

Rationales Behind Irrationality of Decision Making in Groundwater Quality Management

by Daniel Ronen^{1,2}, Shaul Sorek^{3,4}, and Jack Gilron^{3,5}

Abstract

This issue paper presents how certain policies regarding management of groundwater quality lead to unexpected and undesirable results, despite being backed by seemingly reasonable assumptions. This happened in part because the so-called reasonable decisions were not based on an integrative and quantitative methodology. The policies surveyed here are: (1) implementation of a program for aquifer restoration to pristine conditions followed, after failure, by leaving it to natural attenuation; (2) the “Forget About The Aquifer” (FATA) approach, while ignoring possible damage that contaminated groundwater can inflict on the other environmental systems; (3) groundwater recharge in municipal areas while neglecting the presence of contaminants in the unsaturated zone and conditions exerted by upper impervious surfaces; (4) the Soil Aquifer Treatment (SAT) practice considering aquifers to be “filters of infinite capacity”; and (5) focusing on well contamination vs. aquifer contamination to conveniently defer grappling with the problem of the aquifer as a whole.

Possible reasons for the failure of these seemingly rational policies are: (1) the characteristic times of processes associated with groundwater that are usually orders of magnitude greater than the residence times of decision makers in their managerial position; (2) proliferation of improperly trained “groundwater experts” or policymakers with sectoral agendas alongside legitimate differences of opinion among groundwater scientists; (3) the neglect of the cyclic nature of natural phenomena; and (4) ignoring future long-term costs because of immediate costs.

Introduction

Humans are considered to be rational beings. This characterization does not seem to be substantiated by the outcome of human decision making in many areas

related to groundwater quality management. Two vivid examples are the contamination of about 200 km² of Israel’s Coastal Plain aquifer in the Tel Aviv metropolitan area (Graber et al. 2008) and the well-known story of the hexavalent chromium plume from Pacific Gas and Electric in California (Sahagun 2010).

The world faces a severe crisis where around 1.1 billion people live without a safe water supply; 2.4 billion people without sanitation facilities, and about 2 million people die every year because of diseases associated with the lack of access to clean water (WHO 2009). Groundwater is the largest readily available source of fresh water of our planet (Lakes and reservoirs 0.13×10^6 km³, river channels $<0.01 \times 10^6$ km³, groundwater 60×10^6 km³; Freeze and Cherry 1979) and the basis for life and development in many areas of the world. Hand in hand with growing populations in developing countries, one can find water quality rapidly deteriorating as greater stress is placed on limited resources (Swanson et al. 1999).

¹Water Quality Division, Israel Water Authority, Tel Aviv 61203, Israel.

²Corresponding author: Ben-Gurion University of the Negev, J. Blaustein Institutes for Desert Research, Zuckerberg Institute for Water Research, Midreshet Ben-Gurion 84990, Israel; danronen@bgu.ac.il

³Ben-Gurion University of the Negev, J. Blaustein Institutes for Desert Research, Zuckerberg Institute for Water Research, Midreshet Ben-Gurion 84990, Israel.

⁴Ben-Gurion University of the Negev, Mechanical Engineering, Pearlstone Center for Aeronautical Studies, Beer Sheva 84105, Israel.

⁵Ben-Gurion University of the Negev, Environmental Engineering Unit, Midreshet Ben-Gurion 84990, Israel.

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Given the critical role of adequate quality water supply for social and economic development, it is difficult to understand why erroneous policies are so frequently conceived concerning groundwater, even when they could have been shown to be problematic based on available knowledge at the time. Often, it is in the “developed countries” where, in many cases, nonquantifiable and noncorroborated solutions are suggested and where technology is considered, without any proof, to be the solution to all water-related issues.

Sometimes policies are a reflection of a larger spirit of the times. In times of economic crisis and scarcity when there is a seeming political inability to raise revenues for the public (as presently in the United States; Hulse and Herszenhorn 2011; Rudolf 2011) or a limitation of resource to continue providing services to which the public has been accustomed (Directive 2000/60/EC of the European Parliament 2000), there is a serious movement to question the limits of government to influence issues that relate to the common welfare. This leads to a temptation to find rationales “to do nothing.” Even in the past, this has led to politicians and administrators making “gut decisions” that are not always grounded in the assemblage of available information. Often this is phrased in terms of what seem to be reasonable justifications.

Hereinafter, in this issue paper, we shall analyze this syndrome as related to management of groundwater quality, mainly with the aid of examples from Israel and the United States. In the section after that, we suggest four possible factors leading to unreasonableness in groundwater quality management and propose some possible solutions.

