Trends in groundwater pollution:

Loss of groundwater quality & related services

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Groundwater Governance - A Global Framework for Action

Groundwater Governance - A Global Framework for Action (2011-2014) is a joint project supported by the Global Environment Facility (GEF) and implemented by the Food and Agriculture Organisation of the United Nations (FAO), jointly with UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrologists (IAH) and the World Bank.

The project is designed to raise awareness of the importance of groundwater resources for many regions of the world, and identify and promote best practices in groundwater governance as a way to achieve the sustainable management of groundwater resources.

The first phase of the project consists of a review of the global situation of groundwater governance and aims to develop of a Global Groundwater Diagnostic that integrates regional and country experiences with prospects for the future. This first phase builds on a series of case studies, thematic papers and five regional consultations.

Twelve thematic papers have thus been prepared to synthesize the current knowledge and experience concerning key economic, policy, institutional, environmental and technical aspects of groundwater management, and address emerging issues and innovative approaches. The 12 thematic papers are listed below and are available on the project website along with a Synthesis Report on Groundwater Governance that compiles the results of the case studies and the thematic papers.

The second phase of the project will develop the main project outcome, a Global Framework for Action consisting of a set of policy and institutional guidelines, recommendations and best practices designed to improve groundwater management at country/local level, and groundwater governance at local, national and transboundary levels.

Thematic Papers

- **No.1 -** Trends in groundwater pollution; trends in loss of groundwater quality and related aquifers services
- **No.2 -** Conjunctive use and management of groundwater and surface water
- **No.3 -** Urban-rural tensions; opportunities for co-management
- **No.4 -** Management of recharge / discharge processes and aquifer equilibrium states
- **No.5 -** Groundwater policy and governance
- **No.6 -** Legal framework for sustainable groundwater governance
- **No.7 -** Trends in local groundwater management institutions / user partnerships
- **No.8 -** Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction
- **No.9 -** Macro-economic trends that influence demand for groundwater and related aquifer services
- **No. 10 -** Governance of the subsurface and groundwater frontier
- **No.11 -** Political economy of groundwater governance
- **No.12 -** Groundwater and climate change adaptation

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GROUNDWATER GOVERNANCE: A Global Framework for Country Action
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Thematic Paper 1: ***TRENDS IN GROUNDWATER POLLUTION: LOSS OF GROUNDWATER QUALITY & RELATED SERVICES***

by
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1. Introduction

The purpose of this Thematic Paper is to review the trends in groundwater quality and pollution, taking into account the physical, environmental, institutional and social actors involved in groundwater quality governance. The final goal is to diagnose historical and current issues related to groundwater use under the threat of pollution, and to identify prospects for improved and sustainable aquifer governance through prevention and mitigation of the factors that may impact water quality. It is aimed at the macro-view level, based on existing experience from real cases.

With the relatively recent development of centrifugal pumps, mechanized drilling means and energy accessibility, as explained in Technical Paper 8, groundwater is seen as an easily-developable water resource, invisible to people and lacking in social experience on its use as a common good. It is linked to surface water, and is essential for nature and its services (Llamas and Custodio, 2003). Groundwater governance refers to the sustainable and efficient use of this key resource, which is essential for drinking-water supply, food production, human development and the environment (Ragone *et al.*, 2007; Bocanegra *et al.*, 2005), as well as for the resolution of conflicting situations. A working definition is given in Box 1.

Box 1: A working definition of groundwater governance

Groundwater governance is the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global. (Adapted after Saunier and Meganck, 2007: Dictionary and Introduction to Global Environmental Governance)

A technical tool for groundwater governance is integrated water resources management (IWRM), which consists in the coordinated development of water, land and related resources to maximize social and economic welfare without compromising the sustainability of vital ecosystems, as explained in Technical Paper 5 of this series. Government officials, politicians and people in general must be conscious of the state of the resource they are using in order to tailor timely solutions suited to local circumstances. Unfortunately, before action is taken, major deterioration or depletion often has to occur in many aquifers. Water quality requires particular attention as its impairment is hidden, slow and delayed.

Within the concept of groundwater governance, aspects related to quantity and quality of the resource may be distinguished. Groundwater quality governance is often not of primary interest in situations where water quantity is a concern. This explains why groundwater quality protection is still poorly developed, although its importance is certainly growing. In fact, in semi-arid and arid countries in particular, once quantity needs are satisfied, quality issues become progressively more important.

The poor development of groundwater quality governance largely depends on the difficultly to assess water quality, compared to water quantity. This is due to the great number of components and factors involved in water quality assessment, as well as to inconsistencies in the knowledge base, which is therefore often subject to interpretation. Even a satisfactory and widely accepted water quality index is unlikely to be fully reliable.

2. Basics Aspects of Groundwater and its Quality

Groundwater development is relatively recent and rapidly evolving (Figure 1). It mostly started during the 20th century and, in many countries, only a few decades ago. Due to intensive groundwater development, aquifer functioning has been greatly modified (Llamas and Custodio, 2003; Custodio *et al.*, 2005) and needs management to become sustainable (López Gun *et al.*, 2011). This development implies that direct and indirect benefits and costs are produced and often involves an impact on groundwater quality.

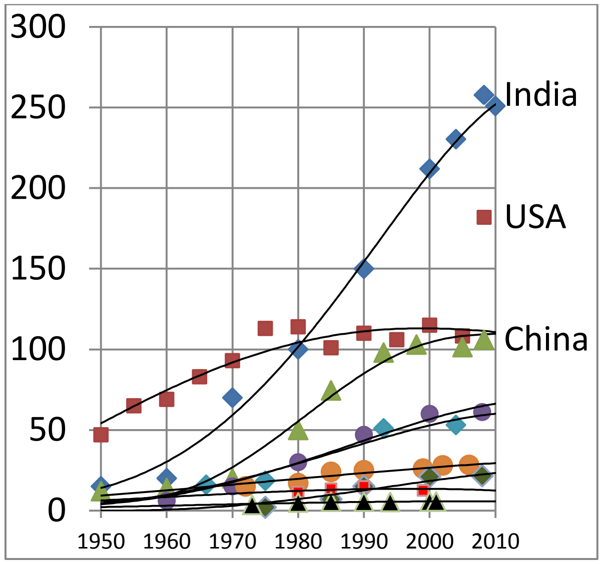


Figure 1. Evolution of groundwater abstraction since 1950 for some countries with intensive groundwater development (after Margat and van der Gun, 2012). While in some countries groundwater abstraction is attaining a steady state or even decreasing as they are more efficient using water and rely on integrated water resources systems, others are still in the early stages of fast development. Abstraction is given in km^3/year.

Intensive aquifer use, in many cases, and especially in large confined aquifers, may involve the transient depletion of groundwater reserves. In some areas of the world, continuous and unrestricted use of groundwater reserves – known as "water mining" – has led to the physical depletion of aquifers, water quality impairment and the increase of abstraction costs (Foster, 1991; Foster and Loucks, 2006; Custodio 2010a).

For a correct evaluation of groundwater resources, a validated conceptual model on how the aquifer system functions is needed, including mass transport as the basis for water quality assessment. Also, information concerning aquifer recharge is very important, even if it is often rather uncertain. These are key issues for groundwater governance that must be addressed to control groundwater development in a coherent and consistent manner.

Three main aspects of groundwater governance have been identified (HJ, 2005):

1) its role in nature and the environmental services it provides;
2) its quantity to supply human needs; and
3) its quality with respect to human uses, including productive activities, and to the environment.

In the European Water Framework Directive (Directive 2000/60/EC of 23 October 2000 establishing a framework for the Community action in the field of water policy), which aims at preserving the quality of the environment, water quality issues are the backbone of governance. As groundwater is mostly used for dinking-water supply, quality issues are particularly important. This happens in relatively rich urban areas, where in some cases (as in Germany) good quality groundwater without further treatment is wanted for urban supply. In the European Union (EU), the dependence on groundwater for drinking-water supply vary between 98 percent in Denmark, to about 50 percent in Sweden, and only 20 percent in Spain. Even in countries with low groundwater use, some areas and many of the small towns are often fully dependent on groundwater. In poor areas, the lack of infrastructures makes quantity issues the main concern for governance, except if serious threats to health appear due to the presence of natural hazardous substances and serious pollution.

In the arid and semi-arid regions, irrigation is often mainly based on groundwater use, and water scarcity makes water quantity a main issue, linked to increasing water cost, depletion of spring flow and river base flow, decrease of wetland areas, and in some cases land subsidence problems. In integrated water systems, groundwater provides the needed water reserve where water shortage due to droughts is a main concern (Estrada and Vargas, 2012). Thus, water quality issues are often of secondary importance in aquifer governance, except in certain coastal aquifers, intensively irrigated agricultural areas, peri-urban areas that depend on local water resources for human supply, and in general where natural groundwater contain solutes recognized as a health problem, such as arsenic (As) and fluor (F). See Boxes 2 and 3.

However, groundwater quality is deteriorating worldwide and a growing concern, often the result of past action. This means that in many areas, currently poorly addressed quality issues will become soon a dominant issue for groundwater governance. Unfortunately, existing experience is short and patchy, and has an important local component. Governance of groundwater quality is at its early stages and often considered as 'an issue for the future' in many countries. In addition, it is not easy to show groundwater quality evolution, worldwide or at regional level, not only due to data scarcity but also to the difficulty of using an index that is able to reflect the different points of view. The evolution on a chemical characteristic at a given point does not always show the general trends.

Poor groundwater quality is due to the presence of contaminants. The term 'contamination' is considered here in broad sense, including salinity, physico-chemical characteristics, inconvenient solutes at very different concentrations, biological components, radioactivity and temperature. Groundwater contaminants may be: (i) of natural origin, induced by aquifer exploitation; (ii) introduced as a result of human activity; or (iii) a combination of the two. Only contamination resulting as a direct consequence of human activity is here considered as pollution.

The main causes of groundwater pollution that should be tackled in groundwater governance arrangements, both at large and at small scale, are:

a) land-use activities, part of which are unrelated to groundwater development;
b) groundwater development, including the means of groundwater abstraction, such as well and borehole construction, operation and maintenance;
c) groundwater–surface water relationships, as in many cases groundwater contamination comes from surface-water infiltration, including seawater in coastal areas, saline lake water and polluted river water;
d) inter-aquifer leakage.

Necessary components of groundwater quality governance are laws, norms, institutions, direct groundwater users and other stakeholders that have interests in groundwater-related issues, such as the environment and its ecological services, surface water, springs and agriculture. Assessment and action depend on adequate monitoring and good understanding of aquifer-system functioning and behaviour, reflected in a validated aquifer-system conceptual model and supported, when appropriate, by numerical modelling and hydrogeochemical and isotopic studies.

Part 1. Baseline

3. Naturally-Occurring Groundwater Quality

3.1 Groundwater composition and salinity

Groundwater is generally fresh under natural conditions, although not always necessarily of good chemical quality. Chemical groundwater composition of recent groundwater is the result of climate-soil processes and lithological influences (Figure 2). Climate-soil processes dominate in arid areas, and lithological influences do in more humid environments. The mineral concentration in water due to atmospheric deposition is increased by evapo-concentration – the concentration of solutes by water evapotranspiration – in the soil. The more arid the climate is and the higher the capacity of soil to hold water is, the greater evapo-concentration is. What remains will be converted into groundwater recharge, which incorporates soil CO_2 from root plant respiration and organic matter decay by oxidation. This favours the dissolution of soil and rock minerals.

These well-known processes (Appello and Postma, 1993; Custodio and Llamas, 1976) control groundwater quality baseline or background (Edmunds and Shand, 2008; Custodio and Manzano, 2007). Marine components dominate generally near the seacoast. Inland-wards, where the marine influence decreases, terrestrial components and anthropogenic influences tend to dominate, particularly in more arid areas. Anthropogenic influences may have an important impact on water quality in and near populated areas, and below agricultural land in which agrochemicals are applied, especially when intensively cultivated under irrigation.

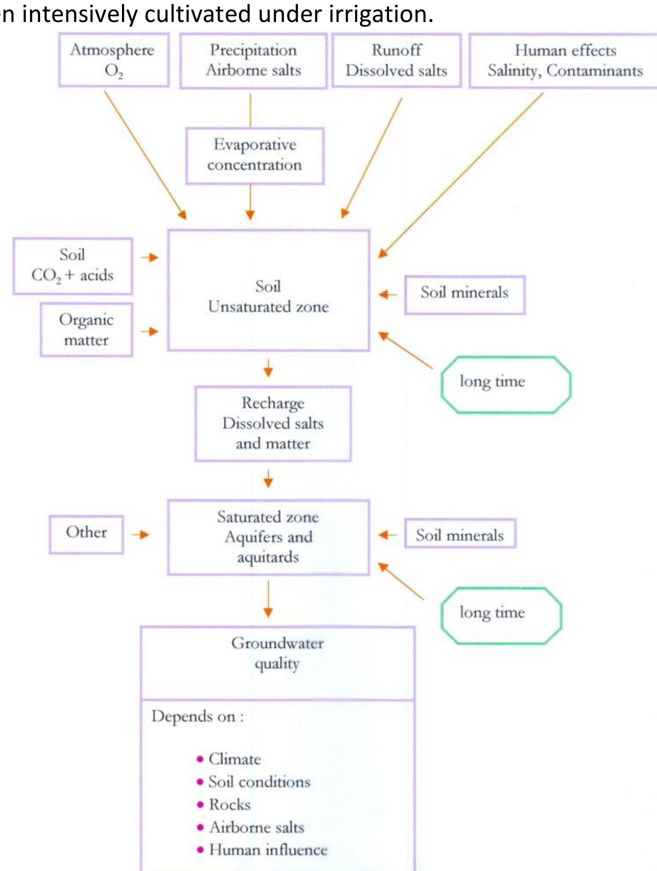


Figure 2. Genesis of groundwater chemical composition due to rainfall diffuse recharge.

Recharged water may suffer other geochemical processes in the ground (Figure 3). Since directly soluble minerals are rare in well-leached rocks, in an oxidizing ambient groundwater percolation (in-transit recharge) will be little modified afterwards, except for the possible incorporation of deep geogenic CO_2 in recent volcanic areas and the resulting reactions, ion exchange processes when groundwater is displacing or displaced by water with a different ion composition, and some redox (reduction-oxidation) processes affecting solutes such as sulphate (SO_4), nitrate (NO_3), and dissolved iron (Fe), manganese (Mn) and arsenic (As), among others.

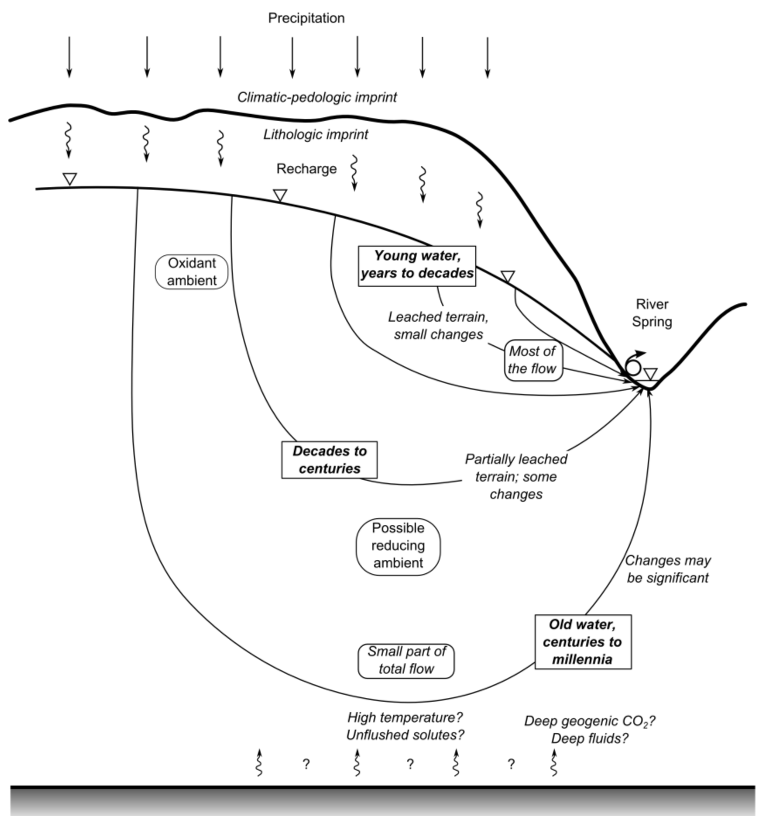


Figure 3. Schematic, highly simplified aquifer flow pattern in a thick water-table aquifer between an extended recharge area and the concentrated discharge along a valley. Circumstances and possible groundwater ages are indicated, although they may vary largely according to size, recharge and aquifer characteristics.

A consequence of the above is natural groundwater quality zoning, depending mostly on climate and distance from the seacoast, shaped by local lithology. Groundwater recharge may be fresh in continental areas, even in arid areas, when continental contribution is small, but rather saline near the coast, even in the absence of direct seawater intrusion. The effect is clearly seen in small, high elevation, variable climate islands, such as the Canaries and Cape Verde (Figure 4).

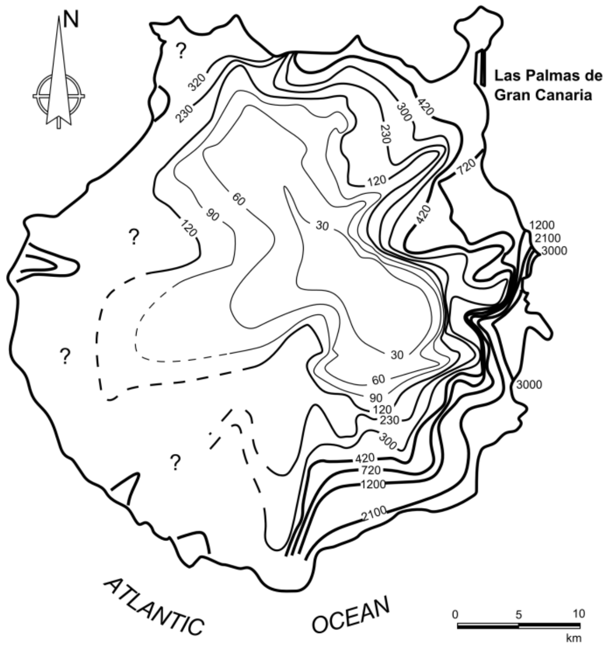


Figure 4. Groundwater quality changes as reflected in the chloride content, in mg/L, in the upper part of the main saturated body of Gran Canaria Island (Canary Islands, Spain), 1500 km^2 in surface area and 1985 m altitude. Increasing Cl reflects the rapid decrease of recharge and the increased atmospheric Cl deposition when going from the highlands toward the coast. Fast Cl changes reflect deep geological boundaries (after Custodio, 1989).

Soluble saline components may be found in still unleached, recent marine or saline lake sediments, and where still unleached evaporite salts are found in the rocks, most often gypsum, but also halides from closed-basins formations or forming part of local rocks. Many different circumstances are possible.

Brackish and saline groundwater is relatively frequent in deep aquifers, especially in slowly renovating, confined aquifers, and also as a consequence of recharge in arid environments. In coastal areas, brackish and saline groundwater is the result of natural seawater intrusion in thick, permeable and relatively poorly recharged aquifers, and the mixing with fresh groundwater in upper layers (UNESCO–PHI, 1986). In small permeable islands a fresh-brackish groundwater lens may be partly or fully floating on a continuous deep groundwater layer of seawater, with a more or less thick mixing zone between them (UNESCO–PHI, 1991). In coastal areas and around large saline lakes and inner seas, salinity can be also the result of periodical land flooding during heavy storms – very acute in tsunami events –, of wind-driven seawater spray or of intense evaporation from surface and shallow saline water bodies.

Soil water and groundwater interaction with sediments and rocks, out of the most common soluble minerals, involve reactions such as the hydrolysis of carbonates and silicates. This may incorporate solutes that may affect groundwater quality for the intended uses, and especially for drinking purposes. See Table 1 for comments on some of them.

Component	Origin	Problems	Comments
Salinity	Aridity Closeness to the sea coast Relict marine water Deep-seated old saline groundwater	Affects potability Impairs urban and industrial use Affects crop yield in irrigated areas	Treatable through expensive desalination processes High salinity makes water useless
Hardness	Rock dissolution	Encrustations	Treatable at a cost
High	Deep CO_2 contribution in	Poor for drinking	Not easily treatable

sodium–bicarbonate	tectonically active and volcanic areas	purposes. Risk of soil alkalinisation in irrigated areas	
Fluoride	From rocks, especially acidic volcanics and dispersed volcanic ash when water hardness is low	Affects health (bone and teeth)	A serious problem in the Argentinean Pampas, Chile, Mexico, India, Pakistan, the East African Rift, some volcanic islands (Tenerife)
Iron	Mineral iron dissolution in acidic and reducing environments	Affects potability. Produce stains, encrustations and precipitates. Water becomes yellowish when oxidized	Easy to treat, at a cost
Manganese	Mineral manganese dissolution in acidic and reducing environments	Affects drinkability Produces black stains and precipitates, with some retardation	Easy to treat, at a higher cost than iron treatment
Arsenic	Sediments and rocks Dissolved under some chemical circumstances, not always well understood	Affects health Old limit of 50 μ/L has been lowered to 10 μ/L	A serious problem over large areas of Bangladesh, East India, Northern China, Argentina, Mexico
Boron	Some minerals and volcanic activity Desorption from fine marine sediments	Affects health at around 1 mg/L Detrimental to plants	

Table 1. Some inconvenient natural groundwater components that may be of natural origin.

Box 2: Groundwater quality governance in presence of high arsenic concentrations

Arsenic is widely dispersed in rocks and sediments. Its hydrogeochemical behaviour is complex and depends among other factors on ambient redox potential. Under reducing conditions it is held in sulphides, and under oxidant conditions it is retained in iron and manganese oxides and oxihydroxides. It may be released if sulphide and organic-rich sediments are exposed to oxygen, as when recent oxygen-carrying water penetrates deep formations or when air enters formerly saturated formations due to the lowering of the water table by groundwater development or drainage. It may be also released when polluted water carrying reactive organic matter produces a reducing ambient in oxidized sediments.

Thus, arsenic in groundwater is often of natural origin or the result of aquifer development. Its presence, especially at the higher oxidation state (As(V)), is a serious health concern for continuous exposal to it, and the medical experience has been in favour of lowering the former limit of 50 μg/L to 10 μg/L. This, however, has rendered large volumes of groundwater unsuitable for drinking purposes without costly treatment, which is often unaffordable in poor areas, or without blending with other sources of water, often a challenging task.

Well-known areas subject to excess As in groundwater are in Blangladesh, West Bengal (India) and the "pampas" of Argentina. Important research efforts have been carried out to know how and when As is present (see Smedley and Kinnibourgh, 2002).

