ARTIFICIAL RECHARGE OF GROUNDWATER

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BUTTERWORTH PUBLISHERS
Boston • London
Sydney • Wellington • Durban • Toronto

Library of Congress Cataloging in Publication Data
Main entry under title:

Artificial recharge of groundwater.

Bibliography: p.
Includes index.
1. Water, Underground—Artificial recharge.
I. Asano, Takashi.
TD404.A78 1985 627′.56 84–14296
ISBN 0–250–40549–0

Butterworth Publishers
80 Montvale Avenue
Stoneham, MA 02180

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

CHAPTER 1

Overview: Artificial Recharge of Groundwater

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The increasing demand for water in the United States and other countries has produced the realization that the vast underground reservoirs formed by aquifers constitute invaluable water supply sources as well as water storage facilities. For instance, it is reported that over 95 percent of the freshwater available in this country is groundwater even after all the surface water bodies, including the Great Lakes, are included in the tally [1].

In the United States, the use of groundwater for freshwater supplies has steadily been increasing (see Chapter 2). During the last 25 years total freshwater withdrawals increased at an annual rate of 2 percent, whereas groundwater withdrawals increased at an average annual rate of 3.8 percent. In 1975, groundwater provided more than 40 percent of the total freshwater withdrawn in 23 of the 106 major hydrologic subregions of the United States. California extracted more groundwater than all of the eastern regions combined. For example, 48 percent of the total freshwater used in California in 1975 was obtained from groundwater wells; this usage accounted for 23 percent of the total national groundwater withdrawal [2].

Natural replenishment of the vast supply of underground water occurs very slowly; therefore, excessive continued exploitation of groundwater at a rate greater than this replenishment causes declining groundwater levels in the long term and, if not corrected, leads to eventual mining of groundwater.

To increase the natural supply of groundwater, artificial recharge of groundwater basins is becoming increasingly important in groundwater management and particularly in situations where the conjunctive use of surface water and groundwater resources is considered. Artificial recharge may be viewed as an augmentation of the natural movement of surface water into underground formations by some method of construction, by surface spreading of water, or by artificially changing natural conditions [3]. In the context of conjunctive use of surface and ground waters, a broader term such as *managed recharge* may be more applicable in water resources planning (see Chapters 3 and 4).

The purpose of artificial recharge of groundwater has been to reduce, stop, or even reverse declining levels of groundwater; to protect underground freshwater in coastal aquifers against saltwater intrusion from the ocean; and to store surface water, including flood or other surplus water, imported water, and reclaimed wastewater for future use. Groundwater recharge can also be accomplished as a result of water renovation in high-rate soil-aquifer wastewater treatment systems or riverbank filtration systems. There are several advantages to storing water underground [3, 4, 5, 6; see also Chapters 2 and 3]. The cost of recharge may be lower than the cost of equivalent surface reservoirs. The aquifer serves as an eventual distribution system and eliminates the need for surface pipelines or canals. Water stored in surface reservoirs is subject to evaporation and pollution, which may be avoided by underground storage. Even more important is the fact that suitable sites for surface reservoirs may not be available or environmentally acceptable. Thus, in most situations, artificial recharge projects not only serve as water conservation mechanisms but also assist in overcoming problems associated with overdrafts [3].

Placing water underground for future use involves obtaining an adequate quantity and quality of water for this purpose. The primary sources of water for artificial recharge may be diversion from surface streams or reclaimed wastewater.

RECHARGE METHODS AND HYDRAULICS

A variety of methods have been developed to recharge groundwater, and most use variations or combinations of direct-surface, direct-subsurface, or indirect recharge techniques (see Chapter 4). However, the most widely practiced methods are direct-surface techniques, including surface flooding, ditch and furrow systems, basins, and stream channel modification. The advantage of groundwater recharge by these direct-surface techniques lies in the ability to replenish underground water supplies in the vicinity of metropolitan and agricultural areas, where groundwater overdraft is severe; and there is an added benefit of the filtering effect of soils and the transmission of water by aquifers.