Finally, one may ask why we raise this issue in this forum for water-related professionals, for whom it may seem obvious. This question is even more acute given the many papers related to groundwater quality management that have already been published in the past (e.g., Bredehoeft 2005; Fischhendler 2008; Tidwell and Brink 2008; Narasimhan 2009; Refsgaard et al. 2010). First, we try here to assemble a variety of different irrational groundwater quality policies and examine the reasons for their adoption. We also point to directions for improving the situation. Second, we claim that it is critical for the community of water-related experts to be in continuous dialogue with policymakers on how to integrate the models and data developed into the decision-making process. We will also reflect on some understandable pitfalls and barriers to the professional community’s involvement.

Some Groundwater Quality Management Policies

Restoration to Pristine Conditions vs. Natural Attenuation

Uncontrolled human, industrial, and agriculture activity in the recharge area of aquifers has led to contamination of groundwater resources (e.g., Kanfi et al.

1983; Graber et al. 2008). In response to these environmental problems, there was a burst of public activity leading to a policy in the United States to require “cleaning aquifers to pristine conditions” (e.g., by pump and treat, Curtis and Doty 1990), as seen in regulations promulgated by the EPA in the 1970s and 1980s, and the establishment of SuperFund sites where contamination was especially egregious. In an analysis of past aquifer restoration policies, the Office of Technology Assessment (OTA) of the Congress of the United States wrote, in June 1988, a report entitled “*Are we CLEANING UP? 10 Superfund Case Studies*” (U.S. Congress, Office of Technology Assessment 1988). The Introduction to this report states: “*Are we cleaning up the mess or messing up the cleanup? In the eighth year of Superfund, this central question is still being asked.*” This statement is followed by the observation: “*Since its inception at the end of 1980, Superfund has received a great deal of money, over US\$ 5 billion so far, to clean up the Nation’s worst toxic waste sites. But OTA’s research, analysis, and case studies support the view shared by most observers—including people in affected communities and people in industry paying for cleanups—that Superfund remains largely ineffective and inefficient.*” In addition, Curtis and Doty (1990) suggest in their paper that “*In spite of intense searching, we were unable to locate a single aquifer in the US that has been confirmed to be successfully restored through pumping and treating.*” In the executive summary of Alternatives for Ground Water Cleanup (1994) and in relation to the large groundwater contamination problem in the United States, it was suggested that: “. . . *there is almost universal concern among groups with diverse interests in groundwater contamination—from government agencies overseeing contaminated sites to industries responsible for the cleanups, environmental groups representing affected citizens, and research scientists—that the nation might be wasting large amounts of money on ineffective remediation efforts. At the same time, many of these groups are concerned that the health of current or future generations may be at risk if contaminated groundwater cannot be cleaned up.*”

In 2010, the U.S. Environmental Protection Agency (USEPA) stresses that: “*Contaminated groundwater is a cleanup problem at most Superfund sites, . . . It is now known that remediation efforts are taking much longer than originally anticipated. Operation and maintenance costs are substantial and conventional remedies may not be able to achieve cleanup objectives in reasonable time frames or at all, particularly for contaminants that are newly found to pose risks at concentrations once deemed acceptable*” (EPA-Groundwater Cleanup 2010).

Expensive technological cleanup failures resulted in the adoption of the monitored natural attenuation approach defined by the USEPA as the “*reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods. The ‘natural attenuation processes’ that are at*

work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These in-situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants” (USGS—Natural Attenuation).

Is this indeed a “natural process” methodology or an escapist ploy for implementing a supposedly cheaper solution after spending billions of dollars trying to achieve the unachievable (i.e., pristine conditions)? Were the bacteriological, physico-chemical, and flow processes (e.g., biodegradation; sorption; dispersion; dilution; volatilization), on which the “natural attenuation” approach is based, not known in the early 1970s when the “pristine conditions” approach was suggested? Can we really predict how many years this “self-cleaning” procedure will take? What are the monitoring and follow-up needs and costs? What may be the outcome of letting nature work for us? Can “volatilization” be considered a natural attenuation approach when it is well known that vapors can penetrate into houses (e.g., Graber et al. 2002; Figure 1)? In some cases, “natural processes” in aquifers may lead to the appearance of more dangerous contaminants. For example, the anaerobic reductive dechlorination of trichloroethene (USEPA Maximum Concentration Level (MCL) = 5 µg/L) may lead to the production of vinyl chloride (USEPA MCL = 2 µg/L).