Groundwater quality governance in these cases needs suited actions. Drilling shallower or deeper wells may avoid the problem for some time, but this solution is costly, needs good detailed monitoring of the concentration of supply wells and may be economically unaffordable in poor areas when deep wells are needed. Careful mapping may help in identifying areas in which hydrogeological conditions are not favourable for dissolution (Biswas *et al.*, 2012), but current experience in this field is still insufficient. This has been the result of two decades of studies in

Bangladesh and West Bengal, in the vast deltaic areas. In the Argentine "pampas" (very flat land), most efforts have been directed to identify areas of current active recharge or where enhanced recharge is engineered. In those areas, shallow water bodies with low arsenic content may form. In any case the help of local authorities and local sanitary and pharmacies is important for control.

Figure B2-1 shows the global distribution.

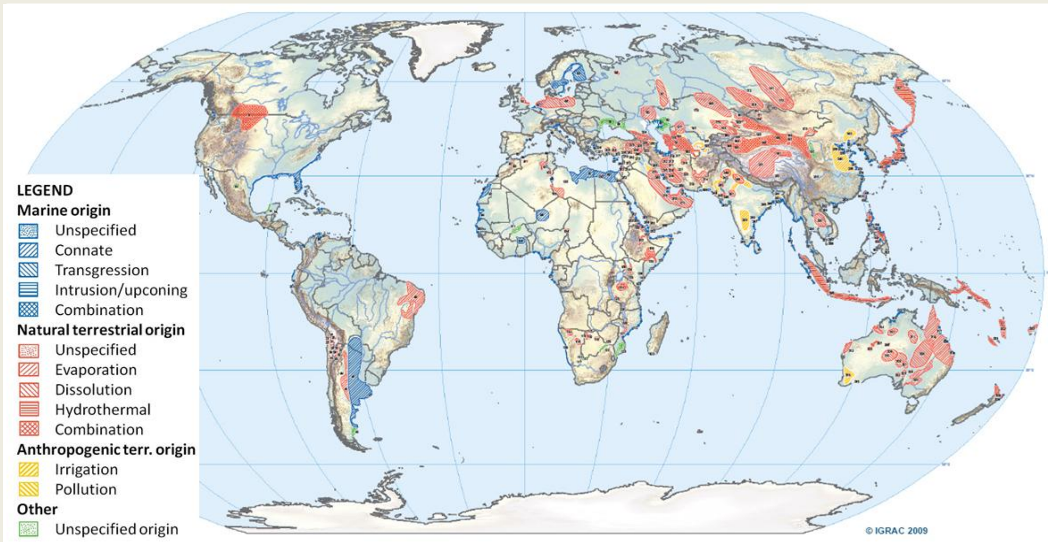


Figure B2-1. World distribution of major reported problems of arsenic content in groundwater at concentrations higher than 50 µg/L (Smedley, 2008; Margat and van der Gun, 2012).

Box 3: Groundwater quality governance in presence of fluoride contents

The origin the fluoride (F), mostly natural, is not always clear, but in general is related to the existence of F–rich sediments with Ca–poor groundwater. These sediments are mostly of acidic and intermediate volcanic origin in subducting areas of the Earth crust, such as that in the western side of the Americas or in eastern Asia, or caused by volcanic activity related to very evolved magmatic chambers, as is the case of Tenerife, or in areas of the African Rift in Ethiopia, Somalia and Tanzania. Acidic volcanic ashes often have high F content, which are spread over large, far away areas, and are incorporated into other sediments, as is the case of large areas in Argentina and Bolivia.

Fluoride is needed in drinking water for healthy teeth and bones but an excess has a counter effect. Recommended values vary between 0,5 mg/L and 1 mg/L. Deficits are sometimes corrected by fluoride addition to drinking water – not always a well–accepted practice –, dietary habits or the use of fluoride-containing toothpaste. The excess is difficult to deal with although this may be done through physic-chemical treatment, at a cost that only relatively rich areas can pay, as is the case of Tenerife, in the Canary Islands, Spain. In other areas of the world, as in Mexico, Argentina, Bolivia, Chile and Peru, people living in poor areas may clearly show the detrimental effect of an excess of fluoride, at times up to several mg/L.

When the cost of water treatment to reduce F content is not affordable, one solution is selecting low F groundwater sources in the area for drinking purposes. Some wells or water galleries have to be discarded, often yielding sodium-bicarbonate water in CO_2-rich areas of endogenic origin. This means locating areas where groundwater renewal is fast, limiting penetration into the aquifer and promoting the use of rainwater collected in cisterns. In Mexico, drinking bottled water and refreshments imported from other areas is currently quite developed.

In figure B3-1 the global distribution of F is shown.

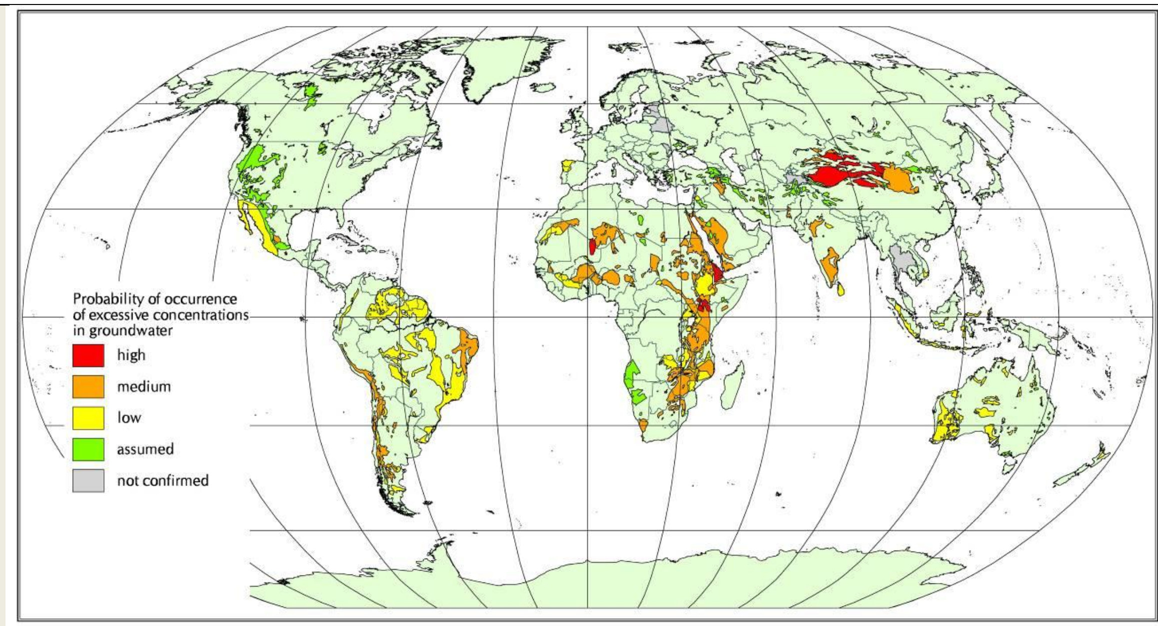


Figure B3-1. World distribution of major reported occurrence of high fluoride contents in groundwater, above drinking water standards (after Vasak et al., 2008; Margat and van der Gun, 2012).

Pathogenic components – bacteria and viruses – are rarely of natural origin in groundwater, since they are subjected to highly hostile conditions in the ground, where they cannot reproduce and they eventually decay. Thus, natural uncontaminated groundwater is pathogen-free, except in special situations, such as when there is a fast penetration from the surface or when the residence time of water in the ground is short, as in karst aquifers, large fissures and shallow coarse gravel formations, especially when soil and low permeability sediments do not form a continuous cover that protects groundwater against direct infiltration from the surface (Goodfrey and Smith, 2005). Pathogenic bacteria and viruses may survive a few weeks to a few months in the ground, although some reports indicate up to one-year survival under favourable conditions. Generally they move slower –often much slower– than groundwater does, since they are strongly sorbed, and thus, before decaying, they spread a short distance – a few metres at most – in soil and fine-grained aquifers, except for coarse gravels and large fissures and conduits, where they may move away hundreds of metres.

3.2 Groundwater quality and tolerance

Natural groundwater quality is important for potable water but also for agriculture and other human economic activities, as well as for the environment and the services it provides. A groundwater discharge area may be linked to a characteristic habitat, and most living species are sensitive to water quality and its changes, both in land and in littoral waters.

Plants have a tolerance limit to salinity of the water that is available to their roots. When irrigation-water salinity increases, an increased irrigation water depth (volume per unit surface) is needed to keep salinity at the roots and flush out the excess of salts. Otherwise crop yield decreases. Moreover, the soil must remain aerated. When applied water has an excess of sodium ion (Na) over earth–alkaline ions (Ca+Mg), as happens for the sodium-bicarbonate-rich waters found in CO_2-rich volcanic areas, the soil becomes less permeable and gets easily saturated; this hinders aeration, hence the plant is stressed and may die. Also when boron concentration in soil water is high, plants – especially the leaves – are poisoned. Water quality effects in irrigated agriculture depend on crop, irrigation frequency and depth, soil characteristics and the presence of some inconvenient components. Salinity tolerance depends on how soil water characteristics can be controlled. Effects need some time to develop and thus tolerance should be considered in the long-term. There are many examples of soil spoiled by persistent application of poor quality irrigation water in Pakistan, India, Spain, Northern Africa and other regions, although they are often poorly documented.

More serious restrictions appear when water is intended for drinking purposes. Salinity should be low, although the commonly acceptable value of 0,5 g/L of total dissolved solids could be increased when no other water is available, especially in semi-arid, arid, and coastal areas. This means that tolerance to Cl and SO_4 and to earth-alkaline ions is admissible, although not as much for Na since an excess over Ca may affect health. Water hardness should be low for cooking purposes and in order to avoid clogging and encrustation of pipes.

Recommendations and norms are strict for nitrate (NO_3) and some minor components with acute or cumulative effects. Tolerance should be minimal for these components. It is not rare that limits are reduced as more medical experience is gained. Such is the recent case of arsenic, whose limit has been lowered from 50 μg/L to 10 μg/L As.

Improved analytical methods allow to detect and measure a much larger number of new compounds – many of which of recent introduction (Table 2) – and help in medical research on human health related to drinking water conditions.

Tolerance to some substances may be argued when drinking water is not the only source of a concerning substance to population. However, since there are alternatives for food but not for water, this explains the strict behaviour of sanitary authorities when referring to water for drinking and cooking.

Moment	Contaminant	Level of detection
1950s	Major solutes Nitrates Dissolved organic carbon	mg/L (10^{-3} g/L)
1960s	Heavy metals Rare heavy metals Pesticides and herbicides Hydrocarbons	μg/L (10^{-6} g/L)
1980s	VOCs (volatile organic carbons) Chlorinated solvents	ng/L (10^{-9} g/L)
1990s	Hormones and endocrine disruptors Antibiotics Other emergent contaminants	pg/L (10^{-12} g/L)

Table 2. Progress in detection level of possible groundwater contaminants (adapted from Ronen et al.*, 2012)*

Similar restrictions to drinking water apply for livestock, although they are more tolerant in what refers to salinity and some components. There is some controversy in what refers to arsenic and other solutes.

For domestic and urban use, and also in modern irrigation systems, hard ground water equilibrated with high CO_2 pressure in the soil ambient is inconvenient, since it produces encrustations when the CO_2 escapes, and may need previous treatment. Dissolved Fe and Mn are also serious problems to all uses, staining surfaces, producing colour, encrustations and blocking pipes, as well as small holes and the tubing of modern irrigation systems. Treatment is affordable for drinking purposes and industrial uses, but this may be a serious burden for population in poor regions, and not affordable for agriculture and livestock, except for special crops and intensive livestock.

3.3 Impact of climate variability on natural groundwater quality

Under natural conditions, aquifers are not static but evolving systems due to past climate variability, land erosion, large land-use changes, sediment accumulation, shoreline changes and other processes. Small aquifers in well-recharged areas adapt rapidly to changes, but large aquifer systems, which have a large water storage, may evolve so slowly – particularly under semi-arid and arid conditions – that they may be considered as being under long-term transient conditions for planning and management purposes, especially in what refers to water quality. Even groundwater quality may not correspond to current recharge. To understand quality patterns, the transient situation has to be considered. Yet, it has to be taken into account that aquifer exploitation accelerates changes because of an enhanced groundwater flow due to greater head gradients. This may be regionally important, especially when referring to vertical water movements. However, existing natural head gradients may be decreased, cancelled and even reversed in some cases.

Climate variability effects may be still preserved in poorly renovating parts of aquifer systems, whose turnover time is similar or longer than climatic cycles. This happens most likely in aquitards and dead-end confined aquifers. At historical and sub-historical time scale, this manifests as relict salinity in recent coastal sediments deposited after the recovery from the glacial age low sea-stand, about 10 000 years ago. Recently recharged water may slowly replace saline water by flushing it out, depending on hydraulic heads, which are controlled by topography, recharge and aquifer properties. While in some cases the flushing process is accomplished, in others it is in its early stages.

In current arid zones, water that was recharged in rainier or favourable-for-recharge past periods may be partly preserved. This old groundwater – often called palaeo-groundwater – is still there due to current, much lower, recharge and/or to the large dimensions of the aquifer (Edmunds and Milne, 2001). This is important in the Mediterranean, Sub–Saharan Africa, north-eastern South America and the Near and Middle East, where relatively fresh palaeo-groundwater is found and used.

Future climate change is very uncertain. The impact on groundwater has been assessed (Medina, 2010) and is quantifiable (Holman *et al.*, 2012) in what refers to recharge and mineral quality, but there is still a wide uncertainty in what refers to other components. The effect on groundwater quality depends on a combination of precipitation and its temporal pattern and the effect of temperature on soil-water balance for the future vegetal cover, taking into account the rate of substitution of current vegetation cover. No dramatic changes in groundwater quality due to climate change are expected during the next decades, except for recharge salinity under extreme situations of dryness or coldness.

A main concern for groundwater quality governance, in most cases, is not climate change but global change, which depends on population, human activity, living standards, land-use and other factors related to development. The impact of these global changes will be dominant, at least in the coming decades, something that is not always duly considered in groundwater planning, research and knowledge transfer.

Forecasts in coastal areas point to a sea level rise of about 0.5 to 2 m. This will significantly impact coastal aquifer freshwater resources only in very flat areas or in low elevation small islands, such as atolls, where the freshwater body may be greatly impacted and reduced. This is a groundwater quality governance issue in some areas in Europe, such as the Netherlands and north-eastern Germany, in part of the eastern coastal areas of North America and in many of the flat small islands in the Pacific. They depend on coastal sediment dynamics, some of which depend also on current activities, such as harbouring, beach modification and erosion changes in streams, as part of global change.

3.4 Governance of groundwater natural quality

Governance of groundwater natural quality refers to management under conditions of poor quality and aims to preserve quality when there are threats from poor natural quality around, above or below the aquifer. Thus, a first step for governance is understanding the origin of the natural quality of the aquifer under consideration and of the other related surface and groundwater bodies. Once there is some aquifer development, then the aquifer is disturbed, and this modifies the flow pattern, locally for small extractions, and affects the whole system for intensive development. The result is induced groundwater displacement inside the aquifer – a slow but sustained process. Besides, wells and other groundwater abstraction works get mixed water from different layers. Their drilling and construction activities may disturb natural flow by introducing by-passes, when low permeability layers are penetrated without carefully grouting the space between the hole and the casing. The same happens when the protection provided by the soil is lessened by breaching it or changing its characteristics, as it is the case in agriculture and deforestation.

When groundwater quality is poor in large areas, management goals intend to minimize the problem (Roset-Palma, 2002) by exploiting the best areas. This means that there is the possibility of institutionalized action over the whole area instead of individual or unrelated and myopic decisions by small groups. However, personal or local action is the most common case, as in Bangladesh with respect the presence of arsenic in groundwater, or salinity in many coastal aquifers. This form of management needs progressive adjustments since the background may change as development progresses. An important improvement that can be introduced, once the causes of poor quality are well understood, is to modify wells (by deepening, shortening, grouting some parts or drilling new well-designed ones), which requires financial resources from the local community or from external sources.

An important issue to bear in mind for groundwater quality governance is that investments to improve currently abstracted groundwater quality, or to ensure its treatment, may be effective for some time but there is a mid- to long-term evolution.

When groundwater quality problems are due to well construction or their inadequate operation, norms are needed. Governance in this case implies getting acceptance of the norms and of the costs involved, as they are paid directly by the groundwater users. It also implies the presence of institutions to set norms and control their application, and as well as to enforce effective sanctions and/or promote compliance among users.

Natural groundwater quality governance has to take into account the different aspects involved and should consider the aquifer system as a whole. A sectoral focus helps to address specific situations and problems, but must be modulated by a global point of view.

4. Human and Induced Changes in Groundwater Quality

4.1 Importance of groundwater behaviour

In managing groundwater resources, governance arrangements have to take into account the sluggishness of groundwater flow and mass transport, which may determine transit times of years or decades, and even centuries or millennia in large aquifer systems (see Figure 5 for the delay of hydraulic changes). Quality changes are often much slower. Thus, the effects of current human activities on groundwater quality may often appear highly delayed, and cause–effect relationships may be difficult to establish. Solutes that can be sorbed or ion-exchanged are still more delayed, attenuated and dispersed. This also means that in some situations current problems are due to activities done decades ago, and that current activities may produce effects that will impact on future generations. This is also true for groundwater quality changes due to land-use activities, such as urbanization, extensive agriculture and changes in forest areas and management. They affect recharge, salinity and quality, besides the possible contribution of contaminants from agricultural practices or the mobilization of those held in the ground.

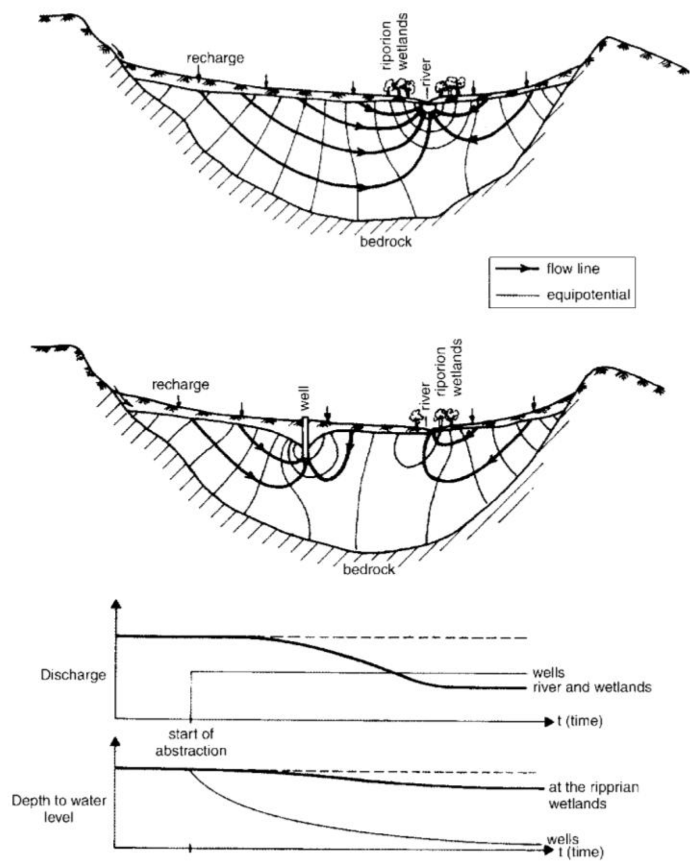


Figure 5. Schematic representation of groundwater withdrawal effects in a sedimentary basin recharged by rainfall infiltration and discharge into a river and through the associated riparian vegetation. A) Natural situation; B) Long–term effect of intensive groundwater development, in which a generalized water–table drawdown is produced in order to divert a large fraction of recharge to the well area, thus reducing discharge into the river and riparian vegetation area; C) Evolution or river and riparian discharge, and of groundwater level at the wells and at the riparian wetlands; the time scale may vary from months to centuries, depending on aquifer hydraulic

characteristics and size. In this case only a fraction of recharge is withdrawn, so a new steady situation will be attained after some time, albeit with some water-table and piezometric draw-down (After Custodio, 2010a).

The medium- and long-term changes – approximately 5 to 10 years and 20 to 30 years respectively – are not easily understood by managers and people in general. Consequently, they are often disregarded when facing pressing short-term problems. Besides, information is often poor and legislation and norms generally do not help. A necessary step for groundwater quality governance is making authorities, institutions and users aware about the slow behaviour of groundwater and about the fact that current problems may come from past activities, thus creating an ethical/moral duty to 'care for the future'.

4.2 Groundwater development effects

Human activities induce two kinds of changes in groundwater quality: introducing contaminants – which cause pollution – and modifying recharge, as well as the flow and mass-transport characteristics of aquifers. As just seen, although impacts were produced earlier in time, they did not become significant until recently – except for large land-use changes and local actions, such as mining activities – when current urban and transportation habits were consolidated and groundwater intensive exploitation started taking place, as shown in Figure 1.

Groundwater development implies decreased water-table and piezometric levels. This not only decreases natural discharges but may also enhance surface water infiltration, inter-aquifer leakage and seawater intrusion in coastal areas.

Surface water infiltration carries the contaminants that have not been filtered out and retained on the surface. The desiccation of wetlands and peat-lands may mobilize solutes and contaminants held in sediments and the organic matter they contain, as some heavy metals.

Inter-aquifer transfer may induce the movement of possible low quality and saline water toward the exploited aquifer, from other aquifers and aquitards or from other areas of the aquifer, such as deep-seated saline groundwater layers containing undesirable solutes due to their special chemical conditions, and the infiltration of groundwater from the sides.

4.3 Pollution effects

Pollution by human activities involves a large series of substances of widely variable origin and diverse contamination processes. Figure 6 shows a cartoon of general polluting activities in a given territory. There are two end-member pollution processes: diffuse and point pollution.

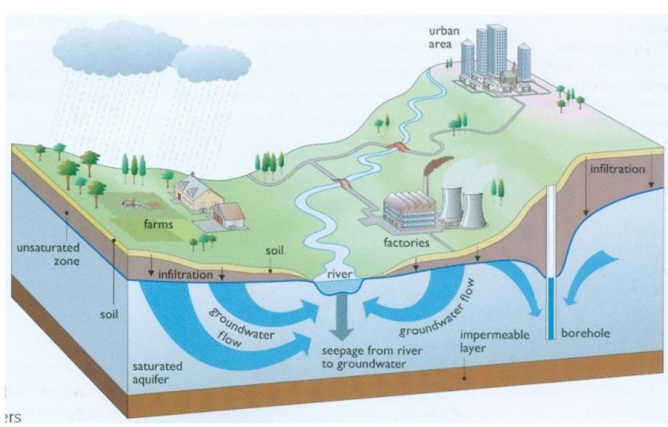


Figure 6. Cartoon on the main contamination sources and water paths through the soil and a water–table aquifer, in an area with rural, industrial and urban influence (after Lawrence and O'Dochartaigh, 1998).