In contrast to the surface recharge techniques, groundwater recharge by subsurface injection is practiced, in most cases where the groundwater is deep or where the topography or existing land use such as in urban areas makes basin recharge impractical or too expensive. This method of groundwater recharge is particularly effective in creating freshwater barriers in coastal aquifers against intrusion of saltwater from the sea.

The third groundwater recharge method involves special cases in which potable water-supply is provided by riverbank or sand dune filtration of generally polluted river water. This method of treatment is practiced in Europe, particularly in the Federal Republic of Germany and in The Netherlands (see Chapters 16 and 17). Groundwater recharge is incorporated in these cases as an element in water supply systems in which the source is usually polluted river water. The filtered water traverses an aquifer to an extraction point at some distance from the riverbank.

Recharge to the aquifer may take place directly from the surface supply or through an unsaturated (vadose) zone. Saturated flow through a porous medium is similar to laminar flow in smooth, narrow tubes but is considerably more complex because of the fortuitous path water must follow in soil voids. In both cases a fluid flow is driven by a head gradient and retarded by friction and intermolecular attractions. However, in a porous medium such as a soil system the pore space consists of passages that are irregular, interconnected, and frequently discontinuous, which significantly complicates flow on a microscopic scale. For simplicity, flow through a saturated, porous medium is often represented on a larger scale as a velocity vector, or an overall average of the microscopic velocities within the total volume of porous medium. Development of an equation to quantify groundwater flow requires the combination of two fundamental physical laws—Darcy's law and the law of mass conservation (see Chapter 4).

In arid climates, where the practice of artificial recharge is most imperative, recharge will occur through such means as dry river beds and spreading basins, and in most situations there will be an unsaturated zone between the surface and the aquifer. The fundamental principles that apply to the saturated flow can also be extended to unsaturated flow. Unsaturated flow processes, however, are complicated by complex relationships between water content, pressure head, and hydraulic conductivity. The driving forces for flow under saturated conditions are total head gradients that include positive pressure heads; whereas for flow under unsaturated conditions, driving forces are total head gradients that include negative pressure heads.

In the presence of an unsaturated zone, flow will take place by infiltration beneath the surface. If water application is discontinued, infiltration will cease and the previously infiltrated water in storage in the vadose zone will continue downward but usually at a slower rate until surface tension forces equal gravitational forces. The "slug" of water will remain suspended until another slug reaches it and pushes it further down. Once the wetting front reaches the water table, recharge starts. Once the wetting front begins to merge with the underlying saturated zone, the incoming discharge changes direction and flows mainly below the water table and generally parallel to the water table (see Chapter 3). The general equation for unsaturated flow takes the same form as the equation for saturated flow where both pressure head and hydraulic conductivity are functions of water content, spatial position, and time (see Chapters 3 and 4).

GROUNDWATER SAMPLING AND MONITORING

The knowledge of the time, space, and chemical relationships of artificially recharged water to the underground environment is important and, therefore, sampling and monitoring systems are required to provide such knowledge with any recharge operation. A monitoring system must be designed to obtain samples in sufficient quantities and in a timely manner to accurately represent the state of the aquifer and the effectiveness of artificial recharge.

More specifically, an effective monitoring system can provide information on such objectives as determining pollution potential, travel time, long-term effects of continuous recharge, aquifer characteristics, aquifer changes, and recharge system performance [14, 15]. Hence, it is necessary that instrumentation and sampling not only accurately monitor the underground environment but also the surface water source to provide comparative bases. In general, two sets of baseline data are obtained for these purposes: the pre-experimental groundwater and aquifer condition, and the pre-experimental and temporal recharge source water quality. These spatial and temporal monitoring data for the groundwater recharge system are of basic importance for analysis and evaluation (see Chapter 6).

MODELING OF GROUNDWATER RESPONSE TO ARTIFICIAL RECHARGE

The saturated and unsaturated groundwater flow equations provide a means of analyzing the impact of hydraulic stresses imposed on a groundwater system. The modeling techniques that have been applied include (1) mathematical models, (2) porous medium models, (3) analog models, and (4) numerical models. The degree to which the hydrologic stresses of artificial recharge can be predicted by these methods depends first on the proper conceptualization of the problem and second on the choice of analytical technique (see Chapters 3, 4, and 5).

