OVERVIEW AND FUTURE DIRECTIONS OF GROUND-WATER CONTAMINATION AND PROTECTION

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INTRODUCTION

Contamination of ground water, although not a new happening, has not appeared as a new environmental challenge until the late 1970s. Before then, it was an obscure problem because until the 1970s ground water was believed to be naturally protected from contamination by the layers of soils and rocks. Since then, however, every nation has reported cases of ground-water contamination, with some instances receiving widespread publicity. Ground-water quality, therefore, can no longer be regarded as a constant natural characteristic.

Contamination of ground water has always been with us because of its close link to human actions. Practically every human activity, every type of facility or structure installed by man represents a potential source of contamination. For centuries man has been disposing waste products by placing them in streams, storing them on the ground, or by various methods putting them into the ground. Every day, a wide variety of potentially harmful substances is regularly introduced into the subsurface formations and the aquifers. Ground-water contamination, as any other form of contamination, is the price the civilised world must pay for its existence. However, many methods are available to minimize or reduce the contamination; they fall into three broad categories: natural attenuation, preventive actions, and corrective actions.

CONTAMINATION OF GROUND WATER

Substances that can contaminate ground water can be divided into substances that occur naturally and substances produced or introduced by human activities. Naturally-occurring substances causing contamination of ground water include manganese, iron, toxic

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elements (e.g. arsenic, selenium), radium, and radon. Substances resulting from human activities include, for example, bacteria, viruses, nitrate, synthetic organic chemicals and hydrocarbons (e.g. solvents, pesticides, petroleum products), heavy metals, and landfill leachate.

NATURAL CONTAMINATION

Frequently, ground water contains one or more naturally-occurring chemical constituents, leached from soils or rocks by percolating water, in concentrations that impair the use of ground water. For example, iron and manganese in concentrations greater than 0.3 milligrams per liter (mg/l) and 0.05 mg/l, respectively, can impair the taste of water and affect the usefulness of water for some domestic and industrial purposes.

Selenium, a naturally-occurring, non-metallic element present in the soils and rocks is believed to be essential to human and animal nutrition in minute amounts but can be toxic at relatively low concentrations (0.01 mg/l). Selenium toxicity has been observed in many parts of the world. High selenium concentrations were found, for example, in the San Joaquin Valley, a heavily irrigated agricultural production area in California, USA. The selenium present in the ground water and drainage water in the Valley is believed to originate from sedimentary rocks of marine origin (Deverel, 1985). High concentrations of selenium (0.1 to 1.4 mg/l) caused high mortality rate of fish and birds in the nearby wildlife refuge.

Natural radioactivity and its effects on human health recently have become a major environmental concern because of the discovery of widespread occurrence of elevated levels of radon in the air of homes in the eastern United States. Radon in ground water is most prevalent in the northeastern United States, especially in the New England area (Zapecza and Szabo, 1988). High concentrations of radon in ground water were attributed to uranium minerals in granite and in pegmatite associated with metamorphic rocks of the states of Maine and New Hampshire.

A less publicized but also important hazard is the presence in ground water of other radionuclides such as radium or uranium. The most common radionuclides, including radon-222, radium-226 and -228, and uranium-234 and -238, are found as trace elements in most rocks and soils and are formed principally by radioactive decay of uranium-238 and thorium-232. The occurrence and distribution of radium and uranium in ground water is controlled primarily by the local geology and geochemistry. Radium in concentrations greater than 5 picocuries per liter (pCi/l), was found to be primarily present in the north-central (in Cambrian and Ordovician sandstones and Cretaceous sandstones) and southeastern United States (in granite), for example (Zapecza and Szabo, 1988). Uranium is widely dispersed in ground water because of the great mobility, the long half-life, and the relative abundance of this element. Uranium, in concentrations greater than 10 pCi/l, was found primarily in uranium-ore provinces, granites, and sediments derived from the granites in the north-central and south-central United States (Zapecza and Szabo, 1988).

ANTHROPOGENIC SOURCES OF CONTAMINATION

There is mounting evidence worldwide that ground-water quality is under threat from an ever-increasing number of chemicals, derived from urban and industrial activities and from agricultural practices. Ground-water contamination can usually be traced to five main origins: municipal (or urban), industrial, agricultural, domestic, and environmental. Typical contamination sources are included in Table 1. Many examples from Europe of contamination caused by these sources were provided in the assessment of problems and threats in the European Communities (Kohsiek et al, 1991). Moody (1990) presented good summary of major ground-water contamination sources in the United States. Examples from other parts of the world were included in Clarke et al (1996).