Thus, we postulate that neither “brute-force cleansing” nor “natural attenuation” can be adopted uncritically, and that either approach requires prior quantitative analysis of likelihood of success based on available



Figure 1. Measuring 822,000 µg TCE/m³ air emanating from a water drain in an underground parking lot of a building located in a VOC contaminated area of the Coastal Plain aquifer of Israel (Israel maximum level for 24-h exposure = 1000 µg TCE/m³ air). The drain opening is about 5 m above the water table (water table depth ~18 m below ground surface; after Graber et al. 2000). The building is located about 500 m from monitoring well M5A (Figure 4). Note that volatilization is considered to be one of the natural attenuation processes.

knowledge. It is also not clear that all the possible alternatives were systematically reviewed when the pristine vs. natural attenuation debate was carried on. As of the date of this writing (February 2011), the authors were unable to find results of a cost-benefit analysis summarizing any of the aquifer cleaning efforts and achievements of the last few decades in the United States or elsewhere.

The FATA Approach

When economic technologies were not available for new fresh water production, an abandonment of an aquifer threatened with contamination was considered unconceivable (U.S. Congressional Record 1976). The “Forget About The Aquifer” (FATA) approach is a result of considering improved water production technologies, such as desalination of sea water, to be cheaper than the utilization of groundwater from the contaminated aquifers. This is because contaminated groundwater utilization may require expensive and extensive site characterization of a continuously increasing and changing list of contaminants (Figure 2), mathematical modeling, monitoring over long periods, and groundwater treatment to meet, for example, drinking water standards.

Indeed, in many groundwater contaminated regions, remediation has lasted over long periods and required large and extensive monitoring and pumping operations. For example, in the former IBM facility in Endicott, New York (Groundwater Sciences Corporation, Harrisburg, Pennsylvania, 2003), where groundwater is contaminated by chlorinated volatile organic compounds (Cl-VOCs), corrective measures started in 1979. At this site, 220 monitoring wells and 20 extraction wells were drilled on an area of about 4 km².

A comparable monitoring and remediation campaign in Metropolitan Tel Aviv, Israel (Graber et al. 2008), where an area of about 200 km² is contaminated by Cl-VOCs, would imply the drilling of hundreds of pumping

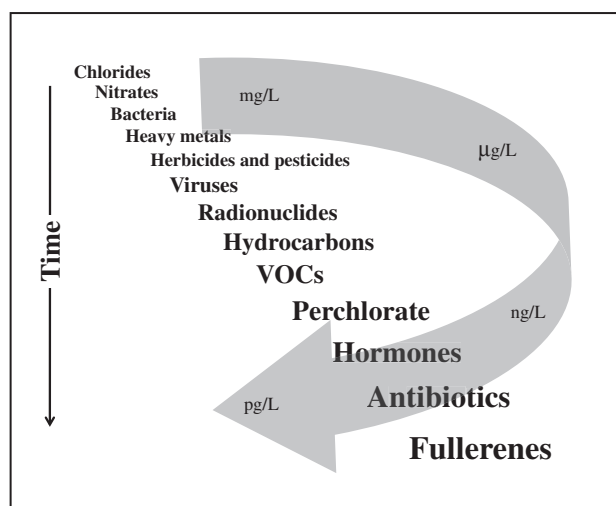


Figure 2. Partial list showing the increasing amount of groundwater contaminants and the detection sensitivity refinements for some components over the last decades. What’s next?

wells and thousands of monitoring wells. In reality, less than 30 monitoring wells were drilled in the Tel Aviv area, the aquifer continues to be heavily contaminated and budget constraints will probably lead to the “natural attenuation” or to the FATA approach.

Water authorities are driven into FATA also due to the complexity associated with the management of contaminated aquifers, including (1) the need to consider the competing interests of different stakeholders (e.g., variable water requirements of urban, industrial and agriculture sectors) and (2) decisions that have to be made under uncertain conditions (e.g., lack of knowledge about the extent and movement of multiple contaminant plumes in the saturated and unsaturated zones).

However, it is quite unusual to encounter a comprehensive managerial analysis that in contemplating the FATA notion also weighs considerations such as: (1) aquifers contaminated by Cl-VOCs as a source of carcinogenic VOC vapors that can penetrate into underground parking lots and residential basements (Figure 1); (2) submarine discharge of contaminated coastal aquifers that may negatively impact shore environments (UNESCO 2004); (3) the changing price of crude oil (Petkov and Stratiev 2008) may influence the economics of desalination; (4) desalination plants and their output may not be required during years of intensive rain; (5) there is a moral obligation toward future generations not to contaminate natural fresh water resources, as has been the case in Curaçao, where groundwater (from a contaminated spring) is given as a gift in a bottle to remember that this was an existing natural fresh water source in the Island’s past history (Figure 3; Water for Life Conference, Curaçao 2003).

