EFFECTS OF GROUNDWATER DEVELOPMENT ON THE ENVIRONMENT

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Abstract: - Groundwater is an essential part of the hydrological cycle. It is characterized by its long turnover time, ubiquity and small variability. Flow and chemical characteristics and properties have to be considered in a three dimensional framework. Groundwater stable flow and definite chemical character play a key role in geological and biological processes and thus has significant environmental implications in maintaining river and spring base flow, wetlands, phreatophyte communities, gallery forest, ..., and also is an essential feature in favour of its development. Groundwater development implies a change in the flow pattern which may result in water table lowering, decrease of outflow and chemical changes, moveover land subsidence in some cases. All this modifies environmental conditions, which leads to water flow decrease, reduction of phreatophyte surface area, wetland desiccation and biological modifications related to chemical changes. But these changes appear with 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 with the impacts of other alternatives. This includes the consideration and the cost of possible correction of the long delayed negative effects. Aquifer salinization and contamination is an important environmental issue that has to be taken into account since groundwater will be soon or later discharged into the environment, carrying with it the contaminants or their transformation products, in a complex way.

Key Words - Groundwater development, environment, interferences

ESSENTIAL CHARACTERISTICS OF GROUNDWATER

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Groundwater is the water inside the pores, fissues and voids below the ground surface, both in the unsaturated zone and in the saturated zone below (Custodio and Llamas, 1976; Candela et al., 1998). Often the designation groundwater refer to water in the saturated zone. Water combined with minerals or hold in small, closed pores of tight rocks is often not strictly considered groundwater, although it may 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 include water table and confined formations. A given formation may be confined, semiconfined or a water table one, depending on the location and water head pattern. The water head may be different from one unit to another and groundwater flows following a 3-D (three-dimensional) pattern. Groundwater flows with a dominant horizontal component in aquifers but it moves mostly vertically through aquitards separating aquifers. It moves downwards in the unsaturated zone, except very close to the land surface where evaporation forces and suction 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 covers, foothills, lake shores, ...