In recent years, the advent of increased computer capabilities has resulted in almost exclusive use of numerical models for solving complex groundwater flow problems. Reviews of the basis and the use of such models can be found in standard groundwater hydrology books. However, some examples of the complex hydrologic conditions that develop during certain types of artificial recharge include (1) flow in water table aquifers having relatively large changes in saturated thickness, (2) flow in partially saturated systems where rainfall-runoff models are coupled with soil-moisture accounting and aquifer-flow models, (3) flow in complex groundwater-surface water systems, (4) interaction of economic and hydrologic considerations, and (5) transport of contaminants in an aquifer [7; see also Chapter 4].

Both the finite element and finite difference approaches are used as numerical analogs of the governing two dimensional, dynamic equation of state. In several special cases, three dimensional models have been advanced, and models that include the unsaturated zone have been developed (see Chapter 5).

GROUNDWATER RECHARGE WITH RECLAIMED WASTEWATER

Among the several sources of available water for groundwater recharge, which include direct precipitation, flood or other surplus water, imported water, and reclaimed wastewater, increasing attention has been given in recent years to the use of reclaimed municipal wastewater. Groundwater recharge with reclaimed municipal wastewater is an approach to water reuse that results in the planned augmentation of groundwater supplies.

In the United States, the 1976–1977 drought in the western states and later droughts in the midwestern and southwestern states focused special attention on several water resources management options to meet the water needs of agriculture, industry, and urban areas. These options include measures to reduce water consumption, water exchanges and transfers, conjunctive use of surface water and groundwater, crop selection, and wastewater reclamation and reuse. While droughts have highlighted the need for additional water resources development, it is anticipated that the next large increment of freshwater supply will be much higher in cost than existing supplies, due mainly to the remoteness of new water sources, escalating energy and delivery costs, environmental considerations, and increasing competition for available water supplies.

There are a number of factors that affect implementation of municipal wastewater reclamation and reuse. Historically, the impetus for wastewater reuse has risen from three prime motivating factors: (1) availability of high-quality effluent, (2) increasing cost of freshwater development, and (3) desirability of establishing comprehensive water resources planning, including water conservation and wastewater reuse. Additionally, the availability of reclaimed water for reuse at relatively low incremental cost and its dependability as a source of water even in a drought year are primary reasons for its consideration in groundwater recharge.

Although the surface spreading method of groundwater recharge is in itself an effective form of wastewater treatment, a certain degree of pretreatment must be provided to untreated municipal wastewater before it can be used for groundwater recharge. Thus, the stringency of preapplication treatment requirements is an important factor in the planning, design, and management of groundwater recharge with reclaimed wastewater.

Four water quality factors are of particular significance in groundwater recharge with reclaimed water [8]: (1) microbiological quality, (2) total mineral content, (3) presence of a mineral toxicant of the heavy metal type, and (4) the concentration of stable organic substances. Thus, groundwater recharge with reclaimed wastewater presents a wide spectrum of technical and health challenges that must be carefully evaluated. Some basic questions that need to be addressed include [6, 9, 10]:

1. What treatment processes are available for producing water suitable for groundwater recharge?
2. How do these processes perform in practice?
3. How does water quality change during infiltration-percolation and in the groundwater zone?
4. What do infiltration-percolation and groundwater passage contribute to the overall treatment system performance and reliability?
5. What are the important health issues?
6. How do these issues influence standards for water quality at the points of recharge and extraction?
7. What benefits and problems have been experienced in practice?

PRETREATMENT PROCESSES FOR GROUNDWATER RECHARGE

In the past, prior to the recent concerns about trace organics and viruses in drinking water, several apparently successful groundwater recharge projects were developed and operated using secondary effluent in spreading basins. However, because of the increasing concern that low concentrations of stable organics and heavy metals may cause long-term health effects and because of the potential presence of pathogenic organisms in reclaimed wastewater, groundwater recharge with reclaimed wastewater normally entails further treatment following conventional secondary treatment. The pretreatment processes may include disinfection, chemical oxidation, coagulation and flocculation, clarification, filtration, air stripping, ion exchange, activated carbon adsorption, and reverse osmosis or other membrane separation processes. However, when a soil-aquifer system is used for treating wastewater and there is controlled underground movement and collection of the water, pretreatment requirements for groundwater recharge could be less and there should be an optimum combination of pretreatment, soil-aquifer treatment, and posttreatment of the renovated water.

