GROUNDWATER AND SURFACE WATER INTERACTIONS

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Summary

Groundwater and surface water interactions represent an important series of issues in water resources management. The exchange of water between these two different states is an important phenomenon that arises from infiltration, spring outcrop, connections between rivers and geological strata, thermal flow, and seawater intrusion. This article considers the different types of interactions: those between groundwater and surface runoff, and with glaciers and the snowy mantle. Artificial aquifer recharge and the interactions between seawater and groundwater are also considered. The last section concerns deep groundwater, and outlines some methods to trace surface water and groundwater exchanges.

1. General Approach

Groundwater and surface water have the same origin within the closed system of the totality of waters existing on Earth. These are estimated to total approximately 1.5×10^9 m^3 and are nearly all concentrated in one layer about 20 km thick, of which 10 km lies above sea level and 10 km beneath it. The waters above sea level take the form of water vapor in the lower atmosphere and of circulating freshwater both on the land surface and underground. Those below sea level are mainly ocean saltwaters, accounting for 95% of the total waters of the Earth. The remaining 5% is freshwater: of this, 80% is stabilized in solid form as ice caps, mountain glaciers, and snowy mantles. Nearly all remaining waters in a liquid state (approximately 99%) are groundwaters, and very little of these are in circulation on the land surface or are accumulating in freshwater lakes. The minimal water element that is in circulation represents a extremely dynamic and important phase of the hydrologic cycle. These processes are responsible for the circulation of the water masses between the oceans and the continents, together with the atmospheric transport of water vapor.

In the hydrologic cycle only 8% of the water evaporated from the oceans is transferred onto continents and an equal amount comes back to the oceans, partly in vapor form (2%) but mostly through the runoff of surface waters and through slow groundwater movements.

The motion and quality characteristics of surface and groundwater vary greatly, often leading to very different effects and conditions. It is because of these differences that the interactions and exchanges between surface and groundwater are of remarkable interest. Much of this interest is connected with their hydrological and hydrogeological implications, and with the potential value of surface and groundwater resources.

The fundamental differences between surface and groundwater can be characterized as follows:

- 1. Most surface water is in a solid state (snow and ice); others surface waters constitute the runoff from hillsides and the water in rivers, springs, and lakes.
- 2. Surface water movement is basically a function of the Earth's gravitational field. Within lakes there are fields of motion caused by variations of temperature or by the action of the wind. The fields of motion in groundwater are essentially regulated by the gravitational field in saturated two-phase flow (solid–liquid). In unsaturated porous media (where three phases—solid, liquid and gas, and vapor—are present) the influence of molecular forces becomes very important, and the superficial tension forces (thermal and vapor forces) often prevail over gravitational ones.
- 3. Groundwater moves at extremely low speeds, and in highly permeable aquifers. By contrast, surface waters flow on hillsides, and in streams and rivers, at higher speeds.
- 4. Surface waters have a free surface at which the piezometric line coincides with the water level; groundwater is often held under pressure in artesian aquifers, and here the piezometric line is above the level of the stratum.
- 5. Groundwater generally contains more dissolved chemical elements than surface water. In groundwater the concentration of such elements increases with the persistence of waters in the soil, the solubility of the rocks traversed by the waters, and the prevailing temperature, pressure, and pH. The oligo-mineral waters have low quantities of dissolved elements because they circulate, over relatively short timespans, in insoluble siliceous rocks. The chemical elements dissolved in groundwater are therefore of natural origin, and are largely governed by the rocks within which it flows. Pollution due to human activities may lead to the presence of chemical compound from other sources. Surface water under natural conditions has lower concentrations of chemical elements, reflecting the short duration of its contact with hillslope rocks and riverbeds.

However, surface waters hold concentrations of pollutants, due to outflow caused by anthropogenic activities, and also contain suspended solid material due to the hydrodynamic forces within its flow.

- 6. As a consequence of (5), surface water is vulnerable to pollution processes and very quickly disperses the polluting element by dilution, or by means of chemical and biological processes in which the role of dissolved oxygen is fundamental. By contrast, groundwaters are less vulnerable, depending on how distant the recharge areas are and on the permeability of the geological deposits that separate the aquifer from the surface. The phreatic strata are therefore more vulnerable than artesian aquifers, due to their direct contact with the surface waters that infiltrate and percolate in the soil. Pollution of an aquifer may be discovered long after its contact with the contaminant source. This delay is a function of the water's travel time, and of the diffusion, dispersion, and transportation of the solute. These detection problems aggravate the pollution issue, since pollution may already have assumed dangerous proportions by the time it is discovered. Any remediation process is therefore lengthy, involving wholesale replacement of waters in the aquifer after elimination of the polluting source.
- 7. Temperatures can vary much more rapidly in surface water bodies than in groundwater. The temperature of surface waters varies with the temperature of the air, and thus between day and night and with the seasons. Groundwater temperatures depend on the thermal gradient inside the aquifer. Variations are therefore slow; many extensive aquifers cannot be influenced by seasonal variations, and temperatures within them remain practically constant. The temperature of very deep groundwater increases with depth due to the presence of geothermal flow. Typical of these bodies are thermo-mineral waters, characterized by relatively high temperatures and high levels of dissolved salts.

