PEARSON NEW INTERNATIONAL EDITION

Applied Hydrogeology

C.W. Fetter, Jr.

Fourth Edition

PEARSON

Pearson New International Edition

Applied Hydrogeology
C.W. Fetter, Jr.
Fourth Edition

PEARSON

Pearson Education Limited
Edinburgh Gate
Harlow
Essex CM20 2JE
England and Associated Companies throughout the world

Visit us on the World Wide Web at: www.pearsoned.co.uk

PEARSON

ISBN 10: 1-292-02290-6
ISBN 13: 978-1-292-02290-1

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Printed in the United States of America

Table of Contents

GLOSSARY

GLOSSARY

Absolute humidity The actual amount of water vapor that is in the air expressed as mass per volume (gm/m^3).

Adiabatic expansion The process that occurs when an air mass rises and expands without exchanging heat with its surroundings.

Adsorption The attraction and adhesion of a layer of ions from an aqueous solution to the solid mineral surfaces with which it is in contact.

Advection The process by which solutes are transported by the motion of flowing ground water.

Alluvium Sediments deposited by flowing rivers. Depending on the location in the floodplain of the river, different-size sediments are deposited.

American rule A ground-water doctrine that holds that an overlying property owner has the right to use only a reasonable amount of ground water.

Anisotropy The condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.

Aquiclude A low-permeability unit that forms either the upper or lower boundary of a ground-water flow system.

Aquifer Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.

Aquifer, confined An aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer.

Aquifer, perched A region in the unsaturated zone where the soil may be locally saturated because it overlies a low-permeability unit.

Aquifer, semiconfined An aquifer confined by a low-permeability layer that permits water to slowly flow through it. During pumping of the aquifer, recharge to the aquifer can occur across the confining layer. Also known as a *leaky artesian* or *leaky confined aquifer.*

Aquifer test *See* pumping test.

Aquifer, unconfined An aquifer in which there are no confining beds between the zone of saturation and the surface. There will be a water table in an unconfined aquifer. *Water-table aquifer* is a synonym.

Aquifuge An absolutely impermeable unit that will neither store nor transmit water.

Aquitard A low-permeability unit that can store ground water and also transmit it slowly from one aquifer to another.

Artificial recharge The process by which water can be injected or added to an aquifer. Dug basins, drilled wells, or simply the spread of water across the land surface are all means of artificial recharge.

Average linear velocity *See* seepage velocity.

Bail-down test A type of slug test performed by using a bailer to remove a volume of water from a small-diameter well.

Bailer A device used to withdraw a water sample from a small-diameter well or piezometer. A bailer typically is a piece of pipe attached to a wire and having a check valve in the bottom.

Barrier boundary An aquifer-system boundary represented by a rock mass that is not a source of water.

Baseflow The water in a stream that comes from effluent ground water. It sustains the stream during periods of no precipitation.

Baseflow recession The declining rate of discharge of a stream fed only by baseflow for an extended period. Typically, a baseflow recession will be exponential.

Baseflow recession hydrograph A hydrograph that shows a baseflow recession curve.

Belt of soil water That part of the vadose zone that lies just below the land surface. It contains the roots of plants.

Bladder pump A positive-displacement pumping device that uses pulses of gas to push a water-quality sample toward the surface.

Borehole geochemical probe A water-quality monitoring device that is lowered into a well on a cable and that can make a direct reading of such parameters as pH, Eh, temperature, and specific conductivity.

Borehole geophysics The general field of geophysics developed around the lowering of various probes into a well.

Boring A hole advanced into the ground by means of a drilling rig.

Boussinesq equation The general equation for two-dimensional, unconfined transient flow.

Caliper log A borehole log of the diameter of an uncased well.

Capillary forces The forces acting on soil moisture in the unsaturated zone, attributable to molecular attraction between soil particles and water.

Capillary fringe That part of the vadose zone that lies just above the water table, where water can be drawn upward by capillary forces.

Capillary water Water found in the capillary fringe.

Casing *See* well casing.

Catchment *See* drainage basin.

Cation-exchange capacity The ability of a particular rock or soil to absorb cations.

Cementation The process by which some of the voids in a sediment are filled with precipitated materials, such as silica, calcite, and iron oxide, and that is a part of diagenesis.

Chemical activity The molal concentration of an ion multiplied by a factor known as the activity coefficient.

Clastic dike Intrusion of sediment forced into fractures in rock or sediments.

Cleat The vertical planes of fracture that are found in coal.

Collection lysimeter A device installed in the unsaturated zone to collect a water-quality sample by having the water drain downward by gravity into a collection pit.

Combining weight *See* equivalent weight.

Common-ion effect The decrease in the solubility of a salt dissolved in water already containing some ions of the salt.

Condensation The process that occurs when an air mass is saturated and water droplets form around nuclei or on surfaces.

Cone of depression *See* pumping cone.

Confining layer A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer.

Connate water Interstitial water that was buried with a rock and has been out of contact with the atmosphere for an appreciable part of a geologic period.

Contact spring A spring that forms at a lithologic contact where a more permeable unit overlies a less permeable unit.

Contaminant *See* pollutant.

Cooper-Jacob straight line method *See* Jacob straight line method.

Current meter A device that is lowered into a stream to record the rate at which the current is moving.

Darcian velocity. *See* specific discharge.

Darcy's law An equation that can be used to compute the quantity of water flowing through an aquifer.

Debye-Húckel equation A means of computing the activity coefficient for an ionic species.

Density The mass or quantity of a substance per unit volume. Units are kilograms per cubic meter or grams per cubic centimeter.

Depression spring A spring formed when the water table reaches a land surface because of a change in topography.

Depression storage The water that accumulates in shallow depressions on the land surface as a result of a precipitation event.

Dew point The temperature of a given air mass at which condensation will begin.

Diagenesis The chemical and physical changes occurring in sediments before consolidation or while in the environment of deposition.

Diffusion The process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

Dipole array A particular arrangement of electrodes used to measure surface electrical resistivity.

Direct precipitation Water that falls directly into a lake or stream without passing through any land phase of the runoff cycle.

Dirichlet condition A boundary condition for a ground-water computer model where the head is known at the boundary of the flow field.

Discharge The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.

Discharge area An area in which there are upward components of hydraulic head in the aquifer. Ground water is flowing toward the surface in a discharge area and may escape as a spring, seep, or baseflow or by evaporation and transpiration.

Discharge velocity *See* specific discharge.

Dispersion The phenomenon by which a solute in flowing ground water is mixed with uncontaminated water and becomes reduced in concentration. Dispersion is caused by both differences in the velocity that the water travels at the pore level and differences in the rate at which water travels through different strata in the flow path.

Distribution coefficient The slope of a linear Freundlich isotherm.

DNAPL Acronym for dense nonaqueous phase liquid. A liquid that is not miscible with water, which is denser than water, and can exist in the earth as a separate phase. Coal tar and trichloroethylene are examples.

Drainage basin An area surrounded by a continuous topographic divide within which all runoff joins a single stream and extends downstream to the point that the stream crosses the divide. *Catchment* is a synonym.

Drainage divide *See* topographic divide.

Drawdown A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells.

Dupuit assumptions Assumptions for flow in an unconfined aquifer that (1) the hydraulic gradient is equal to the slope of the water table, (2) the streamlines are horizontal, and (3) the equipotential lines are vertical.

Dupuit equation An equation for the volume of water flowing in an unconfined aquifer; based upon the Dupuit assumptions.

Duration curve A graph showing the percentage of time that the given flows of a stream will be equaled or exceeded. It is based on a statistical study of historic streamflow records.

Dynamic equilibrium A condition in which the amount of recharge to an aquifer equals the amount of natural discharge.

Dynamic viscosity The internal resistance of a fluid to movement by flowing. It is expressed in units of poise or centipoise.

Effective grain size The grain size corresponding to the one that is 10% finer by weight line on the grain-size distribution curve.

Effective porosity *See* porosity, effective.

Effective uniform depth (EUD) of precipitation The result that would occur if the actual precipitation over a drainage basin, which is variable from place to place, were spread out over the entire basin to an average depth.

Electrical resistance model An analog model of ground-water flow based on the flow of electricity through a circuit containing resistors and capacitors.

Electrical sounding An earth-resistivity survey made at the same location by putting the electrodes progressively farther apart. It shows the change of apparent resistivity with depth.

Electromagnetic conductivity A method of measuring the induced electrical field in the earth to determine the ability of the earth to conduct electricity. Electromagnetic conductivity is the inverse of electrical resistivity. Also known as electric conductivity and terrain conductivity.

English rule A ground-water doctrine that holds that property owners have the right of absolute ownership of the ground water beneath their land.

Equilibrium constant The number defining the conditions of equilibrium for a particular reversible chemical reaction.

Equipotential line A line in a two-dimensional ground-water flow field such that the total hydraulic head is the same for all points along the line.

Equipotential surface A surface in a three-dimensional ground-water flow field such that the total hydraulic head is the same everywhere on the surface.

Equivalent weight The formula weight of a dissolved ionic species divided by the electrical charge. Also known as *combining weight.*

Eutrophication The process of accelerated aging of a surface-water body; caused by excess nutrients and sediments being brought into the lake.

Evaporation The process by which water passes from the liquid to the vapor state.

Evapotranspiration The sum of evaporation plus transpiration.

Evapotranspiration, actual The evapotranspiration that actually occurs under given climatic and soil-moisture conditions.

Evapotranspiration, potential The evapotranspiration that would occur under given climatic conditions if there were unlimited soil moisture.

Fault spring A spring created by the movement of two rock units on a fault.

Field blank A water-quality sample where highly purified water is run through the field-sampling procedure and sent to the laboratory to detect if any contamination of the samples is occurring during the sampling process.

Field capacity The maximum amount of water that the unsaturated zone of a soil can hold against the pull of gravity. The field capacity is dependent on the length of time the soil has been undergoing gravity drainage.

Finite-difference model A particular kind of a digital computer model based on a rectangular grid that sets the boundaries of the model and the nodes where the model will be solved.

Finite-element model A digital ground-water flow model where the aquifer is divided into a mesh formed of a number of polygonal cells.

Flow net The set of intersecting equipotential lines and flowlines representing two-dimensional steady flow through porous media.

Flow, steady The flow that occurs when, at any point in the flow field, the magnitude and direction of the specific discharge are constant in time.

Flow, unsteady The flow that occurs when, at any point in the flow field, the magnitude or direction of the specific discharge changes with time. Also called *transient flow* or *nonsteady flow.*

Force potential The sum of the kinetic energy, elevation energy, and pressure at a point in an aquifer. It is equal to the hydraulic head times the acceleration of gravity.

Fossil water Interstitial water that was buried at the same time as the original sediment.

Fracture spring A spring created by fracturing or jointing of the rock.

Fracture trace The surface representation of a fracture zone. It may be a characteristic line of vegetation or linear soil-moisture pattern or a topographic sag.

Free energy A measure of the thermodynamic driving energy of a chemical reaction. Also known as *Gibbs free energy* or *Gibbs function.*

Freundlich isotherm An empirical equation that describes the amount of solute absorbed onto a soil surface.

Gaining stream *See* stream, gaining.

Gamma-gamma radiation log A borehole log in which a source of gamma radiation and a detector are lowered into the borehole. This log measures bulk density of the formation and fluids.

Gamma log *See* natural gamma radiation log.

Gauss-Seidel method A particular type of method for solving for the head in a finite-difference ground-water model.

Geohydrology A synonym for hydrogeology; also the flow of water through the earth without considering the effects of the geology.

Ghyben-Herzberg principle An equation that relates the depth of a salt-water interface in a coastal aquifer to the height of the fresh-water table above sea level.

Glacial-lacustrine sediments Silt and clay deposits formed in the quiet waters of lakes that received meltwater from glaciers.

Glacial outwash Well-sorted sand, or sand and gravel, deposited by the meltwater from a glacier.

Glacial till A glacial deposit composed of mostly unsorted sand, silt, clay, and boulders and laid down directly by the melting ice.

Gouge Soft, ground-up rock formed between the moving surfaces of a geological fault.

Gravity drainage The downward movement of water in the vadose zone due to gravity.

Gravity potential A potential due to the position of ground water or soil moisture above a datum.

Ground-penetrating radar A surface geophysical technique based on the transmission of repetitive pulses of electromagnetic waves into the ground. Some of the radiated energy is reflected back to the surface and the reflected signal is captured and processed.

Ground water The water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer.

Ground-water basin. A rather vague designation pertaining to a ground-water reservoir that is more or less separate from neighboring ground-water reservoirs. A ground-water basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries.

Ground water, confined The water contained in a confined aquifer. Pore-water pressure is greater than atmospheric at the top of the confined aquifer.

Ground-water divide The boundary between two adjacent ground-water basins. The divide is represented by a high in the water table.

Ground-water flow The movement of water through openings in sediment and rock; occurs in the zone of saturation.

Ground water, perched The water in an isolated, saturated zone located in the zone of aeration. It is the result of the presence of a layer of material of low hydraulic conductivity, called a perching bed. Perched ground water will have a perched water table.

Ground water, unconfined The water in an aquifer where there is a water table.

Grout curtain An underground wall designed to stop ground-water flow; can be created by injecting grout into the ground, which subsequently hardens to become impermeable.

Hantush-Jacob formula An equation to describe the change in hydraulic head with time during pumping of a leaky confined aquifer.

Hazen method An empirical equation that can be used to approximate the hydraulic conductivity of a sediment on the basis of the effective grain size.

Head, total hydraulic The sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer.

Hele-Shaw model An analog model of ground-water flow based on the movement of a viscous fluid between two closely spaced, parallel plates.

Heterogeneous Pertaining to a substance having different characteristics in different locations. A synonym is *nonuniform.*

Hollow-stem auger A particular kind of a drilling device whereby a hole is rapidly advanced into sediments. Sampling and installation of the equipment can take place through the hollow center of the auger.

Homogeneous Pertaining to a substance having identical characteristics everywhere. A synonym is *uniform.*

Horizontal profiling A method of making an earth-resistivity survey by measuring the apparent resistivity using the same electrode spacings at different grid points around an area.

Horton overland flow The part of precipitation that flows across the land surface toward a stream channel. When it reaches a stream channel it becomes part of the runoff. *Overland flow* is a synonym.

Humidity, absolute The amount of moisture in the air as expressed by the number of grams of water per cubic meter of air.

Humidity, relative Percent ratio of the absolute humidity to the saturation humidity for an air mass.

Humidity, saturation The maximum amount of moisture that can be contained by an air mass at a given temperature.

Hvorslev method A procedure for performing a slug test in a piezometer that partially penetrates a water-table aquifer.

Hydraulic conductivity A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.

Hydraulic diffusivity A property of an aquifer or confining bed defined as the ratio of the transmissivity to the storativity.

Hydraulic gradient The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

Hydraulic head *See* head, total.

Hydrochemical facies Bodies of water with separate but distinct chemical compositions contained in an aquifer.

Hydrogeology The study of the interrelationships of geologic materials and processes with water, especially ground water.

Hydrograph A graph that shows some property of ground water or surface water as a function of time.

Hydrologic cycle The circulation of water from the sea to the atmosphere to the land and hence back to the sea.

Hydrologic equation An expression of the law of mass conservation for purposes of water budgets. It may be stated as inflow equals outflow plus or minus changes in storage.

Hydrology The study of the occurrence, distribution, and chemistry of all waters of the earth.

Hydrophyte A type of plant that grows with the root system submerged in standing water.

Image well An imaginary well that can be used to simulate the effect of a hydrologic barrier, such as a recharge boundary or a barrier boundary, on the hydraulics of a pumping or recharge well.

Infiltrate The process of water moving from the land surface into the soil.

Infiltration capacity The maximum rate at which infiltration can occur under specific conditions of soil moisture. For a given soil, the infiltration capacity is a function of the water content.

Influent stream *See* stream, losing.

Interception The process by which precipitation is captured on the surfaces of vegetation before it reaches the land surface.

Interception loss Rainfall that evaporates from standing vegetation.

Interflow Lateral movement of water in the vadose zone during and immediately after a precipitation event.

Intermediate belt That part of the vadose zone that lies below the belt of soil moisture and above the capillary fringe. It contains intermediate water.

Intrinsic permeability Pertaining to the relative ease with which a porous medium can transmit a liquid under a hydraulic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field.

Ion exchange A process by which an ion in a mineral lattice is replaced by another ion that was present in an aqueous solution.

Isohyetal line A line drawn on a map, all points along which receive equal amounts of precipitation.

Isotropy The condition in which hydraulic properties of the aquifer are equal in all directions.

Jacob straight-line method A graphical method using semilogarithmic paper and the Theis equation for evaluating the results of a pumping test.

Joint spring *See* fracture spring.

Juvenile water Water entering the hydrologic cycle for the first time.

Karst The type of geologic terrane underlain by carbonate rocks where significant solution of the rock has occurred due to flowing ground water.

Kemmerer sampler A sampling device that can be lowered either into a deep well or into a lake to retrieve a water sample from a particular depth in the well or the lake.

Kinematic viscosity The dynamic viscosity of a fluid divided by the fluid density.

Laminar flow That type of flow in which the fluid particles follow paths that are smooth, straight, and parallel to the channel walls. In laminar flow, the viscosity of the fluid damps out turbulent motion. *Compare with* turbulent flow.

Land pan A device used to measure free-water evaporation.

Langmuir adsorption isotherm An empirical equation that describes the amount of solute adsorbed onto a soil surface.

Laplace equation The partial differential equation governing steady-state flow of ground water.

Law of mass action The law stating that for a reversible chemical reaction the rate of reaction is proportional to the concentrations of the reactants.

Leachate Water that contains a high amount of dissolved solids and is created by liquid seeping from a landfill.

Leachate-collection system A system installed in conjunction with a liner to capture the leachate that may be generated from a landfill so that it may be taken away and treated.

Leaky confining layer A low-permeability layer that can transmit water at sufficient rates to furnish some recharge to a well pumping from an underlying aquifer. Also called *aquitard.*

Lineament A natural linear surface longer than a mile (1500 m).

Lithologic log A record of the lithology of the rock and soil encountered in a borehole from the surface to the bottom. Also known as a *well log.*

LNAPL Acronym for light nonaqueous phase liquid. A liquid that is not miscible with water, which is less dense than water, and can exist in the earth as a separate phase. Gasoline and benzene are examples.

Losing stream *See* stream, losing.

Lysimeter A field device containing a soil column and vegetation; used for measuring actual evapotranspiration.

Magmatic water Water associated with a magma.

Magnetometer A geophysical device that can be used to locate items that disrupt the earth's localized magnetic field; can be used for finding buried steel.

Manning equation An equation that can be used to compute the average velocity of flow in an open channel.

Maximum contaminant level (MCL) The highest concentration of a solute permissible in a public water supply as specified in the National Interim Primary Drinking Water Standards for the United States.

Maximum contaminant level goal (MCLG) A nonenforceable health goal for solutes in drinking water; set at a level to prevent known or anticipated adverse effects with an adequate margin of safety.

Micrograms per liter A measure of the amount of dissolved solids in a solution in terms of micrograms of solute per liter of solution.

Milliequivalents per liter A measure of the concentration of a solute in solution; obtained by dividing the concentration in milligrams per liter by equivalent weight of the ion.

Milligrams per liter A measure of the amount of dissolved solids in a solute in terms of milligrams of solute per liter of solution.

Model calibration The process by which the independent variables of a digital computer model are varied, to calibrate a dependent variable such as a head against a known value such as a water-table map.

Model field verification The process by which a digital computer model that has been calibrated and verified is tested to see if it can predict the field response of an aquifer to some transient condition.

Model verification The process by which a digital computer model that has been calibrated against a steady-state condition is tested to see if it can generate a transient response, such as the decline in the water table with pumping, that matches the known history of the aquifer.

Moisture potential The tension on the pore water in the unsaturated zone due to the attraction of the soil-water interface.

Molality A measure of chemical concentration. A 1-molal solution has 1 mol of solute dissolved in 1000 g of solvent. One mole of a compound is its formula weight in grams.

Molarity A measure of chemical concentration. A 1-molar solution has 1 mol of solute dissolved in 1 liter of solution.

Mutual-prescription doctrine A ground-water doctrine stating that in the event of an overdraft of a ground-water basin, the available ground water will be apportioned among all users in amounts proportional to their individual pumping rates.

