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Effects of groundwater development on the environment

E. Custodio[1-2]

(1) Prof. Dep. Geothecnical Eng. Technical University of Catalonia. Barcelona: Gran Capità s/n. Mod. D2, 08034-Barcelona (Spain)
e-mail emilio.custodio@upc.es

(2) Geological Survey of Spain, Madrid: Ríos Rosas, 23 - 28003-Madrid (Spain). e-mail: e.custodio@igme.es

ABSTRACT

Groundwater is an essential part of the hydrological cycle. It is characterised by its long turnover time, ubiquitousness and little variability. Its flow, chemical characteristics and properties have all to be considered within a three dimensional framework. Stable groundwater flow and definite chemical characteristics play a key role in geological and biological processes and, thus, have significant environmental implications in maintaining river and spring base flow, wetlands, phreatophyte communities and gallery forest, as well as being essential properties which favour the development of groundwater. Groundwater development implies a change in the flow pattern which may result in water table drawdown, outflow decrease and chemical changes, besides land subsidence in some cases. All this modifies environmental conditions which leads to water flow decrease, a reduction in phreatophyte surface area, wetland desiccation and biological changes related to chemical ones. But these changes appear after a long delay and at a slow pace. Thus the cause-effect relationships are not always evident. Negative impacts have to be compared with the benefits derived from development and the impacts of other alternatives. This includes the consideration and cost of possible correction of these long-delayed negative effects. Aquifer salinization and contamination is an important environmental issue that must be taken into account, since groundwater will sooner or later be released into the environment, carrying with it the pollutants or their end products, in a complex manner.

Key words: Groundwater development, Environment, Interference.

Efectos de la explotación de agua subterránea sobre el medio ambiente

RESUMEN

El agua subterránea es una parte esencial del ciclo hidrológico. Se la caracteriza por su largo tiempo de renovación, ubicuidad y pequeña variabilidad. Es necesario considerar que tanto su flujo, como sus características químicas y sus propiedades se desarrollan en su contexto de tres dimensiones. La estabilidad del flujo del agua subterránea y sus poco variables características químicas juegan un papel esencial en los procesos geológicos y biológicos, que de ese modo tienen un papel importante en el mantenimiento del caudal de los manantiales y de base de los ríos, y en humedales, comunidades de freatofitas y bosques en galería. También son propiedades importantes que favorecen la explotación del agua subterránea. La explotación del agua subterránea supone modificar el modo de flujo, lo que puede comportar un descenso freático, disminución de caudales y cambios químicos, además de subsidencia del terreno en algunos casos. Todo esto modifica las condiciones ambientales, con disminución de flujos, reducción de la extensión de masas de freatofitas, desecación de humedales y cambios biológicos en relación con las modificaciones químicas. Pero estos cambios aparecen con gran retraso y lentamente. Así resulta que las relaciones causa-efecto no siempre resultan evidentes. Los impactos negativos de la explotación del agua subterránea se deben comparar con los beneficios que se derivan de su explotación y con los impactos de otras alternativas. Esto incluye la consideración de la posible corrección de estos efectos muy diferidos, y su coste. La salinización y la contaminación de acuíferos es un aspecto ambiental importante a tener en cuenta, ya que el agua subterránea antes o después aparecerá en el ambiente, transportando con ella los contaminantes y sus productos finales, de forma compleja.

Palabras clave: Explotación del agua subterránea, Ambiente, Interferencia.

ESSENTIAL CHARACTERISTICS OF GROUNDWATER

Groundwater is the water inside the pores, cracks and empty spaces below the ground's surface, both in the unsaturated and saturated area below ground (Custodio and Llamas, 1976; Candela *et al.,* 1998). Often the term *groundwater* refers to water in the saturated area. Water combined with minerals, or held in small, closed pores of tight rocks is often not strictly considered groundwater, although it often play an important role in hydrogeological processes.

An aquifer system is formed by a set of related aquifers and aquitards forming a hydrogeological unit, which includes watertable and confined formations. A given formation may be confined, semi-confined or water table (phreatic), depending on the location and hydraulic head pattern. The hydraulic head may be different from one unit to another, implying that groundwater flows by following a 3-D (three-dimensional) pattern. There is a dominant horizontal component of groundwater flow in aquifers, but it moves mostly vertically through aquitards separating aquifers. It moves downwards in the unsaturated zone, except when it is very close to the land surface, where evaporation and uptake by plant roots may produce an upward movement between rainfall events.

Groundwater is recharged over a large part of the land surface by rainfall infiltration, and under favourable water head conditions. It is also recharged in land strips along creeks, mountain rivers, boundaries of thawing snow cover, foothills, and lake shores.

Groundwater may flow down several kilometres deep under favourable hydrogeological conditions, but most of it moves in the first tens or hundreds of metres below the soil surface. The sluggish movement means that groundwater reserves (total water in the ground) are many times larger than annual flow, just the contrary to what happens in the case of rivers. This is a key difference between surface and groundwater that must be taken into account when considering their environmental role and the use of water resources. They are both part of the same hydrological cycle and are inextricably linked, but they behave quite differently.

The chemical composition of groundwater which has a relatively short turnover time is the result of processes mainly in the soil (fig. 1). Rainfall is evapotranspirated. Airborne salts and matter dissolved in rainfall are evapoconcentrated, at the same time as CO_2 soil gas from the respiration and breakdown of organic matter is added. This means that some minerals (carbonates, silicates) can be hydrolized. The result is that cations from the soil and rock are added, and dissolved CO_2 is converted to HCO_3^-. Under oxidising conditions organic matter is oxidised to CO_2, and nitrogen and sulphur compounds to NO_3^- and SO_4^{2-}, and most heavy metals remain in solid form as almost insoluble high valence oxides, oxyhydroxides and salts. If dissolved O_2 from the air and NO_3^- from plant decay or artificially added, are depleted by organic matter and other electron donors, oxidising conditions become reducing conditions and some heavy metals may dissolve, as reduced ions (Fe^{2+}, Mn^{2+}), sulphate may be reduced to disulphide (HS^-) and, under intense anaerobic conditions, methane gas may form. The ion exchange capacity of minerals, mainly clay minerals and organic matter, plays a significant role in smoothing and retarding ion chemical changes, especially that of cations. A similar role is played by the adsorptive capacity of mineral surfaces, organic matter and colloids with respect to dissolved organic material and some anions.

