER DISCHARGE TO TABLAS AND GUADIANA RIVER
NAVASECA POND
IRRIGATION DIVERSION
ESCOPLILLO POND
LA ALBUFERA POND
630
610
590
570
Elevation, m
GUADIANA RIVER RUNOFF
AZUER RIVER RUNOFF
WATER TABLE
WITH WATER
DRY
1993
TABLAS DE DAIMIEL NATIONAL PARK
CIGUELA RIVER RUNOFF + IMPORTATION
LOCAL CREEKS RUNOFF
IRRIGATION PIVOTS
MALEMOCHO DAM
WATER WELL
DAM
ESPONTANEOUS COMBUSTION OF PEATLANDS
DAM
GUADIANA RIVER "OJOS" DISCHARGE
DAIMIEL WASTEWATER
630
ALBUERA PONDS
600
WATER WELL
580
540
520
Elevation, m
1972
WATERTABLE
1987
1996
VILLARROBLEDO
W.
E.
700
LAS TABLAS DE DAIMIEL
650
OJOS DEL GUADIANA
600
550
?
500
Elevation, m
CARBONATE MIOCENE AQUIFER
DETRITAL MIOCENE AQUITARD
CARBONATE CRETACEOUS AQUIFER
PALAEOZOIC SCHISTS BEDROCK
0
10
20 km

transmissivity to storage coefficient. When development is less than recharge the evolution comes to stabilization after 0.5 to 2.5 times the indicated value (Custodio 1992).

The actual values of L and D depend on aquifer system structure and heterogeneity, and they may change with time as a larger part of the aquifer system is affected and the confined behavior of some layers evolves toward one close to that of a water table aquifer, as groundwater flow through aquitards extends the influence of groundwater development.

The actual impact of groundwater development is often obscured by natural fluctuation and the generally changing abstraction pattern, compounded by the slow, long-term evolution. Changes may be imperceptible in the near term, even for intensive groundwater development. This makes it impossible to forecast future evolution from the few observations obtained shortly after the start of development, but it is feasible by calculation. One or a few wet years in the rainfall sequence may even change the negative general trend into a positive reaction when monitoring is inadequate and interpretation is carried out without a sound knowledge of hydrogeologic facts.

Deducing impacts from the known behavior of other groundwater-dependent wetlands can only be done if there is real similarity, and this can be only established after a sound hydrogeologic evaluation, which has to go much deeper than the mere similarity of climate, surface area or geology. Calculation is the procedure to be followed, which often has to be based on adequate numerical modeling. This has to be updated and improved as development progresses.

Beside hydraulic changes, water quality changes are just as important, both from the hydrologic and the ecological point of view. Generally water quality changes appear even at a slower pace than the hydraulic ones. Some effects may develop after some relatively long time, when fronts are displaced through some layers. Some of them derive from:

a) changes in the wetland salt balances due to modification of input and evaporative surface area (including that produced by plants). This affects salinity and chemical composition, often in a complex form since outflow may also change,

b) mineralization of sediments of de-watered areas with the help of biochemical reactions supported by oxygen penetration by natural diffusion from the atmosphere or enhanced by plowing when farming activities are carried out in them. This mineralization may incorporate nitrate, sulfates and hardness to recharge water. Redox processes may affect not only organic matter-rich topsoils but also deeper formations. When sediments incorporate precipitated salts they may dissolve,

c) incorporation of contaminants from human activities in the surroundings such as farming, animal raising and urbanization, beside the contribution by recharge surface water. Agrochemicals may be of concern, especially nitrate and possibly pesticides and their metabolites. This last aspect is still poorly known, and degradation and sorption play a dominant role. The transport of phosphorous compounds is delayed in river basins (Weiskel and Howes 1992) but in principle they do not appear a serious threat through the underground path since they tend to be fixed in the ground. But there is still insufficient experience since fixation may be only apparent and the result of very delayed movement. Fixation seems important in carbonate-rich sediments but not as much in pure silica sands, although surface effects are still noticeable in them; the iron oxyhydroxide coatings of sand grains, which are frequent in eolian and fluvio-eolian sediments, may help in phosphorous compounds' retention. Even for conservative contaminants such as chloride and nitrate (in oxidizing ambient conditions) the transport to the wetland may be partly or totally delayed for a long period due to advection, when there are long flow paths. This is the case in Doñana (Custodio 1994; Iglesias 1999).