Waste disposal practices seem to be the prevalent source of ground-water contamination. Waste disposal of liquid and solid wastes can take a number of forms: septic systems; municipal, industrial, and military landfills; surface impoundments of wastewater; waste injection wells; and the direct application of wastes to land. In addition, a considerable amount of unregulated disposal, illegal dumping, and accidental spills contributes to ground-water contamination.

Septic systems are the largest source of waste discharged to the land. In the United States alone, between 820 and 1,460 million gallons of wastewater is released annually to the shallow aquifers (Moody, 1990). Septic system effluent contains bacteria, viruses, nitrate, and household chemicals.

Burial in a landfill is the most common means of disposing of municipal refuse and garbage. Precipitation that infiltrates the landfill can leach compounds from the buried solid waste. The result is leachate, a highly mineralized, noxious liquid containing large concentrations of such constituents as chloride, iron, manganese, sodium, and nitrate and a variety of organic chemicals, which leads to high BOD and COD.

Surface impoundments are another common form of waste disposal or storage. They are used to store, treat, or dispose of municipal wastewater and sludge, mine and industrial wastes, and oil and gas brines. Some impoundments are lined to prevent seepage of the liquid fraction of the waste. But most of them dispose the liquid by discharge to streams or by seepage through the bottom of the impoundment.

Storage and handling of waste materials and chemicals is another major source of ground-water contamination, which may result from leaks from both the above-ground and underground storage tanks and from accidental spills during handling or transport of chemicals or waste. Potential contaminants include petroleum products, organic compounds, acids, and trace metals.

In terms of areal extent, *agriculture* is one of the most widespread human activities that directly affect ground-water quality, with the millions of tons of fertilizers and pesticides spread on the ground and with the storage and disposal of animal waste. In agricultural areas nitrate-nitrogen concentrations in shallow ground water commonly exceed the drinking water standard of 10 mg/l. Some nitrate is retained by plants and soil particles. However, if applied in excessive amounts, the excess can be leached by natural precipitation or irrigation water and carried into ground water. Of greater concern is the potential leaching of the more mobile and persistent pesticides into ground water. There is a wide range of pesticides in common agricultural use, and many of them are toxic at very low levels.

Raising large numbers of livestock in feedlots and poultry in confinements generates huge volumes of animal waste, a potential significant source of nitrate contamination. Animal wastes at farms are often collected in storage facilities and later on used to fertilize fields.

Improperly constructed or abandoned wells can be another source of ground-water contamination. The common example of an improperly constructed well is the lack of or inadequate seal in the annular space between the casing and the borehole, which allows contaminated water from the surface to enter the well along the exterior of the surface casing. Many domestic wells are contaminated in this way by surface runoff containing storm water, barnyard waste, or septic system effluent. Improperly abandoned wells are a common potential source of contamination especially in urban and suburban areas. In the years before there were community water supply systems, most people relied on domestic wells to provide their drinking water. As the areas served by public water systems expanded, these private domestic wells were often abandoned without being properly sealed. These old, often long forgotten and built over wells can serve as a means for transmission of contaminants from the surface to an aquifer and can permit contaminated water to migrate freely from one aquifer to another (Zaporozec, 1981).

Saline water intrusion*.* The encroachment of saline water into the freshwater parts of aquifers is an ever-present threat of water supplies developed in coastal aquifers, where fresh ground water is delicately balanced on top of denser saline sea water. Overpumping a well can disturb this natural balance and cause the movement of sea water into the entire freshwater aquifer (Zaporozec, 1981). Once contaminated with salt water, aquifers must usually be abandoned. Overpumping a well can cause the intrusion of saline water also in the inland areas where aquifers are underlain by saline water.