NAPL Acronym for nonaqueous phase liquid. A liquid that is not miscible with water and can exist in the earth as a separate phase. Coal tar and gasoline are examples.

Natural gamma radiation log A borehole log that measures the natural gamma radiation emitted by the formation rocks. It can be used to delineate subsurface rock types.

Neumann condition The boundary condition for a ground-water flow model where a flux across the boundary of the flow region is known.

Neutron log A borehole log obtained by lowering a radioactive element, which is a source of neutrons, and a neutron detector into the well. The neutron log measures the amount of water present, hence, the porosity of the formation.

Nonequilibrium equation *See* Theis equation.

Nonequilibrium type curve A plot on logarithmic paper of the well function $W(u)$ as a function of u.

Numerical model A model of ground-water flow in which the aquifer is described by numerical equations, with specified values for boundary conditions, that are solved on a digital computer.

Observation well A nonpumping well used to observe the elevation of the water table or the potentiometric surface. An observation well is generally of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer.

Overland flow The flow of water over a land surface due to direct precipitation. Overland flow generally occurs when the precipitation rate exceeds the infiltration capacity of the soil and depression storage is full. Also called *Horton overland flow.*

Packer test An aquifer test performed in an open borehole; the segment of the borehole to be tested is sealed off from the rest of the borehole by inflating seals, called packers, both above and below the segment.

p*e* A measure of the chemical activity of a solute in terms of the number of electrons. It is related to Eh by the expression $pe = (F/2.303RT)\mathrm{Eh}$.

Pendular water Water that clings to the surfaces of mineral particles in the zone of aeration.

Permafrost Perenially frozen ground, occurring wherever the temperature remains at or below 0°C for two or more years in a row.

Permeameter A laboratory device used to measure the intrinsic permeability and hydraulic conductivity of a soil or rock sample.

Phreatic cave A cave that forms below the water table.

Phreatophyte A type of plant that typically has a high rate of transpiration by virtue of a taproot extending to the water table.

Piezometer A nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface. A piezometer generally has a short well screen through which water can enter.

Piezometer nest A set of two or more piezometers set close to each other but screened to different depths.

Polar coordinates The means by which the position of a point in a two-dimensional plane is described; based on the radial distance from the origin to the given point and the angle between a horizontal line passing through the origin and a line extending from the origin to the given point.

Pollutant Any solute or cause of change in physical properties that renders water unfit for a given use.

Pore space The volume between mineral grains in a porous medium.

Porosity The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Porosity, effective The volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.

Porosity, primary The porosity that represents the original pore openings when a rock or sediment formed.

Porosity, secondary The porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed.

Potentiometric surface A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

Potentiometric surface map A contour map of the potentiometric surface of a particular hydrogeologic unit.

Prior-appropriation doctrine A doctrine stating that the right to use water is separate from other property rights and that the first person to withdraw and use the water holds the senior right. The doctrine has been applied to both ground and surface water.

Public trust doctrine A legal theory holding that certain lands and waters in the public domain are held in trust for use by the entire populace. It is especially applicable to navigable waters.

Pumping cone The area around a discharging well where the hydraulic head in the aquifer has been lowered by pumping. Also called *cone of depression.*

Pumping test A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. A pumping test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Also called *aquifer test.*

Quantification limit The lower limit to the range in which the concentration of a solute can be determined by a particular analytical instrument.

Radial flow The flow of water in an aquifer toward a vertically oriented well.

Radial symmetry A condition in an aquifer whereby the same hydraulic conductivity and storativity values affect water moving toward a well from all directions.

Rain gauge A piece of equipment used to measure precipitation.

Rating curve A graph of the discharge of a river at a particular point as a function of the elevation of the water surface.

Rational equation The equation used to predict the peak discharge from a precipitation event.

Recharge area An area in which there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in a recharge area.

Recharge basin A basin or pit excavated to provide a means of allowing water to soak into the ground at rates exceeding those that would occur naturally.

Recharge boundary An aquifer system boundary that adds water to the aquifer. Streams and lakes are typically recharge boundaries.

Recharge well A well specifically designed so that water can be pumped into an aquifer to recharge the ground-water reservoir.

Recovery The rate at which the water level in a well rises after the pump has been shut off. It is the inverse of drawdown.

Regolith The upper part of the earth's surface that has been altered by weathering processes. It includes both soil and weathered bedrock.

Resistivity log A borehole log made by lowering two current electrodes into the borehole and measuring the resistivity between two additional electrodes. It measures the electrical resistivity of the formation and contained fluids near the probe.

Retardation A general term for the many processes that act to remove the solutes in ground water; for many solutes the solute front will travel more slowly than the rate of the advecting ground water.

Return flow A type of overland flow that occurs when throughflow reaches the land surface and drains across the land surface before reaching a stream.

Reverse type curve A plot on logarithmic paper of the well function $W(u)$ as a function of $1/(u)$.

Reynolds number A number, defined by an equation, that can be used to determine whether flow will be laminar or turbulent.

Riparian doctrine A doctrine that holds that the property owner adjacent to a surface-water body has first right to withdraw and use the water.

Rock, igneous A rock formed by the cooling and crystallization of a molten rock mass called magma.

Rock, metamorphic A rock formed by the application of heat and pressure to preexisting rocks.

Rock, plutonic An igneous rock formed when magma cools and crystallizes within the earth.

Rock, sedimentary A rock formed from sediments through a process known as diagenesis or formed by chemical precipitation in water.

Rock, volcanic An igneous rock formed when molten rock called lava cools on the earth's surface.

Runoff The total amount of water flowing in a stream. It includes overland flow, return flow, interflow, and baseflow.

Safe yield The amount of naturally occurring ground water that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native ground-water quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge, which is due to the decline in head caused by pumping.

Saline-water encroachment The movement, as a result of human activity, of saline ground water into an aquifer formerly occupied by fresh water. Passive saline-water encroachment occurs at a slow rate owing to a general lowering of the fresh-water potentiometric surface. Active saline-water encroachment proceeds at a more rapid rate owing to the lowering of the fresh-water potentiometric surface below sea level.

Salt-water encroachment *See* saline-water encroachment.

Saprolite A soft, earthy, decomposed rock, typically clay-rich, formed in place by chemical weathering of igneous and metamorphic rocks.

Saturated zone The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

Saturation humidity The maximum amount of water vapor that air can hold at a given temperature, expressed as mass per unit volume.

Saturation ratio The ratio of the volume of contained water in a soil to the volume of the voids of the soil.

Schlumberger array A particular arrangement of electrodes used to measure surface electrical resistivity.

Screen *See* well screen.

Sediment An assemblage of individual mineral grains that were deposited by some geologic agent such as water, wind, ice, or gravity.

Seepage velocity The rate of movement of fluid particles through porous media along a line from one point to another.

Seismic refraction A method of determining subsurface geophysical properties by measuring the length of time it takes for artificially generated seismic waves to pass through the ground.

Shelby tube A sampling device that is pushed into an unconsolidated aquifer ahead of the drill bit. Typically, the Shelby tube is pushed by hydraulic means.

Single-point resistance log A borehole log made by lowering a single electrode into the well with the other electrode at the ground surface. It measures the overall electrical resistivity of the formation and drilling fluid between the surface and the probe.

Sinkhole spring A spring created by ground water flowing from a sinkhole in karst terrane.

Slug test An aquifer test made either by pouring a small instantaneous charge of water into a well or by withdrawing a slug of water from the well. A synonym for this test, when a slug of water is removed from the well, is *bail-down test.*

Slurry wall An underground wall designed to stop ground-water flow; constructed by digging a trench and backfilling it with a slurry rich in bentonite clay.

Soil liquefaction A process that occurs when saturated sediments are shaken by an earthquake. The soil can lose its strength and cause the collapse of structures with foundations in the sediment.

Soil moisture *See* soil water.

Soil water Water in the belt of soil water. *Soil moisture* is a synonym.

Solubility product The equilibrium constant that describes a solution of a slightly soluble salt in water.

Specific capacity An expression of the productivity of a well, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well. Specific capacity should be described on the basis of the number of hours of pumping prior to the time the drawdown measurement is made. It will generally decrease with time as the drawdown increases.

Specific discharge An apparent velocity calculated from Darcy's law; represents the flow rate at which water would flow in an aquifer if the aquifer were an open conduit.

Specific retention The ratio of the volume of water the rock or sediment will retain against the pull of gravity to the total volume of the rock or sediment.

Specific storage The volume of ground water that an aquifer absorbs or expels from a unit volume when the pressure head decreases or increases by a unit amount.

Specific weight The weight of a substance per unit volume. The units are newtons per cubic meter.

Specific yield The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil. Gravity drainage may take many months to occur.

Spiked sample A water sample to which a known quantity of a solute has been added so that the accuracy of the laboratory in analyzing the sample can be determined.

Split-spoon sample. A sample of unconsolidated material taken by driving a sampling device ahead of the drill bit in a boring. The split-spoon sampler is typically advanced by the repetitive dropping of a weight.

Spontaneous potential log A borehole log made by measuring the natural electrical potential that develops between the formation and the borehole fluids.

Stagnation point A place in a ground-water flow field at which the ground water is not moving. The magnitude of vectors of hydraulic head at the point are equal but opposite in direction.

Stem flow The process by which rainwater drips and flows down the stems and branches of plants.

Stiff pattern A graphical means of presenting the chemical analysis of the major cations and anions of a water sample.

Storage, specific The amount of water released from or taken into storage per unit volume of a porous medium per unit change in head.

Storativity The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield. Also called *storage coefficient.*

Storm hydrograph A graph of the discharge of a stream over the time period when, in addition to direct precipitation, overland flow, interflow, and return flow are adding to the flow of the stream. The storm hydrograph will peak owing to the addition of these flow elements.

Stream, gaining A stream or reach of a stream, the flow of which is being increased by inflow of ground water. Also known as an *effluent stream.*

Stream, losing A stream or reach of a stream that is losing water by seepage into the ground. Also known as an *influent stream.*

Successive overrelaxation method. A particular type of method for solving for the head in a finite-difference ground-water model.

Suction lysimeter A device for withdrawing pore-water samples from the unsaturated zone by applying tension to a porous ceramic cup.

Surface water Water found in ponds, lakes, inland seas, streams, and rivers.

Swallow hole A vertical shaft in a karst terrane leading from a surface stream into an underground cavern.

Temperature inversion A situation when a layer of warm air overlies a layer of cold air.

Tensiometer A device used to measure the soil-moisture tension in the unsaturated zone.

Tension The condition under which pore water exists at a pressure less than atmospheric.

Theis equation An equation for the flow of ground water in a fully confined aquifer.

Theis type curve *See* reverse type curve.

Thiessen method A process used to determine the effective uniform depth of precipitation over a drainage basin with a nonuniform distribution of rain gauges.

Throughflow The lateral movement of water in an unsaturated zone during and immediately after a precipitation event. The water from throughflow seeps out at the base of slopes and then flows across the ground surface as return flow, ultimately reaching a stream or lake.

Time of concentration The time it takes for water to flow from the most distant part of the drainage basin to the measuring point.

Topographic divide The boundary between adjacent surface water boundaries. It is represented by a topographically high area.

Tortuosity The actual length of a ground-water flow path, which is sinuous in form, divided by the straight-line distance between the ends of the flow path.

Transmissivity The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

Transpiration The process by which plants give off water vapor through their leaves.

Turbulent flow That type of flow in which the fluid particles move along very irregular paths. Momentum can be exchanged between one portion of the fluid and another. *Compare with* laminar flow.

Uniformity coefficient The ratio of the grain size that is 60% finer by weight to the grain size that is 10% finer by weight on the grain-size distribution curve. It is a measure of how well or poorly sorted sediment is.

Unsaturated zone *See* vadose zone.

Vadose cave A cave that occurs above the water table.

Vadose water Water in the vadose zone.

Vadose zone The zone between the land surface and the water table. It includes the belt of soil water, the intermediate belt, and the capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched ground water, may also exist in the vadose zone. Also called the *zone of aeration* or the *unsaturated zone.*

Viscosity The property of a fluid describing its resistance to flow. Units of viscosity are newton-seconds per meter squared or pascal-seconds. Viscosity is also known as *dynamic viscosity.*

Water budget An evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or a drainage basin.

Water content The weight of contained water in a soil divided by the total weight of the soil mass.

Water equivalent The depth of water obtained by melting a given thickness of snow.

Water quality criteria Values for dissolved substances in water based on their toxicological and ecological impacts.

Water table The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells.

Water-table cave A cave that forms at the approximate position of the water table.

Water-table map A specific type of potentiometric-surface map for an unconfined aquifer; shows lines of equal elevation of the water table.

Weir A device placed across a stream and used to measure the discharge by having the water flow over a specifically designed spillway.

Well casing A solid piece of pipe, typically steel or PVC plastic, used to keep a well open in either unconsolidated materials or unstable rock.

Well development The process whereby a well is pumped or surged to remove any fine material that may be blocking the well screen or the aquifer outside the well screen.

Well, fully penetrating A well drilled to the bottom of an aquifer, constructed in such a way that it withdraws water from the entire thickness of the aquifer.

Well function An infinite-series term that appears in the Theis equation of ground-water flow.

Well log *See* lithologic log.

Well, partially penetrating A well constructed in such a way that it draws water directly from a fractional part of the total thickness of the aquifer. The fractional part may be located at the top or the bottom or anywhere in between in the aquifer.

Well screen A tubular device with either slots, holes, gauze, or continuous-wire wrap; used at the end of a well casing to complete a well. The water enters the well through the well screen.

Wenner array A particular arrangement of electrodes used to measure surface electrical resistivity.

Wilting point The soil-moisture content below which plants are unable to withdraw soil moisture.

Winters doctrine A United States doctrine holding that when Indian reservations were established, the federal government also reserved the water rights necessary to make the land productive.

Xerophyte A desert plant capable of existing by virtue of a shallow and extensive root system in an area of minimal water.

Zone of aeration *See* Vadose zone.

Zone of saturation *See* saturated zone.

Water

In the winter of wet years the streams ran full-freshet, and they swelled the river until it sometimes raged and boiled bank full, and then it was a destroyer. The river tore the edges of the farm lands and washed whole acres down; it toppled barns and houses into itself, to go floating and bobbing away. It trapped cows and pigs and sheep and drowned them in its muddy brown water and carried them to the sea. Then when the late spring came the river drew in from its edges and the sand banks appeared. And in the summer the river didn't at all run above ground.

There were dry years too . . . The water came in a thirty-year cycle. There would be five or six wet and wonderful years when there might be nineteen to twenty-five inches of rain, and the land would shout with grass. Then would come six or seven pretty good years of twelve to sixteen inches of rain. And then the dry years would come, and sometimes there would be only seven or eight inches of rain. The land dried up . . . And it never failed that during the dry years the people forgot the rich years, and during the wet years they lost all memory of the dry years. It was always that way.

East of Eden, John Steinbeck, 1952

1 Water

John Steinbeck wrote the above words 50 years ago to describe the hydrology of the Salinas Valley in northern California. In doing so he revealed an attitude toward water that was held by many in the early part of the twentieth century. Water was always assumed to be available and no one worried about its longevity until it seemed threatened. We perhaps have a more realistic attitude today and know that we must preserve and protect our precious and limited natural resources, including water.

Although our intentions toward preserving the environment may be good, we sometimes act without full consideration of all possible outcomes. In 1990, Congress passed the Clean Air Act. To reduce the mass of smog-creating chemicals released by vehicles, gasoline sold in certain urban areas was required to be reformulated, starting in 1992, so that it contained at least 2% oxygen. At the time there were only two chemicals considered practical to add to gasoline, ethanol and methyl tertiary butyl ether (MTBE). At that time, no one knew if MTBE posed any potential health risks if ingested, but its high solubility in water was known. In addition, it was well known that many gasoline retailers had leaking underground storage tanks.

By 1996, about 100 million barrels of MTBE were used to formulate gasoline in the United States (Andrews 1998). Reformulated gasoline contains 10% MTBE. While air quality has improved in urban areas where MTBE is used in reformulated gasoline, not surprisingly we now find that ground water in some areas has been contaminated with it. Most chemicals found in gasoline degrade rather quickly in the earth, but not MTBE; it is persistent as it resists biodegradation.

As of 2000 there are still no federal drinking-water standards for MTBE; the toxicity is still being evaluated. Yet, legislation was passed a decade ago that could reasonably have been expected to result in the release of MTBE into ground water. In the spring of 2000 the Environmental Protection Agency (EPA) decided to phase out the use of MTBE in gasoline due to ground-water contamination. The lesson to be learned here is even the best of intentions can have unanticipated and extremely undesirable consequences on our limited water resources.

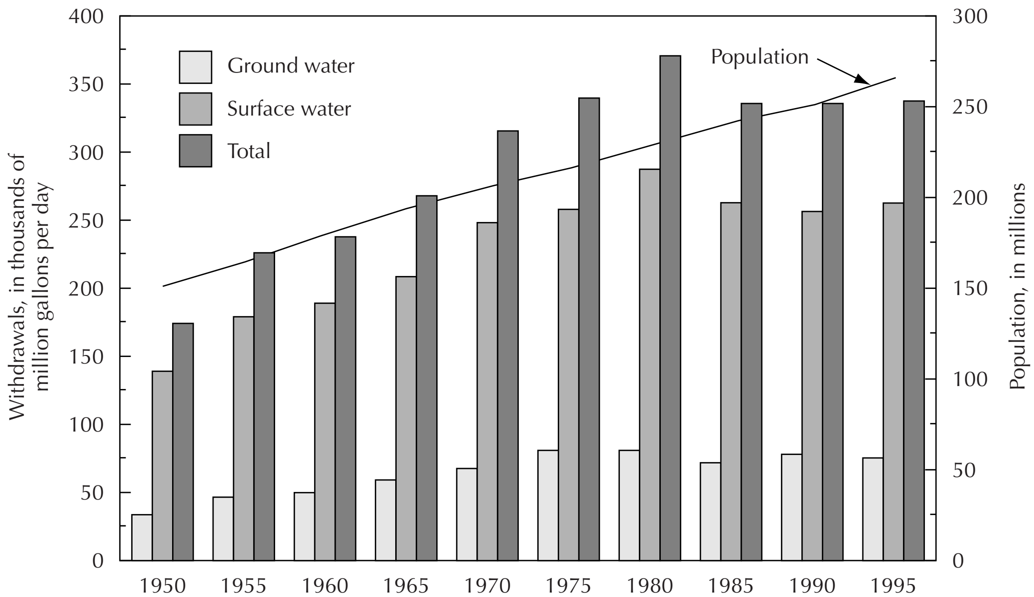
Water is the elixir of life; without it life is not possible. Although many environmental factors determine the density and distribution of vegetation, one of the most important is the amount of precipitation. Agriculture can flourish in some deserts, but only with water either pumped from the ground or imported from other areas.

Civilizations have flourished with the development of reliable water supplies—and then collapsed as their water supplies failed.A person requires about 3 quarts (qt) or liters (L) of potable water per day to maintain the essential fluids of the body. Primitive people in arid lands existed with little more than this amount as their total daily consumption. A single cycle of an older flush toilet may use 5 gallons (gal) (19 L) of water. In New York City the per capita water usage exceeds 260 gal (1000 L) daily; much of this is used for industrial, municipal, and commercial purposes. For personal purposes, the typical American uses 50 to 80 gal (200 to 300 L) per day. Even greater quantities of water are required for energy and food production.

In 1995, the total off-stream water use in the United States was estimated to be 402 billion gallons (1520 billion liters) per day of fresh and saline water. This does not include water used for hydroelectric power generation and other in-stream uses, but does include water used for thermoelectric power plant cooling. Fresh-water use in 1995 included 77.5 billion gallons (290 billion liters) per day of ground water and 263 billion gallons (995 billion liters) per day of surface water (Figure 1). Per capita fresh-water use was 1280 gal (4850 L) per day. Consumptive use of water, that is, water evaporated during use, was about 81 billion gallons (300 billion liters) per day (Solley, Pierce, & Perlman 1998).

Total water use in the United States peaked in 1980 and has declined since then. The estimated total water use in 1995 was 2% less than in 1990 and 10% less than in 1980. Water use for public water supply has shown a continual increase since 1950 due to increasing population. Public water supply (40.2 billion gallons in 1995) accounts for 10% of the total water use in the United States. The largest uses of water are for cooling of electric power generation facilities and for irrigation.