Issues Related to Engineering and Public Health

There are several major engineering issues related to wastewater reclamation and reuse, which specifically concern groundwater recharge or possible potable reuse [11]: (1) the quality of the wastewater source, (2) storage prior to treatment, (3) specification of treatment processes and design criteria, (4) process redundance requirements, (5) parameters affecting plant process control and operation, (6) storage of treated (reclaimed) water prior to use, and (7) operation and maintenance criteria.

National standards for drinking water quality are based on the use of raw waters from the highest quality sources and, therefore, are not considered appropriate when using treated wastewater (reclaimed water) directly as a source. In addition, factors of time, dilution, and natural purification (such as in reservoirs) provide a degree of protection for existing water supplies against the threat of chemical spills and microbiological contamination—a protection that may not be afforded in direct potable reuse systems [11; see also Chapter 7].

In all systems of groundwater recharge there are factors, in addition to those previously mentioned, that add to the safety of reuse. Two of these factors are time and space. Groundwater recharge with reclaimed wastewater involves storage of the mixture of groundwater and treated wastewater. This provides time for sampling and testing of water from the recharged aquifer before the water is used. It also provides time for natural bacterial die-away and biodegradation of organic substances. Further, the points of recharge and the points of withdrawal of the water for use are usually some distance apart. These factors of time-in-storage and separation-in-space are important public health considerations. Perhaps the greatest single advantage of including groundwater recharge in any program of wastewater reuse, especially potable reuse, is the loss of identity that groundwater recharge seems to provide for wastewater [12].

An examination of pretreatment processes for groundwater recharge reveals the emergence of two different philosophies regarding the necessary pretreatment steps for wastewater prior to groundwater recharge. One philosophy dictates that the wastewater should be pretreated to the extent that its addition to the groundwater system will not degrade the formation groundwater with respect to its potential uses. The major result of this policy is the establishment of the best practicable waste treatment technologies that will protect groundwater supplies for their highest beneficial uses (see Chapter 7). The other philosophy of groundwater recharge, characterized as "groundwater recharge for wastewater reuse" [13], incorporates the controlled passage of the effluent through the soil aquifer system for its measurable benefits.

Indeed, there appear to be two different approaches with respect to incorporation of groundwater recharge into wastewater reuse programs:

wastewater reuse for groundwater recharge, the prevailing concept in California [16]; and groundwater recharge for wastewater reuse, the concept of the Dan region project in Israel (see Chapter 15) and the Flushing Meadows project in Arizona (see Chapter 8). In the latter approach, by recharging the effluent to the groundwater aquifer in an area free of potable water supply wells and by installing strategically located groundwater recovery wells, an aquifer treatment area is created that can be segregated from the rest of the aquifer [13; see also Chapter 8]. This arrangement raises the possibility of dedicating a portion of an aquifer to groundwater recharge with reclaimed water and nonpotable water reuse, while minimizing the potential impact on uncontrolled use in other portions of the aquifer. Under such a system, it would be possible to capitalize on the treatment benefits of the soil aquifer system by recharging water of lower quality than that required at the extraction point, in confidence that existing use of the groundwater resource would not be jeopardized [9, 11].

Rapid-Infiltration Land Treatment Systems

As discussed previously, some dilution of the recharged water is provided by mixing with the groundwater existing in the aquifer, and some purification is provided by passage of the water through granular water-bearing materials. In addition, in the case of surface spreading of wastewater, further purification of the wastewater may be provided by (1) percolation through the aerobic zone of soil, (2) uptake of nutrients and other substances by crops or vegetation, (3) filtration and adsorption in the soil overburden above the aquifer, and (4) bacterial or chemical action [12].

With rapid-infiltration systems, wastewater or treated effluent is applied to relatively permeable soil at rates much higher than the evapotranspiration rates. Thus, most of the wastewater moves down to the groundwater and is renovated by filtration through the vadose zone and subsequent movement through the aquifer. This treatment aspect is becoming more and more important as the need for water reuse increases and protection of native groundwater becomes vital.