GROUND-WATER PROTECTION

In spite of this long list of potential contamination problems, there is still time to protect much of the ground water. Although the potential risks of ground-water contamination are significant, they are not quite the crisis we are sometimes led to believe. It seems that ground-water contamination is largely localized and that only a small part of the earth's ground-water resources may now be impaired. Contaminated ground water will in most cases not travel more than a few thousand meters from the source, and in many cases not more than a few hundred of meters (Fetter, 1994). However, if there are multiple sources, or if the contamination is a result of widespread land-use practices, then the contamination can cover a large area. Gass (1980) estimated that approximately one to two percent of the area of usable aquifers in the United States may be contaminated. The problem may be in that these aquifers may well be in urban areas where the ground-water contamination threat is the greatest and the water is needed the most.

Once contaminated, ground water is very difficult and very costly to clean. However, ground-water contamination is not an irreversible process (Fetter, 1994). There are natural conditions that help reduce or remove contaminants by a variety of attenuation mechanisms. And in recent years many useful preventive measures have been recommended for ground-water protection and a number of technologies have been developed for restoring the quality of ground water that has been contaminated.

Strategies for ground-water protection may range from careful, complete protection to "controlled" degradation of ground-water quality, and even to complete dedication of an aquifer or its portion to treat and/or store wastewater. In general, ground-water protection strategies and alternatives can be grouped into three broad categories: natural protection, preventive actions, and corrective actions (Table 2).

NATURAL PROTECTION

Economic pressures have forced the consideration of an old concept of natural attenuation as an useful ground-water protection alternative. The staggering costs spent on ground-water cleanup have forced re-examination of how the cleanups are performed. After years of neglect, the realization that the legal and regulatory framework has made cleanup and remediation of ground water so costly has put natural attenuation again in the forefront of ground-water protection efforts (Brady et al., 1998).

The physical environment may provide some degree of natural protection with regard to contaminants entering the subsurface. The earth materials may act as natural filters to screen out some contaminants. Water infiltrating at the land surface may be contaminated but is naturally purified to some degree as it percolates through the soil and other fine-grained materials in the unsaturated zone.

In order to consider natural attenuation as a remedial method, natural conditions have to be favorable. The potential for natural attenuation is limited and varies from place to place. Different parts of the physical environment have varying capacities for attenuating contaminants; therefore, they have varying degrees of vulnerability to contamination. One of the methods to determine the potential for natural attenuation is vulnerability assessment and mapping.

The vulnerability of ground water to contamination from contamination sources at or near the land surface is controlled by hydrogeological parameters, the ground-water flow system, and the rate of recharge. Many methods and techniques for the assessment and mapping of ground-water vulnerability have been developed since the concept of vulnerability of ground water to contamination was first proposed in the 1960s (Vrba and Zaporozec, 1994). One of the better known approaches is the DRASTIC system developed in the United States (Aller et al, 1987). The available methods most commonly use the overlay approach combining several major physical factors considered important for the evaluation of a given area: soil characteristics, lithological composition and permeability of rocks, depth to bedrock, and depth to the water table.

PREVENTIVE ACTIONS

Contamination of ground water is not normally easily noticed and the detection of the source of contamination may present difficulty, particularly, for example, where the nature of the underground strata permits contaminating substances to travel considerable distances.

Even when the source of contamination has been traced and removed, it may be that the residual contamination of an aquifer will continue to pose problems. Once ground water has been contaminated, it may take many years after the source of contamination has been eliminated for natural processes to remove the contaminants from the aquifer. Therefore, a major effort should be directed toward preventing contamination from occurring. The cost of ground-water protection through prevention is generally much smaller than the cost of remediating the ground water after contamination is found. Freeze and Cherry (1989) emphasized this point almost ten years ago: "We should move away from high capital-cost, quick-fix remedial solutions, and recognize the need for long-term operational investment."

Proper knowledge of the extent and magnitude of potential problems is necessary for the design of an effective ground-water protection program. The inventory of contamination sources is one of the essential, most effective alternatives for protecting ground water. An assessment of both the existing and potential sources is needed before considering methods to prevent future ground-water problems.

In recent years a number of measures that can help prevent contamination of ground water have been recommended. There are two basic groups of alternatives available for the prevention of contamination: non-regulatory and regulatory (Born et al, 1987).

Non-regulatory alternatives include: voluntary best management practices, inspection and training programs, minimizing input of contaminants, and public education.

Managers and operators of facilities producing or handling potential sources of contamination should carefully design and maintain the operations and train the staff so that their activities would not result into introducing contaminants into the ground or ground water. The impact of agricultural practices could be reduced by voluntary actions of farmers managing their own land (e.g. livestock waste management, fertility management, crop rotation, integrated pest control, tillage practices, or irrigation scheduling).