Although it had generally been assumed that economic growth results in increased water use, from 1975 to 1995 per capita water use in the United States actually declined by



▲ FIGURE 1
Trends in fresh ground- and surface-water withdrawals and population in the United States.
Source: Solley, Pierce, and Perlman, 1998.

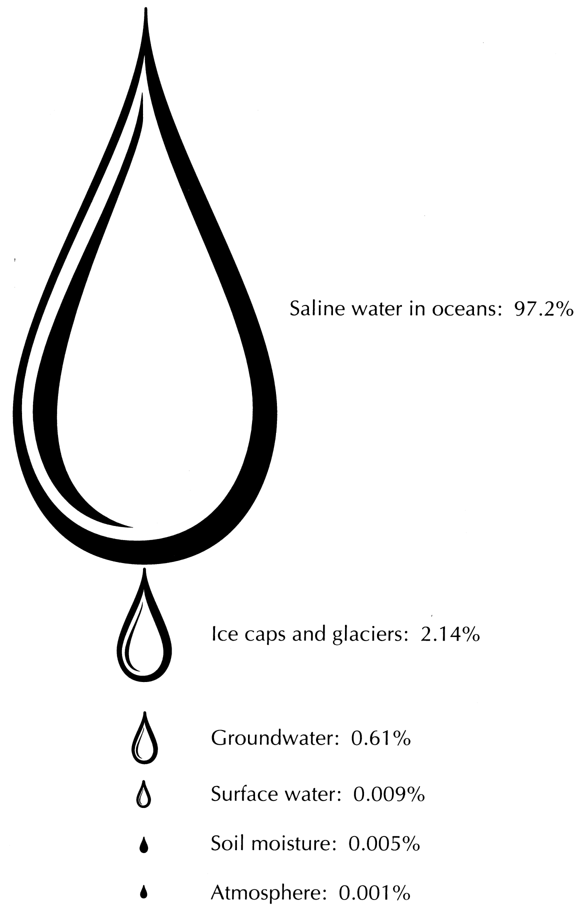
25%. This can be attributed to increased conservation of water (Wood 1999). As an example, toilets now sold in the United States can use no more than 1.5 gal. (6 L) per flush.

2 Hydrology and Hydrogeology

As viewed from a spacecraft, the earth appears to have a blue-green cast owing to the vast quantities of water covering the globe. The oceans may be obscured by billowing swirls of clouds. These vast quantities of water distinguish Earth from the other planets in the solar system. **Hydrology** is the study of water. In the broadest sense, hydrology addresses the occurrence, distribution, movement, and chemistry of all waters of the earth. **Hydrogeology** encompasses the interrelationships of geologic materials and processes with water. (A similar term, **geohydrology,** is sometimes used as a synonym for hydrogeology, although it more properly describes an engineering field dealing with subsurface fluid hydrology.) The physiography, surficial geology, and topography of a drainage basin, and the vegetation, influence the relationship between precipitation over the basin and water draining from it. The creation and distribution of precipitation is heavily influenced by the presence of mountain ranges and other topographic features. Running water and ground water are geologic agents that help shape the land. The movement and chemistry of ground water is heavily dependent upon geology.

Hydrogeology is both a descriptive and an analytic science. Both the development and management of water resources are important parts of hydrogeology as well. An account of the water supply of the world would reveal that saline water in the oceans accounts for 97.2% of the total. Land areas hold 2.8% of the total. Ice caps and glaciers hold 2.14%; ground water to a depth of 13,000 feet (ft) [4000 meters (m)] accounts for 0.61% of the total; soil moisture, 0.005%; fresh-water lakes, 0.009; rivers, 0.0001%; and saline lakes, 0.008% (Feth 1973). More than 75% of the water in land areas is locked in glacial ice or is saline (Figure 2).

► FIGURE 2
Distribution of the world water supply



3 The Hydrologic Cycle

Only a small percentage of the world's total water supply is available to humans as fresh water. More than 98% of the available fresh water is ground water, which far exceeds the volume of surface water. At any given time, only 0.001% of the total water supply is in the atmosphere. However, atmospheric water circulates very rapidly, so that each year enough water falls to cover the conterminous United States to a depth of 30 inches (in.) [75 centimeters (cm)]. Of this amount, 22 in. (55 cm) are returned to the atmosphere through evaporation and transpiration by growing plants, whereas 8 in. (20 cm) flow into the oceans as rivers (Federal Council for Science and Technology 1962). Although the previous sentence implies that the **hydrologic cycle** begins with water from the oceans, the cycle actually has no beginning and no end. As most of the water is in the oceans, it is convenient to describe the hydrologic cycle as starting with the oceans. Water evaporates from the surface of the oceans. The amount of evaporated water varies, being greatest near the equator, where solar radiation is more intense. Evaporated water is pure, because when it is carried into the atmosphere the salts of the sea are left behind. Water vapor moves through the atmosphere as an integral part of the phenomenon we term "the weather." When atmospheric conditions are suitable, water vapor condenses and forms droplets. These droplets may fall to the sea or onto land or may revaporize while still aloft.

Precipitation that falls on the land surface enters various pathways of the hydrologic cycle. Some water may be temporarily stored on the land surface as ice and snow or water in puddles, which is known as **depression storage.** Some of the rain or melting snow will drain across the land to a stream channel. This is termed **overland flow.** If the surface soil is porous, some rain or melting snow will seep into the ground by a process called **infiltration.**

Below the land surface the soil pores contain both air and water. The region is known as the **vadose zone,** or **zone of aeration.** Water stored in the vadose zone is called **vadose water.** At the top of the vadose zone is the belt of soil water. This is the zone where the roots of plants can reach. The soil water contained in the belt of soil water can be drawn into the rootlets of growing plants. As the plant uses the water, it is **transpired** as vapor to the atmosphere. Under some conditions water can flow laterally in the vadose zone, a process known as **interflow.** Water vapor in the vadose zone can also migrate back to the land surface to **evaporate.** Excess vadose water is pulled downward by gravity, a process known as **gravity drainage.** It passes through the intermediate belt to the **capillary fringe.** In the capillary fringe, the pores are filled with capillary water so that the saturation approaches 100%; however, the water is held in place by capillary forces.

At some depth, the pores of the soil or rock are saturated with water. The top of the **zone of saturation** is called the **water table.** Water stored in the zone of saturation is known as **ground water.** It then moves as **ground-water flow** through the rock and soil layers of the earth until it discharges as a spring or as seepage into a pond, lake, stream, river, or ocean (Figure 3).

Water flowing in a stream can come from overland flow or from ground water that has seeped into the streambed. The ground-water contribution to a stream is termed **baseflow,** while the total flow in a stream is **runoff.** Water stored in ponds, lakes, rivers, and streams is called **surface water.**

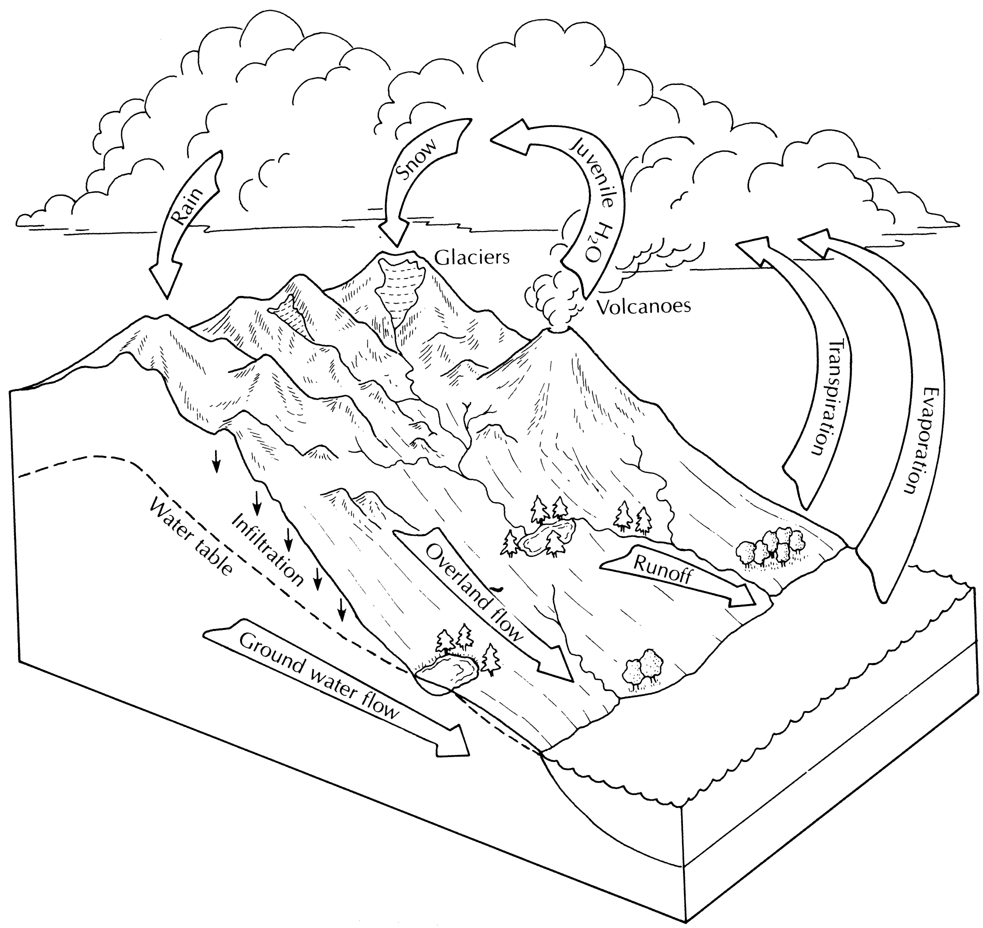
Evaporation is not restricted to open water bodies, such as the ocean, lakes, streams, and reservoirs. Precipitation intercepted by leaves and other vegetative surfaces can also evaporate, as can water detained in land-surface depressions or soil moisture in the upper layers of the soil. Direct evaporation of ground water can take place when the saturated zone is at or near the land surface. Transpiration by plants and evaporation from land surfaces are lumped together as **evapotranspiration.**

Magmatic water is contained within magmas deep in the crust. If the magma reaches the surface of the earth or the ocean floor, the magmatic water is added to the water in the hydrologic cycle. Steam seen in some volcanic eruptions is ground water that comes into contact with the rising magma and is not magmatic water. Some of the water in the ocean sediments is subducted with the sediments and is withdrawn from the hydrologic cycle. This water may eventually become part of a magma.

Figure 4 is a schematic drawing of the hydrologic cycle showing the major reservoirs where water is stored and the pathways by which water can move from one reservoir to others. Figure 5 illustrates the classification system for underground water.

4 Energy Transformations

The hydrologic cycle is an open system in which solar radiation serves as a source of constant energy. This is most evident in the evaporation and atmospheric circulation of water. The energy of a flowing river is due to the work done by solar energy, evaporating water from the ocean surface and lifting it to higher elevations, where it falls to earth. When water changes from one state to another (liquid, vapor, or solid), an accompanying change occurs in the heat energy of the water. The heat energy is the amount of thermal energy contained by a substance. A *calorie* (cal) of heat is defined as the energy necessary to raise the temperature of 1 gram (g) of pure water from 14.5°C to 15.5°C. At other temperatures it takes approximately 1 cal to change the temperature of 1 g of water 1°C. The evaporation of water requires an



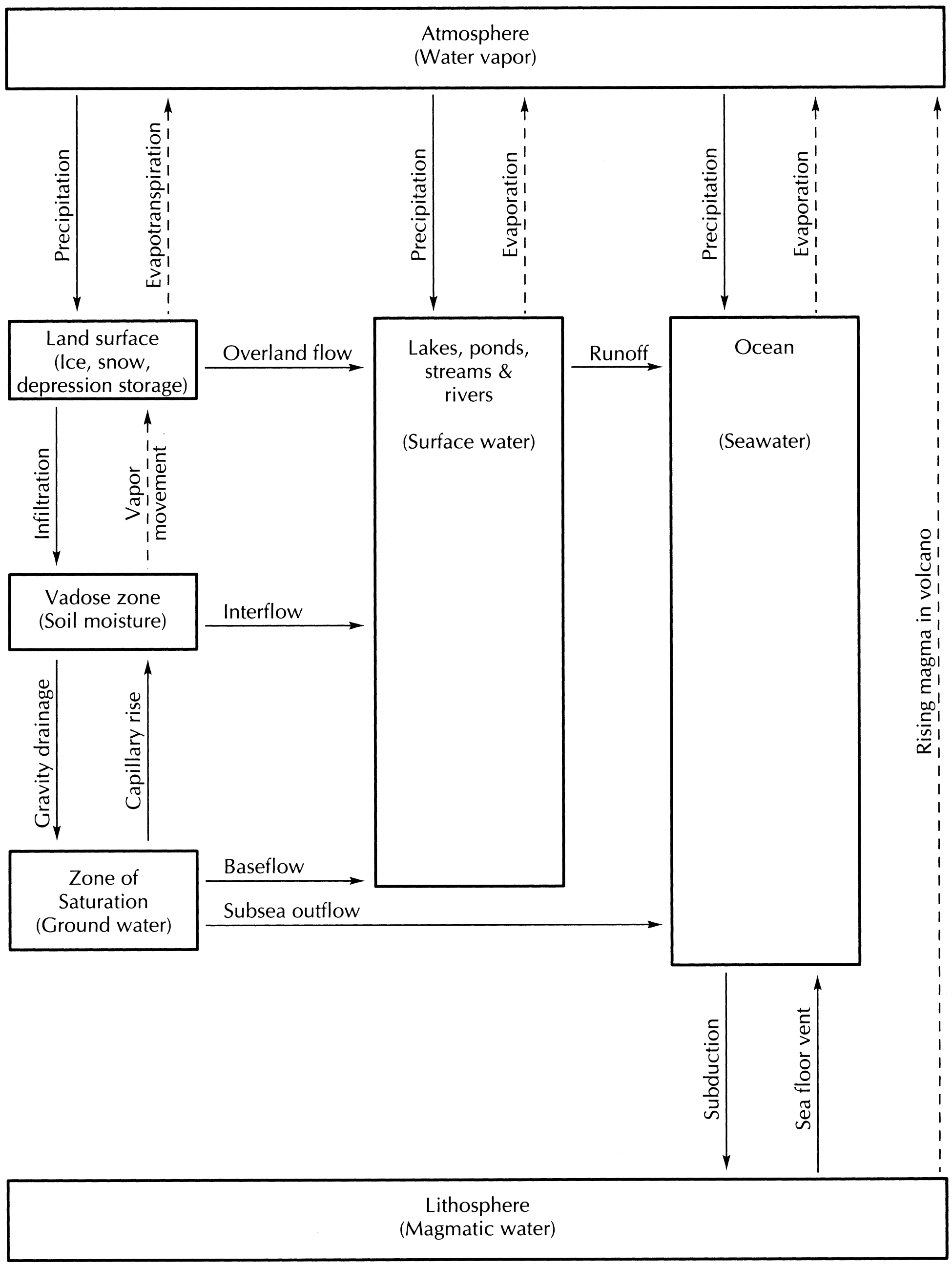
▲ FIGURE 3
The hydrologic cycle.

input of energy, called the *latent heat of vaporization.* At environmental temperatures (0°C to 40°C), the latent heat of vaporization H_v, in calories per gram of water, can be found by

$$H_v = 597.3 - 0.564T \tag{1}$$

where T is the temperature in degrees Celsius.

When water vapor condenses to a liquid form, an equivalent heat amount called the *latent heat of condensation* is released. This factor can also be obtained from Equation 1. To melt 1 g of ice at 0°C, 79.7 cal of heat must be added, to create the *latent heat of fusion.* The resulting water also has a temperature of 0°C, although the gram of water holds more heat energy than the gram of ice. Water can also pass directly from a solid state to a vapor state by a process called *sublimation.* The energy necessary to accomplish this is the sum of the latent heat of vaporization and the latent heat of fusion. At 0°C, this is 677 cal/g. Freezing of water releases 79.7 cal/g, and the formation of frost at 0°C releases 677 cal/g. The transportation of water through the hydrologic cycle and the accompanying heat transfers are vital to the heat balance of the earth. At the equator, the amount of solar radiation is fairly constant through the year, whereas at the poles it varies from near zero during the polar winter to significant amounts during the polar summer. During polar winters, the land is in shadow so the sun does not strike the ground; during the summers, the sun shines con-



▲ FIGURE 4
Schematic drawing of the hydrologic cycle. Movement of liquid water is shown by a solid line and movement of water vapor is shown by a dashed line.

tinuously. Over the year, the Northern Hemisphere northward of 38° latitude has a net heat loss, as the outgoing terrestrial radiation to space exceeds the incoming solar radiation that is absorbed. Between the equator and 38° N, there is more solar radiation absorbed than terrestrial radiation lost to space. To balance these anomalies, heat is transferred by currents in the oceans and through the atmosphere as movement of air masses and water vapor, thus creating climatic conditions and changing weather patterns that profoundly affect the hydrologic cycle.

Water

<table>
<tr><td rowspan="3">Vadose zone
(zone of
aeration)

Water table</td><td rowspan="3">Vadose water</td><td>Soil water</td><td>Belt of
soil water</td></tr>
<tr><td>Intermediate
vadose
water</td><td>Intermediate
belt</td></tr>
<tr><td>Capillary
water</td><td>Capillary
fringe</td></tr>
<tr><td>Zone of
saturation
(phreatic zone)</td><td colspan="3">Ground water</td></tr>
</table>

▲ FIGURE 5
Classification of water beneath the land surface.

5 The Hydrologic Equation

The hydrologic cycle is a useful concept but is quantitatively rather vague. The **hydrologic equation** provides a quantitative means of evaluating the hydrologic cycle. This fundamental equation is a simple statement of the *law of mass conservation.* It may be expressed as

$$\text{Inflow} = \text{outflow} \pm \text{changes in storage}$$

If we consider any hydrologic system—for instance, a lake—it has a certain volume of water at a given time. Several inflows add to this water volume: precipitation that falls on the lake surface, streams that flow into the lake, ground water that seeps into the lake, and overland flow from nearby land surfaces. Water also leaves the lake through evaporation, transpiration by emergent aquatic vegetation, outlet streams, and ground-water seepage from the lake bottom. If, over a given time period, the total inflows are greater than the total outflows, the lake level will rise as more water accumulates. If the outflows exceed the inflows over a time period, the volume of water in the lake will decrease. Any differences between rates of inflow and outflow in a hydrologic system will result in a change in the volume of water stored in the system. The hydrologic equation can be applied to systems of any size. It is as useful for a small reservoir as it is for an entire continent. The equation is time dependent. The elements of inflow must be measured over the same time periods as the outflows.

The basic unit of surface-water hydrology is the **drainage basin,** or **catchment,** which consists of all the land area sloping toward a particular discharge point. It is outlined by surface-water boundaries, or **topographic divides.** In ground-water hydrology, we utilize the concept of a **ground-water basin,** which is the subsurface volume through which ground water flows toward a specific discharge zone. **Ground-water divides** surround it. The boundaries of a surface-water basin and the underlying ground-water basin do not necessarily coincide, although the water budget of the area must account for both ground and surface water. Many times hydrologic budgets are made for areas surrounded by political boundaries and not hydrologic boundaries; however, one still must know the location of the hydrologic boundaries, both surface and subsurface, to perform a water-budget analysis. Water will flow from the hydrologic boundary toward the point of discharge and hence may flow into the study area if the boundary of the study area does not coincide with the hydrologic boundary. The hydrologic inputs to an area may include (1) precipitation; (2) surface-water inflow into the area, including runoff and overland flow; (3) ground-water inflow from outside the area; and (4) artificial import of water into the area through pipes and canals. The hydrologic outputs from an area may include (1) evapotranspiration from land areas; (2) evaporation of surface water; (3) surface water runoff; (4) ground-water outflow; and (5) artificial export of water through pipes and canals. The changes in storage necessary to balance the hydrologic equation include changes in the volume of (1) surface water in streams, rivers, lakes, and ponds; (2) soil moisture in the vadose zone; (3) ice and snow at the surface; (4) temporary depression storage; (5) intercepted water on plant surfaces; and (6) ground water below the water table. The application of the hydrologic equation to a watershed is illustrated in the following case study.