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

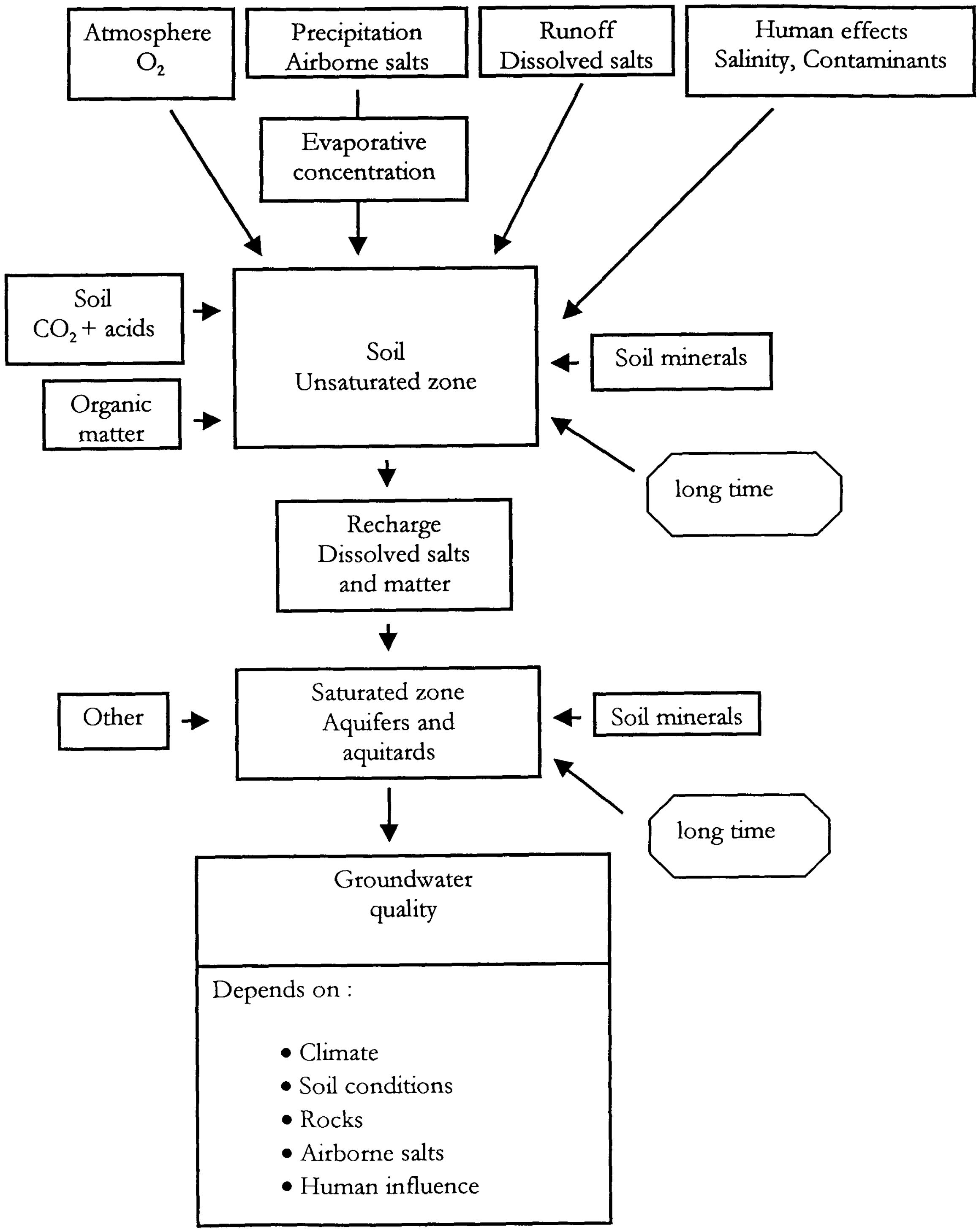

Fig. 1. Simplified presentation of how groundwater chemical composition is generated in the unsaturated and in the saturated zone. The figure refers to precipitation recharge.

The chemical composition of relatively short turnover time groundwater is the result of processes mainly in the soil (fig. 1). Rainfall is evapotranspirated and airborne salts and matter dissolved in the precipitation are evapoconcentrated, at the same time that soil gas CO_2 from organic matter respiration and degradation is incorporated. This means that some minerals (carbonates, silicates) can be hydrolized. The result is that cations from the soil and rock are added and CO_2 is converted to HCO_3^-. Under oxidizing conditions organic matter is oxidized 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 and salts. If dissolved O_2 from the air, and also NO_3^- from plant decay or artificially added, are depleted by organic matter and other electron donors, oxidizing condicions change into reducing conditions and some heavy metals may dissolve as reduced ions (Fe^{2+}, Mn^{2+}), sulphate may be reduced to bisulphide (HS^-) and under intense anaerobic conditions methane gas may form. The ion exchange capacity of minerals, mainly clay minerals and organic matter, play a significant role in smoothing and retarding ion chemical changes, mostly of cations. A similar role is played by the adsorptive capacity of mineral surfaces, organic matter and colloids with respect dissolved organics.

In all these processes chloride behave as conservative (it does not interact) and in most cases becomes a main tracer to identify recharge and groundwater flow. It reflects mostly evapoconcentration. Evapoconcentration can be small in humid climates (a ratio of recharge to rainfall not much greater than 1) but very large in arid areas, which means a ratio of up to 100 or more. This means that recharge water may be brackish under these circumstances (Custodio, 1997b).

But in long turnover time aquifers things can be different since old marine water, evaporation saline water and brines, evaporite salts, water from deep seated layers, ... may be still in them or slowly prenetrating through leaking aquitards. This explains saline springs and rivers.

ENVIRONMENTAL ROLE OF GROUNDWATER

The role of groundwater in the environment present different aspects but all of them refer to the relatively small changes of groundwater flow discharge and chemistry compared to seasonal and interannual clima variability, in contrast to what happens with surface water. This produces enviromental conditions which in the first case favours steady conditions and variability in the second one. The combination leads to enlarged diversity.

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

- Permanent or little variable outflows in spring and along rivers, which maintains base flow. This allows the availability of water all the year around, even when surface water contribution is nil.

- Stable or little variable discharge areas (wetlands), with deep water (lakes) or shallow water (swamps, fens, ...).

- Stable shallow water tables accesible to perennial plants along valley bottoms (gallery forest), around lakes, or elsewhere.

- Sustainability of water salinity of lakes and wetlands placed in endorheic basins where there is an underground outflow of water that keeps the dissolved salt balance.

- Maintaining the water physico-chemical characteristics and conditions to soustain some species of vegetation and associated animals. Such are temperature, pH , bicarbonate supply, silica concentration, ...

- Supplying salts to saline wetlands and "salares", to soustain special environments.

HYDRODYNAMICAL AND CHEMICAL EFFECTS OF GROUNDWATER DEVELOPMENT

The development of groundwater for economic uses (drinking, house and municipal supply, agriculture, industry, tourism and gardening) implies changing 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. The abstracted water is water that is now not available at the natural discharge areas. Thus the effects of groundwater development are (Custodio, 1991; 1996; Margat, 1992):

- Groundwater head drawdown and watertable lowering
- Reduction of natural discharges
- Changes in groundwater flow pattern that affect groundwater quality distribution in the ground and the displacement of saline waters, including intruded sea water.

But abstraction and its effects are not simultaneous and the water head changes may modify the aquifer system recharge as well, often by 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 smaller solute transport velocity. Human experience with surface water, which is easily observable and behaving at a pace measurable by a dayly time scale, is not transferable to groundwater which behaves in three dimensions, over a large territory, unperceived by non experts and at a time scale commensurable to or longer than human life, instead of the dayly experience.