Chemical changes in a wetland, and especially the increase of nutrients, may have significant effects on vegetation and fauna. Nutrients accumulate slowly, which adds to the delay introduced by the underground transport. When nitrate is the only nutrient reaching the wetland, in addition to being eliminated by some kind of vegetation, it does not necessarily promote the growth of algae typical of eutrophic lakes. At the Ruidera lagoons (Upper Guadiana river basin, Central Spain), in spite of relative high nitrate contents water keeps its transparency and carbonate-associated microorganisms may produce a spectacular green-turquoise color when groundwater contribution dominates. The elimination of nitrate contributed by groundwater seem relatively effective in coastal marshes (Barón et al. 1997; Portnoy et al. 1998; Slater and Capone 1987).

The response of plants to decreasing groundwater availability may also be delayed because they may resist water stress during some periods due to the natural fluctuation. However, a water table drawdown trend means that stress periods become progressively longer. Even if the plant is able to extend its roots downward, it may become less resistant to diseases and external attack, until finally it dies out. This is equivalent to a decreasing rainfall contribution.

Groundwater–wetland relationship study methods

The methods to know, measure, observe and monitor groundwater–wetland relationships under natural conditions and to evaluate and forecast the impact of human activities do not differ from common methods of groundwater study. However there are some specific aspects to be taken into account, beside the regional studies which are always needed:

a) local characteristics may play a dominant role and the nature of sediments in and around the wetland must be considered in detail,

b) even if the wetland is on top of the aquifer, most of the water exchange may be limited to restricted areas,

c) the contributing groundwater basin and the inflow and outflow areas may change with groundwater head fluctuation and changes of the abstraction pattern,

d) mass transport may be controlled by local heterogeneities,

e) groundwater flow and groundwater quality must be known in three dimensions, at least close to the wetland,

f) monitoring and water sampling networks must be designed according to the three-dimensional nature of the flow and quality pattern, and the local characteristics of water exchange between the surface and the ground,

g) the detailed knowledge of the water table and the capillary fringe position is a key issue for the wetland and its surroundings,

h) the values of exchange capacity and sorption characteristics of soils and sediments may be needed to define mass transport,

i) to anticipate and forecast contamination problems, studies and monitoring of the unsaturated zone at selected areas may be needed, as well as to take into account local processes such as how much water repellence of dry sand affects recharge pattern and rate.

The knowledge of aquifer geometry requires some drilling accompanied by geophysical logging, extended by surface geophysical surveys. Methods should be adequate to the objectives and the depths. This is costly and thus restricted for budgetary reasons. Therefore careful planning is needed to get as much useful information as possible with limited budget resources. Surveys and prospection should be combined with monitoring plans and the fieldwork needed to get chemically and isotopically representative samples. In order to get representative samples as soon as possible, the use of drilling fluids and additives must be restricted. Otherwise the disturbance will prove difficult or too expensive to redress.

Monitoring groundwater head and quality often requires tubes screened at different depths. In such cases, nested tubes in a same borehole must be devised. However, in cases in which isolations cannot be guaranteed it is advisable to drill separate boreholes. To get representative samples good isolations of the screens are needed, tubes must be resistant to fissuring and corrosion, and the joints must be waterproof. Electrical conductivity and temperature logs are useful tools to understand water origin and renovation within a borehole (Custodio 1995b, 1999).

The best knowledge is derived when hydraulic and geochemical studies are combined. Evaporation of surface wetland water produces isotopic water changes, which are more sensitive than ion concentration at the early stages. In many cases they can be used as tracers for wetland outflow through the ground. Tritium is still a good environmental tracer to define the flow pattern when turnover time is not too long. Its usefulness can be extended by the tritiumhelium method. Strontium isotope ratio also seems a promising tool (Hunt et al. 1998).

Chemical speciation and reaction computer codes are useful to know groundwater changes and behavior, such as ion exchange, precipitation, dissolution and other reactions, but also simple concentration values and ion ratios are generally readily useful tools if carefully used.