Anthropogenic use of the surface water is easy and direct when it is possible to derive the necessary amount from the watercourse using gravity. Extraction becomes expensive and complex when the waters are loaded with sediments, however: surface water use can be difficult when treatment is needed, or when the water required is available at a great distance or only in certain seasons, calling for long aqueducts and reservoirs. The anthropogenic use of groundwater is easier in these respects because spring or well capacities vary less with the seasons. Water extraction from wells involves energy consumption, and this influences operating costs. However, groundwater use does not involve water treatment of the kind needed for surface water.

The conditions of motion in surface water and groundwater are generally different. The motion of surface water is usually governed by open-channel hydraulics, and the flow is almost always turbulent. The motion of groundwater in the aquifers may result from pressure flow (artesian aquifers) or free surface flow (phreatic aquifers), but is governed in most cases by the laminar motions set out in Darcy's law.

2. Groundwater and Surface Water Interactions

The interactions between surface water and groundwater often involve not only the exchange of water masses between the surface and the soil but also the modification of the physical, chemical, biological, and energetic properties of the waters. The form of interaction depends on the characteristics of the water bodies involved, and the prevailing ground characteristics and environment conditions.

In many cases of interaction the compressibility, viscosity, and density of the different water bodies can be regarded as constant; sometimes however the differences in density become fundamental, due to differing temperatures. The chemical and microbiological characteristics of surface water and groundwater are generally different.

The interactions and exchanges between surface and groundwater bodies are governed by the energetic conditions in force, and the consequent conditions of motion. Exchange between surface water and groundwater can happen in the event of direct contact between superficial waters and an aquifer. More often, however, the exchange happens through a series of levels of unsaturated soil.

In the first case there is a common hydraulic head, while in the second the two water bodies have independent hydraulic characteristics and motion. The unsaturated level varies according to the climatic conditions and the levels of the strata involved.

3. Rain and the Feeding of Groundwater

Atmospheric precipitation is the primary source of groundwater supply. This recharge happens mostly in extensive permeable areas, due to processes of diffuse infiltration. Flow in rivers transfers meteoric inflow from relatively rainy areas to areas of aquifer recharge. By way of example, the Nile transfers water from a high, rich river basin with equatorial precipitation through the desert areas of its course until it reaches the cultivated lands of its delta on the Mediterranean coast.

At the moment when the rain reaches the ground, part of it infiltrates and part runs off down the hillslope. The rain also creates superficial ponded accumulations in localized depressions in the soil surface. The rate of soil infiltration varies with soil structure, and with the vertical humidity content gradient in the ground.

In relatively dry soils the rate is high at the outset and tends to diminish, in time reaching a stable condition. If the moisture level of the underlying stratum increases due to contributions from infiltration, and can catch up and exceed the surface moisture level, a new “water body” featuring swamps, ponds, and humid areas may be created.

If, during the percolation process in the unsaturated soil, the water reaches less permeable or impervious levels it creates a level of saturated soil. In the presence of local impermeable levels of soils, as in the case of alluvial soils, a suspended stratum may be created.

The water that percolates in a soil tends to dissolve the soluble salts occurring there, and to transport them towards lower levels. Such processes are more active with increasing temperature, and involve both naturally occurring salts and those introduced by humans for agriculture (fertilizers, pesticides) and for more local industrial and other purposes.

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Biographical Sketches

Samuele Cavazza was born in 1930 in Italy. He is former professor of hydrology, hydrogeology, and water resources in the University of Pisa and Trento, where he is currently Professor of Hydraulic Territorial Control. He was formerly consultant to the FAO, UNESCO, and WMO in developing countries, and a member of working groups for hydrological, hydrogeological, and environmental topics. He was Italian delegate at the International Hydrological Decade (UNESCO), a member of the working group of the International Commission of Irrigation and Drainage (ICID), a member of the editorial board of the international ICID journal, and manager of hydraulic projects for water resources management, river floods control, and groundwater exploitation.. He has been a member of regional commissions for environment impact assessment in Italy. He is the author of various studies and scientific papers published in national and international journals and congresses.

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