Beneficial effects of groundwater development are numerous and well known, as shown in table 1.

But benefits are not without negative effects on the environment and on the sustanaibility and economy of the solution itself, as for any artificial intervention in natural processes. Table 2 show a summary list of negative effects. Part of these negative effects are due to the hydrodynamic behaviour of aquifer systems and thus can be easily internalised and corrected and should form part of the evaluation of any groundwater alternative; if not it is a question of ignorance and malpractice and not a real negative problem. Other negative effects are more difficult to foresee and to evaluate, and thus to be intersalized such as land subsidence, water quality changes and enviromental effects. But the already available, extended experience on groundwater development, the good understanding of basic processes and the powerful study tools now in common use, such as flow and transport modelling, greatly diminish the uncertitude of future behaviour and allows the definition and evaluation of trustable corrective measures. Nature preservation is not a fashion but a need (Ramos, 1993) and an ethical value to be considered together with the social needs (Pérez Adán, 1992), in opposition to speculative, short minded and irrational behaviour (Foster, 1991; Custodio, 1996). Wetland preservation is an important constraint in groundwater management (Llamas, 1988, 1992, 1995) which does not hinders development but demands a rational and wide scoped approach.

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

Large storage

- * *Small variability*
  - *Discharge*
    - *natural*
    - *artificial*
  - *Quality*
  - *Temperature*
- ⇨ *adequate for supply under*
  - *peaks of demand*
  - *droughts*
  - *emergency situations*
- * *No need for storage facilities* ⇨ *an abstraction facility occupies a small surface*
- * *Essential storage in coastal areas*

Sluggish flow through small voids

- * *Time for*
  - *progress of chemical reactions*
  - *biological decay of pathogens*
    - (both:) *homogeneization*, *depuration*
  - *decay of short / medium lived radioisotopes*
  - *temperature equalization*
  - *correcting contamination incidents*
- * *Filtering effect* ⇨ *clear water*

Large surface extension

- * *Availability close to demand*
  - *lower investment*
  - *less land-use problems*

Hydrological

- * *Faster evaluation*
- * *Knowledge increasing with development*
- * *Confiable future scenarios*

Other

- * *Greater security against*
  - *natural hazards*
  - *human failures*
  - *criminal actions*
- * *Possibility of direct supply for drinking purposes*

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

Water quantity effects

* *Groundwater level drawdown* ⇨ *increased water cost*
  ⇨ *changes in* { *wells*, *pumps*, *facilities* }

* *Discharge decrease in* { *spring flow*, *river base flow*, *wetland surface area* }

* *Longer sections where river losser (recharge) water*

  • *In* { *large*, *low permeability* } *systems* ⇨ *long lasting transients months to milleniums*

  • *Effects can be easily internalized*

Water quality effects

* *Quality changes as the flow pattern modifies*

  • *Displacement on low quality water bodies*
  • *Sea water encroachment in coastal aquifers*
  • *Easier surface water infiltration*

* *Wells and boreholes mix different groundwaters*

  • *Produces water quality changes*
  • *Surface and water table water may get into deep aquifers*

Other effects

* *Land subsidence*

* *Increased collapse rate* { *in karstic areas*, *due to poorly constructed wells* }

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

The most important environmental changes produced by groundwater development are in table 3.

Table 3.- Environmental problems related to groundwater exploitation

- Decrease of discharges to spring 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 dryness frequency

They derive from what has been said about groundwater and aquifer system properties (see also Custodio, 1995b; Llamas, 1991). The effect on pheatophyte communities derives directly from the water table drawdown after groundwater development. The effect appears when the water table is kept at a position deeper than the maximun root depth, which depends on plant characteristics and the thickness of soil and weathered rock. But also the rate of water table (or capillary fringe) drawdown have 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 is the water table behaviour and in many cases groundwater development is 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 outcrop (fig. 2).