In all these processes, chloride behaves conservatively (it does not interact) and in most cases becomes a main environmental tracer to identify recharge and groundwater flow. It reflects mostly the increase in concentration due to water evaporation, since the chloride ion is non volatile. Evapoconcentration can be small in damp climates (a ratio of rainfall to recharge not much greater than 1) but very large in arid areas, up to 100 or more. This means that recharge water may be brackish under these circumstances (Custodio, 1997b).

But in aquifers with a long turnover time things can be different, since saline sources such as old marine water, salt water and brines from intensive surface evaporation, evaporated salts and water from deep-seated layers may still be present in them, or slowly penetrating by leakage from aquitards. Even the small Cl content of rocks in hot, low water/rock ratio conditions may produce a significant contribution. This explains the existence of salt water springs and rivers.

ENVIRONMENTAL ROLE OF GROUNDWATER

The environmental role of groundwater presents

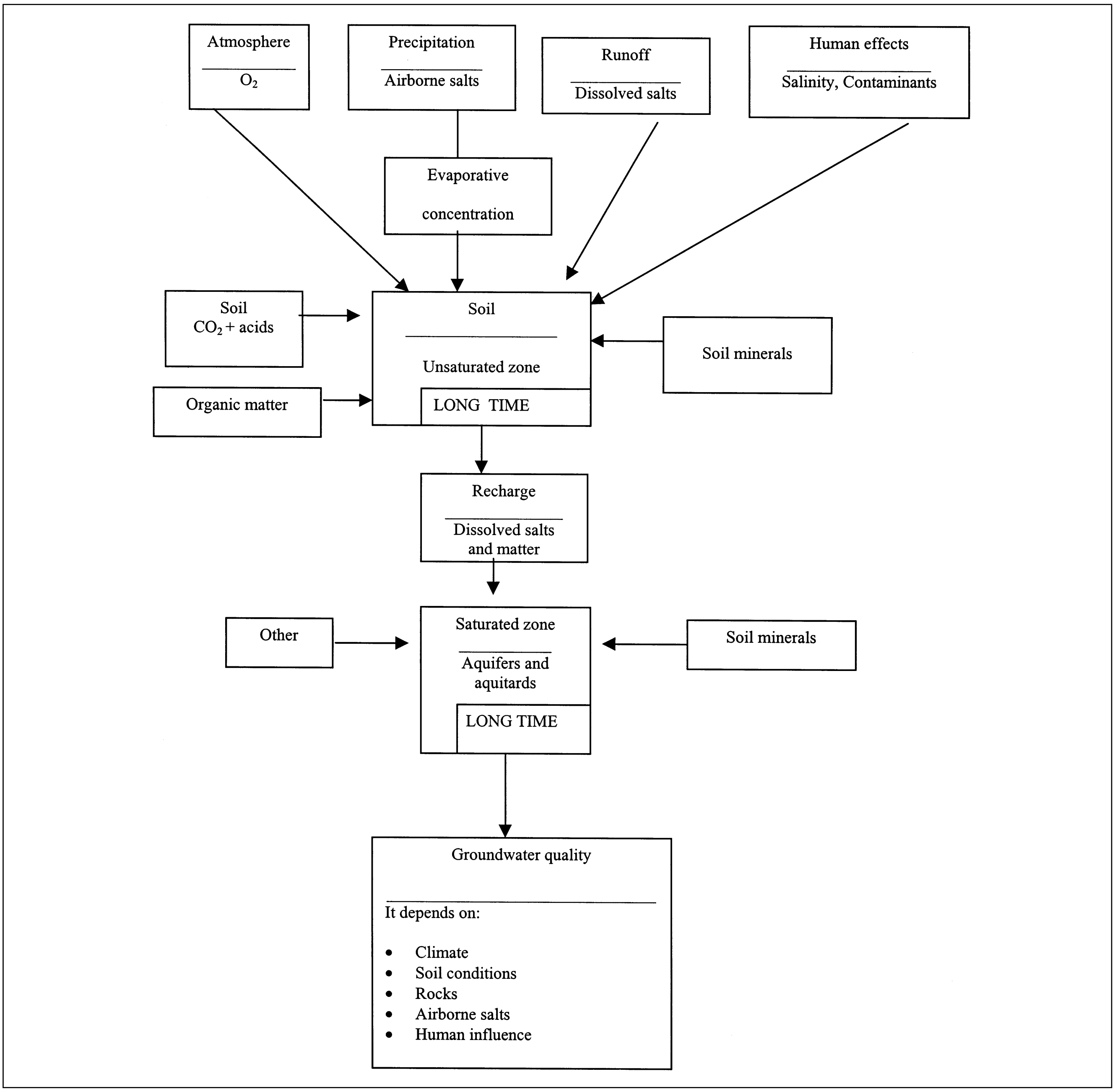

Fig. 1.- Simplified presentation of how groundwater chemical composition is generated in the unsaturated and saturated zones, due to rainfall precipitation recharge.

Fig 1.- Presentación simplificada de cómo se genera la composición química del agua subterránea en las zonas no saturada y saturada, debido a la recarga por la precipitación en forma de lluvia.

different aspects. When compared with surface water the main difference is due to the relatively small changes in groundwater flow discharge and chemistry, due to seasonal and inter-annual climate variability. This produces environmental conditions which are close to steady conditions in the case of groundwater, and commonly are accompanied by major changes in the case of surface water. The combination leads to greater diversity, both in space and habitat.