Diffuse pollution – or non-point pollution – refers to a large territory (see Figure 7). Contamination may be air-borne – a main source in many areas, which may involve soluble salts, volatile nitrogen compounds, organic solvents, hydrocarbons and organics – or caused by agriculture and extensive animal raising, which involve agrochemicals, nutrients, water and soil quality correctors, pesticides, herbicides and other similar chemicals. The effect may be quite serious for intensive irrigated crops, but it is also important in dry (rain-fed) farming, which also uses agrochemicals, in lower doses but over larger surface areas. Among the nutrients, nitrate-nitrogen (N) and potassium (K) are quite mobile, while phosphorous (P) is easily retained by carbonate formations.

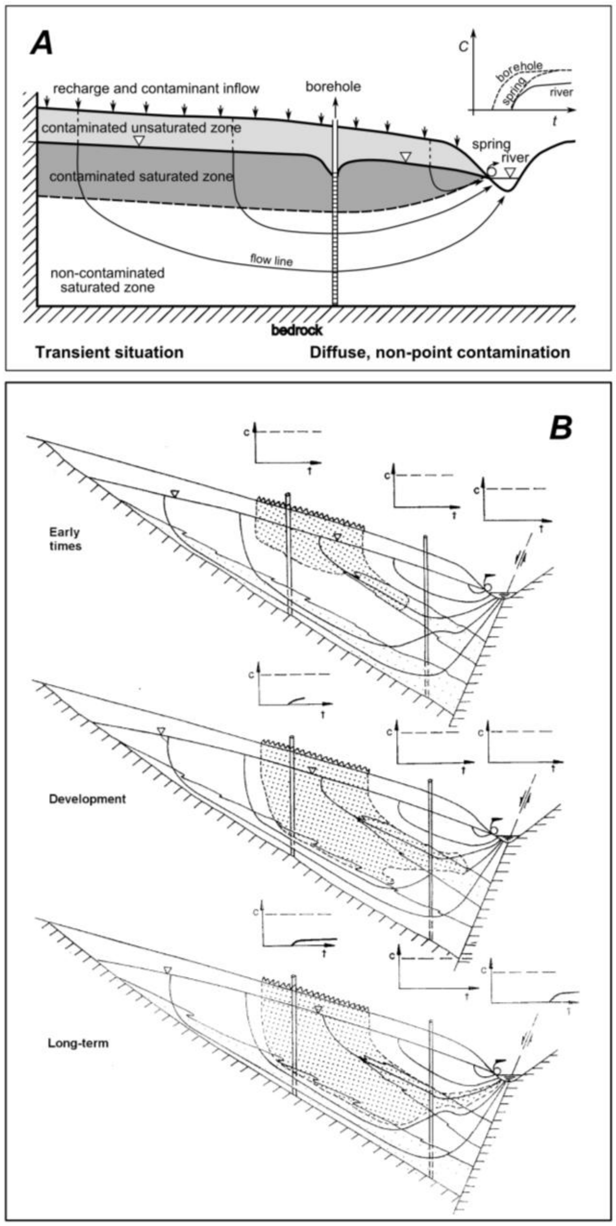


Figure 7. Diffuse (non–point) groundwater contamination from a sustained fertilized agricultural area. A) on the whole area in a homogeneous aquifer; this is a transient situation since the contaminated area expands progressively if agricultural activity persists; B) over a part of the area of a heterogeneous aquifer. The inserts show how contamination appears in the river, the spring and a borehole. c is concentration and t is time.

Point pollution refers to the introduction of contaminants in relatively small areas by a wide variety of circumstances and activities, such as leakage, disposal of wastes, accidental spills, storage of chemicals and wastewater infiltration and injection. They produce contaminant plumes that move laterally and may sink with groundwater flow (Figure 8). Very important point-pollution activities over large areas – which grade into diffuse pollution – are domestic water disposal in urban and peri–urban areas, irrigation of small land plots and concentrated feedstock. The less economically developed the area is, the more widespread such activities are.

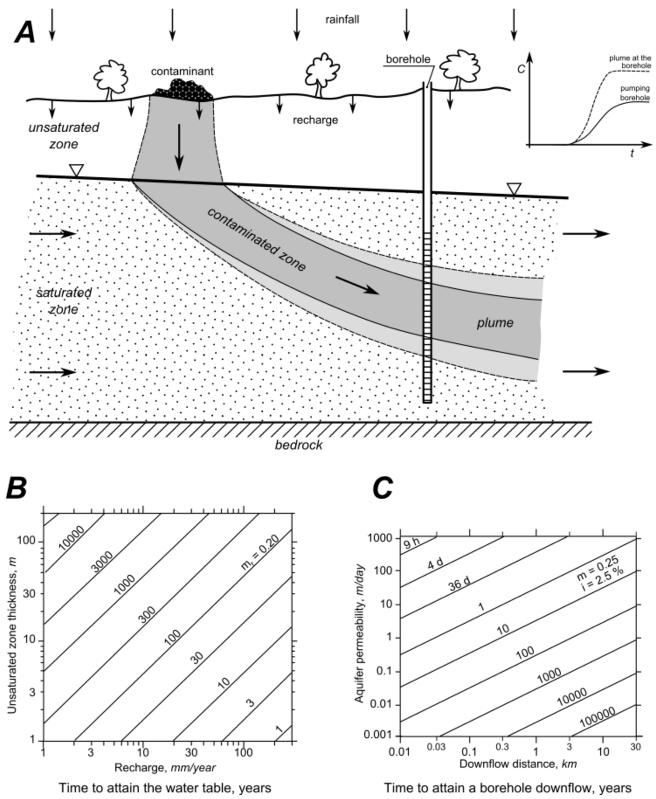


Figure 8. Point (concentrated) groundwater contamination from a disposal site on the land surface, leached by rainfall infiltration that produces recharge through it, in a homogeneous water–table aquifer. A) contaminated plume; the insert shows the evolution of concentration (c) along time(t) at a borehole downflow and intersecting the plume, in the screen and when pumped; B) time (in years) for the contaminated recharge to attain the water table, considering the unsaturated zone thickness and the recharge rate through the tip, for a 0.2 soil water content; C) time (in years) for the plume to attain a borehole on the plume path, according to aquifer permeability and down–tip distance, for a 0.3 dynamic porosity.

4.4 Groundwater quality governance of human and induced changes

Groundwater quality governance should deal with groundwater development as one of the key components. Governance arrangements depend on national policies concerning water development, the producers' attitude and the demand. In many circumstances, water demand is driven by quantity, although when water is for drinking purposes there is a growing concern on quality after information to the public improves and the intervention of sanitary authorities becomes more effective. This refers not only to local population but also to the increasing mobility of persons, tourists and food products. Even agriculture – a main groundwater demander in many regions – is becoming concerned about groundwater quality as improved irrigation techniques are introduced, such as sprinklers and drip irrigation, and is looking for efficiency in water, agrochemicals and energy use.

Fighting and managing pollution depend on the understanding of the involved processes and on the interpretation of monitoring data. Groundwater quality governance has to go hand in hand with authorities, institutions and people that decide on land-use, application of agrochemicals, wastes and wastewater policies and activities, and has to rely on public education on these issues.

5. Groundwater Quality Conditions and Governance in Selected Typological Environments

Groundwater quality is highly variable, depending on aquifer circumstances and characteristics, and may change inside a given aquifer, both horizontally and vertically. The natural situation – or "normal" situation in highly modified aquifers – has to be known or deduced, in order to determine a reference background value or baseline.

Baseline values are required for the application of the European Water Framework Directive in the EU Member States, following the guidelines of the "child" Directive on Groundwater (Directive 2006/118/EC of 12 December 2006 on the protection of groundwater against pollution and deterioration). This has been and still is a controversial issue due to the above-mentioned spatial variability. Several typological environments are presented here as examples, although they do not cover all possible situations.

5.1 Water quality in under-exploited aquifers in under-populated, rural and urban circumstances

Under-exploited aquifers are in principle under close-to-natural hydrodynamic conditions, although not necessarily from the water quality point of view.

Baseline quality conditions are easy to obtain by avoiding wells and springs near urban areas, houses, irrigated cropland and fertilized land. These baseline conditions are highly variable and depend on local, climatic, geological and hydrogeological circumstances, as well as depth. Thus, zoning may be needed to set baseline values and to define sub-aquifers according to depth when guide-layers can be identified.

In rural environments, point pollution sources are mostly related to local sanitation and to the disposal of solids and animal wastes. The impact is usually low, except for high-density rural population, as in many areas of eastern and south-eastern Asia. In some cases, animal impact on water quality may be larger than human pressure. There is a difference between dispersed houses and the concentration in small and medium villages. Villages may severely affect a given territory, which is proportionally small but important for inhabitants who usually relay on close-by groundwater resources that may be close to sanitary disposal sites or poorly isolated from land surface. This is often a major source of health problems, including from the use of household chemicals, such as detergents and oily products. Groundwater quality governance arrangements should bear in mind that, although some dangerous chemicals –often cheap ones– are banned and not used in areas where legal restrictions are enforced, they may continue to be produced and used in poor areas, thus easily getting into the neighbouring shallow aquifers.

Pathogenic problems are only found in groundwater in the case of shallow water table, where there is a poor soil cover or where the soil cover has been disrupted and breached by excavation or drilling. However, coarse materials allow the spreading of bacteria and viruses to the surroundings before they decay. To limit the access of surface contaminants to the water table, the preservation of soil cover is very important. However, even when groundwater is not polluted, contamination of abstracted water may result from poor well construction, isolation and protection of the immediate surroundings. This is often the cause of many health-related problems attributed to groundwater. Thus, appropriate well construction and operation is important to avoid contamination. In water-table aquifers, wells with deep screens and in confined aquifers are recommended, provided careful grouting, isolation and protection against corrosion and tubing ruptures is available. Well construction is often done following the cheaper bid, without clear prescriptions and control that guarantee water quality aspects. This is a source of problems and also kills existing good practices. Adequate well construction may be difficult in poor areas.

Under rural environments, agriculture and feedstock may be – and often are – an important source of aquifer contamination and produce progressive nitrate content increases that may spoil aquifer use. Governance of groundwater quality implies involving institutions and people in sanitation, adequate use of household chemicals, good agricultural and livestock practices, safe storage of potentially polluting substances and safe disposal of refuse. In addition, it is necessary to promote, regulate and provide means for the adequate construction, operation and maintenance of wells, while keeping their surroundings clean. The rural and small village environment needs direct involvement of people, for their own sake and to preserve their common-pool resource (Burness and Brill, 2011).

Groundwater quality is generally impaired under urban environments, even if actual recharge is often still important (Chilton, 1997, 1999; Custodio, 1997; Foster *et al.*, 2011), contrary to what is generally assumed. Figure 9 shows a cartoon on pollution sources. Common contamination problems refer to nitrate increase (see Figure 10), mineral oils, fuels, chlorinated solvents leakage and occasionally the creation of a reducing environment when organic matter concentration is high, which may produce the dissolution of Fe and Mn or the release of trapped As. Separate phase pollutant liquids or non-miscible phase liquids (NPL), which are partly soluble in water in small to medium concentrations, may be lighter then water (LNPL) and float around the water table (Figure 11) or denser (DNPL), in which case they sink through the saturated zone (Figure 12). Besides, a large series of chemicals at low concentration may be found, which are generically called emergent contaminants (Drewes *et al.*, 2003; Shey *et al.*, 2006). They include caffeine, nicotine, pharmaceuticals, antibiotics, estrogens, endocrine substances, cosmetics and psychedelic drugs, whose effect on human health is poorly known. They may be found even in poor urban sectors or near infiltrating polluted rivers. Groundwater may reflect local supply water quality (Vázquez–Suñé *et al.*, 1999). This is an important but poorly understood evolving issue that might have serious impacts on human consumption, as well as on the environment and its services.

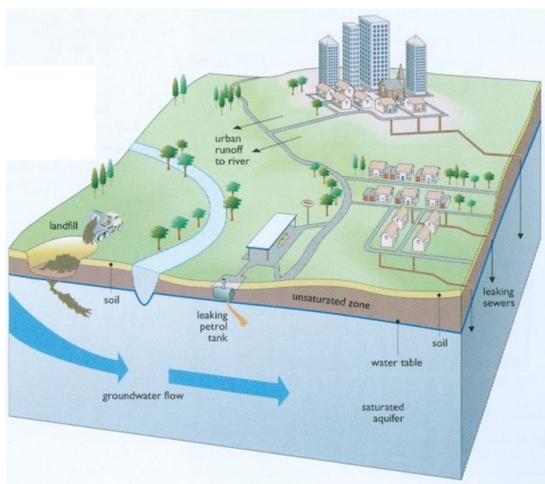


Figure 9. Cartoon showing the main sources of contamination in an urban and peri–urban area (Lawrence and O'Dochartaigh, 1998).

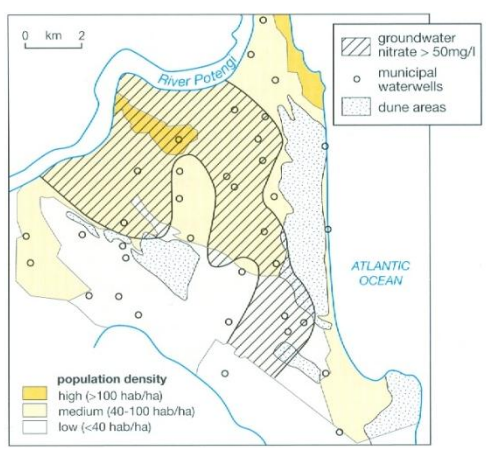


Figure 10. Example of nitrate contamination of mixed urban and agricultural origin in the city of Natal, Brasil, in 2008 (Foster et al., 2011).

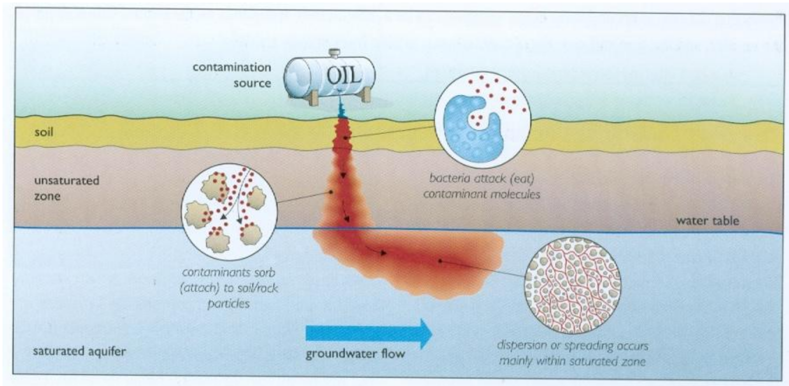


Figure 11. Soil and aquifer pollution by oil tank spills and leakages. Mineral oil is a lighter than water, non–miscible phase liquid (LNPL) that floats on the water table; it is slightly soluble in water and disperses according to water–table fluctuations and groundwater flow (Lawrence and O'Dochertaigh, 1998). Under favourable circumstances, natural processes may help in reducing contamination through degradation, sorption and dispersion.

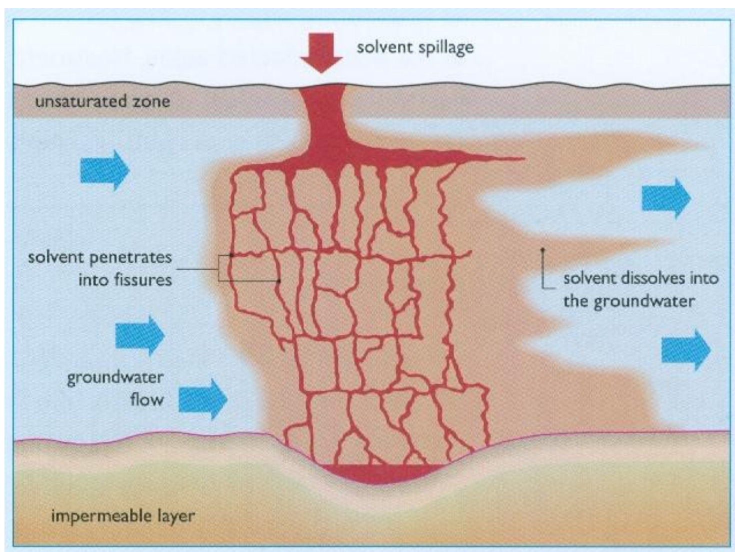


Figure 12. Soil and fractured aquifer pollution by chlorinated solvents spillage. They are denser than water, non–miscible phase liquids (DNPL) that sink slowly through the whole unsaturated zone thickness and cumulate in the aquifer bottom; the plume and main body contaminates groundwater in contact with them due to the slight solubility (Lawrence and O'Dochertaigh, 1998).

Groundwater quality governance is a difficult issue due to the multiple and densely distributed sources of pollution, in a human environment that is not aware or does not value groundwater. Awareness raising activities are needed to promote the progressive reduction and elimination of pollution sources. The government, with the help of civil institutions, has to regulate urban activities, such as storage of fuels and chemicals or collection and disposal of wastes, and replace individual sanitation systems with common and well-maintained sewage systems. This is an achievable goal in relatively rich areas, but a serious challenge in poor cities and marginal areas of otherwise rich towns, such as Buenos Aires, Lima, Mexico City and São Paulo metropolitan areas, as well as many large cities in India. Local groundwater resources from urban areas can be used for non-potable uses – street cleaning, building, industrial cooling and other industrial uses – or for drinking purposes if thorough and safe treatment can be provided. Related expenses will have to be borne by residents or subsidized, when appropriate. In some cases, groundwater exploitation has to be encouraged to avoid problems with high water tables or to delay costly importation of water.

5.2 Water quality in intensively exploited aquifers in arid regions

In an intensively exploited aquifer, abstraction is a significant fraction of recharge. Consequently natural flow conditions and water quality are notably modified. The use of the term overexploitation may be misleading (Custodio, 2002), since it often conveys a negative point of view, which is not necessarily true, or suggest that exploitation is greater than recharge, which may not be the actual case. At least for some time, groundwater exploitation and groundwater mining – the continuous depletion of aquifer reserves – may evolve similarly. Moreover, exploitation and recharge rates are rather difficult to determine and are often highly uncertain. From the point of view of groundwater quality, the abstraction of a fraction of recharge may lead to a clearly unsustainable situation, as in coastal aquifers or when saline groundwater is found below. Contrarily, an exploitation rate greater than recharge can be advisable, without causing serious water quality problems, if freshwater reserves are large and the supplied society is evolving towards new conditions where groundwater mining will not be needed (Foster and Loucks, 2006; Custodio, 2011a).

Determining the baseline quality is not an easy task, since surveys and monitoring are often carried out when aquifer disturbance is already advanced. Careful studies and occasionally drilling surveys are needed. In some cases, the baseline has to be referred to conditions in which aquifer water is from recent recharge under prevailing disturbed conditions.

In intensively exploited aquifers, some degree of water quality impairment may be produced, but this is not the general rule. Aquifer conditions define the evolution. Major threats are saline degradation from seawater intrusion or from existing saline water in aquitards and deep formations, and occasionally the release of natural contaminants from the formerly saturated zone that has become unsaturated and exposed to atmospheric oxygen. Such are hardness increase and pH lowering when organic matter is degraded, which may be accompanied by the release of some heavy metals, among which arsenic. Groundwater use for irrigation may cause salinity problems, besides those derived from fertilizers, especially nitrate built up. Salinity increase may be due to highly saline irrigation return flows –the more efficient the water use, the more saline the return flow– and to leaching of salts in formerly saline soils and overlaying formations. Saline contamination is found below the irrigated areas and spreads downflow slowly since, in most cases, head gradients are small. This may severely affect water-table aquifers and, consequently, deeper aquifers of local relevance when wells are not well isolated. In deep water-tables, contamination may only appear after years or decades and may even go unnoticed for a longer time if there are no wells to monitor the upper part of the water-table aquifers.

Groundwater quality governance issues, in areas where intensive development is the consequence of water scarcity or concentrated water demand, are often of secondary importance since quantity is prioritized, except when water is dominantly for human supply. But when quality problems eventually appear, things are very difficult to redress due to the long time needed for restoration and the high costs involved. Governance means that coming problems have to be forecasted, and that government and civil society institutions must be aware of the need to preserve the common-pool water resource and of the risks of no action.

A different situation of aquifer salinity deterioration in arid areas is due to the existence of brackish to saline water held in the often thick unsaturated zones. This water is the result of intensive evapo-concentration (water salinity increase due to evaporation and transpiration) of atmospheric salt deposition by highly efficient rainfall use by native vegetation. When the forest is thinned or substituted by prairies and cropland, recharge increases conspicuously due to the lower efficiency of rainfall-water capture. This recharge has a lower salinity but pushes down previous saline water through the unsaturated zone at a higher rate. This generates an increased rate of introduction of salts into the aquifer over time, which may often last decades or centuries. When the main recharge of the aquifer is produced in other more favourable areas, which are less saline, this process leads to salinity deterioration in the aquifers below, affecting local wells and downstream springs and river base-flow (Scanlon *et al.*, 2009) (see Figure 13). This is a serious concern not only in the well-known case of the Murray–Darling basin, in south-eastern Australia (Simpson and Herczerg, 1991), but also in other areas where the problem is not recognized due to lack of monitoring or for being the result of old activities. This seems to be the case of the Monegros area, in north-eastern Spain, a semi-arid area covered by medium-size brush that was cut down for timber and fuel between two to four centuries ago. Taking such issues into account in governance arrangements may prove challenging, as land use and other sectoral activities are involved.