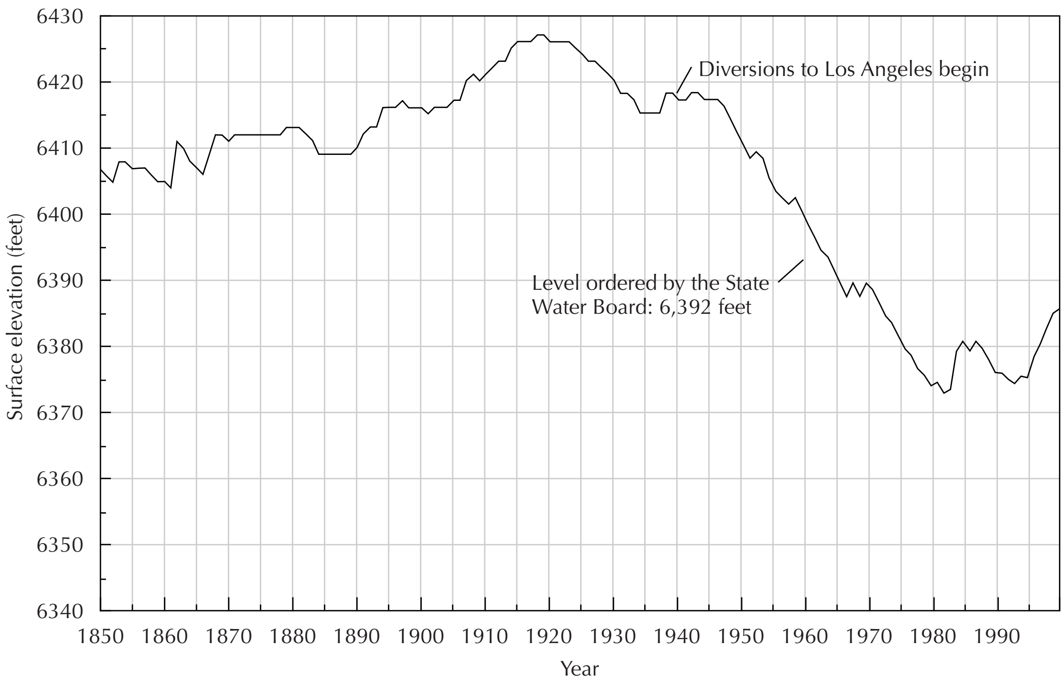
Case Study: Mono Lake

Half a dozen little mountain brooks flow into Mono Lake, but not a stream of any kind flows out of it. What it does with its surplus water is a dark and bloody mystery.

Mark Twain

Mono Lake lies on the eastern slope of the Sierra Nevada near the east entrance to Yosemite National Park. Mono Lake is a terminal lake, which means that although water enters the lake by precipitation and by streams and ground water flowing into it, water can leave only by evaporation. The lake level fluctuates with climatic changes. The volume of water that leaves the lake by evaporation is the product of the surface area times the depth of evaporation. If the volume that leaves by evaporation is exactly balanced by the inflow, the lake level will not change. If the inflow exceeds evaporation, the water level will rise. If the inflow is less than evaporation, the lake level will fall. The Mono Lake basin has an area of 695 square miles (mi^2) [180,000 hectares (ha)]. Inputs to the lake under natural conditions are direct precipitation, with an estimated annual average of 8 in. (0.2 m); runoff from the land areas via gauged streams, which is estimated to average 150,000 acre-feet (ac-ft)* per year [1.85×10^8 cubic meters (m^3)]; and ungauged runoff and ground-water inflow, which is estimated to average 37,000 ac-ft per year (4.56×10^7 m^3). The average annual rate of lake evaporation is about 45 in. (1.1 m) (Vorster 1985). When it was first surveyed in 1856, the elevation of Mono Lake was 6407 ft (1953 m) above sea level. Climatic effects of moister and drier periods caused the lake level to rise to as much as 6428 ft (1959 m) in 1919 and then to fall to 6410 ft (1954 m) by 1941. In that year, water was first diverted from four of the five major streams feeding Mono Lake into the Los Angeles Aqueduct and then into southern California.

*An acre-foot is a measure of the volume of water that is commonly used in the western United States. It is the amount of water that will cover an acre of land to a depth of 1 ft (43,560 ft^3).



▲ FIGURE 6
Changes in the surface elevation of Lake Mono from the year 1850 to 2000. *Source:* Mono Lake Committee (*http://www.monolake.org*). *Used with permission.*

Since the beginning of diversions in 1941, the surface elevation of Mono Lake has declined substantially (Figure 6). Diversions amounted to as much as 100,000 ac-ft (1.23×10^8 m^3) per year. The historic low was reached in December 1981, when the lake elevation was 6372.0 ft (1942.2 m). The decline was arrested and the level rose to 6381 ft (1945 m) during a very wet period from 1982 through 1984. A return to more normal precipitation conditions meant that the lake level began to fall again. In 1989, the diversions were halted under a temporary court restraining order that prohibited any such diversions that would result in a lake level of less than 6377 ft (1944 m). However, even without any diversions the level of Mono Lake still declined due to very dry conditions in the eastern Sierra Nevada, so that by the end of 1992 it was 6373.5 ft (1942.6 m).

In 1994 the California State Water Resources Control Board issued Decision 1631, which established permanent stream-flow values for the tributary streams to Mono Lake in order to protect fish in the streams. In addition, a permanent lake elevation of 6,392 ft (1949 m) was set for Mono Lake. No diversions of influent water are permitted when the lake level is below that set by the decision.

In 1941, the year that diversions began, the surface area of Mono Lake was 53,500 ac (21,670 ha). When the lake elevation declined by 38 ft (12 m) from 1941 to 1981, the surface area shrank to about 40,000 ac (16,200 ha). The annual diversion of 100,000 ac-ft (1.23×10^8 m^3) would cover the 40,000-ac (16,200-ha) lake to a depth of 2.5 ft (0.76 m). The water level fell because the amount of the diversion plus the natural evaporation from the lake was far in excess of the amount of precipitation onto the lake surface plus the remaining surface inflow and the ground-water inflow.

Since 1992, sufficient precipitation has fallen over the Mono Lake drainage basin for lake levels to rise inasmuch as no diversions were permitted. As of January 2000 the lake level stood at 6384.3 ft (1947.2 m). It will take several more years before the lake level reaches the minimum elevation of 6392 ft (1949 m) set in Decision 1631.

One consequence of the volume reduction of Mono Lake was an increase in the salinity of the lake. In its original, natural condition with a surface elevation of 6410 ft (1954 m), the salinity of Mono Lake was 5.4%. At an elevation of 6377 ft (1944 m), the salinity rose to 9.3%. The increase in salt concentration resulted in a reduction of the brine shrimp population of the lake. There is a commercial fishery in Mono Lake for brine shrimp, and the shrimp also serve as an important food source for nesting and migratory birds. Brine flies also inhabit the shallow waters of the lake edge and provide a second food source for the many species of birds that migrate through the area and the nesting colonies of California gulls and snowy plovers. With the elimination of diversions from the lake, and the subsequent rise in water levels, the salinity has been reduced to 8.1%.

6 Hydrogeologists

The professional hydrogeologist has a wide variety of occupations from which to choose. Employment may be found with federal agencies, United Nations groups, state agencies, and local governments. Energy and mining companies may call upon the services of hydrogeologists to help provide water where it is needed or perhaps remove it where it is unwanted. Private consulting organizations also employ many individuals trained in hydrogeology. Water resource management districts and planning agencies often include hydrogeologists on their staffs. Hydrogeology is an interdisciplinary field. The hydrogeologist usually has training in geology, hydrology, chemistry, mathematics, and physics. Hydrogeologists are also being trained in such areas of engineering as fluid mechanics and flow through porous media, as well as in computer science. Such training is necessary, as hydrogeologists must be able to communicate effectively with engineers, planners, ecologists, resource managers, and other professionals. By the same token, an understanding of the basic principles of hydrogeology is useful to soil scientists, engineers, planners, foresters, and others in similar fields. For example, modeling of hydrologic systems is an area requiring knowledge of numerous disciplines.

7 Applied Hydrogeology

Many topics fall within the general rubric of hydrogeology. These include such diverse topics as the role of fluids in the folding of a faulting of rocks, hydrothermal fluids and mineral formation, land subsidence, geothermal energy, cave and karst formation, and water as a resource.

In this text we consider the topic of water as a resource. Classical studies in hydrogeology focused either on the mathematical treatment of flow through porous media or on a general geologic description of the distribution of rock formations in which ground water occurs. One occasionally even finds a paper describing the theoretical flow of fluids through an idealized porous medium that probably does not occur in nature. Likewise, many reports on the ground-water geology of an area made no attempt to evaluate how much water is available for use. Neither type of study has much practical value. Applied hydrogeology integrates the geological occurrence of water with the mathematical description of its movement and its chemical state. Typical outcomes of applied hydrogeological investigations might include plans for development of a ground-water supply, determination of the capture zone for a well field to protect it from contamination, evaluation of the impact of a mine dewatering plan on overlying surface-water bodies, or the delineation of a plume of contaminated ground water.

Hydrogeologists are problem solvers and decision makers. They identify a problem, define the data needs, design a field program for collection of data, propose alternative solutions to the problem, and implement the preferred solution.

8 The Business of Hydrogeology (What Do Hydrogeologists Do All Day?)

8.1 Application of Hydrogeology to Human Concerns

The work done by applied hydrogeologists can be divided into three realms: research, solving problems involving ground-water supply and control, and solving problems involving ground-water contamination.

Research

In the first realm, research, the basic principles of hydrogeology, such as the equations governing fluid flow and movement of contaminants through porous media, have been determined. Professors and graduate students at universities and hydrogeologists employed by nonprofit organizations such as the United States Geological Survey conduct basic research. Basic research involves the search for first principles, which may or may not have either an immediate or an apparent practical application. Applied research is performed to solve a specific problem. The applied researcher utilizes the same research techniques as are appropriate for basic research. However, the planned result of the research program is the development of knowledge that can be applied immediately to the solution of known problems. Applied research may be conducted at universities and by nonprofit organizations, but applied researchers can also be found working for profit-making organizations. The profit-making organization may be trying to develop a marketable product such as a computer program or a new device to withdraw a water sample from a well. These organizations may also have been contracted to solve some hydrogeological problem that a second party is experiencing, for example, the development of a new method of detecting soil contamination under particular geologic conditions. The results of both basic and applied research may be published in journals and formal reports of nonprofit agencies. Presentations of research results may also be given at professional meetings.

Solving Problems Involving Ground-Water Supply and Control

The second realm is the application of principles of hydrogeology to realize some economic benefit. These are sometimes called “clean-water” projects; they deal with ground-water supply and control. As an example, a community or an industry may hire a hydrogeologist to locate and develop a source of ground water. The project is driven by economics. The hydrogeologist will identify a source of ground water, determine if there is enough water of acceptable quality available, and work with an engineer to develop cost estimates. If there are several potential sources of water, the hydrogeologist and engineer will try to determine the best alternative from a standpoint of availability, quality, and cost.

Another project of this type is ground-water control. For some construction projects and most mining projects, excavations must take place below the water table. Dewatering wells can be placed around a project to lower the water level to provide a dry working environment. The cost of the dewatering project must be considered in determining if the project is economically viable. The hydrogeologist will determine how many wells are needed, where they are to be placed, how much water must be pumped, and if the dewatering well will have an undesirable effect on nearby users of ground water, such as their wells going dry.

Hydrogeologists are also involved with issues of aquifer protection and water conservation. Clearly it is far better to prevent the initial contamination of an aquifer than to remediate a contaminated one. Many communities are adopting zoning for the recharge areas of important aquifers to prohibit activities that pose a threat to ground-water quality.

If a municipality or private company has numerous projects requiring hydrogeological work, it may employ hydrogeologists as permanent staff; however, this usually is not the case. Instead, the municipality or private company owner will hire a firm of consulting hydrogeologists or engineers. Employees of the consulting company then perform the actual work. The consulting company will do the hydrogeological work using its own employees, but it may subcontract with a well-drilling company to install both test wells and permanent wells. If a well is for a public water supply, a hydrogeologist working for a state agency will most likely review the preliminary siting studies and final design to determine if the project meets state standards.

To illustrate the type of work performed by a hydrogeologist, we will look in some detail at what might be involved with the search for a new water-supply well. For such a project, a hydrogeologist first gathers all available information about the area's hydrogeology, such as well logs and published geological and water supply reports from various sources. Geological mapping and examination of air photos may supplement the review of available data. The data are then evaluated to give an initial idea of where to locate a test well. The hydrogeologist works with the project owners to locate available land for a potential well site, and then prepares the plans and specifications that are used to obtain bids from drilling contractors for constructing a test boring and well. The hydrogeologist spends time in the field overseeing the drilling of a test boring to obtain geologic samples, and then describes these samples and performs subsequent laboratory tests to evaluate them in order to identify a promising aquifer. A test well is then designed based on the geologic samples and is installed under the field supervision of the hydrogeologist. An aquifer test is then conducted using the test well and (perhaps) nearby observation wells. The data from the aquifer test are analyzed and the hydraulic properties of the aquifer are determined. The hydrogeologist may then make a computer model of the aquifer to determine if a permanent well or well field could yield the desired amount of water on a sustained basis, and prepares a written report for the project owners to inform them of the results of the work to date and the recommendations for a permanent well. The report is probably also submitted to the proper state agency for approval. If the state approves, then the owners must decide whether to go ahead with a permanent well. If the decision is affirmative, the hydrogeologist prepares the plans and specifications for the new well, and works with the engineer who is selecting the pump, determining the layout of the above-ground piping for the well, and designing the building to house the well head. Approval of the design by a hydrogeologist or engineer working for a state agency might be necessary. The final steps involve overseeing the construction of the well to ensure that the contractor follows the plans and specifications and to conduct a performance test of the completed well.

Solving Problems Involving Ground-Water Contamination

The third and newest realm of the hydrogeologist is the application of hydrogeology to satisfy some regulatory or legal requirement. These projects are usually "dirty-water" projects; that is, they deal with contaminated sites. A host of recent federal and state laws and regulations require studies to be conducted by hydrogeologists and reports to be prepared for submittal to state agencies or the federal government. For example, the Federal Resource Conservation and Recovery Act (RCRA) requires owners or operators of facilities that treat, store, or dispose of hazardous waste to have a ground-water-monitoring plan in place. Ground-water samples must be collected quarterly, and an annual report must be filed with either the EPA or a state agency that has been designated to act for the EPA. The collection of the ground-water samples and the preparation of the reports are frequently done by hydrogeologists. If ground-water monitoring shows that a release of hazardous waste or hazardous waste constituents to ground water has occurred, the site owner or operator must submit a plan for a ground-water-quality assessment program that has been certified by a qualified geologist or geotechnical engineer. The plan must be approved by a hydrogeologist or engineer working for the regulatory agency and then carried out by hydrogeologists working for a consulting company that has been contracted by the site owner or operator.

RCRA is only one of many state and federal regulations that require work to be performed by hydrogeologists. This type of work requires that the hydrogeologist become thoroughly familiar with the specific requirements of existing regulations. Work must be scientifically correct, and it must also conform to the exact letter of the regulatory code. These regulations cover activities such as treatment, storage, and disposal of hazardous and radioactive waste and tailings from the mining and milling of radioactive minerals; the disposal of municipal waste; the injection of liquid waste into deep injection wells; the investigation and remediation of contaminated soil at abandoned hazardous waste sites; and the removal of underground storage tanks.

Hydrogeologists working for owners or consulting firms conduct the field studies, analyze the field and laboratory data, and write the necessary final reports. Hydrogeologists working for regulatory agencies conduct field inspections of regulated facilities and review and approve the submitted reports. Work is often done under the cloak of a legal document such as a consent decree. Such a document specifies the scope of the work, the procedures to be utilized, and the schedule that must be followed. Failure to comply with the document may result in the assessment of fines and penalties against the site owner. This creates an incentive for the hydrogeologist to work in an effective and efficient manner. Litigation may arise from cases involving contamination of soil and ground water. The litigation may be initiated by the federal government or a state to compel the cleanup of a contaminated site. A private party can also file a lawsuit to recover damages due to the release of a toxic or hazardous substance to soil or ground water. The damages may be to property or to the health of the plaintiff. In all such lawsuits, both sides will generally rely upon the expert testimony of hydrogeologists.

8.2 Business Aspects of Hydrogeology

Hydrogeologists who perform any of the interesting work just described also expect to be compensated for their time. There must be a source of funds to pay their wages. The salary of a hydrogeologist working for a project owner is paid by the owner out of the revenue that is generated by the business. A hydrogeologist working for a consulting company is paid by the company with funds that come from fees charged to the project owner for the work that is contracted. The salary of a hydrogeologist working for a state review agency is paid with either tax revenue or a combination of tax revenue, fees charged to project owners who submit plans to the agency for review, and costs recovered from polluters by means of lawsuits filed by the state or federal government.

A hydrogeologist working for a consulting firm is required to keep track of the amount of time spent working directly on each assigned project and record it daily on a time sheet that is turned in every one to two weeks. Consulting work can be contracted in several ways. One method is a lump-sum cost for an entire project. Alternatively, the fee may be based on total hours spent plus direct expenses, such as travel costs and drilling subcontracts. For lump-sum projects, the consulting company management needs to know the total number of hours employees spend on a project to determine if the project made or lost money. For hourly rate projects, the management needs to know how many hours were spent on a project to determine the fee. The hourly rate charged is usually several times the actual hourly wage paid to the employee, because it must also cover employee benefits, such as insurance, social security, paid holidays and vacations; fixed overhead, such as rent, insurance, and utilities; office overhead, such as office furniture, computers, field equipment, copiers, and secretarial help; administrative overhead for the salaries of management; sales overhead for the time the staff spends preparing proposals for new work and calling on prospective clients; training costs, including both salaries and expenses for employees to receive both safety training and advanced education; and, finally, some profit for the firm's owners.

Many of the hours that a firm's employees spend, including general company management as opposed to project management, new business development, and training, cannot be billed to a client. However, if a consulting firm is to succeed, the employees must be able to bill a certain number of hours a year. To remain profitable, a firm must bring in enough business at a fair price, and the employees must work hard and efficiently to complete the work within the budget. If the firm fails to bring in enough new business, there might not be enough billable work available, thus leading to losses for the firm's owners and layoffs of employees.

If employees do not perform up to expectations, too many projects might result in financial loss, and the firm might not be able to remain in business. Employees also must be thorough and careful in their work. If sloppy work occurs, a firm can be sued for malpractice. The legal costs of defending a firm against a malpractice suit can be great, and the damage awards if a firm loses a suit can jeopardize the economic viability of the business. Many firms carry errors and omissions insurance to protect themselves from malpractice lawsuits. This type of insurance is expensive and difficult to obtain. The policy has a deductible amount (the minimum sum the firm must pay if the lawsuit is lost) and a maximum amount (the greatest amount the insurance company must pay, no matter how high the award to the plaintiff). If a firm has a history of being sued for malpractice and losing, then such insurance might be impossible to obtain.

8.3 Ethical Aspects of Hydrogeology

Hydrogeologists have ethical responsibilities to their employers, clients, and the general public. As an employee, a hydrogeologist has a responsibility to perform the best work at all times, to be diligent in personal work habits, and to be honest in financial matters with the employer. Hydrogeologists who work for consulting firms must treat the firm's clients fairly in financial matters and do work that is as precise and correct as is possible. Only that work necessary to fulfill the contractual obligations should be conducted, even if the project still has money available in the budget. If the contracted work cannot be completed within the budget because of unforeseen or changed circumstances, the client can be approached for a modification of the terms of the contract.

Ethical problems can potentially arise for employees if a firm has obtained a fixed-price contract or a contract that calls for an hourly rate plus expenses with a maximum billable amount. If all project funds are expended before the work is completed and the employees working on the project keep charging hours to that project, it will become a money loser. This does not look good for the employees since the objective of a consulting business is to make money, not lose it. There might be a temptation to keep working on a losing project but to charge one's time to a project that still has some funds available; however, this practice is not only unethical, but could also be construed as fraud. The manager of one consulting project where the client was the federal government was convicted of falsifying time cards in such a case and was sentenced to a federal penitentiary.

If a hydrogeologist determines that a particular situation may adversely affect the client, such as contamination at a site that was thought to be clean, the client should be advised promptly. This information is confidential and should not be disclosed to others unless it is required by law. Once advised by the hydrogeologist, the property owner may have the legal requirement to report the contamination to the appropriate regulatory agency.

