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Groundwater Protection and Contamination

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Abstract

Groundwater is a key part of the water cycle. It is generally characterized by its large storage/flow ratio and slow rate of flow as compared with surface water that has a small storage/flow ratio and rapid rate of flow. Groundwater, which interacts chemically and biologically with minerals and substances in the ground, is generally of good quality, although in some cases salinity or chemical composition may be naturally detrimental for human health or its intended use. Most causes of poor groundwater quality are the result of human activities that modify the aquifer functioning, enhance the leaching of some substances, or by the disposal or introduction into the ground of chemical and biological contaminants. Anthropic effects may appear slowly and after a long delay. The result is that aquifers are potentially vulnerable to contamination. Sorption, ion exchange and microbiologically mediated redox reactions play an important role in contaminant transport and abatement as some substances, including microorganisms and viruses, may decay after some time. However, other substances suffer little change. The unsaturated zone, and especially the soil, plays a key role in contaminant behavior and transport, and thus they are a key element for effective protection. Real situations are often very complex due to the existence of heterogeneities that on the one hand may facilitate a relatively fast movement of contaminants through preferential pathways and, on the other hand, retain them by diffusion into low permeability features from which they cannot be easily recovered. Turnover time of water in the ground is often measured in years to many hundreds of years. This means that groundwater quality recovery after a diffuse or point contamination process may be very slow. Although some artificial remediation is possible, it is often inefficient and expensive. Consequently, groundwater protection appears as the right policy to be adopted. Many aquifers worldwide are still of good quality but others have been severely contaminated or will be in the near future, both in developed and in developing countries. Shallow aquifers in and around urban areas or below intensive agricultural and animal-raising areas are especially vulnerable. Also, large quantities of contaminants are currently held in the vadose zone that can be leached down. Groundwater contamination is a general problem since it may affect, sooner or later, surface water and coastal marine groundwater quality, and groundwater-related ecosystems. Groundwater contamination control and effective aquifer protection are major challenges for science, technology and natural resources management. They are a social priority. Although clear advances have been made, further research is needed, jointly with increased social awareness of the problem, cooperative action between institutions and stakeholders, and the integrated management of natural resources. This is especially true for densely populated developing areas since good quality groundwater is an important asset for the future.

Introduction

Under water-scarcity conditions water quantity is often the dominant issue, especially in arid and semiarid regions. Science and engineering have devoted great efforts to alleviate this scarcity by a

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combination of making more water available and reducing demand while trying to keep the flow of social benefits and services provided under natural conditions. Nevertheless, water quality is also a key aspect that plays an important role in nature and may often decide whether available water is a usable resource to supply human needs. Downplaying the role of water quality is often a serious mistake that is made by many engineers and policy makers, which may result in high costs and negative consequences.

Water is capable of dissolving many substances and facilitates the existence and proliferation of many microorganisms, all of which are able to move with water, penetrate many environments and affect living bodies, including humans. Experience indicates the threshold concentrations to be used to decide if a given water is potable, fit for agriculture or usable in industrial processes—as it is or after some corrective treatment. Dissolved and colloidal substances may be a problem or a poison for humans, and their effects may be acute (in a short time) or cumulative (after continuous use for a long time). This is a complex field of knowledge in which important scientific and technological progress has been made, and guidelines and limits have been set, although they are the subject of revisions, often to lower values. Besides medical studies, user risk and social cost-benefit analysis should be also considered, taking into account the real context under which water is to be used in a given region or circumstances. Consequently, some limits are a subject of argument, such as that of nitrate, which may become a major ion in some groundwaters, and also pesticides.

A large variety of microorganisms and viruses are present in water, even in deep groundwater. Most of them are not harmful to humans, although they may affect some industrial processes and uses, and play a key role in natural chemical evolution. However, some microorganisms and viruses are pathogenic and may produce serious illness in humans and animals, maintain unhealthy conditions in some areas, and even start epidemics. Waterborne diseases have been and are a serious problem for human populations and are a serious concern in developing countries in which unsafe local sanitation coexists with poorly protected shallow groundwater supply sources, such as springs and wells.

Relevant Characteristics of Groundwater

Groundwater is a key part of the hydrological cycle as water moves from the oceans and back again with multiple and essential links with surface waters. It plays a key role in nature and intervenes decisively in geological processes, landscape forming and biological processes. Also, as a freshwater resource groundwater is an important asset for the survival and well-being of humans and for their economic activities.

Custodio and Llamas (1976) have characterized groundwater by its: very slow flow and large water storage, or long turnover time; close interaction with ground minerals and saline bodies in it; exchange with surface water; existence over large parts of the territory; three-dimensional flow and quality distribution pattern; water free of suspended matter; and its important role in sustaining aquatic ecosystems.

Under common natural circumstances, groundwater does not bear pathogenic microorganisms and viruses, and in most cases does not contain noxious solutes. In some cases water salinity may be excessive due to mixing with modern or old seawater in coastal areas and old deep-basin brines, by the dissolution of evaporite salts remaining in the terrain, or by evaporation from shallow water tables. It may also become too hard (excess of earth-alkaline ions) or incorporate solutes such as Fe and Mn in reducing environments or excesses of F, As, B and V, for instance. Many of these substances are often present in the ground under insoluble forms at relatively high concentration. Changes in environmental conditions may favor the dissolution. Quality anomalies may affect a large part of the whole groundwater body or be limited in some volume or transition front with other water bodies where there may be changes in oxidation-reduction (redox) potential or CO_2 concentrations that are derived from deep sources. All these are examples of natural contamination. Human-originated contaminants are mineral, organic and biological substances—including radioisotopes—produced and stored by man. Contaminants may also be the result of land use activities that may cause leaching of natural salts that are present in the ground or enhance evaporation of surface and shallow groundwater.