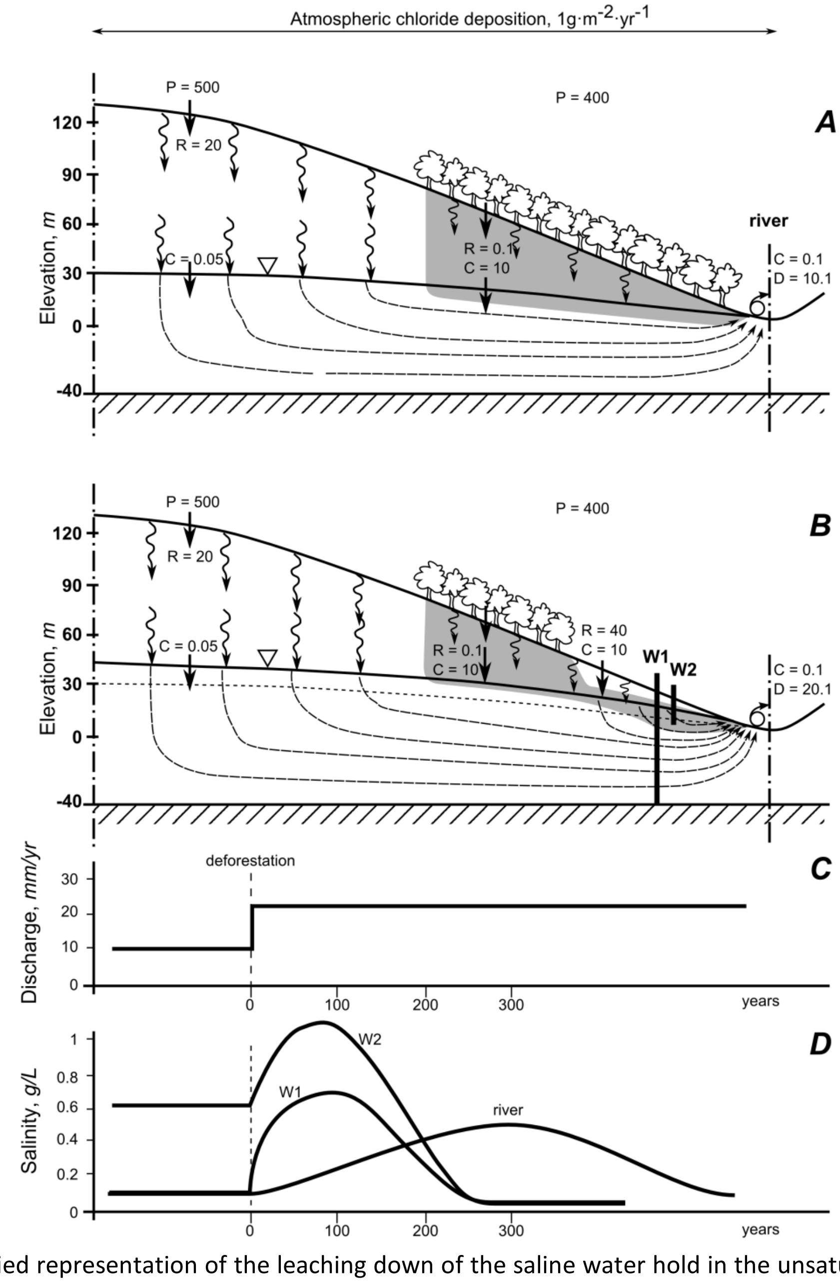


Figure 13. Simplified representation of the leaching down of the saline water hold in the unsaturated zone below a highly efficient natural forest in an arid area, when the aquifer receives freshwater recharge from upflow areas. A) natural situation; B) transient situation after partial deforestation of the area, C) change in river discharge after increased recharge in the deforested area, D) indicative evolution of salinity in two pumped wells downstream and in the river; the time scale is only indicative and depends on the size of the system. P = average rainfall (mm/yr), R = recharge (mm/yr), D = discharge (mm/yr), C = chloride concentration (g/L). (Modified from Custodio et al., 1997).

When irrigation with imported water produces a significant recharge increase through more or less saline return flows in otherwise low recharge areas, the water table may close land surface and become further salinized by direct evaporation from the soil, with detrimental results for agricultural activity and local supplies. An old, well known case is that of the Punjab, in the Indus Plain, Pakistan (Figure 14).

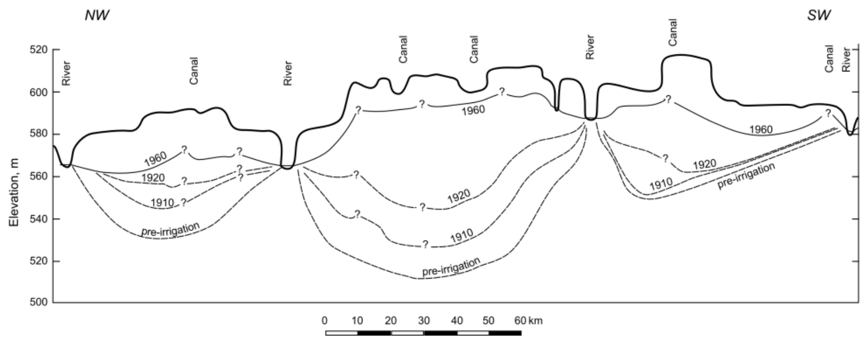


Figure 14. Water–table rise below a plain irrigated with imported water, with added recharge from high canal losses and return irrigation flows, as exemplified from the arid Indus Plain, Punjab, Pakistan (after Greenman et al., 1967). Groundwater evaporation from areas developing very shallow water tables increases salinity and further deteriorates groundwater quality.

5.3 Water quantity evolution in regions of high annual recharge

The main characteristic of regions with high annual recharge is the fast renovation of water in shallow aquifers. Thus, salinity increase due to evapo-concentration and mineral weathering is small, and groundwater mineral quality is close to average rainfall. However, organic-rich soils yield soluble and colloidal organic compounds, mostly humic and fulvic acids, which may become a problem for human supply – although this is not the common case for groundwater, where the Total Organic Carbon (TOC) is at most a few mg/L. In the aquifer, available dissolved oxygen is often consumed, and thus reducing conditions appear. This may be accompanied by Fe and sometimes Mn dissolution, if they are available in minerals, mineral particles or grain coatings. Also nitrate may be reduced to NH_4 instead of N_2, which interferes with water disinfection. Natural vegetation is generally very efficient in capturing available mineral N, except when forest is thinned out or substituted by grassland and agricultural fields, in which case soil organic matter decays and frees the nutrients held in it.

Under these circumstances, baseline quality can be derived through simple sampling, although special local situations may be found, which may need a separate consideration and could be considered as an exception.

In regions of high annual recharge, groundwater quality does not pose serious problems, beyond those mentioned above, due to the fast turnover time of groundwater and the scarce use of groundwater for irrigation, thus easing the pressure on the aquifer. The main issue is related to changes in the underground ambient by local exploitation – some limitation may be needed – and to the control of pollution sources. A frequent pollution source is the use of herbicides to control weeds in open areas, train tracks and roads. When soil is thin, coarse, breached or non-existent, these herbicides may find their way down to the aquifer, where retention may be low thus allowing them to travel some distance along the groundwater flow before they decay – if they do at all. Atrazine and simazine have been - and in many places they are still - commonly used products. Currently, glyphosate formulations are widely used in some cases; they decay fast and do not seem to pose a problem for groundwater, although they may leach downwards to the aquifer from coarse soils on weathered granite and volcanic formations (Candela *et al.*, 2010).

Deep confined aquifers with long turnover time contain freshwater in the outcropping and renovating parts in high recharge areas, but may hold old brackish and saline water in the rest. This is the case in parts of the aquifer (ALHSUD, 2007; Heredia et al., 2012), and seems to be the case of the Tikuna confined aquifer in the Upper Amazonas deep aquifer (do Rosario, 2011), both being large trans-boundary aquifers in South-America.

5.4 Groundwater quality evolution related to agricultural development

Most new agricultural areas are established in old forest and brush areas, causing the degradation of organic-rich soil. After available nutrients are depleted, agricultural productivity decreases if not compensated by the application of agrochemicals. In both cases, nutrients are leached down – especially nitrate – that, after some time, appear in the water-table. This depends on recharge and depth of the water table, as well as on the characteristics of the soil and of the unsaturated zone (Foster and Candela, 2008; Candela and Aureli, 1998; Vrba, 1991; Rippa *et al.*, 2006; Landon *et al.*, 2011). Different aspects are considered in Section 5.2.

This is an increasing and expanding problem in most agricultural areas of the world that will continue to grow in developing areas, as greater fertilizer quantities are needed and made available to sustain fertility, especially in intensively cultivated areas. Poor application technology is part of the problem, but even with good technology some leaching is unavoidable, especially in irrigated areas. Existing data show that salinity tends to increase below crop land (Krapp and Baerenklau, 2006).

High concentrations of nitrate – well above the 45 to 50 mg/L limit for drinking water – can be found in many agricultural areas, especially when intensively cultivated and irrigated or due to intensive feedstock farms. Reported values may be up to several hundred mg/L.

Leaching down to the water table of part of the applied nitrate is almost unavoidable (Albiac, 2009), although efforts and modelling helps in reducing the problem (de Paz *et al.*, 2009; Delgado, 2002; Cowin *et al.*, 1997; Jabeo *et al.*, 2006). The most common practice is applying an excess of nitrate (Ramos, 2002; Donnehy *et al.*, 2002), above the commonly recommended quantities (150 to 180 t/ha/year). In some cases, the excess is due to other causes that are unrelated to fertilization, which are rarely taken into account, This is the case when applied groundwater has already high nitrate contents and is used as a main source for irrigation water o when this water applied for emergency irrigation to fight possible frost. Such cases are difficult to manage because fertilization and irrigation needs do not occur at the same time (Wallis, 2011; Candela *et al.*, 2008).

The US Environmental Protection Agency (EPA) and the European Commission are seriously dealing with the nitrate problem, as a major water supply problem that requires appropriate management and governance (see Box 4).

Box 4: European Water Directives dealing with groundwater quality

The EU enacted the Nitrates Directive (Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources) to deal with groundwater pollution due to agricultural sources, which includes fertilization, livestock and animal waste storage and use. The Nitrates Directive, jointly with the other Water Directives, has been incorporated into member states legislation and have to be enforced in the respective territories. Vulnerable zones to nitrate pollution of agricultural origin have been defined and are subject to special measures, including limitations to fertilizer use, minimum storage volumes for feedstock wastes and their control, good agricultural practices and an adequate level of monitoring and reporting.

The Water Framework and Groundwater Directives require that by 2015 groundwater bodies identified as legal administrative units – reach good quantity and chemical quality status. This good quality status is close to baseline value of the aquifers. However, due to their characteristics and to the high economic cost of halting and reversing quality trends, a great number of aquifers – about 20 to 50 percent of the groundwater bodies, depending on the country – will not meet the target. If required, new deadlines can be set for the next six-year planning period in 2021, or even for 2027, but this needs careful studies and an action plan with defined and approved steps. The consideration of practically unrecoverable situations is a pending issue that involves problems of comparative grievance and costs transferred to the future. In fact, it is unclear how efficient this action will be, especially considering the cost to society relative to the benefits from improved environmental quality, which is the main objective of the Water Framework Directive. Results for groundwater are currently poor, but it is too early to appreciate future results (Silgram *et al.*, 2005). In spite of stationarity and even further deterioration in some areas, in others improvements are reported, as in the Netherlands (Crammer *et al.*, 2010; Zwart *et al.*, 2008; see Figure B4-1).

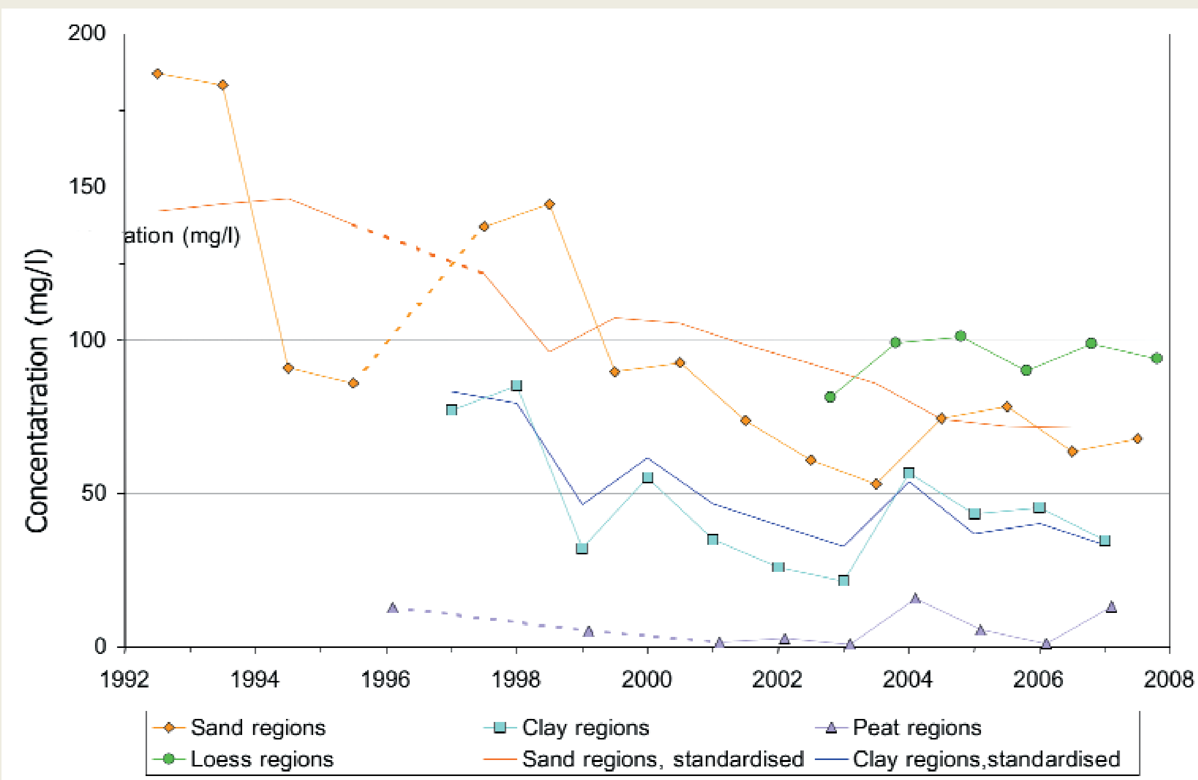


Figure B4-1. Nitrate content improvement in the upper part of the saturated zone in agricultural areas in The Netherlands (after Zwart et al., 2008). Points show annual average nitrate concentration.

How this can be applied to other countries and regions as a groundwater quality governance action related to nitrate pollution is not known. The implementation of such measures is proving complex and expensive even in the EU, particularly in the current difficult economic conjuncture. One option is to consider some aquifers as non usable for drinking purposes, but this transfers a higher cost on drinking-water supply systems and does not prevent that pollution will eventually appear in springs, rivers and the littoral sea, thus frustrating pollution abatement efforts. A number of studies show that in many aquifers, the economically and socially costly action to reduce nitrate pollution will not produce the wanted results for some decades and may result in further deterioration for some time, due to the larger quantity stored in the soil and in the ground. This makes groundwater quality governance a challenging task, as results may be highly delayed.

The use of pesticides in agriculture – a wide variety of them for very different purposes – is a growing concern, as is the use of pharmaceuticals for livestock. Pesticides may be sorbed in the soil, subject to degradation and may produce concerning derivatives (metabolites). There are numerous studies on their behaviour in the soil and in the ground, but effective solutions have yet to be developed (Mouvet, 2008). Baran *et al.* (2010) provide an example from France. Pesticide contamination of groundwater is not only a threat to health, but also an economic loss when supply wells have to be closed down (Figure 15). Governance arrangements should consider that several sectorial government departments are involved in pesticides management and use and have to be coordinated. This is a complex and difficult task that may fail, even in simple situations.

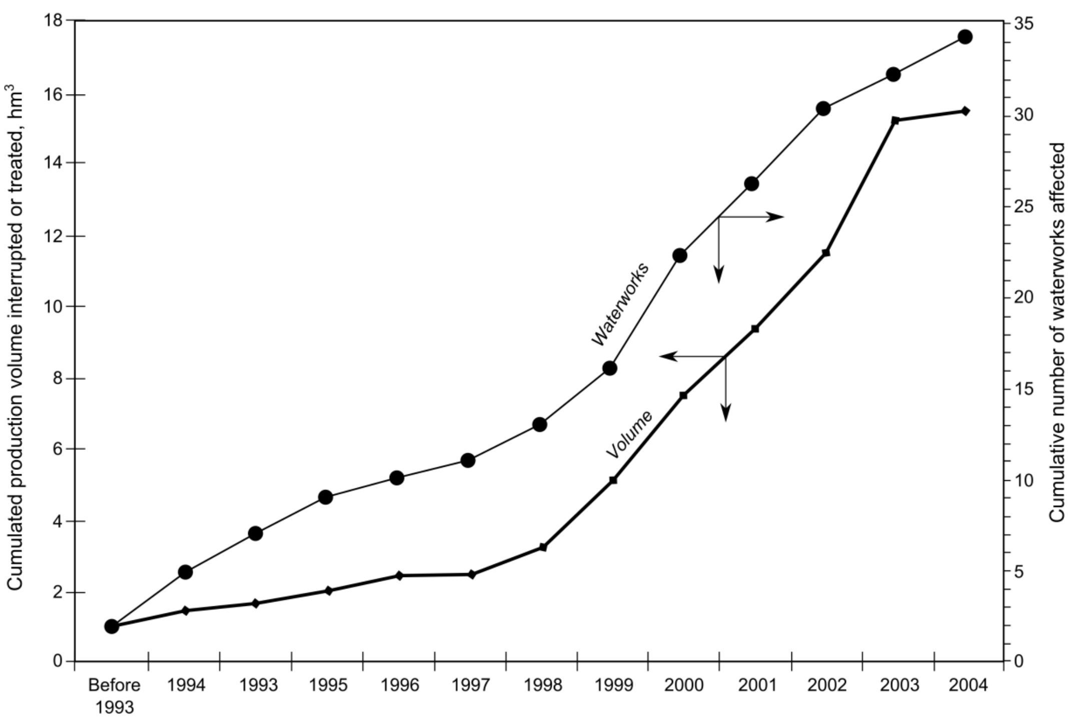


Figure 15. Time evolution of the cumulative volume of groundwater and the number of drinking water production wells closed down or needing water treatment due to pesticide contamination, in Wallony, Belgium (after Mouvet, 2008).

Groundwater salinity pollution by changing natural vegetation for prairies and cultivated areas is considered in Section 5.2.

5.5 Saline water in coastal areas

Seawater intrusion in coastal aquifers is the result of hydrodynamic conditions in a variable water-density flow system. Seawater is denser than freshwater and thus tends to penetrate the land from the coast and to lie at the bottom of aquifers. The penetration is limited by groundwater flow, as aquifer properties and geometry define the extent of seawater intrusion (see Figure 16 for a typical example in a recent deltaic area with a dune belt). Groundwater development decreases freshwater flow towards the coast and may even reverse it, which consequently induces seawater inflow. These are well known processes (UNESCO–IHP, 1986; Custodio, 2005). A mixing or transition zone develops between freshwater and salt water, whose thickness depends on local conditions and grows with increasing groundwater development. Abundant information can be found in the proceedings of the 22 Salt Water Intrusion Meetings (SWIM), and in a recent issue of the Hydrogeology Journal (HJ, 2010). Although the basics are simple, the behaviour of real aquifers is complex due to the large influence of local heterogeneities, aquifer fluctuations and recent sea-level changes. Seawater advancement is spatially variable and may follow preferential paths through more permeable layers when artificially-induced head gradients are large. This is enhanced in karstic aquifers due to the conspicuous local permeability increase by carbonate rock dissolution.

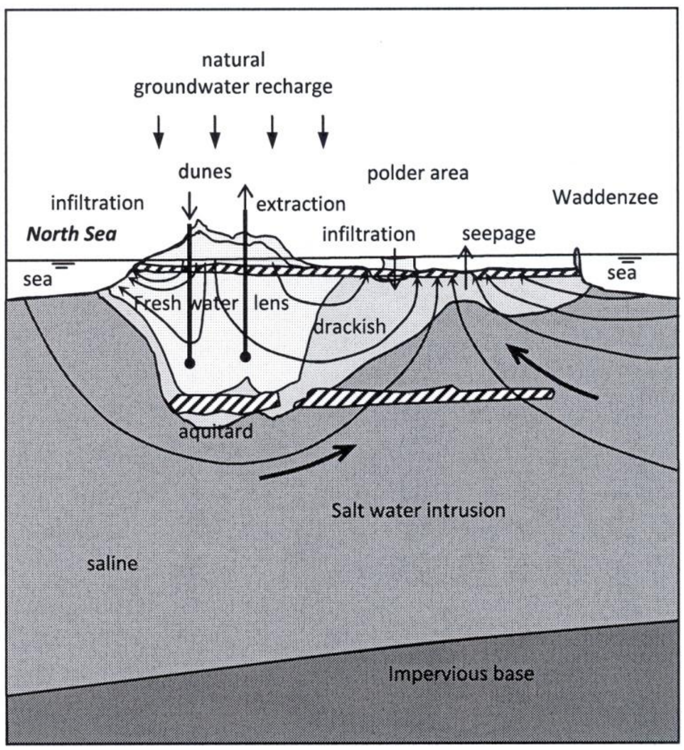


Figure 16. Groundwater salinity in the Rhine delta, near Amsterdam, the Netherlands, due to seawater intrusion in a low–laying, flat area, and the mixing with recharged freshwater in the dune belt and with irrigation water in the polder area.

Many seawater contamination problems are not the direct result of lateral seawater advancement, but are due to water up-coning below wells, drains and excavations, when there is saline water below. This saline water may be of natural origin or the result of the marine water wedge advancement. This creates very complex situations. Even the origin of abstracted water salinity is often unclear, due to mixing with seawater remnants in low permeability parts of recent coastal formations. The infiltration of return irrigation flows may produce similar results. Figure 17 shows an example. In order to screen out the different possible origins, detailed studies are needed. Knowing the right salinity origin and dynamics is important for coastal aquifer governance.

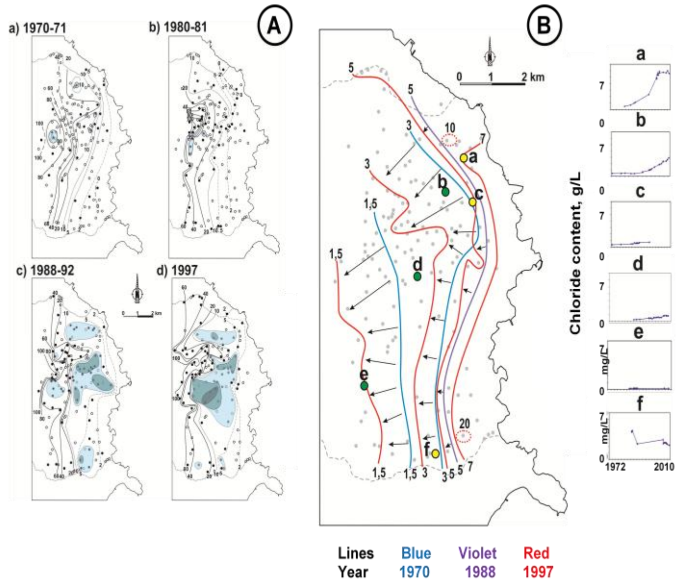


Figure 17. Complex salinization problems in the volcanic and volcani–clastic aquifer of Telde, Gran Canaria, Canary Islands, Spain (after Cabrera and Custodio, 2010). A) the successive figures show the changes of water–table elevation (in metres) due to intensive aquifer development since 1970, when development was already intensive; shaded areas show water–table levels below sea level, 0 m to –10 m; –10 m to –50 m and deeper than –50 m, according to more intensive gray colour; black points show wells currently used to get brackish water for reverse osmosis desalination. B) progress of chloride content; the insets show chloride content evolution in some wells. Salinization near the coast is due to sea water intrusion and up coning, but in the mid inner area it is due to a combination of return irrigation flow and the use of saline water in industrial and urban activities (Cabrera and Custodio, 2012).

