Water Quality …. Lecture 3

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Characteristics of groundwater

Groundwater is held in the pore space of sediments such as sands or gravels or in the fissures of fractured rock such as crystalline rock and limestone. The body of rock or sediments containing the water is termed an aquifer and the upper water level in the saturated body is termed the water table. Typically, groundwaters have a steady flow pattern. Velocity is governed mainly by the porosity and permeability of the material through which the water flows, and mixing is poor.

The media (rock or sediment) in an aquifer are characterized by porosity and permeability. Porosity is the ratio of pore and fissure volume to the total volume of the media. It is measured as percentage voids and denotes the storage or water volume of the media. Permeability is a measure of the ease with which fluids in general may pass through the media under a potential gradient and indicates the relative rate of travel of water or fluids through media under given conditions. For water it is termed hydraulic conductivity.

Types of aquifer

Underground formations are of three basic types: hard crystalline rocks, consolidated sedimentary formations and unconsolidated sediments. The hard crystalline rocks include granites, gneisses, schists and quartzite and certain types of volcanic rocks such as basalts and dolerites (a dark, medium-grained igneous rock). These formations generally have little or no original porosity, and the existence of aquifers depends on fractures and fissures in the rock mass providing porosity and pathways for groundwater movement. Although these are often further enhanced by weathering, aquifers in hard rocks are usually small and localized and not very productive.

Groundwater in volcanic formations in regions of “recent” volcanic activity frequently contains fluoride and boron in concentrations that are unacceptably high for certain uses. Consolidated sedimentary formations are often thick and extensive, and sometimes artesian. Limestone and sandstone formations may be highly porous and permeable and form some of the largest, most important and highest-yielding aquifers in the world. The permeability of these formations is largely due to fissures (fractures, faults, bedding planes). Porosity is also significant for the movement and storage of some pollutants. Dissolution of the rock can increase the permeability. The dissolution of carbonates, in particular, is responsible for the formation of karst aquifers [water naturally goes underground sinkholes to caves (solution caverns)], which can have large underground caverns and channels yielding substantial quantities of water. Unconsolidated sediments occur as thin, superficial deposits over other rock types or as thick sequences in the major river or lake basins. Porosity and permeability are related to grain size. Sand and gravel deposits can provide important and high-yielding aquifers, whereas silts and clays are less productive. In the largest river basins, thick sedimentary deposits may contain many layers of different materials built up over long periods of time, producing important multi-aquifer sequences. Aquifers may be confined or unconfined. A confined aquifer is overlain by an impermeable layer that prevents recharge (and contamination) by rainfall or surface water. Recharge of confined aquifers occurs where the permeable rock outcrops at or near the surface, which may be some distance from the area of exploitation. This feature may make control of quality and of pollution more difficult. Some aquifers are not perfectly confined and are termed semi-confined or leaky. Unconfined aquifers are overlain by a permeable, unsaturated zone that allows surface water to percolate down to the water table. Consequently, they are generally recharged over a wide area and are often shallow with a tendency for interaction with surface water.

Confined aquifers are less vulnerable than unconfined aquifers to pollution outside their recharge zone because surface water and contaminants cannot percolate to the water table. If contamination does occur, however, it is often difficult to remedy because confined aquifers are usually deep and the number of points where contaminated water may be pumped out is limited. Given the limited outflow, contaminants may also be increasingly concentrated in confined aquifers and this may restrict abstraction of water. The greater vulnerability of unconfined aquifers to contamination is a result of the wider area over which they are recharged and in which contamination may enter, and the greater interaction with polluted surface water bodies which may lead to contaminant movement into groundwater. The risk of contamination will depend on the depth of the overlying unsaturated layer, the rate of infiltration to the water table and the land use in areas surrounding groundwater sources.

Water quality

The quality of groundwater depends on the composition of the recharge water, the interactions between the water and the soil, soil-gas and rocks with which it comes into contact in the unsaturated zone, and the residence time and reactions that take place within the aquifer. Therefore, considerable variation can be found, even in the same general area, especially where rocks of different compositions and solubility occur. The principal processes influencing water quality in aquifers are physical (dispersion/dilution, filtration and gas movement), geochemical (complexation, acid-base reactions, oxidation-reduction, precipitation-solution, and adsorption-desorption) and biochemical (microbial respiration and decay, cell synthesis).

