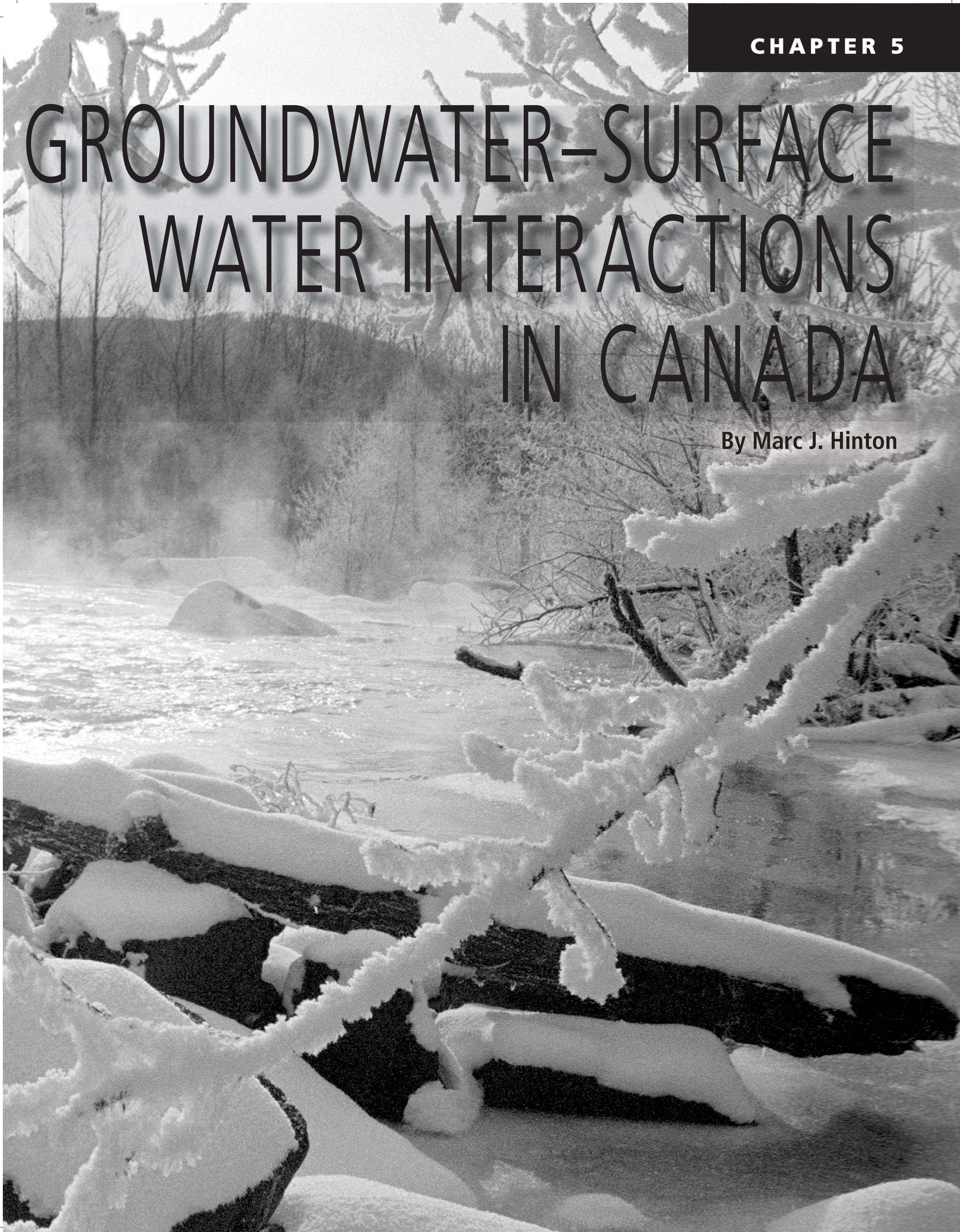
GROUNDWATER–SURFACE WATER INTERACTIONS IN CANADA

By Marc J. Hinton



5.1 INTRODUCTION

The dominant processes for returning water back to the ocean from land surfaces are: surface water flow, groundwater flow, and transport of atmospheric vapour from evaporation or transpiration (Figure 5.1). Storage and exchange of water among these surface, subsurface and atmospheric reservoirs is spatially and temporally variable and, as a result, is important for aquatic and terrestrial ecosystems, management and protection of water resources and, ultimately, land use management and planning.

