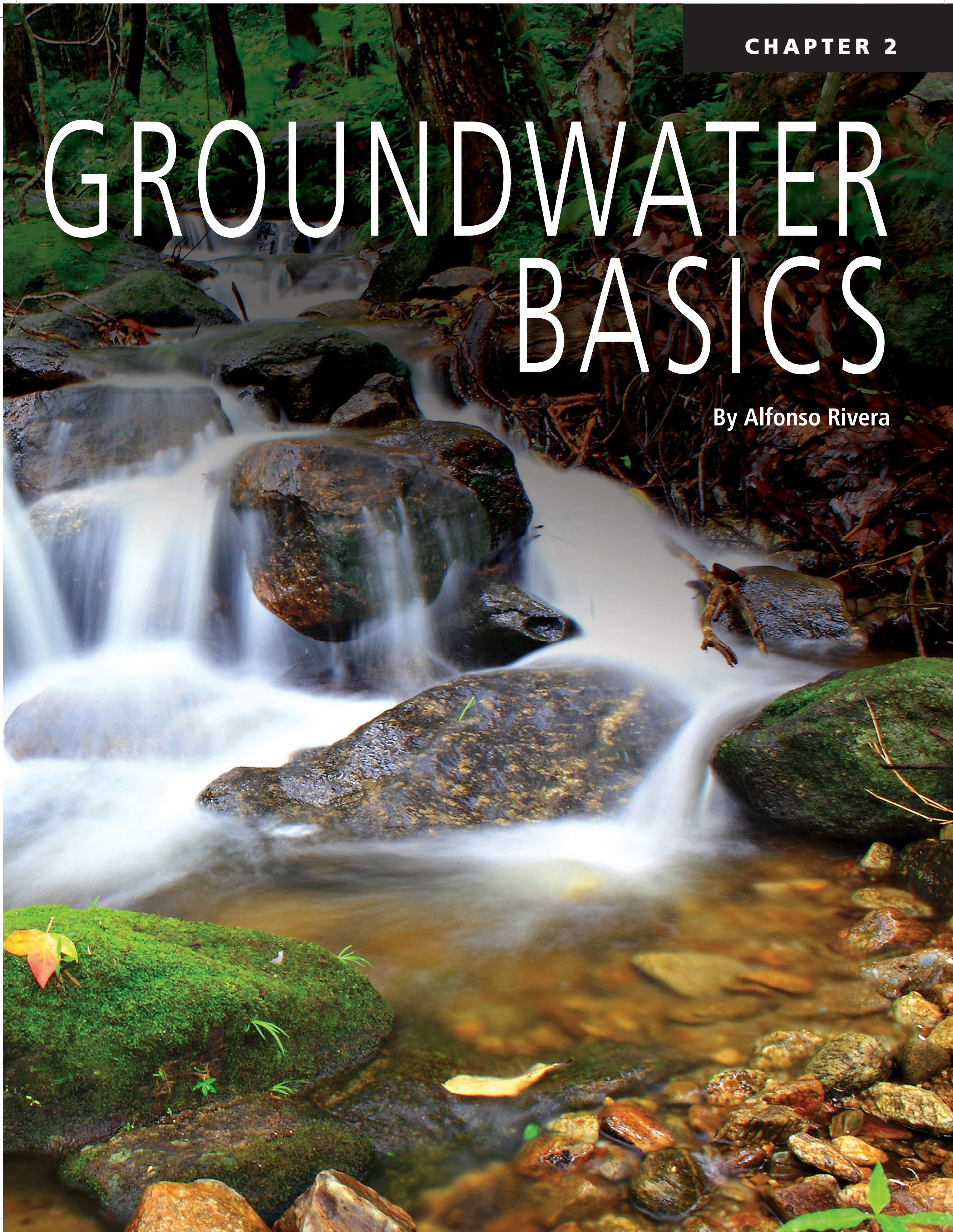
# GROUNDWATER BASICS

By Alfonso Rivera



## 2.1 INTRODUCTION

Groundwater accounts for nearly all of the potentially drinkable water on Earth, with the exception of water in polar caps. New exploration and production techniques and a better understanding of the dynamics of natural groundwater reservoirs are helping Earth scientists find new sources of this essential commodity.

Global changes, such as population growth, climate variability, expanding urbanization, often combined with pollution, severely affect water availability and are leading to chronic water shortages in a growing number of regions. The World Health Organization estimates that, within 12 years, two thirds of the world's inhabitants will live in countries with serious water problems. Inventive approaches and innovative technologies must be developed for every possible water resource.

Groundwater is one of the most important natural resources; it is the main source of water for irrigation worldwide (more than one-third of the arable landmass is irrigated with groundwater), and it is the main source of drinking water for a number of countries.

Within this chapter, we provide an overview of groundwater's basic characteristics as a resource by exploring aquifers, groundwater flow mechanisms, wells, the natural quality of groundwater and its interaction with the environment. Together with Chapter 3, this chapter expands on regional aquifer characterization and groundwater resource assessments for an integrated understanding of aquifer systems and the science required for sustainable management of groundwater resources.

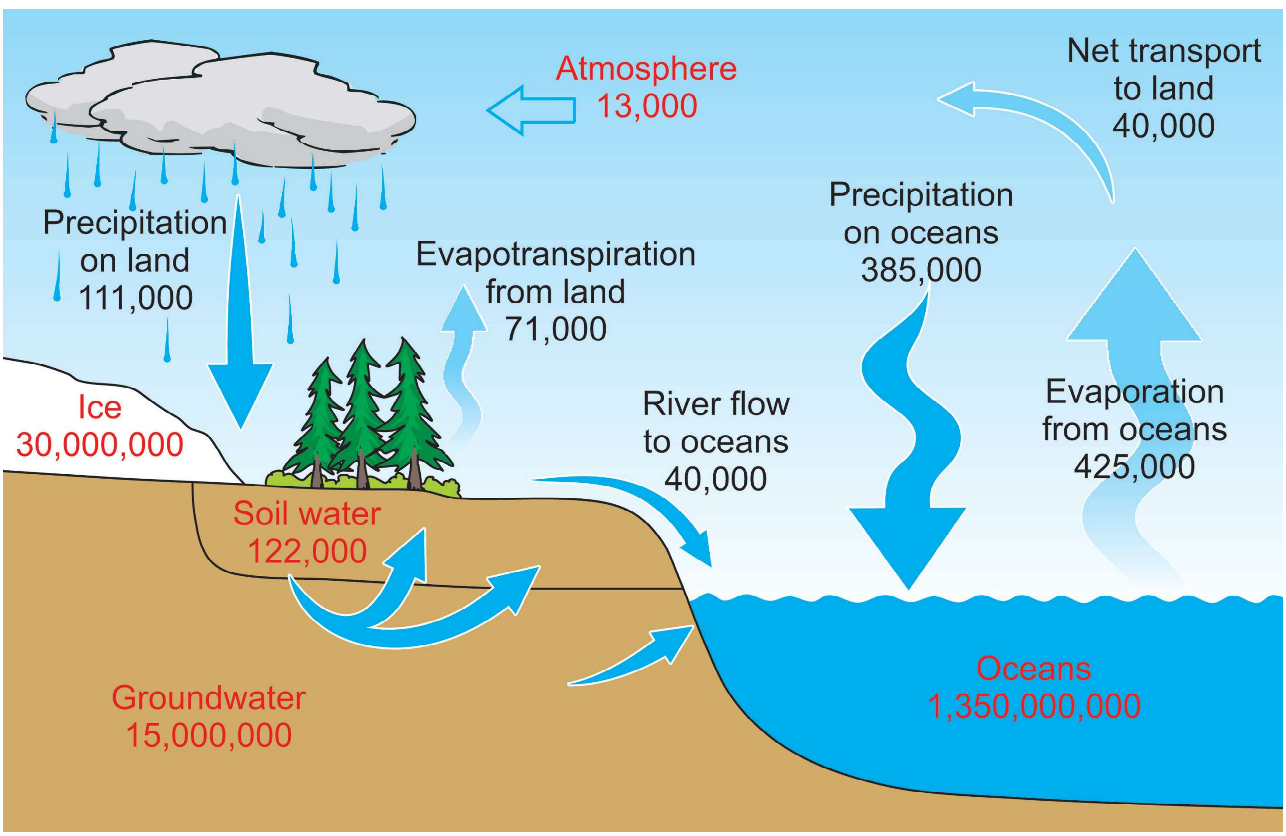


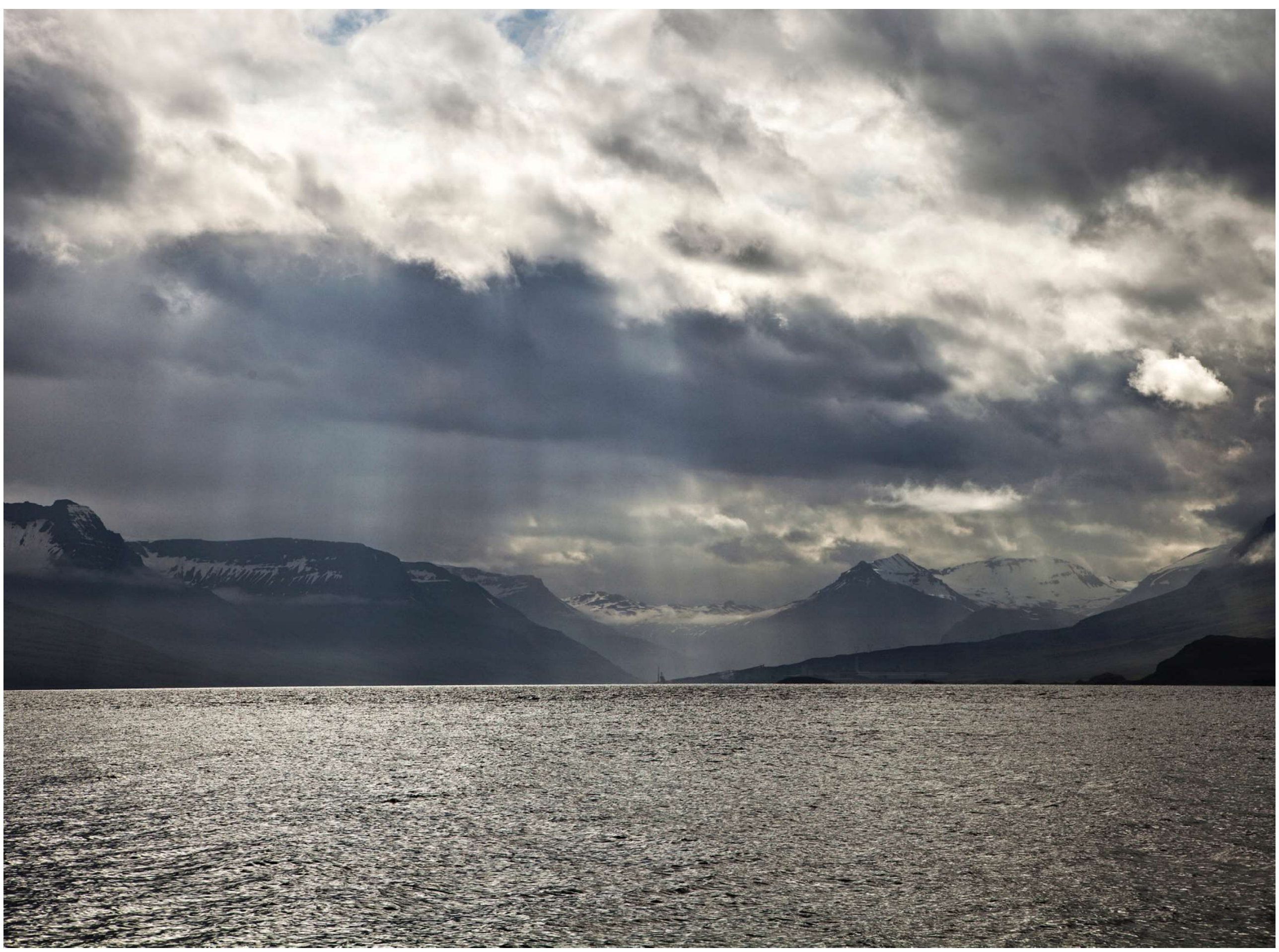

**Figure 2.1** Global pools and fluxes of water on Earth, showing the magnitude of groundwater storage relative to other major water storage and fluxes (reproduced and modified from Schlesinger, 1997). Pools (in red text) are in cubic kilometres; fluxes are in cubic kilometres per year.

## 2.2 WHAT IS GROUNDWATER?

Groundwater is a vital and essential part of the water or hydrologic cycle; it is the water that seeps into the ground, filling voids, cracks and fractures in rocks. The water cycle (schematically represented in Figure 2.1 in the form of pools and fluxes) is driven by thermal energy provided by the Sun. Water evaporates from the surface of the oceans and continents and is transported through the atmosphere, where it remains no longer than eight days before it precipitates as rain on continents and oceans. Once on the ground, precipitation fluxes are redistributed. Direct evaporation returns one part of the flux to the atmosphere during and after rainfall. Transpiration from vegetation returns to the atmosphere as part of the water that has seeped into the ground during rainfall. The sum of both fluxes is called evapotranspiration and it is by far the most important flux of the cycle, representing, on average, 63% of annual precipitation.

During the summer, ground infiltration helps form the near-surface stock of water needed for evaporation and transpiration. In cooler seasons, however, water infiltrates deeper into the ground, recharging the groundwater contained in soils and rocks. This deeper infiltration represents, on average, 13% of annual precipitation.

Runoff, representing, on average, 24% of precipitation, is another important flux of the hydrologic cycle. Runoff occurs immediately after soil saturation, when the soil can no longer absorb more water. Runoff has high variability, depending on



the type of soil and rain intensity; it may, as surface water, eventually form rivers. A large part of groundwater also ends up in rivers, forming what is known as river "baseflow," or natural water flow in the absence of rain (these occurrences explain the differences between ocean fluxes and land fluxes in Figure 2.1).

The sum of evapotranspiration (ET), ~ 496,000 km$^3$/year from oceans and land, equals the sum of precipitation (P) at the global scale (Figure 2.1). Rainfall, on average, exceeds evaporation on the Earth's continents, whereas evaporation exceeds rainfall on the Earth's oceans. This difference is 40,000 km$^3$/year at the global scale. The equilibrium

**TABLE 2.1 GLOBAL VALUES OF WATER FLUXES ON THE SCALE OF THE PLANET (IN VOLUME, KM$^3$/YR, AND IN EQUIVALENT WATER BAND, MM/YR; WRI, 1990)**

| | | |
|---|---|---|
| Evaporation on oceans | 425,000 km$^3$/yr | (1,250 mm/yr) |
| Evaporation on continents | 71,000 km$^3$/yr | (410 mm/yr) |
| Precipitation on oceans | 385,000 km$^3$/yr | (1,120 mm/yr) |
| Precipitation on continents | 111,000 km$^3$/yr | (720 mm/yr) |

**TABLE 2.2 WATER FLUXES FROM CONTINENTS TO OCEANS (IN KM$^3$/YR)**

| | |
|---|---|
| Flow rate of rivers | 27,000 km$^3$/yr |
| Base flow from aquifers to rivers and oceans | 10,500 km3/yr |
| Input from glaciers to oceans | 2,500 km$^3$/yr |
| Total | 111,000 km$^3$/yr |

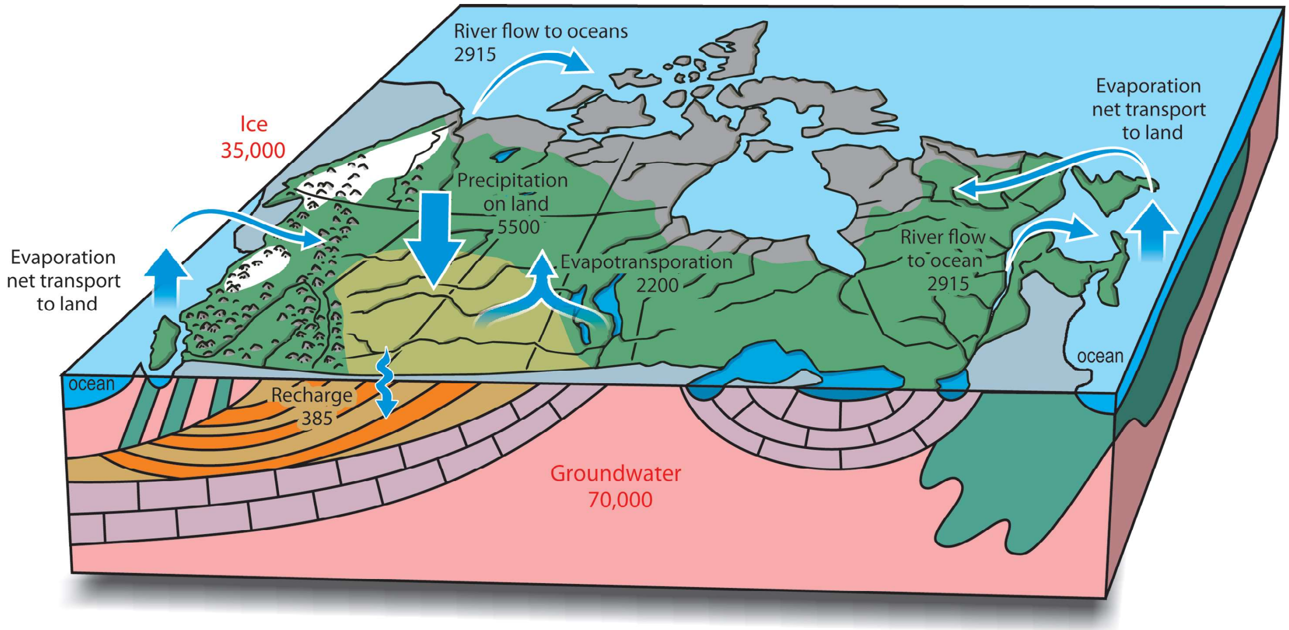



**Figure 2.2** Pools and fluxes of water in Canada. Pools (in red text) are in cubic kilometres; fluxes are in cubic kilometres per year (Sources: P from Statistics Canada, 2003; ET from Liu et al., 2003; RF from WRI, 1990; ice from Demuth, 1997; I from WRI, 2007, and groundwater in storage [pool], Rivera, 2008; Rivera and Vigneault, 2010).

of the Earth's water cycle means that every year continents send 40,000 km$^3$ of water to the oceans (World Resources Institute [WRI], 1990) (Tables 2.1 and 2.2).