Some of the environmental roles of groundwater are (Custodio, 1995a):

- Sustaining permanent or little variable groundwater outflows in springs and base flow along rivers. This often permits availability of water all the year round, which is important when surface water contribution ceases.

- Sustaining of scarcely variable discharge areas (wetlands), either deep water (lakes) or shallow water areas (swamps, bogs, meadows, fens, ...) .

- Keeping stable shallow water tables accessible to perennial plants along valley floors (gallery forests), around lakes, or elsewhere.

- Limiting water salinity of lakes and wetlands located in endorheic (closed) basins, provided there is groundwater outflow that balances surface water-dissolved salt concentration.

- Maintaining the physicochemical characteristics and conditions of water which are needed to sustain some species of vegetation and the animals which depend on them. These are temperature, pH , bicarbonate supply, silica concentration ...

- Supplying salts to saline wetlands and “salares” to sustain special environments.

HYDRODYNAMIC AND CHEMICAL EFFECTS OF GROUNDWATER DEVELOPMENT

The development of groundwater for economic uses (drinking, house and town water supply, agriculture, industry, tourism and gardening) requires altering the groundwater flow pattern to direct water to the abstraction works (wells, boreholes, galleries, drains) by lowering the water table and /or the piezometric levels around them. The abstracted water is then not available at the natural discharge areas. Thus, the effects of groundwater development are (Custodio, 1991; 1996; Margat, 1992):

- *Groundwater head drawdown and deepening of the water table*

- *Reduction of natural discharges*

- *Changes in groundwater flow pattern that affect groundwater quality distribution in the ground, which may bring on displacement of salt waters, including sea water intrusion.*

But groundwater abstraction and its effects are not simultaneous. Also, the hydraulic head changes may modify aquifer system recharge, often increasing it. This means that there is not a simple, straightforward cause-effect relationship. This is due to the large ratio of water storage to water flow, the small hydraulic diffusivity of aquifers (the ratio of permeability to specific storage) and the still slower average solute transport rate. Human experience with surface water, which is easily observable and occurs at a pace measurable by a time scale of days, is not transferable to groundwater. Groundwater flows in three dimensions, over a large territory, unperceived by non-experts and on a time scale similar to or longer than human life, which means that it is well beyond daily experience.

Beneficial effects of groundwater development are numerous and well known, as shown in table 1. But obtaining these benefits is not without some negative effects on the environment and on the sustainability and economics of the solution itself. This is common to any artificial intervention in natural processes. Table 2 shows a summary list of negative effects. Part of these negative effects are due to the hydrodynamic behaviour of aquifer systems. They can be easily internalised and corrected, and their consideration should be part of the evaluation of any project for groundwater use. The drawbacks which are often mentioned are more a question of ignorance and malpractice than a real negative problem. Other negative effects are more difficult to foresee and to evaluate. As a consequence their internalisation is not as easy, and often it is the subject of argument. Such are land subsidence, water quality changes and environmental effects. But the already wide experience in groundwater development which is now available, the good understanding of basic groundwater processes and the powerful study tools now in common use, such as flow and transport modelling, may greatly diminish the uncertainty of future behaviour.

Since nature preservation is not a fashion but a

- **Large storage**

        - *discharge (natural/artificall)*
        - *quality*
        - *temperature*

    * Small variability of water ⇒ adequate for supply in case of
        - *peaks of demand*
        - *drought*
        - *emergency situations*

    ⇒ Abstraction facilities occupy a small surface

    * No large storage facilities are needed

    * Essential water storage in coastal areas

- **Sluggish flow through small voids in a 3-dimensional pattern**

    * Mixing of flow paths homogeneisation
        - *progress of chemical reactions*
        - *biological decay of pathogenic microbiological components*
        - *decay of short/medium lived radioisotopes*
        - *temperature equalisation*
        - *Fighting contamination incidents*

    * Time for ⇒ purification

    * Fitering effect ⇒ clear water

- **Large surface extension**

    * Availability close to water demand
        - *lower investment*
        - *small land-use problems*

- **Hydrological**

    * Faster evaluation
    * Knowledge increasing with development
    * Reliable future scenarios

- **Other**

        - *natural disasters*
        - *human failures*
        - *criminal action*
    * Greater security
    * against
    * Possibility of safe direct supply for drinking purposes

Table1.- Advantages of using groundwater. Positive consequences of aquifer properties.

Tabla 1.- Ventajas del uso del agua subterránea. Consecuencias positivas de las propiedades del acuífero.

- **Water quantity effects**
    * Groundwater level drawdown
        ⇒ increased water cost
        ⇒ early substitution of
            - *wells*
            - *pumps*
            - *facilities*
    * Discharge decrease in
        - spring flow
        - river base flow
        - wetland surface area
    * Llonger sections where rivers lose water to the ground
        ⇒ can be easily internalised

    These effects imply long-lasting transient periods

    (months to millennia) in large, low permeability aquifers/aquifer systems

- **Water quantity effects**
    * Quality changes as the flow pattern modifies
        - Displacement of low quality water bodies
        - Sea water encroachment in coastal aquifers
        - Easier surface water infiltration
    * Wells and bore holes mix different groundwaters
        - Water quality changes with pumping rate/time
        - Surface and water table water may get into deep aquifers

- **Other effects**
    * Land subsidence
        - *In karstic areas*
        - *Due to poorly constructed wells*
    * Increased collapse rate

Table 2. Drawbacks of using groundwater. Negative consequences of aquifer properties

Tabla 2.- Desventajas del uso del agua subterránea. Consecuencias negativas de las propiedades de los acuíferos.

need (Ramos, 1993) and an ethical value to be considered together with social needs (Pérez Adán, 1992), in opposition to speculative, short-sighted and irrational behaviour (Foster, 1991; Custodio, 1996), the mentioned negative effects have to be considered. The benefits of developing natural resources should be greater than the damage produced in the short and long term, after introducing corrective measures and setting constraints on the use of the resource. Current groundwater study methods allow a reasonable definition and evaluation of trustworthy corrective measures. Wetland preservation is an important constraint in groundwater management

(Llamas, 1988, 1992, 1995). However this should not and does not hinder any groundwater development but it does demand a rational and broad-based approach before groundwater is intensively developed.