This chapter focuses on the interactions of two of these reservoirs: groundwater and surface water, and on summarizing key concepts of groundwater-surface water (GW-SW) interactions. Canadian research and data about GW-SW interactions are considered, in addition to examples of GW-SW interactions in specific Canadian settings. The chapter concludes with future challenges for scientists and decision makers.

5.2 KEY CONCEPTS OF GROUNDWATER–SURFACE WATER INTERACTIONS

To make informed decisions that protect water and aquatic resources, we must understand how groundwater and surface water interact. This section summarizes several key concepts by drawing upon recent research, overviews and reviews of several aspects of GW-SW interactions (e.g., Winter, 1995; Brunke and Gonser, 1997; Boulton et al., 1998; Winter et al., 1998; Winter, 1999; Jones

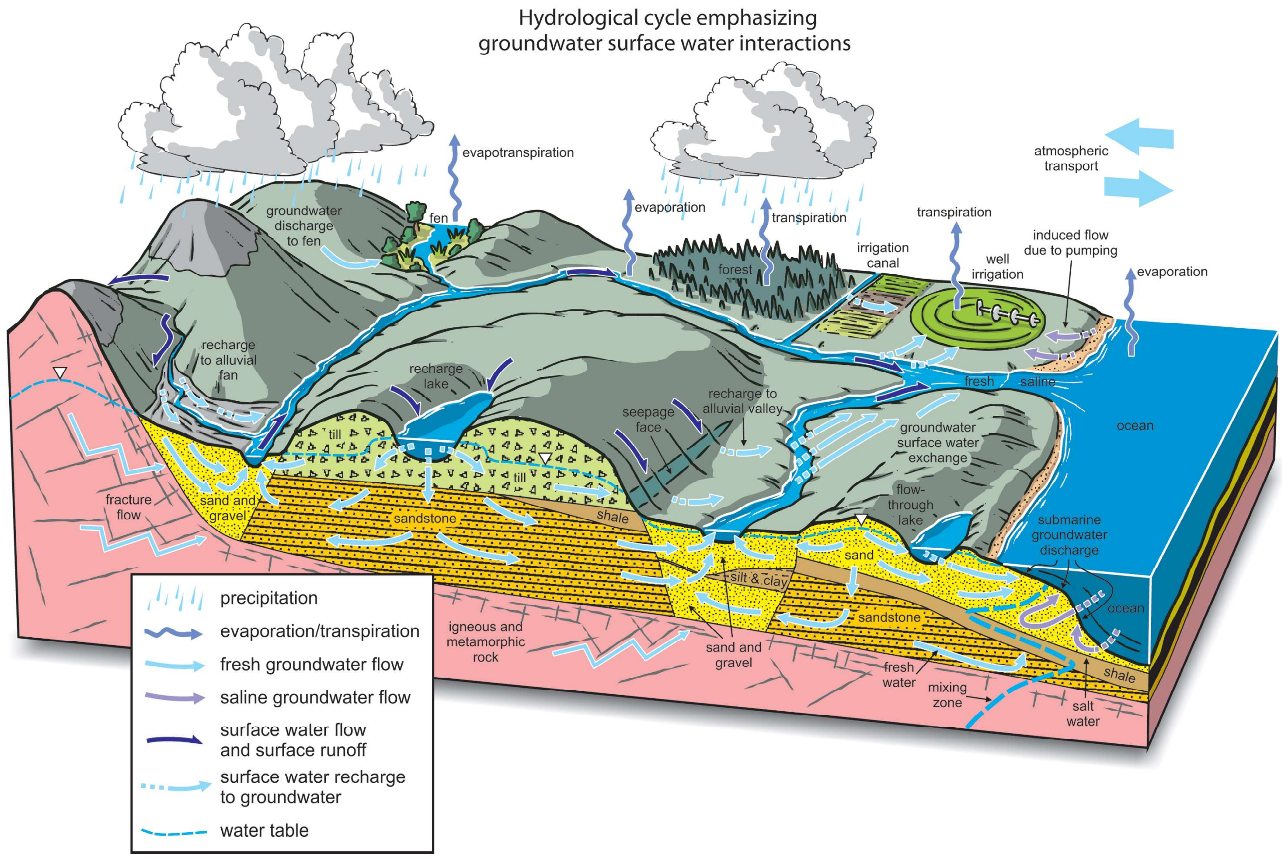


Figure 5.1 Hydrological cycle emphasizing groundwater-surface water interactions.

and Mulholland, 2000; Hayashi and Rosenberry, 2002; Sophocleous, 2002; Smith, 2005; Kalbus et al., 2006).