The hydrogeologist must also be aware of and avoid any conflicts of interest. For example, an employee of a state regulatory agency should not accept any private consulting work on projects within the state, nor accept any consulting work from firms that are regulated within the state, even if the work is on an out-of-state project. A consulting firm that works for a client who has a contamination plume extending offsite to an adjacent property should not work for the owner of the adjacent property unless both parties agree to be bound by the findings of a single study covering both properties. If a hydrogeologist becomes aware of any decision or action of a client or the employer that violates any law or regulation, then the hydrogeologist should advise against that action or decision. If the violation continues and appears materially to affect the public health, safety, or welfare, the hydrogeologist should promptly advise the proper authorities. (As a practical matter, although illegal, such action may result in the hydrogeologist being fired. Being ethical sometimes comes with a price.) If a report for submission to a regulatory agency is being prepared, it should honestly report all findings of a study, even if parts may be adverse to the client's position. Many times a client is given a draft of a report to review prior to submittal. In this case, the hydrogeologist must resist suggestions to delete or change data or conclusions that should be contained in an honest report, because she or he has an ethical responsibility to the general public to protect human health, safety, and welfare—as well as the environment.

Hydrogeologists who work for review agencies have an ethical responsibility to base their reviews only on scientific considerations. Such agencies can be politicized, and pressure may be put on a reviewer to base a decision on political rather than scientific grounds. Just as the hydrogeologist working for the client must be honest in preparing a report, the reviewer who reads it has an ethical responsibility to be equally honest. Hydrogeologists working for review agencies also usually keep time sheets. Certain enforcement actions allow the regulatory agencies to recover their costs from the polluters, including the wages and benefits of employees. The regulatory hydrogeologist has an ethical responsibility to be as accurate as possible in assigning time to specific enforcement actions for which cost recovery is anticipated.

9 Sources of Hydrogeologic Information

Hydrogeologic information is available from a wide range of sources. In terms of sheer volume, the Water Resources Division of the United States Geological Survey (USGS) is the leading source in the United States. This agency collects basic data on streamflow, surface-water quality, ground-water levels, and ground-water quality. The USGS also conducts water resources investigations and basic research. USGS publications are available in libraries that are designated depositories of federal documents; these publications are also available from the U.S. Government Printing Office.

The USGS maintains a large volume of data on both ground and surface water. Most of these data are available through the internet. The URL for the USGS home page is *http://www.usgs.gov.* Streamflow data are available at *http://waterdata.usgs.gov.* At that address one can select a specific state and then search for specific streamflow gauging stations by county or drainage basin. Both current and historical data are available. One can either obtain a table of values or a graph of daily or peak flows.

Links are available to home pages for state offices of the USGS. These pages include lists of publications for each district office. A link is also available for each watershed to EPA databases. Lists of EPA-regulated sites can be generated for the watershed.

The URL for the EPA home page is *http://epa.gov.* A wealth of information is available for various EPA program offices. You might be especially interested in the EPA's Office of Ground Water and Drinking Water at *http://www.epa.gov/OGWDW/.*

The National Oceanic and Atmospheric Administration (NOAA) is the parent organization of the National Weather Service. The *Climatic Record of the United States* is published for each state and contains precipitation, temperature, evaporation, and other climatic data. Climatic data are available from the NOAA. The URL for its home page is *http://noaa.gov.* Climatic data from land-surface stations (e.g., temperature and precipitation) are available at *http://www.ncdc.noaa.gov/ol/climate/climatedata.html.*

The National Ground Water Association (NGWA) maintains Ground Water On-Line, a computerized database of bibliographic information. As of 2000 there were more than 80,000 documents indexed by more than 700 hydrogeological descriptors. A bibliographic search can be conducted by computer that will seek out all indexed documents that correspond to the selected descriptors. This service is available at no cost to members of the NGWA (including student members).* To access this service go to *http://www.ngwa.org.* Locate the button on their home page marked GWOL and click on it to start a search. An interlibrary loan and photocopying service is also available to obtain copies of the articles that the database search found.

Other U.S. federal agencies that may conduct studies related to hydrogeology include the Corps of Engineers, Bureau of Land Management, Bureau of Reclamation, Soil Conservation Service, Environmental Protection Agency, Nuclear Regulatory Agency, and Department of Energy. In most states, one or more agencies are responsible for water-oriented research and other activities. The functions, responsibilities, and organizational formats of state agencies in water resources activities vary from state to state. Typical state agency designations include departments of water resources or water survey, geological surveys, departments of conservation or natural resources or environmental protection, and departments or boards of health. In many states, various responsibilities are allocated among several agencies. In addition, Congress has established provisions for a water resources research center or institute in each state and in Puerto Rico. These are associated with a major university in each state. Reports of current research and recent developments in hydrogeology and ground water are included in the following journals:

- *Bulletin,* International Association of Scientific Hydrology
- *Environmental Science and Technology*
- *Geochimica et Cosmochimica Acta*
- *Ground Water*
- *Ground Water Monitoring and Remediation*
- *Journal of the American Water Works Association*
- *Journal of Applied Hydrogeology*
- *Journal of Contaminant Hydrology*
- *Journal of Hydrology*
- *Memoirs*, International Association of Hydrogeologists
- *Transactions,* American Society of Civil Engineers
- *Water Resources Bulletin*
- *Water Resources Research*

Several professional organizations sponsor symposia and meetings where technical sessions on hydrogeology or ground water are held. These include the following:

- American Geophysical Union
- American Institute of Hydrology

*The National Ground Water Association can be contacted for membership information at 1-800-332-2104 or by e-mail at *ngwa@ngwa.org* or by snail mail at NGWA, 601 Dempsey Road, Westerville, OH 43081-8987.

- American Society of Civil Engineers
- American Water Resources Association
- Geological Society of America
- Geological Society of Canada
- International Association of Hydrogeologists
- International Association of Scientific Hydrology
- International Water Resources Association
- National Ground Water Association

10 American Society of Testing and Materials Standards

The American Society of Testing and Materials (ASTM) is a voluntary organization that publishes consensus standards and guides for a wide variety of engineering and technological applications ranging from construction and materials testing to environmental assessment. A committee of volunteers drawn from industry, academia, manufacturing, consulting, and government writes each standard or guide. Anyone from the technical community can volunteer to be on one of the subcommittees.

The ASTM standards are voluntary in the sense that the organization has no authority to require their use. In fact, many states have specific requirements for such practices as design and installation of ground-water monitoring wells that are also covered by ASTM standards. The state requirements do not necessarily conform to those published by ASTM.

At the present time there are in excess of 750 ASTM standard practices and guides that are applicable to the ground-water industry. The proliferation of these standards has caused some concern among hydrogeologists that "cookie cutter" procedures are replacing professional judgment. They are also in competition with guides and practices published by the EPA, USGS, and various state agencies. Conversely, standardization of test methods leads to more uniform results so that studies by different organizations can be more easily compared. Likewise, in the absence of specific state requirements, consultants may find some protection against malpractice lawsuits if work is performed in rigorous compliance with the corresponding voluntary ASTM standard. Hydrogeologists can also use ASTM standards in the preparation of contract specifications for subcontract work such as that which is done by drillers and laboratories. By specifying an ASTM standard, the hydrogeologist can communicate to the driller exactly what procedures are to be used in the field.

11 Working the Problems

The chapter has end-of-chapter problems for students to work. Step-by-step solutions to the odd-numbered problems can be found on the author's web page; *www.appliedhydrogeology.com.* These problems are designed so that students can work them using only calculators, graph paper, and tables found in the appendices.

By working the problems, students will gain a much deeper understanding of the material.

In working the problems, students should pay attention to the number of significant digits (significant figures) used. Significant digits arise when using measured values. Although we can count objects exactly, a measurement is always an approximation. The last digit in the measurement shows the degree of approximation. For example, a measurement of 17.63 cm is only an estimate. All we know for sure is that the object measured is actually somewhere between 17.625 and 17.635 cm long. The measurement 17.63 cm has four significant digits. If someone else measures the same objects and says that it is 18 cm long, the actual length is between 17.5 and 18.5 cm, and the measurement has been made to two significant digits. When two or more numbers are multiplied (or divided), their product (or quotient) should have the same number of significant digits as the multiplier (or divisor) with the least number. For example, if we measure the sides of a rectangle as 17.63 cm and 14.2356 cm, the area of the rectangle is 251.0 cm^2, not 250.97363 cm^2. We use the number of significant digits of the least precise measurement, in this case four. We report the number as 251.0, not 251, to show the number of significant digits. When measurements are added (or subtracted), the sum (or difference) should not have any significant digits to the right of the last significant digit of any of the addends (or subtrahends). For example, if we add $17 + 2.35 + 1.346 + 0.072$, the sum is 21, not 20.768. Since 17 has only two significant digits, the sum can only have two significant digits. Notice that we have rounded the number that is obtained from the calculator to the appropriate number of significant digits. However, if the measurements were 17.0, 2.35, 1.346, and 0.072, the sum would be 20.8, not 21, because 17.0 has three significant digits. Be aware that the numbers 17, 17.0, 17.00, and 17.000 differ in the number of significant digits. When zeros occur to the left of the decimal, it is harder to determine the number of significant digits. For example, 100.0 has four significant digits, and 100. has three significant digits, but does 100 have one, two, or three significant digits? Unless an uncertainty range is specified, this question is unanswered. For example, 100 ± 1 has three significant digits and 100 ± 10 has two significant digits. For purposes of working problems in the text, for a number such as 100 (or 2500 or 10,000), assume that it is exact and determine the number of significant digits from other numbers in the problem.

In solving the problems in the text we frequently employ the concept of dimensional analysis. In dimensional analysis the units of measurement are used as a guide in the calculations to obtain the desired units for the answer. A simple example of dimensional analysis is in calculating the number of inches in a measured distance of 1.7 mi. We know that there are exactly 12 in. in 1 ft and exactly 5280 ft in 1 mi. The problem can be set up as follows:

$$1.7 \text{ mi} \times 5280 \text{ ft}/1 \text{ mi} \times 12 \text{ in.}/1 \text{ ft} = 107{,}212 \text{ in.}$$

Some of the units cancel each other, since they appear in both the numerator and the denominator. In this example, miles and feet cancel, leaving inches as the unit.

The answer of 107,712 in. then must be adjusted to the proper number of significant digits.

PROBLEM

How many significant digits are in 107,712 in.?

The mileage measurement of 1.7 has only two significant digits, so we round the answer to 110,000 in., a number with two significant digits.

In working the problems, you will also need to use conversion factors. These are shortcuts to dimensional analysis when converting units from one system of measurement to another. Conversion factors for length, area, volume, and time are found in the appendices; those of flow are inside the front cover.

PROBLEM

Use a conversion factor to find the number of inches in 1.7 mi.

In the appendix "Table for length conversion" we see that 1 mi is equal to 63,360 in. Therefore, 1.7 mi × 63,360 in. = 107,710 in.

Since there are only two significant figures in 1.7 mi, the correct answer is 110,000 in.

One needs to be careful in making unit conversions between measuring systems. We know by definition that a mile is exactly 63,360 in. long. However, when converting from the English system to the International System of Units (SI), the conversion factors may be rounded: 1 ft is 0.3048 m to four significant digits; 1 ft is also 0.305 m to three significant digits and 0.30 m to two significant digits. When converting units between systems, either the measured value or the unit conversion factor could control the number of significant digits.

The units with which you will work have all been derived from three basic factors, mass (M), time (T), and length (L). Areas are in units of length times length (L^2) and volumes are in units of length cubed (L^3). For example, velocity is length divided by time (L/T) and is expressed in such units as feet per day (ft/d) or meters per second (m/s). Concentration is mass of solute per unit volume of solution (M/L^3) and is expressed in units such as milligrams per liter (mg/L). Density is the mass of an object per unit volume (M/L^3) and is expressed in units such as kilograms per cubic meter (kg/m^3). As a check on dimensional analysis using units, it is often helpful to conduct dimensional analysis using M, L, and T.

The United States is now the only county in the world that has not completely adopted the SI system for units of measurement. Instead of the logical and simple system of millimeters, centimeters, meters, and kilometers, we have inches, feet, yards, and miles; ounces and pounds instead of grams and kilograms; and gallons and cubic feet instead of liters and cubic meters. In this edition we continue to use both the English and the SI systems of units in the example problems. In professional practice, hydrogeologists can use the system that is in widest use in their home country, but all should have at least a passing knowledge of both systems.

12 Solving Problems Using Spreadsheets

Many of the end-of-chapter problems can be solved using a spreadsheet program, such as Microsoft Excel. Excel is a powerful program with many features. There are a host of books published on how to use Excel and the program itself has an excellent help section. What you will find here is a very brief introduction to Excel and a demonstration of how algebraic equations can be written and solved.

The spreadsheet is a matrix of cells set up in rows and columns. The columns are labeled with a letter along the top and the rows with a number on the right side. Each cell has an address, which lists the column and a row in which it appears. The cell in the upper left corner is A1. A cell can hold text, a value, or a formula. The formulas can refer to other cells in which the values to be acted upon are stored.

The basic numeric operators in Excel are as follows:

+	addition
–	subtraction
*	multiplication
/	division
/\	exponentiation

Other functions include:

ACOS	Returns the arccosine of a number
ASIN	Returns the arcsin of a number
ATAN	Returns the arctangent of a number
AVERAGE	Returns the average value of a group of numbers
COS	Returns the cosine of a number
EXP	Returns *e* raised to the power of a given number
LN	Returns a natural log of a given number
LOG10	Returns the base 10 log of a number
SIN	Returns the sine of a number
SQRT	Returns the square root of a number
SUM	Returns the sum of a group of numbers
TAN	Returns the tangent of a number

Numbers in Excel include positive and negative real numbers. Numbers that are very large or very small are often written in scientific notation. One million can be written as 1.0×10^6. In Excel we would write this number as 1.0E6. Likewise, the value 7.56×10^{-7} is written as 7.56E−7.

When a formula is entered into a cell, one always starts with the = sign to indicate that a formula is being entered. The direction keys are used to move the cursor to a cell. The active cell is indicated in the "name box," which is near the top left side of the screen. As the formula is typed, it will appear in both the cell and a bar above the matrix called the formula bar. After the formula has been entered, and the return key pushed, the formula in the cell is replaced by the value that it returns. If the cursor is placed over a cell that contains a formula, the formula will appear in the formula bar, and the returned value in the cell.

Excel will perform the numeric operations in the following order: first exponentiation, then multiplication and division, and then addition and subtraction. Parentheses can be used to not only control the order of execution of the numeric operations, but also to clarify the equation.

An Excel formula for the area of a circle, where the value of the radius is stored in cell B1, can be written as follows:

=3.1416*B1^2

The value of B1 is first raised to the power of 2 and then multiplied by pi. If we have the value of the diameter of the circle stored in cell B3, then we could write the formula as

=3.1416*(B3/2)^2

Here the parentheses indicate that the value in B3 must first be divided by 2 and then that value squared before being multiplied by pi.

Excel can perform statistical operations on an array of values. For example, a column of numbers can be summed with the SUM function. If the column of numbers appears in column B from cell B3 to cell B10, one can put the following formula in any cell but B3 through B10.

=SUM(B3:B10)

The : indicates that all numbers between B3 and B10 are to be summed. If we wanted to sum B3 + B4 + B5 + B6 + B10, we could write

=SUM(B3:B6,B10)

It is a good practice to identify the contents of a cell that contain a value or a formula by entering text in a cell to the left or the right.

Notation

H_v	Heat of vaporization	T	Temperature

Analysis

a. In Decision 1631 on the Amendments of the City of Los Angeles' Water Right Licenses for Diversion of Water from Streams Tributary to Mono Lake, the State of California Water Resources Control Board took a middle road and allowed some diversions if and when the level of Mono Lake rises above an elevation of 6392 ft. The full text of the decision can be found at *http://www.monolake.org*, and on the *Applied Hydrogeology* home page.

Assume that you are a lawyer for either of the two sides in the case. The decision has been appealed and you are to prepare a brief to support one of the following two extreme positions.

1. All water in the tributary streams should be reserved to support the fish and aquatic life in the tributary streams as well as the unique ecology of Mono Lake. Therefore, no diversions should be permitted regardless of the water level of Mono Lake.
2. It is more important to supply water to the thriving communities of southern California than to worry about brine shrimp. Moreover, the City of Los Angeles has had a long-standing legal permit for the diversions and has invested a lot of money in the aqueduct to transport water from the diversion to the city.

b. Make a spreadsheet program to convert measurements in feet to inches, yards, miles, millimeters, centimeters, meters, and kilometers. The conversion factors can be found in in the appendix at the end of this chapter.

Problems

Note that the answers to odd-numbered problems are at the end of the and step-by-step solutions to the odd-numbered problems can be found on the *Applied Hydrogeology* home page: *http://www.appliedhydrogeology.com.*

1. A vertical water tank is 15 ft in diameter and 60 ft high. What is the volume of the tank in cubic feet?
2. What is the volume of the above tank in cubic meters?
3. If the above tank were measured and found to have an inside diameter of exactly 15.00 ft and a height of 60.00 ft, what would be the volume in cubic feet?
4. What would be the above tank's volume in cubic meters?
5. If a well pumps at a rate of 8.4 gal per minute, how long would it take to fill the tank described above?
6. The only swimming pool at the El Cheapo Motel is outdoors. It is 5.0 m wide and 12.0 m long. If the weekly evaporation is 2.35 in., how many gallons of water must be added to the pool if it does not rain?
7. If during the next week the pool still loses 2.35 in. of water to evaporation, even with 29 mm of rainfall, how many liters of water must be added?
8. A ground-water basin has a surface area of 125 km^2. The following long-term annual averages have been measured:

   Precipitation 60.6 cm

   Evapotranspiration 46.3 cm

   Overland flow 3.4 cm

   Baseflow 10.6 cm

   There is no streamflow into the basin and no ground-water flow either into or out of the basin.

   (A) Prepare an annual water budget for the basin as a whole, listing inputs in one column and outputs in another. Make sure that the two columns balance as these are long-term values and we assume no change in the volume of water stored in the basin.

   (B) Prepare an annual water budget for the streams.

   (C) Prepare an annual water budget for the ground-water basin.

   (D) What is the annual runoff from the basin expressed in centimeters?

   (E) What is the annual runoff from the basin expressed as an average rate in cubic meters per second?
9. The parking lot of the Spendmore Megamall has an area of 128 ac. It is partially landscaped to provide some areas of grass. Assume that an average 63% of the water that falls on the parking lot will flow into a

nearby drainage ditch, and the rest either evaporates or soaks into unpaved areas. If a summer thunderstorm drops 3.23 cm of rain, how many cubic feet of water will flow into the drainage ditch?

10. What mass of water at 15°C can be cooled 1°C by heat necessary to melt 185 g of ice at 0°C?

11. What mass of water at 15°C can be cooled 1°C by the amount of heat needed to sublime (go from a solid to a vapor state) 18 g of ice at 0°C?

12. A 500-milliliter (mL) bottle of spring water, which is at room temperature of 25°C, is poured over 120 g of ice that is at –8°C. What will be the final temperature of the water when all of the ice has melted, assuming that it is in an insulated container that does not change temperature?

13. At a water elevation of 6391 ft, Mono Lake has a volume of 2,939,000 ac-ft, and a surface area of 48,100 ac. Annual inputs to the lake include 8 in. of direct precipitation, runoff from gauged streams of 150,000 ac-ft per year, and ungauged runoff and ground-water inflow of 37,000 ac-ft per year. Evaporation is 45 in. per year.

(A) Make a water budget showing inputs, in ac-ft per year and outputs in ac-ft per year. Does the input balance the output?

(B) Will the average lake level rise or fall from the 6391-ft elevation over the long term?

(C) What would be the lake surface area when the inputs balance the outputs? (Assume that the volume of gauged and ungauged runoff and ground-water inflows remain constant with a change in lake surface area.)

(D) What is the residence time* for water in Mono Lake when the water surface is at 6391 ft?

14. Assume that Mono Lake stood at an elevation of 6391 ft, as described in problem 13, and a total annual diversion of 85,000 ac-ft of water were allowed from the Mono Lake basin.

(A) Would the average lake level rise or fall?

(B) What would the final lake surface area be after a new equilibrium is established? (Assume that the volume of gauged and ungauged runoff and ground-water inflows remain constant with a change in lake surface area.)