Contaminants may be conservative in the water (they remain in the water and are not transformed) or conservative in the solid-water system (they may separate from the water and be precipitated or sorbed, but not transformed). They may decrease by chemical reactions, radioactive decay or biological transformation and cell death, with or without significant retention in the ground by sorption. Substances may end in relatively innocuous products (water, CO_2, N_2, for instance) or originate intermediate products (e.g., metabolites) that in some cases may be even more inconvenient or noxious than the original ones. The actual degradation chains in natural soil and groundwater environment are often poorly known.

Water flow in the ground is often very complex due to the variable nature of geological formations both at large and small scale. Heterogeneities of different kinds play a significant role in water flow and even more in solute and colloid transport. Studies taking into account details are unfeasible, so simplified conceptual models are needed of a deterministic or stochastic nature. This means that real behavior is substituted by simplified schemes in which the low permeability features (aquitards at large scale, heterogeneities at small scale) are often reduced to the role of exchanging water and solutes by diffusion between the rock matrix and low permeability layers, and the more permeable formations and fissures. If this is neglected, some serious differences may appear between what is calculated and what actually happens. Improving these aspects is an encouraging research issue and a challenge for applied science and technology.

Commonly, contaminants from the surface or the near subsurface penetrate the aquifers through the unsaturated zone, and especially the soil, which is geochemically very active. For a porous medium, this often introduces a delay in the movement and arrival to the aquifer. But in the case of fissures the movement can be fast and with small interaction with the terrain, depending on the recharge rate and water content of the rock matrix. This means that in some cases contaminants may directly reach the subsoil and even the saturated zone with little alteration. Contaminants can also directly reach the saturated zone when artificially introduced into the ground.

Pollution of groundwater can be localized (point contamination) or affect a large territory (diffuse or non-point contamination). In the first case the contaminant tends to produce a plume in the water body. In the second case the contaminant may penetrate a large area or the whole water body, and this is a serious concern even at low contaminant concentrations due to the large water volumes involved. In any case there is a three-dimensional distribution. Contaminated groundwater may grade to non-contaminated groundwater, both laterally and vertically, upwards and downwards.

Contaminants behave accordingly with their diverse characteristics. Soluble contaminants move with groundwater. They are subject to retardation if sorbed and are affected by diffusion into small permeability heterogeneities or into block matrices in fissured rocks. Volatile contaminants, such as light fuels, may partially diffuse back into the atmosphere through the unsaturated zone. Non-miscible liquids in excess of the solubility in water form a separate fluid phase that moves down through the unsaturated zone if concentrations are greater than irreducible saturation (Pankow and Cherry 1996). Then, the excess of lighter (than water) non-aqueous phase liquids (LNAPLs) accumulate and float on the water table or move down through the saturated zone if they are heavier than water (DNAPLs, dense non-aqueous phase liquids), leaving a trail of contaminated formation that will be slowly leached by flowing groundwater. Often these separate fluid phases consist of mixtures of diverse substances with different solubilities and behavior, as is the case of many fuels. Groundwater passing through the ground that contains the separate phase dissolves part of the products according to their specific characteristics to form plumes with concentrations that may attain up to several mg/L for some undesirable compounds. Microbiological contaminants are often sorbed on soil particles and move occasionally or through course formations and fissures. Viruses move more readily as a colloid or attached to colloidal particles.

Processes in the Ground

Important scientific and technical progress (e.g., in monitoring, sampling and analysis) has been made in the last few decades regarding the processes that affect the fate of natural and anthropic contamination in groundwater. Such knowledge is essential for aquifer protection and restoration. Currently, a full branch of hydrogeology (Fetter 1999; Robins 1998; Yaron et al. 1996) exists that serves to understand these processes. Some key aspects already mentioned earlier in this paper are summarized later.

Mass transport in unsaturated and saturated media depends on advection and diffusion. Advection dominates large-scale processes and includes the effect of the heterogeneous layout of the terrain. Advection leads to groundwater mixing in springs, seepages, pumping wells and long screened boreholes. Diffusion plays an important role in local exchange with low permeability heterogeneities and between fissures and rock matrix, and may have a dominant role in transport and affect aquifer remediation effectiveness.

Sorption plays an important role in retarding the movement of solutes and of exchangeable ions. Retardation by partition may favor chemical reactions in the water, especially the slow rate redox reactions and the important cathalitic action of microorganisms in the ground. This activity depends on temperature, the supply of electron acceptors (oxidants) and also of nutrients, and on the absence of inhibitors. These complex relationships are still insufficiently known but there have been very significant advances in laboratory, microcosm and field tests. New, accurate sampling and analytical methods for chemistry and isotope ratio changes are current powerful study tools (see examples in Spence et al. 2005; Verstraetens et al. 2005).

The most physically, chemically and biologically active part of the ground is the pedologic soil. Below it, activity in the remaining part of the unsaturated (vadose) zone decreases. It may be slow to very slow in the saturated zone. This explains that when the soil is poor or missing (by excavation, deep injection), aquifers can be easily contaminated.

In the unsaturated zone there is generally a supply of oxygen that diffuses from the atmosphere or is advected with infiltrating water. Gases that are produced can be vented out (in an open system). In the saturated zone (acting as a closed system to many substances) redox reactions and their associated microbiological activity, if electron donors are abundant, may deplete all available oxygen. When oxygen is depleted reactions must proceed using other possible electron acceptors (NO_3^-, Fe(III), Mn(IV), SO_4^{2-}) with the help of anaerobic microorganisms. Such reactions proceed until the exhaustion of electron acceptors, provided oxidable contaminants (electron donors) are in large supply. Under highly reducing conditions methanogenesis (transformation of organic matter to methane and carbon dioxide) is possible. These processes have been observed in the natural, or enhanced, slow abatement of petroleum products and halogenated hydrocarbon plumes, in which the different compounds behave very differently depending on their nature, the presence of other components and the availability of electron acceptors (Cheremisinoff et al. 1984).