In temperate regions, like Canada, when rain arrives on the ground, one part infiltrates and is essentially used to recharge the "soil reservoir" from where evapotranspiration transports it back to the atmosphere. During the cooler seasons, when evaporation is lowest, water continues downward and reaches the water table. This process is complex and variable, depending on the region. Permafrost, for instance, has often been considered an impermeable barrier (or aquiclude) to groundwater movement because of the presence of ice-filled pores and fractures. Consequently, many people believe that northern Canada lacks active groundwater flow systems. Although permafrost does have a significant impact on groundwater flow regimes, especially the recharge component, active groundwater flow can be found to varying degrees throughout Canada's permafrost regions (see Chapter 15).

How does Canada fit into the global water-balance picture? Figure 2.2 summarizes Canada's pools and water fluxes. 5,500 km$^3$ of precipitation (P) falls on Canada every year, mainly in the form of rain and snow. Evapotranspiration (ET) accounts for 40% of P with 2,200 km$^3$. River flow (RF), fed by runoff and groundwater (baseflow), accounts for 53% of P with 2,915 km$^3$. The contribution of runoff to streamflow varies seasonally, depending on precipitation, snowmelt, and in some locations, the summer melting of glaciers. Lastly, groundwater recharge (I) accounts for 7% of P with 385 km$^3$ (estimated from the sum of all baseflow of the rivers in Canada for which data exist). The pools in the figure, ice and groundwater, are much larger than the yearly precipitation and all river flow combined (Figure 2.2). However, the ice pool cannot be used directly, although it does serve to maintain river flow and to recharge aquifers in some

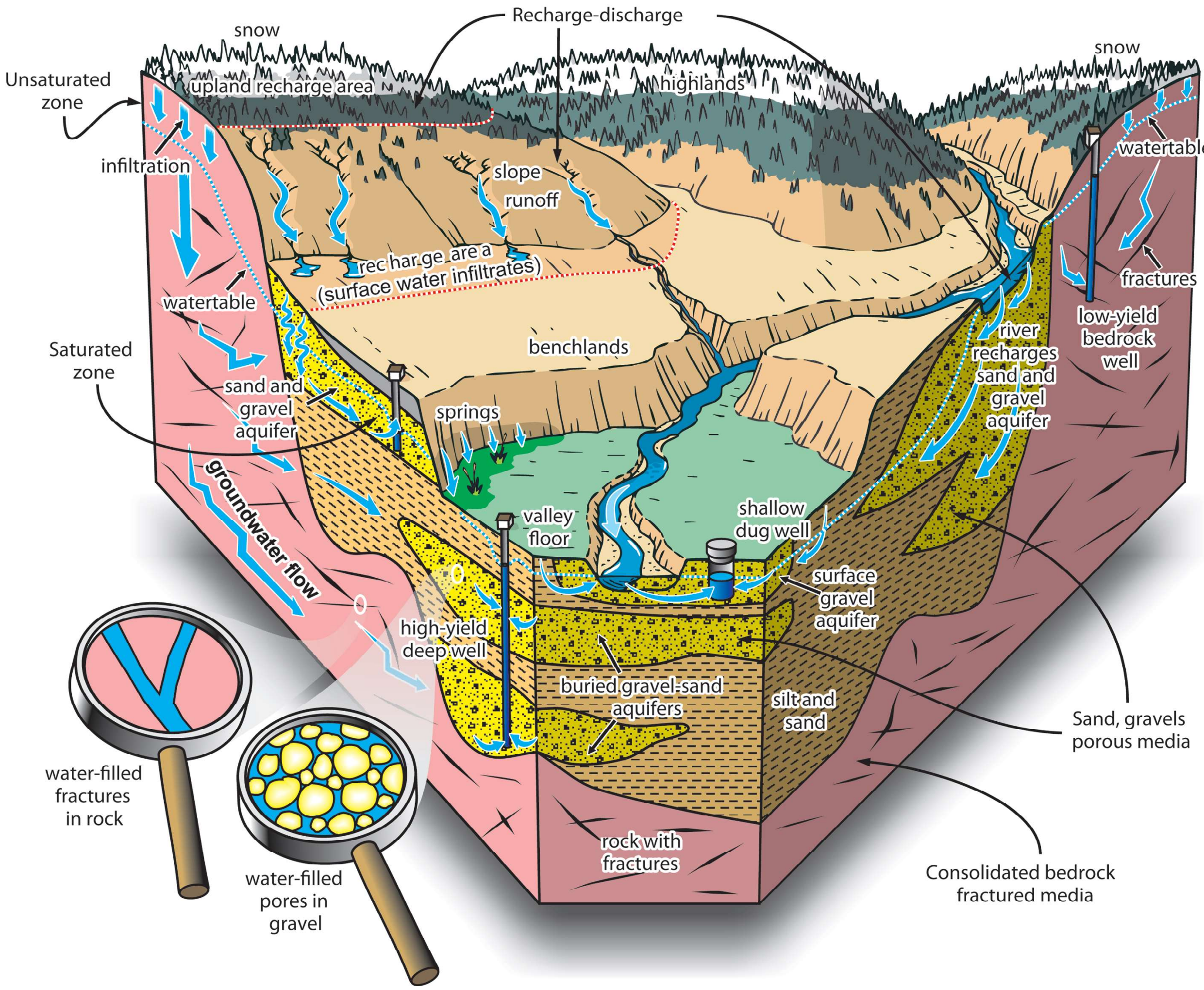



**Figure 2.3** Groundwater flow and geological units forming aquifers.

locations (e.g., the foothills of Alberta).

Canada's large groundwater pool (estimated to be 70,000 km$^3$, Figure 2.2; Rivera and Vigneault, 2010) represents the storage volume of groundwater in aquifers, other than the yearly recharge. This storage volume is estimated to be an average of the upper 150 metres only; it is not all usable and might not be sustainable over the long term. Currently, there are no precise estimates available of the volume that would be sustainable on a national scale.

A comparison of Canada's average yearly water fluxes with global water fluxes on Earth (water cycle, Figure 2.1), reveals some particular differences. Evapotranspiration is much lower in Canada than the world average, while runoff is more than twice the world average. Recharge, on the other hand, is smaller than the world average (although there is much uncertainty about estimates of this flux). Canada's climatic, geographic and geological characteristics impact on the country's water cycles, making Canada quite different from many other countries.

### 2.2.1 Groundwater flow mechanisms

Groundwater refers to water that resides within the zone of saturation beneath the Earth's surface;

An aquifer is a permeable material that can transmit significant quantities of water to a well, springs or surface water bodies.

it is the liquid that completely fills pore and fracture spaces in the subsurface, as shown in Figure 2.3. Geological units can be defined on the basis of their ability to store and transmit water. An aquifer is a permeable material that can transmit significant quantities of water to a well, springs or surface water bodies. An aquifer is by no means equivalent to a single geologic, lithographic or stratigraphic unit; two contiguous layers of sand and limestone, for instance, may form a *single* aquifer. Conversely, a single regional stratigraphic unit may have more than one groundwater flow type, depending on the space and time scales considered. In some cases, we define *aquifer systems*, which include more than one type of groundwater flow. Aquifers may be composed of (a) unconsolidated sand and/or gravel; (b) permeable consolidated deposits, e.g., sandstone, limestone; or (c) consolidated less-permeable fractured rocks (granitic and metamorphic rocks).

Figure 2.3 shows unsaturated and saturated zones defined by water table or piezometric levels. In general, groundwater is gravity-driven: it moves from areas of high hydraulic head (pressure) to areas of lower hydraulic head (e.g., toward lowland areas in Figure 2.3). In some exceptional circumstances, groundwater can move against gravity, as in the case of density-driven flow (e.g., the occurrence of dense non-aqueous phase liquids, commonly known as DNAPLs, or interaction between fresh water and saltwater). However, on a regional scale, groundwater always moves from high to low topographic points.

Aquifers are recharged in many different ways. In addition to direct recharge from precipitation (Figure 2.3), surface water bodies can be both sources and sinks for groundwater. For example, the right-hand side of Figure 2.3 shows groundwater recharged by river water, which later discharges back to the river. Thus, surface water–groundwater interaction is highly dynamic. This interaction may not always take place, depending on the type of aquifer system, the permeability of rocks, and climate. In Canada, this interaction is extremely important because most of the currently exploited aquifers are shallow, and located in unconsolidated Quaternary sediments. Groundwater also maintains wetlands and aquatic health by buffering nutrients and temperature fluctuations, especially in riparian and hyporheic zones (Hayashi and Rosenberry, 2001).

### 2.2.2 How do groundwater aquifers differ from surface water watersheds?

Groundwater flow occurs in aquifers, while surface water flow occurs in watersheds. Watershed boundaries can be clearly defined by topography, whereas aquifer boundaries cannot. Aquifer boundaries and watershed boundaries may or may not coincide, but more often they overlap. In some cases, very deep aquifers may be recharged in remote mountain ranges. Water infiltrating into fractured rock within the mountains may flow downward and then move laterally into confined aquifers. In some regions, these aquifers extend for many hundreds of kilometres beneath the land surface, and sometimes crossing natural surface watershed boundaries or jurisdictional boundaries. Thus, groundwater in a confined aquifer may recharge in one watershed and discharge in another, or perhaps recharge in one province or nation and discharge in another; the latter

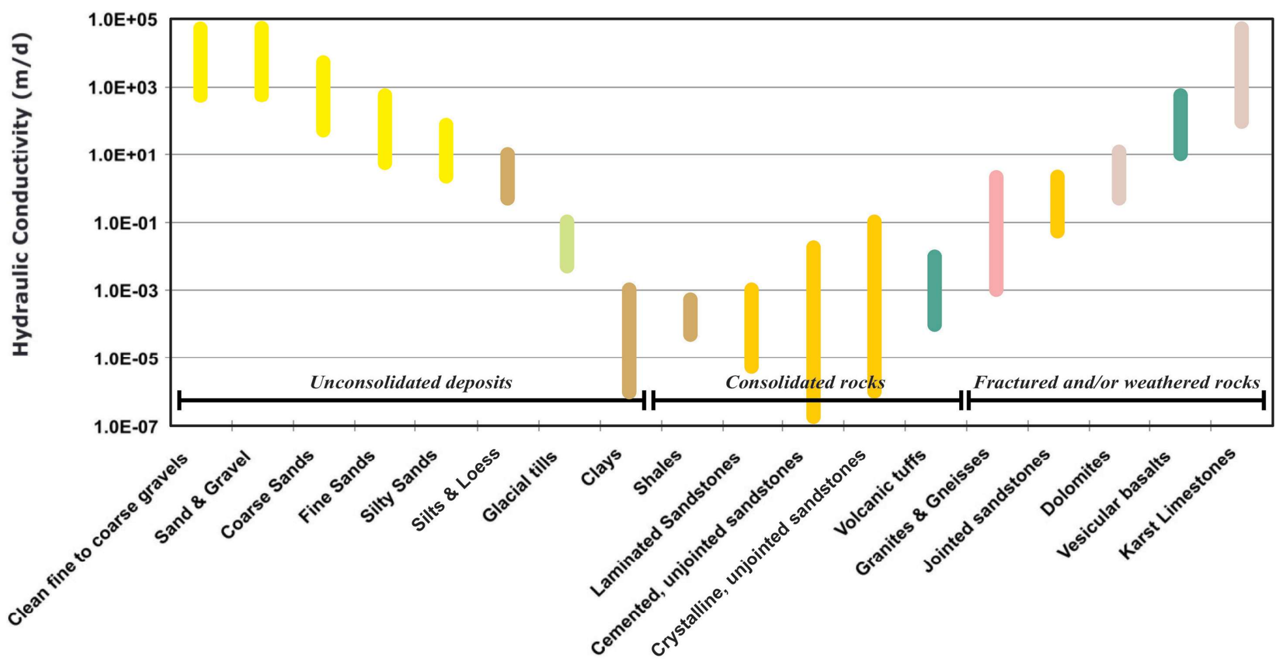



**Figure 2.4** Range of hydraulic conductivity (K) values for geological materials (modified from Driscoll, 1986 and Todd, 1980).

phenomenon is classified as a "trans-boundary aquifer" (see section 2.6 and Chapter 16).

Watershed boundaries and aquifer boundaries may coincide when aquifers are located in unconsolidated shallow sediments, under unconfined conditions, such as valleys and deltas composed of glaciolacustrine or glaciofluvial sediments. In those cases, interaction between surface water flow and groundwater flow occurs as a result of hydraulic interconnections between surface water bodies and aquifers under phreatic conditions (at atmospheric pressure).

In cases where surface water and groundwater interact, seasonal water table fluctuations follow a pattern similar to those of river levels (more details in Chapter 4 and 5).

> Materials through which groundwater can pass easily are said to be permeable and those that scarcely allow groundwater to pass or only with difficulty are described as impermeable.

## 2.3 NATURE OF PERMEABILITY

Permeability is an essential physical property of rock-forming aquifers. Scientists distinguish two permeability types: intrinsic, or specific, permeability (in $m^2$) and hydraulic conductivity (in m/s). The former relates to the porous medium regardless of the fluid characteristics (as used in soil/rock mechanics), while the latter is a vector as used in hydrogeology. The intrinsic permeability is only defined at the macroscopic scale with dimensions of a surface area. However, permeability is often expressed in darcys, which is a unit equal to 0.987 $10^{-12}$ $m^2$. Intrinsic permeability and hydraulic conductivity are linked by the intrinsic properties of the medium and physical nature of the fluid, defined as:

$$K = k \rho g / \mu \tag{2.1}$$

where K is the hydraulic conductivity; k is the intrinsic permeability; $\rho$ is the water density (kg/

$m^3$); g is the acceleration of gravity ($m/s^2$); and μ is the dynamic viscosity of the fluid (usually water) (kg/m s). Intrinsic permeability depends on the porous matrix properties exclusively. The medium is termed *homogeneous* if k does not vary in space. If k varies in different points in space, the medium is called *heterogeneous* and if k varies in different directions, the medium is called *anisotropic*, otherwise it is *isotropic*.

Other factors, which can affect the intrinsic permeability of a medium, include deformation of the porous matrix (e.g., consolidation leading to land subsidence), dissolution of solid particles, and chemical and biological processes.

The relationship between K and k in Eq. 2.1 is not very often used in studies of groundwater resources, but rather in studies of coupled phenomena such as hydraulic-mechanic (subsidence due to intense pumping), and hydraulic-transport (solute or heat transfer in groundwater pollution problems or in variable-density problems).

Groundwater resource studies most commonly use the hydraulic permeability, K (the permeability of hydrogeologists), generally without distinction with k. For most practical purposes, and under isothermal conditions, intrinsic permeability (k) can be related to hydraulic conductivity (K) as k ($m^2$) = $10^{-7} \cdot$ K (m/s).

Hydraulic conductivity is a measure of the ease with which groundwater flows through the rock-forming aquifers. The ease with which groundwater flows through a rock mass in a porous aquifer, or the fractures in a fractured aquifer, depends on a combination of the size of the pores, or the fractures, and the degree to which they are interconnected. These features determine the overall permeability of the aquifers. For instance, in clean, granular materials, hydraulic conductivity increases with grain size. Typical ranges of hydraulic conductivity for the main types of aquifer materials are shown in Figure 2.4. The limit separating permeable from impermeable material is often (arbitrarily) set at $10^{-9}$ m/s, which is acceptable for most groundwater resources studies.

### 2.3.1 Darcy's Law

Darcy's Law (formulated by Henry Darcy in 1856) is an equation which describes groundwater flow. This law states that the volumetric flow rate through porous media is proportional to flow area A, the hydraulic conductivity K, and the hydraulic gradient i:

$$Q = A\,K\,i \qquad (2.2)$$

in which

$$i = (h_2 - h_1)/\Delta l \qquad (2.3)$$

where Q is the volumetric rate of flow through area A under a hydraulic gradient $\Delta h/\Delta l$ (the difference in hydraulic heads ($h_2 - h_1$) between two measuring points), divided by the distance between them.

Equations 2.2 and 2.3 can be combined to represent the volumetric flow per unit surface area q, as:

$$Q/A = q = -K\,(h_1 - h_2)/L = -K\,\Delta h/\Delta l \qquad (2.4)$$

The direction of groundwater flow in an isotropic aquifer is at right angles to lines of equal head. A simple experimental apparatus used to demonstrate Darcy's Law is shown in Figure 2.5, indicating also the elevation and pressure components of hydraulic head referred to above. The equation for Darcy's Law is conventionally written with a minus sign because flow is in the direction of decreasing hydraulic heads.