In most rapid-infiltration land treatment systems, the wastewater is applied to the soil in the infiltration basins. On sloping land, contour terraces or furrows can be used. Hydraulic loading rates of 20 to 150 m per year are used in these systems and 90 to almost 100 percent of the applied wastewater will move downward to the subsurface water and/or groundwater.

While some early rapid-infiltration systems undoubtedly were constructed to get rid of the wastewater and to put it out of sight, more recent systems are constructed primarily to reduce pollution of surface waters or to obtain the benefits of soil-aquifer treatment for subsequent reuse. Where there is no surface water that the renovated water can drain into and where soil-aquifer treatment and direct reuse of the water are the main objectives, the renovated water can be collected by wells if the groundwater is deep, or by open or closed drains if it is shallow (see Chapter 8).

HEALTH ASPECTS OF GROUNDWATER RECHARGE WITH RECLAIMED WASTEWATER

The health aspects of reclaimed water use have been the subject of much recent research and are the prime concern for the safe use of reclaimed wastewater for groundwater recharge as well as agricultural and landscape irrigation. Groundwater contamination by pathogenic microorganisms has not received as much attention as that of surface water because it is generally assumed that groundwater has a good microbiological quality and is free of pathogenic microorganisms. A number of well-documented disease outbreaks, however, have been traced to contaminated groundwater (see Chapter 9).

The extent to which soils can remove these pathogens depends on several specific factors, such as the nature of the soils, the nature of the pathogen concerned, temperature, and antagonism from native microflora. Because of their large size, parasitic protozoa and helminths may be efficiently removed by filtration through soils and may not be able to gain entrance into the groundwater. Bacterial removal by soils also occurs largely by filtration, although adsorption is also involved. Viruses, on the other hand, are thought to be removed from water by adsorption to soils only. Viruses cannot, however, be considered as permanently immobilized because they have been shown to elute and migrate further in soils following rainfall (see Chapter 9).

The acute effects from pathogenic microorganisms in wastewater are of immediate health concern; however, health effects due to prolonged exposure to low levels of chemical contaminants also warrant careful evaluation. There is substantial information available regarding the chronic effects from ingestion of trace amounts of metals, and the permissible levels of these contaminants have been established for drinking water. Information on stable organic substances in reclaimed wastewater is relatively scarce, and there is increasing concern that low concentrations of these substances may cause long-term health effects such as carcinogenesis and mutagenesis. Consequently, interest in research on the health effects of reclaimed wastewater for potable purposes increased in 1977 when the U.S. Federal Safe Drinking Water Act [17] specifically mandated that special studies were to be carried out to investigate health implications involved in the reclamation, recycling, and reuse of wastewater for drinking water.

Research carried out to date has emphasized the organics and toxicology areas (see Chapter 10). In many cases, effluents from advanced wastewater treatment plants were concentrated and then analyzed by the gas chromatographic and mass spectrophotometric (GC–MS) procedures for specific organic compounds, and they were also checked for mutagenic potential by the Ames technique. Comprehensive toxicologic studies, designed to evaluate the potential health effects of the application of reclaimed wastewater for drinking purposes, were carried out using the effluent from the Blue Plains Pilot Wastewater Treatment Plant located in Washington, D.C. It is generally recognized, however, that hazards potentially associated with potable use of reclaimed wastewater cannot be defined on a chemical basis alone. A broad approach is being taken to develop and apply methods for measuring the biological effects of chemicals present in drinking water regardless of supply source (see Chapter 10).

Since 1962, groundwater in the Montebello Forebay area of Los Angeles County, California has been replenished with reclaimed wastewater (the Whittier Narrows Groundwater Recharge Project). Well water in this area provides a substantial portion of the water supply for the residents. The existing groundwater recharge project provided an opportunity to gather data needed to evaluate the health significance of wastewater reuse in groundwater recharge. A wide range of research tasks was undertaken to meet the Health Effects Study objectives, including (1) water quality characterization, (2) toxicological and chemical studies, (3) percolation studies to evaluate the efficiency of soils in attenuating inorganic and organic chemicals in reclaimed wastewater, (4) hydrogeological studies to determine the movement of reclaimed wastewater through groundwater, and (5) epidemiological studies of populations ingesting reclaimed wastewater. The primary goal of the Health Effects Study was to reach some consensus regarding the status of the use of reclaimed wastewater for groundwater replenishment at the Whittier Narrows Groundwater Recharge Project, i.e., whether it should be discontinued, continued, or expanded (see Chapter 11).