Heavy metals in water may be a serious health concern. In an oxidizing water environment most of them remain as insoluble oxides, or sorbed in Fe and Mn oxides and oxyhydroxides. In a reduced environment they remain also as insoluble sulfides or incorporated into them. But at some intermediate redox potentials and with a favorable pH they can be dissolved or desorbed from the terrain, where some of them are often at relatively high concentrations. The result is excessive concentrations in groundwater, giving rise to some serious health problems in populations that consume regularly this water. This is the case for fluor or arsenic in some areas where the origin is natural, although they can be also contaminants or due to human influence in dissolution conditions, such as aeration after water table lowering, arrival of oxygenated groundwater or acidification. Although many chemical reactions are slow, especially redox reactions, residence times of water in aquifer systems are also long (years to many decades, and even thousands of years) in many of the common circumstances, so reactions may progress conspicuously.

The transport of pathogenic viruses and microorganisms in the ground has been the subject of many studies. Their common absence from groundwater is a clear advantage, but this is true when the groundwater source (well, spring, gallery) is protected from surface water penetration and when the recharged water has remained in the ground a long enough time for biocontaminants to be inactivated or destroyed. Recent studies have extended decay times for microorganisms and viruses from some tens of days to some months (Goodfrey and Smith 2005; Balkwill et al. 2001; Pang et al. 2005). This is not a serious limitation to use water from most aquifers due to the long delay produced by the slow flow velocity and the sorption along the path, both in the unsaturated and saturated media. Desinfection is generally accomplished in fine grained material when the water table is a few meters deep, or at a distance of a few tens of meters. But contaminated groundwater may be found far away (up to several km) from the source area when the terrain is coarse (for instance, gravels), or fissured, or in karstic formations. Biological contamination is not rare in developing areas in which sanitation consists of latrines and cesspools penetrating the protective soil, and when drinking water is obtained from nearby shallow, poorly constructed, ill-protected wells and springs. Often the situation is amenable to technical improvement with good practice and modest investments, but local cooperation is crucial.

Current Views of Groundwater Contamination

Pessimistic views about the progressive loss of aquifer water quality by contamination can be found (Falkenmark 2005), even doomsday predictions. The use of a wide range of very different chemicals in agriculture, in the home and in industrial activities, many of which are already stored in the soil, is compared to a time bomb that is close to exploding. Field surveys in some areas show quite widespread contamination of some water table aquifers in many areas of the world. Some good inventories are published from the USA (Cohen 1992; Moran et al. 2004). Notwithstanding, in a thorough recent review of the future of hydrogeology (Voss 2005) groundwater contamination issues are only a small fraction of the most critical scientific topics.

It has to be taken into account that there is natural degradation of many substances in the ground, and that flow reversals may happen. This tends to restore original conditions. Modern water treatment technology adds new possibilities to get usable water from contaminated water at reasonable costs. This view tends to downplay the seriousness of groundwater contamination. There is a middle point between these two extreme views. Caution is needed but recovery is not impossible.

The risk of widespread groundwater contamination has been considered by some to be a punishment by nature to men for malpractice and greed in industrialized and agriculturally intensive countries. However, it is also a serious current concern for developing areas where the negative consequences are reinforced by lack of opportunities, funds and technology to fight groundwater contamination and its consequences on other water sources, human health, economic development and the maintenance of the flow of services and benefits from natural habitats.

Earth's aquifers still contain good to reasonably good groundwater, especially the deep ones and those in mountainous areas. The main known problems affect mostly shallow aquifers, especially below large urban and industrial areas, and below intensive agricultural fields in which agrochemicals are commonly applied for soil correction, as nutrients, and to control plant diseases, other plants and pests. Pesticides are also applied in critical quantities in non-agricultural uses to maintain open spaces, roads and railways (Chilton et al. 2005). The relative recent massive use of motor fuels and oils, and industrial and household chemicals (solvents, detergents), is a serious cause of concern due to leakages and their unsafe disposal or deposition on the land or through atmospheric dispersion and transport. The massive use of fuels increases acid rain which enhances the hydrolysis of soil materials and also contributes sulfur, mainly as SO_4^{2-}, and nitrogen compounds which finally appear as NO_3^-. Leaking waste disposal sites and mining waters and wastes are also serious groundwater pollution sources.

Salinity increase involves evaporation (for instance, through irrigation return flows), enhanced soil hydrolysis and other reactions (such as increased hardness by calcite dissolution, sodium increase from the exchanged cation complex and silicate weathering), mixing with seawater (in coastal areas) or existing saline waters in the ground (mostly due to groundwater head changes), and excess nutrients and pesticides from croplands.

Nitrate buildup in groundwater is an issue due to the health effects on humans at large concentrations (greater than 50 mg/L NO_3^-). This is a concern in North America and Europe but it also begins to be a threat in many other countries such as Brazil, China and India. There is no simple, low-cost treatment to abate nitrate contamination. It disappears naturally from groundwater when the ambient downflow becomes reducing (nitrate is reduced to N_2), as it happens in confined aquifers containing some organic matter or sulfides. Excess of nutrients such as phosphorus and potassium, which may be a serious problem for surface water, especially for lakes and wetlands, often is not a concern for groundwater discharges since they tend to be precipitated or exchanged in the ground. But phosphates may move in non-reactive soils, such as sands (Foster 2000).

Groundwater nitrate will probably continue to be a growing problem in many areas in spite of the considerable efforts to reduce losses from agriculture, as food production is a priority for many countries. It will be necessary to live with it, but consequences can be mitigated by introducing improved farming practices and land use plans that preserve some aquifers or parts of them for drinking purposes. Incentives are needed to do this. It is also important to explain to the taxpayers the social benefits derived from them.