Current behavior, evolution forecasts and the analysis of scenarios for future action (groundwater development, changes in land use and vegetation cover, restoration projects) must be quantified. This can be carried out by well-known groundwater hydraulic methods, even by simple formulae, but complexity and fluctuation favor the use of numerical flow and mass transport simulation models. A large series of useful models are available, but considering the three dimensions may be a major drawback, since they are not prepared for or cannot be run in common computers due to memory capacity problems, and the lack of tools to easily display and analyze the results. In these cases vertical cross-section models may be useful, but flow line convergence or divergence must be taken into account. The radial effect of pumping wells can be incorporated, under some conditions, by introducing corrections based on well hydraulics closed solutions (Trick 1998). Figures 11 and 12 present simulation results for the sandy El Abalario Area, in the Doñana Natural Park, in southwestern Spain.

Representative models, even if crude, are very useful for carrying out sensitivity analyses and thus directing study and monitoring effort to the most influential factors. The analyses of future scenarios are needed to carry out risk assessments of the impact of man's activities and future new conditions, including climatic change.

Unsolved current issues on groundwater-dependent wetlands

The hydrological function of groundwater-dependent wetlands is not sufficiently known, experience is still scarce and complete case studies are lacking. This is a common situation in hydrology when dealing with specific situations, which generally involve a large set of scientific, technical, economical, social and political issues. Scientific and technical issues are generally the best known and the easiest to deal with. This paper refers preferentially to them. The others are much more speculative and involve a large set of non-measurable or difficult-to-measure variables, which also depend on local social perception, regulations and laws, and on a complex network of social and political pressures and objectives. They are mostly licit. But in some cases they may involve obscure interests, which may have little relationship to wetland issues although they use current public sensitivity toward wetlands as an excuse to foster other goals.

Scientific and technical issues, as explained before, besides expanding the basis of knowledge, do not present new specific difficulties that cannot be dealt with existing tools. But some tools are too crude or too sophisticated. How to select