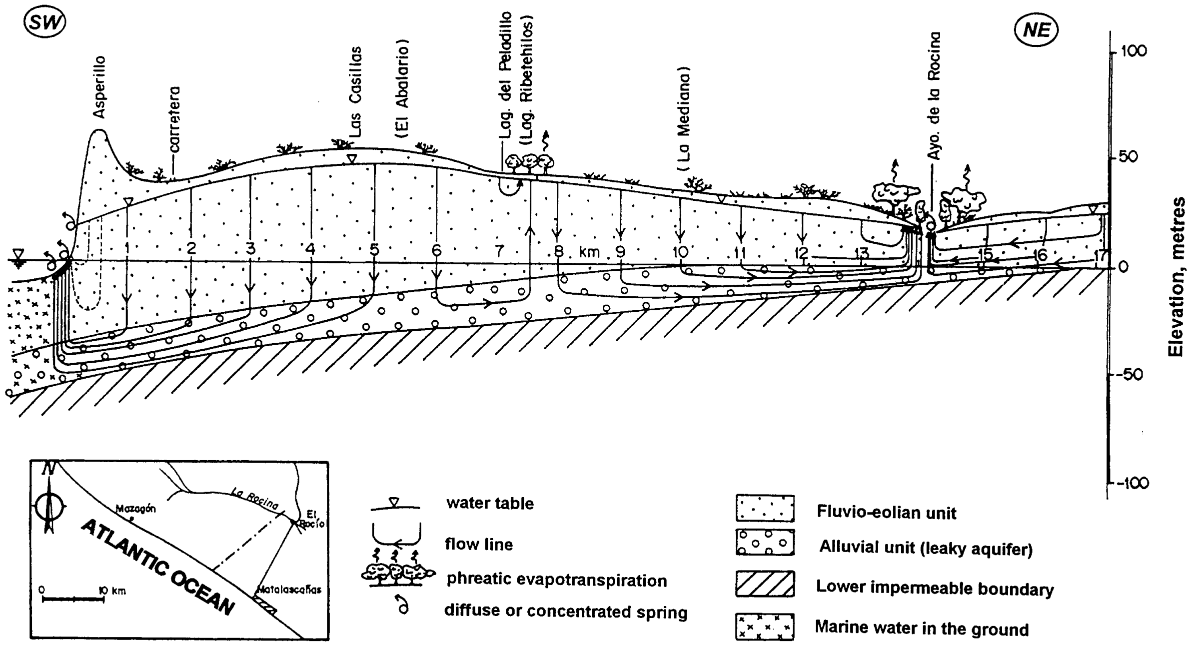

Fig. 2. Idealized groundwater flow pattern in a cross-section through the sandy formation of the El Abalario (Doñana, Southern Sapin) where a deep aquifer is under a thick layer of fine to medium silica sands which contains the water table (Custodio 1995). Groundwater flowing through the sands discharges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

In cases in which the water table drawdown is produced in low permeability formations (aquitards) as a consequence of groundwater development from deep, more permeable layers (aquifers) the rate of drawdown is small and may proceed unnoticed for some time since natural variability produced by changes of recharge by rainfall obscure the trend, and even after wet periods it seems that there is a full restoration of past high water situations (fig. 3).