ENVIRONMENTAL EFFECTS OF WATER TABLE DRAWDOWN: EFFECT OF DRYING UP AND ARIDITY

The most important environmental changes produced by groundwater development are:

- *Decrease in discharge to springs and rivers*
- *Dessication of lakes, lagoons and wetlands*
- *Water stress and vanishing of phreatophytes in wetlands and gallery forests*
- *Changes in water logging, high water situations and soil dryness frequency*

These are the result of what has been said about the properties of groundwater and aquifer system (see also Custodio, 1995b; Llamas, 1991). The effect on pheatophyte communities arises directly from watertable drawdown after groundwater development. The effect appears when the water table is kept at a position deeper than the maximum root depth, which depends on the characteristics of the vegetation and the thickness of soil and weathered rock. But also the rate of water table (or capillary fringe) drawdown has

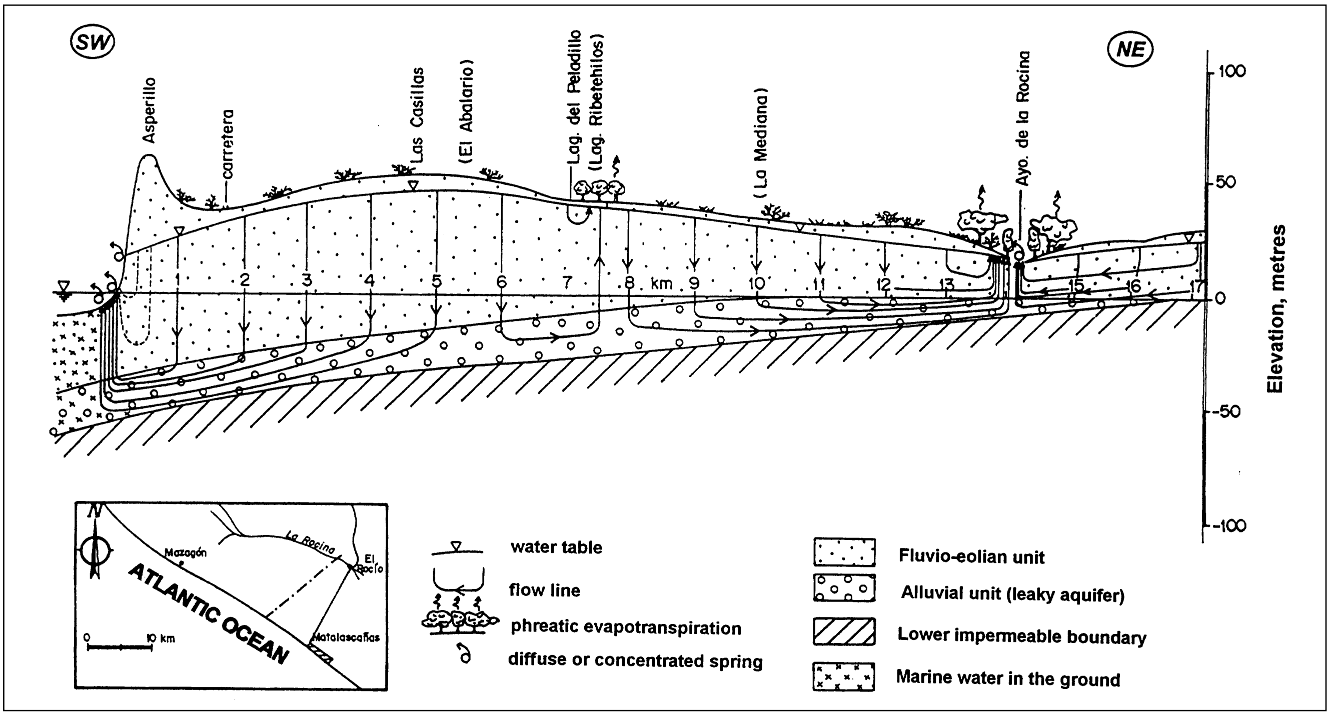

Fig. 2.- Idealised groundwater flow pattern in a cross-section through the sandy formation of the El Abalario (Doñana, Southern Spain) where a deep aquifer is under a thick layer of fine to medium silica sands which contains the water table (Custodio, 1995b). Groundwater flowing through the sands discharges through springs and diffuse flow at the sea shore and in the La Rocina creek as well as phreatic evaporation by plants near La Rocina creek and in intermediate, shallow water table areas.

Fig 2.- Esquema idealizado de flujo del agua subterránea en una sección que corta la formación arenosa de El Abalario (Doñana, Sur de España) donde aún existe un acuífero profundo bajo una gruesa capa de arenas silíceas de tamaño fino a medio en la cual se encuentra el nivel freático (Custodio, 1995 b). El agua subterránea que fluye por las arenas descarga en nacientes y como flujo difuso en el litoral marino y en el arroyo de La Rocina, así como por evaporación freática por las plantas cerca del arroyo de La Rocina y en áreas intermedias de nivel freático somero.

to be matched by the ability of plants to extend their roots downwards. But real situations are often complex and not straightforward. What actually interests us from an ecological point of view is water table behaviour. However, often groundwater development comes from deep layers. Depending on local hydrogeological circumstances the effect on the water table may be small, or slow and long delayed, or the drawdown is produced far away, where the confined deep aquifer layers being developed crop out (fig. 2).