Seawater intrusion problems are naturally found in many aquifers worldwide (HJ, 2006; Custodio, 2006; Bocanegra *et al.*, 1992; Cardoso da Silva, 2010), but they are mostly due to groundwater development, with well known cases, such as those of California, Yucatan, eastern USA, the Netherlands, Belgium and northern Germany. Salinity problems in some high-yielding recent coastal formations are important since they supply urban areas without other freshwater sources, as in Mar del Plata, Argentina (Bocanegra *et al.*, 1992) (see Figure 18), or currently as a water source and an important reserve in dry periods, as in the Lower Llobregat area, Barcelona, Spain (Iribar and Custodio, 1992; Custodio, 2012) (see Figure 19).

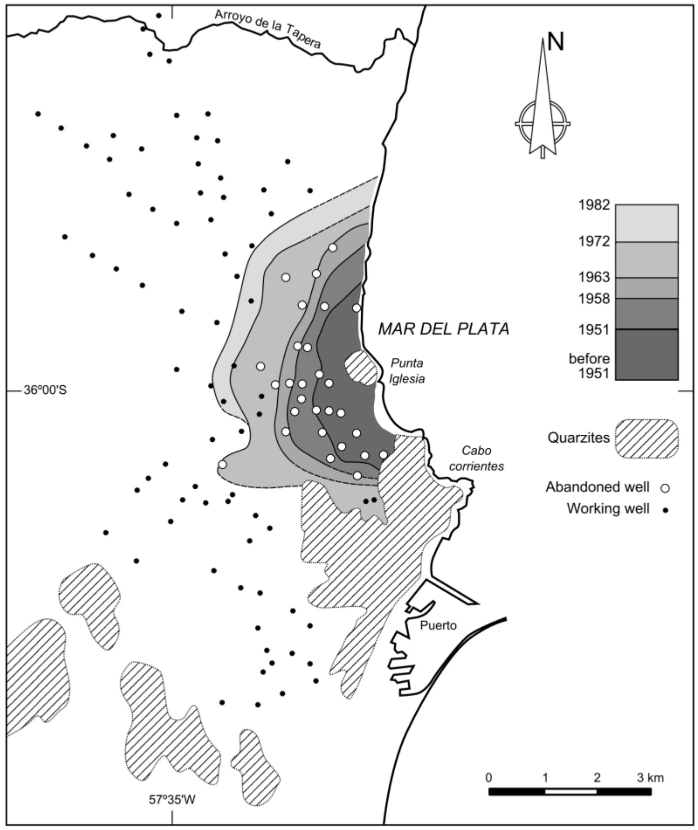


Figure 18. Salinity advancement in the Mar del Plata urban area, Argentina, due to local intensive pumping for supply (after Bocanegra et al., 1992). Due to salinization problems, wells have been progressively moved away from the town, interfering with rural areas. Governance has meant agreements, in this case not a difficult task since there is only a main groundwater user in the urban area. High salinity wells were closed–down in the town area. Tthis was followed by water–table recovery, in this case brackish to saline water, and further to underground space inundation problems, enhanced corrosion is a concern (Bocanegra et al., 1992).

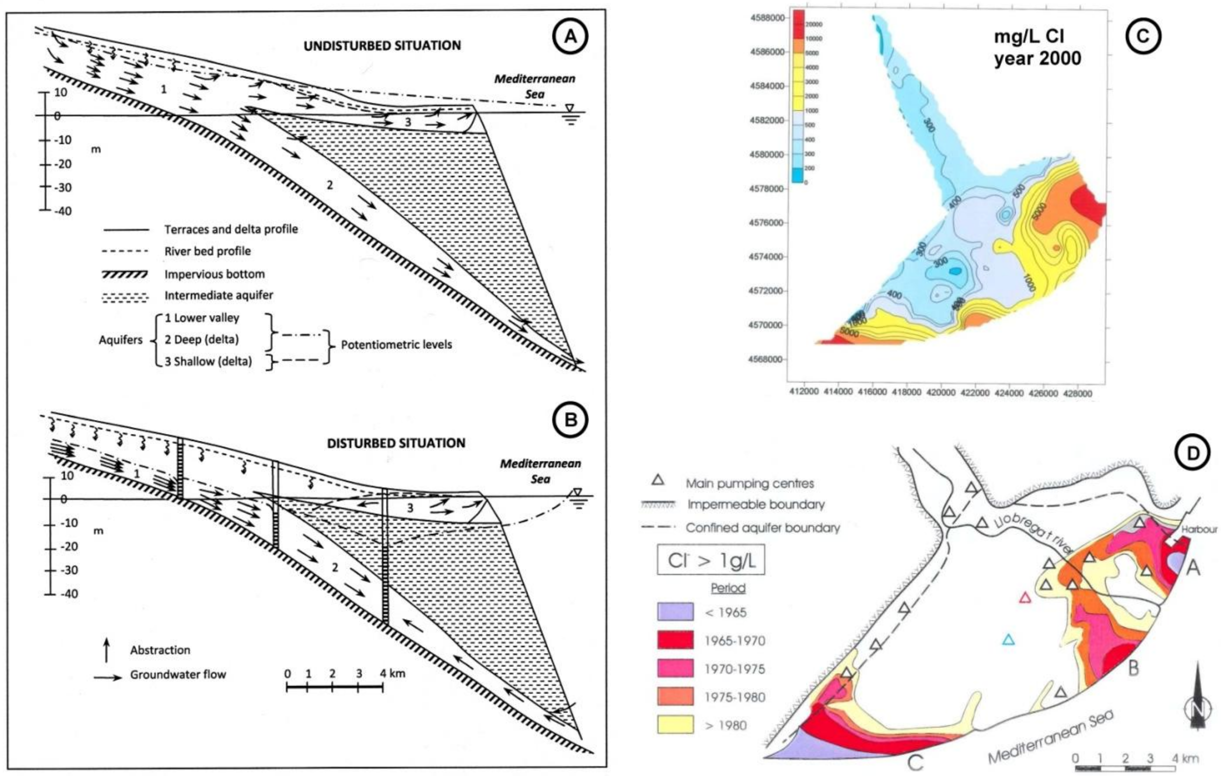


Figure 19. Loss of groundwater quality in the Llobregat River Delta, Barcelona, Spain, due to a combination of progressive sea water intrusion and recharge river water deterioration by potash mining upstream. A) natural situation in the early 1900s; B) situation around 1975, when groundwater abstraction was at its maximum. C) chloride content in 2006 in the delta deep aquifer and the lower valley aquifer (after the Users' Community), which also shows the chloride pollution due to mining activities; D) advancement of saline contamination due to seawater intrusion in the delta deep aquifer (after Iribar and Custodio, 1991).

In coastal aquifer governance, water quality often becomes a dominant concern. Progress has been done in some areas, such as California, the Netherlands and the surroundings of Barcelona. Participation of the involved social sectors and the users is needed, as well as the adoption of rules for safe drilling and well abandonment and of appropriate management techniques, such as abstraction control, redistribution of wells, artificial recharge and hydraulic barriers to limit the seawater wedge penetration. All this has a rather high investment and operation cost.

Deep-seated saline water – often old seawater – is found in many areas of the world, both inland and near the coast. This is a common situation in large areas of northern Germany and Poland, where such water may contaminate wells in these generally well-recharged areas, when wells are too deep, breach clay layers or are excessively pumped. Groundwater quality governance has to take into account the pervasive existence of saline water held in some layers or at depth, and may need limiting well depth, pumping rate and well distribution.

5.6 Groundwater quality related to mining

Mining is an important activity in many developing countries, but also in past or present industrialized areas, and often represents a main national income and a source of employment. It results in multiple point-pollution sources. Tailings, deep and open mine drainage, and mineral transportation and treatment are important sources of acid waters, dissolved heavy metals, salinity and some organics associated to fuel exploitation or used in mineral processing.

These are difficult situations from the groundwater governance point of view since sectoral institutions that are not sensitive about groundwater conservation issues may press to turn a blind eye to risks. Civil society groups are generally effective in introducing environmental responsibility and promote good governance, but this needs time. Clear advances have been produced to control the damage of large territorial activities and constructions, and to act soon after some large accident is produced, but small mining activities are much more difficult to control, thus action at municipal and groundwater users' associations' level is needed.

Oil extraction produces large quantities of salt water and brines, loaded with organics and some heavy metals, which are potential – and in most cases actual – groundwater pollutants. These waters are sometimes infiltrated in nearby aquifers, heavily contaminating them. It may be possible to inject this water, after treatment, into the exploited layers, but if not feasible, injection into other deep saline aquifers is practiced. Current and future leakages are a serious contamination threat to be considered in groundwater quality governance.

Salt mines pose special problems due to the high solubility of the minerals. Halite exploitation is often a rather controlled problem, out of natural leaching of salt outcroppings, since the product is sold or fully used in factories to produce common salt, chlorine and soda. The most important impacts are produced by mines producing potassium chloride – potash – from sylvite and carnalite. These salts need a processing that generate Na–Mg–Cl brines and a large quantity of halite and other salt wastes that are disposed in easily leachable, often poorly protected salt tips. The amount of halite wastes and other soluble minerals may be decreased by backfilling the abandoned parts of the mine, but there is always an excess that goes to tips. Classical examples are the Werra mines in Germany, the mines in Alsace, France, nearby the river Rhine, and those in the middle Llobregat and the Arga river basins in Spain.

Aquifers and rivers can be directly or indirectly heavily salinized. In the aquifers of the Low Llobregat valley, with an important recharge from river water, the chloride content background of about 80 mg/L before 1925 raised up to 600 mg/L in the 1970s when mining started, although it was then lowered to 150-200 mg/L after tight controls in the mining area and the construction of a pipeline to carry and dispose the brines into the sea (see Figure 20). The cost to society due to increased corrosion and poor water quality along many decades is not known, but surely high. Remaining high chloride content in river and aquifer water has recently imposed the application of salinity reduction by electrodialysis and reverse osmosis, at a significant cost to citizens.

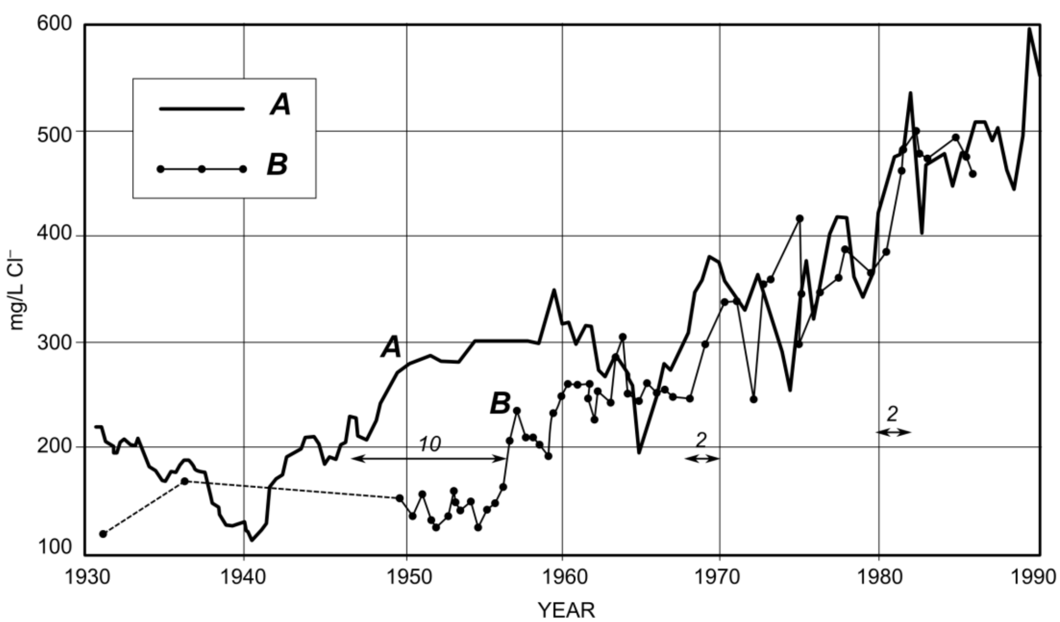


Figure 20. Evolution of chloride contamination in the Llobregat River lower valley, Barcelona, Spain, due to river water pollution, mostly due to upstream evaporite salt mining activities to produce potash. Mining started in the

mid 1920s, stopped from 1936 to 1939 during the Spanish civil war, and resumed afterwards. A brine–pipe constructed in the 1980s alleviated and halted new increases but has not fully solved the problem. Well A is just at the mouth of the delta and well B is about 4 km downflow, in the centre of the delta; in this small, highly permeable, and intensively exploited aquifer system (turnover time of about 2 to 3 years in the unconfined part) the transit time from A to B was about 10 years in the 1960s, and afterwards it reduced to about 2 year when exploitation was at its maximum, and currently is again about 10 years after abstraction reduction, well relocation, and piezometric level recovery.

Abandoned coal and sulphide mines get inundated with water. Near the water table, sulphide oxidation produces high acidity and metal dissolution, mostly Fe. Most of these mines are found in very low permeability formations but contaminated water often finds its way to local springs and aquifers. In the case of carbonate rock the pollution effect is partly tamed due to the pH being raised by carbonate dissolution, although the aquifer becomes contaminated, mainly by sulphate and earth-alkaline cations, but also by some heavy metals that form soluble carbonate complexes or remain in solution while the ambient is reducing. In nearby springs, Fe and Mn precipitate affecting large areas, and wells extract Fe and Mn loaded water.

Highly polluted springs and rivers in metal mining areas, as those in southern Spain, may become a serious groundwater contamination problem when surface water infiltrates the ground in mountainous areas, especially in arid areas. This can be limited by careful mining operation, at a cost. Sulphide mining produces large quantities of sulphide-rich wastes, able to generate highly acidic waters. They are stored in sludge basins, some of large dimensions. They often leak and recharge local aquifers. Some serious breakdowns of such storage basins have occurred, although only a few cases have been monitored and documented in what refers to groundwater contamination and restoration. One such large accident happened in the 1960s in Arizona, near Tucson, and a recent one in Aznalcóllar, south-western Spain (Ayora et al., 2001); this last was reasonably well-controlled after intensive cleaning works, at a high cost, and a strip of land along the river was expropriated to avoid the use of potentially polluted groundwater containing heavy metals for drinking and irrigation purposes, and is currently an ecological corridor along the river to connect two ecologically important areas.

Mining for construction materials (cement, rocks, ornamental products, gravels and sands) are important activities near urban areas and populated areas. Many of them are practiced in river valleys by extracting and processing alluvium. These sites are prone to pollution due to the use of oils, the breaching of the soil cover and the inflow of surface water. However the main risk is when the pits are later on filled with materials, such as demolition wastes or soils from others excavations – often called "inert" although they are really not –, and also with urban refuse and industrial wastes. This is not rare when controlled disposal sites are not available or too expensive, environmental control is poor and wastes are given to non qualified, uncontrolled and even suspected firms. This is a main concern around large towns, especially in developing countries.

Often mining is artisanal (informal), carried out by small groups, which lack technical support and rarely care for the environment. They may produce serious pollution sources. In the case of minerals in alluvium and sediments (called *placeres*) large earth movements are done and large volumes of terrain and wastes are exposed to air and water, thus accelerating oxidation and dissolution processes. Many of these activities are for gold mining, and to recover it quicksilver (mercury, Hg) is used to amalgamate gold. The resulting environmental pollution by Hg is a serious concern in many areas in Central and South America.

For old abandoned mining operations of very diverse kinds and size, the responsible person or entity to restore and redress damage on groundwater may not be found or may lack the required financial resources. In this case, society has to subsidarily assume responsibility through public investments, mostly funded by general taxes. This may be unaffordable for poor areas, which often need not only external technical assistance but also funding.

In arid areas, such as those in the central Andean region, mining needs large water supplies for ore processing and transportation through pipelines, and often scarce local groundwater resources are used. It is not rare that these intra-montane basins be closed, ending in salt flats (called *salares*) in which brines form. The high density of brines favours an extensive deep layer of saline water (Figure 21) that easily spread due to groundwater withdrawal for the supply of mining activities, thus producing salinization, further to spring-flow decrease.

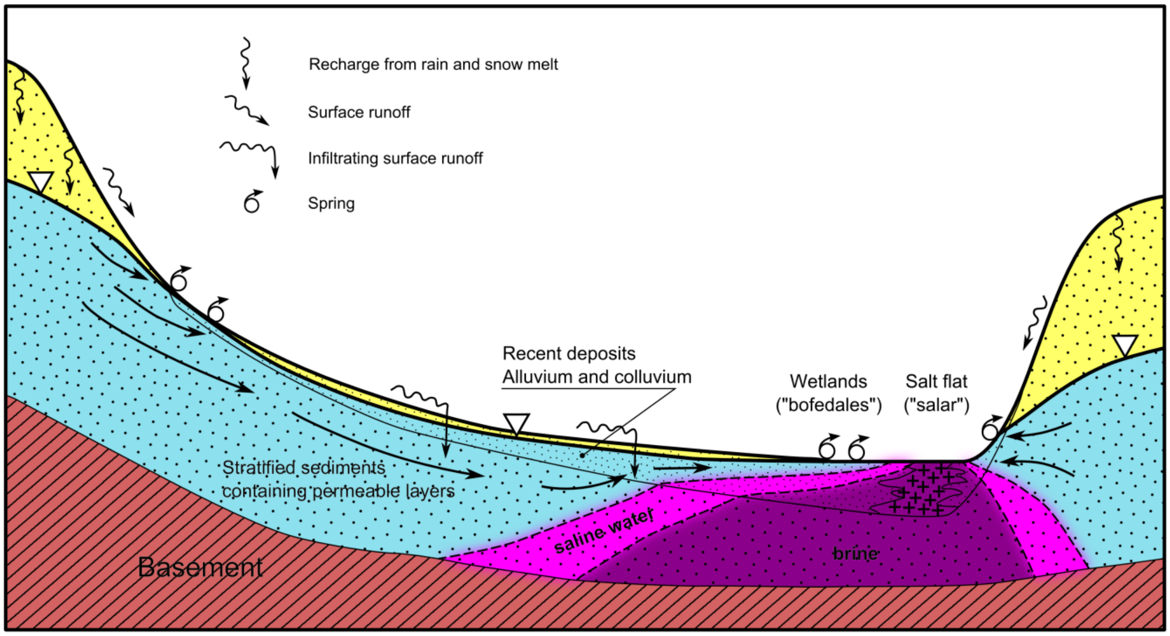


Figure 21. Schematic cross–section showing a closed basin ending in a salt flat ("salar") with surrounding wetlands. Inspired in the high altitude, intramontane Andean basins of northern Chile. Dense brines tend to expand over a large area and are easily mobilized when groundwater is developed, especially following permeable horizontal displacement faults along these basins.

Similar comments on groundwater quality governance as those in Section 5.7 apply. Action at municipal level is a key issue since this is generally the responsible level in many legal frameworks. However, large mining activities are of regional and national interest, being a source of large incomes and, in some case, of widespread corruption. Governance needs clear legislation, political will, good information and training (both at central and municipal level), as well as means to deal with external pressure when supra-municipal interests are at stake. However, at municipal level norms have to be based on and supported by wider-scale legislation, an efficient justice and police system and political commitment.

5.7 Groundwater quality in areas subject to waste-water discharges

Urban and peri-urban areas, including associated industrial areas, are mostly subject to waste-water discharge. Groundwater conditions in such areas are rather different from those found in natural, rural and agricultural areas. Since land surface is compacted and largely paved, a common assumption is that rainfall recharge highly decreases and converts into surface runoff. This is only partially true since experience shows that recharge continues to be high and even greater than it was previously, mostly due to losses from water distribution and sanitation networks, irrigation of green areas and infiltration of local runoff (Chilton *et al.*, 1997; 1999; Foster *et al.*, 2011). This has a clear influence on local groundwater quality (Bruce and McMahon, 1996; Custodio, 1997; Vázquez–Suñé *et al.*, 1999). The issue is partly addressed in Section 5.1. Mining for construction materials is a related issue, as commented in Section 5.6.

Municipal wastewaters are characterized by high organic contents and some salinity increase with respect to supply water. This water may significantly contribute to aquifer recharge, especially in areas with old, poorly maintained sewage networks.

In poorly controlled areas, municipal refuse and urban wastes are often disposed by dumping into excavations, mostly sand and gravel pits. Local authorities often argue that if wastes are not in direct contact with the saturated zone, groundwater pollution does not occur. Albeit, rain percolates easily through the wastes since, in most cases, a true impervious cover is missing. This percolating water leaches solutes and organic matter in an often highly reducing ambient. Thus, water recharging the aquifer is often highly contaminated and possibly loaded with heavy metals, boron and poorly degrading and persistent organics, such as chlorinated solvents and mineral oils (see Section 5.1 for further details). A heavily polluted plume may develop and move down-flow, which sinks advectively into the saturated zone due to the flow-lines pattern, and sometimes due to buoyancy forces when there is a salinity/density difference. Some components decay anaerobically, producing CH_4 and NH_4, decreasing SO_4 and increasing Fe(II), until progressively less reducing conditions are found downstream and laterally, as the plume disperses and mixes with aquifer water. Some pollutants may disappear gradually due to natural processes, but often what is considered decay is really dilution.

In well-designed sanitary fillings, it is assumed that percolation is very small due to the stratification created by alternating clay layers, and what penetrates is drained for treatment. Unfortunately, this is not always the case, and what are called clay layers may actually be rather permeable and cheap local materials. Thus deep recharge is produced, and no or little leachate is collected, which is wrongly perceived as a good result that eases drainage water treatment. The aquifer below may become highly contaminated and after some time – often a short time in karstic and fractured rocks – may affect down-flow wells, springs and rivers. Local climate plays an important role in leachate composition. In some protected sanitary fillings, especially under dry conditions, the leachate may be highly saline and may contain high dissolved organic matter concentrations.

Industrial wastes are as diverse as industrial production is. The most polluting activities are paper mills, textiles, tanneries, mineral oil refining and chemicals and food processing. Small factories may pose a problem when poorly controlled – as is often the case – since they tend to dispose their liquid wastes by infiltrating them or dumping their solid wastes in excavations as filling materials. Especially concerning are small platting industries using chromates and other metals, often dispersed in peri-urban areas pits and backyards.

