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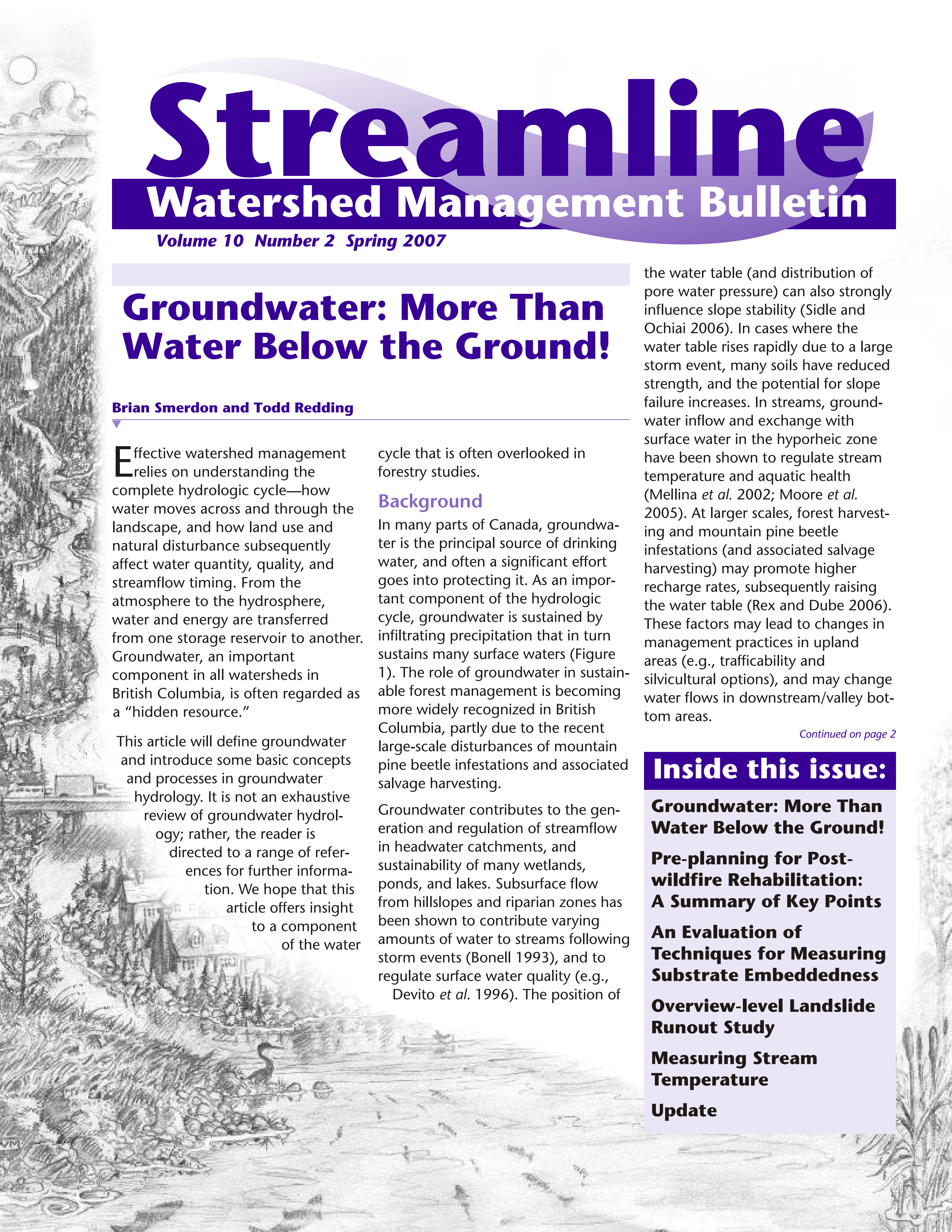

Groundwater: More Than Water Below the Ground!

Brian Smerdon and Todd Redding

Effective watershed management relies on understanding the complete hydrologic cycle—how water moves across and through the landscape, and how land use and natural disturbance subsequently affect water quantity, quality, and streamflow timing. From the atmosphere to the hydrosphere, water and energy are transferred from one storage reservoir to another. Groundwater, an important component in all watersheds in British Columbia, is often regarded as a "hidden resource."

