ARTIFICIAL GROUNDWATER RECHARGE

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Contents

1. Introduction
1.1. Augmentation of Water Resources by Conventional Methods
1.2. Augmentation of Water Resources by Non-Conventional Methods
1.2.1. Desalination
1.2.2. Wastewater Regeneration (WWR)
1.2.3. Climate Modification
1.2.4. Reduction of Evaporation
2. Artificial Groundwater Recharge (AGR)
3. Influence of Recharge Factors
3.1. Geological Factors
3.2. Hydrogeologic Factors
3.3. Physical–Chemical Factors
3.3.1. Physical Characteristics
3.3.2. Chemical Characteristics
3.3.3. Groundwater Recharge Precautions
4. Methods of Artificial Recharge
4.1. Choice of Recharge Method
4.2. Treatment of Water for Recharge
4.3. Indirect Artificial Recharge (IAR)
4.3.1. Basins
4.3.2. Channels
4.3.3. Ditches
4.3.4. Holes
4.3.5. Floods
4.4. Direct Artificial Recharge (DAR)
4.4.1. Water Recharge Wells
5. Mixed Systems of Water Recharge
6. Evaluation of Aquifer Recharge Area by Piezometric Map Analysis
7. Advantages and Disadvantages of Artificial Groundwater Recharge
7.1. Advantages
7.2. Disadvantages
Glossary
Bibliography
Biographical Sketch

Summary

The increasing demand for water in many regions around the world has led to the implementation of more intensive water management measures to achieve more efficient utilization of limited available water supplies. The natural replenishment of groundwater occurs very slowly. If groundwater is exploited at a rate greater than that of its natural replenishment this will cause declining groundwater levels and, in the long term, destruction of the groundwater resource. To augment natural replenishment of groundwater reserves, the artificial recharge of groundwater has become increasingly important in many countries. In artificial recharge schemes aquifers are treated as a naturally-regulated system which may be used to store surface water, thereby leveling out seasonal variations in surface water availability and providing a steady supply of potable water. Furthermore, the soil can be utilized as a reactive agent for improving the quality of the surface water.

The main reasons for carrying out artificial recharge may be summarized as follows:

- promoting recovery of overexploited aquifers;
- storage of surficial waters during flood periods to maintain and improve supply in the dry season;
- storage of local or imported water in the aquifer;
- preventing seawater intrusion by creating freshwater barriers;
- increasing the value of aquifers for water distribution in areas with many wells;
- discharging certain wastewaters, such as cooling water;
- reducing groundwater salinity in agricultural areas;
- reducing subsidence caused by high pumping rates; and
- groundwater quality improvement.

1. Introduction

Groundwater resources can be defined as the waters present in the subsurface in a specific area during a specific period of time. These resources can be divided into:

- *natural water resources* (water resources present in the environment);
- *potential groundwater resources* (the maximum volume of groundwater resources that can be replaced by artificial methods); and
- *available* or *exploitable groundwater resources* (groundwater resources that can be exploited under particular socioeconomic constraints).

Natural groundwater resources include static and dynamic waters. The *natural static* resources are connate waters, which are contained by exploitable aquifers. Connate waters were formed during periods in which climatic and hydrogeologic conditions were very different from those today, as illustrated by the case of the present-day groundwater resources of the Sahara. *Natural dynamic* resources are the volumes of moving water on the Earth's surface (runoff) and in aquifers (groundwater).

Potential groundwater resources represent the maximum exploitable natural resource, accessible with or without the use of mechanical devices. Their potential is limited by hydrographic, hydrogeologic, geological, environmental, and ecological limitations. These resources are generally less than the total of all natural resources.

Available or exploitable groundwater resources are less than the total of potential resources because their extraction is subject to socioeconomic restrictions as well as natural physical limitations.

A distinction has also been drawn between conventional and non-conventional water resources. *Conventional resources* are exploited by traditional methods, while *non-conventional* resources require the application of new and innovative methods. The boundaries and scales of the two categories require updating continuously in the light of the development of scientific and technical knowledge and the application of new technologies. For example, for many years artificial recharge of aquifers was an innovative experimental method: today it is a well-established technology.