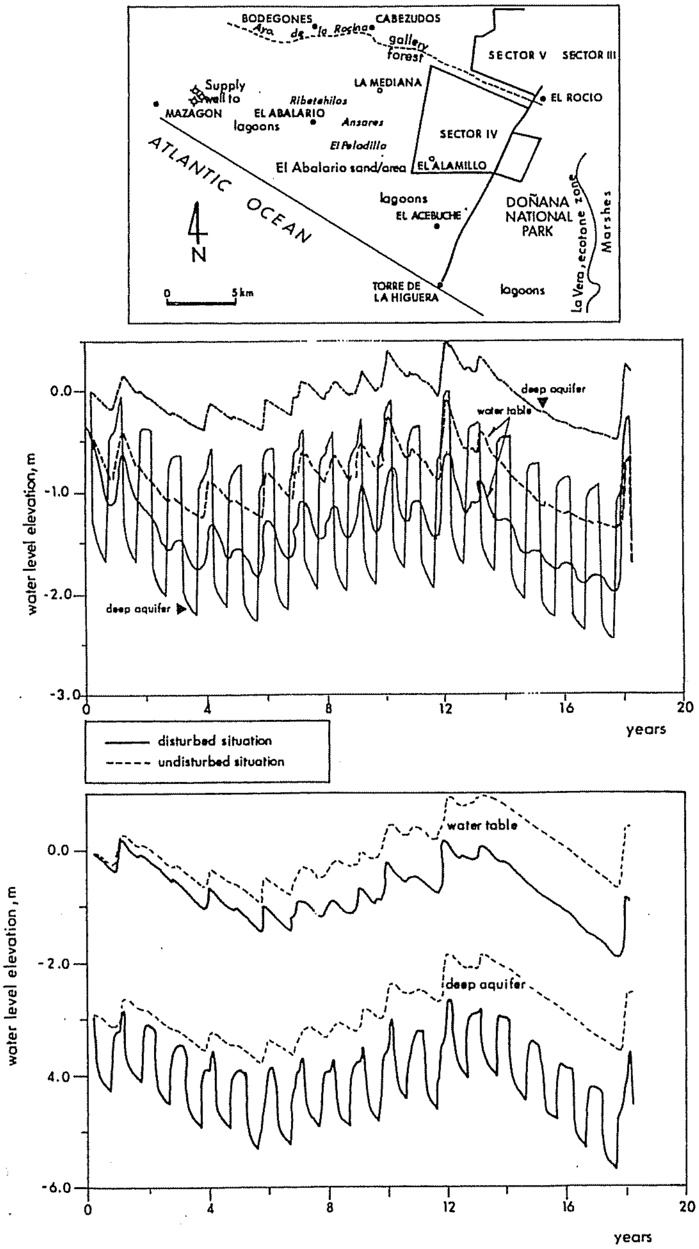


Fig. 11
Simulated effect of groundwater withdrawal from the deep aquifer of El Abalario area, Doñana, SW Spain, after Trick (1998), differentiating the water table from the deep groundwater head. The undisturbed situation is compared to the effect of agricultural abstraction in Sector IV, starting in year 0. Recharge is that calibrated for the 18-year period of data. Other groundwater abstraction is assumed under steady conditions