Groundwater quality is influenced by the effects of human activities which cause pollution at the land surface because most groundwater originates by recharge of rainwater infiltrating from the surface. The rainwater itself may also have an increased acidity due to human activity. The unsaturated zone can help reduce the concentrations of some pollutants entering groundwater (especially micro-organisms), but it can also act as a store for significant quantities of pollutants such as nitrates, which may eventually be released. Some contaminants enter groundwaters directly from abandoned wells, mines, quarries and buried sewerage pipes which by-pass the unsaturated zone.

Pollution

Artificial pollution of groundwater may arise from either point or diffuse sources. Some of the more common sources include domestic sewage and latrines, municipal solid waste, agricultural wastes and manure, and industrial wastes (including tipping, direct injection, spillage and leakage). The contamination of groundwaters can be a complex process. Contaminants, such as agricultural chemicals, spread over large sections of the aquifer recharge area may take decades to appear in the groundwater and perhaps longer to disappear after their use has ceased. Major accidental spills and other point sources of pollutants may initially cause rapid local contamination, which then spreads through the aquifer. Pollutants that are fully soluble in water and of about the same density (such as chloride-contaminated water from sewage) will spread through the aquifer at a rate related to the groundwater flow velocity. Pollutants that are less dense than water will tend to accumulate at the water table and flow along the surface. Dense compounds such as chlorinated solvents will move vertically downwards and accumulate at the bottom of an aquifer.

There is usually a delay between a pollution incident and detection of the contaminant at the point of water abstraction because movement in the unsaturated zone and flow in the aquifer are often slow. For similar reasons the time needed to "flush out" a pollutant is long and in some cases the degradation of groundwater quality may be considered irreversible.

Land use in areas surrounding boreholes and where aquifers are recharged should be carefully monitored as part of a pollution control program. The vulnerability of the aquifer to pollution will depend, in part, on the human activity and land use in areas where rainfall or surface water may percolate into the aquifer. In these areas, contamination of surface water or of the unsaturated layer above an aquifer is likely to cause groundwater pollution.

Natural processes affecting water quality

Although degradation of water quality is almost invariably the result of human activities, certain natural phenomena can result in water quality falling below that required for particular purposes. Natural events such as torrential rainfall and hurricanes lead to excessive erosion and landslides, which in turn increase the content of suspended material in affected rivers and lakes. Seasonal overturn of the water in some lakes can bring water with little or no dissolved oxygen to the surface. Such natural events may be frequent or occasional. Permanent natural conditions in some areas may make water unfit for drinking or for specific uses, such as irrigation. Common examples of this are the salinization of surface waters through evaporation in arid and semi-arid regions and the high salt content of some groundwaters under certain geological conditions. Many groundwaters are naturally high in carbonates (hardness), thus necessitating their treatment before use for certain industrial applications. Groundwaters in some regions contain specific ions (such as fluoride) and toxic elements (such as arsenic and selenium) in quantities that are harmful to health, while others contain elements or compounds that cause other types of problems (such as iron and manganese).

The nature and concentration of chemical elements and compounds in a freshwater system are subject to change by various types of natural process, i.e. physical, chemical, hydrological and biological.

The effects on water quality of the processes will depend to a large extent on environmental factors brought about by climatic, geographical and geological conditions. The major environmental factors are:

• Distance from the ocean: extent of sea sprays rich in Na^+, Cl^-, Mg^{2+}, SO_4^{2-} and other ions.

• Climate and vegetation: regulation of erosion and mineral weathering; concentration of dissolved material through evaporation and evapo- transpiration.

• Rock composition (lithology): the susceptibility of rocks to weathering ranges from 1 for granite to 12 for limestone; it is much greater for more highly soluble rocks (for example, 80 for rock salt).

• Terrestrial vegetation: the production of terrestrial plants and the way in which plant tissue is decomposed in soil affect the amount of organic carbon and nitrogenous compounds found in water.

• Aquatic vegetation: growth, death and decomposition of aquatic plants and algae will affect the concentration of nitrogenous and phosphorous nutrients, pH, carbonates, dissolved oxygen and other chemicals sensitive to oxidation/reduction conditions. Aquatic vegetation has a profound effect on the chemistry of lake water and a less pronounced, but possibly significant effect, on river water.

Under the influence of these major environmental factors, the concentrations of many chemicals in river water are liable to change from season to season. In small watersheds (<100 km^2) the influence of a single factor can cause a variation of several orders of magnitude. Water quality is generally more constant in watersheds greater than 100,000 km^2, and the variation is usually within one order of magnitude for most of the measured variables.