If groundwater development is from deep layers (aquifers) the rate of water table drawdown is often small and may proceed unnoticed for some time. This is due to the natural variability produced by changes in recharge by rainfall, which obscures the trend. Also, in agricultural areas, when it rains, well pumps are generally turned off. The result is that after wet periods it seems that there is full restoration of past high water situations (fig. 3), and the real drawdown trend is not evident.

But the actual result from the point of view of the phreatophytes is that wet periods are becoming shorter and less frequent and dry periods of water stress are becoming longer and more frequent. This means that sensitive plants do not grow, or dry up or suffer and die from water stress and diseases, and the area is reduced in size or progressively disappears. This is a subtle move towards desertification, which mimics a climate change evolving towards drier and more irregular conditions.

Many of these effects have been extensively documented in the Doñana area in Southern Spain (Suso and Llamas, 1991; Custodio, 1992; 1995;

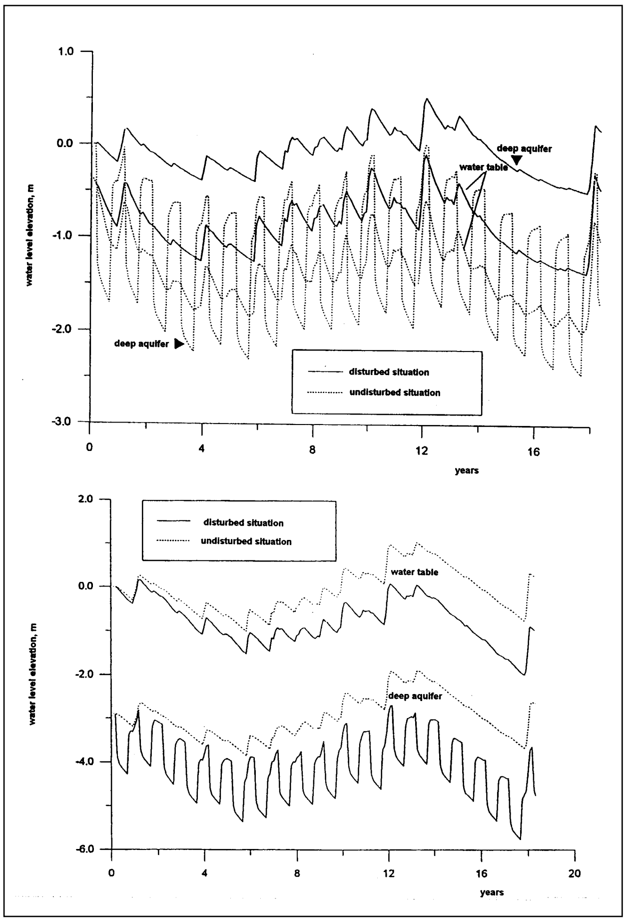

Fig.3.- Results of seasonal groundwater development of a deep aquifer about 1.5 km away from the area considered here. The aquifer system is as in figure 2. The datum for elevation is arbitrarily taken as the starting water table position. There is a conspicuous drawdown in the low hydraulic diffusivity semiconfined aquifer and a smoothed and increasingly marked drawdown of the water table (after Trick, 1992) The upper figure refers to an intermediate position in which downward vertical flow dominates. The lower figure is for an area close to the La Rocina creek, where under undisturbed conditions there is upward vertical flow which is, however, temporarily reversed by groundwater abstraction. In wet years there is a partial recovery of groundwater levels, but at present wet periods (shallow water table) are becoming shorter and dry periods (deep water table) longer and more frequent.

Fig 3.- Resultados del desarrollo estacional de agua subterránea de un acuífero profundo a 1,5 km de distancia del área que aquí se considera. El sistema acuífero es como el que muestra la figura 2. La referencia altimétrica se toma artificialmente como la posición inicial del nivel freático. Se produce un claro descenso piezométrico en el acuífero semiconfinado, que tiene una pequeña difusividad hidráulica, y un descenso suave y cada vez más marcado del nivel freático (según Trick, 1992). La figura superior se refiere a una posición intermedia en la cual domina el flujo vertical descendente. La figura inferior es para un área cercana al arroyo de La Rocina, caracterizada por flujo vertical ascendente en condiciones naturales, el cual se puede invertir temporalmente por la extracción de agua subterránea. En años húmedos se produce una recuperación parcial de los niveles freáticos, pero actualmente los períodos húmedos (desnivel freático somero) van haciéndose más cortos y los períodos secos (de nivel freático profundo) se hacen más largos y más frecuentes.

Custodio and Palancar, 1995; Llamas, 1990; Trick, 1998). Another area with documented impacts is the Tablas de Daimiel, in La Mancha, central Spain (Llamas, 1988; López-Camacho and García Jiménez, 1991).

LAND SUBSIDENCE AND EFFECTS OF COLLAPSE: CHANGES IN FLOOD PATTERN

Land subsidence due to groundwater development is produced in relatively young, unconsolidated sediments when interstitial water (or oil or gas) pressure reduction, and the consequent increase in intergranular stress, produces an inelastic (non-reversible) porosity reduction by compaction. Thus, land surface subsides. The effect is very small per unit thickness of sediments, but in many sedimentary basins and coastal areas the affected thickness is hundreds and sometimes thousands of metres. This leads to surface land subsidence of decimetres up to several metres over large areas, as happens in California, Gulf of Mexico, Bangkok, Tokyo, Mexico City, Venice and other areas. The main result is changes in flood characteristics of the area, which becomes more prone to inundation and may even evolve towards an endorheic situation if it is not artificially drained. This has an effect on the environment and plant communities. When the water table is not affected by groundwater development from well-confined, deep layers, the water table rises due not only to land subsidence but also to increased recharge. This may lead to the formation of groundwater-fed lakes and wetlands if they are not artificially drained. Drainage means deepening valleys and digging channels, which may produce watertable drawdown in areas outside the subsidence area. In coastal areas not only flooding is easier but the coast line retreats and flat land may be covered by the sea or becomes more prone to covering during rough sea conditions.