RECHARGE OPERATIONS WITH RECLAIMED WASTEWATER

Artificial recharge of groundwater with freshwater has been practiced for more than 200 years throughout the world for a variety of purposes [18]. The United Nations [19] identified 31 sites outside of the United States where artificial recharge is either practiced or has been investigated. The examples reported are not comprehensive but point out rather extensive use of artificial recharge with freshwater throughout the world. By far the widest use of artificial recharge in countries outside of the United States is to supplement dwindling municipal and industrial groundwater supplies or to improve groundwater quality. Artificial recharge with freshwater has been practiced in the United States for nearly a century and probably at least one system is presently being operated in every state. The greatest number of systems are relatively small in size and are used to reduce the rate of water level decline in order to avoid water rationing or to supplement the yield from existing well fields [18, 20].

Among the several sources of available water for groundwater recharge, increasing attention has been given to the use of reclaimed wastewater. However, in spite of the obvious advantages inherent in groundwater recharge with reclaimed wastewater, planned wastewater reuse by this means is practiced at present on only a limited scale worldwide—less than 100 mgd or 112,000 acre feet (af) per year (see Chapter 7).

In addition to designs and structures contrived solely for artificial recharge of groundwater with reclaimed wastewater, a large quantity of water and wastewater provides unplanned and unmonitored incidental recharge. Inadvertent groundwater recharge includes seepage from wastewater treatment or storage facilities, particularly those methods using excavations, ponds, and lagoons. It also includes the waters applied for irrigation, some of which infiltrate to the water table carrying increased concentrations of dissolved solids and agricultural chemicals [18].

A number of planned artificial recharge operations with reclaimed wastewater exist in the United States and abroad. Several have been in operation for many years, others are in some stage of development, and still others have been abandoned for one reason or another. The current recharge operations that are described in detail in Chapters 8 and 12 through 19 are but a few examples. The cases selected exemplify some of the generalized concepts and techniques that have been developed over several decades. Because of the increasing concern for long-term health effects due to prolonged exposure to low levels of chemical contaminants, extensive treatment and monitoring are usually required.

The pretreatment processes may be relatively simple and conventional, such as at the Wrocław wastewater farm in Poland (Chapter 18), or may be highly sophisticated and complex, such as at Orange County's Water Factory 21 and at Nassau County's Cedar Creek Wastewater Reclamation-Recharge Facilities (see Chapters 12 and 13).

As discussed previously, three types of groundwater recharge are described in this book: surface spreading or percolation of reclaimed wastewater; direct injection of reclaimed wastewater; and riverbank or sand dune filtration of polluted river water. The role of riverbank filtration along the Rhine River in the Federal Republic of Germany is discussed in Chapter 16. The bank and dune filtration of surface waters in The Netherlands is explained in Chapter 17.

Three major groundwater recharge operations in the United States, which are located in Orange County, California; Nassau County, New York; and El Paso, Texas, are discussed in Chapters 12 through 14, respectively. A summary of the five-year experience in the Dan Region groundwater recharge project in Israel is provided in Chapter 15. In addition to its major purification effect in a soil-aquifer system, groundwater recharge as practiced in the Dan Region project fulfills a series of additional functions: it provides seasonal and multi-annual storage; it is a safety barrier against any unpredictable water quality deterioration; and it increases the system's reliability and has an important psychological effect, since the consumers are supplied from groundwater wells and not from the treatment plant outlet.

Groundwater recharge practices, including both artificial recharge methods and underground disposal of stormwater, in Japan are discussed in Chapter 19. Rainwater from areas surrounding a large apartment complex is percolated through seepage facilities, and the results indicate that both groundwater recharge and stormwater disposal can be accomplished simultaneously.