Abandoning a contaminated groundwater source is just postponing the solution of a problem that may lead to other environmental issues that are not easy to solve such as the VOC problem mentioned earlier. However, groundwater unlike a contaminated river or lake is, at first, an imperceptible nuisance and the dilemma can conveniently be transferred to future generations.

Giving up on aquifers has another potentially devastating consequence: If social stability breaks down in a region and desalination plants are partly or completely crippled for any length of time, then society is thrown back again on the same contaminated aquifers that were abandoned, with the attendant health consequences. Aquifer rehabilitation by a combination of man-made and natural processes along with protection of still intact aquifers must be kept in society’s arsenal against the days of social instability when keeping complex desalination plants operating may be problematic.

Groundwater Recharge in Municipal Areas

In arid and semi-arid areas, water is an especially precious commodity. In Israel, water scarcity was the trigger for considering rain water recharge at home-scale level (e.g., by directing infiltration of rain water falling on the roofs into the subsurface) as a worthwhile water-saving approach. This may be an appealing methodology if the unsaturated zone is analyzed for the existence



Figure 3. A bottle of groundwater (from spring at Roi Rinkon, Curaçao) given as a gift to remember that this was once a usable resource on the island (Water for Life Conference, Curaçao 2003). The front label (in Papiamentu) reads “Awa fresku natural” (Natural fresh water). However, as the aquifer is contaminated, a label on the backside of the bottle reads “Not for consumption.”

of contaminants associated with the solid matrix, the interstitial water and/or the vapor phase prior to instituting a recharge program. The potential impact of sporadic leaching of trichloroethene (TCE) vapors through the unsaturated zone, by forced infiltration of rain water is illustrated by the following example. At an industrial contaminated site within the city of Tel Aviv, it was decided (in 2001) to remove several meters of surface soil layers contaminated with heavy metals. During winter, the resulting land depressions filled with rain water that infiltrated into the aquifer (Graber et al. 2002). As the unsaturated zone in the area is heavily contaminated with vapors of Cl-VOCs (e.g., TCE 1250 to 13,000 $\mu\text{g}/\text{L}_{\text{air}}$; Figure 4), groundwater is replenished with rain water heavily contaminated with TCE (e.g., $\sim 38,000 \mu\text{g}/\text{L}_{\text{water}}$).

Furthermore, the necessity of evaluating the impact of urban development on the quality of groundwater has been clearly demonstrated. For example, it has been found that increase of impervious surfaces increases pollutant concentration from point and nonpoint sources endangering groundwater quality (Mueller et al. 2002). Simulations prove that in an urban environment characterized by such a patchwork of permeable and impervious surfaces, the underground migration of contaminants may be enhanced due to the highly nonuniform recharge of rain