This representation is very convenient because it

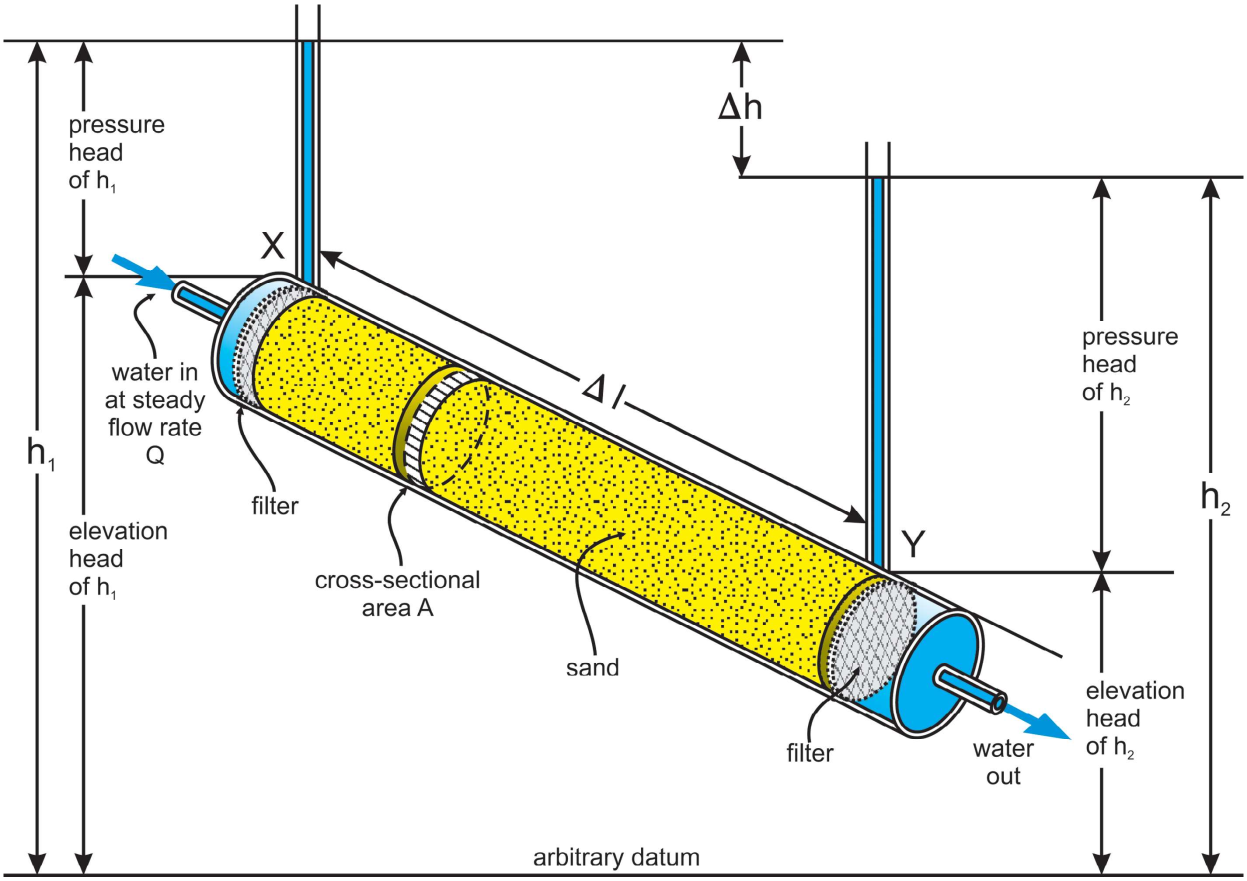



**Figure 2.5** Darcy's experimental setup (modified from Price, 1996).

provides rapid and easy estimates of groundwater flow where values of groundwater elevations are known or available. A graphical illustration of the use of the steady-state groundwater flow equation (based on Darcy's Law and the conservation of mass) is in the construction of groundwater flow lines (or equipotentials), to quantify the amount of groundwater flowing under a dam or an aquifer. An example of this is given below (see Figure 2.6).

Darcy's Law is only valid for slow, viscous flow, but, fortunately, most groundwater flow cases fall in this category. Typically any flow with a Reynolds number[1] less than 1 is clearly laminar, and Darcy's Law would apply. Experimental tests have shown that flow regimes with Reynolds value numbers of up to 10 may still be Darcian.

A very simple and practical example of the usefulness of Darcy's Law is given below.

Consider the aquifer depicted on a 2D-horizontal dimension over a three-dimensional schematic aquifer in Figure 2.6; using Darcy's Law, calculate:

1) The time it takes to transport a drop of groundwater from point B to point A
2) The groundwater volumetric fluxes per streamline and per metre thickness of aquifer, in $m^3$/year
3) The water infiltrated over the whole area of the aquifer in an equivalent recharge, in mm/year

The aquifer is composed of a porous medium

1. In fluid mechanics, the Reynolds number (Re) is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. Re is used to characterize different flow regimes, such as laminar or turbulent flow: laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion, that is generally the case for groundwater flow in porous medium.

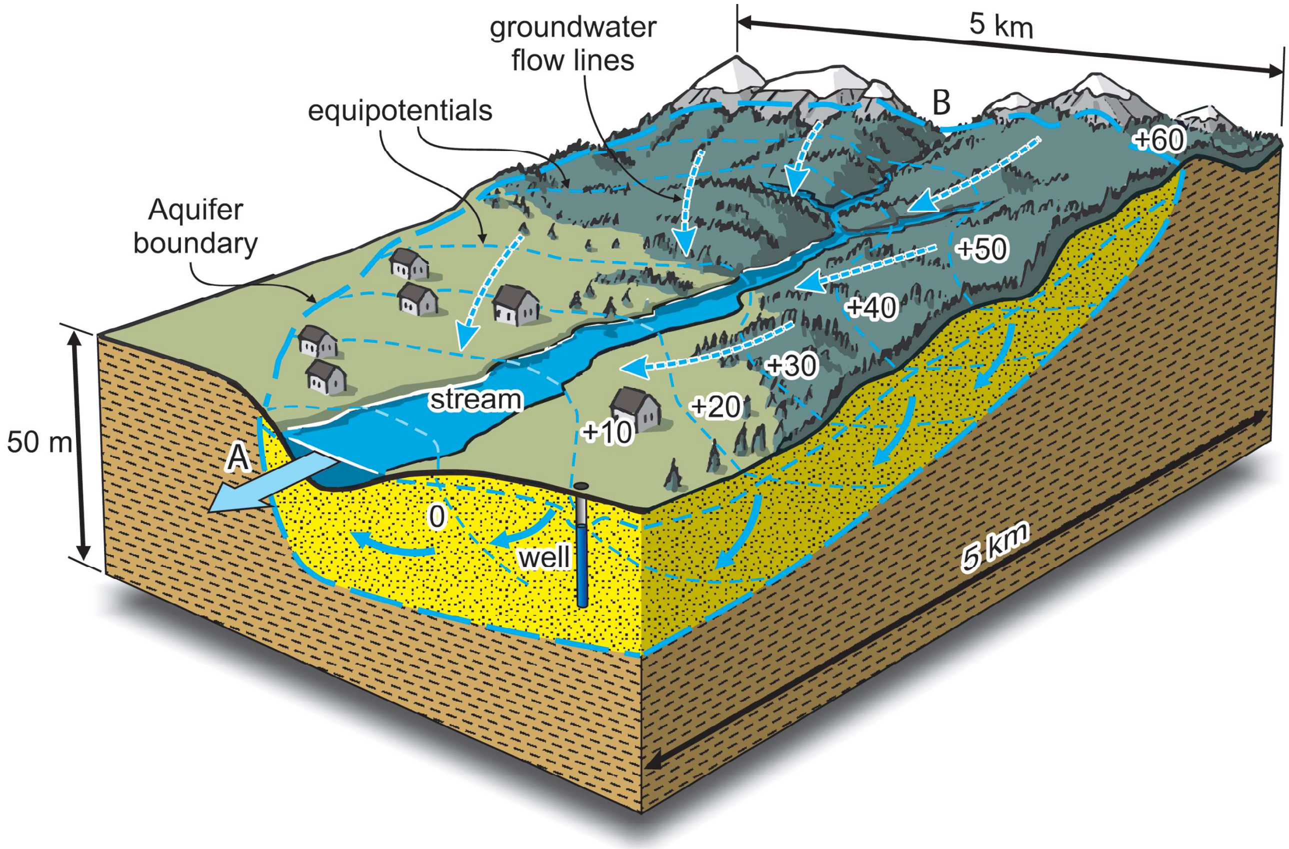



**Figure 2.6** Example of application of groundwater flow lines and Darcy flow.

with sand and gravels. Let's take typical values from Figure 2.4 and Table 2.3: a hydraulic conductivity of $K=10^{-3}$ m/s and a specific yield (Sy) of 10%.

Using equations 2.2, 2.3 and 2.4 we have:

**Darcy flux and groundwater velocity:**

Using $q = -K \cdot i$; with i from Eq. 2.3:

$i = (h_{60} - h_0)/L = 60/5000 = 1.2 \cdot 10^{-2}$

$$q = 10^{-3}\ \text{m/s} \cdot 1.2 \cdot 10^{-2}$$
$$= 1.2 \cdot 10^{-5}\ \text{m/s}$$

A linear pore velocity (average linear groundwater velocity), v, which is the volumetric flow rate per area of connected pore space can be calculated as v=q/n, if the porosity, n, is known (it is necessary to know the effective or dynamic porosity, ne, which represents the proportion of the total porosity involved in groundwater movement). This can often be difficult to measure, although, for unconfined aquifers, n is probably close to the specific yield values given in Table 2.3. Thus we can define:

$$V = q / S_y = 1.2 \cdot 10^{-4}\ \text{m/s}$$

and the travel time from B to A as: $L/v = 4.17 \cdot 10^7$ sec, or 1.32 years

**Volumetric fluxes:**

Using Eq. 2.4, we can calculate the groundwater flux across each unit surface area ($\Delta h = 10$ m):

A= 5000 m X 10 m; and

$Q = q \cdot A = (1.2 \cdot 10^{-5})\ (5 \cdot 10^4) = 0.6\ m^3/s$

Or a total of 19 $Mm^3$/year, per flow line, per metre

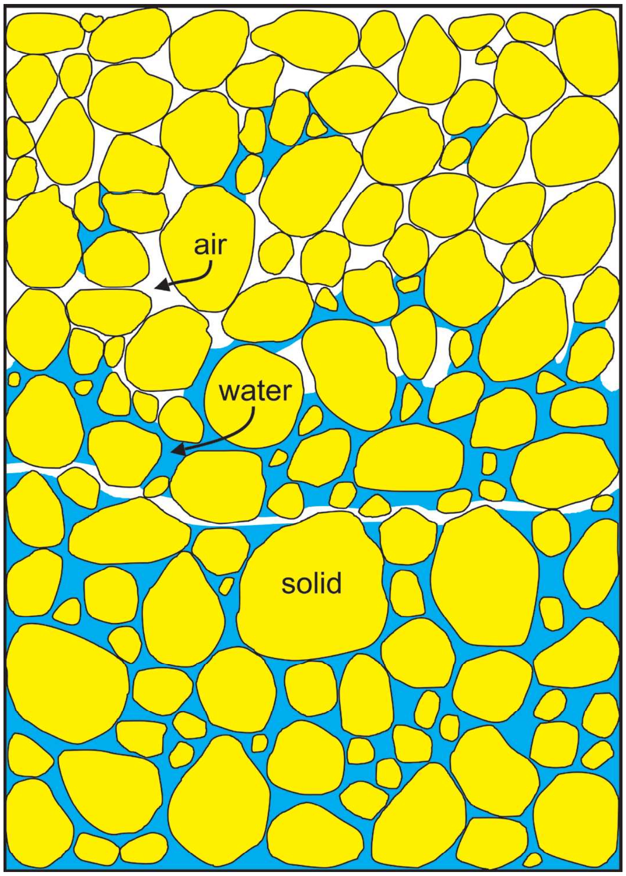



**Figure 2.7** Water, solid and air phases in a porous media rock formation.

thickness of aquifer.

**Infiltrated equivalent water band:**

I = Volume/surface area ($m^3$/year/$m^2$)

I = 1.9 $\cdot 10^7$ ($m^3$/year) / (Length ·Width) ($m^2$) = 760 mm/year

## 2.4 ROCK-FORMING AQUIFERS

Groundwater occurs in most geological formations because nearly all rocks in the uppermost part of the Earth's crust possess openings called pores or voids. Figure 2.7 depicts schematically water situated in the voids or pores of a porous media rock formation. Geologists traditionally subdivide rock formations into three classes according to origin and creation: *Sedimentary rocks, Igneous rocks* and *Metamorphic rocks.*

Sedimentary rocks are formed by deposition of material, usually underwater, from lakes, rivers and the sea. Unconsolidated granular materials such as sand and gravels have voids, or spaces between the grains (Figure 2.8A). The material may become consolidated, through physical compaction and chemical cementation (Figure 2.8D), to form typical sedimentary rocks such as sandstone, limestone and shale, with the void space much reduced between grains, but with a porosity high enough to allow groundwater flow. These type of rocks form many important aquifers in Canada.

Igneous rocks are formed from molten geological material rising from great depths within the Earth, then cooling to form crystalline rocks either below ground or at the Earth's surface. These rocks include the granites and many volcanic types of lava such as basalts. Most igneous rocks are relatively dense and, being crystalline, usually have some voids between the grains, although these are not well-connected. Igneous rocks cover nearly one third of Canada's total land area (forming the Canadian Shield).

Metamorphic rocks are formed by deep burial, compaction, melting and alteration or re-crystallization of other rocks during periods of intense geological activity. These rocks include gneisses and slates. They are dense with few void spaces in the matrix between grains.

The only void spaces in some dense rocks, may be as a result of fractures caused by fold and fault stresses. These fractures may be completely closed or they may have small, not very extensive (or even poor) interconnected openings of relatively narrow aperture (Figure 2.8F). Weathering and decomposition of igneous and metamorphic rocks may significantly increase void spaces in both the rock matrix and in the fractures. Fractures may

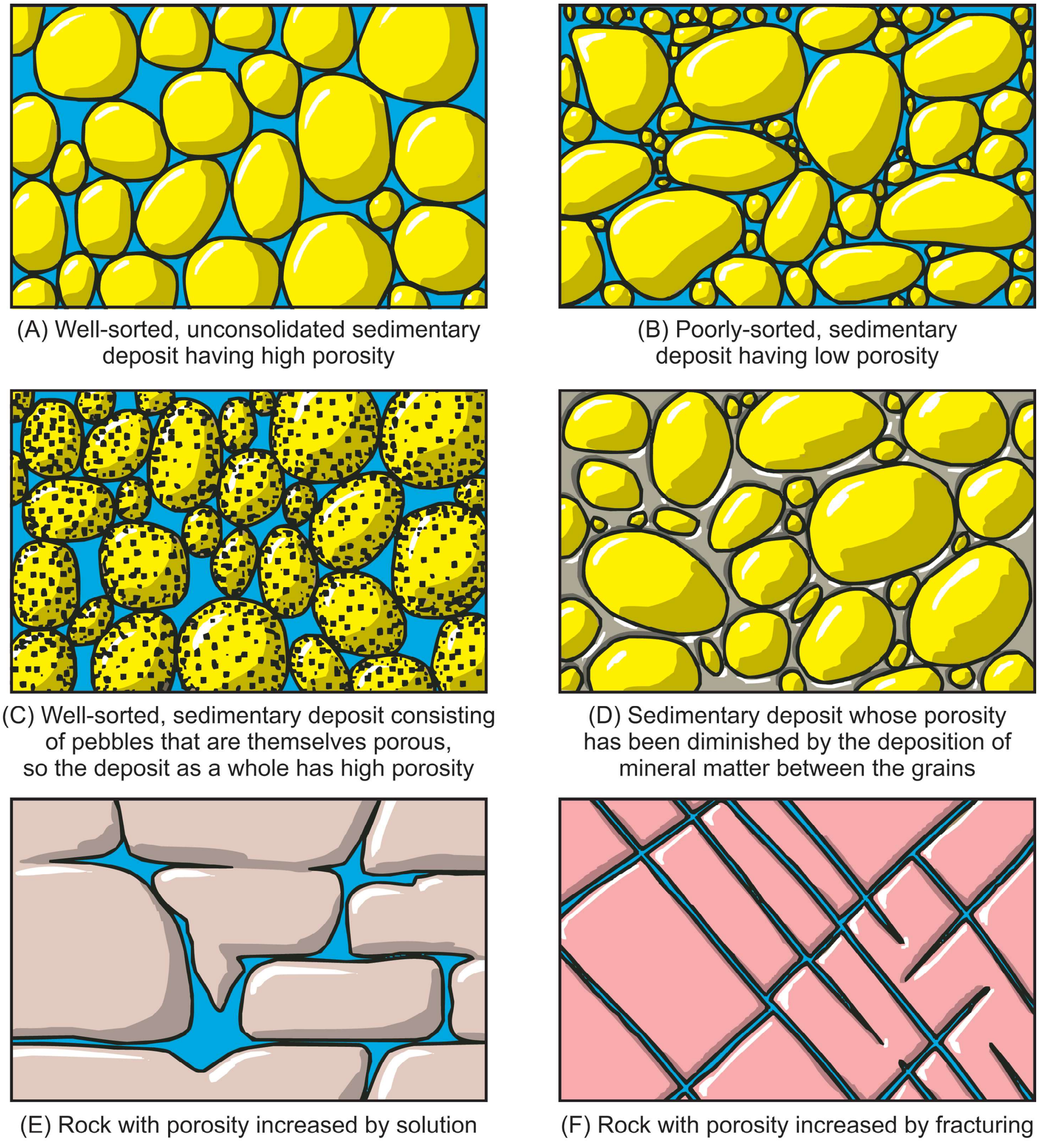



**Figure 2.8** Rock texture and porosity of typical aquifer materials (based on Todd, 1980).

also be enlarged into open fissures as a result of dissolution by flowing groundwater (Figure 2.8E). Limestone, largely composed of calcium carbonate, and evaporates composed of gypsum or other salts, are particularly susceptible to active dissolution, which often produces the caverns, sinkholes and other characteristic features of karstic aquifers.