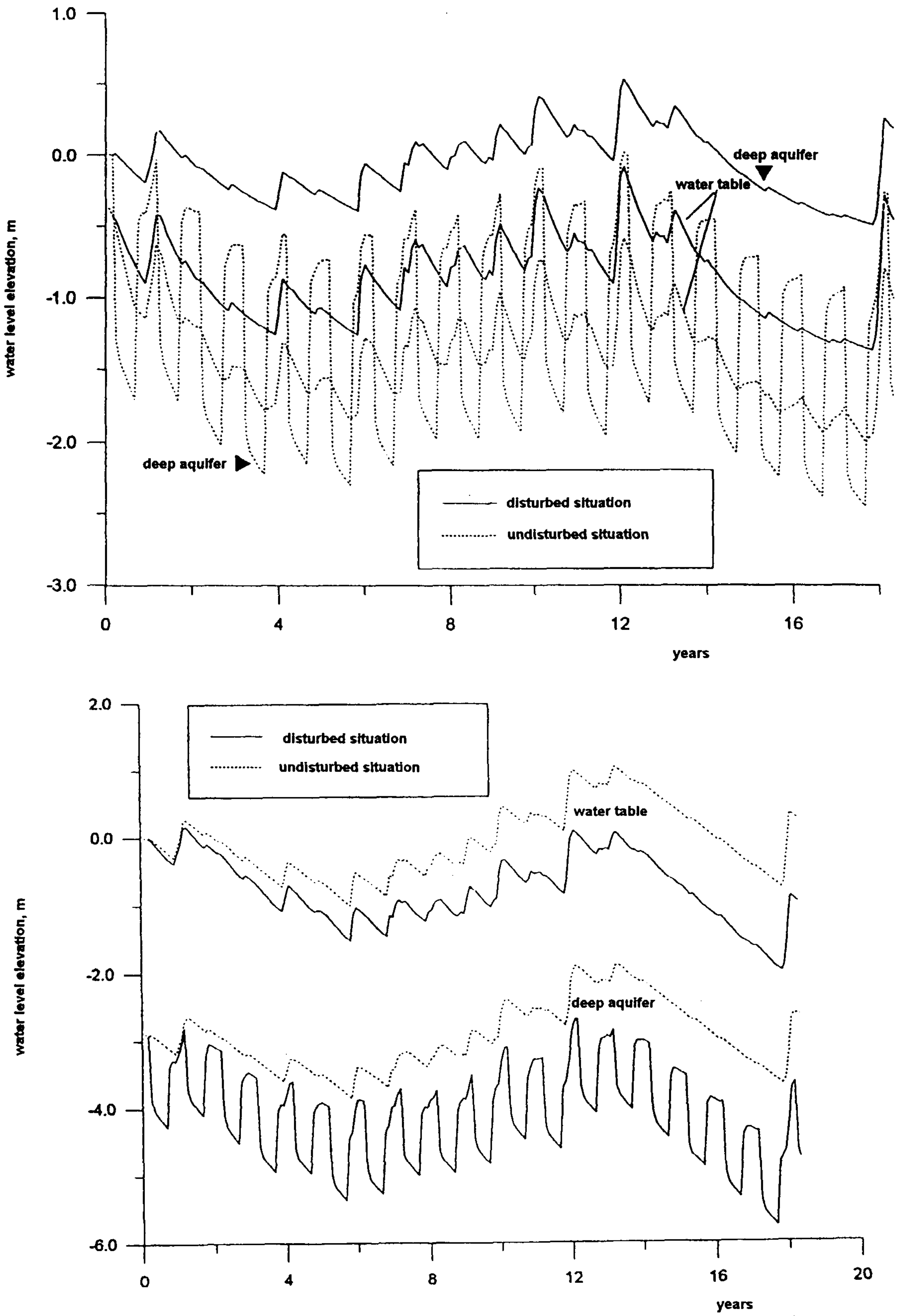

Fig. 3. Results of a seasonal groundwater development about 1.5 km from the area considered, exploiting the aquifer of figure 8. There is a couspicuous drawdown in the low hydraulic diffusivity semiconfined aquifer and a smoothed and every time more marked drawdown un the water table (after Trick, 1992) The upper figure

refers to an intermediate position in which downwards vertical flow dominates and the lower one to the discharge area near the La Rocina creek, where under non perturbed conditions there is upwards vertical flow, but it is temporarily reversed by abstraction. In wet years there is a partid recovery of groundwater levels but actually wet periods (shallow water table) become shorter and the dry periods (deep water table) longer and more.

But the actual result from the point of view of the phreatophytes is that wet situacions are becoming shorter and less frequent and dry periods of water stress become longer and more frequent. This means that sensitive plants do not develop, dry up or suffer from water stress and diseases, and the area is reduced in size or disappears. This is a subtle march towards desertification, which mimics a climate change evolving to dryer and more irregular situations.

Many of these effects have been extensively documented in the Doñana area, in Southern Spain (Suso and Llamas, 1991; Custodio, 1992; 1995; Custodio and Palancar, 1995; Llamas, 1990; Trick, 1998). Another area of documented impacts is the Tablas de Daimiel, in La Mancha, Central Spain (Llamas, 1988; López-Camacho and García Jiménez, 1991).

LAND SUBSIDENCE AND COLLAPSE EFFECTS: CHANGES IN FLOODING 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, produce an ineslastic (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 of hundreds and sometimes thousands of metres. This leads to surface land subsidence of decimetres 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 flooding characteristics of the area, which is now more prone to be inundated and even may become endorheic 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 not only the water table rises due to land subsidence but to increased recharge. This may lead to the formation of groundwater fed lakes and wetlands if not artificially drained. Drainage means deepening valleys and excavating channels, which may produce a water table drawdown in areas outside the subsidence area. In coastal areas not only flooding is easier but the coast line retreats and flat land is covered by sea or becomes more prone to be covered 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 lead to house and building failures, as in the boundaires 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, sunk 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 produces a progressing step in the motorway to Phenix.

Subsidence does not appear in hard, consolidated rock. But changes in groundwater pressure may effect seismic properties of the area in a currently poor understood way. The effects of groundwater development are more important in hard rocks susceptible of being dissolved by groundwater (karstification), such as carbonates (limestones and to a lesser extent dolostones) and massive sulphates. Low depth cavities may increase the colapse rate (formation of sinkholes) when water pressure inside them is lowered or they become dewatered due to groundwater development, and also when artificially produced water table fluctuations and the induced air pressure changes weaken the structure.

EFFECT OF WATER TABLE RECOVERY: WATER LOGGING IN URBAN AND PERIURBAN AREAS

Groundwater table development may be not permanent. It may cease after a new source of water is available to the area, the quality of abstracted water impairs (return irrigation flows, contamination, saline water intrusion), the area changes its land use, or any other cause (Custodio, 1997a).

Thus the main effect during development, which is water table drawdown, begins to recover looking for the natural elevation 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 infrastructures present on the territory, which often were installed when the water table was low and without considering its possible recovery.

These situations appear both in the rural and the urban environment, but are more serious in urban areas. In rural environments local wells 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 salinization by direct evaporation from the soil and loss of farming land by water logging is what may happen if a costly drainage system is not installed.

In large towns and periurban areas the water table recovery (fig. 11) may the cause of logging of cellars, underground parking lots, tunnels, sewers, underground space for different uses (electric transformers, ...) (Chilton, 1997), as is the case in many cities 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).