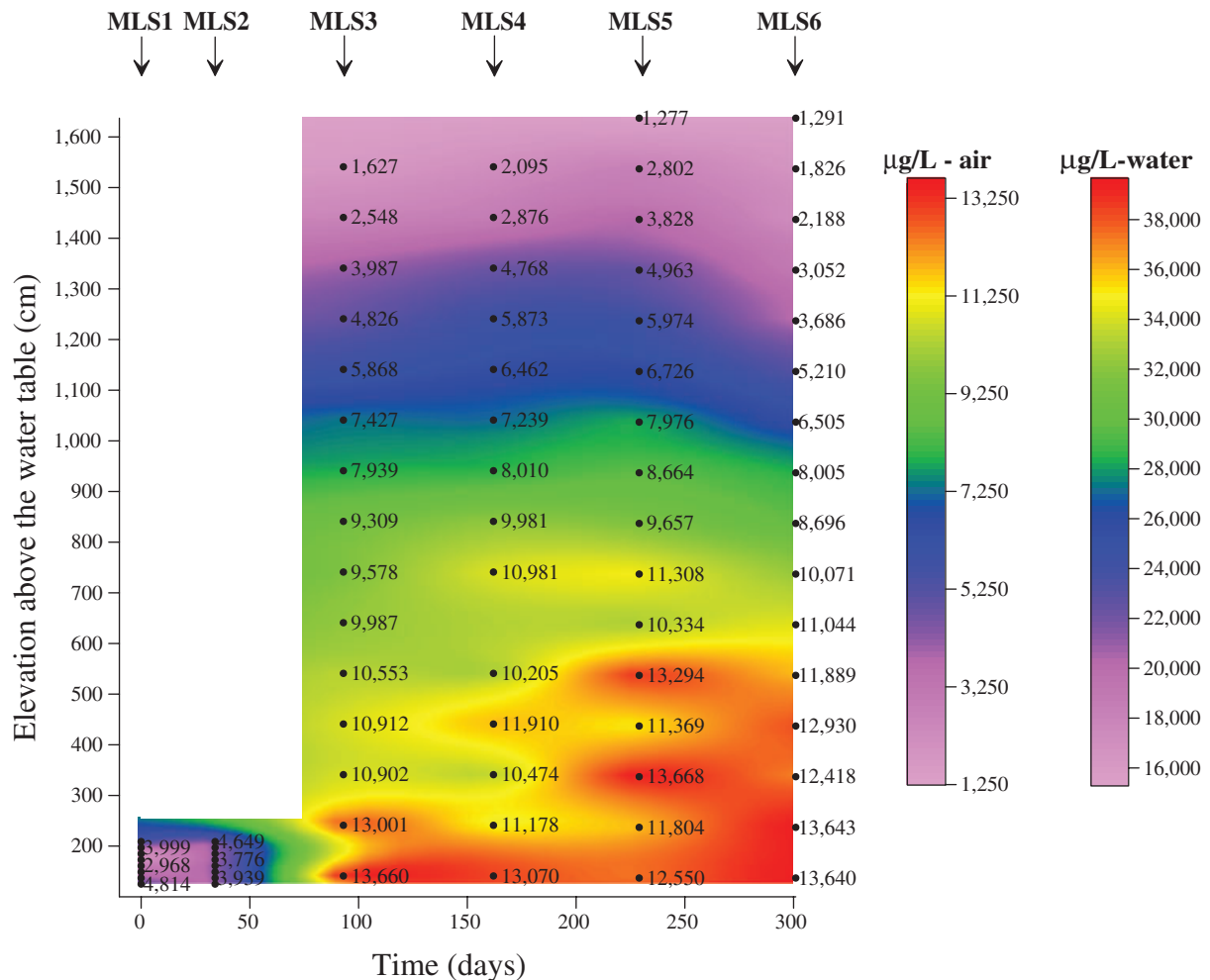


Figure 4. Krigging interpolation of TCE concentration in the gas phase of the unsaturated zone in monitoring well M5A. The well is located in a contaminated industrial site in the city of Tel Aviv. MLS 1 to MLS 6 denote profiles obtained with a passive multilayer sampler (March 16, 2004 to January 11, 2005). Well M5A penetrates through the unsaturated zone down to approximately 1 m above the water table (after Ronen et al. 2007). MLS 1 and MLS 2 covered only a small section of the unsaturated zone. Just nearby (~20 m), several meters of surface soil layers contaminated with heavy metals were removed creating land depressions that in winter are filled with rain water. Rain water recharge will equilibrate with the gas phase in the unsaturated zone reaching TCE concentrations shown on the TCE $\mu\text{g/L}_{\text{water}}$ scale (~16,000 to 38,000 $\mu\text{g TCE/L}_{\text{water}}$).

water (Sorek et al. 2005). Thus, mapping contaminated areas of an unsaturated zone can lead to a rational placement of recharge points. Detailed quantitative simulations can then predict the additional amounts of infiltrated rain water in urban areas that can be considered as a net positive input to the fresh water balance, and to what extent such a practice may lead to intensive and extensive aquifer contamination.

The Unsaturated Zone and Soil Aquifer Treatment (SAT) Practice

Porous media are considered to have different grades of “purification properties” for contaminated water solutions passing through them (e.g., see discussion of “natural attenuation” in section “Restoration to Pristine Conditions vs. Natural Attenuation”). This approach has led to consider Soil Aquifer Treatment (SAT) as an efficient tertiary process for sewage effluents after secondary treatment. According to Oren et al. (2007) during SAT “the

effluents are purified by physical, chemical and biological processes in the vadose zone and in the aquifer that remove essentially all biodegradable organics, suspended solids, bacteria and viruses from the wastewater, and almost all the phosphorous and heavy metals.”

Granular filters are used in many municipal water supply systems and in private houses. The SAT technique seems to be a psychological projection of this methodology. If, for example, a 30-cm long home-scale filter can remove contaminants why not rely on the purification properties of, say, a 30-m long unsaturated zone followed by flow through hundreds of meters of saturated porous media?