Many factories using, producing and disposing toxic substances move from industrialized areas to developing countries and poor areas, where environmental restrictions are loose, not enforced or just lacking. This is a serious concern for groundwater quality in these areas. Contamination may go unnoticed or concealed for a long time, thus creating difficult and long-lasting health and social problems, of very difficult and costly solution, if feasible at all.

Groundwater quality governance should include and address these issues, which may involve complex situations due to the many interests around. Often governance should relay on a higher level of decision and policy.

Part 2. Diagnostic

6. Constraints to Groundwater Quality Governance

Constraints refer mostly to groundwater quality governance and management limitations. In most cases, scientific and technical shortcomings are less relevant than institutional, human and economic ones, as commented in the following sections.

6.1 Constraints due to knowledge and monitoring

Basic science and technology are generally not a limitation for groundwater quality governance, but aquifer knowledge and their functioning under existing conditions, as well as monitoring of the relevant variables are. Monitoring is expensive and has to be suited to the actual groundwater quality and pollution problems to be addressed according to their relevance. Monitoring may be a serious constraint in many areas, especially developing ones, due to the cost of staff training, data processing and knowledge sharing with society, without which monitoring loses most of its intended impact. On the other hand, since monitoring is cheaper than many public activities and undertakings, investments do not attract the public and mass media, and also difficult to show,i so it is less politically and personally rewarding. This explains why studies and monitoring do not have the consideration they deserve and are often subject to budget cuts when economic restrictions have to be applied. This is currently the situation in some aquifers of Europe, where in order to reduce expenses only what is expressly required by law is carried out. However, the existence of mandatory minimum requirements and their enforcement are an important step towards good groundwater quality governance. The adoption of compulsory minimum requirements and the availability of means to comply with them may be a challenging task in developing countries, but should be a clear objective to be accomplished, when necessary, with the help of external assistance.

Groundwater quality assessment often suffers from poor, incomplete and biased information. This is due to lack of representative sampling points, poor understanding of groundwater, scarce trained staff, insufficient financial resources and the localized nature of pollution sources. Natural and diffuse contamination is easier to detect than point pollution, due to the widespread effects it produces. However, its impact may appear slowly and highly delayed. In any case, knowledge of the vertical distribution of pollutants is a difficult task due to the general lack of dedicated deep sampling points. Currently, water samples from long- and multi-screened boreholes are composed of mixed waters from different depths – probably ignoring the deepest layers due to insufficient penetration and isolation. Consequently, during pumping to get a sample, water from contaminated layers is diluted with that of other layers. This produces a distorted and misleading image of actual contamination.

Transparency in action, programs, spending and accountability is appearing as a major issue to create trust and confidence, and its lack is often identified as a mayor constraint to governance. Experience is scarce and at most first steps are being done out of a few countries, such as the USA, and is seriously promoted in the EU, but still not fully developed. However there is little practical experience in groundwater quality transparency.

6.2 Constraints due to staff

Groundwater knowledge, monitoring and management need specially trained personnel, not only hydrogeologists, but also experts from other branches, such as engineers, environmentalists, biologists, chemists, economists and lawyers. Moreover, trained technicians and field staff with good knowledge of the territory and of local institutions and people are essential. This is often a serious human and economic constraint in many cases in developed countries and a major drawback in poor developing countries. Education on groundwater quality governance should start at school level, as well as from specialized training and informative courses for medium and high level stages, with special emphasis on the local issues to be dealt with. Finally, employment stability of field personnel and the availability of sufficient operative means are key issues for groundwater quality governance.

6.3 Constraints due to institutional barriers on knowledge and action

Governance relies on government institutions, as well as on other institutions of the civil society and water users, with convergent goals and common interests. These institutions need adequate knowledge, sufficient staff, means to act and a legislative umbrella. Problems for groundwater quality governance arise when institutions do not exist, have poorly defined roles or lack sufficient resources. This is the case of many developing countries, but also of developed ones when institutions are weak, not interested in groundwater issues, sectoral, or politically controlled. But even with sound institutions, some barriers may appear.

Different institutional barriers hinder the knowledge of the contamination status and of pollution sources of an aquifer system. The lack of interest in groundwater issues is due to poor understanding of groundwater importance and of its long-term and delayed behaviour. This happens especially when people in charge of groundwater management are engineers trained in operation and management of surface water works, but not in groundwater management, water quality and governance. This is the case of the personnel of some traditional water authorities who are good professionals in their training fields, but not in the new responsibilities. It may happen that even knowing their limitations, they tend to act cooperatively and often reject other professionals to keep privileges or to preserve their jobs. Things become more complex when groundwater is privately exploited – legally or in practice – without due regulation. Often engineers, managers and decision makers – including politicians – erroneously assume that groundwater management is a 'private affair' that does not fall into the competence of public administrations, thus ignoring or neglecting surface water–groundwater relationships and the importance of groundwater itself. They rarely realize that a common pool resource of great social relevance is at stake and that issues affecting groundwater will eventually affect surface water as well, and *vice versa*.

Barriers are more severe when other water administration staff are involved, such as lawyers and economists, who are generally not aware of groundwater characteristics. Groundwater and its characteristics are often inadequately, erroneously or not at all considered in norms and laws. In most countries and regions, the poor consideration of long-term, delayed and progressive effects constitutes a major barrier that does not allow the adoption of appropriate governance arrangements to deal with groundwater contamination and pollution.

The above-mentioned circumstances are barriers that hinder the adoption of protection measures unless there is a specific legal mandate to do so. If no legal obligation exists, action is taken – when possible – only when the problem is noticed, which often happens when contamination is at an advanced stage of contamination. Further barriers are related to the different sectoral institutions that intervene: water, environment, housing, agriculture, forest, industry, tourism, land-use planning, transport, etc. These institutions are often poorly interconnected and have their own sectoral goals and priorities and they do not only often disregard the possible side-effects of their actions, but they also try to dominate the scene, disregarding other circumstances.

Good governance requires a higher-level coordinating institution and wide-scope legislation. Deviations and conflicts should to be solved as fast as possible by agreements, with the help of the coordinating institution, instead of resorting to administrative and civil courts. Even in developed countries, court decisions are commonly slow and often come late, when the problem has worsened and remediation has become costlier or unaffordable. In some occasions, a court may impose the halting of existing groundwater withdrawals until some quantity of quality problems that has appeared are studied and documented and solutions drafted; this may become an added burden to groundwater developers and may worsen an existing situation.

6.4 Action to deal with groundwater pollution

In case of serious contamination impact, action should be taken, in particular to control the contamination source, although in some cases the source may have already disappeared or may have been modified earlier in time. Remediation is often required, but is a costly operation – hardly affordable in developing countries – that may lead to poor results if not carefully done. In certain cases, remediation is just unfeasible (Norris *et al.*, 1994; NRC, 1993, 1997, 2008; Pankow and Cherry, 1996; Barcelona, 2005). Remediation rarely works for diffuse pollution, except locally by enhancing and creating non-contaminated groundwater bodies through enhancing natural recharge or through artificial recharge or managed aquifer recharge (MAR) (Fernández Escalante and San Sebastian Santo, 2012).

For contaminated aquifers, the action proposed is often the abandonment of the aquifer for the intended use, although other uses may continue if they do not worsen the situation. However, action is needed to prevent further progress of pollution and the spread of contaminants. The abandonment of a given groundwater resource implies cutting on water demand or looking for other local or imported freshwater resources – generally at a higher cost – and the introduction of protection measures to preserve these new sources. In some cases, in-the-aquifer treatment or the construction of reactive barriers are possible actions for pollution abatement, but they are not easy to implement and operate. Costs are often high and failures are frequent. Advanced groundwater legislation – as in the USA (where EPA is the responsible authority) and in the EU – is generally against aquifer abandonment and requires remediation, but in practice implementation may be too costly or too slow. Thus, exceptions have to be admitted on grounds of disproportionate social and local costs. This is still a poorly developed area of water legislation. The situation may become critical when norms do not exist or are not applied, as is the case in many developing countries, thus creating these norms – and ensuring availability of the means to apply them – is an essential step for good groundwater quality governance.

6.5 Protection areas in groundwater quality governance

Protection areas can be defined for the conservation of drinking groundwater sources. In such areas, human activities are limited and special cautions are introduced to avoid contamination (Figure 22). Protection areas are provided for in the legislation of many countries, mostly in North America and Europe, where rules are established for the definition of such areas (Martínez-Navarrete and García–García, 2003). Methods vary from those based on hydrogeological maps to model-assisted methods, following conceptual developments (Foster and Skinner, 1995; Matthess *et al.*, 1985; Hirata and Rebouças, 1999). The establishment of protection areas may involve restrictions on private property and on permitted activities. Consequently, their application and enforcement may become highly controversial and generate legal disputes between landowners and government institutions. The definition of a geographical boundary may become a challenging task, especially in karst and fissured rock areas. Limitations refer mostly to water-table aquifers. The application to confined aquifers is more complex and less experienced; it depends on groundwater transfer times and involves drilling norms, and their enforcement.

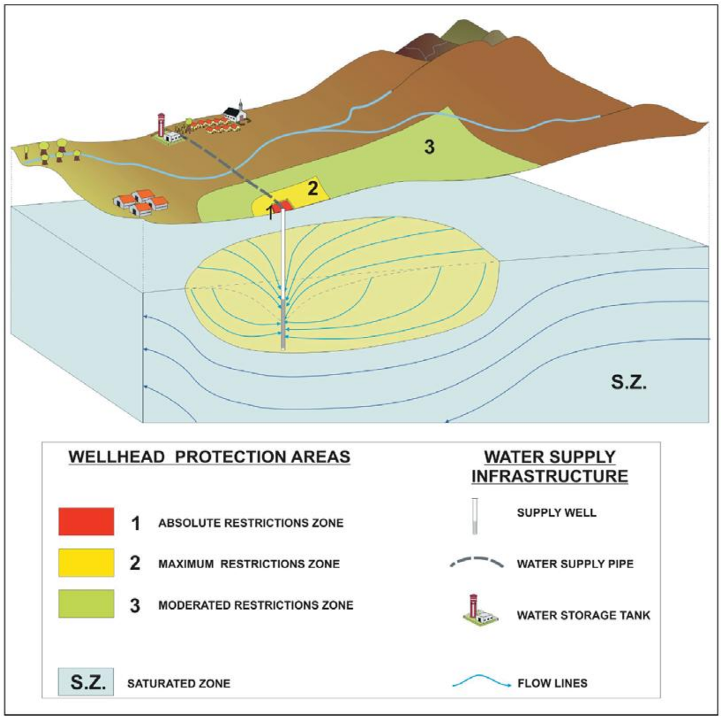
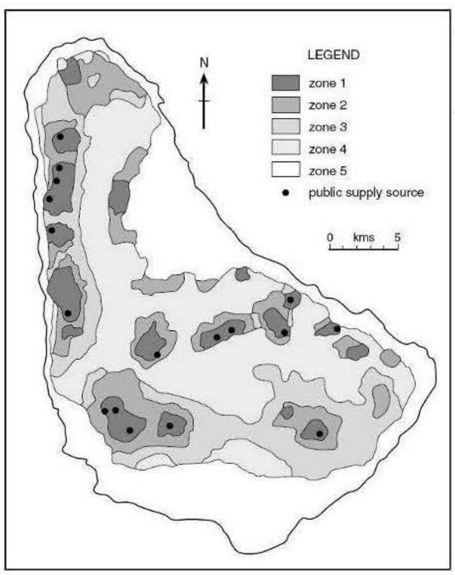


Figure 22. Schematic representation of well–head protection areas and their zonation (after Martínez Navarrete and García García, 2003).



Zone	Definition of outer boundary	Maximum depth of soakaways	Domestic controls	Industrial controls
1	300 day travel time	None allowed	No new housing or water connections. No changes to existing wastewater disposal except when Water Authority secures improvements	No new industrial development
2	600 day travel time	6.5 m	Septic tank of approved design, discharge to soakaway pits. Separate soakaway pits for toilet effluent and other domestic wastewater. No storm run-off to sewage soakaway pits. No new petrol or fuel oil tanks	All liquid industrial wastes to be dealt with as specified by Water Authority. Maximum soakaway pit depths as for domestic waste (column 3)
3	5-6 year travel time	13 m	As above for domestic wastewater. Petrol or fuel oil tanks of approved leak proof design	
4	All high land	No limit	No restrictions on domestic wastewater disposal. Petrol or fuel oil tanks of approved leak proof design	
5	Coastline	No limit	No restrictions on domestic wastewater disposal. Siting of new fuel storage tanks subject to approval of Water Authority	

Figure 23. Example of groundwater protection areas in Barbados Island and explanations (after Chilton et al., 2006; Margat and van der Gun, 2012).

There are initial successes to define and enforce groundwater protection areas in some countries, like Germany and the United Kingdom. An example for an island is given in Figure 23. However, the establishment of new areas may prove difficult once people, social and private institutions and the public administration become aware of the limitations, costs and handicaps protection areas involve.

In many countries, the definition and the enforcement of protection areas have not progressed due to inadequate legislation, difficulty or incapacity to enforce restrictions – within and outside the public administration – and lack of means. The implementation of protection areas requires mobilization of important staff and economic resources to compensate for disproportionate charges and to maintain monitoring and control. This is difficult to carry out without close involvement of municipalities and groundwater users – not only those extracting the water to be supplied, but also the other aquifer users and stakeholders. Lack of social involvement and means explains the poor success of this management measure in many countries in spite of existing regulations. The number and dispersion of small supply systems renders the matter even more complex.

The establishment of protection areas for mineral springs and spas has been more successful, possibly for regarding often scarcely populated areas and for attracting powerful interests. Often such activities are under the responsibility of mining authorities, without involving water authorities. The former have traditionally been more successful in enforcing the rules, especially in Europe, but failures due to poor control are found in other countries, such as Argentina and Brazil.

6.6 Socio-economic constraints on groundwater quality governance

The main socio-economic constraints arise from the fact that neither the quality nor the quantity of water in nature are given any economic value, taking into account the ecological services provided and the opportunity costs, as is the case for many common goods. Water only takes on economic value once it has been appropriated for use, without considering its intrinsic worth in nature. Ensuring good quality of the appropriated water arises from the potential to trade it, at a sale price reflecting its quality. On the other hand, ensuring good quality for a common resource is problematic because the externalities referred to its use are not taken into account. Such are the need for adding treatment or the early deterioration of equipment.

The big challenge for good groundwater quality governance is to identify arrangements to claim externality costs while ensuring good quality. The EU Water Framework Directive obliges to take into account all costs, but this is still insufficiently developed in many of the member states, especially for agricultural uses. Government, institutions and society have to be aware that, because groundwater is important to the environment and the services it provides, its development affects them both. Economic evaluation is needed, although this is a difficult task. Economists have developed means for quantity and – less frequently – quality assessment of damage to ecosystems, although some basic issues are still under discussion (Esteban and Albiac, 2011).

Social constraints are important, such as the attitude of people and their institutions with respect to groundwater contamination. Having properly trained and empowered personnel, as involving groundwater users and stakeholders, are also essential. But the economic component is usually a dominant issue in most implementation processes. Resources are needed for adequate monitoring and data processing, to establish protection areas, to eliminate pollution sources or to find, develop and protect alternative water resources. They are also required for remediation, for public training and information, and for the support of users' involvement. Due to the lack of funds in developing countries, groundwater quality impairment is likely to continue leading to the progressive loss of their natural heritage. A serious and accepted technology to deal with these problems, as well as initial foreign funding or subsidies may be needed, but should not become a source of corruption or produce "wicked" results.

The effective application of the "polluter pays" principle in water quality governance relies on strong political will. It can be readily applied in urban and industrial environments, especially when water supply and sewage networks exist. However, the effective application in other circumstances may be difficult or unfeasible. Its application to groundwater and agricultural water use is particularly difficult, since the cause–effect nexus does not readily appear to people, and pollution appears delayed, progressive and difficult to be noticed early if adequate monitoring is not available.

A further problem is how make "polluters" pay for the damage they produce or will produce. Applying the collected fees and fines to improve knowledge, monitoring, aquifer conditions and the environment may induce payers to comply with new restrictions, as they feel their money is being correctly used and in their own benefit, instead of just supporting the burden of an increasing bureaucracy or used to pay for for other unrelated purposes. With specialized technical and legal support, funds for the prevention and correction of pollution may be established – under existing water authorities, or specialized public or private institutions – with the contribution of taxes and fines paid by the polluters.

From a global point of view, strict application of the polluter-pays principle in one region may generate local socio-economical problems – probably less than the long-term damage from pollution, depending on the applied discount rate – and may favour the transfer polluting activities to other regions with looser regulations. This happens as factory translocation to other more permissive countries and importation of foods.

Virtual water is the water that has been consumed in a given area to produce goods that are traded between countries or regions (Allan, 2009, 2010; Hoeckstra and Chapagain, 2008), mostly importation of food, but also fibers and a log series of minerals and manufactured goods. Virtual pollution" could be considered the water quality and groundwater quality loss due to the production of the traded goods. Virtual water trade is increasing worldwide and currently part of the economy of many areas is based on adding value to imported products that carry with them a large quantity of virtual water. This is an important issue in global and regional water governance, which involve groundwater quality aspects as well.

7. Scope for Securing Social and Environmental Benefits through Governance

7.1 Basis for groundwater quality governance

Impaired groundwater quality is a serious social and economic loss of water resources, ecological services and heritage. This may be more difficult to recognize and more pervasive than water quantity impairment, even in arid areas. To avoid further deterioration, it is necessary to remediate and protect what is still unaffected. Appropriate water and land-use management measures are needed, in the framework of well-prepared and accepted water management plans, and under clear and enforceable laws and norms. Groundwater governance must ensure the participation of civil society and stakeholders' institutions, which should co-operate and accept their specific responsibility.

Groundwater quality governance partly relies on direct action to control and reduce pollution (Table 3) and partly on "soft" action for prevention.

Pollution source		**Possible control method**
Landfills		Regulation of sitting, operation and closure Monitoring the site
Underground storage tanks		Periodic inspection Pressure testing Improved construction
Spill, leaks, improper disposal of hazardous wastes		Control of distribution and use Storage regulations Effective fining of malpractices Mandatory inspection of: ● transportation ● storage ● use Fast removal of spill damage Monitoring the facility
Agrochemicals: ● fertilizers ● pesticides ● herbicides		Introducing good agricultural practices: ● application limits ● timing of application ● application methods ● permits for use Ban dangerous substances Control the disposal of used containers

Feedstock wastes		For intensive farms: ● sufficient storage facilities ● document waste use and disposal ● control of pharmaceuticals use For extensive farms: ● Limits to animal spatial density
Septic systems		Regulation of ● sitting ● installations Periodic inspection Licensing installers

Table 3. Some methods for controlling pollution sources to be considered for groundwater quality governance

Governance of groundwater quality issues is highly influenced by the poor integration of groundwater users and other stakeholders, and by the poor coordination among water authorities, regulators and those responsible for the environment. This is a key issue for securing social and environmental services and for hindering negative actions, but there are some peculiarities about groundwater compared to other water resources. Aquifers occupy a large territory that supports dispersed human activities, economic and social interests, traditions and practices, often supplying a large number of groundwater users.

A first step in governance is to assure that users and institutions understand that common interests are at stake. The aquifer is a common-pool water resource and heritage, a source not only of water but also of ecological services to be preserved to a reasonable extent, in a win-win mode. Governance is needed to explicit the common benefits. Based on this, new steps can be taken. Top-down actions are seldom effective since groundwater users tend to be suspicious about the final goals of government's and top level persons, and thus try to avoid compliance. It is not rare that they hide and behold information, and even cheat, especially when they suspect there is political manoeuvring and alien personal interests, their rights may be cut down, or new taxes and charges are expected. Building institutions is a necessary second step. Involved agents have to understand the slow, delayed, long-term behaviour of groundwater, and act accordingly.

The subsidiarity principle –a basic principle in the EU– should be generously and effectively considered, besides other governance principles, when they apply: equity, solidarity, participation, prevention and precaution – to avoid large or irreparable damage, but without a paralysis through analysis. The subsidiarity principle states that what can be better done at a lower level, closer to society and individuals, should not be done a higher level. Decentralization should be promoted as well as staff training and qualifications. Concentrating decisions and power in high administrative levels, particularly when unqualified, leads to widening the governance gap – especially when referring to groundwater quality –, thus increasing mistrust, giving a poorer social service by cutting on benefits and increasing costs, and leading to a progressive and often irreversible loss of natural values and their associated services.

Groundwater quality governance is deeply related to and relying on groundwater ethics – including moral and religious principles –, a modern subject in development (Llamas and Delli Priscolli, 2007; Llamas *et al.*, 2009; Custodio 2010b) and an UNESCO and IAH priority subject.

7.2 Monitoring for groundwater quality governance

Good monitoring is an important issue for water governance, and especially for groundwater quality. Without reliable data it is not possible to understand and valuate real situations and make reasonable forecasts on the evolution and the involved economic, social and political costs. Produced data have to be retrieved, treated adequately and made available and usable to regulators, decisions-makers and stakeholders. Many recent and effective tools are available. There is wide body of scientific and technical knowledge (Everett, 1987; Condesso de Melo *et al.*, 2007; Rouhani and Hall, 1998), although local situations and economic and human resources play a key role. This is the case of the Doñana National Park aquifer system, in southwestern Spain (Manzano *et al.*, 2009).

Even if good data retrieval technology for monitoring is available, a main problem is the need to cover a large territory, with a rather low sampling and measuring frequency. This is quite different from surface water. The need for trained teams and for a large number of boreholes and observation points spread over a large territory make monitoring expensive, especially for deep aquifers. In the case of point pollution of groundwater, the cost is high due to the need of a dense monitoring network able to follow the pollutant movement, which often needs a 3-D point of view and the support of some modelling.

Sampling may be simple or expensive, although the appropriate technology is generally affordable. Obtaining reliable and representative water samples is key to good monitoring. Existing wells and boreholes and large springs generally yield a groundwater mixture whose interpretation may be difficult and may lead to biased results. Well-trained personnel is needed, with the advice of senior hydrogeologists.

Well-trained and adequately equipped institutional staff is needed for surveillance and maintenance. For groundwater quality, this is often a heavy burden that the authorities may successfully share with trained local people, entities and communities, cooperating as part of their duty to preserve groundwater quality as their heritage, even if using simple methods.

There are many water quality parameters to be considered for monitoring. A what-to-do list should be tailored to each case. Many of these parameters are rarely obtainable automatically, and need in-the-field sampling and in-lab analytical capacity. The required measurements need to be carefully designed to reduce costs and personnel. A common practice to save money and effort is using easy-to-get proxi and lumped water quality parameters to detect changes, but some studies are needed to show they are able to yield the wanted monitoring results.