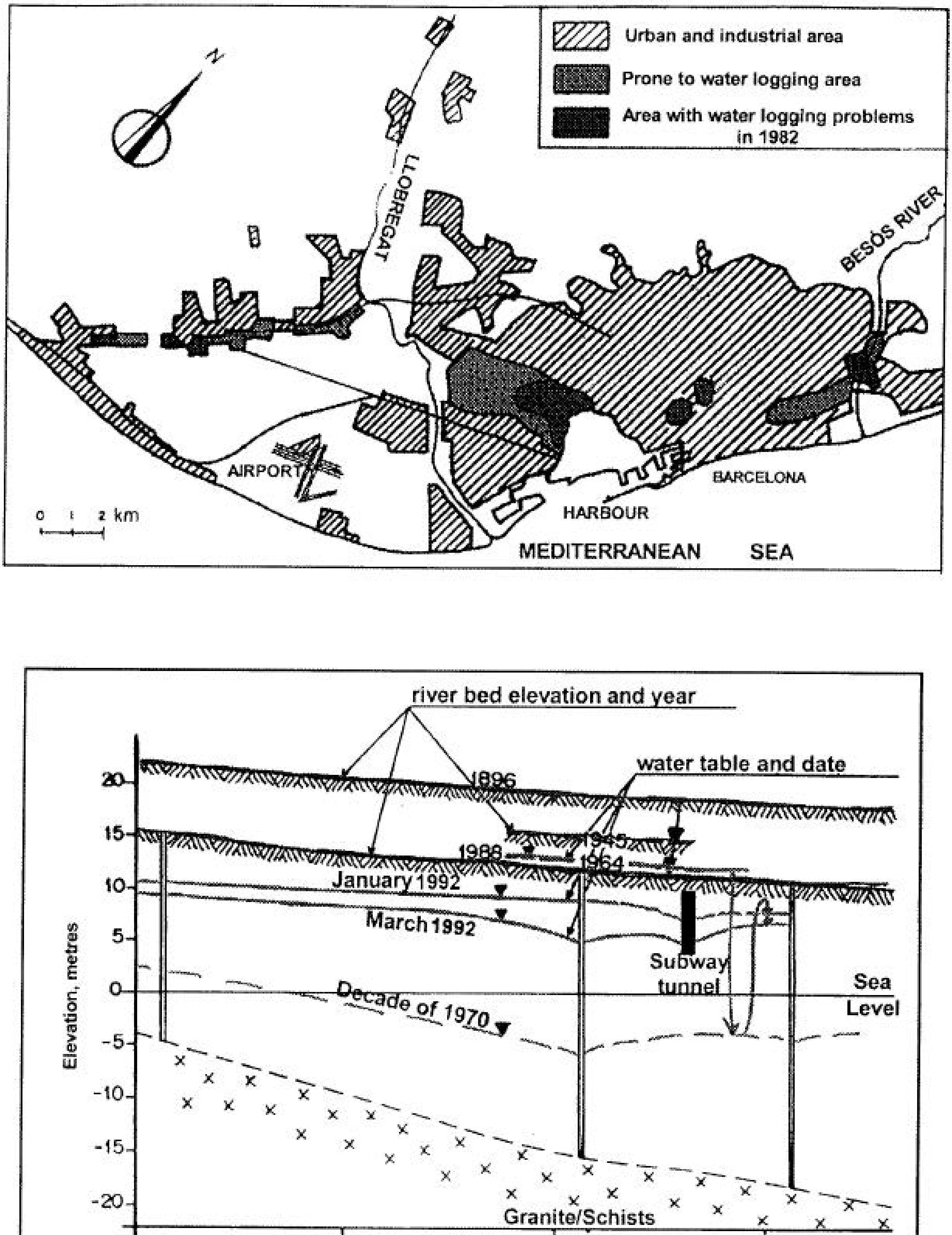

Fig. 4. Areas prone to and with water logging in 1982 (after Custodio and Bayó, 1986) in the coastal plain of Barcelona (upper figure) due to progressive abandoning of wells in formerly shallow aquifer areas. This affects underground structures. such as the subway network. The lower figure shows the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