5.2.1 GW-SW interactions, an element of the hydrological cycle

Groundwater and surface water have markedly different flowpaths and residence times through the landscape (Figure 5.1) and, consequently, different physical and chemical characteristics that affect their ecological roles. GW-SW interactions generally refer to the processes associated with the transfer or mixing of water between groundwater and surface water reservoirs. Traditionally, surface water and groundwater have been investigated separately with subsequent consideration of GW-SW interactions only at the interfaces where they meet. However, an important conclusion of this chapter is that understanding the issues of GW-SW interactions should also include greater consideration of the processes that influence groundwater and surface water throughout the watershed. Furthermore, groundwater and streams should be considered as integrated components of a hydrological continuum (Brunke and Gonser, 1997).

5.2.2 Importance of GW-SW interactions

Groundwater and surface water interactions are often most recognizable where large localized flows exist between these two reservoirs, for example, at springs where water flows out of the ground to form headwaters of streams or, less commonly, where streams disappear into the ground in karstic terrain. GW-SW interactions, however, are far more

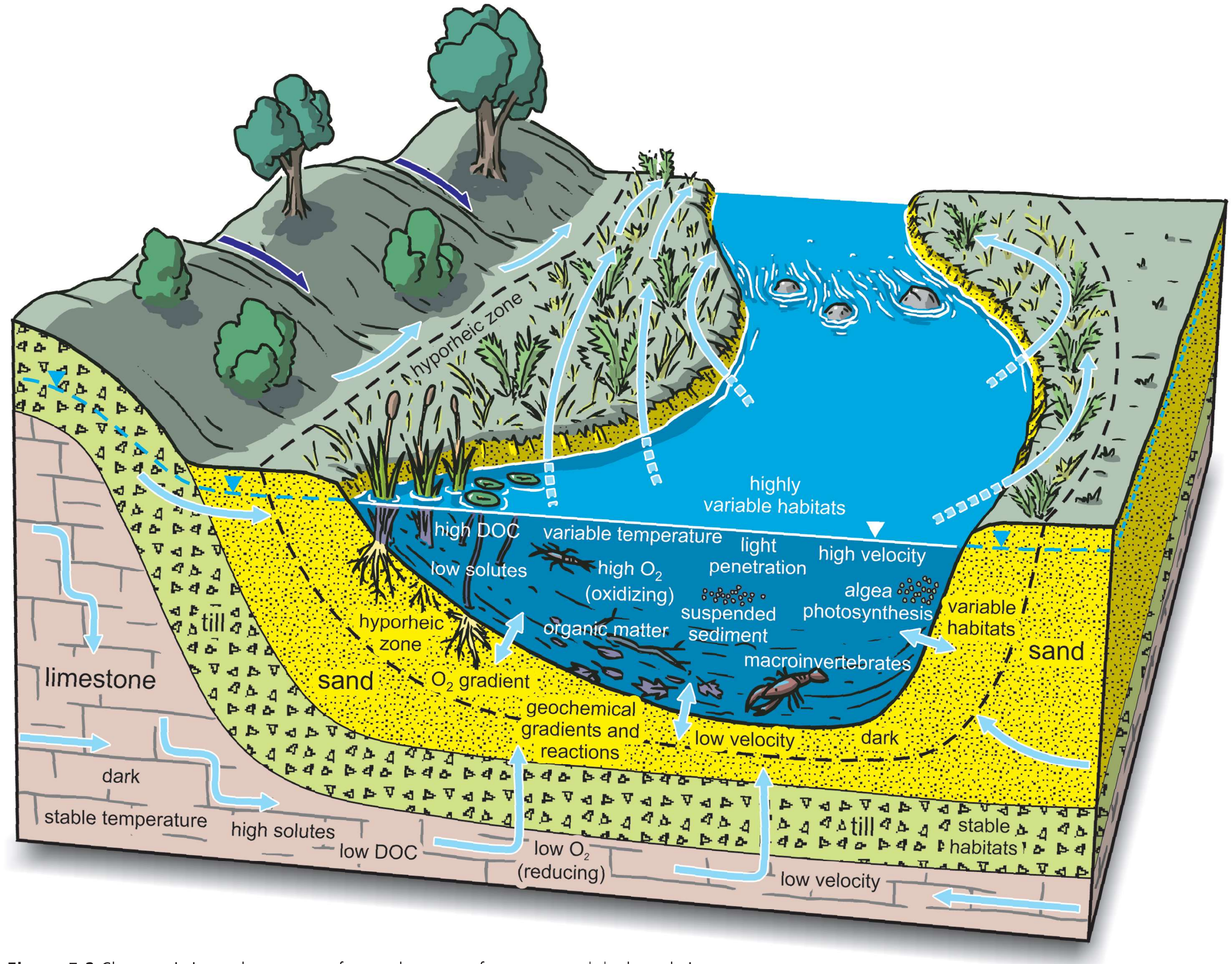


Figure 5.2 Characteristics and processes of groundwater, surface water and the hyporheic zone.