These natural variations are reflected in the range of total dissolved solids in various water bodies. Total dissolved solids is the sum of the silica plus the major ions in the water. A close approximation of its value may be obtained by the measurement of electrical conductivity.

Some chemical elements have a strong affinity for particulate matter and, as a result of precipitation/dissolution and adsorption/desorption reactions, they may be found in only trace amounts in solution. Other elements, however, are highly soluble and rarely, if ever, present in water in particulate form. The tendency for a chemical to be present in the soluble form rather than associated with particulates is expressed as the Soluble Transport Index. Particulate matter is separated from material in solution by filtering a water sample through a filter with pore size 0.45 μm or 0.50 μm. It is recognized that some fine colloids such as the hydroxides of iron, aluminium and manganese may pass through the filter, but the use of finer filters is very costly and requires long filtration times.

The elemental composition of river particulates is less variable than the dissolved concentrations for the same elements. This is true for the major elements aluminium, iron, silicon, calcium, magnesium, sodium, potassium, manganese, titanium and phosphorus but less so for the trace elements arsenic, cadmium, cobalt, chromium, copper, mercury, nickel, lead, selenium, tin, zinc, etc. Except for aluminium, iron, calcium and sodium, the composition of major elements in particulates is very similar in tropical rivers and in temperate and cold rivers. In small watersheds, local geological conditions can lead to wide variations in the concentration of trace elements in particulates.

Within any one water body water quality can differ with time and with place. Differences due to time are of five types:

• Minute-to-minute and day-to-day differences resulting from water mixing and fluctuations in inputs, usually as a result of meteorological conditions. These differences are most evident in small water bodies.

• Diurnal (24-hour) variations resulting from biological cycles and daylight/darkness cycles which cause changes in, for example, dissolved oxygen and pH. Diurnal patterns also result from the cyclic nature of waste discharges from domestic and industrial sources.

• Irregular patterns. Irregular sources of pollution include fertilizers, pesticides and herbicides, present in the run-off from agricultural land, and wastes discharged from food processing plants. The resultant variations in water quality may be apparent over a matter of days or months.

• Seasonal biological and hydrological cycles.

• Year-to-year trends, usually as a result of increased human activities in the watershed.

Water quality differences may result from either internal or external processes. Internal processes are usually cyclic, with either daily or seasonal recurrence, and are not directly related to the size of the water body. External processes, such as the addition of pollutants, may be buffered by large water bodies (depending on flow regimes) and long water residence times. As a result, the average composition of a very large lake probably changes little from one year to the next. Similarly, the differences in water quality at different times of the year will be much greater for a stream than for a large river. This means that the sampling frequency necessary to allow average water quality to be described correctly is normally much greater for a stream than for a river; for lakes it is normally much lower than for rivers.

Water quality differences from place to place depend more on the homogeneity of the water body than on its size. The water in a round lake, for example, may be adequately described by one sample taken from near the center of the lake. Long, thin lakes and lakes with many bays and inlets will require more samples; the minimum is 3 while the optimum number could be 10 or more. In lakes deeper than about 30 m, or that are stratified, it is especially important to obtain samples from different depths, so that a vertical profile can be obtained. Depending on the depth of the lake, up to five samples should be taken at depths determined by conditions measured in the field.

The flow pattern, or regime, of any particular river will be the product of very specific conditions. Although similar to that of rivers in the surrounding geographical region, it will be extensively influenced by altitude, exposure of the slope to wind and variations in rainfall.

Historically, the development of civilizations has led to a shift in the pattern of water use from rural/agricultural to urban/industrial, generally according to the following sequence: drinking and personal hygiene, fisheries, navigation and transport, livestock watering and agricultural irrigation, hydroelectric power, industrial production (e.g. and paper, food processing), industrial cooling water (e.g. fossil fuel and nuclear power plants), recreational activities and wildlife conservation. Fortunately, the water uses with the highest demands for quantity often have the lowest demands for quality. Drinking water, by contrast, requires the highest quality water but in relatively small quantities.

Increasing industrialization and the growth of large urban centers have been accompanied by increases in the pollution stress on the aquatic environment. Since ancient times, water in rivers, lakes and oceans has also been considered as a convenient receiver of wastes. This use (or abuse) conflicts with almost all other uses of water and most seriously with the use of freshwater for drinking, personal hygiene and food processing.

All water uses have impacts on the quality of the aquatic environment, including hydrological changes such as storing water in reservoirs or transferring water from one drainage area to another. Human use of water for almost all purposes results in the deterioration of water quality and generally limits the further potential use of the water.