Knowledge about the behavior of pesticides and other agrochemicals in the ground has progressed but it is still far from satisfactory. The different substances and their metabolites, often poorly known, are transported and degraded in many different forms. This depends on soil characteristics, climate and agricultural practice. Some are readily soluble in water and others are strongly sorbed in soil particles and organic matter; some are highly persistent and others have a short half-life. Accumulation in soil of some of them is a reality and perhaps a time bomb, since they may be desorbed in the future or find a fast path to groundwater through heterogeneities before being degraded to non-noxious substances. Desorption may be due to an environmental redox potential change, increased recharge or acidification, and this may produce a concentrated leachate depending on pesticide characteristics (Mehnert et al. 2005). The global situation is poorly known.

Petroleum compounds, chlorinated solvents and other derivatives are mostly point pollution sources. They may create serious site-specific problems, except in and around urban and industrial areas where the number of possible leaks is very large and atmospheric transport and deposition may be significant. They degrade slowly in the ground, with great differences from one product to another and with a great influence of ambient circumstances. However, some are quite resilient to degradation, such as the TBA (tert-butyl alcohol) derived from the MBTE (methyl-tert-butyl ether) in motor fuels.

Pharmaceuticals in waste water (Drewes et al. 2003; Romero et al. 2004) and wastes may reach groundwater in and around urban areas either directly through leakages or after using treated sewage water for irrigation. It is not well known how serious the problem is, especially in rich urban areas where the use of these pharmaceuticals is widespread. Some pharmaceuticals are readily eliminated in the ground but others may be transported to the aquifer (Scheytt et al. 2006). Some experts see a serious impact on human health and population characteristics, but this needs further research, both on the effects and the transport and persistence in groundwater, as well as on their real incidence as endocrine disrupters. This is a concern in long life expectancy areas, but still a minor problem in poor areas in which other threats to human life dominate.

The presence of many different kinds of potentially noxious substances in some aquifers is a concern for many people, especially in rich areas in which residents often want to be supplied with contaminant-free, untreated groundwater. Health specialists argue against using water with even small concentrations of artificial chemicals due to their poorly known cumulative effects, which may appear at a later time as lifetime expectancy increases or be transmitted to future generations as genetic changes.

All this has promoted detailed chemical and isotopic studies of aquifer systems to determine "groundwater ages" and mixing patterns, in order to identify volumes of the groundwater bodies containing mostly or exclusively pre-industrial-age water, which is free from the earlier mentioned chemicals. These studies have added, as a further benefit, a lot of hydrogeological knowledge in general, and of some aquifers in particular.

Microbiological contamination in poor areas where waste disposal points are located too close to wells, and to poorly constructed wells, is currently a serious concern, especially if abstracted water is used directly for drinking purposes and without sufficient disinfection. Public institutions may mandate distance and construction norms to reduce cross-contamination, but they are neither followed—often are ignored—nor a guarantee of protection.

Arsenic in groundwater is considered a serious concern in many areas of Argentina and elsewhere, and especially in Bangladesh and East India. In the latter two countries the current health situation with groundwater, being unsatisfactory due to the large populations exposed to medium and long-term cancer risk, is far better than it was when biologically polluted surface and shallow groundwater were used for supply. Efforts should be directed to correct current deficiencies in well design and operation, but without losing or putting at risk what has been already gained in human health. Studies and denouncements may help to identify current problems and force the search for new solutions, but an excessive, irresponsible pressure may invalidate the conspicuous gains from former projects.

Defining groundwater contamination requires the knowledge of aquifer baseline quality (Manzano et al. 2003). This baseline or background quality is given by the statistical distribution of chemical and quality parameters under undisturbed or "normal" conditions in a given water body. Knowing baseline quality is not an easy task given the long-lasting human influences on groundwater recharge relative to turnover time. The perception varies with the country and the activity sector. In any case enough information is needed, which is expensive and has to be managed carefully (Borisova et al. 2005). There is an important role of stakeholders in shared management and co-responsibility (López–Gunn and Martínez Cortina 2006).

Groundwater Protection

According to Webster's Dictionary, conservation is the preservation and protection of something from loss, the planned management of a natural resource to prevent exploitation, destruction or neglect. This definition involves preservation and protection. Preservation is to keep safe from injury, harm or destruction (that is, to protect), and to keep alive, intact or free from decay (that is, to maintain). Correspondingly, protection is to cover or shield from exposure, injury, or destruction.

Consequently, groundwater protection refers to the actions and rules to maintain the role, the flow of goods and services, and the functioning of aquifers. All this has to be taken in a broad-scoped context that considers the role of groundwater in nature and its usefulness to supply human water needs. All this has to be considered under the context of a continuously modifying world which receives the benefits of scientific and technological progress, whose social priorities evolve, and whose demography and economy changes. The result has to take into account the related sustainable use or depletion of other natural resources such as energy, food, raw materials, space and sites to dispose wastes.

Protection of groundwater refers to both quantity aspects (volume of stored freshwater, recharge rates, groundwater levels and discharges into other water bodies and habitats) and quality aspects (salinity; natural and man-made contamination; temperature, chemical and biological effects on ecosystems) and the related activities to accomplish the goals and to restore and improve a given situation.

Taking into account aquifer characteristics and the long time involved in groundwater flow and mass transport, and the large cost of redressing a given situation, aquifer protection is a priority for groundwater management. This is a widely accepted principle to professionals, managers and planners who have a good understanding of groundwater. However, the principle is largely ignored by many policy makers and groundwater users who do not have a good enough knowledge of groundwater characteristics and behavior. Thus, they often respond to problems by applying inappropriate concepts such as those taken from surface water behavior. This often leads to unsustainable situations

(Custodio 2005) that need later, slow and very expensive corrections, if possible at all, or the loss of part of the freshwater resource. This may also produce serious social stress. This thinking is embedded in the European Water Framework Directive, enacted in 2000. After WIR (2004), in the United Kingdom between 1973 and 2003 about 1.5 million m^3 (Mm^3) per day of supply pumping capacity was abandoned due to contamination, at a cost exceeding 500 million euros, or 0.1 euros/m^3 of capital cost for a 0.3 use factor. This is an example of costs derived from groundwater contamination.