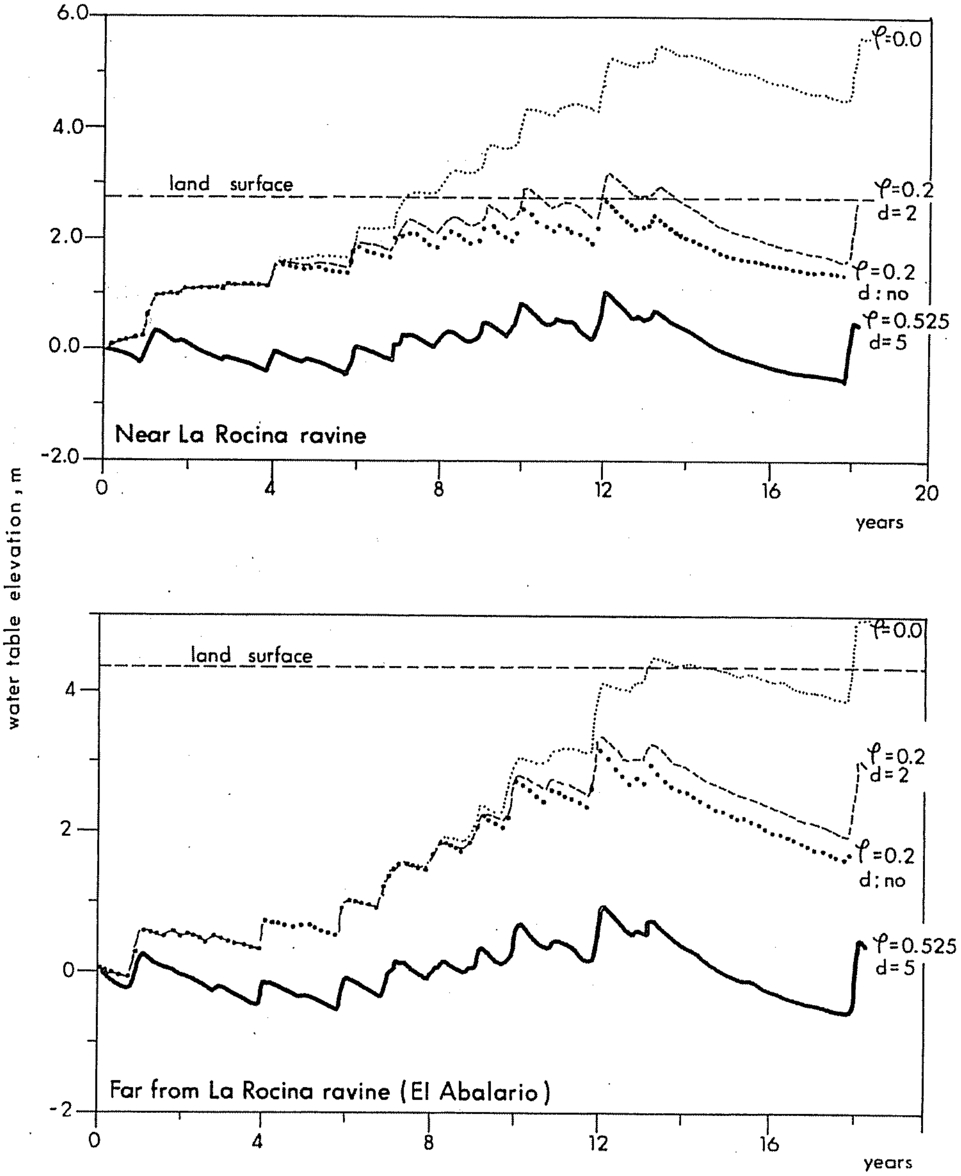


Fig. 12
Simulated effect on water table elevation of land management options in the El Abalario area, Doñana, SW Spain (after Trick 1998). φ is the maximum phreatic evaporation (m a^{-1}); 0,525 is the calibrated situation with eucalyptus plantations; 0.2 is assumed representative of re-established native forest vegetation; 0.0 is after eradication of eucalyptus plantations without new tree cover; d is maximum depth of phreatic evaporation (m); 5 is the value for eucalyptus; 2 is assumed the value for native black forest; "no" means vegetation may adapt to any water table depth

and use the right ones, according to the wanted objectives, is a challenge demanding not only experience, but also wisdom. There is tendency to look for the more complex ones, which demand a large series of data which are mostly unavailable, very expensive and time-consuming, and which are relatively difficult to operate. This is inadequate to make decisions at the right moment and for those who can make them, although there is some pressure by conservationists and biased "scientists" to do so.

Another related issue is how to transform calculations (the significant ones with respect to the problems to be considered) into useful evaluations, forecasts and analyses of scenarios, to make decisions and to help in obtaining agreements among the involved stakeholders.

All this is related to which level of knowledge and monitoring is sufficient to define the problems to be solved and make the adequate decisions. The following list presents a series of economic and social issues, which has political implications, and which are the subject of further research, agreement, and experience:

a) Is a pristine natural situation what is really wanted and needed?

b) How much interference from groundwater development and land use is adequate and bearable, taking into account benefits and social needs?

c) Is it possible and advisable to intervene to maintain an evolving groundwater-dependent wetland as it is today or it was in the past, or it is better leaving Nature to follow its course?

d) Who pays for the lost economic and social benefits which otherwise would be obtained from the now undeveloped groundwater resources, limitations imposed by water quality protection and restrictions to land use due to wetland protection?

e) How to apply fair and equitable limitations to groundwater development and land use to some, while the close neighbors at the other side of an area boundary do not have to support them? Is compensation a solution and by whom and how is it established and carried out?

f) Who pays for the unaccounted side (indirect) effects of groundwater development, groundwater quality changes and wetland value decrease or deterioration?

g) What level of prevention and protection is adequate and enough?

h) How to produce unbiased information for experts, managers and decision-makers, involved people, the public and the mass media?

Conclusion

Groundwater-dependent wetlands, with or without surface water contribution, are important and productive ecosystems characterized by less fluctuation than surface water-dependent ones. Often they are complementary, thus contributing still more diversity and productivity to the wetland. A large diversity of groundwater-dependent wetlands is possible, from small patches to relatively large elongated areas, from fresh water to brine and its associated salt deposits. The underground outlet of many wetlands is also a kind of groundwater-dependent situation which greatly influences water and salt balances. It is a poorly known feature.

Groundwater development of aquifers change hydrodynamic conditions and influence the groundwater quality pattern of related wetlands. Commonly, wetland surface area is decreased and eventually may disappear. The wetland and downstream groundwater may become more saline, although this is often the result of a wide variety of factors. All of these are delayed and slow processes.

An important issue is how to combine wetland preservation and groundwater development. There is a trade-off between some inevitable environmental damage and the desirable benefits from groundwater development. This is not only a scientific and technical issue but also an economic, social and political one, in which not only direct and indirect costs and benefits are to be considered but also many other aspects which are difficult to be reduced to figures easily agreed upon by all concerned. These are the aspects which need more new experience and research, since the scientific and technical ones can be dealt with existing hydrogeologic tools, provided the three-dimensionality of flow and water quality patterns is taken into account, especially near wetlands, where local heterogeneities and sedimentary features may play a dominant role. In any case an adequate degree of knowledge and monitoring needs to be achieved.

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