However, filters have a finite purification capacity and must be replaced. Is it reasonable to assume that the “purification capacity” of the porous media will never be exhausted or that the system will be immune to the impact of the solutions flowing through it? Indeed, this approach was shown to be quite problematic when,

after 25 years of operation, high concentrations of Mn ($2 \mu\text{mol/L} \leq \text{Mn} \leq 40 \mu\text{mol}$) appeared in the production wells of the Dan Region Sewage Reclamation Project that utilizes the SAT approach in Israel (Oren et al. 2007). Concentrations were often higher than the Israeli recommended maximum concentration for irrigation with effluents ($3.6 \mu\text{mol/L}$) and subsequently, Mn-oxides precipitated in the pipeline supplying reclaimed effluents to southern Israel and clogged drip irrigation systems. Oren et al. (2007) suggested that Mn is mobilized within the SAT system as a result of the concomitant reductive dissolution of Mn-oxides and the oxidation of organic matter.

A similar misconception led to the utilization of sewage effluents (after treatment by, e.g., oxidation ponds, extended aeration and trickling filters) for irrigation on the replenishment area of the Coastal Plain aquifer of Israel since the late 1950s (Ronen and Magaritz 1985). However, already in 1990, Amiel et al. (1990) reported that in that aquifer under land irrigated with sewage effluents (in Glil Yam, an area situated 15 km north of Tel Aviv), about 60% of the dissolved organic carbon (DOC) applied with the sewage effluents could still be found along the 30-m thick unsaturated zone where DOC is not biodegraded because of lack of bacterial activity. DOC influx into the saturated zone and the increased water content in the capillary fringe, lead to DOC biodegradation, the production of CO_2 (Affek et al. 1998) and the concomitant creation of an anoxic environment in the aquifer (Ronen et al. 1987). In the same study area, toluene (up to $50 \mu\text{g/L}$), *N*-butyl benzenesulfonamide (up to $140 \mu\text{g/L}$; Muszkat et al. 1993) and sulfamethoxazole (up to 35 ng/L ; Avisar et al. 2009), an antibiotic of the sulfonamide group, were detected in the water table region of the aquifer.

Therefore, also in relation to SAT it is evident that processes operative in porous media must be thoroughly recognized, studied, and quantified before recharging natural systems with contaminated solutions.

Well Contamination vs. Aquifer Contamination

The radically different attitudes often taken by administrators toward contaminated wells as opposed to contaminated aquifers are quite remarkable. A contaminated well (located by a largely uncontaminated aquifer) becomes the present pressing problem of the water supplier and the water manager. A contaminated aquifer (from where wells are still pumping noncontaminated water) will be the dilemma of the future administration.

For this reason, most aquifers of the world lack early warning monitoring systems that can alert decision makers about the arrival of contaminants, for example, to the water table region. Such information would create a managerial “to do” pressure while the supply of fresh water can most likely continue for many years. Therefore, in most cases, contamination is detected in pumping wells only after massive contamination of large portions of the aquifer, a situation that leads to the aforementioned FATA syndrome.

The definition of a shield radius (protection area) for a pumping well (e.g., Florida, Department of Environmental Protection 2008) provides an additional example that management sometimes prefers protecting a water extraction source as opposed to safeguarding the entire reservoir. The shield radius concept was initially established to prevent bacterial contamination of pumping wells. It was based on empirical evidence related to the transport time and survival of bacteria in the aquifer from the contamination source to the well. In some countries (e.g., Israel), this concept was further extended and applied to chemical contaminants in general considering, for example, dilution (one of the “natural attenuation” processes) to be the mitigating factor.

Actually, the shield radius concept addresses the present problem of the water supply source and the water supplier, disregarding the possible massive contamination of the entire aquifer.

Some of the Reasons for Unreasonableness in Groundwater Quality Management

We suggest several possible causes, leading to unreasonableness in groundwater management, to be: (1) the residence time of processes associated with groundwater; (2) the proliferation of “groundwater experts” that are not properly trained to quantitatively analyze and understand interdisciplinary water-related topics; (3) the neglect of the cyclic nature of natural phenomena; and (4) ignoring future long-term costs caused by irreversible aquifer damage when deferring monitoring, measurement, and modeling activities because of their immediate costs.

(1) It is quite difficult for a decision maker holding a political-administrative position for, say, 5 years, to pay attention and react to the expected results of processes occurring in aquifers estimated to be observed after, for example, 15 years (e.g., transport of contaminants along a 30-m thick unsaturated zone at a velocity of about 2 m/year; Gvirtzman et al. 1986). Are we justified in criticizing giving priority to a “now” and “here” pressing difficulty, such as the deteriorating water supply of a city, while postponing (consciously or unconsciously) long-lasting activities (e.g., site characterization, monitoring, and mathematical modeling) related to an uncertain future groundwater problem?