The three basic rock formations described above

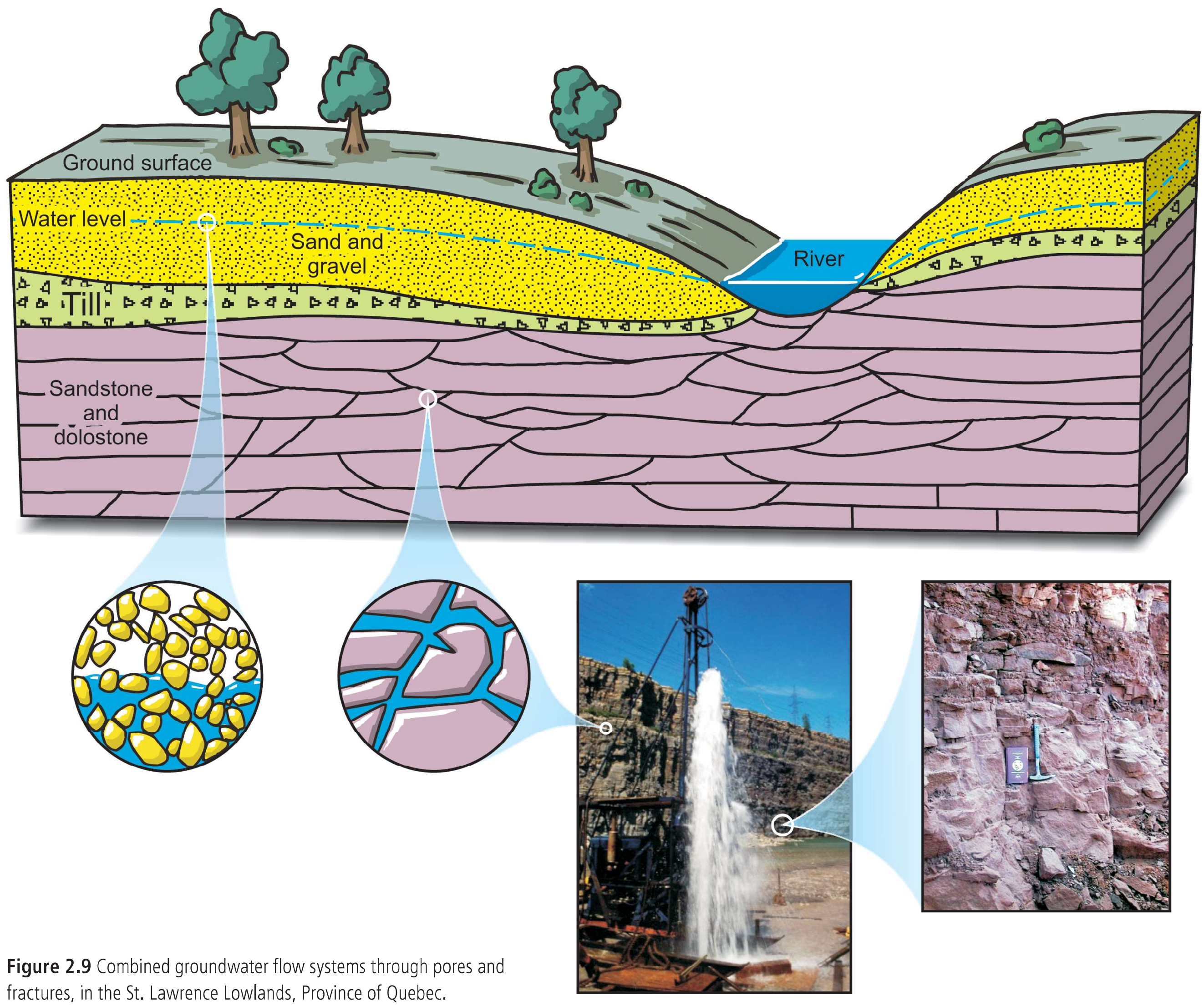



**Figure 2.9** Combined groundwater flow systems through pores and fractures, in the St. Lawrence Lowlands, Province of Quebec.

are usually subdivided by geologists to study origins, structure and other natural processes. Hydrogeologists, on the other hand, tend to classify rock-forming aquifers as unconsolidated or consolidated, depending on whether water is stored and on how it moves between grains of the rock matrix, or through fractures. Because geological maps are one of the main sources of information required to characterize aquifers and to assess groundwater flow systems, it is worthwhile to understand the main geological terms geologists use (see also Chapter 3).

### 2.4.1 Porosity

Rock *porosity* depends on the volume of water that can be stored in the rock, which in turn, depends on the proportion of openings or pores in any given rock volume. Thus, the porosity of a geological material is the ratio of the rock volume to total volume, expressed as a decimal fraction or percentage.

Figure 2.9 shows a typical case in the St. Lawrence Lowlands, Province of Quebec (see the Central St. Lawrence Lowlands Hydrogeological Region in chapter 13), where groundwater flows through both the pores and fractures.

**TABLE 2.3 POROSITY AND SPECIFIC YIELD OF GEOLOGICAL MATERIALS (FREEZE AND CHERRY, 1979; DOMENICO AND SCHWARTZ, 1998)**

| MATERIAL | POROSITY | SPECIFIC YIELD |
|---|---|---|
| **Unconsolidated sediments** | | |
| Gravel | 0.25-0.35 | 0.16-0.23 |
| Coarse sand | 0.30-0.45 | 0.1-0.22 |
| Fine sand | 0.26-0.5 | 0.1-0.25 |
| Silt | 0.35-0.5 | 0.05-0.1 |
| Clay | 0.45-0.55 | 0.01-0.03 |
| Sand and gravel | 0.2-0.3 | 0.1-0.2 |
| Glacial till | 0.2-0.3 | 0.05-0.15 |
| **Consolidated sediments** | | |
| Sandstone | 0.05-0.3 | 0.03-0.15 |
| Siltstone | 0.2-0.4 | 0.05-0.1 |
| Limestone and dolomite | 0.01-0.25 | 0.005-0.1 |
| Karstic limestone | 0.05-0.35 | 0.02-0.15 |
| Shale | 0.01-0.1 | 0.005-0.05 |
| **Igneous and metamorphic rocks** | | |
| Vesicular basalt | 0.1-0.4 | 0.05-0.15 |
| Fractured basalt | 0.05-0.3 | 0.02-0.1 |
| Tuff | 0.1-0.55 | 0.05-0.2 |
| Fresh granite and gneiss | 0.0001-0.03 | <0.001 |
| Weathered granite and gneiss | 0.05-0.25 | 0.005-0.05 |

Although water is present in the unsaturated zone between the surface of the soil and the top of the saturated zone underneath, it cannot be considered as a resource because its residence time is short and transient: the water is not in hydrodynamic equilibrium. The deeper saturated zone of soil and rock, with its ensemble of voids, allows water to accumulate. It is in this area where groundwater is considered as a resource, and the soils and rocks containing the groundwater considered as aquifers.
In this book we consider groundwater as a resource only within the saturate zone.

Porosity is a very useful property in hydrogeology, as increasing pore space results in higher porosity and greater water storage potential. Typical porosity ranges for common geological materials are shown in Table 2.3, with emphasis on the hydrogeologists' division of unconsolidated and consolidated aquifer types referred to above.

## 2.5 GROUNDWATER SYSTEMS

One common belief about groundwater is that it

A sinkhole in a karstic aquifer

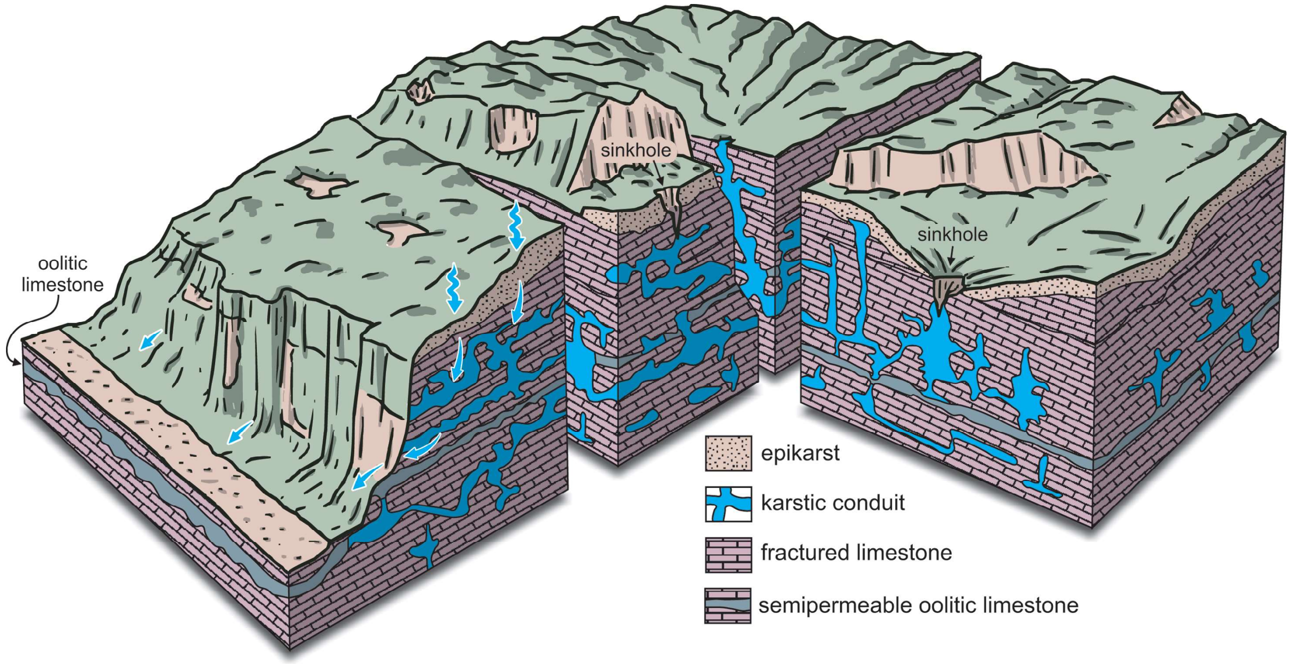



**Figure 2.10** Karstic aquifer systems (modified from Bakalowicz, 2005).

flows through underground rivers or collects in underground lakes. Groundwater is not confined to only a few channels or depressions in the same way that surface water is concentrated in streams and lakes. Rather, it exists almost everywhere underground, in the spaces between particles of rock and soil, or in crevices, fractures and cracks in rock.

The water filling these openings is usually within 100 metres of the Earth's surface, although it can also be found hundreds of metres lower, in deeper formations, depending on rock conditions (much of the Earth's fresh water is found in these voids). These openings are much smaller at greater depths because of the weight of overlying rock. They hold considerably smaller quantities of water, which may be of significantly poorer quality.

Very often these saturate zone voids are small, even sub-millimetric, sometimes existing as spaces between the grains of sedimentary rock, or as small holes visible only under the magnifying glass in rocks like chalk or sandstone. These voids can also exist as very fine fissures (a fraction of a millimetre aperture) formed over time in hard rocks like granites, some lavas and certain hard carbonate rocks. In very special cases, these apertures may be centimetres or even metres wide; forming what are known as karstic systems.

Dolostone and carbonate rocks of the Chateauguay aquifer south of Montreal.

Sandstone outcropping on a cliff in Prince Edward Island

### 2.5.1 Aquifers

An aquifer can be defined as a single geologic unit, or as a set of interconnect hydrostratigraphic units which can yield significant quantities of water to wells. Aquifers are classified as unconsolidated or consolidated, and, in the latter case, reclassified as to whether water is stored and moves mainly between the grains of the rock matrix, or through fractures. In Canada, aquifers formed of unconsolidated granular material, such as sand and gravels, abound in deltas and buried valleys, and are typically formed by deposition of material usually underwater from lakes, rivers and the sea, or as remnants of past glaciations. Sedimentary rocks, on the other hand, turn into consolidated aquifers through physical compaction and chemical cementation, as the voids between the grains in sandstone, limestone, and shale are much reduced. In these types of consolidated aquifers, water is stored and transmitted through fractures, rather than through pores.

Other types of consolidated aquifers include igneous and metamorphic rocks of differing origins and types (granites, lavas, basalts, gneisses). These rock formation specimens have very few void spaces in the matrix between grains. Indeed, the only void spaces may be fractures resulting from fold and fault stresses; these fractures may be completely closed or have very small, and not extensive, or poorly interconnected openings of relatively narrow aperture. Fractures may be enlarged into open fissures as result of dissolution

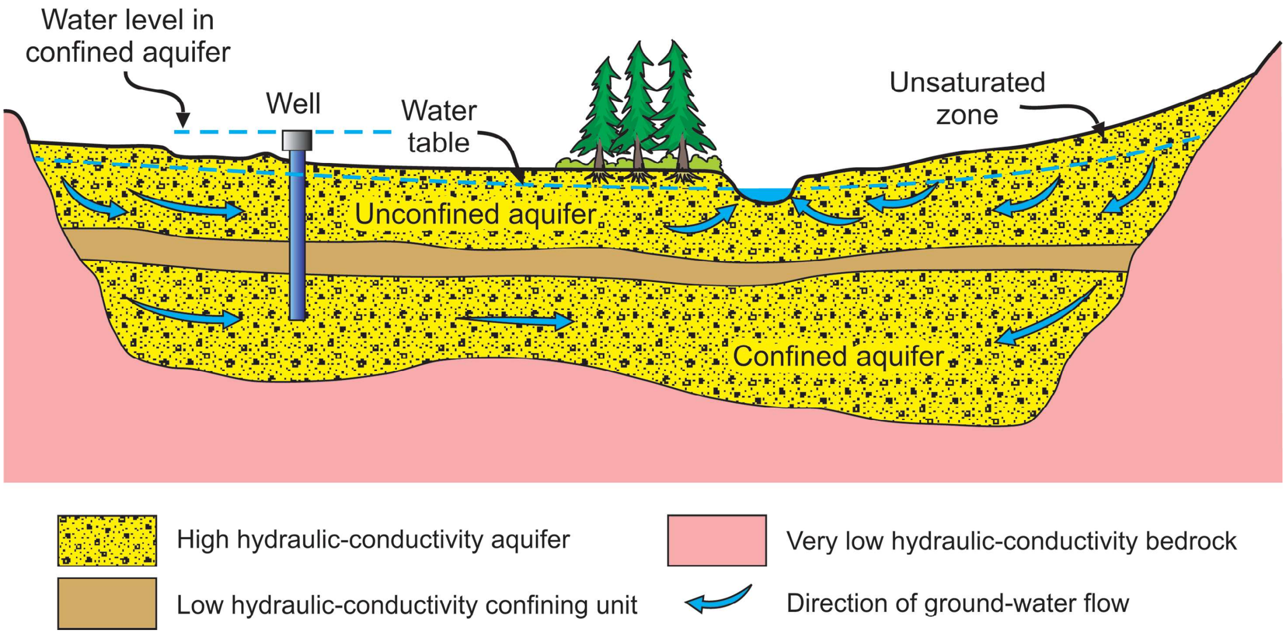



**Figure 2.11** Unconfined and confined aquifers.

An artesian well north of Montreal

by flowing groundwater. One particular case of rock susceptible to active dissolution is limestone, which is largely made up of calcium carbonate, and evaporates of gypsum or other salts. This limestone dissolution can produce the caverns, sinkholes and other characteristic features of karstic aquifers (see Figure 2.10).

Many Canadian aquifers are in unconsolidated deposits of sand and gravel formed by rivers or lakes created from melting glaciers during the last ice age; some regional examples of these granular aquifers include

- Waterloo Moraine, Ontario
- Fredericton area, New Brunswick
- Carberry aquifer, Manitoba
- Fraser Valley aquifer, British Columbia

Many other regional aquifers are in fractured-rock formations; regional examples of these include

- The entire province of Prince Edward Island (sandstone)
- Winnipeg region (carbonate, shale), Manitoba
- Montreal region (carbonate, dolostone, dolomite),

Quebec

- Moncton area (carboniferous), New Brunswick

Aquifers can be further differentiated under *confined* and *unconfined* conditions (Figure 2.11). This distinction has important implications for groundwater development and protection.