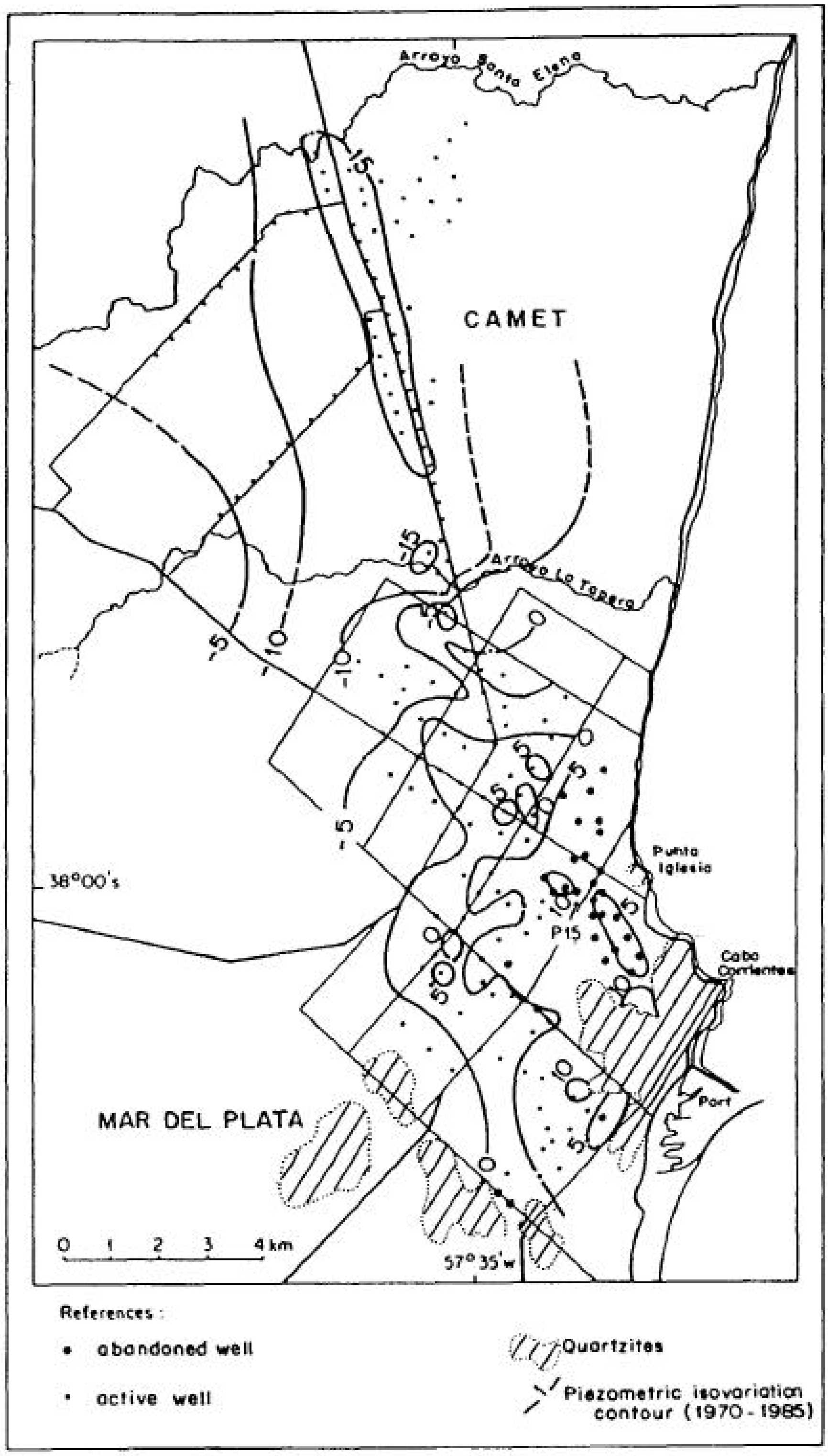

Fig. 5. Results of groundwater development in urban and periurban Mar del Plata (Argentina) after wells in town has been closed down due to poor quelity and saline contamination, and substituted by wells in the periphery. The isolines show the water table change (in metres) between 1970 and 1985 (after Bocanegra et al., 1992; Bocanegra and Custodio, 1995), Whilst there is a progressive water table drawdown in the periphery, in the city there is a recovery that affects the basements of high building due to underpressure and corrosive environment.

WATER QUALITY CHANGES DUE TO GROUNDWATER DEVELOPMENT

Groundwater development may affect groundwater quality by changing the flow pattern and the distribution of saline water in the ground, and by the penetration of contaminated water as well. This contaminated water may be the result of the use of the abstracted groundwater itself. This is the case of return irrigation flows, which in semiarid climates with efficient use of water, or by applying high salinity water, may be brackish, and incorporating agrochemicals as well. All this is a main concern in rural areas and a principal cause of groundwater degradation. In central areas seawater intrusion and mobilization of saline water by wells and drains may produce environmental damages downstream and in the fields especially when there is upconing of brackish water (Custodio and Bruggeman, 1986; Falkland and Custodio, 1991). In urban and periurban areas, moreover the increased pollution risk by point contamination sources (leakages, leaching of pollutants) there is a diffuse source formed by the scattered points of sewage penetration through cesspits and leaking sewers, and the reducing environment due to enhanced availabity of organic matter with poor aeration due to soil compaction, pavement and buildings.

The environmental implications refer to the chemical changes of groundwater available to plants and discharging into rivers, springs, lakes and wetlands, and even to the coast (Portnoy at al., 1998). This is a delayed effect, which may appear after years or tens of years, depending on aquifer system size and characteristics, and with a variable pattern due to modification of contaminants in the ground by ion exchange, adsoption and redox processes. Often there is not a sharp front of pollutant arrival but a slow increase, and the effects may last long after the cause ceases.

