Groundwater and Energy

I. Introduction

Groundwater is used to maintain a healthy lifestyle not only by serving as a source of drinking water, but also as a catalyst of energy development and production. While surface water is likewise used for energy production, many states rely on groundwater in areas where surface water resources are not abundant. Without groundwater, daily activities such as watching television or driving a vehicle would be hindered because groundwater is necessary for power generation and fuel extraction.

While groundwater is indispensable for energy production, the reverse is also true, as energy is required for groundwater withdrawal, treatment, and delivery. Groundwater and energy are, therefore, closely interconnected, so as the demand for energy increases, the demand for groundwater increases as well. Similarly, energy conservation is directly linked to water conservation, which is necessary to ensure a lasting groundwater supply for future generations.

As the need for water continues to grow to meet the demands of a growing population, understanding the relationship between groundwater and energy will be essential for safeguarding continued delivery of energy and water to consumers.

II. Electrical Power Generation

In the United States, 90% of electricity comes from thermoelectric power plants that rely on fossil fuel or nuclear energy for power generation, while the other 10% rely on hydroelectricity or renewable energy (1). Surface water is the primary source of water used to cool thermoelectric power generators, while only 0.4% of groundwater is used to meet the total cooling water demand (2).

III. Fuel Extraction and Processing

Although 73% of the total amount of water used for mining geological deposits from the subsurface—such as coal, natural gas, and oil—comes from groundwater, most of the groundwater withdrawn is saline (2).

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Coal

In addition to using water for mineral extraction (about 3% of total water withdrawn by mining (3)), processing, cleaning, and controlling dust, mining also has the potential to change the hydrogeology of the region, meaning it can temporarily or permanently disrupt groundwater flow (4). Mine-related materials and waste, if not properly managed, can also contaminate groundwater supplies.

Abandoned hardrock and coal mine sites, numbered to be more than a million in the United States (5), as well as coal storage sites can be hazardous to the environment as a result of mine drainage laden with acids and heavy metals from waste rock and tailings. These contaminants can degrade local aquatic habitats and populations, impact drinking water supplies, and act as a corrosive agent on infrastructure.

Oil and natural gas

Conventional oil and gas extraction methods typically require between 39 to 94 gallons of water per one million British thermal units (a unit of measuring electric power) for drilling purposes (6). Additionally, oil and natural gas drilling may cause groundwater contamination, as equipment failures and mistakes do occur. Pennsylvania, for example, has reported 106 water wells contaminated by drilling operations since 2005 and West Virginia has reported 122 complaints of which four required the driller to take corrective action (7).

As energy security becomes an increasingly critical issue, oil and gas extraction methods such as hydraulic fracturing using horizontal wells have been more widely introduced to provide increased access to unconventional oil and natural gas reserves. Hydraulic fracturing, a method developed in the 1940s, injects high-pressure fluids into rock formations to create geologic pathways that help to release trapped oil and gas. Although hydraulic fracturing does require more water than conventional oil production, studies have recently shown that such larger quantities are associated with higher energy production (8). In order to prevent groundwater contamination, best practices should be in place for oil and gas well construction and maintenance, handling and storage of chemicals at the land surface, wastewater disposal, and filling and sealing of abandoned wells, as well as groundwater monitoring programs. Several states such as Wyoming, Arkansas, Pennsylvania, Michigan, and Texas have implemented regulations requiring hydraulic fracturing companies to reveal the chemicals used in the process. Some states require water testing prior to and after oil and gas drilling (9).

Uranium

Mining for uranium largely expanded in the years following World War II. Many legacy uranium mines and mills remain as current or potential sources of groundwater contamination.

Today, the most commonly used method of uranium extraction in the United States is in-situ leach mining (ISL) which uses a series of water injection and extraction wells. Water and chemicals are injected into the aquifer, the mixture dissolves the uranium, and the dissolved uranium is recovered as water is pumped to the surface (10). The process is repeated until uranium can no longer be economically recovered. In the United States, the affected aquifer is required by law to be restored to pre-mining conditions to enable future water usage. If not properly managed, in-situ mining has the potential to affect both the quality and quantity of adjacent groundwater via leaks, spills, or migration of contaminated groundwater.

Biofuel

Biofuel development is an energy-producing method derived from plant material. Ethanol production is typically based upon highly water-intensive crops such as corn and sugar cane. These crops compete for land and water resources with the food agriculture industry (11). It is estimated 15 gallons of water are required to produce 1 gallon of corn-derived ethanol (3). In addition to the large water requirement, fertilizer and pesticide application to crops used for biofuel production pose a potential threat to groundwater quality.