widespread, particularly in the form of groundwater discharge to streams, rivers, lakes, wetlands, reservoirs, estuaries and oceans. Groundwater is often the main source of dry weather flow in streams and rivers. Conversely, in some areas, surface water recharges aquifers to form a significant proportion of the groundwater resource. The fact that many surface water and groundwater systems are hydraulically interconnected has such obvious implications for the management of water resources that some advocated treatment of groundwater and surface water as a single resource (Winter et al., 1998).

Another consequence of hydraulic GW-SW interactions is the effect on aquatic and riparian habitats and their ecosystems. Chemical and physical characteristics of groundwater and surface water often differ greatly due to differences in the nature, rates and duration of their processes (Table 5.1). Groundwater usually displays higher solute content, lower dissolved oxygen, and more stable temperature, whereas surface water is generally characterized by lower solute content, high dissolved oxygen, high detrital organic matter and more variable temperature. Large physiochemical gradients between groundwater and surface water result in an ecotone (boundary between ecosystems) called the hyporheic zone which is a

TABLE 5.1 GENERALIZED COMPARISON OF PHYSICAL, CHEMICAL AND ECOLOGICAL CHARACTERISTICS AND PROCESSES BETWEEN SURFACE WATER (PRIMARILY STREAMS AND RIVERS) AND GROUNDWATER (ECOLOGICAL CONCEPTS FROM GIBERT ET AL., 1994)

PROCESSES		CHARACTERISTICS	
Groundwater	Surface water	Groundwater	Surface water
greater depth of flow	water flow at surface	high solutes	low solutes
low flow velocity	high flow velocity, variable	particle movement limited to colloids	variable sediment load, erosion, sedimentation
long residence time	short residence time	wide range of ages	"young" water
extensive contact with mineral surfaces	greater contact with organic matter and organisms	low organic matter	high organic matter
contact with soil gases	contact with the atmosphere	low dissolved oxygen, reducing conditions common	high dissolved oxygen, oxidizing conditions common
no exposure to solar radiation	exposure to solar radiation	stable temperature	variable temperature
heterotrophy(energy from carbohydrates and other organic materials)	photosynthesis, autotrophy (synthesize organic substances from inorganic compounds)	short and simple food webs	complex food webs
low productivity	high productivity	low richness, diversity and density of organisms in ecological communities	high richness, diversity and density of organisms in ecological communities

transition between groundwater and surface water systems (Figure 5.2, see Gooseff (2010) for various definitions of hyporheic zone). The hyporheic zone performs many important functions, such as water transfer, storage and transformation of nutrients and contaminants, buffering of acidity and redox (reduction-oxidation) gradients, metabolism of organic matter, and habitat for distinct biota (Boulton et al., 1998).

GW-SW interactions can influence water quantity and quality, aquatic and riparian ecosystems and, by extension, societal activities that depend on these resources and their functions. The reverse situation, however, is more common when societal activities influence one or more of these resources and have an effect on the state or function of the linked systems. For example, changes in land use and land management practices (e.g., land development, application of fertilizers) can influence both diffuse and focused groundwater recharge (see Chapter 4), water use, water quality, water fluxes and flowpaths, sedimentation and erosion, sediment clogging, and terrestrial and aquatic ecosystems. Minimizing potential impacts of land use changes requires a holistic understanding of the interactions among these systems in which GW-SW interactions are sometimes of particular importance. Furthermore, consideration of the interactions between groundwater and surface water systems should extend beyond their interface to the entire watershed. Consideration of the interchange between groundwater, surface

water and aquatic and riparian ecosystems extends beyond scientists, water managers and conservation officers to encompass policy makers, planners and the general public whose activities directly and indirectly affect these resources.