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 contaminants of regional value are salinity increase (table 4) and the augmented availability of nitrate. Both of them, and especially nitrate, which is a nutrient, affect plant species and vegetal productivity. The behaviour of phophorous, also and essential nutrient applied in agricultural land is less known. In calcareous soils it is retained as insoluble calcium phosphate. The behaviour in silica soils is uncertain and still there is 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 not only stains large areas but affects life as well, by poissoing, changing water transparency and lowering pH .

The transport of pesticides is still under study but in some cases some substances or its intermediate degradation products are known to be appearing in springs and rivers.

Table 4.- Possible salinity origins in groundwater

* Penetration of modern seawater * Existence of old unleached marine water due to 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 the upper soil zone
* Watertable evaporation in wetlands * Evaporite salt dissolution when present in the aquifer system * Displacement of deep seated, saline groundwater, naturally or induced by development
* Irrigation return flow infiltration in arid climates or when high salinity water is applied
* Industrial, mining and ice-production processes * Saline water transport over the territory

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

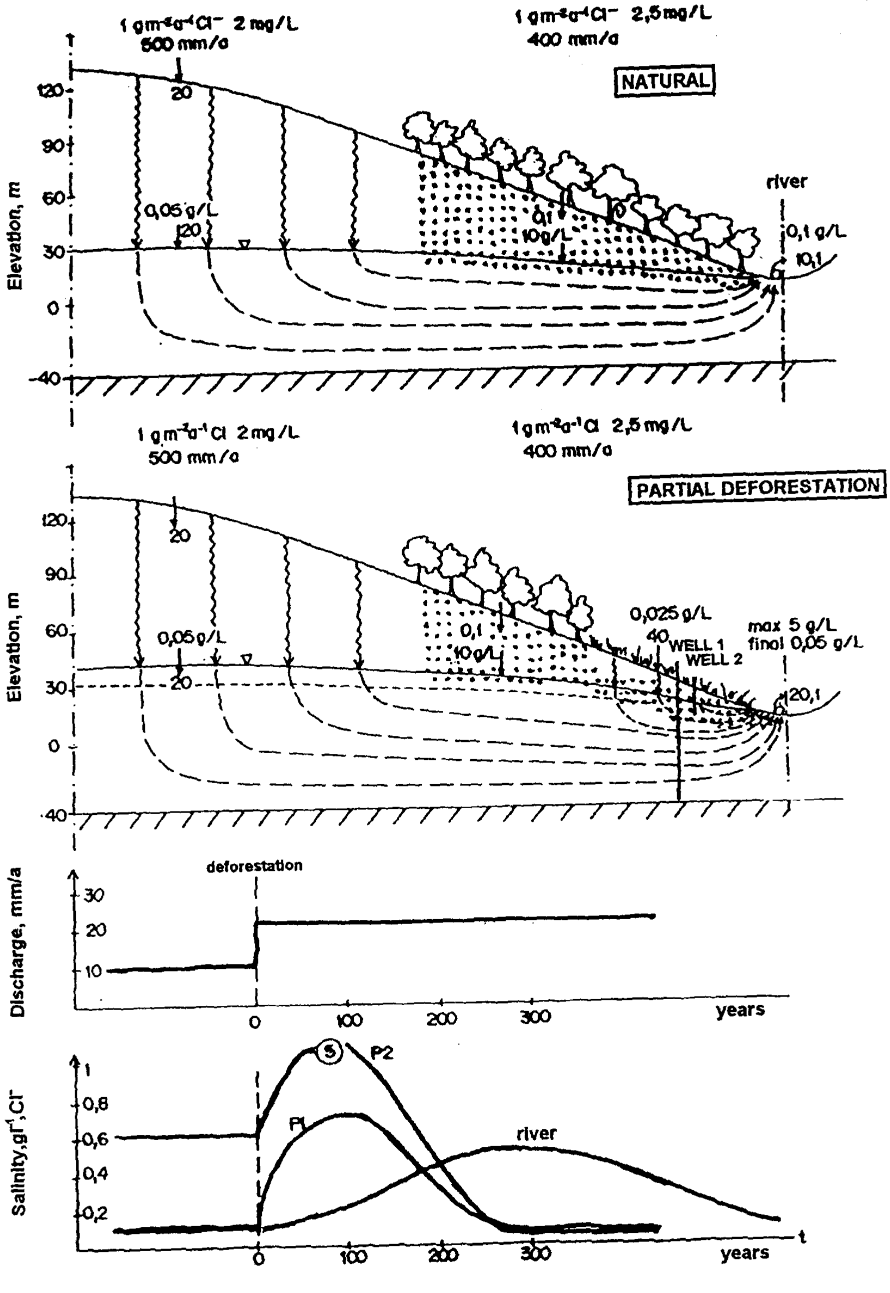

Fig. 6.The upper figure shows the slow production of saline water below forested areas in semiarid areas and how this has some effect on discharged water. The central figure shows the effect of saline water leaching by incresed recharge in deforested

areas and the increased salinity of discharge into the river. The time evolution is depicted in the graphs (after Custodio, 1997)

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