Good understanding of behavior and processes is needed to assess groundwater development and the effects of land use on aquifers, which, in turn, has to rely on adequate monitoring of aquifers and land activities. Such monitoring should consider early warning and trend detection. Monitoring may not show immediately the results of applied policies since they may appear very slowly.

Groundwater protection deals not only with groundwater issues, overexploitation (Custodio 2002) and intensive development (Llamas and Custodio 2003; Sahuquillo et al. 2005; Custodio et al. 2005) but also with surface water and land use, which in spite of being closely linked are often the subject of different laws, regulations and administrations, and also involve important economic, social and political interests in concurrence. An integrated water resources and natural resources approach is needed but it is often missing. This is one of the weakest points of governance, and still a poorly addressed aspect in science, technology, economics and social behavior. The integrated approach is a priority in UNESCO's International Hydrological Programme. It involves surface, groundwater and other water resources, agriculture, livestock, urban development, transport, rural objectives, and forest, natural spaces and habitat policies, and also coastal aquifer management.

There are local protection activities such as the definition of especially protected areas to produce drinking water. Wellhead—safeguard—protection areas around supply wells must also be considered to ensure that there is sufficient time to remove any microbiological and chemical contaminants that may have been introduced into the area surrounding the well or to find alternate water supplies (Martínez Navarrete and García García 2003; Matthess et al. 1985). Some successes can be mentioned in the United States and Europe, as is the case of Jutland, Denmark (Thomsen and Thorling 2003). But wellhead protection areas are difficult to establish, because of the problems to define and enact the limits, costs and loss of income to some local inhabitants and owners. In many European countries (Germany, Czech Republic, The Netherlands, Slovakia, Switzerland and others) two successive protection zones around public groundwater supplies have been established many years ago. In the previously-mentioned countries the protection zones are part of water legislation and are obligatory for public water supply systems in operation. In some countries a policy has been established to compensate for the lower agricultural production in protection zones due to the controlled use of fertilizers and other agricultural activities. Similar concepts have been applied to mineral water (for spas, to be bottled) and have proven to be effective due to strict and better enforced legislation by mining authorities. There is a lot to do in this field and to analyze the effective results of what has been done until now. In some cases the full aquifer recharge area has to be protected, or the entire groundwater body. Currently this is done by some private firms that sell bottled mineral water. Some recent good results are mentioned from the control of activities in the nitrate sensitive areas defined by the European regulations (Silgram et al. 2005).

Vulnerability-oriented maps for groundwater contamination have been devised to help land use planners and managers define and guide human activities on the territory, such as new waste landfills, industrial settlements or animal-raising activities. A main objective is land zoning (Foster and Skinner 1995). Existing methods are oversimplified, mostly to take into account human activities on the surface above unconfined aquifers. They refer mainly to agricultural areas or extensive urban areas, often at the 1:10,000 to 1:200,000 scale. The goal is just to help in land use planning decision making, but the final evaluation always has to be subject to detailed hydrogeological study of particular sites by experts.

Groundwater vulnerability assessment and mapping has two aspects: intrinsic and specific. Intrinsic vulnerability is defined solely as a function of natural factors such as the characteristics of the unsaturated and saturated zone, the overlying soil, the geomorphology and the recharge. Intrinsic vulnerability maps combined with hydrogelogical maps and land use maps are widely used in many countries on different scales (national, regional, local) for planning, decision making, managerial and other purposes (Vrba and Zaporozec 1994).

Specific vulnerability is mostly an assessment of the danger of the groundwater system becoming exposed to contaminant loading. Contaminant properties and attenuation capacity of the geological environment are critical for assessment of specific vulnerability. Toward this end it is important that a distinction is made between conservative contaminants—those that sooner or later will reach the water table—and those that are retarded, degraded or may decay before infiltrating into the aquifer. Many specific vulnerability maps include travel time, advection, dispersion, reduction and sorption capacity, cation exchange capacity, dilution and other retardation factors (Vrba and Zaporozec 1994).

Vulnerability mapping is a useful but often insufficient tool for groundwater protection as the impact of human activities on the aquifer depends not only on vulnerability but on the contaminant load applied. Combining both of them creates a risk. In the wrong hands, vulnerability maps may produce undesirable results for aquifer protection. In any case, there is no substitute for specific hydrogeological studies.

Aquifer Restoration and Remediation

Restoring an aquifer means bringing it back to a former condition. From the point of view of water quality, this includes activities that are aimed at recovering a previous condition considered to be of good quality. Restoration is often called remediation or a treatment that corrects and counteracts a situation, and includes the legal means to recover, prevent or redress for a wrong (Webster's Dictionary).

Remediation means that contaminants have to be destroyed or taken out, and that contaminated water be replaced by uncontaminated water or diluted sufficiently (Norris et al. 1994; Boulding and Ginn 2004; NRC 1997; Barcelona 2005). This includes contaminants being sorbed onto terrain minerals or diffused into ground heterogeneities.

Natural remediation takes advantage of chemical and biological decay and can be enhanced by providing favorable conditions to take out or destroy the contaminants (NRC 1993, 2000; Bekins et al. 2001; Wilson et al. 2005). Artificial remediation consists of simple to complex methods to decrease contaminants by forced abstraction from the saturated and/or unsaturated zone (if they are volatile), by favoring redox processes and the associated microbiologically mediated reactions in the ground, or by attaching contaminants to the ground as insoluble matter. Retention favors radioisotope and microorganism decay. Artificial remediation includes permanent confinement of the contaminant source or its removal (NRC 1997). In many cases existing experience is significant, but relevant information is poor or concealed due to proprietary restrictions since a large part of activity is carried out by the private sector, which often prefers to keep indoors these types of problems.