Very important are those actions that can lead to minimising the input of contaminants: emergency spill response plans, waste reduction through recycling, and a public education program that would help citizens and land managers better understand the relationship of land-use activities to ground-water contamination.

There are many *regulatory options*: use restrictions, land-use controls, operation permits, ground-water standards, and national, state, and local laws and regulations.

Prevention of contamination involves in the first place the control or elimination of sources of ground-water contamination. This can be achieved by better product control, by banning certain harmful products, or by modifying the composition of others. Legal constraints can be placed on land uses or particular activities that have a potential to contaminate the ground water.

In addition to the protection provided to the ground water, or an aquifer, drinking-water supplies may need individual protection. This can be done by establishing water-well construction and abandonment regulations and by delineating protection zones around the water supply sources. Ideally, the protection zone should include the entire catchment contributing water to the source. Such protection zone would be complex and relatively large, placing severe economic burden on a community. In practice, the catchment area is divided into two or three subzones, and the most severe restrictions are applied only close to the source.

CORRECTIVE ACTIONS

Coping with ground-water contamination after it has occurred generates technical and management problems. Many great techniques and innovative technologies have emerged in response to cleanup regulations. Most of them are time-consuming and very expensive, and their successful application has not been completely proven. A great number of hydrogeologists and environmental scientists are beginning to doubt that the cleanup of contaminated ground water is feasible or achievable at all, especially in the case of dense nonaqueous phase liquids (DNAPLs).

Freeze and Cherry (1989) addressed this problem already ten years ago in their well-written editorial in *Ground Water*, and concluded that "We should move away from the present overemphasis on attempts at correction of ground-water problems caused by actions of past decades, ... and move toward investment in current water-resource protection by the prevention of leaks, soils, and improper disposal." Many authors since then have reached the same conclusion. The National Research Council report pointed out that "It is now recognized that for many sites, there are few if any technical remedies for meeting the goal of a permanent remedy." (National Research Council, 1994). And in the latest book, analyzing the current environmental cleanup laws and environmental remediation, Brady et al (1998) also suggested that the cleanup efforts will not return most soils and ground water to "anything approximating their precontaminated state."

There is a large number of remedial technologies available that can be implemented at contaminated sites. They fall into three broad categories: (1) source removal or isolation, (2) source/contaminant containment, and (3) cleanup and treatment.

Source Removal or Isolation. One extreme method of source control is to excavate and remove the source. Contaminated soil is often removed in order to prevent contamination from reaching ground water. High-toxicity, low-volume contaminant sources are often physically removed. Various surface controls can be used to reduce infiltration into a site: changing the surface drainage, constructing a low-permeability cap above the waste, and modifying ground-water flow patterns.

Source/Contaminant Containment. Control of ground water is often critical to the success of contaminant containment efforts. Three common methods used for the control are the installation of low-permeability vertical barriers around the waste body (sheet piling, slurry walls, or grout curtains), interceptor trenches to divert ground water, and hydraulic barriers to lower the water table by pumping. Physical containment includes encapsulation of a source or contaminated water or vitrification (fusion of soils and wastes into a glassy monolith). Hydraulic containment relies on ground-water pumping on a single well or a line of well points to change the hydraulic gradient to divert ground water or withdraw contaminated water. Permeable reactive barriers reverse this concept. Instead of serving to contain migration of contaminated water, they are designed to intercept the contaminated water, provide a preferential flow path through the reactive media, and immobilize or transform the contaminant(s) into a more desirable form.

Cleanup and Treatment. The most widely used approach for ground-water remediation is extraction of the contaminated water and its treatment at the surface, which is referred to as the pump-and-treat technology. This technology, however, is limited in its effectiveness for contaminant removal. A number of studies has indicated that after an initial, rapid decline in the concentration of contaminant, the concentration shows little change with additional pumping (Fetter, 1994).

In-situ treatment of contaminated water is accomplished by injecting chemicals, microorganisms, or oxygen into contaminated water. In-situ bioremediation uses microorganisms to convert contaminants to less harmful form. Bioventing is defined as the delivery of oxygen to soil to stimulate aerobic biodegradation of contaminants. Air sparging is the similar process except that air is injected under pressure below the water table.