Groundwater quality monitoring is generally focused on single aquifers. This is often enough but in some cases monitoring has to be extended to other related aquifers, aquitards – e.g. for saline water bodies displacement or inter-aquifer pollution transfer – or the unsaturated zone – e.g. to follow downward movement of diffuse pollution or the depletion of non-aqueous separate phase pollutant accumulations (NPLs), such as oil and organic solvents. This detailed monitoring is expensive and needs specialized teams, but is often needed for groundwater quality remediation and management. Unfortunately, this is an expensive activity for poor areas that often proves difficult to implement. In some cases undertakings that have the capacity to control the groundwater contamination produced by them, try to not comply by using legal subterfuges or by corrupting officials. A large governance effort is needed to redress this, when this is the case.

To make people aware of local groundwater being naturally unsuitable or inconvenient for some uses, and especially for drinking and food processing, specific information must be made available to them. This should be prepared carefully to call the attention and promote action, but avoiding undue alarm and irrational rejection. Education is important. Information is needed to progressively introduce the basic knowledge and understanding of real risks, how to avoid them, and the alternatives compatible with current situations. These tasks are not easy and need communication specialists who understand the problems, know how to explain them to laymen, and are able to achieve co-operation and involvement instead of confrontation. There are some experiences in different countries, such as Mexico, India, Bangladesh and Argentina.

7.3 Institutions and users' involvement for groundwater quality governance

Governance depends on effective institutional relations between the government and the users. When institutions do not exist, a first step is promoting them. These institutions, both authorities and participatory ones, make government action more effective (Hanak *et al.*, 2011), especially in groundwater management, and improve relations with users (Pahl-Worst *et al.*, 2008). Well-designed institutions are needed to avoid administrative slowness and other legal hindrances, as well as to facilitate adaptive evolution (Hanak *et al.*, 2011). However, institutions are not always successful in groundwater management (Howe, 2002), particularly in what refers to groundwater quality. Failure is mostly due to inadequate or unenforced legal framework, economic constraints and behaviour of persons at the top decision level.

The need to involve governmental institutions in groundwater management is a current subject of debate. The Gisler–Sánchez effect (Gisler and Sánchez, 1980) shows that these institutions are not needed and that the same final economic results are attained under unrestricted competition. This refers mostly to groundwater quantity under unbounded conditions, but in most real cases limits have to be taken into account, and then some extent of governmental control is advisable to reduce social costs (Esteban and Albiac, 2012). No detailed studies taking into account groundwater quality and the related externalities are known. Since there are clear restrictions, public control should probably appear as the optimal solution.

The dialogue between water regulators and groundwater users has been and is often poor or inexistent. This is partly due to water regulators being poorly involved in groundwater issues, especially on what refers to groundwater quality. Another reason is the existence of many dispersed and unrelated groundwater exploiters – a large number of wells –, often unaware of groundwater quality problems or at most having a myopic vision of reality. In many cases, top-down public information campaigns and discussion forums at local level –more rare– are the easiest way for the water administration to make contact with small groundwater developers and users, while direct contact is more likely in the case of large water supply companies and municipalities in charge of their own supply. To solve this lack of links, groundwater users should be organized and have democratically elected – following local rules– and trusted representatives. Currently, this is a difficult task due to lack of experience, individualism, mistrust and poor knowledge of users. Information on existing problems and on possible solutions is required to raise awareness about the need to protect aquifers as a common heritage. Collective action is especially needed to control non-point pollution (Esteban, 2010).

Creating the conditions to involve groundwater users is time-consuming, as local practices must be honoured. The task should be conducted bottom-up instead of being the result of often suspected and rejected top-down decisions and regulations. However, should public support be needed at the start, it should be provided discreetly. Good examples are the several decades old experience in California (Box 5), and more recently that of Arizona, USA. Other successes already exist (Custodio, 2010a), with different backgrounds and tailored to local situations and interests, as in Mexico (Guerrero, 2000; Foster *et al.*, 2004) (Box 6), India (Krest and Vincent, 2001), and Spain (Aragonés, 1995; Codina, 2004; Hernández-Mora *et al.*, 2010) (Box 7). It is important that these institutions act transparently and pursuing clear and agreed goals. Otherwise they may lose a large part of their potential, as is the case of part of the numerous Groundwater Technical Councils in Mexico (Webster *et al.*, 2011), in which federal government, local authorities and users' goals are poorly related, and users representation is often biased toward large corporate groups.

Box 5: Groundwater governance institutions in California dealing with seawater intrusion

In California, landowners have the right to extract as much groundwater as can be put to beneficial use. The State cannot directly manage groundwater according to the California State Water Code. Agencies, adjudications and districts have been created under special legislation to allow users to manage groundwater inside their boundaries. Currently there are 12 districts, not all of them involved primarily in groundwater quality. Tasks vary from agency to agency, from monitoring to limiting extractions, including water imports to alleviate nitrate pollution and seawater intrusion problems, or to agree in exporting groundwater to other areas.

Orange and Santa Clara Valley Water Districts have carried out and operated aquifer recharge facilities in which imported water, and in some areas highly-treated municipal waste waters, are upgraded to drinking water standards, and then stored underground, partly to mitigate seawater intrusion problems.

The Los Angeles County Water Replenishment District has a long experience in operating artificial recharge facilities and seawater intrusion barriers since the 1960s, in order to improve conditions in the Central and West Coast basins.

Box 6: Collective groundwater for governance: the COTAS of Mexico

The central region of Mexico has a large population, well-established irrigated agriculture and important industrial developments. Groundwater is crucial for supply in the 192 000 km^2, high altitude, partially closed basin on the Lerma-Chapala river basin, in a semi-arid environment. It extends over five states, including the Federal District of Mexico and the State of Guanajuato to the north. There are about 100 aquifers that are considered over-drafted.

In order to foster better groundwater management at the local level, with more stakeholders' involvement, the *Comisión Nacional del Agua* (CNA, National Water Commission) promoted and supported civil society organizations called *Comités Técnicos de Aguas Subterráneas* (COTAS, Technical Groundwater Committees) in 1992, with the goal of helping to address local groundwater resource management. About 70 COTAS were created. A few can be considered successful but many others lack appropriate support from stakeholders since they are 'suspicious' of the hidden goals of public administration initiatives. However, the COTAS are a notable leap forward to attain aquifer governance after the problems derived from the early development stages. Their full success needs to also consider groundwater quality, since nitrates are dramatically increasing in many areas. Some areas are experiencing great pressure from a groundwater quality governance point of view, especially around the Chapala Lake, which receives waste water from Mexico City and produces drinking water that is at risk.

Box 7: Groundwater users' communities – Governance experience in Spain: the Lower Llobregat case

The development of groundwater for irrigation started late in the 19th century and mostly in mid the 20th century, often carried out by individuals or small groups sharing expenses. This led to a rather uncontrolled aquifer development, with scarce public regulation after the 1879 Water Act, since groundwater was considered a private affair.

To try to cope with groundwater intensive development, preserve the benefits and correct drawbacks, groundwater was declared in the public domain by the 1985 Water Act, which required new groundwater developers to obtain a concession from the corresponding Water Authority. Already existing groundwater users were given the option to remain just as they were. Groundwater users communities are recognized as public entities for collective management of aquifers. Currently there are more than 1 400 groundwater users' associations registered, and hundreds of others organized as private corporations, but they are mostly for sharing water and manage irrigation networks, and so they cannot be considered as institutions for the collective management of aquifers, except a few ones, and groundwater quality is not their main concern.

The top-down creation of *Comunidades de Usuarios de Aguas Subterráneas* (CUAS, Groundwater Users' Communities), even the compulsory ones in the areas legally declared as overexploited have been largely a failure. However, those created bottom-up to solve actual problems or to have a voice in public water management do well and are highly efficient. Currently, 20 groundwater users associations have been formed and are active, or are close to start, and a fast expansion is foreseen. Each association is tailored to the specific situation of their area. They are dominated by irrigation interests and have a limited interest in groundwater quality, except for those in coastal areas. A Spanish Association of Groundwater Users was established for mutual promotion and assistance.

The first Groundwater Users' Community was that of the Lower Llobregat aquifer system, close to Barcelona (Catalonia, north–western Spain). Groundwater dynamic storage, mostly in the valley, is up to about 200 km^3. The detailed hydrogeological studies carried out from the 1960s by the Public Water Administration were made known to groundwater users, who decided to cope with existing and foreseeable problems, largely due to quality issues. As a consequence, in 1975 a Groundwater Users' Community was created, well before groundwater was declared in the public domain, in an area in which aquifer management already existed and groundwater quality was an issue due to the high river water salinity from the salt – potash – mines upstream, from large industrial and urban pressure and from seawater intrusion, besides increasing costs.

The Water Authority and the Users' Community, that includes the main water supplier, have been active in monitoring, studies, and action on pollution sources. Now brines and saline water upstream are collected in pipelines, wastewater treatment has been improved, uncontrolled disposal of wastes has ceased, and artificial recharge continues to be carried out since the 1950s. The result is that groundwater quality has improved. The intensive aquifer development produced groundwater levels below sea level, in the important delta deep aquifer, starting a serious seawater intrusion, first detected in 1965. Many salinized wells were abandoned – although others continued to be operated for industrial cooling –, thus helping to slow the seawater intrusion process. The current extraction decrease and the increased artificial recharge are improving the situation. In 2007, a well barrier to control and redress seawater intrusion was constructed to inject into deep wells deeply treated (including reverse osmosis) municipal wastewater (Ortuño et al., 2010).

At any administrative level: county, region, state or country, the number of groundwater representatives should be limited due to operative reasons. The higher the level, the wider the representation should be. This means that local users' associations have to agree on being part of progressively larger groups. In fact, in Spain, the current national users' association, that mixes interests in groundwater quantity and quality, was recently given a seat in the National Water Council and participates in a number of River Basin Water Councils.

Water authorities are often reluctant to the establishment of users' associations, either because they fear it could decreases their power and decision capacity, or simply because they are not trained in communication and social sciences and shared decision-making. This is an important barrier that has to be overcome to achieve governance. Updated laws and regulations are needed and have to be enforced to foster groundwater users' self-regulation (López-Gunn, 2007).

Most of existing institutions dealing with groundwater issues are found in semi-arid areas with intensively exploited aquifers, dominantly for agricultural and livestock purposes, where water quantity is the main concern, and water quality issues are only marginally addressed or ignored. One exception is the Lower Llobregat aquifer system groundwater users' communities (Box 7), mainly dominated by suppliers and industrialists, where groundwater quality problems are derived from river and environmental pollution and from seawater intrusion (Custodio, 2011). There, the Water Authority and one of the users' communities are currently working on a freshwater deep injection barrier to reduce and control seawater intrusion (Ortuño *et al.*, 2010). Groundwater quality management is well developed in coastal Southern California, since decades ago, and seawater intrusion is an important issue for some of them. These are specialized institutions for groundwater resources management, besides those of the state and the counties, which operate within the framework of an integrated water resources management plan that binds governmental institutions.

A sometimes complex combination of top-down actions and bottom-up initiatives is needed. The assumption is that governmental and related institutions have a wide-scale and integrated point of view, while single users have the local knowledge but with a restricted vision focusing on myopic interests. Thus, as conflicts arise, institutions may provide a space for dialogue and facilitate dispute resolution in a non-compromised environment. Governmental decisions and actions are more effective when agreed upon. Groundwater governance experience is scarce and recent, especially for groundwater quality.

8. Rationale for Slowing Down, Halting and Eventually Reversing Degradation of Water Quality

8.1 Costs and discount rate considerations

In most cases, groundwater in aquifer systems is considered as having no economic value. Economic evaluation of water costs and benefits is carried out under this assumption, and at most some externalities are included, if any. This does not reflect the true value of groundwater, which includes the ecological services it provides and the opportunity value. There is scarce experience in the social/ecological evaluation of groundwater – an important issue for governance. A first estimation can be roughly obtained through the value of lost services. Intangible values, such as those related to local people feelings, social acceptability and preferences, and sentimental and religious issues have to be taken into account and integrated in a transparent way in governance arrangements.

Evaluation is all the more difficult when dealing with groundwater quality. Groundwater pollution implies a loss of usable water resources with an alternative cost, impairment of water uses, including irrigated crop yield decrease, and increased expenses for water quality correction and for aquifer remediation.

Costs and benefits have to be considered over a long period of time due to the slow behaviour of aquifer systems. To compare them, costs and benefits have to be cumulated after being discounted at a given rate to a given moment. The value of this discount rate is a subject of debate in social and economic forums, and inside the institutions that carry out the studies. This involves social, ethical and ecological points of view. Low discount rates increase the value given to the future. This means that current generation saves economic resources and invest to benefit future generations, which are assumed to live under similar circumstances as today. However, in the future, science and technology may be quite different from current ones, thus partially invalidating the effort of present savings. High discount rates just do the contrary and favour the transfer of part of the economic burden of current activities to future generations; it is expected that future generations will be able to deal with water problems more efficiently than does the current generation and will benefit from progress made by the current generation through the intensive use of natural resources. This implies the acceptance of some degradation, loss of resources and quality impairment. All this involves ethical principles and behaviour and is perceived differently according to the general economic and political conjuncture. The long-term discount rate is different from the interest rates applied by banks in a given moment. Besides the perception of the value changes from times of good economic circumstances to moments of economic crisis, as is the current case in the USA and the EU.

In general, rich areas favour the use of high discount rates. Besides what has been explained, this is partly at the expenses of the poor areas producing part of the goods, which try to survive by sacrificing part of their heritage and overcharging future generations in exchange of possible future improvements, technology transfer and assistance. This is especially significant for groundwater quality. Ethics should inform management and governance decisions. The economic aspects of groundwater contamination are still an emerging field of economy. There are some evaluation attempts (WIR, 2004), but how to apply them need to be developed for practical applications, especially for developing countries.

In the urban environment, the value of water and its quality is rarely understood by the population, who often has a blurred – if not erroneous – idea of the origin of water and of the problems and costs involved. When domestic supply is permanently guaranteed and people do not suffer the effect of droughts – which is a goal for governments and supply companies – water is given for granted and considered a right. People are often unaware of the need to periodically increase prices to obtain more costly new water resources, to ensure maintenance and substitution of infrastructure – especially when this has not been done properly in the past – and to secure and improve water quality. Besides, politicians typically fear a loss of votes if they allow prices to increase. Awareness about the value of water should be promoted through public education, information, transparency and involvement in water supply affairs, and this is badly needed for governance.

Experience varies significantly worldwide, but the temptation of transferring costs to the future appears when there is a sustained economic crisis. To avoid this, bold government action supported by regulations is often necessary, even at a political cost. Under most circumstances, fuel, electricity and gas price increases are eventually accepted by citizens, but not for water and sanitation, and this is mostly due to poor information and communication, as well an insufficient transparency and citizen participation, which allows protest groups to appear.

A limited inquiry regarding some European groundwater-related institutions and users yielded mixed results: a number of users declared themselves as uninterested and not willing to pay for improvements; others found the issue to be concerning (Custodio *et al.*, 2007). However, in some European countries, people are worried about water quality – especially groundwater quality – and consider that chlorinated water is unhealthy, thus requiring that groundwater be directly supplied to the tap. But in other areas people prefer to resort to bottled water for drinking and cooking, which, on a monthly basis, is often more expensive than the tap water price increase they are unwilling to pay. This attitude denotes mistrust towards public supply companies, considered as being unable to guarantee safe and good quality water, although this may not be currently the case. In addition, the issue of emerging pollutants is just appearing, which will affect current demands and preferences for drinking water.

8.2 Rationale to control groundwater quality impairment

As explained in previous sections, groundwater quality is an important characteristic that limits water use for the intended purposes. Thus, groundwater quality impairment through pollution may mean a loss of available freshwater resources or the need for water treatment before being used. The loss of resources has often to be compensated by the development of additional local, imported or new water resources, at a cost. Also water treatment has a cost – sometimes a high one – depending on the kind of pollution and its intensity. In both cases, the physical and economic burden is charged to users, who are generally not the ones causing the pollution and only receive a small part – if any at all – of the benefits produced by activities that cause pollution.

Given the characteristics of aquifers, polluting activities and actual groundwater pollution may not occur simultaneously, as the latter may result from past activities that were carried out even decades earlier. Similarly, the effect of current activities may not appear before decades in the future. This means that large volumes of water in the unsaturated and in the saturated zone may be polluted in a given moment, with turnover times of years to centuries, depending on local circumstances and pollutant characteristics, such as sorption and decay.

The generally admitted statement for surface water resources that controlling pollutants at the source is socially – and often at private level – cheaper than dealing with the consequences, is even truer for groundwater. The cost of restoring groundwater quality is generally higher than that of avoiding pollution at the origin, even considering the discount rate to be applied to values accrued in different times. Detailed studies are scarce or incomplete. Economic data on aquifer restoration after point pollution events show that high costs are involved, and often with limited success.

8.3 Risk assessment and norms in groundwater quality governance

Risk and risk assessment are important for governance. Fundamentals have not been developed until recently (NRC, 1989, 1994 and 1996; Covello and Merkhofer, 1993; Haines, 1998). Following common understanding, hazard has to be distinguished from risk. A hazard is a phenomenon or an activity that can cause adverse effects, such as using contaminants in an area overlying an aquifer or drilling through protective soil. A risk is the likelihood that a hazard really causes its adverse effects, together with the measure of the effect. Risks can be caused by real phenomena but can also be the result of human or societal perception (Müller, 2010). Actual harm – damage – may occur as a consequence of risk, and may vary according to the system's vulnerability. It involves qualitative and quantitative measuring of the probability of an adverse effect, such as the actual infiltration of a contaminant in the ground or its release from a storage site, and its presence in groundwater or in water pumped from a well at a given concentration. Measurements and data are rather uncertain.

Risk assessment of action or of lack of action in groundwater quality issues is a poorly developed area, in spite of the large economic resources and financial expenses involved, and the possible loss of water resources and heritage. In what refers to groundwater quantity, mathematical models help to evaluate scenarios to study possible failures, problems and associated costs. However, many of the parameters to be used are poorly known and calibration with observed reality is often impossible due to insufficient temporal and spatial monitoring, and the changing economic and social conditions. This is even more difficult for groundwater quality. Except for conservative solutes and major ions scenarios, results may be highly biased and uncertain, even worthless, and cause–effect relationships – taking into account the delayed and slow behaviour of groundwater – are seldom available or estimable from case studies and previous experience.

Very simplified unchecked assumptions have often to be introduced for groundwater quality risk assessment. Evaluation of risk in environmental management, including groundwater quality, is currently based on coarse assumptions and the opinion of experts. Besides considering risk assessment based in careful and supported studies – where they exist –, regulatory frameworks are often the result of social and lobbies' pressure, reflecting a compromise reached among social organizations, ecological groups, mass media and politicians, within their political goals in a given moment.

In what refers to the application of the EU Water Framework Directive, risk has other meaning, since it refers to the probability of achieving the established goals at the established dates. There are guidelines on the evaluation of the likelihood of failing to meet the objectives (Scheiddeler *et al.*, 2008). This is also relevant for groundwater quality governance inside the EU, besides the administrative and legal implications. 'Risk assessment' is considered a forecast of the future at different scales, while current situation analysis is called 'status assessment'. The application of risk assessment to groundwater quality needs a sound understanding of aquifer system behaviour, based on a validated conceptual model. The evaluation is done through a tiered process (Müller, 2010): (i) qualitative risk screening for groundwater bodies (pre-assessment) – in which they are classified into three categories (not at risk, information uncertain and at risk) –; (ii) appraisal or semi-quantitative assessment, after investigation and data collection; and (iii) characterization and evaluation or risk assessment (at risk or not at risk) through further investigation and data collection. This goes in the direction of decreasing uncertainty. This is followed by a second-cycle characterization and risk assessment.

Norms are usually based on general principles such as no further deterioration, reversing trends and recovery of polluted aquifers, as in the case of the EU Water Framework and Groundwater Directives, now incorporated into the Water Acts of the EU Member States. Target dates for accomplishing goals are needed, as well as how to deal with special situations and how to define groundwater quality baselines and the minimum monitoring that is needed. This approach seems to be producing quite good results in the European Union. However, this is partly due to these norms being supranational regulations with the capacity to apply sanctions to member states that do not comply. Something alike happens in federal countries, as in the USA, but not always, depending on the power and means of federal institutions and on states' laws. This is much more difficult inside a given state or region, especially when legislative and judicial powers are not truly independent and often become politically and socially controlled. Under these circumstances groundwater quality governance seems a difficult task that needs previous reinforcement and changes in the legal framework, as well as in the ability of the government to enforce it.

The EU directives are important and compulsory for member states having yielded part of their sovereignty, and they involve important economic, administrative and social efforts to preserve and restore the environment. There are good results, but also failures and still many on-going activities related to groundwater quality preservation, control and improvement. The balance is reportedly positive for many countries, particularly thanks to the governance opportunities offered by efficient top-level institutions, which are in charge of implementing EU legislation at the national level. However, some analysts find some weak points that point to a too powerful Commission and a weak Parliament, and some bias in the orientation due to not all members being able to put forward their own interests. However the balance is positive, even for those that complain of not adequate consideration of their peculiarities. The USA has a different approach, but the two systems have points in common. However, it is not sure that these approaches can be directly transferred to other countries since local circumstances and capabilities may substantially differ.

State level norms, when applied to a large territory, often do not consider the variability of local circumstances and the existence of special situations. Thus, some regulated flexibility is needed. Also, groundwater quality norms and laws at state level are generally not based on detailed prospective studies, real risk, and socio-economic evaluations. This is currently an almost impossible and uncertain task, heavily dependent on the physical, economic and social circumstances found at the local level. Mid- and long-term objectives should be applied taking into account the changing socio-economic environment. To be effective, periodical updating of norms is needed. They should have an end date, with carefully designed steps for substitution or deep revision, starting well before the 'dead end'. Otherwise, as often happens, norms become outdated and unrealistic and are thus loosely applied, often becoming a burden to society. Thus, norms may hinder proper action by institutions and open the way to chaotic behaviour, in which groundwater quality is often the big loser. All these issues have to be taken into account for groundwater quality governance.