This article will define groundwater and introduce some basic concepts and processes in groundwater hydrology. It is not an exhaustive review of groundwater hydrology; rather, the reader is directed to a range of references for further information. We hope that this article offers insight to a component of the water cycle that is often overlooked in forestry studies.

Background

In many parts of Canada, groundwater is the principal source of drinking water, and often a significant effort goes into protecting it. As an important component of the hydrologic cycle, groundwater is sustained by infiltrating precipitation that in turn sustains many surface waters (Figure 1). The role of groundwater in sustainable forest management is becoming more widely recognized in British Columbia, partly due to the recent large-scale disturbances of mountain pine beetle infestations and associated salvage harvesting.

Groundwater contributes to the generation and regulation of streamflow in headwater catchments, and sustainability of many wetlands, ponds, and lakes. Subsurface flow from hillslopes and riparian zones has been shown to contribute varying amounts of water to streams following storm events (Bonell 1993), and to regulate surface water quality (e.g., Devito *et al.* 1996). The position of the water table (and distribution of pore water pressure) can also strongly influence slope stability (Sidle and Ochiai 2006). In cases where the water table rises rapidly due to a large storm event, many soils have reduced strength, and the potential for slope failure increases. In streams, groundwater inflow and exchange with surface water in the hyporheic zone have been shown to regulate stream temperature and aquatic health (Mellina *et al.* 2002; Moore *et al.* 2005). At larger scales, forest harvesting and mountain pine beetle infestations (and associated salvage harvesting) may promote higher recharge rates, subsequently raising the water table (Rex and Dube 2006). These factors may lead to changes in management practices in upland areas (e.g., trafficability and silvicultural options), and may change water flows in downstream/valley bottom areas.

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What Is Groundwater?

Such a seemingly straightforward question may have various answers, depending on which educational pathway you have travelled. The field of hydrology is broad and multidisciplinary, and the educational pathways are as diverse as the ever-widening range of practitioners, which includes earth scientists (geologists), environmental scientists, foresters, engineers, biologists, and land/resource managers.

In the early 1900s, a definition of groundwater emerged from the U.S. Geological Survey that has adequately served North American practitioners of groundwater hydrology (also termed hydrogeology). Groundwater refers to water that occurs within the zone of saturation beneath the Earth's surface (Meinzer 1923). This definition has been preserved in many introductory references on hydrogeology (e.g., Freeze and Cherry 1979; Fetter 2001), and embraced by the scientific journal of the same name (Ground Water; Anderson 2003).

A common misconception is that groundwater is any water occurring in the ground. While this oversimplification may be useful when conveying information to non-scientific groups, the increasing importance of groundwater in our society is just cause for water scientists and managers to know and use proper terms (Woessner and Anderson 2002). Following the classic definition, groundwater is the liquid that completely fills pore spaces in the subsurface—it is the water occurring within the saturated zone (Figures 1 and 2).

Such a rigorous definition requires an understanding of the physical properties of soils and geologic materials, which are commonly referred to as porous media. For groundwater to exist and move, the structure of porous materials must be considered. All geologic materials are composed of solids (i.e., actual grains, sediment, or rock matrix) and pore space (i.e., voids). The amount of available pore space and the interconnectivity of pores govern the storage and transmission of groundwater. If all pore spaces are filled with liquid, then a porous medium is considered saturated. If air fills some pores, the material is considered unsaturated (Figures 1 and 2).

The distinction between zones of the subsurface that are unsaturated and zones that are saturated is not arbitrary. The division is based on location of the water table, which is found at the top of the saturated zone (Figure 2), where the pore water pressure is equal to atmospheric pressure. Above the water table, water and air occupy pore spaces (Figure 2), and water is held under tension by capillary forces at less than atmospheric pressure. Water in this unsaturated zone (Figure 2) is commonly termed soil moisture, soil water, or vadose zone water. Below the water table, the pore water pressure is greater than atmospheric pressure, and spatial variation in pore water pressure governs groundwater flow. Thus, understanding the difference between zones that are unsaturated or saturated is fundamental to understanding the definition of groundwater.