An unconfined aquifer is one in which the upper limit of the zone wherein all pore spaces are fully saturated (i.e., the water table) is at atmospheric pressure (see Figure 2.11). When the aquifer extends to greater depths, less permeable layers are found. These diminish the aquifer's effective thickness, but may induce water pressures much greater than atmospheric. When the overlying layer of an aquifer has such low permeability (as in clay) that it prevents water movement through it, the aquifer is defined as fully confined. Water pressure at any point in a confined aquifer is greater than atmospheric. When a well is drilled down through the confined layer into the aquifer, groundwater will rise up the borehole to a level that balances the aquifer pressure. An imaginary surface joining well water levels in wells and drilled boreholes in a confined aquifer is called the piezometric (or equipotential) surface, which can be above or below the ground surface. An example of this surface is illustrated in Figure 2.11 (for more detailed examples of these hydrogeological conditions see also Figures 2.12 and 2.13). If the pressure in the confined aquifer is such that the piezometric surface is above ground level, then a well drilled through the aquifer will overflow. These types of overflowing wells are called artesian wells.

A large percentage of Canadian wells can be found in unconfined aquifers. These aquifers are favoured, from a groundwater development perspective, because their storage properties make them more efficient, and they are also likely to be shallower and therefore cheaper to drill into and pump from. A confined aquifer, on the other hand, even with a modest overlying less permeable layer, is likely to be much less vulnerable to pollution.

Development of groundwater resources in unconfined, shallow Canadian aquifers may have important consequences in terms of groundwater sustainability and vulnerability. Shallow, unconfined aquifers are generally hydraulically connected to surface water bodies and, thus, more likely to affect or be affected by these water bodies (in terms of baseflow or surface water pollution); alternatively, many of these shallow aquifers provide essential water needs for ecosystems (wetlands, riparian zones, fish, etc.; see Chapter 5). Development and effective management of shallow unconfined aquifers must consider long-term implications of water availability and water quality for all users.

#### 2.5.1.1 Aquifer systems

Any "aquifer system," from the hydrogeological viewpoint, is a set of spatially and hydraulically interconnected stratigraphic units of different origins having the ability to store and transmit water. One excellent example of such a system is Alberta's Paskapoo aquifer system (Figure 10.20).

Figure 2.12 illustrates the effects of groundwater pumping in aquifers. Without pumping (Figure 2.12a), water recharge from the sandy area flows toward the deepest part of the aquifer, then rises locally to discharge close to a surface water body, or to the sea. When this state is disturbed by groundwater pumping (Figure 2.12b), both the piezometric level of deeper beds and the water table in upper sands descend; the hydraulic gradient between them increases and most flowpaths

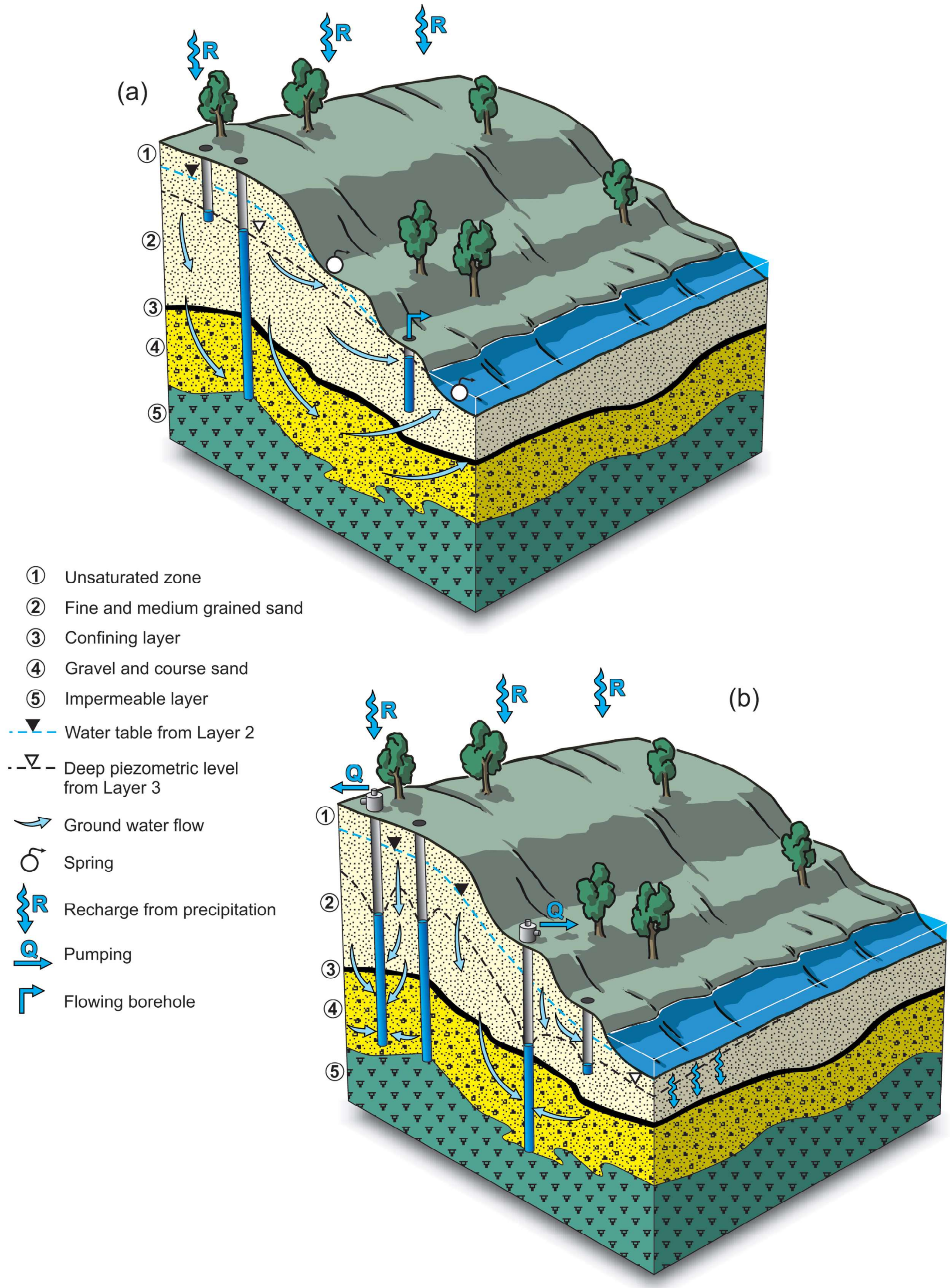



**Figure 2.12** Simplified sketch, showing groundwater pumping effects: **(a)** without groundwater pumping; and **(b)** with groundwater pumping.

turn downward, decreasing natural discharge to surface water bodies.

Developed aquifers are defined as those aquifers within which wells have been constructed to utilize groundwater.

### 2.5.2 Aquitard characteristics

An aquitard is a zone within the earth that restricts the flow of groundwater from one aquifer to another. An aquitard, when completely impermeable, can sometimes be called an *aquiclude* or *aquifuge*. Aquitards comprise layers of either clay or non-porous rock with low hydraulic conductivity. Northern Canada's permafrost layers can also be considered as a type of aquitard.

An aquitard may behave as an impermeable layer relative to the much more permeable aquifer layers above or below it. An aquitard is impermeable and it will remain impermeable, although an aquitard layer may eventually contribute to groundwater flow through layers in the vertical direction. This process can be artificially induced through heavy pumping into an aquifer underlying an aquitard (causing aquitard leakage). Such activity can lead to consolidation, or to subsidence, a phenomenon which occurs in many parts of the world (e.g., Mexico City, Venice, Houston, California, etc.).

### 2.5.3 Groundwater storage in aquifers

What is groundwater storage? How is water put into and taken out of storage?

The storativity of a saturated confined aquifer can be defined as "the volume of water that an aquifer releases or takes into storage per unit surface area of aquifer per unit change in the component of hydraulic head normal to the surface". The specific storage coefficient for a saturated porous media was originally derived from purely hydraulic principles in soil mechanics (Jacob, 1950; Cooper, 1966; Lohman et al., 1972), and defined as:

$$S_s = \rho\, g\, n\, (\beta_l + \alpha/n) \qquad (2.5)$$

where $S_s$ is the specific storage coefficient (1/m), n is the porosity, $\beta_l$ is the coefficient of compressibility of the fluid (water, in $Pa^{-1}$ or kg/m $s^2$), and $\alpha$ is the coefficient of compressibility of the porous matrix ($Pa^{-1}$). It is convenient to think of the specific storage coefficient in terms of the storage related to the elasticity of the water, as well as storage related to the elasticity of the porous medium.

The coefficient defined by Eq. 2.5 is not often used by hydrogeologists studying groundwater resources. Instead, these scientists more often employ the storage coefficient S, which is related to $S_s$ by:

$$S = S_s \cdot b \qquad (2.6)$$

where b is the thickness of the aquifer and S is dimensionless. S can be estimated with long-term pumping tests using observation wells or boreholes. However, in the absence of pumping tests, which in most cases are very expensive to carry out, $S_s$ can be easily calculated if the compressibility and the porosity of the material are known. Indeed, as $\beta_l$ is very small ($5{\cdot}10^{-10}$ $Pa^{-1}$), it can be neglected with respect to the value of $\alpha$ (except in low-porosity hard rocks).

Typical values of compressibility for some common materials are given below:

| | |
|---|---|
| Clays | $10^{-6}$ to $10^{-8}$ $Pa^{-1}$ |
| Sand | $10^{-7}$ to $10^{-9}$ $Pa^{-1}$ |
| Gravel | $10^{-8}$ to $10^{-10}$ $Pa^{-1}$ |
| Sandstone | $10^{-9}$ to $10^{-11}$ $Pa^{-1}$ |

**TABLE 2.4 SELECTED VALUES OF STORAGE AND SPECIFIC STORAGE COEFFICIENTS**

| AQUIFERS/ROCK TYPES/REFERENCE | SPECIFIC STORAGE COEFFICIENT ($S_S$) [1/M] | STORAGE COEFFICIENT (S) |
|---|---|---|
| Mirabel aquifer St. Lawrence Lowlands; fractured/porous aquifer (Nastev et al., 2005) | Not available | Bedrock = $5\times10^{-5}$ to $4\times10^{-3}$ |
| Chateauguay aquifer; fractured/porous aquifer (Lavigne et al., 2010) | Not available | $5\times10^{-5}$ |
| Bedrock aquifers in the Appalachians; fractured rock aquifer (Rivard et al., see Chapter 14) | Not available | Bedrock = $10^{-4}$ (averaged)<br>Sediments= $1\times10^{-2}$ (averaged); $10^{-4}$ and 0.5 (range) |
| Oak Ridges Moraine porous medium aquifer, sand, gravel, till | $5\times10^{-3}$ to $5\times10^{-4}$ | ~0.3 |
| Assiniboine aquifer Manitoba porous medium aquifer, sand and gravel | Not available | $6\times10^{-4}$ to $1\times10^{-3}$ |
| Alluvial gravels of old river channels in Old Crow, Yukon; located on an old floodplain of the Porcupine River (see Chapter 15 and Trimble et al., 1983) | Not available | $1.52\times10^{-3}$ to $3.62\times10^{-3}$ |

Some selected values of specific storage coefficients (Ss) and of storage coefficients (S) in Canada are provided in Table 2.4, although, these values are approximate numbers obtained, for the most part, from consultants' reports or from pumping tests performed by the Geological Survey of Canada; their interpretation is often difficult and their values questionable. The lack of accurate storage coefficients is an important data gap throughout Canada, and one that hinders estimates and simulation of transient conditions in most aquifers.

## 2.6 PRINCIPLES OF REGIONAL GROUNDWATER FLOW

A groundwater flow system is a three-dimensional entity having the following components:

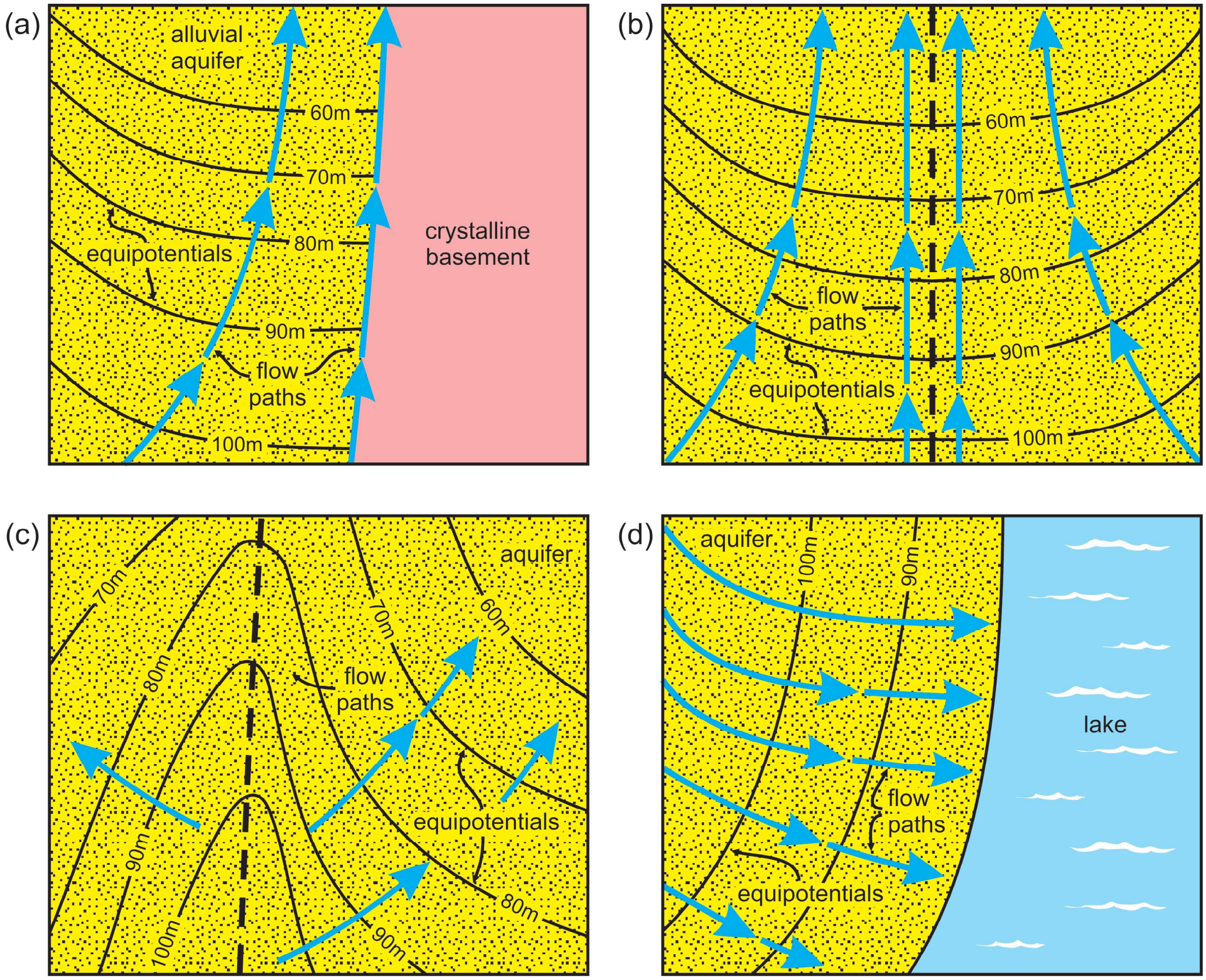
- a recharge area where water enters the flow system
- a discharge area where water exits the flow system
- hydraulic boundary conditions and physical dimensions

In addition to these features, groundwater flow is highly dependent on temporal and spatial scales.

### 2.6.1 Recharge

Recharge refers to water entering a groundwater system regardless of scale. Areas where recharge occurs are designated as *recharge areas* or *recharge zones*. There are several mechanisms through which recharge enters a flow system: these can include direct infiltration of precipitation, or by infiltration through streambeds or reservoirs (see Chapters 4 and 5). In some parts of the world, especially arid regions, infiltration of storm runoff through intermittent stream beds is the dominant recharge form. Water can also enter a groundwater flow system through inter-layered flow, or interformational flow, usually in the form of flow through leaky confining layers (see aquitards) where water is drawn in by drawdowns at wells, or where underlying aquifers have significant overpressure and water is forced upward.

Most research studies and numerical models



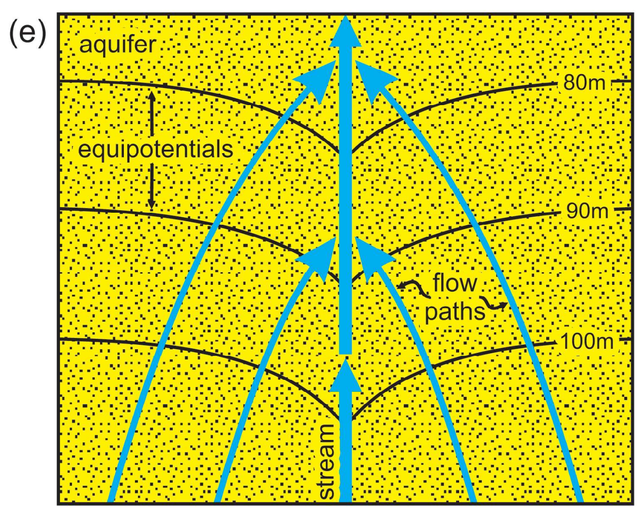




**Figure 2.13** Plan views of boundary conditions for groundwater flow: **(a)** no-flow boundary created by juxtaposition of permeable alluvial sediments and low-permeability crystalline bedrock. **(b)** Parallel flow lines create a no-flow symmetry boundary. **(c)** Groundwater divide produced by high water levels. **(d)** A constant-head boundary at a non-flowing body of water (in this case, a lake). **(e)** A stream constant-head boundary.