IV. Renewable Energy Production

Geothermal energy production

Geothermal energy development takes advantage of heat stored beneath the earth's surface to generate electricity for power plants, and to provide direct heat to buildings, roadways, sidewalks, and other above-ground infrastructure. Geothermal power plants direct water through wells from geothermal groundwater reservoirs deep underground to produce steam used to drive turbines. Such power generation is most frequently utilized in the western United States, Alaska, and Hawaii, where geothermal reservoirs are more abundant (12).

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Another geothermal energy-producing method is the use of groundwater-source heat pump (GSHP) systems to provide heating in winter and cooling in summer. GSHP units are designed to maximize the use of earth's thermal energy by using groundwater as a heat source in the winter and a heat sink in the summer. Since the heat pump system relies on the constancy of groundwater temperature, GSHP units save energy, cut electric bills, reduce greenhouse gas emissions, and offer lower hot-water costs than conventional heating and cooling systems (13).

Aquifer thermal energy storage (ATES) units are also a method of energy conservation, as they can store excess thermal energy from the summer and cooling potential from the winter.

Wind and solar energy production

Wind and solar energy technologies require minimal amounts of groundwater for construction and maintenance. Since wind power is generated mainly via kinetic energy, water for wind technology is required only for dust control and cleanup purposes. The construction of wind turbines generates a groundwater pollution risk no greater than that of other building projects.

Solar energy production varies in its use of groundwater, depending on the system. Solar thermal energy systems use water to produce steam to drive turbine electricity generators (14).

V. Subsurface Energy Storage and Disposal

Common types of underground energy storage and disposal are of hydrocarbons, thermal energy, carbon, and radioactive waste.

Hydrocarbon storage

The storage of refined petroleum in underground storage tanks (USTs) creates a challenging groundwater pollution risk. Ten gallons of gas from a UST can contaminate nearly 12 million gallons of water (5). Leaks from USTs can occur when petroleum product is pumped from the tank, while it is stored, and when it is transferred to the tank. While great strides have been made in underground storage practices, petroleum cleanup initiatives, and technology, groundwater can still be at risk.

Carbon capture and sequestration

Burning hydrocarbons for energy releases carbon dioxide (CO_2) into the atmosphere and contributes to the accumulation of greenhouse gases. Carbon capture and sequestration (CCS) is a means of mitigating CO_2 emissions by depositing captured carbon into underground geologic formations. Carbon sequestration has an estimated 2,600 to 22,000 billion metric tons of prospective CO_2 storage resources in oil and natural gas reservoirs, unmineable coal deposits, and saline formations, yet the process requires further research to determine its economic viability and potential consequences (15). If leaked from underground storage, CO_2 may increase the acidity of groundwater, potentially causing rock to leach toxic metals (16). Additionally, CCS pressure buildup at the injection site could cause saline groundwater to infiltrate freshwater aquifers.

Radioactive waste storage and disposal

Despite precautionary measures taken to prevent contamination, radioactive waste does have the potential to percolate into nearby groundwater sources if radioactive waste storage units are damaged, deteriorated, mishandled, or improperly constructed. For example, nuclear waste has been leaking irregularly from the Hanford, Washington storage site since the 1940s and it is estimated more than 80 square miles of groundwater have been contaminated (17).

VI. Groundwater Pumping, Treatment, and Use

In 2010, an average of 79 billion gallons per day of groundwater were withdrawn in the United States to meet industrial, agricultural, and public supply demands (3). Groundwater supply, on average, requires 30% more electricity than surface water distribution.

Groundwater pumping

On average, 2.7 kWh of electricity are required to lift 100,000 gallons of water toward the surface, although the exact amount of energy needed depends on the depth to water and the efficiency of the system (3). California, for example, uses approximately 6 billion kWh of energy to pump groundwater—which is higher than the total amount of energy necessary to sustain the California State Water Project, a series of surface canals conveying water from northern to southern California.

Groundwater treatment and distribution

Groundwater often only requires disinfection, such as chlorination, to meet drinking-water standards, whereas surface water treatment is a multistage process. As a result, fresh groundwater typically requires less energy for treatment than surface water. The energy intensity of groundwater chlorination is estimated to be about 9.8 kWh per million gallons (3). The distribution of treated ground-water to end users of public supplies, however, can have a much higher energy intensity. The amount of energy needed for distribution varies with the efficiency of the system, as older structures are more prone to break down and leak. Between 10% to 60% of treated water is estimated to be lost during delivery in the U.S. due to damaged and leaking pipelines (3). Water loss is, therefore, associated with energy loss, since energy that could have otherwise been used for different purposes is now used for water distribution.