Groundwater Flow Through Porous Media

Geologic units can be defined based on their ability to store and transmit water. An aquifer is a permeable material that can transmit significant quantities of water to a well, spring, or surface water body. Often, aquifers are composed of unconsolidated sand and (or) gravel deposits (Figure 1), consolidated deposits that are permeable (e.g., sandstone, limestone), or consolidated formations that are generally less permeable (e.g., granitic and metamorphic rocks) and have become fractured. Generally, "significant" is defined based on human need, rather than on an absolute stan-

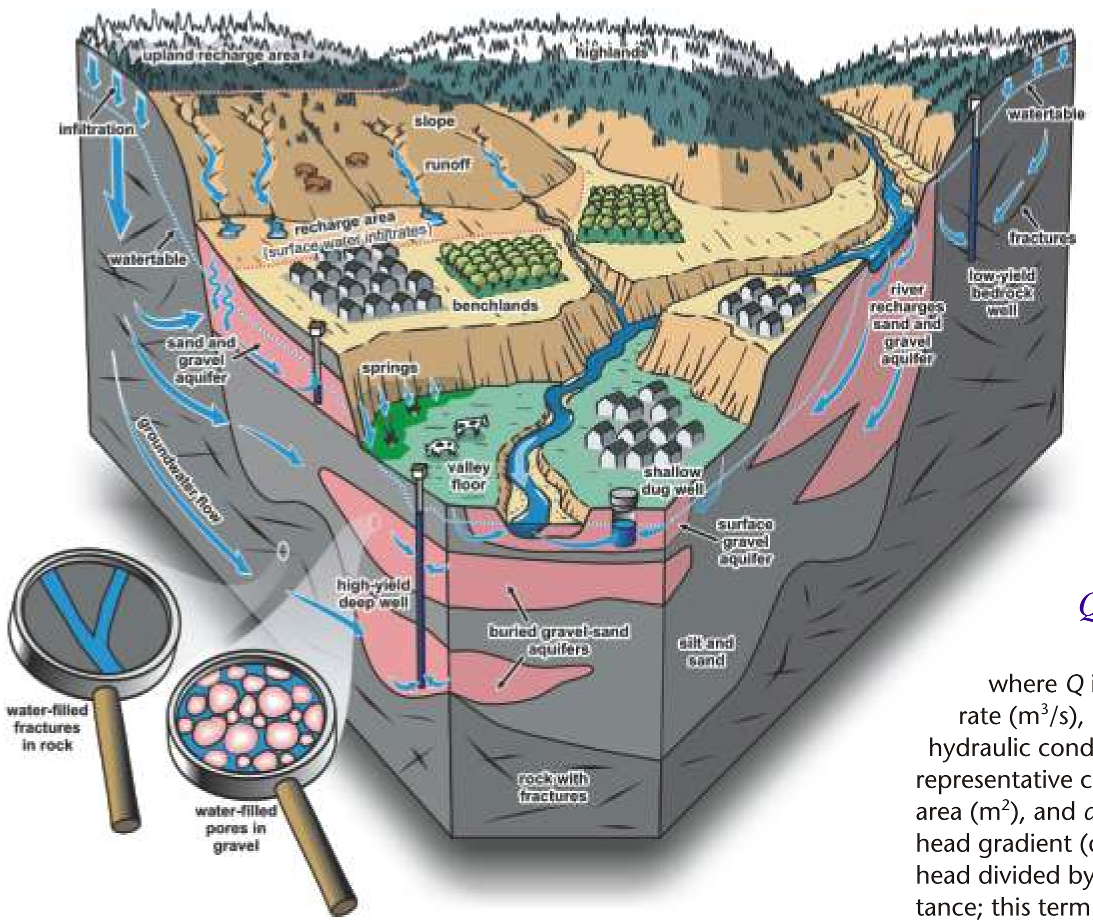

Figure 1. The role of groundwater in the hydrologic cycle. (Image provided by R.J.W. Turner, and used with permission of the Geological Survey of Canada.)

dard. An aquitard is a saturated geologic unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Typically, aquitards are composed of clay, silt, shale, or other dense geologic materials. Aquifers may be unconfined (those permeable geologic units open to the atmosphere where the water table forms the upper boundary) or confined (those covered by an aquitard) as illustrated in Figure 2.