Answers

1. $V = 11{,}000\ ft^3$ or $1.1 \times 10^4\ ft^3$
3. $V = 10{,}600\ ft^3$
5. 160 hrs.
7. Water added = 1800 L
9. $3.72 \times 10^5\ ft^3$ into ditch
11. 12000 g water
13. (a) input is greater than output.
    (b) lake level will rise over the long term.
    (c) 61,000 ac.
    (d) 16.3 yrs

*The residence time of a body of water is the average time that it would take for the volume of water to be exchanged once.

Appendix

Table for length conversion

Unit	mm	cm	m	km	in	ft	yd	mi
1 millimeter	1	0.1	0.001	10^{-6}	0.0397	0.00328	0.00109	6.21×10^{-7}
1 centimeter	10	1	0.01	0.0001	0.3937	0.0328	0.0109	6.21×10^{-6}
1 meter	1000	100	1	0.001	39.37	3.281	1.094	6.21×10^{-4}
1 kilometer	10^6	10^5	1000	1	39,370	3281	1093.6	0.621
1 inch	25.4	2.54	0.0254	2.54×10^{-5}	1	0.0833	0.0278	1.58×10^{-5}
1 foot	304.8	30.48	0.3048	3.05×10^{-4}	12	1	0.333	1.89×10^{-4}
1 yard	914.4	91.44	0.9144	9.14×10^{-4}	36	3	1	5.68×10^{-4}
1 mile	1.61×10^6	1.01×10^5	1.61×10^3	1.6093	63,360	5280	1760	1

Table for area conversion

Unit	cm^2	m^2	km^2	ha	in^2	ft^2	yd^2	mi^2	ac
1 sq. centimeter	1	0.0001	10^{-10}	10^{-8}	0.155	1.08×10^{-3}	1.2×10^{-4}	3.86×10^{-11}	2.47×10^{-8}
1 sq. meter	10^4	1	10^{-6}	10^{-4}	1550	10.76	1.196	3.86×10^{-7}	2.47×10^{-4}
1 sq. kilometer	10^{10}	10^6	1	100	1.55×10^9	1.076×10^7	1.196×10^6	0.3861	247.1
1 hectare	10^8	10^4	0.01	1	1.55×10^7	1.076×10^5	1.196×10^4	3.861×10^{-3}	2.471
1 sq. inch	6.452	6.45×10^{-4}	6.45×10^{10}	6.45×10^{-8}	1	6.94×10^{-3}	7.7×10^{-4}	2.49×10^{-10}	1.574×10^7
1 sq. foot	929	0.0929	9.29×10^{-8}	9.29×10^{-6}	144	1	0.111	3.587×10^{-8}	2.3×10^{-5}
1 sq. yard	8361	0.8361	8.36×10^{-7}	8.36×10^{-5}	1296	9	1	3.23×10^{-7}	2.07×10^{-4}
1 sq. mile	2.59×10^{10}	2.59×10^6	2.59	259	4.01×10^9	2.79×10^7	3.098×10^6	1	640
1 acre	4.04×10^7	4047	4.047×10^{-3}	0.4047	6.27×10^6	43,560	4840	1.562×10^{-3}	1

Table for volume conversion

Unit	mL	liters	m^3	in^3	ft^3	gal	ac-ft	million gal
1 milliliter	1	0.001	10^{-6}	0.06102	3.53×10^{-5}	2.64×10^{-4}	8.1×10^{-10}	2.64×10^{-10}
1 liter	10^3	1	0.001	61.02	0.0353	0.264	8.1×10^{-7}	2.64×10^{-7}
1 cu. meter	10^6	1000	1	61,023	35.31	264.17	8.1×10^{-4}	2.64×10^{-4}
1 cu. inch	16.39	1.64×10^{-2}	1.64×10^{-5}	1	5.79×10^{-4}	4.33×10^{-3}	1.218×10^{-8}	4.329×10^{-9}
1 cu. foot	28,317	28.317	0.02832	1728	1	7.48	2.296×10^{-5}	7.48×10^{6}
1 U.S. gallon	3785.4	3.785	3.78×10^{-3}	231	0.134	1	3.069×10^{-6}	10^6
1 acre-foot	1.233×10^9	1.233×10^6	1233.5	75.27×10^6	43,560	3.26×10^5	1	0.3260
1 million gallons	3.785×10^9	3.785×10^6	3785	2.31×10^8	1.338×10^5	10^6	3.0684	1

Table for time conversion

Unit	sec	min	hours	days	years
1 second	1	1.67×10^{-2}	2.77×10^{-4}	1.157×10^{-5}	3.17×10^{-8}
1 minute	60	1	1.67×10^{-2}	6.94×10^{-4}	1.90×10^{-6}
1 hour	3600	60	1	4.17×10^{-2}	1.14×10^{-4}
1 day	8.64×10^4	1440	24	1	2.74×10^{-3}
1 year	3.15×10^7	5.256×10^5	8760	365	1

Elements of the Hydrologic Cycle

Elements of the Hydrologic Cycle

Rivers depend for their existence on the rains and on the waters within the earth, as the earth is hollow, and has water in its cavities.

Anaxagoras of Clazomenae, 500–428 B.C.

1 Evaporation

Water molecules are continually being exchanged between liquid and atmospheric water vapor. If the number passing to the vapor state exceeds the number joining the liquid, the result is **evaporation.** When water passes from the liquid to the vapor state, it will absorb 590 cal of heat from the evaporative surface for every gram of water evaporated. The vapor pressure of the liquid is directly proportional to the temperature. Evaporation will proceed until the air becomes saturated with moisture. The **absolute humidity** of a given air mass is the number of grams of water per cubic meter of air.

At any given temperature, air can hold a maximum amount of moisture, called the **saturation humidity,** which is directly proportional to the temperature of the air. Table 1 gives the saturation humidity for several environmental temperatures. The **relative humidity** for an air mass is the percent ratio of the absolute humidity to the saturation humidity for the temperature of the air mass. As the relative humidity approaches 100%, evaporation ceases.

When an air mass is cooled and the saturation humidity value drops, **condensation** occurs as the air mass can no longer hold all of its humidity. If the absolute humidity remains constant, the relative humidity will rise. When it reaches 100%, any further cooling will result in condensation. The **dew point** for an air mass is the temperature at which condensation will begin. As condensation is the reverse of evaporation, the process of condensation releases 590 cal of heat to the surroundings per gram of water, termed the latent heat of condensation. Evaporation of water takes place

Table 1 Saturation humidity of air (grams per cubic meter)

Temperature (°C)	Humidity (gm/m^3)
−25	0.705
−20	1.074
−15	1.605
−10	2.358
−5	3.407
0	4.874
5	6.797
10	9.399
15	12.83
20	17.30
25	23.05
30	30.38

Source: Handbook of Chemistry and Physics *(Cleveland, Ohio: CRC Publishing Company, 1976).*

from free-water surfaces—lakes, reservoirs, puddles, dew droplets, for example. The rate depends on factors such as the water temperature and the temperature and absolute humidity of the layer of air just above the free-water surface. Solar radiation is the driving energy force behind evaporation, as it warms both the water and the air. The rate of evaporation is also related to the wind, especially over land. The wind carries vapor away from the free-water surface and keeps absolute humidity low. By disturbing the water surface, the wind may also increase the rate of molecular diffusion from it.

Evaporation from lakes and reservoirs is an important consideration in water-budget studies. It can be computed for a lake or reservoir if all inflows (precipitation over the surface, surface-water inflow, and ground-water inflow), outflows (ground-water outseepage, spillway discharge, and pumpage), and change in storage are known. The hydrologic equation (inflow = outflow ± changes in storage) is used. These factors, with the exception of the ground-water flux, can be measured with an error of perhaps ± 10%. In a carefully prepared water-budget study for Lake Hefner, Oklahoma, daily evaporation was computed to an accuracy of 5% to 10% (Harbeck & Kennon 1954). For many reservoirs, monthly or annual evaporation can be computed easily. The most difficult factor to determine is the ground-water flux.

Free-water evaporation is measured quite simply by using shallow pans. The most commonly used is the **land pan.** The U.S. National Weather Service maintains about 450 evaporation stations using Class A land pans. Similar pans are used in Canada. They are 4 ft (122 cm) in diameter and 10 in. (25.4 cm) deep, made of unpainted galvanized metal. Land pans are placed on supports so that air can circulate all around. Water depths from 7 to 8 in. (18 to 20 cm) are maintained. Records are kept of the daily depth of water, the volume of water added to replace evaporated water, and the daily precipitation into the pan. Using the hydrologic budget, the daily evaporation can be computed. Errors may result from splash caused by heavy rainfall and drinking by birds. The wind movement is also measured and expressed in units of miles per day (mi/d). (A steady wind blowing at a velocity of 10 miles per hour (mi/h) would have a 24-h wind movement of 240 mi/d.)

Research has shown that the manner in which precipitation is measured can affect the amount of evaporation that is calculated at an evaporation station. Precipitation can be determined with a **rain gauge** placed next to the evaporation pan. There are two basic

Table 2 Class A land pan coefficients for midwestern United States

January	0.62	August	0.75
February	0.72	September	0.73
March	0.77	October	0.69
April	0.77	November	0.63
May	0.78	December	0.58
June	0.77		
July	0.76		
	Annual	0.75	

Source: W. J. Roberts & J. B. Stall, Illinois State Water Survey Report of Investigation *(1967): 57.*

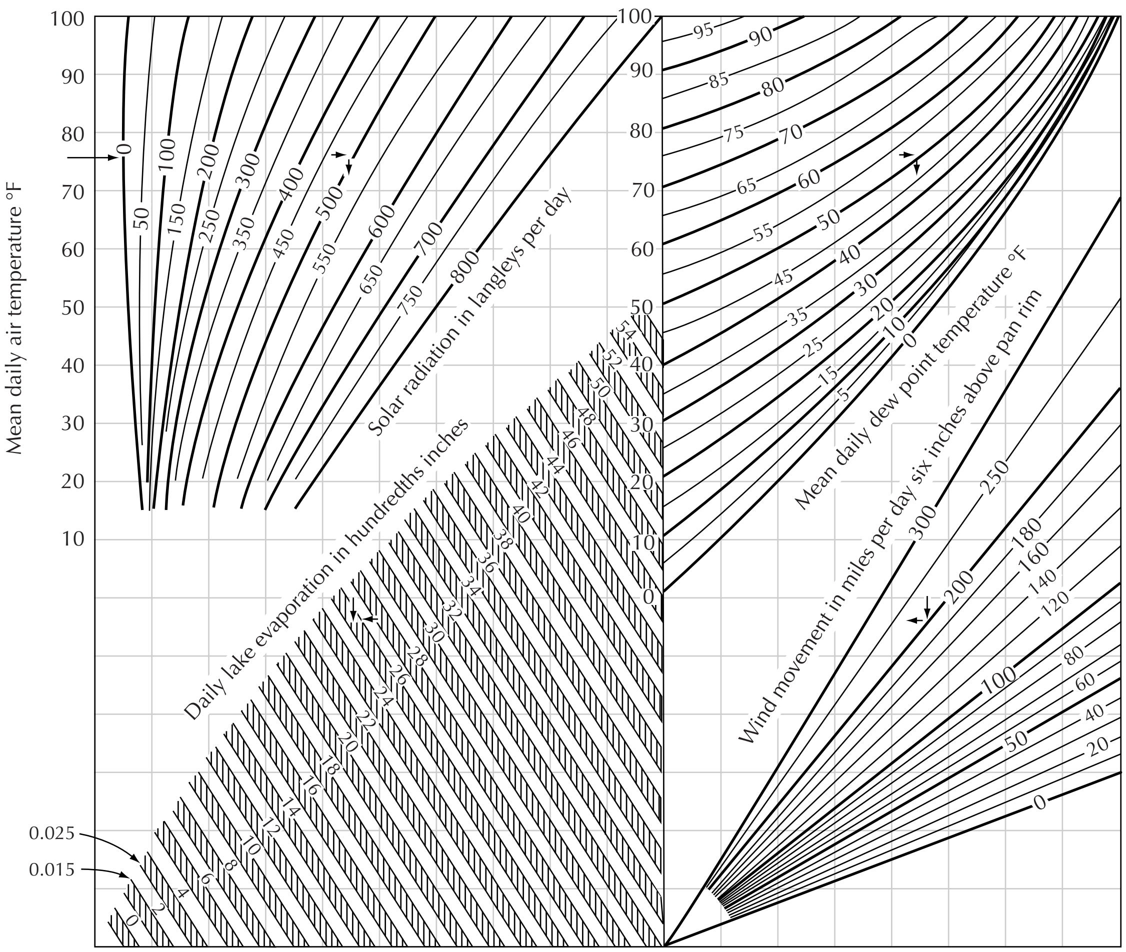
varieties of rain gauges. A nonrecording rain gauge is simply a container in which water accumulates and then the volume of water is measured periodically, typically once a day. The depth of precipitation is found by dividing the volume of water by the cross-sectional area of the collector. A recording rain gauge is designed so that it will indicate the time of day when the precipitation occurs. The volume of water that collects in a rain gauge can be affected by the exposure of the gauge to wind.

Daily measurements of water level in the pan and precipitation as measured by the rain gauge are made. An alternative method is to use a sensitive water-level recorder and continuously record the water level in the evaporation pan. Net evaporation is determined by summing all measured declines in the water level. In this instance, the evaporation pan is acting as the rain gauge. In a study of evaporation in the Florida Everglades, during rain-free periods both types of evaporation stations yielded similar results; however, during rainy periods, measured evaporation at the stations that utilized rain gauges was significantly greater than the station with a level recorder. The conclusion of the study was that the rain gauge caught more rain than the pan. As a result, the calculated evaporation was higher at the stations using rain gauges, as the input to the hydrologic equation was greater (Gunderson 1989).

The water in a Class A land pan will be warmed much more readily by solar radiation than the surface waters of a lake or reservoir. The chief reason is the difference between the water depth in the pan and the depth of the surface layer of reservoir water. The pan may also gain or lose heat through the sides and bottom, a process that does not occur in reservoirs. For these reasons, observed pan evaporation is multiplied by a factor with a value less than 1.0, the pan coefficient, to estimate reservoir evaporation during the period of observation. Detailed studies in the United States Midwest have yielded monthly pan coefficients ranging from 0.58 in December to 0.78 in May, with an annual value of 0.75 (Roberts & Stall 1967) (see Table 2). The National Weather Service has developed a lake evaporation nomograph (Kohler, Nordenson, & Fox 1955). From this diagram, daily lake evaporation can be determined using mean daily temperature, solar radiation in langleys* per day, mean daily dew-point temperature, and wind movement in miles per day.

Begin reading the graph in Figure 1 from the left side at the mean daily air temperature, for example, 75°F. Note the horizontal line drawn across the chart along the 75°F axis. Perpendicular lines are dropped at the intersections of the values of solar radiation and

*A langley is a measure of solar radiation equal to 1 cal per square centimeter of surface. In the SI system (International System of Units, based on the meter, kilogram, second, and ampere), the unit is the joule per square meter, which is equal to 4.194×10^4 langleys.



▲ FIGURE 1
Nomograph used to determine the value of daily lake evaporation for shallow lakes if solar radiation, mean daily air temperature, mean daily dew-point temperature, and wind movement are known. *Source: Roberts & Stall,* Illinois State Water Survey Report of Investigation *(1967): 57.*

mean daily dew-point temperature. In the example, these are 500 langleys per day and 50°F. The right perpendicular line extends from the mean daily dew-point temperature to the total daily wind movement. The example value is 200 mi/d. From this intersection, a horizontal line extends toward the left. This horizontal line and the left perpendicular line will intersect in a field indicating the mean daily lake evaporation. For the example in Figure 1, this is 0.25 in./d.

In some instances, it may be necessary to estimate evaporation without the availability of evaporation pan data. Such estimates are possible via methods based on heat budgets (Hornberger et al. 1998). The energy budget for a reservoir may be used to find the amount of energy used for evaporation, which in turn can yield the amount of evaporation.

2 Transpiration

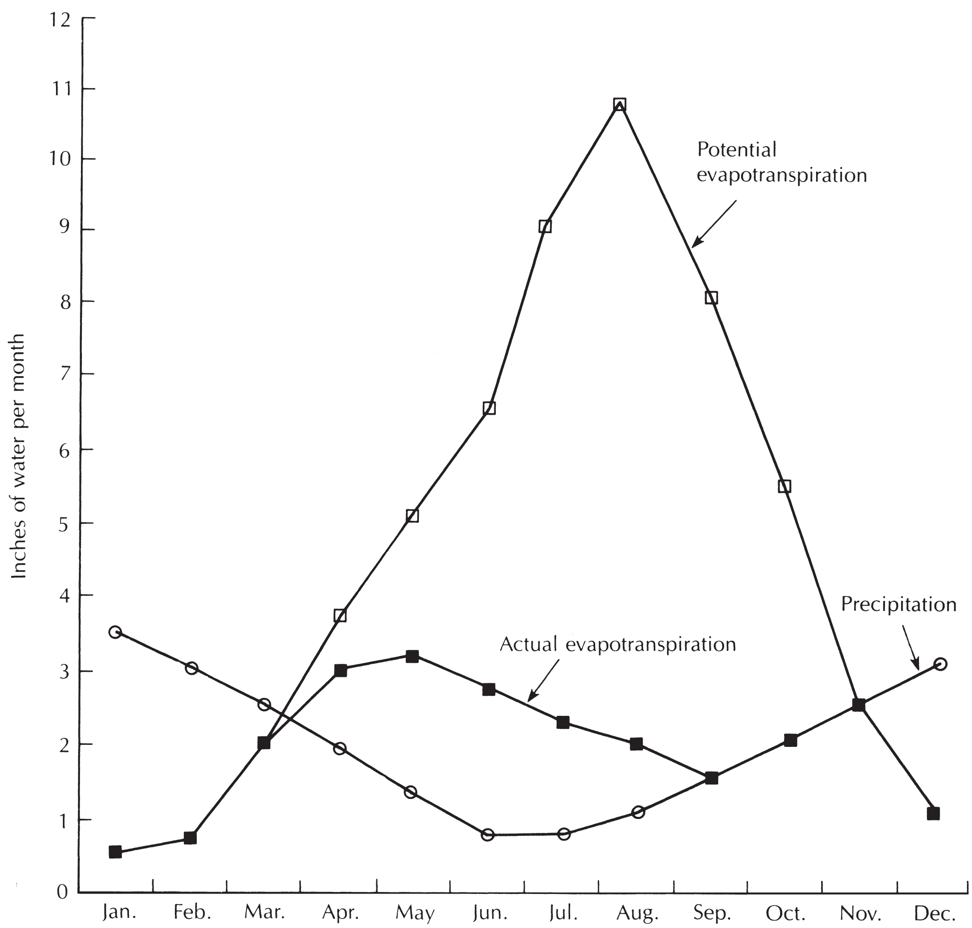
Free-water evaporation is only part of the mechanism for mass transfer of water to the atmosphere. Growing plants are continuously pumping water from the ground into the atmosphere through a process called **transpiration.** Water is drawn into a plant rootlet from the soil moisture owing to osmotic pressure, whereupon it moves through the plant to the leaves. The turgidity of nonwoody vascular plants is caused by the cellular pressures of the contained water. The water is passed as vapor through openings in the surface of the leaves known as stomata. Air also passes through these openings. A small portion (less than 1%) of the water is used to manufacture plant tissue, but most is transpired to the atmosphere. The process of transpiration accounts for most of the vapor losses from a land-dominated drainage basin. The amount of transpiration is a function of the density and size of the vegetation. As an example, transpiration from a cornfield in May, when the plants are a few centimeters high, is much less than in August, when they may exceed 7 ft (2 m) in height. Transpiration is obviously important only during the growing season; about 95% takes place during the daylight hours, when photosynthesis is occurring. Transpiration is also limited by available **soil water.** When the soil-water content becomes so low that the surface tension of the soil-water interface exceeds the osmotic pressure of the roots, water will no longer enter the roots. This is termed the **wilting point** of the soil. When available water becomes limited, deep-rooted plants are more resistant to drought wilting than shallow-rooted plants, as the former can draw moisture from deeper layers. Also, some plants have fewer stomata and can close them through the use of special cells to reduce water loss during drought periods. Such drought-resistant species can transpire less water during periods of stress.