If sediment thickness and characteristics are homogeneous, subsidence does not produce conspicuous relative changes in land elevation, but differential subsidence may happen otherwise. This leads to house and building failures, as on the boundaries of Mexico City lacustrine deposits (very clear in the fractures and uneven ground of the old Cathedral, whilst the old Theatre House, in the city centre, sank regularly), or disruption of roads, railways, pipes and canals. This is the case in the Tucson basin, where a sudden change in recent sediment thickness due to deep tectonics is producing a step in the motorway to Phoenix, which grows progressively. In the town of Murcia (Eastern Spain), groundwater abstraction during a drought period produced some distributed subsidence which differently affected wall to wall, high apartment houses, due to foundation work differences. Open spaces between buildings appeared and some large cracks developed, besides a concerning loss of verticality.

Subsidence does not appear in hard, consolidated rock. But changes in groundwater pressure may effect seismic properties in the area in a currently poorly understood way. The effects of groundwater development are more important in hard rocks which may be dissolved by groundwater (karstification), such as carbonates (limestone and to a lesser extent dolostone) and massive sulphates. Low depth cavities may increase the collapse rate (formation of sinkholes) when water pressure inside them is lowered or they become dehydrated due to groundwater development, and also when artificially produced water table fluctuations and induced air pressure changes weaken the structure. Gypsum-rich formations (silts, colluvium, sand, gypsum layers) may easily develop sinkholes in areas of concentrated recharge, such as along canals and leaking ponds.

EFFECT OF WATER TABLE RECOVERY: WATER-LOGGING IN URBAN AND SURROUNDING AREAS

Groundwater table development may be non-permanent. It may cease after a new source of water is available to the area, or the quality of abstracted water impairs (return irrigation flows, contamination, salt water intrusion), or there is a change in land-use, or due to any other cause (Custodio, 1997a).

Thus the main effect during groundwater development, which is water table drawdown, begins to regain its natural height before development, or a new position controlled by existing drainage works. This has a clear environmental effect, since old shallow water table areas and wetlands may reappear, but now with infrastructure already present in the area. Since these structures were constructed and installed when the water table was low, the possible water table recovery was often not taken into account .

These situations appear in both in the rural and urban environment, but are more serious in urban areas.

In rural environments local wells may keep the water table below root depth, and then, in permeable soils, excess irrigation water is naturally drained downwards. When imported irrigation water is available and local wells stop pumping, not only the water table recovers but return flows keeps it higher. Damage to plants and crops, soil salinisation by direct evaporation from the soil and loss of farming land by water logging is what may happen if a drainage system is not installed, which often is an expensive solution.

In large towns and their surrounding areas, water table recovery may cause water-logging in cellars, underground parking lots, tunnels, sewers, underground space for different uses (such as electric transformers), as is the case in many large towns (Chilton, 1997), such as Barcelona, Paris, London, New York, ... (fig. 4 and 5), as well as conspicuous changes in groundwater quality (Custodio, 1997; Bruce and McMahon, 1996).

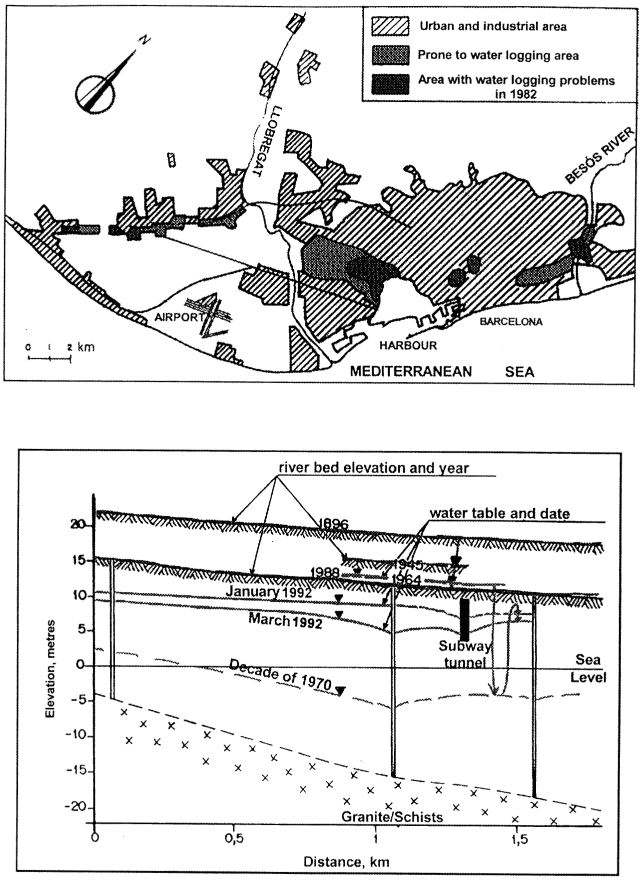

Fig. 4.- Areas prone to and with water logging in 1982 (after Custodio and Bayó, 1986) in the coastal plain of Barcelona (upper figure) due to progressive abandoning of wells in formerly shallow aquifer areas. This affects underground structures, such as the subway network. The lower figure shows the effect on a section below the Besós river (Vázquez and Sánchez-Vila, 1997; Vázquez, 1997).

Fig 4.- Arenas del llano costero de Barcelona (figura superior) que en 1982 eran anegables o con tendencia al anegamiento (según Custodio y Bayó, 1986), debido al abandono progresivo de pozos en áreas que originariamente fueron de nivel freático somero. Esto afecta a estructuras subterráneas, tales como la red del ferrocarril metropolitano. La figura inferior muestra el efecto en una sección bajo el río Besós (Vázquez y Sánchez-Vila, 1997; Vázquez, 1997).