Fresh groundwater typically requires less energy for treatment than surface water.

Energy for groundwater irrigation

Energy is required to supply the 55.3 billion gallons of water per day needed (18) for U.S. agriculture (the largest groundwater user). In states such as Kansas, Colorado, and Nebraska electricity and diesel fuel are primarily used to power groundwater irrigation pumps (19), while California mainly relies on electricity for irrigation.

Currently, the economic value of groundwater for agriculture use is $12–$4,500 per acre-foot (20). As groundwater use for irrigation increases, higher energy prices for pumping and distribution may increase the cost of agriculture and, consequently, food prices.

Desalination of brackish groundwater

Brackish groundwater is more saline than freshwater, but less so than seawater. It is typically found along the coast where saltwater meets freshwater or in inland areas deep underground. Due to its lower salt content, the desalination of brackish groundwater is relatively inexpensive and is, therefore, the primary reason why brackish water is viewed as a potential water source for energy production.

The desalination of brackish groundwater for drinking water or other uses requires significant amounts of energy, costing approximately $2 per 1,000 gallons of water. Desalination practices currently release between 15%–40% of the water pumped as concentrated brackish water-waste which, if not properly disposed, could contaminate groundwater supplies and reduce soil fertility (21).

Renewable energy used in groundwater production

Renewable energy, in addition to using water for its own maintenance, can be used to pump groundwater. The implementation of solar-powered groundwater systems is dependent on a number of factors, including water demand, long-term costs, and site location (22). In countries such as India where farmers are subsidized for implementing solar technology, authorities worry solar energy will lead to excessive groundwater extraction (23).

Groundwater circulation wells, a newly developed technology, is a groundwater treatment system powered by wind turbines. By screen-filtering extracted groundwater, a circulation well can remove contaminants from aquifers with zero net loss of water and little pollution to the environment (24).

VII. Groundwater-Energy Sustainability

In areas where water is removed faster than recharge enters the aquifer, groundwater pumping over the past few decades has caused groundwater tables to decline. Water levels in the High Plains aquifer region have declined by more than 100 feet in some areas. In other areas, the saturated thickness (depth between the water table and the base of the aquifer) decreased by half (25). Chicago, which had been using groundwater as the sole source of drinking water, experienced a 900-foot decline in groundwater levels between 1864 and 1980 (26). Although federal initiatives have since led Chicago water levels to recovery, decreased water levels in the Central Valley and the Great Plains will require increased amounts of energy to lift water for continued water supply.

Groundwater sustainability is necessary to ensure that future generations retain access to a steady supply of groundwater despite its growing demand. A number of initiatives, such as aquifer recharge and infrastructure changes, have been introduced to achieve such a goal, yet other factors, such as climate change, continue to pose challenges to the energy-groundwater nexus.

Managed aquifer recharge

Managed aquifer recharge (MAR) is the intentional recharge of aquifers. MAR systems promote energy conservation, as higher water levels require less energy to pump water. Although still under research, MAR systems are expected to have energy demands similar to typical groundwater pumping. In fact, MAR methods may prove to be more efficient and cost effective than conveying water over long distances (3).

Infrastructure changes

The implementation of water-efficient technology into daily domestic and industrial practices has contributed to significant decreases in water use. After the implementation of thermoelectric power plants with recirculating cooling systems, water use rates are now less than they were in 1970, signifying the reversal of a 25-year increasing trend in water use for energy production (27). Between 1985 and 2010, water use per capita experienced declines as a result of water-efficient appliances and improved use practices; however, many of these improvements were offset by population growth of cities in the driest parts of the country (27).

Climate change

Rising temperatures and extreme weather patterns may contribute to the decline of groundwater levels, increasing the depth of water in wells and the amount of energy needed to pump groundwater. Increased precipitation as a result of weather fluctuations does not indicate increased groundwater levels, since most of the precipitation may be collected as runoff, instead of percolating through the soil. Rising sea levels associated with climate change could potentially require increased effort, energy, and cost to treat groundwater affected by seawater intrusion or to create barriers to prevent seawater intrusion into fresh groundwater zones.

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