Phreatophytes are plants with a taproot system extending to the water table. They can transpire at a high rate even in the desert, so long as the water table does not drop below the taproot. In areas of low precipitation, the native vegetation is adapted to that which is existing with minimal water. These desert plants are called **xerophytes.** They have a shallow root system that spreads out away from the plant. Aquatic plants, or **hydrophytes,** are a special case. They exist with their root systems submerged, and the special cells some plants have to close the stomata are lacking. As long as adequate water is available, transpiration proceeds at a high rate. The rate of transpiration is controlled by the amount of solar energy and the heat content of the water. The water loss from a pond is about the same, regardless if emergent aquatic vegetation is present.

Measurement of transpiration can be performed under carefully controlled laboratory conditions. A phytometer is a sealed container partially filled with soil. Transpiration by plants rooted in the soil causes an increase in the humidity, which can be measured in the air space around the plant. However, such laboratory studies reveal little about the behavior of plants in natural or agricultural conditions.

3 Evapotranspiration

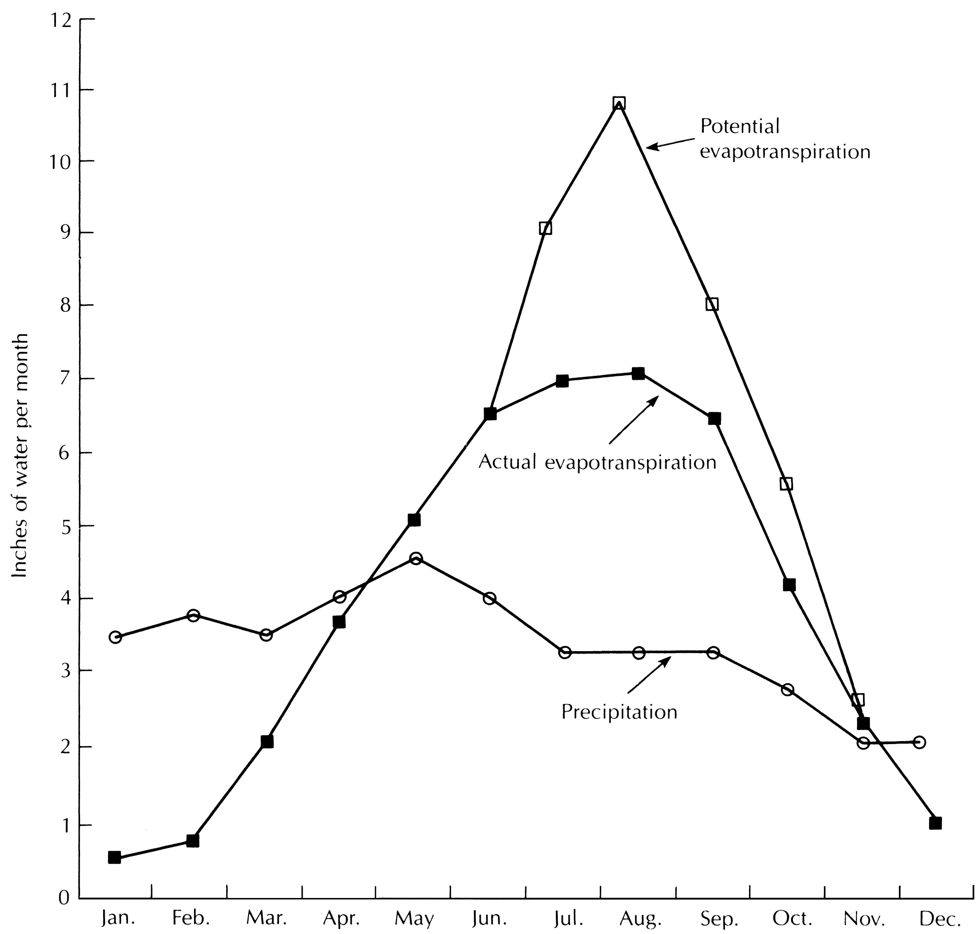
Under field conditions it is not possible to separate evaporation from transpiration totally. Indeed, we are generally concerned with the total water loss, or **evapotranspiration,** from a basin. Whether the loss is due to free-water evaporation, plant transpiration, or soil-moisture evaporation is of little importance. The term **potential evapotranspiration** was introduced by Thornthwaite (1944) as equal to "the water loss, which will occur if at no time there is a deficiency of water in the soil for the use of vegetation." Thornthwaite recognized an upper limit to the amount of water an ecosystem will lose by evapotranspiration. The majority of the water loss due to evapotranspiration takes place during the summer months, with little or no loss during the winter. Because there is often not sufficient water available from soil water, the term **actual evapotranspiration** is used to describe the amount of evapotranspiration that occurs under field conditions. Figure 2 shows potential evapotranspiration and actual evapotranspiration for a region with a warm, dry summer and a cool, moist fall, winter, and spring.



▲ FIGURE 2
Diagram of potential and actual evapotranspiration in an area that has coarse soil with limited soil-moisture storage; warm, dry summers; and cool, moist winters.

Under these conditions the actual evapotranspiration is much less than the potential, especially if the soil-water storage capacity is limited. In months when the potential evapotranspiration is less than the rainfall, some of the demand will be met by drawing upon moisture stored in the soil. When available soil water is depleted, the actual evapotranspiration will be limited to the monthly precipitation. Figure 3 shows potential and actual evapotranspiration in an area where the precipitation is more or less evenly distributed through the year. This circumstance results in the actual evapotranspiration being closer to the potential value.

Thornthwaite's (1944) method is based upon the assumption that potential evapotranspiration was dependent only upon meteorological conditions and ignored the effect of vegetative density and maturity. While this assumption is incorrect, the method devised by Thornthwaite to compute potential evapotranspiration is still useful. The only necessary factors to input are mean monthly air temperature, latitude, and month (Thornthwaite & Mather 1955, 1957). The last two factors yield average monthly sunlight. The Thornthwaite method is reasonably accurate in determining annual values, especially in humid areas. As no factor for vegetative growth is included, values computed for spring



▲ FIGURE 3
Diagram of potential and actual evapotranspiration in an area with fine soils with ample soil-moisture storage, warm summers, cool winters, and little seasonal change in precipitation.

and early summer are too high, as the crop is just emerging; midsummer values may be too low.

Evapotranspiration can also be calculated by the energy balance method (Hornberger et al. 1998). To use this method, one needs to know the following parameters: net solar radiation input, energy output through conduction to the ground, net output of sensible heat to the atmosphere, change in heat energy stored in the ground per unit surface area, and the latent heat of vaporization at the given temperature. Not all parameters are easy to measure or estimate and the method can be difficult to utilize.

Evapotranspiration can be measured directly using a lysimeter—a large container holding soil and plants. The lysimeter is set outdoors, and the initial soil-water content is determined. Precipitation into the lysimeter and any irrigation water added are measured. Changes in soil-moisture storage reveal how much of the added water is lost to evapotranspiration. It is necessary to design the lysimeter so that any moisture in excess of that specifically retained by the soil is collected. The following equation can be used with the lysimeter:

$$E_T = S_i + P_R + I_R - S_f - D_E \tag{1}$$

where

E_T is the evapotranspiration for a period

S_i is the volume of initial soil water

S_f is the volume of final soil water

P_R is the precipitation into the lysimeter

I_R is the irrigation water added to the lysimeter

D_E is the excess moisture drained from the soil

Lysimeters should be designed so that they accurately reproduce the soil type and profile, moisture content, and type and size of vegetation of the surrounding area. They should be buried so that the soil surface is at the same level inside and outside the container. Soil-water changes can be determined by sampling the soil, by means of moisture meters, or by weighing the entire mass of soil, water, and plants. Regardless of the method employed, operation of a lysimeter is both time consuming and expensive. If water is applied to the lysimeter at a rate sufficient to keep the soil at, or nearly at, the amount of water it can hold against gravity by surface tension, the lysimeter will measure potential evapotranspiration. When the soil water drops below that amount, lack of available water may limit evapotranspiration to some value less than the potential evapotranspiration. If the soil water drops below the wilting point, the plants may wither and die.

Evapotranspiration is the major use of water in all but extremely humid, cool climates. If evapotranspiration were reduced, then runoff or ground-water infiltration or both could increase, as would the available water supply. Studies have shown that basin runoff from a forested watershed has increased following the timbering of the forest (Hibbert 1967). The increase is greatest during the first year, when there is little reforestation. As the forest regrows, the runoff again decreases. Cutting of forests to increase runoff may also result in increased erosion from the uplands and concurrent sedimentation in the lowlands. Conversion of one plant cover to another can also affect the evapotranspiration rate. In Arizona, the conversion of a plot of land formerly covered with chaparral to grasses resulted in streamflow increases of several hundred percent. This was due in part to lower evapotranspiration, as the grass was not as deep rooted as the chaparral (Hibbert 1971). However, in Colorado, the conversion of sagebrush to bunchgrass had no appreciable effect on the amount of watershed runoff, although an increase in cattle forage did result (Shown, Lusby, & Branson 1972).

In some areas of the humid eastern United States, which were originally wooded, marginal farms have been abandoned. The old fields are gradually reverting to forest. There has been a concomitant decrease in streamflow from these watersheds. The replacement of deciduous forests with conifers results in an increase in evapotranspiration (Urie 1967).

In an urbanized watershed, one would naturally expect that the flood flows would increase as previous soil is replaced by impervious pavement. A surprising effect of urbanization is that in dry periods total runoff appears to be reduced (Ferguson & Suckling

1990). Thus, urbanization has actually increased evapotranspiration, even as the vegetative cover has decreased, perhaps due to the pattern of vegetation surrounded by pavement. Heat from the pavement areas causes overlying air to warm and rise, which can increase the evapotranspiration from the vegetated areas.

4 Condensation

When an air mass with a relative humidity lower than 100% is cooled without losing moisture, the relative humidity will approach 100% as the air approaches the dew-point temperature. When the air mass is saturated, condensation may start to occur. Condensation generally requires a surface or nucleus on which to form. The morning dew or frost is the result of condensation taking place on plants or other surfaces. Rain or ice crystals need nuclei in the atmosphere in order to form. Particles serving as nuclei include clay minerals, salt, and combustion products. In the absence of sufficient nuclei, the air mass may become supersaturated without the formation of raindrops or ice crystals. Once droplets or ice crystals have formed, they initially grow by attraction (diffusion) of water vapor and additional condensation. Rising air masses or upward movements of clouds tend to keep newly formed fog and cloud elements aloft. These elements range from 10 to 50 micrometers (μm) in size. As cloud elements collide and coalesce, raindrops begin to form. When the raindrops start to fall, further collisions occur, so that some raindrops may grow as large as 6 millimeters (mm) in diameter. Rain that falls through an unsaturated air mass may evaporate before it reaches the ground. Falling ice crystals grow by diffusion and collision to form snowflakes. The largest snowflakes form when temperatures are close to freezing.

5 Formation of Precipitation

For precipitation to occur, several conditions must be met: (1) a humid air mass must be cooled to the dew-point temperature, (2) condensation or freezing nuclei must be present, (3) droplets must coalesce to form raindrops, and (4) the raindrops must be of sufficient size when they leave the clouds to ensure that they will not totally evaporate before they reach the ground. Air masses are cooled by a process known as **adiabatic expansion,** which occurs when the air mass rises in the atmosphere. Since the atmosphere becomes less dense with altitude, a rising air mass must expand owing to the lower pressure. If no exchange of heat occurs between the air mass and its surroundings, the laws of thermodynamics dictate that the temperature will fall. When the air mass reaches the dew-point temperature, further lifting and cooling will cause condensation and the latent heat of vaporization is released.

6 Measurement of Precipitation and Snow

Any open container can be used to catch and measure rainfall. Experiments have shown that the size of the opening has little effect on the catch, except for very small (less than 3 cm in diameter) gauges (Huff 1955). The U.S. standard rain gauge has an opening 8 in. (20.3 cm) in diameter, whereas the Canadian standard gauge is 9 cm (3.57 in.) in diameter. These are manually read gauges; the water is emptied and the gauges are read once a day.

The catch of precipitation gauges is affected by high winds. Such gauges generally catch less than the true amount of rainfall because of updrafts around the gauge opening. The location of the gauge is also critical. In one study, two identical 8-in. gauges were placed 10 ft (3 m) apart on a ridge. One gauge consistently caught 50% more rainfall than the other (Court 1960). Gauges should be placed as close to the ground as possible to avoid wind. They should be in the open, away from trees and buildings. Low bushes and shrubs can provide a windbreak. Level ground is best, with the top of the gauge horizontal. On steep slopes, it may be desirable to have the orifice opening parallel to the slope. The effect of wind is greatest for light rain or snow. Some rain gauges are equipped with a shield, or wind deflector, around the opening to overcome wind problems. This will improve the catch of snow, but it will still be less than 100% effective in substantial winds.

Several available types of recording rain gauges can automatically measure or weigh the precipitation. The temporal distribution of precipitation through a day can thus be obtained. Such data are necessary for any studies of precipitation intensity. For remote areas, recording rain gauges can be used to record daily precipitation for long time periods. In such circumstances, manual gauges could provide only a total rainfall for the period between readings.

In the United States there are approximately 13,500 precipitation stations, for the most part operated by trained volunteers. Daily records from these weather stations are published monthly on a state-by-state basis in *Climatological Data;* data from recording stations are published in *Hourly Precipitation Data.* Both of these are publications of the U.S. Environmental Data Service. Data are also available at the National Oceanographic and Atmospheric Administrations website. Canada has about 2000 precipitation stations, the data from which are published by the Canadian Atmospheric Environment Service in the *Monthly Record of Observations.*

Radar can be used to measure the intensity of precipitation over a wide area. In the United States, the NEXRAD radar system is being implemented. It offers a better detailed view of the spatial distribution of rainfall than the traditional point measurements of gauging stations. In one study of a basin with a fairly dense network of precipitation stations, NEXRAD detected numerous storms with a precipitation intensity of 50 mm/h that were completely missed by the network of gauges (Smith et al. 1996).

The measurement of snowfall in standard rain gauges is subject to error due to turbulence around the gauge. The snow that is caught is melted and the water equivalent reported. If only an approximation is required, a water content of 10% of the snow depth can be assumed. However, as anyone who regularly shovels snow knows, the density of newly fallen snow can vary considerably.

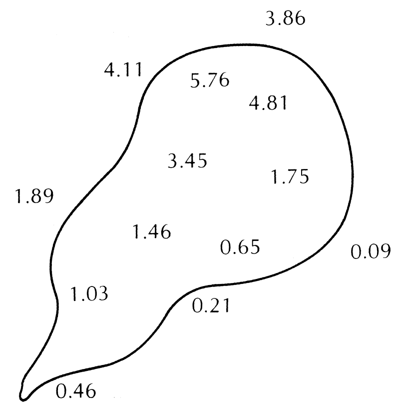
In northern and mountainous climates, the accumulation of snow on the ground is an important hydrologic parameter. In some areas, the runoff of melting snow in the spring is a predominant source of water for reservoirs used for water supply, irrigation, and power generation. A thick accumulation of snow can also mean a high flood potential when snowmelt occurs in the spring. Melting snow also recharges soil moisture and the water table. Snow surveys are made periodically through the winter to measure the thickness and water content of the snow in some areas.

7 Effective Depth of Precipitation

In water-budget studies, it is necessary to know the average depth of precipitation over a drainage basin. This may be determined for time periods ranging from the duration of part of a single storm to a year. The data are generally measurements of precipitation and/or equivalent snowfall at a number of points throughout the drainage basin.

Data that are missing at one or more stations as a result of equipment malfunction or operator absence creates a problem. To solve the problem, three close precipitation stations with full records that are evenly spaced around the station with a missing record are used. The following equation yields an estimate of the missing data at station Z. The mean annual precipitation (N) at station Z and the three index stations, A, B, and C, and the actual

► FIGURE 4
Rain gauge network over a drainage basin. Precipitation amounts are given in centimeters. Station locations are at decimal places.



precipitation (P) at the index stations for the time period over which data are missing, are needed:

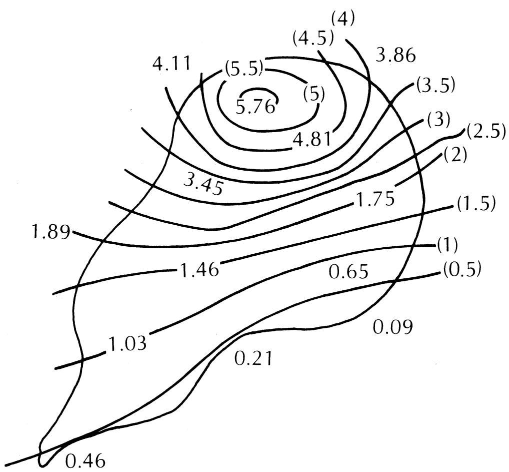
$$P_Z = \frac{1}{3}\left[\frac{N_Z}{N_A}P_A + \frac{N_Z}{N_B}P_B + \frac{N_Z}{N_C}P_C\right] \tag{2}$$

If the rain gauge network is of uniform density, then a simple arithmetic average of the point-rainfall data for each station is sufficient to determine the **effective uniform depth (EUD) of precipitation** over the drainage basin (Figure 4).

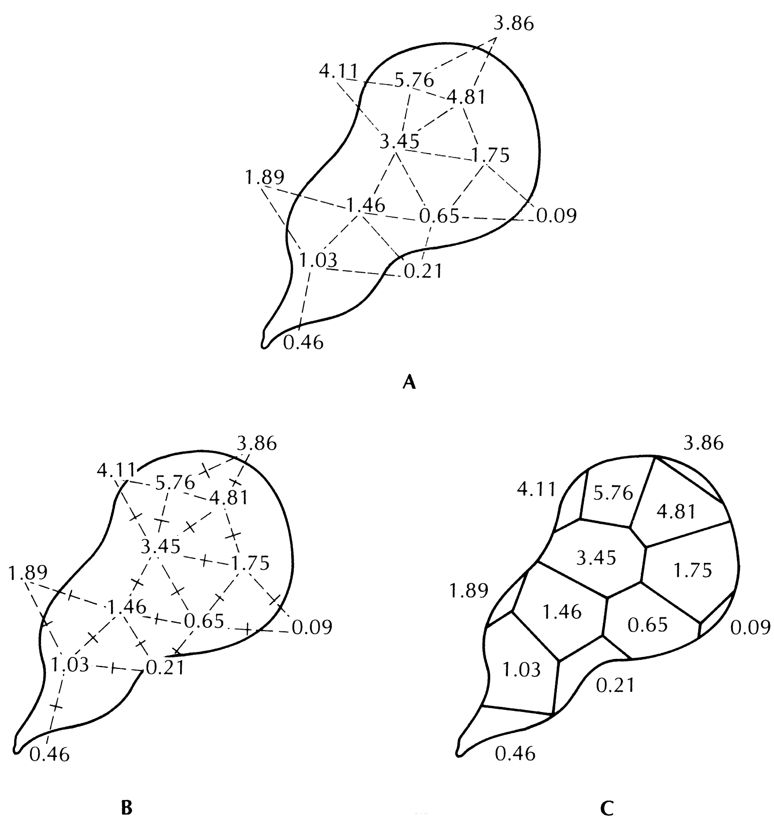
If the rain gauge network is not uniform, then some adjustment is necessary. The most accurate method, excluding use of radar data, is to draw a precipitation contour map with lines of equal rainfall (**isohyetal lines**). In drawing the isohyets, such factors as known influence of topography on precipitation can be taken into account. Simple linear interpolation between precipitation stations can also be used. The area bounded by adjacent isohyets is measured with a planimeter, and the average depth of precipitation over the area is the mean of the bounding isohyets. The effective uniform depth of precipitation is the weighted average based on the relative size of each isohyetal area (Figure 5). The drawback of the isohyetal method is that the isohyets must be redrawn and the areas remeasured for each analysis.

The Thiessen method to adjust for nonuniform gauge distribution uses a weighing factor for each rain gauge. The factor is based on the size of the area within the drainage basin that is closest to a given rain gauge. These areas are irregular polygons. The method of constructing them can be described rather easily; however, it takes a bit of practice to master the technique. The rain gauge network is drawn on a map of the drainage basin. Adjacent stations are connected by a network of lines (Figure 6A). Should there be doubt as to which stations to connect, lines should be between the closest stations. A perpendicular line is then drawn at the midpoint of each line connecting two stations (Figure 6B), and extensions of the perpendicular bisectors are used to draw polygons around each station (Figure 6C). It is best to start with a centrally located station and then expand the polygonal network outward. The area of each polygon is measured, and a weighted average for each station's precipitation is used to find the EUD.