In general, it can be said that natural remediation is often a slow to very slow process although there are some successful accomplishments, especially in small alluvial and sand aquifers of short turnover time. Often, artificial remediation is not only expensive and slow, but also of doubtful results since contaminants that have penetrated into low permeability heterogeneities resist being extracted and degraded when the movement is controlled by diffusion. An intensive aquifer cleanup process may be able to progress upward to produce good quality abstracted water but contamination may reappear shortly afterwards, when hydraulic conditions change and contaminants held in low permeability heterogeneities continue to be slowly released. Contaminant recovery is often low to very low. Numerous experiences exist in reducing hydrocarbon compounds and chlorinated solvent plumes and sources, but results are often poor. The effects of groundwater remediation processes depend particularly on the treatment of contaminated soil and the unsaturated zone. If the unsaturated zone is not considered and cleaned up, it is not possible to improve the state of groundwater quality.

In the case of diffuse (non-point) contamination, even if concentrations of substances of concern are not very high, volumes of contaminated aquifer water are so large that artificial remediation is often economically, and even physically, unfeasible. This may mean that the affected part of the aquifer has to be temporarily or permanently abandoned for some uses, and the non-contaminated part of the water body has to be developed under strict conditions to extend its useful life. This means no further degradation. All these issues are good reasons to seriously protect groundwater instead of delaying action, and trust in restoring pollution damage.

National or supranational legislation has a key role in public administration activities, especially if it has wide social support. In the United States enormous financial means have been applied by the Environmental Protection Agency to reduce and remediate toxic waste disposal sites, with mixed—sometimes poor—results, but knowledge has progressed a lot and this is a clear benefit for the present and future generations. In the European Union the Water Framework Directive (year 2000), now incorporated into members' national laws, asks for a substantial reduction of contaminated groundwater and the reversal of deteriorating trends by 2015. A lot of scientific, technical, economic and social challenges are ahead.

A Glimpse at the Future

Groundwater contamination control is one of the major challenges to the sustainable use of groundwater. It is worth recalling that intensive use of groundwater is a relatively recent phenomenon (Llamas and Custodio 2003). Intensive use of groundwater started about 100 years ago in the western United States and some islands, and about half a century ago in semiarid areas of countries such as Mexico, Spain, Australia and northeastern Brazil. It has been used for only a few decades in India, China, Pakistan and the Middle East. This means that, in many cases, groundwater development occurred with little management experience. The belief of policy makers in many developing countries that contamination is the problem of rich, developed areas and countries but not their own problem is simply the result of the slow and delayed response of aquifers to human intervention, the result of poor monitoring and insufficient knowledge. There is already enough experience to show that groundwater contamination is a common problem that may seriously damage the sustainability of developing areas.

No global figures on the extent and the economic and social cost of groundwater contamination are known to the author. It is very difficult to try to quantify the order of magnitude of the problem, which is a three-dimensional one. It can be expected that further contamination of groundwater will still be the rule for coming decades in many places, although at a decreasing pace. In the meanwhile, protection should be concentrated in areas of special significance for human water supply, as it is the policy that seems to be developing around some megacities, such as São Paulo and Mexico City.

Current trends to develop thick aquifers in semiarid and arid areas and to drill deeper and deeper wells have to be carefully controlled with the help of involved people. This will help in protecting deep aquifer layers against contamination. Aquifers in mountainous and remote areas will continue to be reasonably protected, especially if they become natural protected areas. Potentially polluting agricultural farming and forest activities in these areas, besides their relatively small impact, can be regulated to avoid contamination by means of some financial support to provide protection (not as a simple subsidy), as is currently done with variable success in some areas of Europe.

Improved and cheaper water treatment processes will allow the use of mildly contaminated groundwater around large urban areas, thus also favoring some degree of natural restoration. Part of the contaminated Besós aquifer, in Barcelona's metropolitan area, has resumed the role of a water supply source after about 30 years of natural remediation, but also with a sophisticated water treatment plant.

Role of Science and Technology

Protection against groundwater contamination and, in some cases, enhanced natural and artificial restoration depends on good knowledge of aquifer behavior and the fate of contaminants in the ground under different actual conditions. Further scientific research is needed to better define and parametrize processes, both under controlled laboratory and field conditions. Dramatic improvements in scientific knowledge have been produced in the last two decades, and most probably will continue in the near future. Maintaining such activity is crucial, but also the scientific information must be translated into technological developments, mostly for surveying, sampling, measuring and treating groundwater. In this respect the United States, Europe, Japan, Australia, Canada and a few other places concentrate most of the world's activity in hydrology and groundwater research and technology. This means that groundwater protection may fail in many other places due to insufficient local knowledge and capabilities. Hydrogeology needs a decisive boost to redress this possibility. It is important to make explicit the economic and social value of good quality groundwater and encourage support for its continued improvement and protection from those who benefit from it. This is still far from being accepted and applied as a normal policy. Likewise it is important to encourage adequate scientist, engineer and technician training, along with sufficient economic resources, for research and technical development. We must move beyond nice declarations in order to make society and its leaders more fully aware of the relevance and priority of this need. This is a failure not only of water resources managers but also of scientists and engineers. Worldwide action is needed to involve politicians and policy makers in science and technology issues.

The protection, improvement and sustainable use of water resources cannot be solved only in the scientific and technical arena. Solutions to such problems also require the involvement of economists and social scientists, and need the partnership and co-responsibility of stakeholders. Effective aquifer protection and sound development require that people have unbiased information that is free from short-term opportunistic goals and political maneuvering. It is with such information that the stakeholder can seek clarification, support or reject decisions from policy makers and politicians. In this respect current accomplishments through the various World Water Fora have been poor, although there has been some progress in the fourth edition of the World Water Forum in Mexico in March 2006.