Rates of groundwater turnover vary from years to millennia, depending on aquifer location, type, depth, properties, and connectivity.

consider recharge as some percentage of precipitation. These percentages have a wide range depending on the climate of the region and the geological and hydraulic characteristics of the aquifer. Chapter 4 provides a very detailed analysis of these. In Canada, recharge rates have a very large geographical distribution, varying from 7% of annual precipitation rates up to 65% in some specific locations (BC) (see Figures 4.3 and 4.5, and Table 4.2).

Recharge rates are difficult to quantify; many methods involve measuring precipitation and performing a water balance by quantifying all the other surface water fluxes (surface runoff, evaporation, transpiration).

### 2.6.2 Discharge

There are several mechanisms through which water discharges from a groundwater flow system. These include discrete discharge to a spring or seep, discharge into a gaining stream or lake, flow through formations, or pumping from a well. In some arid and semiarid regions (the Canadian Prairies, for example), direct evaporation and/or evapotranspiration from the shallow water table is the primary discharge mechanism.

Discharge can also be hard to quantify, especially in areas dominated by well pumping or evaporation. Discharge flow through formations (multilayered systems) is usually much less than that of other mechanisms. Flow through springs and gaining streams can be measured, and changes in flow across a certain areas attributed to either recharge or discharge. Chapter 4 provides detailed explanations of these mechanisms. Chapter 5 describes discharge mechanisms through riverbeds and other surface water bodies.

### 2.6.3 Boundary conditions

Groundwater flow systems are three-dimensional bodies with boundaries. There are two types of basic boundaries, or *boundary conditions*, which characterize the limits of groundwater flow systems at any scale: *no-flow boundaries* and *constant-head boundaries.*

A *no-flow* boundary has a hydraulic gradient of zero, expressed as $dh/dxi=0$ (where h is the hydraulic head and xi the flow directions), therefore no flow occurs across boundaries. No-flow boundaries can be physical when permeable aquifer units are in contact with low-permeability bedrock (Figure 2.13a). A no-flow boundary can also exist when flow lines are parallel, creating a *symmetry boundary* (Figure 2.13b). Modellers often use symmetry boundaries to constrain numerical groundwater models of aquifers. On a smaller scale, high water levels can create a type of no-flow boundary known as a **groundwater divide** (Figure 2.13c) wherein water flows away from the partition on either side (similar to surface runoff at a drainage divide).

A **constant-head boundary** is characterized by hydraulic heads that do not change. Non-flowing bodies of water, such as lakes, ponds, or oceans, can create a constant-head boundary (Figure 2.13d) as, in each case, the shore of the body represents a single equipotential line (or line of constant head) in the aquifer: water flow is perpendicular to the shoreline (either into the aquifer from the surface body or vice versa). A stream can also act as a constant-head boundary (Figure 2.13e); although the actual heads will vary along the stream gradient, each point is considered constant and represents a point on an equipotential.

### 2.6.4 Issues of scale: Time and space

Groundwater is often misinterpreted because of the lack of knowledge of time and space scales associated with the response of groundwater flow to natural and anthropogenic stresses.

Groundwater flow systems occur at different scales both in space and in time. Hydrogeologists distinguish three spatial scales and two temporal scales (Rivera, 2008).

Spatial scales are identified as: (a) regional (greater than 1,000 km$^2$; found usually under steady-state conditions), (b) local (typically hundreds of square kilometres; found both in steady-state and transient conditions), and (c) site (generally less than 100 km$^2$; typically found under transient conditions).

Temporal scales refer to (a) steady-state conditions of hydrodynamic equilibrium, and (b) transient conditions in which the system is under stress (by pumping).

Although absolute areas for each spatial scale are somewhat arbitrary, they do indicate important differences in Canadian aquifers (Rivera, 2005). Figure 2.14 is a schematic representation of these scales. In general, aquifers are heterogeneous in nature, and their hydraulic/hydrogeological behaviour (flow rates, flow volumes, mass and heat transport) is partially dictated by this heterogeneity. Site-scale shallow aquifers demonstrate a relatively rapid response to applied stresses; the effect of these stresses is limited in time and in space, from hundreds of metres to a few kilometres, and from tens of days to hundreds of days. Aquifers at local to regional scales have a much broader and longer-term response; the effects are spread out over tens of kilometres, and tens to hundreds of years. These space and time effects are even more striking when aquifer systems contain aquitards (relatively impermeable layers) (Figure 2.14), a situation not uncommon in Canada, as has been observed in the Prairies

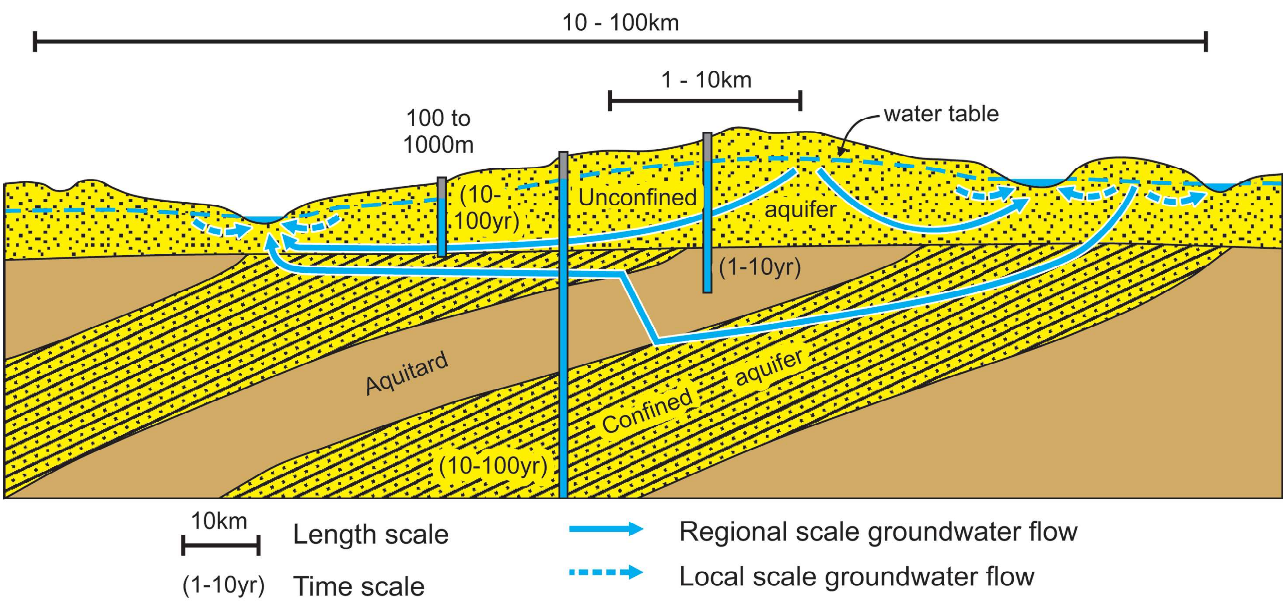



**Figure 2.14** Schematic representation of space and time scales for groundwater (modified from Johnston, 1999).

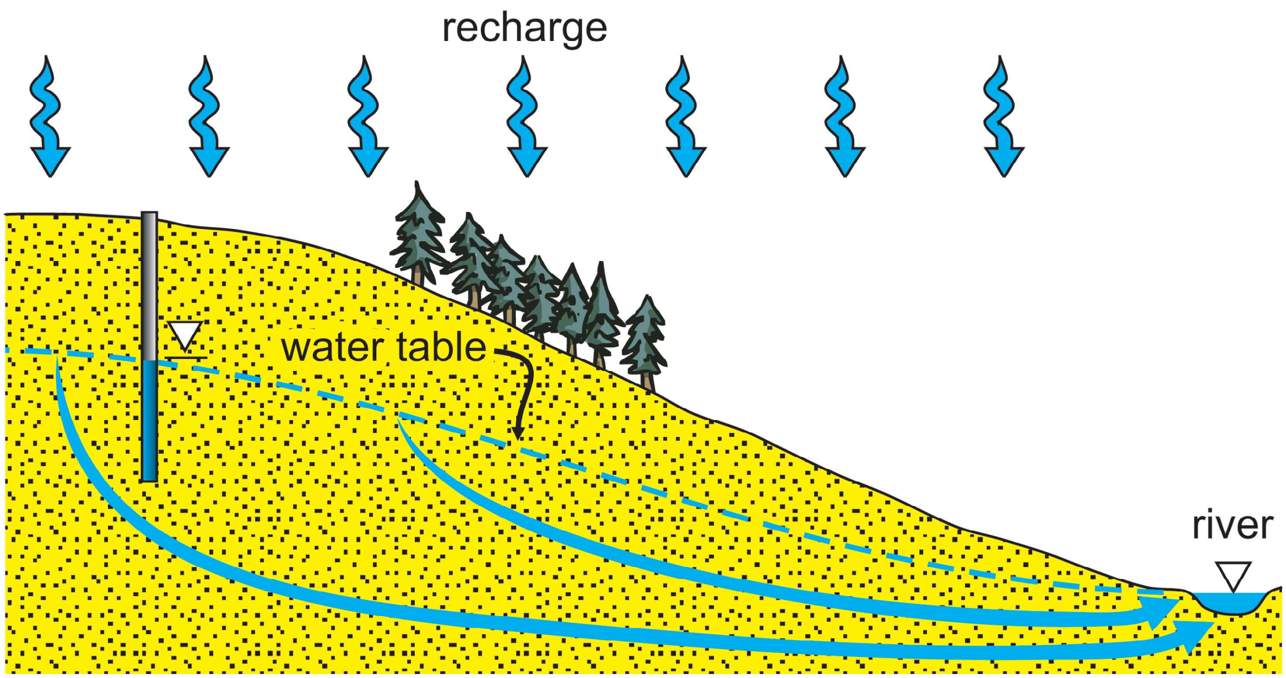



**Figure 2.15** Cross section of a water-table aquifer showing the relationship between topography and the orientation of the water table.

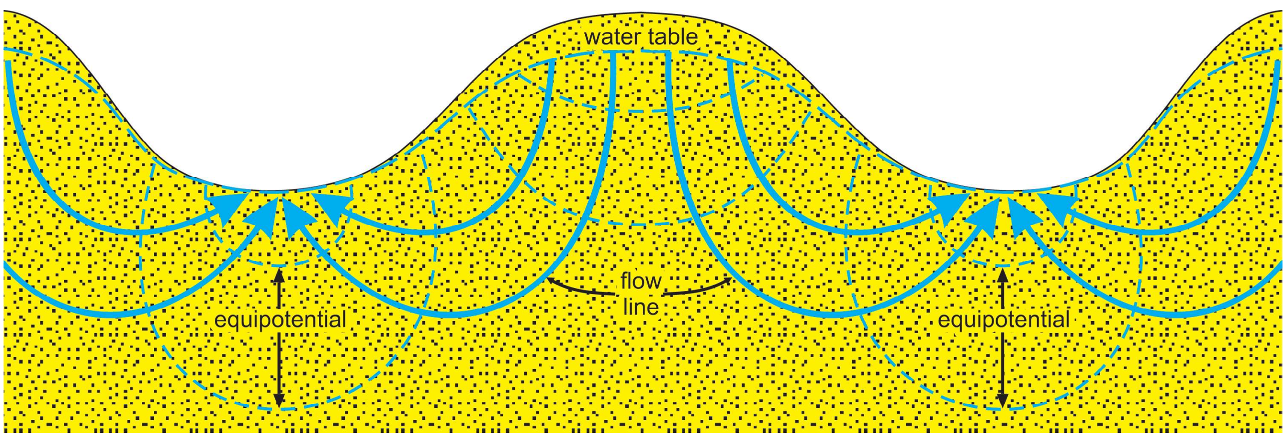



**Figure 2.16** Flow patterns control by topography (after Hubbert, 1940).

(Maathuis and Thorleifson, 2000).

The scale issue is not trivial and cannot be ignored. One question a water resource manager or a community might ask is: "How quickly can we expect to detect a change in groundwater level during a drought?" or "Should nutrient source controls be implemented, how fast would we see a change in nitrate concentration of the aquifer?"

How rapidly an aquifer responds to change in hydraulic stress (increase or decrease in the amount of water input or increase in well pumping), or chemical stress (decrease in nitrogen loading) can be estimated by calculating an aquifer's *hydraulic* or *chemical response time*.

Hydrogeologists are able to calculate hydraulic response time once they know the key aquifer parameters and the relative permeability of adjacent rocks. If chemical reactions and transport parameters are known, the chemical response time can also be calculated.

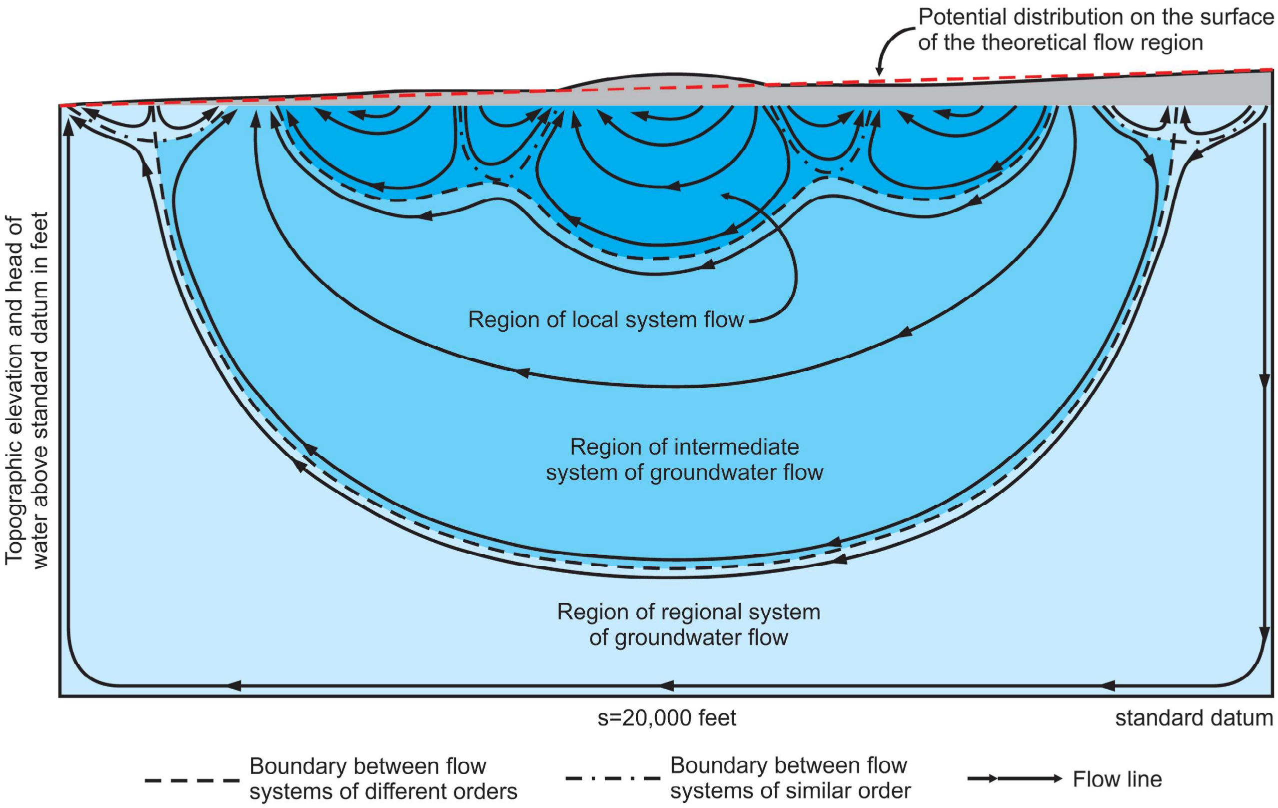



**Figure 2.17** Hierarchically nested gravity-flow systems of groundwater in drainage basin with complex topography (after Tóth, 1962).

### 2.6.5 Gravity-driven groundwater flow

Scientists were aware of the relationship between topography and groundwater flow patterns in unconfined aquifers as early as the end of the 19th century. King (1899) and Hubbert (1940) noticed that any water table tends to become a subdued replica of its topography (Figure 2.15), while Hubbert (1940) suggested that topography can control groundwater flow patterns so that high elevations become recharge areas and low elevations discharge areas (Figure 2.16). Tóth (1962) and Freeze and Witherspoon (1967), working in the 20th century, developed computer models that simulated the effects of topography on groundwater flow systems: both of these simulations supported King's and Hubbert's conclusions. The models also illustrated the fact that sinusoidal topography can result in the formation of smaller local flow systems, with local recharge and discharge areas, within larger regional systems (Figure 2.17, after Tóth, 1962).

## 2.7 GROUNDWATER EXTRACTION AND WELLS

Developed aquifers are those aquifers wherein wells have been installed to utilize groundwater. Over the long term, a developed aquifer may function by inducing recharge from surface water sources and/or by decreasing discharge to streams and springs. The sum of these two flow components is sometimes termed as the "capture" (Bredehoeft et al., 1982); capture is dynamic, highly dependent on aquifer properties, space and time scales, and aquifer geometry. Any increase in aquifer inflow usually originates from three primary sources: 1) a rise in percolation due to irrigation surplus,

changed soil characteristics and decreased evapotranspiration; 2) induced recharge from surface water bodies; and 3) induced recharge from neighbouring aquifers or groundwater basins. A combination of conditions 2 and 3 may also happen at regional scales.