8.4 Aquifer vulnerability to pollution assessment for governance

In groundwater science, the risk of diffuse contamination is evaluated by multiplying the vulnerability to pollution by the quantity of contaminant released to produce a concentration. Vulnerability to pollution is an abstract concept that qualifies or quantifies the susceptibility of an aquifer to be attained by a pollutant once it is on the surface (Margat, 1968; Foster, 1987; Adams and Foster, 1992; Vrba and Zaporozec, 1994; Robins, 1998). This is a debated concept, not easy to be used in practice but widely applied in institutional and university environments. Figure 24 is an example. Although there are no absolute values, several methods to grade vulnerability are available. Some are relatively simple and can be applied in areas with scarce data – e.g. GOD (Foster and Hirata, 1991; Foster *et al.*, 2002). Others are more data demanding, such as DRASTIC (Aller *et al.*, 1997) and SINTACS (Civita and De Maio, 1987). There are numerous efforts to compare methods and to adapt them to specific pollutants (Colman *et al.*, 2005; Conell and den Daele, 2003; Worral and Kolpin, 2004; Ramos Leat *et al.*, 2012). Since the 1980s and mostly since the 1990s, a large effort has been done in many areas to produce vulnerability maps, which are intended to assist in decision-making. Such maps do not provide readily available local answers, which need accurate assessment at detailed scale by experts, an aspect that is not always understood by planners, water authorities and decision-makers.

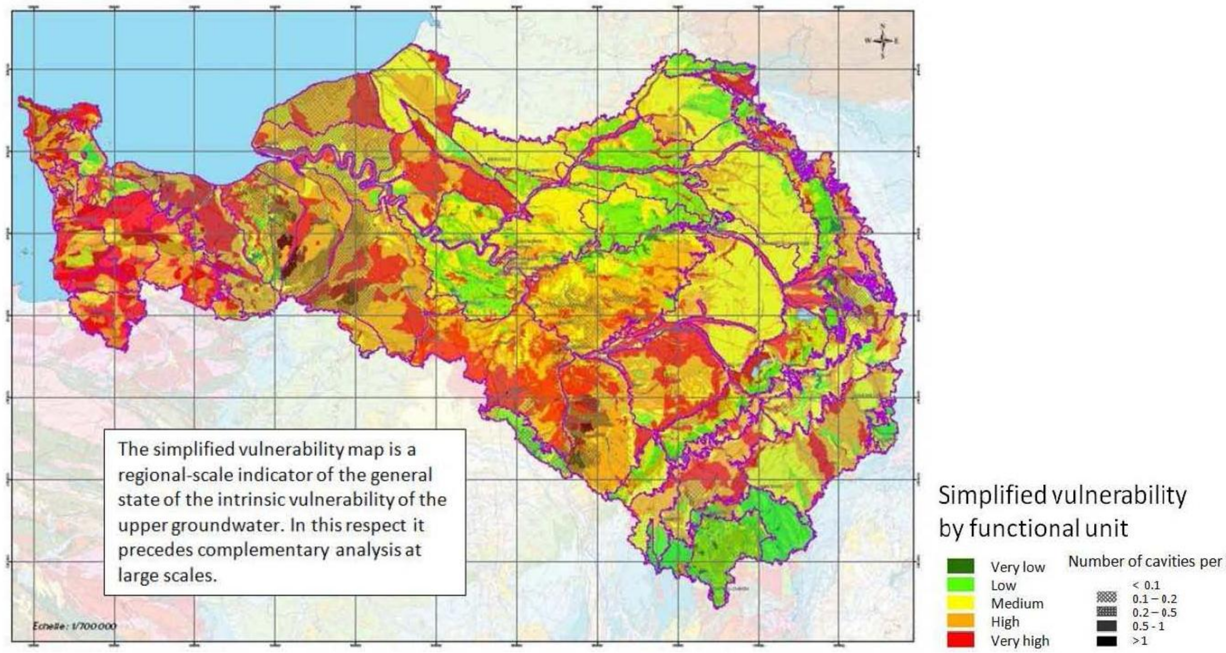


Figure 24. Map of intrinsic vulnerability to pollution of groundwater in the Seine–Normandie Basin, France (after BRGM, in Margat and van der Gun, 2012). Details and usefulness for groundwater governance increase the more detailed is the scale is, but more data is needed.

However, vulnerability does not mean pollution risk. Groundwater contamination has to be measured in real terms, e.g. for a given contaminant, under current conditions and concentrations or quantities (EC, 2004), which is rarely done. Low vulnerability does not necessarily mean low risk when the contaminant load is high, and high vulnerability may imply no risk at all if there is no contaminant source. Vulnerability is an intrinsic value of a site or an aquifer (intrinsic vulnerability). There is an unbounded time dimension implicit in the definition of the concept under the designations of susceptibility of the aquifer being attained by a contaminant, and the contaminant penetrating the aquifer.

For a given pollutant or groups of pollutants, specific vulnerability can be defined. Specific vulnerability depends on the contaminant, and soil processes have to be considered in some way. Degradable and radioactive contaminants decay with time – the more exchanged or sorbed they are, the more they decay – and may reach concentrations below thresholds. Stable concentrations will eventually arrive, although they may be diluted and delayed; in the meanwhile, they cumulate in the aquifer until an equilibrium between inflow and outflow is attained. This is a common situation for salinity and for nitrate in an oxidizing ambient.

Despite the limits to the usefulness of the vulnerability approach, it is an interesting exercise for aquifer quality protection, and consequently for groundwater quality governance. However, real data is needed, but may not be available in many areas, especially in developing ones. The use of probable average values after a literature search and comparison with other cases is risky and often tends to smooth results, thus making zoning rather useless.

Part 3. Prospects

9. Prospective on Groundwater Quality and its Governance

9.1 Projected evolution of groundwater quality trends under no action

One possible scenario for groundwater quality is no action under current circumstances, that is to say, no further activity directed to influence contamination and pollution of groundwater, out of what is already being done under current legal pressure to reduce pollution, existing pollution sources and socioeconomic circumstances. This varies from country to country.

Salinity increase and nitrate build up are of special concern. Under current groundwater development circumstances, salinity increase will be a growing concern in coastal areas, especially where alternative water resources are not easily available, as well in continental aquifers where saline water exists in aquitards and deep seated layers, or where irrigated agriculture produce saline return flows –the more efficient irrigation is and the higher irrigation water salinity is, the higher the production of saline return flows is. River, spring and aquifer salinity is expected to increase below new deforested areas in the dry belts. This may mean increased water demand for irrigation to compensate for the decreasing crop yield and to leach the soil as irrigation water salinity increases.

The erroneous – although widespread – assumption among water regulators and managers that aquifer exploitable resources are equal to recharge will certainly lead to salinity increase in many areas of the world, as well as to increased natural and artificial contamination due to excessive water level drawdown, besides other impacts on other water resources, the environment and the territory (Llamas and Custodio, 2003). Determining and agreeing on the right aquifer development is part of its governance, depending on actual physical, administrative, legal and social constraints and on what the society asks, in a mid- and long-term perspective. These constraints are variable over time and should be taken into consideration, given the slow behaviour of groundwater.

Nitrate build-up is and will continue to be a serious concern with the current trends in agriculture and food production, and with non-sewered sanitation practices in urban areas. In many aquifers, nitrate build-up happens, even if there is no more pressure, when the steady state has not yet been reached after past disturbance. Other major groundwater quality problems are more local. Arsenic is a growing concern as groundwater development intensifies in many areas of the world. The increase of fluoride is of concern as deeper groundwater is being used, especially in volcanic areas and in areas affected by fine volcanic ashes.

Expanding urban areas in poor countries entail an increase in the number and size of local pollution points, such as wastewater discharge points, refuse disposal areas and burial of wastes in pits. Problems related to salinity, nitrate, possibly soluble iron (Fe(II)), hardness and mineral oil are likely to grow, as well as contamination from domestic chemicals and wastes from poorly equipped and unconcerned small industries. Water-table fluctuations in response to recharge events will produce pollution peaks as wastes and contaminants in the unsaturated zone will be more readily mobilized.

When widespread groundwater contamination forces to look for new supply wells in new areas or when existing wells are closed down as others water sources are made available, there is a water-table level recovery that may mobilize contaminants held in the unsaturated zone, mostly mineral oils, non-aqueous liquids and slowly-degrading organic matter. This worsens groundwater quality and affects the remaining wells in operation – often domestic-supply wells. This is a serious problem around many large cities, especially in slum areas, as in the peri-urban areas surrounding Buenos Aires, the "Conurbano Bonaerense", Argentina, where there is a continuous shallow aquifer.

The widespread use of caffeine, nicotine, pharmaceuticals, antibiotics, body care products, domestic cleaners, endocrine disruptors, and psychedelic drugs is growing, both in developed and developing areas, although the involved chemicals may be different according to local living standards. Many of them degrade slowly or are recalcitrant and thus cumulate, which means they will be predictably added to groundwater in increasing concentrations. Being only partly degraded in wastewater treatment processes, they are likely to reach downstream aquifers. These emerging contaminants still have a poorly known effect on population at the low concentrations they are commonly found. This is a growing concern, not only in rich areas, but also in poor areas where some contaminants are used in similar quantities and sanitation systems are not functioning. However, in poor areas other groundwater contaminants are currently more concerning since they affect health more immediately. While in some rich areas people are asking for untreated groundwater at home – aquifers have to be maintained unpolluted –, in other areas, there is no alternative to the use of poor-quality groundwater and the priority concern for governance in the short run is avoiding further deterioration rather then improving quality.

It is difficult to make an assessment of contamination by pesticides and fertilizers used in agriculture, as well as antibiotics and other substances used in feedstock, both in developed and developing countries. Such substances have evolved from very persistent and highly retained products, such as the widely used in the past DDT (dichlor–diphenil–trichoroethanne) and lindane (hexachlor–cyclohexane), to more active, specific and degradable ones, although some of them result rather mobile in the biosphere. A trend toward increasing contamination by these substances and their metabolites seems to be the rule. In some cases, however, it is unclear whether they actually increase or they are more frequently found due to the continuously improving sampling and analytical methods and to the increased availability of well-equipped laboratories. Remobilization of the more persistent chemicals held in the soil may happen when there is a land-use change, but this is poorly known.

Impairment of groundwater quality by pollution from mineral oils, fuels, chlorinated solvents and other non-miscible products seems to be decreasing, in frequency and intensity, in many areas of the world as a result of improved technology and standards to avoid leakages and unsafe disposal, of more effective enforcement of regulations and of improved monitoring. But this may not be the case in developing countries, where the pressure toward economic development dominates the scene and is often accompanied by further point-pollution events and aquifer quality deterioration.

Groundwater quality governance largely depends on social understanding and conscience of the need to protect aquifer from pollution. In some areas of the world, protection and restoration measures have been adopted. However, in many other areas further groundwater quality deterioration will have to occur before corrective action is taken. Groundwater quality governance arrangements must provide an adequate framework and the means to promote action before degradation goes too far.

9.2 Prospects for better management of groundwater quality trends

Improved governance of groundwater quality trends relies on three legs:

a) Legislation on water resources management, land-use and other related aspects, and the means for effective enforcement and updating.
b) Adequate monitoring and information exchange – results should be made easily and readily available to all concerned people,
c) Cooperation and shared responsibility among groundwater users, civil society and local authorities in the control, protection and surveillance.

Direct management measures consist of:

a) halting active pollution sources – this refers to: sound use of chemicals and care of wastes, including mineral oils and organic and chlorinated solvents; leakage correction; safe disposal of wastes; adequate use of agrochemicals; good management of feedstock wastes; protection of storage sites for hazardous fuels, chemicals and agrochemicals; transportation of dangerous substances on safe routes; and early action as soon as a leakage is known;
b) providing controlled and effectively operated waste disposal sites;
c) identifying old pollution sources, with plans to assess the associated hazard and to clean out, restore or confine contaminated sites, as required;
d) introducing sound design of wells, boreholes and drilling practices, and adopting standards for drains, drainage tunnels, dewatering systems, public works that affect soils and aquifers – including protection against inter-aquifer leakage, isolation from surface and from poor quality aquifer layers, and prevention of the effect of deep saline groundwater;
e) making groundwater development compatible with quality protection;
f) protecting and enhancing aquifer recharge, and considering the possibility of artificial recharge when it is really needed;
g) providing instruments to know aquifer vulnerability and define protection areas for supply groundwater;
h) limiting seawater intrusion by controlling groundwater abstraction, timing and pattern, combined with increased aquifer recharge and barriers – when they are advisable, possible and affordable – such as freshwater injection and saline water abstraction;
i) introducing barriers to limit the spread of some pollutants, both passive (impermeable, reactive) or active (pumping and recycling, injection);
j) taking out deposits that contain polluting substances to a controlled dump site, to be buried or discharged on the surface;
k) operating *in situ* groundwater treatment facilities – there are different kinds – as a tailored but costly and slow solution.

The list is not complete. It includes actions that are progressively more complex, costly and sophisticated. The first ones are generally affordable, although they imply a cost and need enforceable norms, but the last ones may require high investment and difficult-to-obtain expertise. Thus, they are rarely suitable to developing areas.

For groundwater quality governance, due consideration should be paid to the fact that cleaning polluted aquifers and restoring polluted sites is generally a long-lasting affair, with unsure results (Anderson and McCray, 2011). It is not easy to decide when a cleaning process is accomplished. A common situation is that after the cleaning process is assumed to be finished – contaminants in abstracted water or air are below thresholds – later on pollution re-appears as contaminants held in low permeability bodies diffuse again to the aquifer.

Another way of dealing with groundwater contamination, which is neither the best nor an environmentally desirable one, is just by accepting that the aquifer is contaminated and treat abstracted groundwater adequately before use. The feasibility of this approach depends on the type and degree of contamination, as treatment is costly and may require sophisticated means. Over time, when costs are discounted and added, it may result in a large economic expense.

In groundwater quality management, the alternative between controlling and addressing pollution at the source and treating the polluting water afterwards is often posed. Avoiding groundwater pollution by acting at the source is cheaper but complex and needs the joint action of several government sectors with different goals, which often requires a higher or external level of decision. In addition, such preventive action does not solve currently existing pollution problems, as many of them were caused by activities carried out a long time ago. It is an investment for the future that might not be attractive for short-minded politicians without pressure from the civil society. At some point, a decision has to be taken to avoid further deterioration and, at the same time, deal with inheritance, which is costly and perhaps a poorly rewarding activity. It is affordable in moments of economic bonanza, as when the EU Directives were drafted, but not so clearly under the current economic crisis. This means that groundwater quality governance has to be able to adapt to the changing economic and social conditions, which may influence the way the present and the future are valued.

The question of who pays the costs associated to pollution is related to the above considerations. Treating and controlling the pollution source charge the cost to the potential polluter – indirectly to people through increased prices of goods – and may deteriorate producers' ability to compete in free markets. The cost of treating polluted water is charged to groundwater exploiters (increased operation costs), to groundwater users (increased prices) and to society (increased taxes), with possible complexities when public funds are applied as co–payments or subventions, often wicked subventions if they last, since they may produce a counter-effect.

Indirect or 'soft' measures are as effective as direct measures. They may not solve existing problems but may be useful to prevent further deterioration. They include:

a) raising awareness of the public, decision makers and managers on the value of groundwater, the cost of degrading its quality, the large expenses needed for restoration – if feasible at all –, the cost of what is irreversibly lost, and the methods of protection. Awareness raising measures should involve schools and include public forums, training courses, conferences, posters and videos;
b) adapting the institutions to new tasks for which they are not prepared. This means training staff, incorporating new trained people and providing adequate financial and technical means, which is not necessarily costly when compared to other common expenses;
c) improving monitoring, processing information and data, and making them easily available to all interested people. This may be accompanied by action to encourage people to study the information and data and to make proposals;
d) providing institutions and users' associations with means to carry out surveillance and to correct deviated or criminal behaviour. This needs some well-trained staff, a suited department or office, and the cooperation of local police;
e) reinforcing courts in order to have specialized teams and public prosecutors to deal with groundwater pollution and the impairment of ecological services. They should be able to speed up court decisions and guarantee compliance.

9.3 Prospects for engaging well users, regulators and technology providers in water quality improvements

In many areas of the world, hydrogeology and groundwater knowledge are becoming more common, at least among users and water authorities. Important efforts on regulation are being made. But this is not the common situation worldwide. Further effort is needed. The role of UN agencies, universities and associations, such as the IAH and the Association of Groundwater Scientists and Engineers of the National Ground Water Association, USA – the latter with special regard to groundwater quality – are opening new grounds and making groundwater users, regulators and engineers more aware of groundwater. However, many important groundwater properties, especially the large water storage associated – meaning long-term behaviour – and water quality issues, are still poorly understood, even in areas with a good tradition in groundwater use and management. This is a serious handicap to be overcome and a major hindrance to understanding what is actually occurring, how to deal with problems and how they may affect current and future generations. This knowledge is needed to raise awareness of the fact that groundwater is a common heritage and that environmental services are valuable and need preservation. Up to now, insufficient knowledge has prevented major advances in the joint or collective action of groundwater users, regulators and engineers, although there are encouraging achievements in understanding the basis of groundwater quality governance.

Groundwater quantity issues in semi-arid and arid areas are relatively easy to be understood, and agreement on joint action may be easily reached, although discussions may sometimes generate serious fights and rivalry. However, quality issues are more pervasive and difficult to identify and address, due to their slow appearance and delayed manifestation, to the scarcity of available data and to their invisibility, except for some dramatic cases. To make people aware of groundwater quality issues and of the need to participate in groundwater governance, more effort is needed. Some short-term results have to be obtained, shown and explained, in order to introduce the most important long-term ones, which are more difficult and costly to deal with.

Regulators – water authorities – are becoming more aware of the need to deal with groundwater quality improvements issues, at least because in many countries this is now a legal mandate. But they can do little if local people and stakeholders do not support them and cooperate with them. Prospects for engaging water users, regulators, engineers and technology providers in improving groundwater governance depend heavily on obtaining good results in diverse areas that represent different typical situations. These groundwater quality governance examples are currently very scarce. Efforts should be done to indirectly promote and help bottom-up initiatives from local people who understand the problems, my act as leaders and are able to make efficient use of the resources that can be provided. Engineers and technology providers have been mostly interested in complex issues and sophisticated methodologies, which are good for research, rich areas and powerful companies. However, in most common situations, simple and affordable techniques may be successfully applied for evaluation, monitoring, protection, remediation and management.

The prospective for these simple and affordable techniques is unclear, partly because possible markets are still too small and short of economic resources, and partly because water authorities have been reluctant – and still are – in expending on groundwater quality. Solving groundwater quality often offers less political reward than solving groundwater quantity issues, which are short-term, thus wanted results. The short-term goals of the often politically-controlled water authorities is a serious hindrance for progress, as well as the mass media preference for negative news instead of giving long-term positive messages. Groundwater quality problems and deterioration are badly acknowledged and accepted, since they create alarm, they are difficult to be solved and results – if attainable – appear late. Consequently, they are often concealed or down-played. In order to avoid this, regulations need to be enforced, the transparency rule must be applied and civil society is to be involved. Unfortunately, in many countries civil society is poorly organized or unwanted by the often less competent political society. Good governance has to create the appropriate environment for civil society to develop and grow.

Education is needed at different levels, although it is an investment for future generations. It is especially important in rural areas where locals should play an important role in protecting and managing groundwater quality.

10. Conclusions

Groundwater quality is, in many areas, a serious concern that will increase in the future. Concerning aspects are salinity, inadequate chemical composition and the presence of inconvenient and/or harmful solutes, organics, mineral oils, organic solvents, degradation substances and emergent contaminants. Saline water encroachment and/or up-coning is a growing problem in coastal areas, near saline lakes and as the result of three main situations: the widespread existence of deep saline aquifers in many areas of the world, the presence of return irrigation flows in dry areas or the transformation of natural forest into cropland and grassland in semi-arid and arid areas.

In semi-arid and arid countries, water quantity problems tend to dominate over quality, although this will probably change in the future, as groundwater resources become more stressed, aquifer functioning is growingly modified, human activities increase, better health conditions are introduced and the economic situation and living standards of people improve, as well as the increased knowledge and availability of monitoring data.

Groundwater quality is an important part of water governance. The main issue is related to poor awareness of the problem, on the regulatory side, on the groundwater users' side and within the society in general, which is also due to the often and slow reaction and long delay of cause–effect behaviour that is characteristic of aquifers. Delayed effects are poorly sensed and understood, and may involve the transfer of part of the burden to future generations, to the same extent that we are currently observing what previous generations did.

Groundwater quality governance examples are currently scarce, in part due to the recent history of groundwater intensive development. An important role is played by the not-so-recent large land-use-intensive activities and changes, as well as by the recently-introduced large variety of potentially polluting chemicals and agrochemicals.

For groundwater quality governance some issues and facts are basic premises to be considered:

1. The aquifer system functioning has to be known – conceptual model –, which includes groundwater-surface water interactions and the highly delayed and progressive changes of groundwater.
2. Groundwater quality and pollution are the result of many different factors, involving diverse government and social sectors, besides water; they have to play their role in groundwater quality governance through agreed action or as a consequence of decisions from a higher hierarchical level.
3. Land-use changes may produce important impacts on groundwater quality.
4. Water quantity issues may currently dominate in many areas, but quality issues will soon become relevant and have to be urgently addressed.
5. How groundwater is captured and exploited may greatly influence its quality. Wells and other groundwater wining works should be properly constructed and maintained, subject to norms and licensing, and follow periodically updated and agreed groundwater development plans.
6. Data on groundwater and its quality, as well as adequate monitoring are needed for governance, and results have to be made available to all interested sectors.
7. The cost of degrading groundwater quality may be high for the developer, the user and society; it may involve important externalities and the degradation of environmental services. It may also affect future generations and, in many cases, restoration may be economically unfeasible. Thus, protection of groundwater from contamination is generally cheaper than treating polluted groundwater – now or in the future – or than looking for new freshwater sources to replace what is lost through pollution.
8. Groundwater quality governance is the responsibility of governments, but they have to act jointly and with the support of civil society institutions, users and people. Effective action requires specialized institutions and participation of the often numerous.
9. Institutional barriers to groundwater quality governance have to be identified and corrected, inside a framework that represents social needs in a broad space and with a mid- and long-term vision. A needed goal is transparency.

10. Laws and norms are needed, and should be periodically reviewed and updated. They have to be enforceable and enforced, with the support of politically independent government agencies and courts.

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Acronyms

EC	European Community
EEC	European Economic Community
EPA	US Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environment Facility
IAH	International Association of Hydrogeologists
IHP	International Hydrological Programme
IWRM	Integrated Water Resources Management
USA	United States of America
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

The following chemical symbols have been used for dissolved substances (mostly ions):

As, AS(V)	Arsenic, arsenic at valence +5
Ca	Calcium
Cl	Chloride
CO_2	Carbon dioxide
F	Fluor, as fluorine
Fe, Fe(II)	Iron, reduced iron (valence +2)
Mg	Magnesium
Mn	Manganese
Na	Sodium
NH_4	Ammonia
NO_3	Nitrate
SO_4	Sulphate

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