1.1. Augmentation of Water Resources by Conventional Methods

The most widespread methods for resource augmentation rely on *artificial storage* of water on the land surface using barrages, dams, weirs, and other structures. The major problem with surface storage is the loss of land covered with water, and the ecological, environmental, and social problems generated. These solutions are especially difficult to implement in countries with high population densities and land values.

Storage of water in the subsurface can avoid these problems. Induced recharge of aquifers by artificial means, or *artificial recharge*, has been used for many years in many different countries and may be considered a proven, conventional method for water resource augmentation. Artificial recharge uses aquifers as reservoirs to store and conserve natural river waters and other surface runoff. Its application depends heavily on the disciplines of hydrogeology and groundwater engineering.

Groundwater reservoirs do not occupy the land surface or lose water to evaporation and plant transpiration: both very important advantages in arid and semiarid regions. In addition, recharged water undergoes slow natural filtration in the subsurface, which tends to clean and purify it. For these reasons, surface waters should increasingly be used to augment groundwater reservoirs and supplies.

1.2. Augmentation of Water Resources by Non-Conventional Methods

Non-conventional water resource technologies that may be used in artificial recharge schemes include:

- desalination of salty or brackish waters
- wastewater recovery or regeneration
- climate modification programs
- schemes to reduce evaporation

In the near future it may also be possible to use water stored in Antarctic or Arctic icebergs. Usually it is only in situations where the need for water is extreme, such as in arid regions, that non-conventional solutions are used in water supply and the storage of water by artificial recharge.

1.2.1. Desalination

Desalination is a process that removes dissolved minerals (including salt, but also other minerals) from seawater, brackish water, or treated wastewater. A number of desalination technologies have been developed, including reverse osmosis, distillation, electrodialysis, and vacuum freezing.

The desalination of water in small plants has been carried out for centuries, but only in the later twentieth century were substantial technological advances and cost reductions achieved. Cost reductions have allowed this method to be used to supply areas without other water resources, such as deserts and islands, and to be integrated within larger water supply systems in areas where traditional water resources are inadequate.

An essential requirement for the process is the availability of abundant energy in various forms. Desalination plants are generally integrated with power generation plants using a common source of energy. A plant may produce more energy than necessary for desalination and use the surplus for other purposes, for example to produce electric energy.

Worldwide there are more than 7500 desalination plants in operation: the largest, in Saudi Arabia, produces about 128 million gallons of desalted water per day.

1.2.2. Wastewater Regeneration (WWR)

Wastewater regeneration is a process by which wastewater is treated to permit reuse for irrigation, and for industrial and municipal supply. The processes are similar to wastewater treatment prior to discharge to lakes or rivers. However, regeneration is more thorough because it must give the waters special qualitative characteristics to permit direct reuse, and to maximize a groundwater body's capacity for self-purification. A major problem with regard to water supply generally is that while water resources are decreasing at a steady rate, water demand for civil and industrial uses are increasing correspondingly rapidly. For this reason natural water bodies become increasingly contaminated, and more advanced decontamination methods are needed as a result.

Wastewater regeneration is common in remote areas, and those where water is very scarce. To a lesser extent, it is also used in areas where water resources are relatively abundant but where industrial water demand and high prices make treatment and reuse of water economically profitable. Limits to regeneration are imposed by the cost of water treatments needed to meet the chemical quality standards established by local laws and regulations.

1.2.3. Climate Modification

Increases in natural meteoric precipitation can been induced by cloud seeding. Rainfall is enhanced by introducing solid particles into the atmosphere that increase the number of natural freezing or condensing particles.

1.2.4. Reduction of Evaporation

Loss of water by evaporation is a very important issue. Its rate depends largely on local climatic conditions. The construction of large artificial storage reservoirs in arid or semiarid areas with very high temperatures may lead to high evaporation losses. Advances in research and large-scale testing have shown that protecting water with a molecular film prevents molecular diffusion into the air and greatly reduces losses.