Physical in-situ treatment technologies are used for both contaminated soil and contaminated water. They include soil flushing, or soil vapor extraction and steam injection. The efficiency of remedial technologies can be improved by hydraulic fracturing to induce contaminant migration or by addition of compatible surfactants to enhance contaminant solubility.

***Site Characterization**.* Corrective action usually is a three-step program consisting of site characterization, selection of remedial technology, and site remediation. Site characterization is a very important step in site remediation because it will determine the type of cleanup activities and the costs associated with them. Site characterization consists of investigation of the nature, extent, and distribution of contaminants, potential receptors and risks posed by contaminated ground water, and hydrogeological and contaminant properties. Inadequate site characterization can lead to flawed design of a remedial program and poor system performance or its failure.

MONITORING

Monitoring is not a method of protecting ground-water quality although it is often considered to be one. However, monitoring is an important device to detect ground-water contamination and provide an advanced warning of the approaching contaminated ground water to important sources of water supply. Ground-water quality monitoring has four objectives in relation to ground-water protection: (1) early discovery of ground-water contamination from a given source, (2) definition of the extent of ground-water contamination, (3) advance warning of the approaching ground-water contamination, and (4) quality control of drinking water (Clarke et al, 1996).

THE FUTURE

As populations grow and their standard of living increases, the pressures on ground-water resources also increase. Human activities including industrial production, agriculture, mining, transportation, and commercial and residential development will continue to pose the potential threats to ground-water quality. Our knowledge of the mechanisms of ground-water contamination needs to be expanded. Better understanding of the physical, chemical, and biological processes that effect soluble concentrations in the ground and processes controlling contaminant transport is needed for reliable and quantitative predictions of contaminant behavior and movement in the subsurface. Methods for assessing ground-water vulnerability need to be improved and formalized.

Cleanup of contaminated ground water is difficult and expensive, and generally requires long periods of time. The difficulty, costs, and time of major cleanup operations serve to help emphasize the need for true preventive programs over remediation. Over the next 20 to 30 years, federal, state, and local governments and private industry will continue to commit billions of dollars to cleanup sites contaminated with hazardous wastes and petroleum products. The future of environmental remediation lies in a recognition that money matters and that results matter even more.

The focus of environmental remediation needs to quickly change. Remedial technology is but one of the ground-water protection alternatives. Natural attenuation should always be considered as an useful alternative. However, caution should be exercised to avoid overusing natural attenuation as a remedy. Clearly some sites may be effectively remediated by natural attenuation processes, but others will still need the application of remedial technologies. Prevention of ground-water contamination is the only technically and economically viable option for protecting ground-water quality on a broad scale. A major effort should be directed, at all levels of government, toward prevention, which can save significant amounts of money and time, and will help preserve ground-water quality for future generations.

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Table 1. Major sources of ground-water contamination.

MUNICIPAL	AGRICULTURE
Solid waste disposal Wastewater impoundments Disposal of sewage sludge Leaking sewers Leaking underground tanks Improperly abandoned wells	Animal feedlots Animal waste storage Fertilizer storage and use Pesticide storage and use Silage
INDUSTRIAL	**DOMESTIC**
Liquid waste disposal Hazardous waste storage and disposal Storage tank and pipeline leaks Spills of chemicals Mining waste Injection wells Stockpiles, refuse piles Oilfield brines	Septic tanks, cesspools, privies Improperly constructed and abandoned wells Lawn fertilizer **ENVIRONMENTAL** Seawater intrusion Dissolved and particular matter in precipitation Natural contaminants

Table 2. Ground-water protection alternatives.

NATURAL PROTECTION	CORRECTIVE ACTIONS
Attenuation processes Vulnerability assessment **PREVENTIVE ACTIONS** Contamination source inventory Product control/restriction Land-use controls Design/operation requirements Well construction regulations Source protection zones Laws, regulations, enforcement Inspection and training Voluntary management practices Waste reduction Public education	Source removal/isolation Source/contaminant containment Physical encapsulation Vitrification Vertical barriers Interceptor trenches Hydraulic containment Permeable reactive barriers Cleanup and Treatment Pump and treat system In-situ bioremediation Bioventing/air sparging Soil vapor extraction Steam injection Soil flushing
Monitoring	Site characterization