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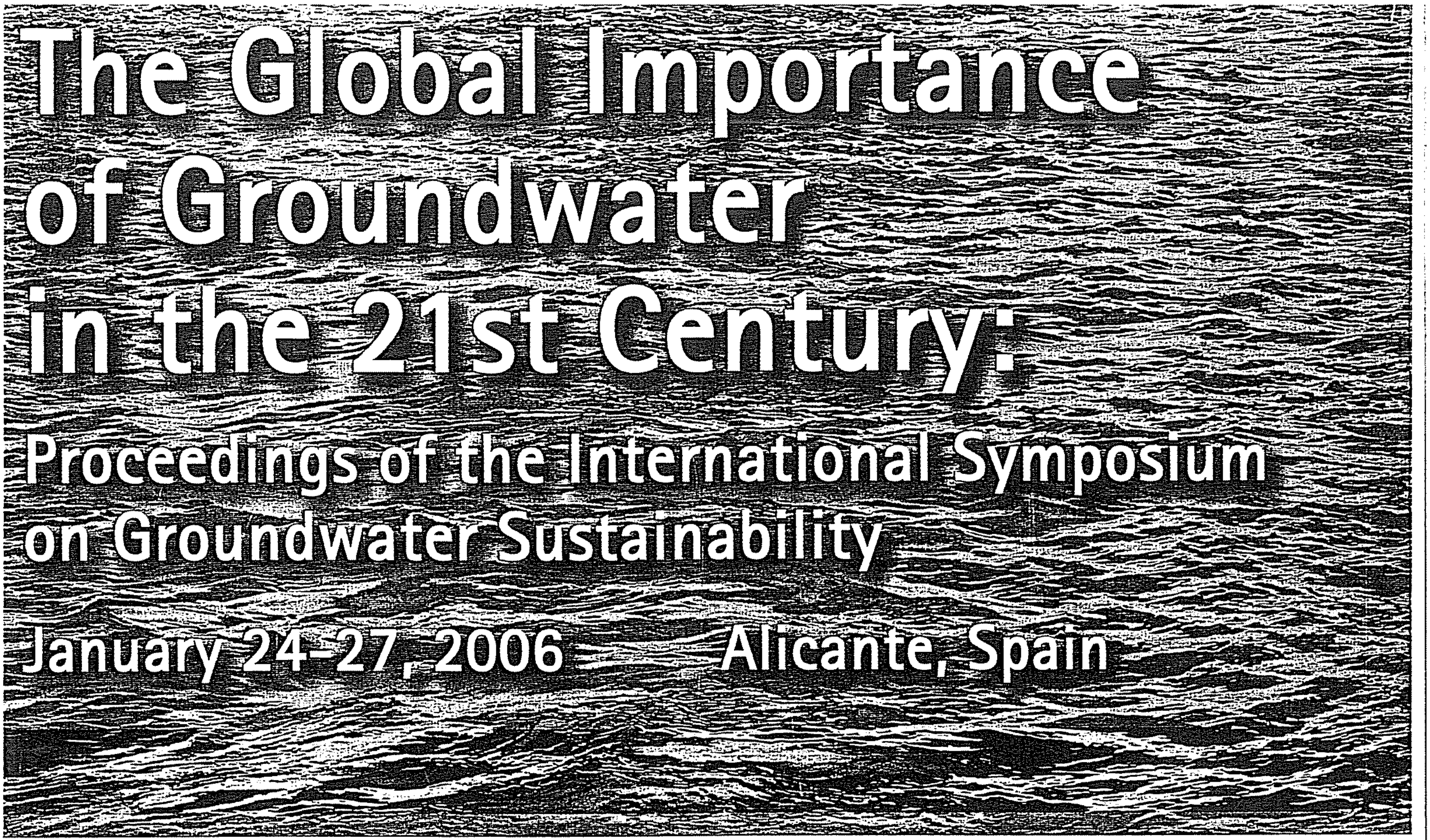