WATER QUALITY CHANGES DUE TO GROUNDWATER DEVELOPMENT

Groundwater development may affect groundwater quality by changing the flow pattern and distribution of salt water in the ground, and also the penetration of contaminated water. This contaminated water may be the result of the use of abstracted groundwater itself. This is the case of return irrigation flows, which in semi-arid climates with efficient use of water, or by applying high salinity water, may be brackish and contain agro-chemicals. All this is a key concern in rural areas and one of the main causes of groundwater degradation. In coastal areas seawater intrusion and mobilisation of salt water by wells and drains may produce environmental damage downstream and in cultivated fields, especially when there is a rise in brackish water (Custodio and Bruggeman, 1986; Falkland and Custodio, 1991). In urban and surrounding areas, besides, the increased pollution risk by individual sources of contamination (leakage, leaching of pollutants), there is a widespread source of contamination

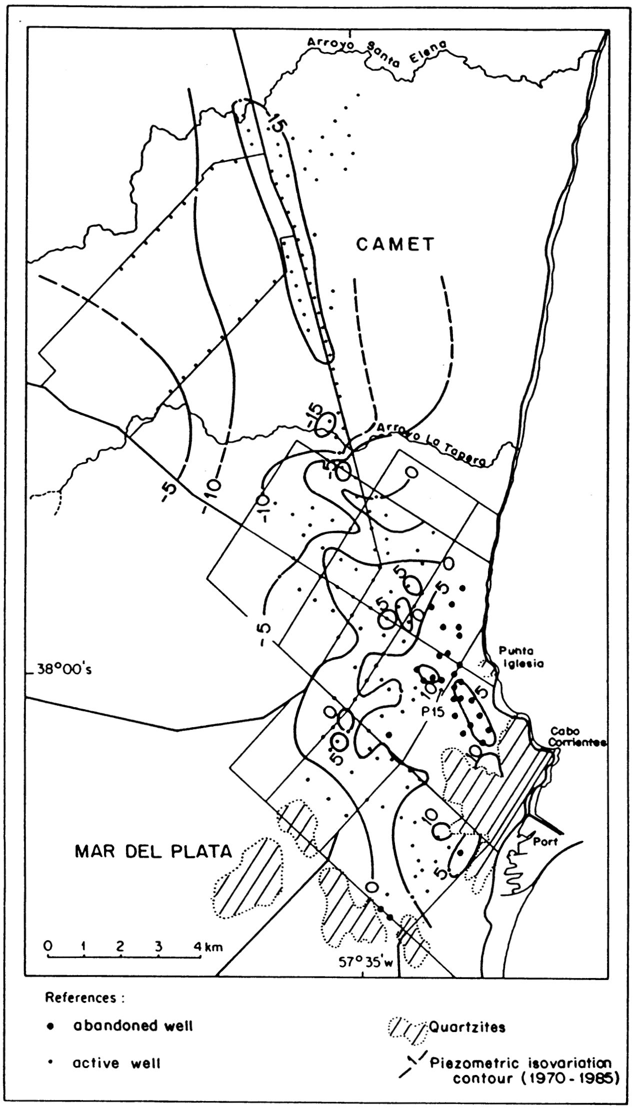

Fig. 5.- Results of groundwater development in urban Mar del Plata (Argentina) and surrounding areas, after wells inside the town were closed down due to poor quality and saline contamination, and substituded by wells on the periphery. The isolines show the water table change (in metres) between 1970 and 1985 (after Bocanegra et al., 1992; Bocanegra and Custodio, 1995). Whilst there is a progressive water table drawdown on the periphery, in the town there is a recovery. Underpressure and a corrosive environment are affecting the basements of high buildings.

Fig 5.- Consecuencias de la explotación del agua subterránea en la parte urbana del Mar del Plata (Argentina) y áreas periféricas, después de que los pozos dentro de la ciudad fueron clausurados a causa de la mala calidad y contaminación salina, y substituidos por pozos en la periferia. Las isolíneas muestran al cambio del nivel freático (en metros) entre 1970 y 1975 (según Bocanegra et al., 1992; Bocanegra y Custodio, 1995). Mientras se produce un descenso freático progresivo en la periferia, en la ciudad se produce un ascenso. Las subpresiones y el ambiente corrosivo afectan a las cimentaciones de los edificios altos.

formed by the scattered points of sewage penetration through cesspits and leaking sewers, and an anaerobic environment, due to the enhanced availability of organic matter and poor aeration as a result of soil compaction, pavements and buildings.

The environmental implications refer to the chemical changes in groundwater available to plants and the flow decrease into rivers, springs, lakes and wetlands, and even the coast (Portnoy *at al.,* 1998). These are a delayed effects, which may appear after years or decades, depending on aquifer system size and characteristics, and with a variable pattern due to changes in pollutants in the ground by ion exchange, adsoption and redox processes. Often there is not a clearly defined onset of pollutant arrival but rather a slow increase. The effects may last long after the actual cause is no longer present.

The processes are well known, but well-documented cases are scarce and the environmental effects are not well understood, due to the long observation time needed to follow the changes and to complete a comprehensive case study.

The two more conspicuous pollutants of regional value are increase in salinity (table 3) and the increased availability of nitrate. Both, and especially nitrate, which is a nutrient, affect plant species and productivity. The behaviour of phosphorus, which is also an essential nutrient used on agricultural land, is less known. In calcareous soils it is retained as insoluble calcium phosphate. Its behaviour in silica soils is uncertain and there is still basic research to be carried out, although there is some retention. Reducing underground environments may produce the discharge of soluble reduced iron and manganese, which may not only stain large areas after being reoxidized in contact with air but also affect life as well, by poisoning, changing water transparency and lowering the pH.