Movement of water in the saturated zone is driven by spatial differences in the potential energy supplied by elevation and pore fluid pressure. This energy potential, termed hydraulic head, incorporates the driving forces due to gravity and differences in pore pressure from point to point in the subsurface. The flux will depend on the size of the gradient in hydraulic head and the properties of the porous medium (i.e., an aquifer or aquitard). In the field, hydraulic head is measured using a piezometer, or a water well. As shown on Figure 2, hydraulic head is measured at a known point, which means that the exact intake depth of a particular well (or piezometer) must be known. By measuring the depth to water, the hydraulic head—the combination of elevation head and pressure head—can be determined. Spatially distributed measurements of hydraulic head throughout a watershed can be compiled to infer the directions of groundwater flow as water moves from areas of high hydraulic head, to areas of lower hydraulic head (e.g., toward lowland areas in Figures 1 and 2).

In 1856, Henry Darcy determined an empirical relationship relating the volume of groundwater flow to the driving force and properties of the porous medium (Darcy's Law):

$$Q \quad KA\frac{dh}{dL}$$

where Q is the volumetric flow rate (m^3/s), K is the (saturated) hydraulic conductivity (m/s), A is a representative cross-sectional seepage area (m^2), and dh/dL is the hydraulic head gradient (difference in hydraulic head divided by difference in distance; this term is dimensionless). Hydraulic conductivity (uppercase K) is an empirical proportionality constant describing the ease with which water passes through porous media. It is essentially a specific version of permeability (lowercase k), which is an empirical constant describing the ease with which any fluid (water, oil, etc.) passes through porous media. These empirical constants range over many orders of magnitude, with higher values corresponding to aquifers (i.e., highly permeable) and lower values corresponding to aquitards (i.e., less permeable).

From the above equation, we can see that groundwater flow is greatest with larger gradients of hydraulic head (i.e., steeply sloping water table) and higher hydraulic conductivity values. The geology (surficial and bedrock) of the area of interest strongly affects both gradient and hydraulic conductivity. The pore-size distribution and

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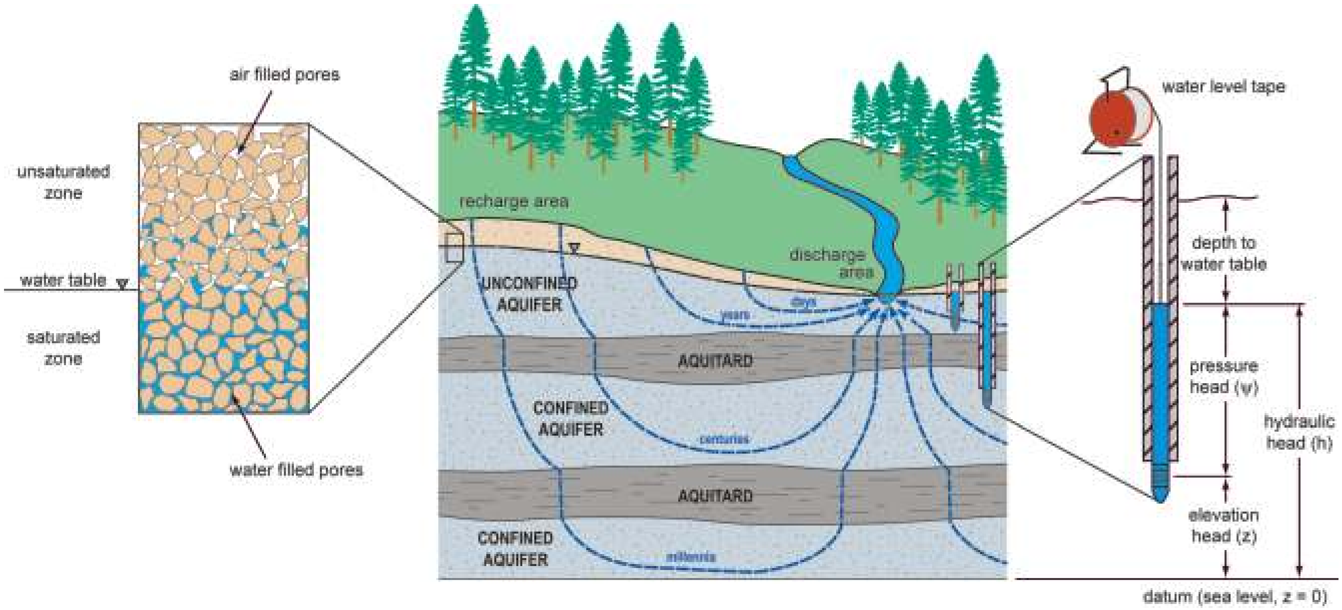