2. Artificial Groundwater Recharge (AGR)

Traditionally, most water supply systems have been based on either surface water or groundwater. While surface water is being increasingly contaminated by domestic and industrial pollutants, microorganisms, and inorganic solutes, groundwater is generally of better quality and needs only simple, inexpensive treatment to meet the high standards required for water supply. However, the use of groundwater for water supply has led to a situation where natural replenishment cannot match exploitation rates, leading to falling groundwater levels. In view of likely future water shortages the two resources cannot be viewed as isolated bodies, and water resources management will need to give more attention to the combined use of surface and groundwater. Artificial recharge is one method that allows for management of this kind.

Artificial recharge (also sometimes called *planned recharge*) is a method of storing water underground at times of water surplus to meet demand in times of shortage. It has several potential advantages. They include the use of aquifers for storing and distributing water, and for the removal of contaminants by the natural cleaning processes that occur as polluted rain and surface water infiltrate the soil and percolate through soils and geological formations.

Artificial recharge is a process by which excess surface water is directed into suitable geological formations using infiltration basins, ditches, wells, or sprinkler systems. Bank filtration, or *induced recharge*, can be used if there is a direct hydraulic connection between an aquifer and a surface water body. In most artificial recharge schemes, aquifers are used for water storage and reuse.

Natural and artificial groundwater recharge involve the same basic physical and geochemical processes, but with some important differences. In artificial recharge the infiltration rate is much higher, thereby decreasing the period over which pollutants are exposed to the natural cleaning processes. This can pose problems, both for the quality of the water and for the operation of the artificial recharge plants. Increased knowledge of the processes involved obtained through research projects will be useful when planning and operating new artificial recharge plants.

The main objectives of artificial recharge are to increase available reserves of water and the water-resource potential of aquifers more generally. It can also be used for the following purposes (the percentages in brackets reflect the main purpose of documented schemes):

- promoting recovery of overexploited aquifers (25%);

- storage of surficial waters during flood periods to maintain and improve supply in the dry season (20%);
- storage of local or imported water in the aquifer (15%);
- preventing seawater intrusion by creating freshwater barriers (15%);
- increasing the value of aquifers for water distribution in areas with a high density of wells;
- discharging certain wastewaters, such as cooling water;
- reducing groundwater salinity in agricultural areas (10%);
- reducing subsidence caused by high pumping rates; and
- groundwater quality improvement.

(Objectives (e), (f), (h), and (i) combined account for ca. 15% of recharge schemes.)

3. Influence of Recharge Factors

Not all aquifers can be artificially recharged. The hydraulic characteristics of the aquifer, the nature of the existing groundwater, and the characteristics of the recharge water can have a major influence on the outcome of a recharge operation.

3.1. Geological Factors

One of the main factors affecting recharge is aquifer porosity. Porosity must be as high as possible, and this factor depends on a uniformity coefficient: where the coefficient is small, porosity is high. Another factor is the hydraulic conductivity of an aquifer: when the hydraulic conductivity is high, recharge is very quick. Hydraulic conductivity values tend to be high when the aquifer grain size is large. However, high conductivity means that an aquifer's ability to clean recharged water is low, so recharge must be carried out with clean water.

The chemical equilibrium in the aquifer is very important. In most cases the aquifer materials and groundwater are in chemical equilibrium, and care must be taken to ensure that the recharge water does not change this.

Clays tend to be good ion exchangers: if recharge water has a high sodium content then clay flocculation can result, with the consequent blocking of pores. It should also be noted that recharge water can dissolve aquifer materials, and special care should be taken with recharge in rocks that contain carbonates (limestone and dolomite), sulfates (evaporites), chlorides, and iron (pyrite) because of their high water solubility.

3.2. Hydrogeologic Factors

Artificial recharge depends on transmissivity and porosity values, and the uniformity of these parameters is very important. The receiving aquifer must be as homogeneous and isotropic as possible.

The velocity of recharge is directly proportional to transmissivity and hydraulic gradient in the aquifer. For this reason the water table or piezometric surface must be very well defined, so that the depression's water table or piezometric surface can be identified and used to optimize recharge conditions.