A three-point strategy has been developed to resolve the conflicts between quality deterioration and water use as follows:

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• Wastes are treated before discharge to a water body in order to control pollution.

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• Unsatisfactory water is treated before use in order to meet specific water quality requirements.

Human activities are the source of particulate, dissolved and volatile materials which may eventually reach water. Dissolved materials and many particulates are discharged directly to water bodies, while the particulate and volatile materials that pollute the atmosphere are picked up by rain and then deposited on land or in water.

Specific locations where pollution resulting from human populations and human activities occurs, such as discharges from sewage treatment works, industrial wastewater outlets, solid waste disposal sites, animal feedlots and quarries, can be described as point sources. The effect of a point source on the receiving water body is dependent on: the population, or size and type of activity, discharging the waste, the capacity of the water body to dilute the discharge, the ecological sensitivity of the receiving water bod.

Pollutants may also be derived from diffuse and multi-point sources. Diffuse sources are often of agricultural origin and enter surface waters with run-off or infiltrate into groundwaters (particularly pesticides and fertilizers). Multi-point sources, such as latrines and septic tanks in rural and urban areas may be treated as diffuse sources for the purposes of monitoring and assessment because it is not possible to monitor each source individually.

Point sources of pollution can usually be identified and the polluting material eventually collected and treated. This cannot be done, however, with diffuse terrestrial sources, atmospheric depositions and the internal recycling of nutrients, metals and some organics. Pollution from these sources can be controlled only by prevention. Internal recycling is a particularly difficult problem because it occurs mostly under the anoxic conditions present in the interstitial water of some lake sediments and in some groundwaters. Pollution from accidental spills is unpredictable and its prevention requires the strict observance of safety procedures.

Water and human health

Water, although an absolute necessity for life, can be a carrier of many diseases. Paradoxically, the ready availability of water makes possible the personal hygiene measures that are essential to prevent the transmission of enteric diseases. Infectious water-related diseases can be categorized as waterborne, water-hygiene, water-contact and water-habitat vector diseases. Some water-related diseases, however, may fall into more than one category.

Waterborne infectious diseases are those in which the pathogen, or causative organism, is present in water and ingested when the water is consumed. Most of the pathogens involved are derived from human faeces, and the diseases transmitted by consumption of faecally contaminated water are called "faecal-oral" diseases. All of the faecal-oral diseases can also be transmitted through media other than water, for example faecally contaminated food,

fingers or utensils. The principal faecal-oral diseases are cholera, typhoid, shigellosis, amoebic dysentery, hepatitis A and various types of diarrhea.

The incidence, prevalence and severity of water hygiene diseases can be reduced by the observance of high levels of personal, domestic and community hygiene. Almost all waterborne diseases are water hygiene diseases. Other water hygiene diseases include tinea, scabies, pediculosis and skin and eye infections. Tinea, a skin disease, trachoma, an eye disease, and insect infestations such as scabies and pediculosis (lice) occur less frequently when personal hygiene and cleanliness are of a high standard. Water must be available in adequate quantities to permit hand washing, bathing, laundering, house cleaning, and the cleaning of cooking and eating utensils. The quantity required for these purposes is substantially greater than that needed for drinking.

Water contact diseases are transmitted when an individual's skin is in contact with pathogen infested water. The most important example is schistosomiasis (bilharziasis), in which the eggs of the pathogen (Schistosoma spp.) are present in the faeces and/or urine of an infected individual. The eggs hatch when they reach water and the larvae invade a suitable snail host where they multiply and develop, finally escaping from the snail as free swimming cercariae that infect humans by penetrating immersed or wetted skin.

Some of the pathogenic organisms spend a portion of their life cycles in a specific vector. The best known examples are malaria and filariasis (mosquito vector) and onchocerciasis (aquatic fly vector). One method of controlling these diseases is to control the vector which, in some cases, involves some physical or chemical treatment of the water habitat.

Health effects from chemicals in water occur when an individual consumes water containing a harmful amount of a toxic substance. Infant methaemoglobinaemia, caused by the consumption of water with a high nitrate concentration by infants (usually those which are bottle fed), is an example. The occurrence of methaemoglobinaemia is usually related to nitrate (often in groundwaters) which has been derived from extensive use of nitrate fertilizers. Fluorosis, damage to the teeth and bones, results from long-term consumption of water containing excess fluorides (usually from natural sources).