FATE OF MICROPOLLUTANTS DURING GROUNDWATER RECHARGE

The need for definitive information on the extent of contaminant removal by the soil system and the fate of micropollutants during groundwater recharge has been recognized and is being studied extensively. The concentrations of wastewater constituents are affected by processes encompassing physical, chemical, and biological means during groundwater recharge. The following basic phenomena must be taken into account in speculating on the water quality changes likely to occur in groundwater recharge: biodegradation by and growth of microorganisms, chemical oxidation and reduction, sorption and ion exchange, filtration, chemical precipitation or dilution, and volatilization or photochemical reactions [9]. The constituents of particular importance in groundwater recharge with reclaimed wastewater are organic and inorganic contaminants and microorganisms. Several questions of importance can be identified: How effectively are these contaminants removed during travel of water into and through soil-aquifer systems? What are the mechanisms of removal or transformation? What are the end products of possible transformations? And what is the speed of transport of the contaminants with respect to that of the water with which they are associated? (see Chapter 22).

In Chapters 8 and 20, micropollutant removal in a rapid infiltration land treatment system is reviewed. Trace organics, inorganics, and microorganisms are the constituents addressed in the chapters. For each constituent, health effects and removal mechanisms are reviewed. Several rapid-infiltration systems and their performance are also discussed in Chapter 20.

Soil deposition of trace metals in spreading basins as well as behavior of inorganic contaminants in reclaimed wastewater are the subject matter of Chapter 21. Unlike trapped organic contaminants, which may gradually decompose in soils, relatively immobile trace metals are expected to be deposited in soils almost permanently. The retention of trace metals in soils, therefore, may have long-term impacts on land use even after the groundwater recharge operation is terminated. For instance, after nearly 20 years of groundwater recharge with reclaimed wastewater at Whittier Narrows, California, appreciable amounts of trace metals contained in the reclaimed wastewater were found only in the surface 60 cm (24 in) of the soil profile but not below this depth (see Chapter 21).

Processes affecting the movement of trace organics in the subsurface environment deserve the highest priority attention so that the contribution of groundwater recharge to the water quality improvement can be reliably estimated. Organic contaminants reach the subsurface environment when reclaimed wastewaters are percolated through the soil surface or injected into aquifers for groundwater replenishment. Organic contaminants may also pass into the subsurface environment by land treatment of wastewater, such as by rapid-infiltration systems or transport and handling accidents involving organic materials or through leakage from storage facilities. Questions concerning the movement, transformation, and ultimate fate of trace organics need to be answered in order to assess the risks of contamination of potable groundwater supplies and the feasibility of groundwater recharge with reclaimed wastewater (see Chapters 8 and 22).

Two mechanisms involving sorption and biodegradation appear to be responsible for the movement and fate of organic contaminants in the subsurface environment. Sorption affects the rate of travel of organic contaminants through subsurface systems relative to that of water. Sorption also allows for the accumulation of organic contaminants on surface and subsurface soils. The ultimate fate of organic contaminants in a soil-aquifer system depends also on their biodegradability. However, appreciable biodegradation of such organic contaminants can occur only if they are used as secondary substrate: that is, if there is an abundant primary organic substrate available along with bacteria capable of decomposing both the primary and secondary substrates. Biodegradation is also possible if several organic substrates are present in a sufficiently large total concentration [21; also see Chapter 22]. These concepts are relatively new and little is known of the kinetics of biodegradation of such trace organics in soil-aquifer systems.

Chapter 23 summarizes the results of field work directed at understanding the behavior of trace organic contaminants in groundwater. The chapter represents a portion of the work carried out under a five-year research project dealing with the water quality aspects of groundwater recharge by direct injection of reclaimed wastewater in the Palo Alto Baylands near San Francisco, California.

Water quality changes were observed by analyzing samples from wells at distances of 10 to 40 m and in differing directions from the injection point. Data on trace organics showed evidence of retardation of movement in varying degrees, presumably caused by adsorptive interactions with the aquifer. Trihalomethane compounds showed evidence of biodegradation under anaerobic conditions in the aquifer but not under aerobic conditions. Other organic contaminants apparently did not degrade appreciably during the three-year duration of the field test. Concentration variations were attenuated substantially during aquifer passage (see Chapter 23).