3.3. Physical–Chemical Factors

The chemical and physical characteristics of groundwater and recharge water have a great effect on the results of artificial recharge. The chemical, physical, and biological compatibility of the two kinds of waters must be investigated, as these properties can greatly influence plugging of the aquifer and therefore the rate and duration of recharge.

3.3.1. Physical Characteristics

The main physical characteristics to consider are:

- temperature
- pH
- total dissolved solids (TDS)
- electrical conductivity
- color and odor

Temperature can affect water viscosity, as the two properties are inversely proportional. Since the hydraulic conductivity of the ground is inversely proportional to water viscosity, this means that water that is cold flows more slowly in the aquifer than warmer water. Moreover, if temperature decreases water density grows proportionally, leading to thermal stratification of water in the aquifer. This stratification lead to the obstruction of pores and reduces water infiltration into the aquifer. Because of these factors, it is always recommended that an aquifer be recharged with water that is warmer than the groundwater; thermal effects arising from direct recharge are thus reduced, because surface water balances its temperature with groundwater during infiltration through the unsaturated zone. Even biological life (including microorganisms and bacteria) may be affected by thermal effects, both in the unsaturated and saturated zones.

3.3.2. Chemical Characteristics

The main important parameters affecting artificial recharge are dissolved gas and dissolved salts.

Dissolved or suspended gas (air) has a double function—chemical and physical—inside the aquifer. The presence of small air bubbles inside the pores may cause blockage of the aquifer and reduce percolation into the unsaturated zone. Oxygen in the air causes redox reactions in the ground that can chemically precipitate compounds that block the aquifer, reducing water quality.

Oxidation can destroy pathogenic organisms, prevent the leaching of iron and manganese, and cause the precipitation of iron salts in groundwater. The redox reactions raise the iron content of the water by increasing the solubility of the iron. The different chemical compositions and levels of dissolved salts in recharge water can change the geochemical equilibrium, producing ion exchanges with the aquifer matrix and groundwater. These ion exchanges precipitate salts such as sulfides, sulfates, carbonates, and hydrates. They can cause swelling of clays due to the exchange between sodium and hydrogen, and the coagulation of suspended clay particles in the water. These processes generally reduce porosity and lower the quality of water.

Great care must be taken with regard to the microorganism concentration in the recharge water. Its microbial content is generally higher than that of the receiving groundwater, and pollution of the aquifer may result.

The ground's ability to cleanse recharged water is very high, and is directly proportional to the residence time of water in the aquifer. Residence time, in turn, is directly proportional to subsurface flow distance and inversely proportional to the grain size of the aquifer matrix.

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Biographical Sketch

Dr. Roberto Spandre was born on 30 April 1950. He took his M.Sc. in Hydrogeology at Complutense University, Madrid, Spain, and his Ph.D. in Geology at the University of Pisa, Italy. Since 1979 he has been Professor of Hydrology at UNAM (Universidad Nacional Autonoma de Mexico), Mexico City. In 1980 he was appointed Senior Geologist (Libya) at the Geological Research Center, Florence, Italy. From 1981–91 he was Research Hydrogeologist at the Universidad Autonoma of Madrid, and was also employed by the Foreign Office Ministry of Italy. Since 1991 he has been Research Hydrogeologist and Titular Professor in the Earth Sciences Department at the University of Pisa.

Dr. Spandre has undertaken research projects for the European Community, the Italian Ministry of Universities and Scientific and Technologic Research, the National Research Council of Italy, the Italian Foreign Office, and UNEP. He has worked throughout Spain and in Cuba, El Salvador, Ecuador, Colombia), Mexico (DF, Aguascalientes, San Luis Potosi, Michoacan), Angola), Libya), India), the Czech Republic, the United States), and Argentina). He is a member of AGID (Association of Geoscientists for International Development), IAH (International Association of Hydrogeologists), IAEH (International Association of Environmental Hydrology), UNCCD (Convention to Combat Desertificacion), ALHSUD (Asociación Latinoamericana de Hidrologia para el Desarrollo), and the CST (Committee on Science and Technology) of the United Nations. He has more than 70 publications to his credit.