The initial lowering of the water table, or piezometric surface, sparked by pumping, ceases when capture and pumping stresses reach a new equilibrium. An extraction which may have initially appeared as "excessive" overdraft can later reveal itself to be sustainable, albeit with some loss of local surface water or aquifer discharge. Should groundwater pumping exceed available capture, therefore preventing an equilibrium, the difference will be drawn from storage, and groundwater levels will decrease (see more in Chapters 6 and 10).

In the preceding sections of this chapter, we have described the regional approach, or aquifer scale. Hydrogeologists and planning engineers must also consider the scale of pumping wells—what happens in the vicinity of an individual well and how to determine the **drawdown** produced in the well itself and in its vicinity?

A pumped aquifer may reach a new equilibrium within the expected time frame and hydraulic conditions described above, or it may not.

Consider the case of Saskatchewan's Estevan aquifer, a preglacial, buried-valley formation described in Box 10-2. In 2011, 17 years after pumping ceased, residual drawdown in the aquifer was still far from equilibrium, as shown by Maathuis and van der Kamp (2011). Thus, the

In this book, we examine wells only as input or output sources which affect the overall groundwater flow pattern of any aquifer. Actual well structure, drilling, completion techniques and sealing are not elements we have considered. Instead, we refer readers to specialized texts on these subjects (e.g., Johnson Inc., 1966; Campbell and Lehr, 1973)

combination of conditions 2 and 3, as described above, does not seem to include all equilibrium factors. In the case of the Estevan aquifer, the most likely explanation is that excessive groundwater continued to be removed from storage, dictating a much longer recovery time frame than would have been the case if conditions 2 and 3 (outlined above) had been rigorously applied.

Long-term analysis of well data indicates that sustainable yield for this type of aquifer can often be significantly less than originally expected (Maathuis and van der Kamp, 2011).

Hydrogeologists evaluating groundwater resources use terms like groundwater yield, well yield, aquifer yield, and more recently, sustainable yields. These concepts are important and applicable at several scales, and they are clear indicators of the main question hydrogeologists seek to discover: what are the maximum possible pumping rates compatible with the hydrogeological environment from which aquifer water will be taken? As scientists search for answers, they need to find a compatible compromise between the environment and groundwater availability; they must evaluate those groundwater yields in terms of balance between the benefits of pumpage and the undesirable changes such pumpage induces. The most common change pumping produces is a lowering of groundwater levels. Thus yield can be defined, in the simplest cases and at more local scales, as the maximum rate of allowable pumpage to ensure that water-level declines are kept within acceptable limits.

Chapter 6 provides a more detailed analysis of aquifer scale sustainability.

The hydraulics of pumping wells is in itself a vast domain, developed mostly from well pumping tests drilled in confined, leaky, and phreatic aquifers, under a myriad of conditions. The resulting literature is comprehensive, consisting of a large number of analytical equations designed to solve for groundwater flow to a well and to provide boundary values, which define aquifer parameters. Some of the most complete handbooks on this topic include Kruseman and de Ridder (1970), Ferris et al. (1962) and Walton (1970). Bear (1979) also provides an exhaustive summary of the mathematical treatment of pumping hydraulics and recharging wells.

What is the response of an aquifer to pumping, as measured by *aquifer yield*? This yield depends both on the manner in which the effects of withdrawal (pumping) are transmitted through the aquifer and on changes in groundwater recharge rates and discharge induced by withdrawals. Note that aquifer withdrawal is not only the result of pumping (anthropogenic conditions); it can also occur as a result of natural climate changes, for example, increase in evapotranspiration or decrease in river flow.

In its simplest, the transient hydrologic projection for any saturated portion of an aquifer can be described as

$$Q(t) = R(t) - D(t) + dS/dt \qquad (2.7)$$

where:

$Q(t)$ = total rate of groundwater withdrawal

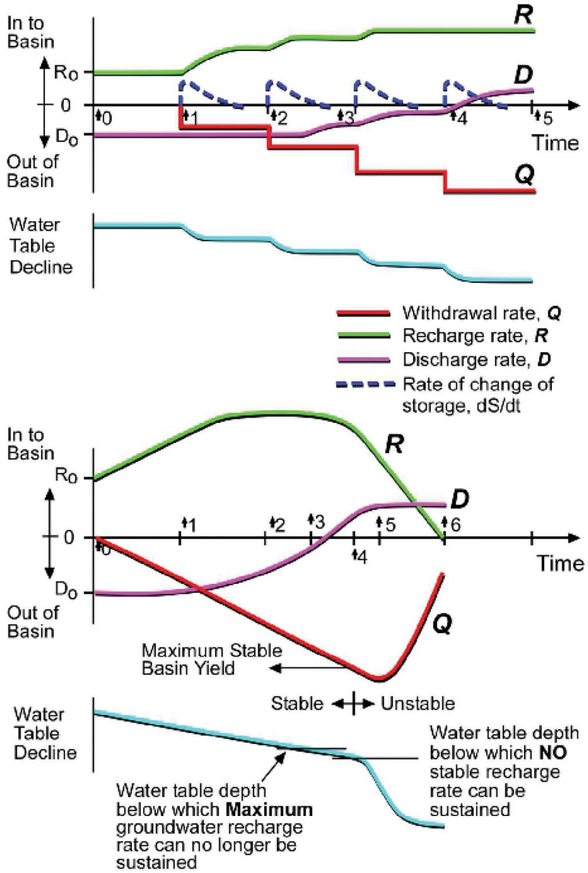



**Figure 2.18** Relationship between pumping (Q), recharge (R), and discharge (D) in a basin (reproduced from Freeze, 1971).

R(t)= total rate of groundwater recharge to aquifer

D(t)= total rate of groundwater discharge from aquifer

dS/dt= rate of change in storage in the saturated zone of the aquifer

Freeze (1971) examined the response of R(t) and D(t) to an increase in Q(t), applying Eq. 2.7 to a hypothetical aquifer in a humid climate where the water table is located near the Earth's surface. He simulated the response using a three-dimensional transient analysis of a complete saturated-unsaturated system equipped with a pumping well.

Figure 2.18 (reproduced from Freeze, 1971), illustrates the hydraulic behaviour of an aquifer as a function of time as groundwater is pumped. These diagrams depict time-dependent changes, which might be expected as a result of Eq. 2.7 variables under increased pumpage. Groundwater pumping increase in a step-wise manner causes recharge increase in a subtly similar stepwise manner because the resultant signal impacts are spread over a large area, causing a stepwise discharge decrease.

The upper portion of Figure 2.18 initially depicts a steady-state condition at to wherein recharge Ro equals discharge Do. New wells begin to tap the system and the pumping rate Q undergoes a set of stepped increases. Each increase in an unconfined aquifer is initially balanced by a change in storage (dS/dt). Increases in Q translate to immediate water-table declines in this case (see also Figure 2.12). Forces within the aquifer move to find a new hydraulic equilibrium under conditions of increased recharge, R. After a certain pumping time (t5), Q is fed entirely by recharge and induced discharge, D, resulting in a significant water table decline. Steady-state equilibrium conditions are reached prior to each new increase in withdrawal rate (Q).

The lower portion of Figure 2.18 shows the same sequence of events under conditions of continuously increasing groundwater development (pumping) over several years. This schematic clearly illustrates that, when pumping rates increase indefinitely, an unstable situation may arise. The declining water table will reach a depth below which the maximum rate of groundwater recharge R can no longer be sustained. It is impossible for an aquifer to supply increased rates of withdrawals once the maximum available rate of induced discharge is attained. The only remaining groundwater source lies in an increased rate of storage withdrawal (dS/dt), which manifests itself in a rapidly decreasing water table, among other consequences.

One of the most well-known consequences of groundwater overexploitation is land subsidence. Many areas around the world are coping with problems of regional subsidence on a regional scale: some of the better-known examples have been documented in California's San Joaquin Valley, the Houston-Galveston area, Bangkok, Venice and Ravenna, and Mexico City (Rivera et al., 1991).

Groundwater pumping may, and often does, have an important impact on our environment, specifically in the form of water level reduction, baseflow decline, subsidence and saltwater intrusion. These issues, and other environmental concerns are described in more detail in Chapters 5 and 6.

## 2.8 INTERACTIONS WITH SURFACE WATER

The scientific community has long recognized that, within the water cycle, there are continuous dynamic interactions between surface water bodies (e.g., rivers, lakes, wetlands) and groundwater (aquifers). These occur at various spatial and temporal scales.

Clearly, surface water and groundwater should be considered and treated in an integrated way, despite their very different nature and scales. Very few scientists, however, let alone water resource managers, take this holistic approach; surface water resources are usually studied, and managed, without consideration of groundwater. Most water investment research funding in Canada is used to assess and develop surface water resources; much less is allocated to groundwater study.

Much of this funding discrepancy can be attributed to persistent knowledge gaps about the interaction between surface water and groundwater, although the physical processes and mathematics needed to assess surface water/groundwater interactions (SW-GW) are known and relatively well established. Scientists today couple basic hydraulics principles, hydrological processes and geology with equations describing groundwater flow (i.e., Darcy's Law) to assess these interactions. However, the application of theory is not straightforward, even when basic theoretical knowledge exists, due to complex interactions between groundwater and surface water.

> Shallow groundwater flow systems should be distinguished from deep groundwater flow systems; the former interact with surface water, the latter do not.

A sound hydrogeological framework is needed to understand these interactions in relation to climate, landforms, geology, hydrology and biotic factors. It is the lack of such a framework that represents the main knowledge gap in Canada.

Studies of SW-GW interactions have expanded in recent years (Sophocleous, 2002) to include studies of headwater streams, lakes, wetlands, and estuaries. Those countries with limited water resources have widened their SW-GW research scope to include conjunctive use of surface water and groundwater in water management practices. A major factor in modern-day SW-GW research is the introduction of comprehensive conceptualizations of SW-GW interactions involving teams of geologists, hydrogeologists, hydrologists and ecologists.

Research needs and challenges facing this evolving field are linked components of a hydrological continuum leading to related water sustainability issues:

- Current frontiers in SW-GW interactions seem to be near-channel and in-channel exchange of water solutes and energy. Understanding these processes is key to evaluating the ecological structure of stream systems and their management (Sophocleous, 2002)

- Analysis over time of sediment and reach scales within the hyporheic zone (that thin layer beneath the river bed) remains unclear at present, and can be neglected when dealing with regional-scale integrated water resources (water quantity). For detailed biochemical analysis and transport, however, this layer is very significant and must be considered in any detailed biochemical and transport investigation
- SW-GW should not be estimated but measured
- The use of heat, chemical tracers, and age dating should be studied, and the results integrated into numerical models
- Groundwater-level measurements should continue and be increased. When and where possible, these measurements should be taken in real-time, especially in shallow, sensitive aquifers. The resultant figures should be analyzed at the basin-scale and in association with river hydrographs

Chapter 5 presents a more comprehensive analysis of surface water and groundwater interactions and related issues pertaining to Canadian conditions of use, dynamics and occurrence.

### 2.8.1 Differences in flows between surface water and groundwater

When we consider groundwater in terms of flowpaths and fate, there are two classifications: shallow groundwater flow and deep groundwater flow. Shallow groundwater flow, termed as groundwater *runoff* by some scientists, intercepts the land surface, feeding springs which seep back to surface waters as the perennial flow (or baseflow) of streams/rivers and other freshwater bodies (swamps, wetlands and lakes, for example). Deep groundwater flow, or groundwater *runout*, on the other hand, does not intercept the land surface; instead, it flows directly, albeit very slowly, into the Earth's oceans. The source of shallow groundwater flow is shallow percolation (or shallow groundwater infiltration). On a global basis, deeper groundwater infiltration accounts for an average of 13% of the Earth's precipitation, while the amount of shallow percolation is equal to the annual amount of baseflow discharging into the world's streams and rivers. Since baseflow constitutes about 30% of streamflow (or runoff) and streamflow is on average about 24% of precipitation, it follows that baseflow or shallow percolation constitutes $(0.30 \times 0.24) \times 100 = 7.2\%$ of precipitation.

Chapter 5 describes groundwater extraction and its influence on surface water bodies (rivers, lakes, wetlands) in greater detail.

## 2.9 GROUNDWATER QUALITY (NATURAL AND CONTAMINATED)

### 2.9.1 Natural quality

Water, in nature, is never "pure". It picks up small amounts of everything with which it comes into contact, including minerals, silt, vegetation, fertilizers, and agricultural runoff. Canada's diverse physical geography (from coastal regions to mountains from prairies, to northern tundra and the Canadian Shield) means that the characteristics of its natural water will vary greatly across the country, and, even in relatively pristine areas, will usually requires some type of treatment before it is safe to drink.

Canada's drinking water comes either from groundwater (wells in aquifers), or from surface waters (lakes and rivers). Most Canadians get their drinking water from public water systems which must meet quality requirements set by provincial and territorial governments. People living in rural and remote areas may get their drinking water from wells, or from surface water sources located on private property. These consumers are individually responsible for the safety of their drinking water.

68.7% of all of the Earth's fresh water is permanently stored in icecaps and glaciers, 30.1% is groundwater, 0.3% is surface water, and 0.9% is other minor storage (soil water, plants) (Figure 2.1). Further, an analysis of available fresh water on the planet shows that groundwater is about one hundred times more plentiful than surface water, although surface water is typically low in salt ions. Groundwater, however, particularly that lying at great depth, may contain high concentrations of salt ions, significantly limiting its use as natural drinking water.

The natural quality of groundwater has important implications for its use and sustainable development.

Water quality is assessed by measuring the amounts of its various constituents; these are often expressed as milligrams of substance per litre of water (mg/L) (which is equivalent to the number of grams of a substance per million grams of water).

The natural quality of groundwater differs from that of surface water because (a) groundwater quality, temperature and other parameters, for any given source, are less variable over the course of time; and (b) the range of groundwater parameters encountered is much greater than that for surface water. TDS (total dissolved solids[2]) in groundwater can range from 25 mg/L within some areas within the Canadian Shield to 300,000 mg/L in the deep saline waters of the Interior Plains.

Deep groundwater infiltration, by definition, does not belong to the surface water catchment area and, therefore, it cannot affect its quantity.

Groundwater tends to be harder and more saline than surface water, when the two are compared, at any given location, although this is by no means a universal rule. Another generality is the fact that groundwater becomes more saline with increasing depth, although, again, there are many exceptions to this rule.

The salinity of fresh water is less than 500 mg/L, while the salinity of ocean water is about 35,000 mg/L. Definitions of water salinity vary within the literature. For example,

- Brackish water is defined as having a TDS concentration ranging from 1,000 to 10,000 mg/L; saline water from 10,000 mg/L to 100,000 mg/L, and brine as >100,000 mg/L (Freeze and Cherry, 1979; Fetter, 1993).
- Hem (1970) defines moderately saline water as ranging from 3,000 mg/L to 10,000 mg/L.

Slightly saline water, an example of which might be irrigation water, has concentrations from 500 to 1,500 mg/L. Moderately saline water, such as drainage water, ranges from 1,500 to 5,000 mg/L, while highly saline groundwater may have salinity concentrations in excess of 10,000 mg/L. Groundwater is considered "saline" with concentrations in excess of 10,000 parts per million (mg/L).

Saline groundwater depth in the United States varies from less than 150 metres to more than 300 metres (Alley, 2003). Saline groundwater in Canada may be found at various depths depending on the "saline" definition. In Alberta, for example, saline groundwater is defined as water with a TDS concentration exceeding 4,000 mg/L (this

2. Total Dissolved Solids (TDS) concentrations are comprised of dissolved inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonate, chloride and sulphate) and small amounts of organic matter.