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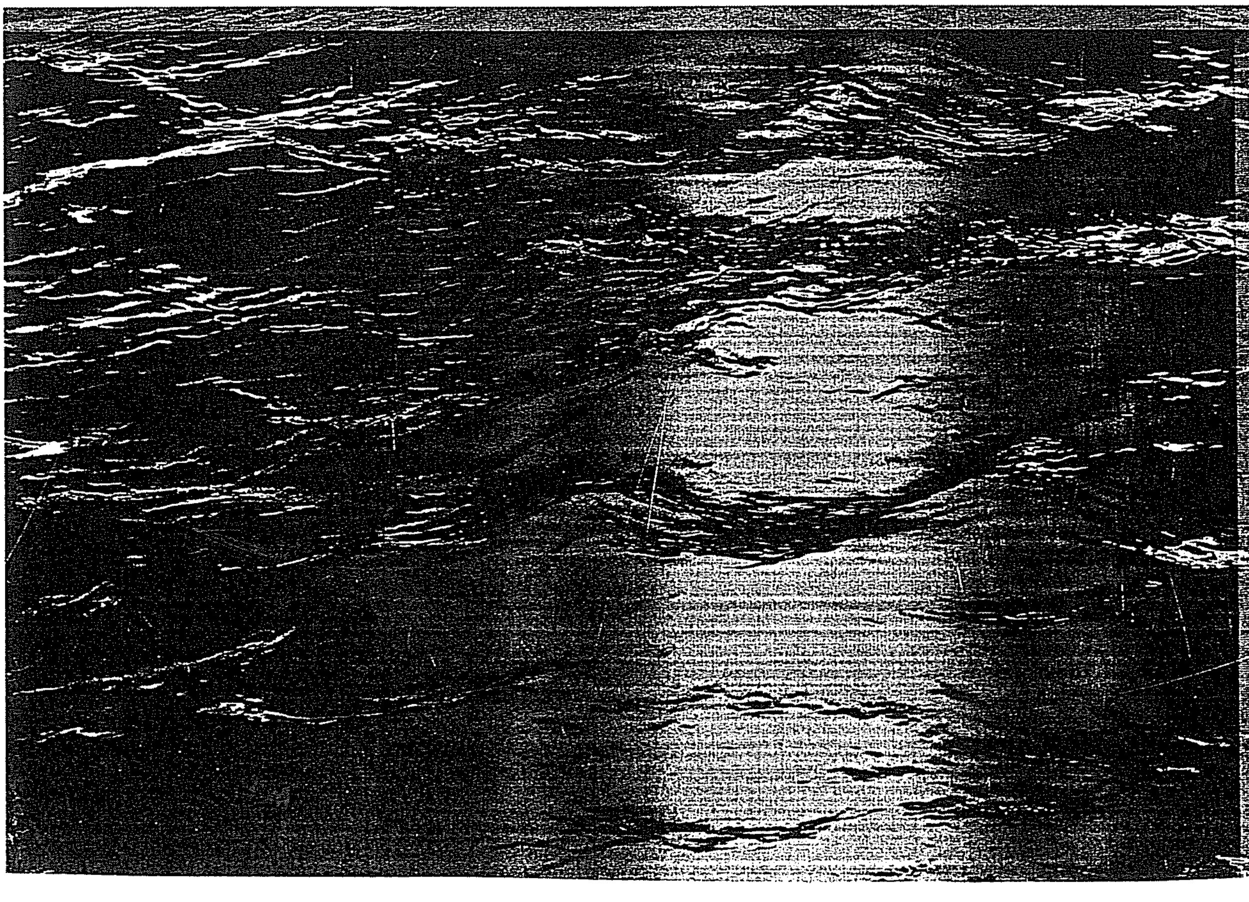

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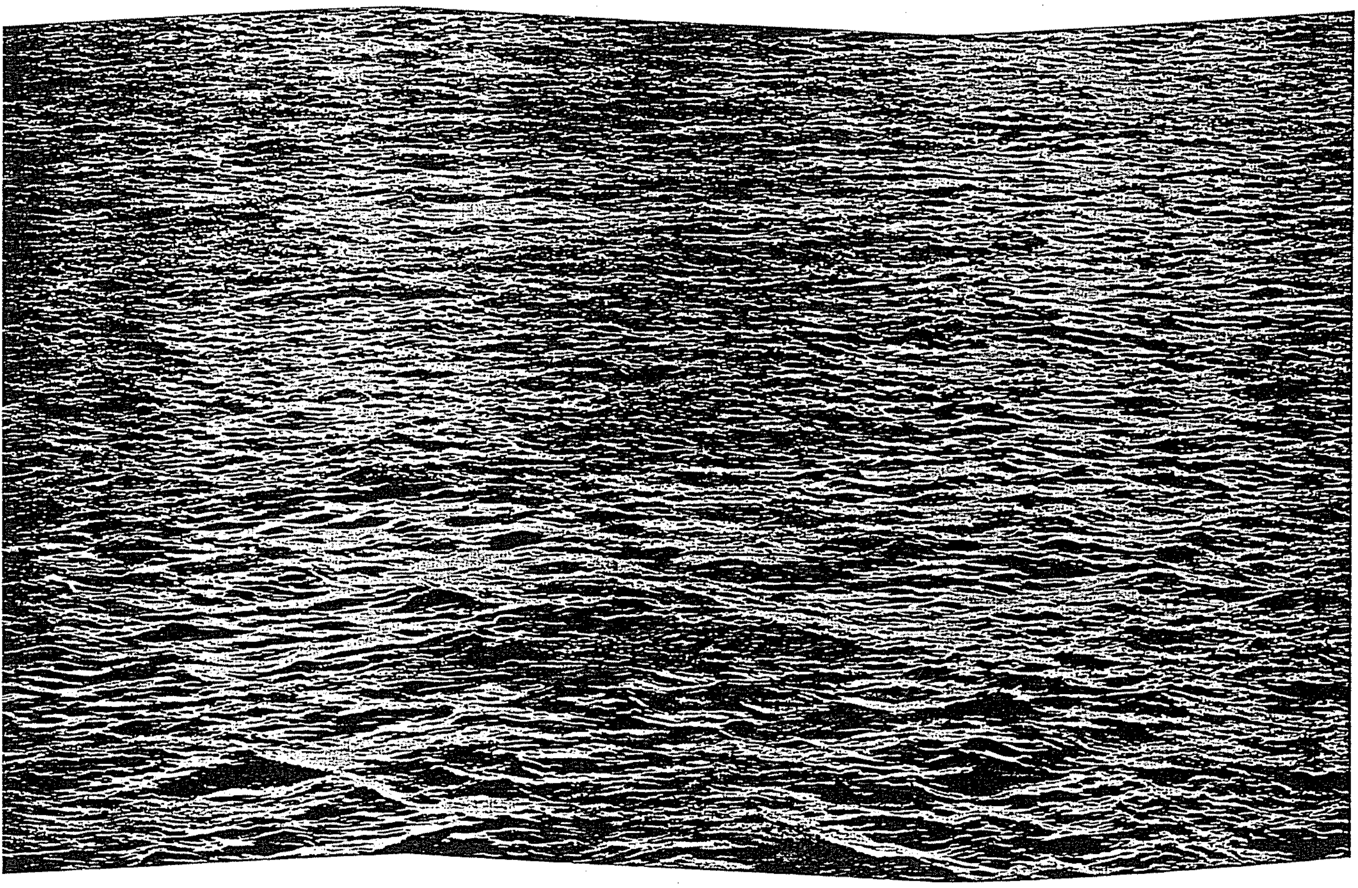

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