Part of the impatience that may characterize policy making with groundwater quality could arise from the shorter timeframe to which people have become accustomed as a result of relative successes in rehabilitating quality of riparian systems. The Cuyahoga River in Ohio and the Rhine River in Europe were both at one time severely polluted, but regulations in response to public pressure to control point source pollution resulted in both rivers showing significant improvements in water quality within two decades (Raat 2001; Zeitler 2001). Tellingly the sediment in the Cuyahoga River is still contaminated and this points to the problem when dealing with groundwater without fast-moving streams to flush out contaminants.

Considering the time frame of kinetic processes in aquifers, an adequate quantitative managerial scheme would require two interconnected stages of short- and long-term planning and management involving continuous as well as inter-related analysis and feedback (Sorek et al. 2010). Explicitly, an iterative process is required involving: (1) monitoring the results of activities and outcomes of short-term planning and management and (2) analyzing the influence of these results on long-term managerial objectives—modeling will play a key role in the latter.

(2) Hydrology is considered to be an open field where any expert from almost any discipline can make a statement and provide recommendations not directly related to his or her area of knowledge. Thus, groundwater management is frequently influenced by wrong perceptions, approaches, and solutions.

Indeed, Feitelson et al. (2007), in their analyses of Israel's water commissioners, prove professional background and career path to be an important factor in water decision making. Considering the period 1959 to 2006, they examined the attitude of seven Israeli water commissioners, four of them without formal water education, and three engineers. Feitelson et al. (2007) acknowledge two distinct patterns of policy making: (1) that of brinkmanship, adopted by the first group (without a water-related education), "*whose goal is to provide the maximal amount of water for agriculture, even at the expense of the reliability and future quality of the resource*" and (2) that of "*precedence of the state of the resource over immediate agricultural needs,*" a policy advocated by the water commissioners with a professional background.

(3) The cyclic nature of natural phenomena as well as the influence of climatic fluctuations is reflected in the biblical account of Joseph and Pharaoh (maybe reflecting an ancient El Niño effect as suggested by Yakir et al. (1996) and Kondrashov et al. (2005)). It was also in those early days that a good planning policy of storage and preservation was first adopted to overcome dry stressful climate episodes. However, in many cases, modern management is triggered by the "hydro-illogical cycle," where rain leads to tranquility and apathy, and drought encourages awareness, followed by concern and panic, which vanish with the first drops of the following rain. Thus, in the same biblical area, rainy seasons have caused managers to ignore Jerusalem's long-term annual rainfall records (showing, e.g., a very dry, 390 mm, period from 1925 to 1934 after a very wet, 700 mm, period from 1889 to 1898; EXACT 1998) and to overlook nature's unpredictability and thus, for example, to postpone the building of needed desalination plants. This attitude has led Israel to face a severe scenario of groundwater quality deterioration as a result of overexploitation of, for example, the Coastal Plain aquifer (e.g., Gvirtzman 2002; Melloul and Wollman 2003) and, in 2009, the possibility of having to limit municipal water allowances and to restrict agricultural production.

The consequences of the "hydro-illogical cycle" is not necessarily a syndrome of arid and semi-arid areas only. For example, in 2009 some areas of South

America were experiencing "the worst draught of the last 50 years" and as a consequence in Argentina, for example, some 10^6 heads of livestock died (IPS News 2009; CNN.com/world). Yet, some of the afflicted areas were located over and near one of the largest aquifers of the planet (the Guaraní aquifer with an area of $\sim 1,100,000$ km²) and near the Parana river with a discharge of approximately 15,000 m³/s. In view of this outcome, it is plausible to assume that abundant rain during the last 50 years triggered tranquility and apathy postponing the managerial measures that should have been taken after the last drought, 50 years ago.

(4) Although there are existing models and data for estimating the cost of various monitoring and remediation efforts involved in rehabilitating or containing damaged aquifers, methods for estimation of the long-term costs arising from losing the aquifer are not as developed (Rolfe 2010). This is partly because of the uncertainty regarding predicting future changes in populations and needs of the society using the aquifer. In such a case, there may be a tendency to use the present costs of water abstraction from the damaged aquifer and its treatment to usable quality and compare it to present costs of other water sources without considering other longer term considerations and costs. However, if an aquifer is irrevocably damaged, the costs in terms of developing alternative water resources and water transport to the population center (e.g., coastal plants to inland populations), possible health problems if no other water source is available, or the costs of moving populations if alternative water resources cannot be found, could easily dwarf present costs. If no serious effort is made to estimate the costs associated with these worst case long-term scenarios, then there is no yardstick against which to measure the present costs as to whether they are truly expensive with respect to their alternatives.