Figure 2. A groundwater flow system with water table, aquifers, and aquitards. (Images based on drawing by C.A. Mendoza, University of Alberta.)

interconnectivity of the pores govern hydraulic conductivity. Larger pores will typically conduct water more effectively than smaller pores. Many geologic materials also possess preferential flow pathways, such as fractures in bedrock or macropores, which allow water to be transported at high rates relative to that in the surrounding substrate. Preferential flow is very important for runoff generation and transport of chemicals (e.g., nutrients and pollutants) from hillslopes to the water table or surface water bodies.

Role of Groundwater in Watersheds

Understanding the basics of groundwater hydrology allows water scientists and managers to better quantify the movement of chemical constituents (dissolved solutes) through a watershed, and better forecast responses of the hydrosphere (surface water and groundwater) to various human-caused stresses. Below the water table, groundwater is established into a groundwater flow system. These organized systems comprise recharge areas (high hydraulic head) that drive water to discharge areas (of low hydraulic head) (Figures 1 and 2), where stream baseflow originated some distance away from the stream (e.g., from upland areas to benches and valley floor in Figure 1). The travel time from recharge to discharge areas may be as short as days, and longer than centuries, depending on flow system depth, and whether the flow path is at a "local" or "regional" scale (Toth 1962). Shallow, local-scale flow systems will exhibit seasonal variability in flow rate, and may be greatly impacted by land use or climate changes in the short term (Figure 1). Deeper, regional-scale flow systems tend to buffer short-term variability, but integrate a multitude of changes over a long term, making deleterious impacts more difficult to reverse. The concept of local and regional scales of groundwater flow systems can lead to different surface and subsurface catchments (Winter *et al.* 2003). That is, a well-defined surface water catchment may not be the same as the groundwater catchment in that region, which is controlled by geology.

Effective water resource management requires an understanding of how water is transferred between the atmosphere and the hydrosphere. The interaction of surface water and groundwater is highly dynamic (Sophocleous 2002). Surface water bodies are both sources and sinks for groundwater. For example, Figure 1 (right-hand side) shows groundwater recharged by river water, which later discharges back to the river.

Groundwater is commonly expressed in streams as baseflow, which is streamflow that occurs during dry times of the year (not due to specific storm events or seasonal phenomena such as snowmelt). The centre section of Figure 2 illustrates a typical groundwater flow system, and groundwater that supplies a stream. This is an example of a gaining stream, which gains discharging groundwater along its length. Losing streams occur where stream discharge is decreasing downstream, due to water losses through the streambed to groundwater (Figure 1, right-hand side). Flow-through streams are those that are simultaneously gaining and losing groundwater along their length. A single stream can have reaches or sections that are gaining, losing, or flow-through—this is largely determined by the underlying sediments (Winter 1999) and the topography of the watershed. Other surface water bodies, such as wetlands or lakes, exhibit the same gaining/losing/flow-through characteristics, depending on the groundwater flow system and their position within the landscape. This leads to many wetland types being classified by their interaction with groundwater (Rydin and Jeglum 2006).

In addition to the complexity of flow systems described so far, some saturated zones may become perched above a deeper, regional water table. For these isolated zones of saturation, which meet the definition of groundwater, the adjective "perched" is added to note their disconnection from most of the groundwater regime. Perched conditions often develop on a layer of low-permeability material (perching layer), which creates a saturated pool in a generally unsaturated subsurface zone (Sidle and Ochiai 2006). Perched water tables may be relatively long-term or transient (seasonal) events, and can be common in environments with high rainfall and shallow soils over a suitable perching layer. The development of these transient perched systems is a common driver of hillslope runoff (Weiler *et al.* 2005).