## TABLE 2.5 MAXIMUM ACCEPTABLE CONCENTRATIONS (MAC) IN GROUNDWATER IN CANADA (HEALTH CANADA, 2010)

| PARAMETER | MAXIMUM ACCEPTABLE CONCENTRATION (MAC) |
|---|---|
| **BACTERIOLOGICAL** | |
| *Escherichia Coli* | 0 per 100 mL |
| Total coliforms | 0 per 100 mL |
| Heterotrophic plate count | No numerical guideline required |
| Emerging pathogens | No numerical guideline required |
| Protozoa | No numerical guideline required |
| Enteric viruses | No numerical guideline required |
| Turbidity | 0.3/1.0/0.1 NTU |
| **CHEMICAL AND PHYSICAL PARAMETERS** | |
| Aluminum | 0.1/0.2 (mg/L) |
| Ammonia | No numerical guideline required |
| Antimony | 0.006 (mg/L) |
| Arsenic | 0.010 (mg/L) |
| Asbestos | No numerical guideline required |
| Benzene | 0.005 (mg/L) |
| Bromate | 0.01 (mg/L) |
| Chlorate | 1.0 (mg/L) |
| Chlorine | No numerical guideline required |
| Chloride | ≤250 (mg/L) |
| Chlorite | 1.0 (mg/L) |
| Cyanobacterial toxins--microcystin-LR | 0.0015 (mg/L) |
| Fluoride | 1.5 (mg/L) |
| Formaldehyde | No numerical guideline required |
| Haloacetic Acids--Total (HAAs) | 0.080 (mg/L) |
| Hardness | No numerical guideline required |
| Iron | ≤0.03 (mg/L) |
| Lead | 0.01 (mg/L) |
| Magnesium | No numerical guideline required |
| Manganese | ≤0.05 (mg/L) |
| Mercury | 0.001 (mg/L) |
| 2-Methyl-4-chlorophenoxyacetic acid (MCPA) | 0.1 (mg/L) |
| Methyl *tertiary*-butyl ether (MTBE) | 0.015 (mg/L) |
| Nitrate | 45 (mg/L) |
| pH | 6.5-8.5 |
| Silver | No numerical guideline required |
| Sodium | ≤200 (mg/L) |
| Sulphate | ≤500 (mg/L) |
| Sulphide (as $H_2S$) | ≤0.05 (mg/L) |
| Trichloroethylene (TCE) | 0.005 (mg/L) |
| Trihalomethanes--Total (THMs) | 0.100 (mg/L) |
| Uranium | 0.02 (mg/L) |
| **RADIOLOGICAL PARAMETERS** | |
| Cesium-137 ($^{137}Cs$) | 10 Bq/L |
| Iodine-131 ($^{131}I$) | 6 Bq/L |
| Lead-210 ($^{210}Pb$) | 0.2 Bq/L |
| Radium-226 ($^{226}Ra$) | 0.5 Bq/L |
| Strontium-90 ($^{90}Sr$) | 5 Bq/L |
| Tritium ($^{3}H$) | 7,000 Bq/L |

definition was developed to distinguish between saline and non-saline water use, largely as it related to agricultural purposes and crop tolerances, e. g., irrigation). Saline groundwater depth varies from 300 metres to 500 metres. Saline waters in other Prairie Provinces (Saskatchewan, for example) can contain over 300,000 mg/L at a depth of 600 metres (Grasby and Chen, 2005).

Water suitability for specific uses also depends on a variety of other factors including hardness, pH, and naturally occurring chemical elements or compounds found within the water (e.g. sodium, sulphate, etc.). Acceptable values for each of these parameters depend on the end water use, not on the source; thus those considerations important for surface water are equally applicable to groundwater.

The chemical nature of water continually evolves as it moves through the hydrologic cycle. Chemical constituents found in any groundwater sample depend, in part, on the chemistry of the related precipitation and recharge water. Precipitation near coastlines contains higher concentrations of sodium chloride, while airborne sulphur and nitrogen compounds, downwind of industrial areas, make precipitation in those areas acidic.

One of the most important natural changes in groundwater chemistry occurs in the soil, which contains high concentrations of carbon dioxide readily dissolvable in groundwater, creating a weak acid capable, in turn, of dissolving many silicate minerals. As groundwater passes from recharge to discharge area, it may absorb and dissolve those substances it encounters, or it may deposit some of those constituents along the way. The eventual groundwater quality depends on temperature and pressure conditions, on the kinds of rock and soil formations through which the water flows, and possibly on the residence time. In general, faster flowing water dissolves less material although groundwater carries with it any soluble contaminants with which it comes in contact.

### 2.9.2 Quality standards

In general we evaluate groundwater quality in relation to its end use.

Most of us think of water quality as a matter of taste, clarity and odour, and those additional terms which determine whether water is potable or not. Different properties, however, may be important when water is used for other purposes, and most of these properties depend on the types of substances dissolved or suspended in the water. Water for many industrial purposes need not be as pure as water used for drinking, but it must not

> Arsenic (As) occurs naturally in Canada, although its concentration is generally below the recommended standard for drinking water (0.01 mg/L), and, in most cases below detection limits. Environment Canada has reported arsenic values less than 6 µg/L, and there are cases where As concentration is above the drinking standards (in Nova Scotia, for example, due to weathering of mining waste piles containing arsenopyrite). These instances are not of "natural occurrence," rather, they represent anthropogenic (human activity related) sources. This type of dissolved metal (As) contamination exists across Canada, sometimes in high concentrations (considered as point-source contaminates, because they travel via groundwater flow only tens and in some case hundreds of metres, but not kilometres, from mine waste sites; should these contaminates reach rivers or streams, however, they can easily travel hundreds of kilometres and more).

Health Canada reports of the highest concentrations of arsenic (and its inorganic compounds) within the Canadian environment occur near active and abandoned gold- and base-metal mining and/or ore processing facilities, as well as in those areas affected by the use of arsenical pesticides. Mean arsenic concentrations of up to 45 µg/L in surface waters, 100 to 5,000 mg/kg in sediments and 50 to 110 mg/kg in soils have been found near such sources in many areas throughout the country.

be corrosive and must not contain dissolved solids that might precipitate on the surfaces of machinery and equipment.

In Canada, all levels of government play a role making sure our water supplies are safe. Although provincial and territorial governments are generally in charge of protecting our water supply, the federal government also has a number of responsibilities in this area.

Groundwater quality is managed in part by the provinces and territories through

- Regulation of waste discharges to the ground
- Remediation of contaminated sites
- Regulation of drinking water sources
- Watershed planning and source protection measures
- Wellhead protection initiatives
- Application of best management practices
- Water quality standards and guidelines

The Federal Department of Health Canada works with the provincial and territorial governments to develop guidelines that set up the maximum acceptable concentrations of various substances in drinking water. The guidelines set out the basic parameters that every water system should strive to achieve in order to provide the cleanest, safest and most reliable drinking water possible.

*Guidelines for Canadian Drinking Water Quality,* published by Health Canada on behalf of the Federal-Provincial-Territorial Committee on Drinking Water (CDW), examines microbiological, chemical and radiological water contaminants, in addition to addressing concerns with physical characteristics, such as taste and odour.

These guidelines are updated regularly and published on Health Canada's website (www.healthcanada.gc.ca/waterquality). Table 2.5 provides a summary list of current numerical guidelines for microbiological, chemical and physical parameters.

According to Health Canada, quality standards specify (a) maximum acceptable concentration (MAC) of pollutants in groundwater which can be tolerated without creating a threat to human health, (b) aesthetic objectives (AO), an excess of which renders groundwater unsuitable for use as a drinking water source, and (c) operational considerations, listed as Operational Guidance Values (OG).

Trace metals (Ag, Cd, Cr, Cu, Hg, Fe, Mn, Zn) found in natural flowing groundwater rarely occur at concentrations high enough to comprise a significant percentage of the TDS; however, depending on the source and hydrochemical environment, some of the elements in this group (referred to as *heavy metals)* may have concentration above the limits specified in drinking water standards. Nevertheless, with the exception of iron, trace metals in natural groundwater almost invariably occur at concentration well below 1 mg/L.

Some elements, on the other hand, those known as *trace nonmetals* (including, for example, dissolved forms of chlorine and sulphur), occur in abundance in most natural and contaminated groundwater.

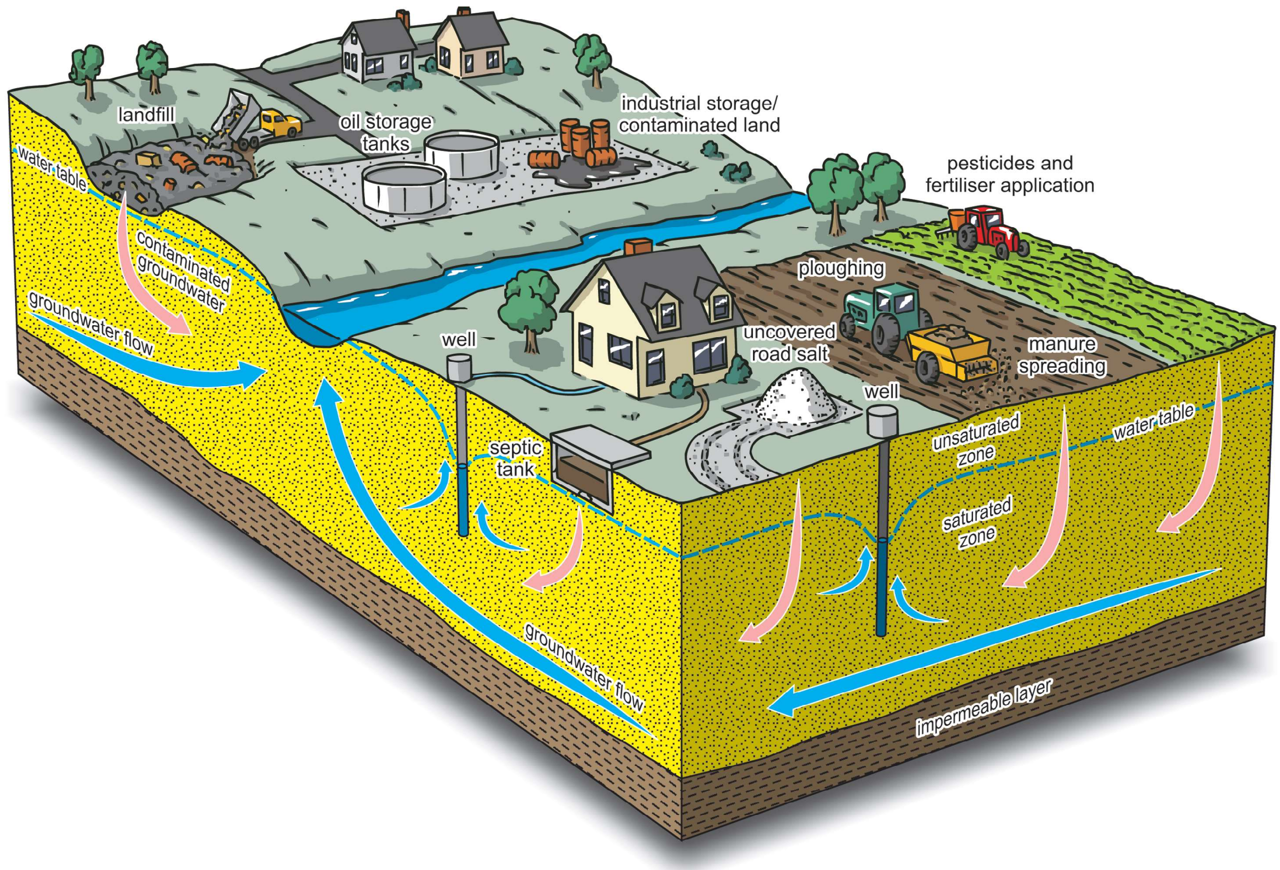



**Figure 2.19** Groundwater contaminations from waste disposal sites.

### 2.9.3 Contaminated groundwater

Any human-activity-caused addition of undesirable substances to groundwater is considered contamination, and, although many people throughout history have assumed that contaminants left on or under the ground will remain there, this premise has proved a prime example of wishful thinking. Groundwater frequently spreads the effects of dumps and spills far beyond the original contamination sites; the resultant damage is extremely difficult, very costly, and sometimes impossible, to clean up.

Groundwater contaminants originate from two source categories: point sources and distributed, or non-point, sources.

Landfills, leaking gasoline storage tanks, leaking septic tanks, and other accidental spills are point source examples. Other point sources are individually less significant, but occur in large numbers all across the country. Examples of these dangerous and widespread contamination sources are septic tanks, cesspool leaks and spills of petroleum products and of dense industrial organic liquids.

Infiltration from farm land treated with pesticides and fertilizers is one example of a non-point source; others include municipal landfills and industrial waste disposal sites. When any of these occurs in or near a sand and/or gravel aquifer, the potential for widespread contamination is enormous (see Figure 2.19).

Septic systems are designed to degrade (or break down) a certain percentage of waste sewage within the septic tank proper, while dispersing the remaining sewage for absorption and breakdown into the surrounding sand and subsoil. Contaminants known to enter groundwater from septic and cesspool systems include bacteria, viruses, nitrates, detergents, and household cleaners. These can all create serious contamination problems, and, despite the fact that septic tanks are known contaminant sources, they usually are poorly monitored and very little studied.

Contamination often renders groundwater unsuitable for use, although the overall extent of the problem across the country is unknown. There are, however, many individually documented high profile contamination in Canada, including Ville Mercier (Quebec, see Box 13-3, chapter 13), Nova Scotia's highway deicing salt problem, the industrial effluents runoff in Elmira (Ontario), various pesticide infiltrations in the Prairie provinces, and industrial contamination in Vancouver, to name a few. In most of these, the contamination was identified only after groundwater users had been exposed to potential health risks.

Canada's groundwater contamination problems are increasing because of the large number of toxic compounds used in our industry and agriculture. This usage is increasing rapidly. Scientists suspect that many rural Canadian household wells are contaminated by substances from such common sources as septic systems, underground tanks, used motor oil, road salt, fertilizer, pesticides, and livestock wastes. Scientists also predict that, within the next few decades, more contaminated aquifers will be discovered, new contaminants will be identified, and more contaminated groundwater will be discharged into wetlands, streams and lakes.

Once an aquifer is contaminated, it is often unusable for decades. The response time, as noted in Section 2.6, can be anywhere from two weeks to hundreds or even thousands of years.

The effects of groundwater contamination do not end with the loss of well-water supply. Several studies have documented the migration of contaminants from disposal or spill sites to nearby lakes and rivers as the tainted groundwater passes through the hydrologic cycle; scientific opinion remains inconclusive at this time because these processes are not yet well understood.

Pollution of surface water by groundwater in Canada is probably at least as serious as contamination of the groundwater supply. The most practical solution to this problem is the prevention of contamination in the first place, which can be implemented through the adoption of effective groundwater management practices by all levels of government, by industry and by all Canadians. Current progress in this direction is hampered by a serious shortage of groundwater experts and a general lack of public knowledge about how groundwater behaves.

Some provinces have begun adopting a multi-barrier approach to safe drinking water; and understanding and meeting the guidelines described above is a very important component of this approach.

The most effective way to ensure our drinking water supply is clean, safe and reliable is to take a preventive risk management approach, herein we understand each water supply from its natural beginning to its final destination, the consumer. This approach presupposes knowledge of the water's characteristics, potential methods of contamination, and the type of treatment the water may require to become suitable for public use. Answers to all of these issues can be determined, and corrective procedures implemented through the collection and study of the drinking water supply and its three components: source water, the drinking water treatment system, and the water distribution system (which carries treated water to homes— the treated water inside every residence is an extension of this system—businesses, schools, and others).

As drinking water travels on its journey to the users, it can become contaminated in many ways. Thus, the multi-barrier approach to manage drinking water supplies is a preventive risk management approach that identifies all known and potential hazards and makes sure barriers are in place to reduce or eliminate the risk of contamination.

# CANADA'S GROUNDWATER RESOURCES

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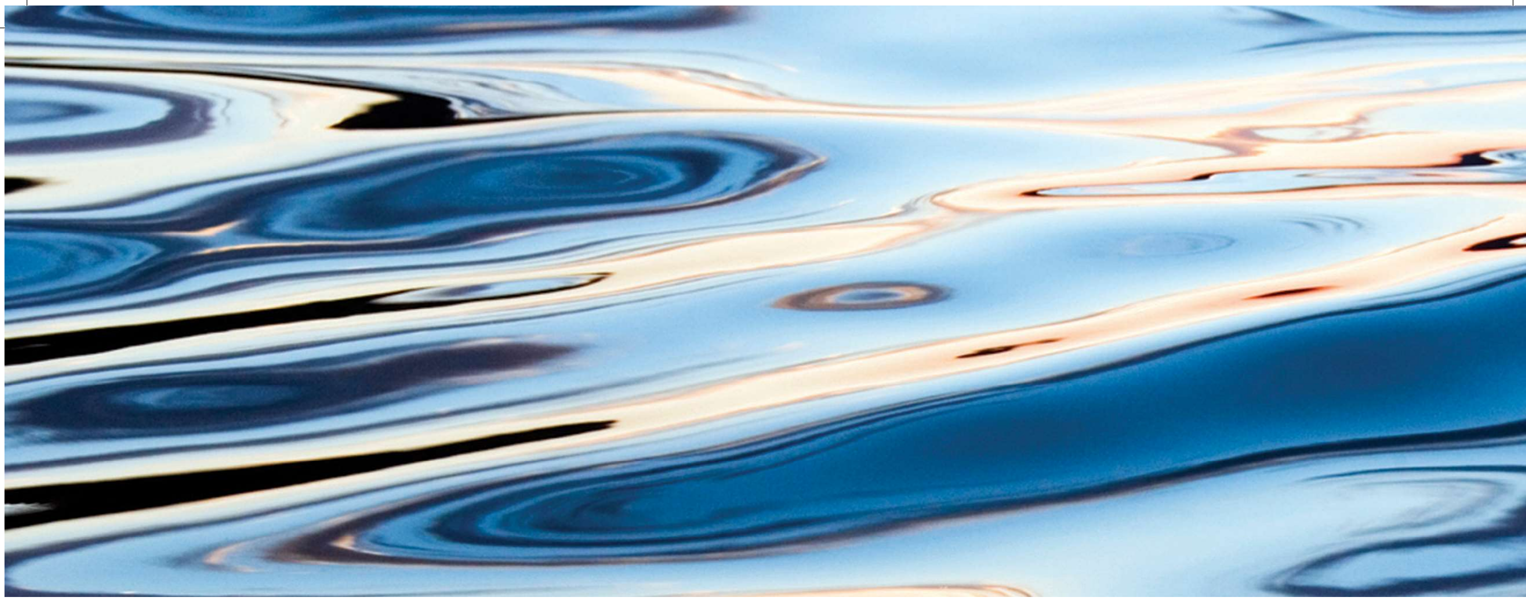

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