LEGAL AND ECONOMIC ASPECTS OF GROUNDWATER RECHARGE

Artificial recharge of groundwater, particularly that using reclaimed wastewater, has a number of effects on water quality as well as on water right issues. Uncertainty as to ownership of reclaimed wastewater and potential liability for problems that might be caused by recharge of groundwater basins with reclaimed wastewater could complicate and jeopardize future large groundwater recharge projects in many parts of the country. For example, information recently developed by the Orange and Los Angeles Counties Water Reuse Study [22] indicates that as much as 120,000 af of reclaimed wastewater could be used annually for groundwater recharge in the water-short coastal areas of southern California. But even the wide support of wastewater reclamation and reuse experienced in California and the existence of successful groundwater recharge projects have not produced a substantially favorable climate among regulatory agencies for allowing new, large-scale reclaimed wastewater recharge projects at this time. It appears that the issues related to groundwater recharge with reclaimed wastewater center around questions far beyond engineering feasibility, such as pretreatment reliability and groundwater management. Because of the very nature of the municipal wastewater used for this purpose, significant public health, legal and institutional, and economic issues must be addressed and carefully evaluated.

Chapter 24 discusses legal aspects of groundwater recharge when water rights and water quality issues are dealt with in the context of control and management of groundwater basin storage. Special references are made to groundwater recharge with reclaimed wastewater and to legal questions pertaining to California cases.

Another important but somewhat elusive issue is related to the economic and institutional aspects of groundwater recharge. As a general rule, groundwater is most efficiently used when it is extracted at rates such that the net benefits from use are maximized over time. This objective can be expressed as a maximization problem and solved for conditions characteristic of the marginal user cost (see Chapter 25). It is important to recognize that, under some circumstances, the overdrafting of groundwater can be optimal and efficient from an economic standpoint. As a result, the existence of groundwater overdraft *per se* does not necessarily warrant the conclusion that groundwater is being exploited too rapidly (see Chapters 3 and 25). However, in the long run, pumping rates for any given aquifer cannot exceed groundwater recharge rates. Thus, the relative magnitude of pumping costs and benefits from use ultimately serve to ensure that only the annual recharge is extracted at an economically optimal depth.

Experience with full-scale groundwater recharge operations using reclaimed wastewater is still limited, and, as a consequence, the cost information of such operations is incomplete. The available data suggest that the costs of groundwater recharge with reclaimed wastewater vary substantially. These costs are a function of any upgrading necessary for preapplication treatment and conveyance facilities, as well as the costs of reclaimed wastewater application, land acquisition, and groundwater pumping and monitoring. The principal barrier to groundwater recharge with reclaimed wastewater, however, appears to be neither technical nor economic, but institutional. Where competitively exploited groundwaters are unmanaged, prices reflecting the real value of the water are absent. Thus, competing uses that yield even small positive returns can successfully bid for reclaimed water supplies because of the absence of institutional arrangements that reflect the true value of groundwater. Effective institutional arrangements for managing groundwater are a prerequisite for any successful groundwater recharge program (see Chapter 25).

RESEARCH NEEDS FOR GROUNDWATER QUALITY MANAGEMENT

As discussed previously, an understanding of the processes that affect the movement and degradation of contaminants in the subsurface environment is essential for effective groundwater quality management. The state of knowledge concerning these processes is, in many ways, insufficient to ensure protection of groundwater quality without excessive restrictions on other surface and subsurface activities.

Chapter 26 addresses the research needs for groundwater quality management and outlines research strategies based on the type of processes that affect pollutant movement in the subsurface environment: hydrologic, abiotic, and biotic. These processes act to influence the movement of water, the physical and chemical interactions that cause the pollutants to move at rates different from those of the water, and the decomposition (chemical or microbial) that removes the pollutant from the subsurface. In view of resolving the uncertainties related to the health effects of groundwater recharge with reclaimed wastewater, research emphasis is placed on stable organic substances and epidemiological studies of exposed populations [6, 23; also see Chapter 11].

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