In mountainous areas, orographic effects can create vastly different microclimates over small distances. Significant precipitation can fall on one side of a ridge but little on the other. In such regions the Thiessen method and contouring by linear interpolation can yield erroneous results. Detailed study of the vegetation can identify wet and dry slopes. This information, in conjunction with topographic maps, can be used to make interpreted contour maps with isohyetal lines reflecting the presence of wet and dry slopes.



◄ FIGURE 5
Isohyetal lines for the rain gauge network of Figure 4. The isohyets show contours of equal rainfall depth, with a contour interval of 0.5 cm. The contours are based on simple linear interpolation.



▲ FIGURE 6
Construction of Thiessen polygons based on the rain gauge network of Figure 4. **A.** The stations are connected with lines. **B.** The perpendicular bisector of each line is found. **C.** The bisectors are extended to form the polygons around each station.

PROBLEM

Determine the effective uniform depth of precipitation using the arithmetic mean, isohyetal, and Thiessen methods.

Arithmetic Mean Method

Figure 4 shows a drainage basin with seven stations in its boundaries. An additional six stations are located outside the drainage divide. In the arithmetic mean method, only the gauges inside the drainage basin boundary are considered.

$$\text{Mean} = \frac{1.03 + 0.65 + 1.46 + 1.75 + 4.81 + 3.45 + 5.76}{7} = 2.70 \text{ cm}$$

Isohyetal Method

The first step is to draw lines of equal precipitation (isohyets) on the drainage basin map. Isohyets are usually whole numbers or decimals (every 0.1 in., every 0.5 in., every 1 mm, etc.). The following rules apply:

1. Isohyets never cross.
2. Isohyets never split.
3. Isohyets never meet.
4. A station that does not fall on an isohyet will be between two isohyets. The isohyets will both be equal (either larger or smaller than the station value) or one will be larger and one smaller.
5. Adjacent isohyets must be equal or only one contour interval difference in value.
6. Isohyets should be scaled between stations using linear interpolation.

Figure 5 shows the isohyetal map of the problem area. The area between adjacent isohyets is determined by use of a planimeter. The equivalent uniform depth of precipitation between isohyets is usually assumed to be equal to the median value of the two isohyets. For example, the EUD between a 1-cm isohyet and a 2-cm isohyet is 1.5 cm. Areas enclosed by a single isohyet require judgment when estimating the equivalent uniform depth. The weighted average precipitation is based on the equivalent uniform depth of precipitation between adjacent isohyets and their areas.

A Isohyet (cm)	B Estimated EUD	C Net Area (km^2)	D Percent of Total Area	E Weighted Precipitation (cm) (B × D)
5.5+	5.6	1.1	0.8	0.045
5.0–5.5	5.25	7.6	5.3	0.278
4.5–5.0	4.75	10.6	7.4	0.352
4.0–4.5	4.25	9.5	6.7	0.285
3.5–4.0	3.75	8.6	6.0	0.225
3.0–3.5	3.25	8.3	5.8	0.189
2.5–3.0	2.75	10.7	7.5	0.206
2.0–2.5	2.25	12.3	8.6	0.194
1.5–2.0	1.75	15.1	10.6	0.186
1.0–1.5	1.25	23.8	16.7	0.209
0.5–1.0	0.75	31.2	21.8	0.164
<0.5	0.3	4.0	2.8	0.008
Total		142.8 km^2		2.34 cm Net EUD

Thiessen Method

The Thiessen method provides for the nonuniform distribution of gauges by determining a weighting factor for each gauge. A weighted mean of the precipitation values can then be computed. Thiessen polygons for the example problem are shown on Figure 6C. The area of each polygon is determined by a planimeter.

A Station Precipitation (cm)	**B Net area (km^2)**	**C Percent of Total Area**	**D Weighted Precipitation (cm) (A × C)**
5.76	16.9	11.9	0.686
4.81	16.1	11.4	0.546
4.11	3.4	2.4	0.099
3.86	1.6	1.1	0.044
3.45	19.3	13.6	0.470
1.89	2.5	1.8	0.033
1.75	12.0	8.5	0.148
1.46	19.8	14.0	0.204
1.03	18.0	12.7	0.131
0.65	17.0	12.0	0.078
0.46	6.0	4.2	0.019
0.21	7.2	5.1	0.011
0.09	2.0	1.4	0.001
Total	141.8 km^2		2.47 cm Net EUD

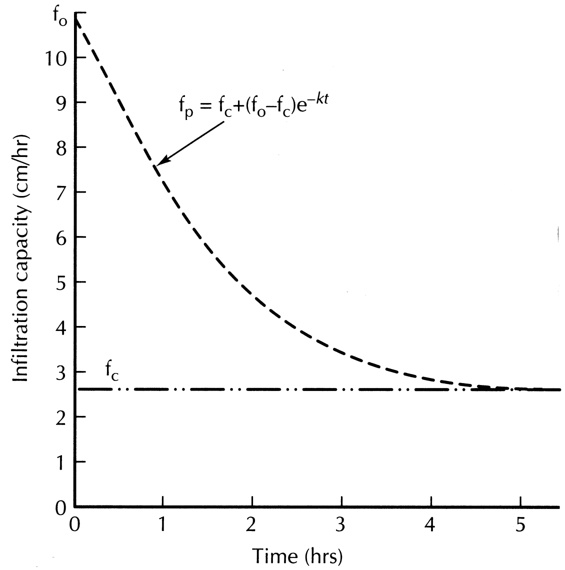
8 Events During Precipitation

During a precipitation event, some rainfall is **intercepted** by vegetation before it reaches the ground. This may later fall to the ground or evaporate. In a heavily forested area, most of the precipitation is caught by leaves and twigs. Initially, during a summer thunderstorm, no raindrops reach the forest floor, although drops can be heard striking the leaves overhead. When the storage capacity of the leaf surfaces is exhausted, water will run down tree trunks and drip downward (**stem flow**). The amount of water intercepted by dense forests ranges from 8% to 35% of total annual precipitation (Dunne & Leopold 1978). In a mixed hardwood forest in the northeastern United States, intercepted rainfall averaged 20% in the summer and winter seasons (Trimble & Weitzman 1954). Although evaporation of intercepted water reduces the net transpiration by the plants, in some cases most of the evaporated water is simply lost. One study concluded that only about 10% of the intercepted water actually reduced evapotranspiration (Thorud 1967).

The rate of interception is greatest at the beginning of a precipitation event and declines exponentially with time. If the rain is short lived and light, a large percentage of the precipitation may be intercepted. If it is heavy and long lived, only a small percentage may be intercepted.

Rainfall reaching the land surface can **infiltrate** into pervious soil, which has a finite capacity to absorb water. The **infiltration capacity** varies not only from soil to soil, but also is different for dry versus moist conditions in the same soil. If a soil is initially dry, the infiltration capacity is high. Surface effects between the soil particles and the water exert a tension that draws the moisture downward into the soil through labyrinthine capillary

► FIGURE 7
Decreasing infiltration capacity of an initially dry soil as the soil-water content of the surface layer increases.



passages. As the capillary forces diminish with increased soil-moisture content, the infiltration capacity drops (Figure 7). In addition, colloidal particles in the soil swell as the moisture content increases. Eventually, the infiltration capacity reaches a more or less constant, or equilibrium, value.

The infiltration capacity curve can be described by Equation 3 (Horton 1933, 1940):

$$f_p = f_c + (f_o - f_c)e^{-kt} \tag{3}$$

where

f_p is the infiltration capacity (L/T; ft/s or m/s) at time t (T; s)

f_c is the equilibrium infiltration capacity (L/T; ft/s or m/s)

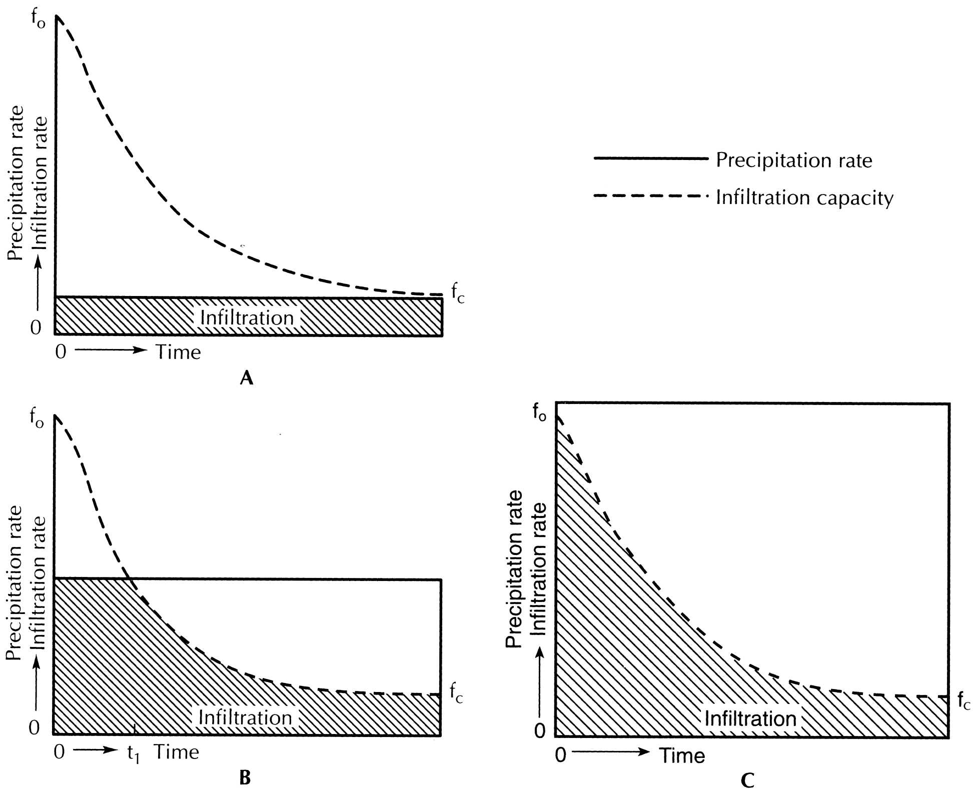
f_o is the initial infiltration capacity (L/T; ft/s or m/s)

k is a constant representing the rate of decreased infiltration capacity ($1/T$; 1/s)

t is the time since the start of the infiltration (T; s)

If the precipitation rate is lower than the equilibrium infiltration capacity, then all precipitation reaching the land surface will infiltrate (Figure 8A). If the precipitation rate is greater than the equilibrium infiltration capacity but less than the initial infiltration capacity, at the beginning all the precipitation will infiltrate, but when the infiltration rate drops below the precipitation rate, some of the precipitation will remain on the ground surface (Figure 8B). Finally, if the precipitation rate is greater than the initial infiltration capacity, some water will immediately remain on the land surface (Figure 8C).

Conditions that encourage a high infiltration rate include coarse soils, well-vegetated land, low soil moisture, and a topsoil layer made porous by insects and other burrowing animals, in addition to land-use practices that avoid soil compaction. Once the final infiltration rate is reached, the depth of ponded water also promotes high infiltration. The water reaching the ground can infiltrate into the soil, form puddles, or flow as a thin sheet of water across the land surface. Hydrologists refer to the water trapped in puddles as **depression storage.** It ultimately evaporates or infiltrates. The overland flow process, sometimes called **Horton overland flow** after Robert Horton (Horton 1933, 1940), occurs only



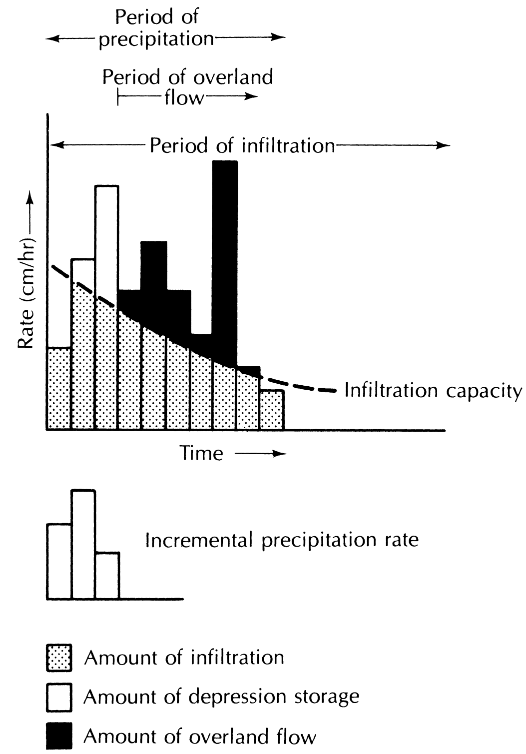
▲ FIGURE 8
Relationship of infiltration capacity and precipitation rate. **A.** Precipitation rate less than equilibrium infiltration capacity. **B.** Precipitation rate greater than equilibrium infiltration capacity but less than initial infiltration capacity. **C.** Precipitation rate greater than initial infiltration capacity.

when the precipitation rate exceeds the infiltration capacity. In areas where soils have a high infiltration capacity, this process may occur only during intense storms or when the soil is saturated or frozen. For overland flow to occur, the infiltration capacity of the soil must first be exceeded; then the depression storage must be filled (Figure 9).

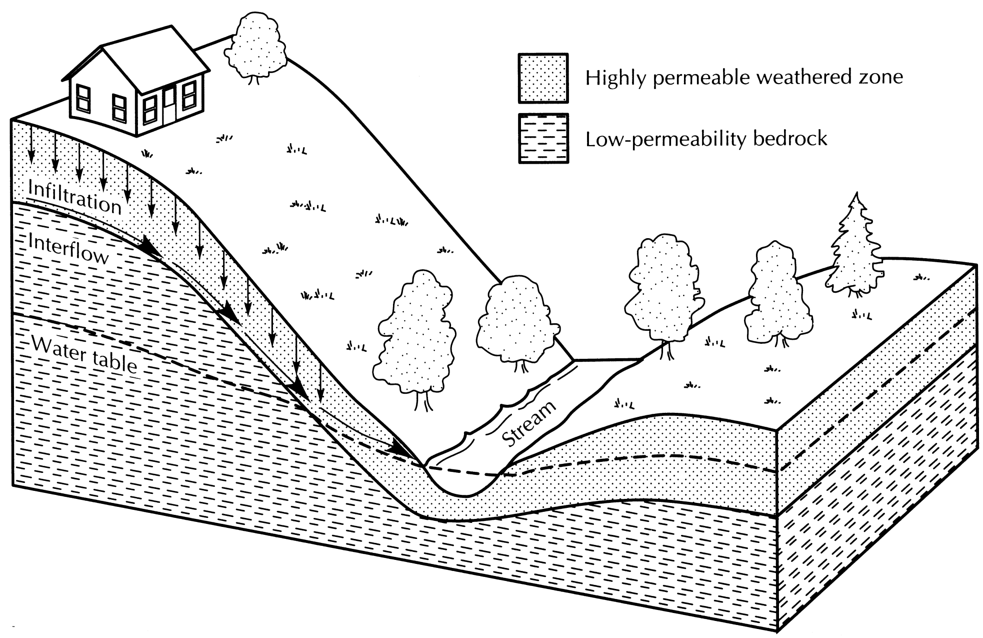
If the unsaturated zone is uniformly permeable, most of the infiltrated water percolates more or less vertically. Should layers of soil with a lower vertical hydraulic conductivity occur beneath the surface, then infiltrated water may move horizontally in the unsaturated zone. This **interflow** may be substantial in some drainage basins and contribute significantly to total runoff. Thin, permeable soil overlying fractured bedrock of low permeability would provide a geologic condition contributing to significant interflow (Figure 10).

Water will fall directly onto the surfaces of lakes and reservoirs during a period of precipitation. This amount may be insignificant for streams, but for lakes and reservoirs it could be considerable. Lake Michigan and its associated water bodies have a surface area of 22,300 mi^2. The land area of the surrounding drainage basin is 45,000 mi^2 (International Great Lakes Levels Board 1973). Assuming equal distribution of precipitation over the entire Lake Michigan basin, about one-third falls as **direct precipitation** on a water body.

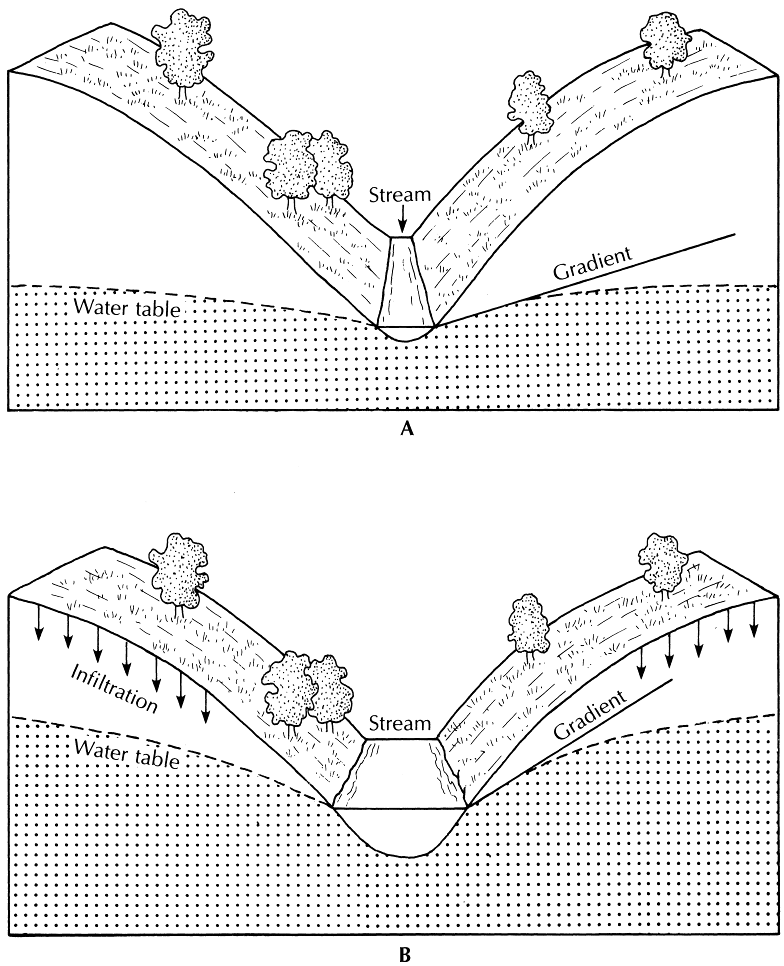
Infiltrated water that reaches the water table becomes stored in the ground-water reservoir. This storage is not static, as ground water is in constant movement. While freshly infiltrated precipitation is entering the ground-water reservoir, other ground water, known as **baseflow,** is discharging into a stream. If infiltration causes the water table to rise, ground-water discharge into nearby streams will also increase. For baseflow streams,



► FIGURE 9
Incremental precipitation rates and their dissociation into amounts of infiltration, depression storage, and overland flow. Infiltration begins along with precipitation. Overland flow does not begin until the depression storage is exhausted. Overland flow continues past the termination of precipitation. Infiltration will continue as long as any water remains in depression storage—usually past the period of overland flow.



▲ FIGURE 10
Interflow developing where a highly permeable but thin layer of weathered rock overlies a bedrock unit of lower permeability.



▲ FIGURE 11
Influence of the water-table gradient on baseflow. The stream in part A is being fed by ground water with a low hydraulic gradient. A gentle rain does not produce overland flow, but infiltration raises the water table. The increased hydraulic gradient of part B causes more baseflow to the stream, which is now deeper and has a greater discharge.

the amount of ground-water discharge is directly proportional to the hydraulic gradient toward the stream (Figure 11).

Horton overland flow is rarely observed in the field outside of urban and suburban areas, except after very heavy precipitation events, especially if the ground is covered with vegetation or humus such as leaf litter (Kirkby & Chorley 1967). Horton overland flow appears to be more common in arid regions or areas where the soil has been compacted by vehicles or animals, for example (Dunne 1978). Overland flow can also occur when precipitation falls on soils that are saturated. Water that infiltrates into the soil on a slope can move downslope as lateral unsaturated flow in the soil zone, called **throughflow** (Kirkby & Chorley 1967). The difference between throughflow and interflow is that throughflow emerges as seepage at the foot of the slope rather than entering a stream, as interflow does. Thus, the throughflow appears as overland flow before entering a stream channel. This type of overland flow is called **return flow** (Dunne & Black 1970) to distinguish it from Horton overland flow.