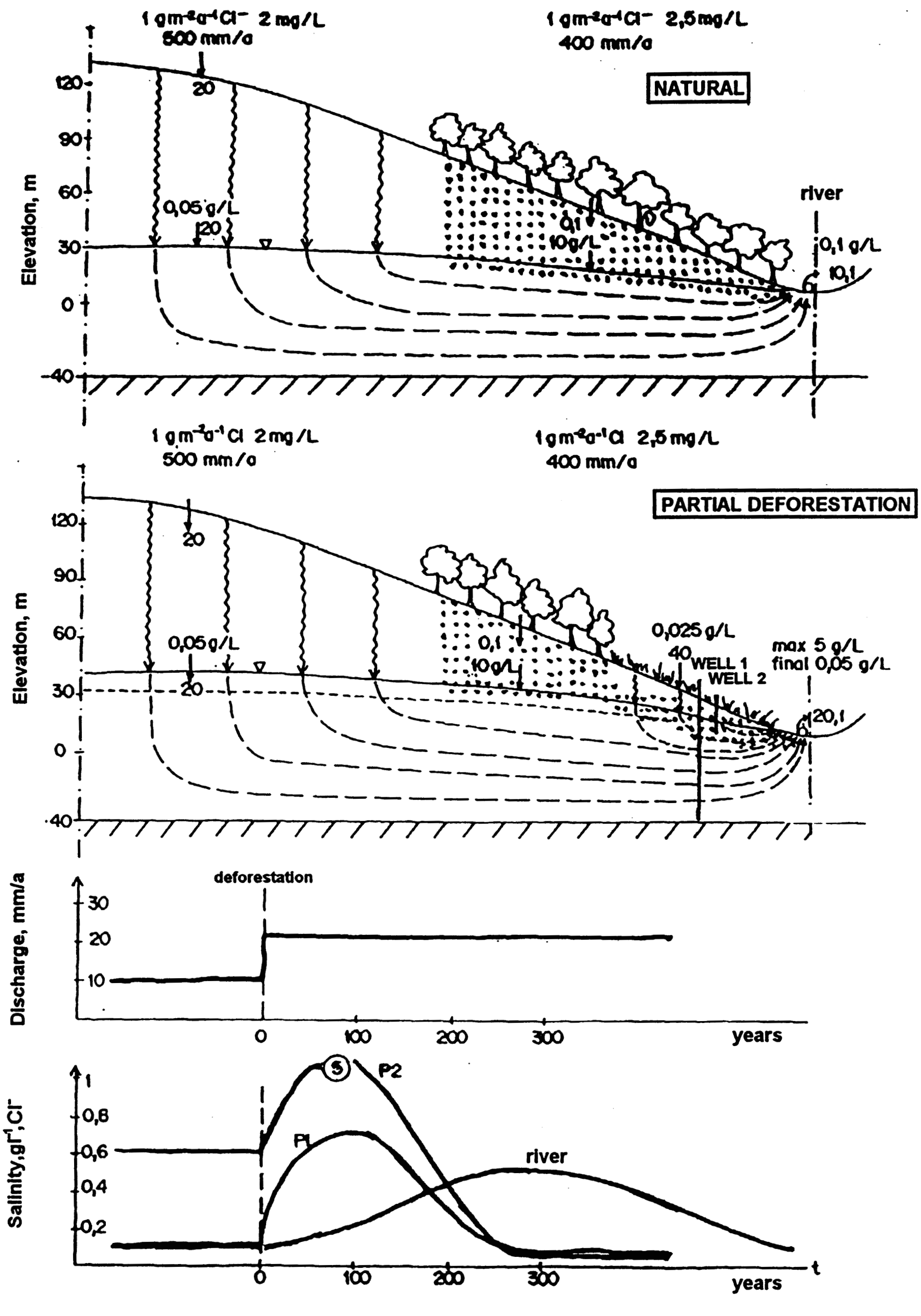

Fig. 6.- The upper figure shows the slow production of salt water below forested areas in semi-arid areas and how this has some effect on discharged groundwater. The central figure shows the effect of saline water leaching by increased recharge in deforested areas and the increased salinity of discharge into the river. Evolution over time is shown in the graphs (after Custodio, 1997b) .

Fig 6.- La figura superior muestra la lenta producción de agua salina bajo áreas boscosas y como esto tiene cierto efecto en el agua subterránea que se extrae. La figura central muestra el efecto del lixiviado de agua salina por aumento de la recarga en áreas deforestadas, y el aumento de salinidad de la descarga al río. En los gráficos se muestra la evolución a lo largo del tiempo (según Custodio, 1997b).

* Penetration of new seawater * Existence of old, unleached marine water due to a very small water head gradient and / or very low permeability
* Marine spray in windy areas close to the coast line * Concentration of rain water by evaporation at the soil surface or in upper soil
* Watertable evaporation in wetlands * Evaporated salt dissolution when present in the aquifer system * Displacement of deep seated, saline groundwater, naturally or induced by groundwater development
* Irrigation return flow infiltration in arid climates or when high salinity water is applied
* Industrial, mining and ice-production processes * Salt water transport over the area

Table 3.- Possible sources of salinity in groundwater.

Tabla 3.- Posibles fuentes de salinidad en el agua subterránea.

The transport of pesticides is still under study but in some cases some substances or their intermediate breakdown products are known to appear in springs and rivers.

Another aspect of the environmental impact of groundwater changes is due to the faster movement of brackish and saline water in the ground, following the recharge increase which follows deforestation of large areas for crop and pasture land in semi-arid areas (fig. 6) . Currently this is a worrying cause of downstream river water salinisation in some areas of Australia, such as the Murray basin (Simpson and Herczeg, 1991), and was probably one of the main causes of environmental changes in the past, when large areas of land were deforested, as in the Monegros (NE Spain)

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