Reflections

It is quite impossible to demonstrate that the world would be a better place if only Ph.D. water experts were allowed to manage the water resources of our planet. Managerial capabilities, and political wisdom, are essential and important attributes that are not commonly found. However, hydrological ignorance is certainly not a prerequisite for such an enterprise. Although it is natural to understand that decisions about the standards for the configuration and strength of a building must be taken with the input of civil engineers and that health policy is set by people with a background in the medical sciences (e.g., Surgeon General of the United States), there does not seem to be the same expectation (at least in some countries) that groundwater policy be administered by someone with a modicum of expertise in water-related issues. As seen from the example of Israel's water commissioners mentioned earlier, one of the lessons to learn is that the water resources of a country should be under the leadership of a water expert with managerial capabilities. At the very least, there should be transparency that allows determining

if professional considerations were duly incorporated into the policy-making process. In general, we postulate that managers with knowledge on water-related topics will be in a better position to identify the spectrum of scientific knowhow needed for quantitatively assessing the possible outcomes of their decisions.

Administrators could argue that one source of the problem is the legitimate differences of opinion between scientists in evaluating different phenomena and problems. How are the administrators supposed to decide who is right? One tool which can be helpful in resolving such conflicts regarding water policy is the decision support system methodology (DSSM). At the first stage, DSSM enables resolution based on ranking alternatives vs. criteria (stakeholders). At the second stage, the decisions/policy developed in the first stage are then verified by simulation models that address the individual criteria, and refinements to the decisions are made where necessary (Sorek et al. 2010).

Conflicting expert opinions can be found in every area of science and public policy and the tribulations of global warming issue is an excellent example of this. However, this example shows that when enough evidence accumulates in the scientific community it can influence policy. What should be guarded against is that controversy is not used as an excuse to ignore scientific inputs (again global warming is the object lesson).

Can we a posteriori criticize past actions based on our present state of knowledge? Is it possible that major scientific developments in hydrology took place during the last decades so that in reality a lot of damage was done out of ignorance? As Bredehoeft (2005) pointed out, models and conclusions regarding groundwater quality have changed as additional data has become available. Indeed, knowledge is evolving continuously and such a question will always be valid for any scientific and technological area. However, we must make sure that the proper questions are asked and a way found so that groundwater management is based on the best available knowledge at the time.

It is suggested that raising awareness of policymakers on how to properly integrate quantitative analyses into the decision making regarding groundwater quality is a necessary antidote for the flaws highlighted here. Furthermore, we propose that it is the professional responsibility of the community of groundwater scientists to take up this challenge in addition to carrying out the quantitative analyses themselves.

The reticence of some professionals to get involved in the policy arena is understandable as it is not “purely” science. However if they do not do it, then who will? Only water-related experts can help administrators in sorting out conflicting data and prioritizing what data is most urgently needed.

Conclusions

During the last decades, groundwater quality management has been partly driven by apparently “rational”

approaches and decisions that lead to unexpected results. Lack of meaningful scientific data, unwillingness to apply integrative approaches in the analyses of groundwater systems and reluctance to develop quantitative managerial decision-making models coupled with the desire for providing prompt solutions concerning water supply, contributed to this state of affairs.

Moreover, the long cycle times involved in natural groundwater processes conflict with human beings’ natural tendency to look at short-term processes and results. This problem is further confounded when efforts to take the long-term view (e.g., aquifer rehabilitation) are not backed up by an adequate systematic study of the problem. Such a study is essential to choose rational strategies based on the water-related knowledge available at the time. Rather, the decisions are generally made in an atmosphere of crisis which is all too often the prerequisite for public action. To a certain extent, at least in the past experience of Israel, this has been exacerbated by appointing policymakers without the necessary technical background to appreciate the tradeoffs.

Groundwater quality management should be guided by comprehensive quantitative approaches that take into consideration inter-related processes that take place on different time scales. In water-related areas, the need for expert managerial systems (e.g., Seppälä 2003) based on adequate field monitoring schemes (as suggested by the European Water Framework Directive, e.g., WISE 2008) to support decision making is an imperative necessity. At the same time, more serious efforts must be made to educate policymakers and the public, so that the inherent conflict between the longer natural time scale and the shorter social time scale is mediated more effectively. Uncertainty will always accompany environmental systems, but a quantitative decision path has the virtue that it can always be corrected and refined.

A Chinese proverb suggests that, “Prophecy is extremely difficult, especially with respect to the future.” There is no need for prophets or prophecies to understand that regarding the quality of the groundwater resources of our planet we have chosen the wrong path. We hope that in many cases, we have not yet reached the point of no return, and in the cases we did, it is important to know it.

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