Considering that groundwater flow systems may have cycling times that range from days to centuries, and that the interaction with surface water may be gaining, losing, or flow-through, the role of groundwater in a watershed is complex (Winter *et al.* 2003). Besides contributing to stream baseflow, groundwater adjacent to streams can buffer peak flows if bank sediments are sufficiently permeable. A rise in stream stage may temporarily exceed the level of the adjacent water table, and cause gaining stream reaches to become losing streams until the stream stage declines (known as a groundwater flow reversal). Also, groundwater maintains aquatic health through buffering nutrients and temperature fluctuations (Story *et al.* 2003), especially in riparian and hyporheic zones (Dahm *et al.* 1998; Hayashi and Rosenberry 2001).

Groundwater is also critical for maintaining aquatic habitat. In northern climates, where many surface water bodies freeze in winter, groundwater inflows or seepage can maintain open water, thus providing temperature refugia for fish (Power *et al.* 1999). In addition, groundwater inflows can also help to maintain healthy temperatures for overwintering eggs of sockeye salmon (Leman 1993). In summer, groundwater inflows to streams may reduce stream temperatures, which is critical for fish survival. Groundwater flowing through riparian zones brings nutrients and chemicals into the surface water environment; these biogeochemical fluxes are important to ensure healthy aquatic environments (Dahm *et al.* 1998).

Groundwater in British Columbia

Approximately 25% of British Columbia's population relies on groundwater as a drinking water source. This article defines groundwater and introduces some general hydrogeologic concepts, which we hope will inform a broader community of watershed scientists and managers. Links to additional information on BC groundwater resources are provided at the end of this article.

The Water Stewardship Division of the BC Ministry of Environment has established an aquifer classification system for identifying and categorizing aquifers in the province. This system will aid in managing and protecting groundwater resources. Aquifers that have been identified and classified can be viewed on the BC Water Resource Atlas Web site. Development of protection plans responds to a growing interest in addressing known groundwater issues, such as potential declines in surface water discharge due to groundwater pumping; the impact of land use on surface water and groundwater quality (e.g., nitrate contamination in the Abbotsford–Sumas aquifer; Environment Canada 2006); and the influence of climate change on water resources (e.g., change in water flows of the Grand Forks area; Allen *et al.* 2004).

Nationally, the Okanagan Basin has been identified as one of Canada's key regions for hydrogeological mapping. Groundwater Assessment in the Okanagan Basin (GAOB) has brought together the BC Ministry of Environment with Natural Resources Canada and several research groups (Simon Fraser University, University of British Columbia, Geological Survey of Canada) to assess groundwater resources in the unconsolidated (valley sediments) and bedrock aquifers along the Okanagan Valley. Research project goals are to increase current knowledge of groundwater and assist with sustainable groundwater management and protection. With funding from the Canadian Water Network, a project to study groundwater recharge in the Okanagan was begun in 2005. The project seeks to better understand recharge to the groundwater regime, quantify the interaction between surface water and groundwater, and transfer scientific findings to local decision makers (e.g., Figure 1).

Under the current regulatory regime for forest management in British Columbia (*Forest Range and Practices Act*), understanding the impacts of forest management practice and disturbance to groundwater systems is critical to protect core resource values. Thus, the role of groundwater in watershed management activities must be considered, as it influences all aspects of the hydrologic cycle and is relevant to many potential risks in forest management activities. Knowledge of potential changes in groundwater dynamics resulting from disturbance may influence a range of hydrologic (low and peak flows) and operational (trafficability and

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silvicultural) activities that are critical for successful resource planning to achieve sustainable forest management objectives.

Sources of Additional Information on BC Groundwater Resources

Groundwater Information,
BC Ministry of Environment,
Water Stewardship Division
http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/index.html

BC Water Resource Atlas
http://srmapps.gov.bc.ca/apps/wrbc/

BC Ground Water Association
http://www.bcgwa.org/index.htm

Okanagan Basin Waterscape, Natural Resources Canada
http://geoscape.nrcan.gc.ca/h2o/okanagan/index_e.php

Groundwater Assessment in the Okanagan Basin (GAOB), Natural Resources Canada
http://ess.nrcan.gc.ca/2002_2006/gwp/p3/a5/index_e.php

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