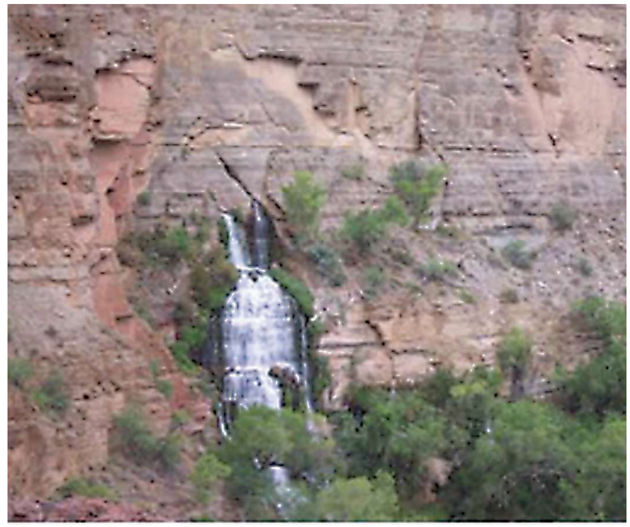
5.2.3 Hydraulic connection

GW-SW interactions are only possible because of hydraulic connections between the two systems. The degree of interaction depends on the amount of water flowing between the systems. As in Darcy's Law (see Chapter 2), volumetric flow is directly proportional to three factors: hydraulic conductivity, hydraulic gradient, and area perpendicular to flow. Hydraulic conductivity is generally the most important factor determining the intensity (or fluxes) of GW-SW interactions. Low hydraulic conductivity can limit the groundwater flow to values much less than available climatically (see Chapter 4). Since most groundwater flows along the path of least resistance, intense GW-SW interactions are often associated with high hydraulic conductivity. Due to the considerable heterogeneity of most sediments and bedrock, large spatial variability in GW-SW interactions is common at many scales. Therefore, it is necessary to consider the hydraulic conductivity of both the groundwater system and the GW-SW interface.

Surface water bodies often deposit sediment that originates from primary productivity or erosion; their deposits differ from those of the groundwater system in hydraulic conductivity, geochemical characteristics and ecological function. Fine-grained lake sediments, for example, can form a low conductivity layer above a high conductivity aquifer that would limit fluxes between the aquifer and the lake, whereas coarser sediments in a nearby streambed would allow groundwater and surface water to exchange more freely. While the hydraulic conductivity of a groundwater system influences the magnitude and patterns of flow in the entire flow system, the hydraulic conductivity of the interface often influences the magnitudes and smaller-scale patterns of flow near surface water bodies (Conant Jr., 2004). Several physical, chemical, biological and microbiological processes can result in the clogging of the surface interface sediments, thereby reducing hydrological exchanges (Brunke and Gonser, 1997; Brunke, 1999; Rehg et al., 2005). In contrast, bioturbation by benthic invertebrates can reduce clogging of sediment and increase GW-SW exchange (Nogaro et al., 2006).

The gradient of hydraulic potentials is the driving force of water flow and direction. Temporal changes in hydraulic gradients provide insight on the fluctuations in GW-SW interactions over time. Spatial patterns of groundwater potentials and hydraulic gradients at a watershed scale are usually fairly constant under natural conditions; therefore, the general patterns and magnitudes of groundwater flow are often stable. The dynamic nature of GW-SW interactions is most apparent near surface waters and is frequently the result of changes in surface water elevations (e.g., due to precipitation, runoff or damming) or fluctuations in shallow water tables (usually adjacent to surface water) in response to precipitation. An exception to this generalization is the large change in hydraulic gradients that can result from groundwater pumping.

The area of the interface between groundwater and surface water systems can also be important, particularly for groundwater systems with low



hydraulic conductivity; if the area is large, substantial flows (volume/time) can occur even when fluxes (volume/area/time) are small. In geological units with high conductivity, large volumes of flow may occur within small areas (e.g., large springs).

Important exceptions are karst environments where Darcy's Law does not necessarily apply as high flows between surface water and groundwater may occur in conduits or fractures even under low hydraulic gradients (Ford and Williams, 2007; Worthington and Ford, 2009).

5.2.4 Types of GW-SW interactions

There are three basic types of GW-SW interactions based on the direction of flow at the interface: groundwater discharge, groundwater recharge, and GW-SW exchange. Groundwater discharges to surface water when groundwater levels are higher than adjacent surface water levels. Surface water recharges groundwater when surface water levels are higher than groundwater levels. GW-SW exchange occurs where surface water flows into the adjacent groundwater and then back into the surface water, usually when the direction of groundwater flow is sub-parallel to surface water bodies (Figure 5.1).

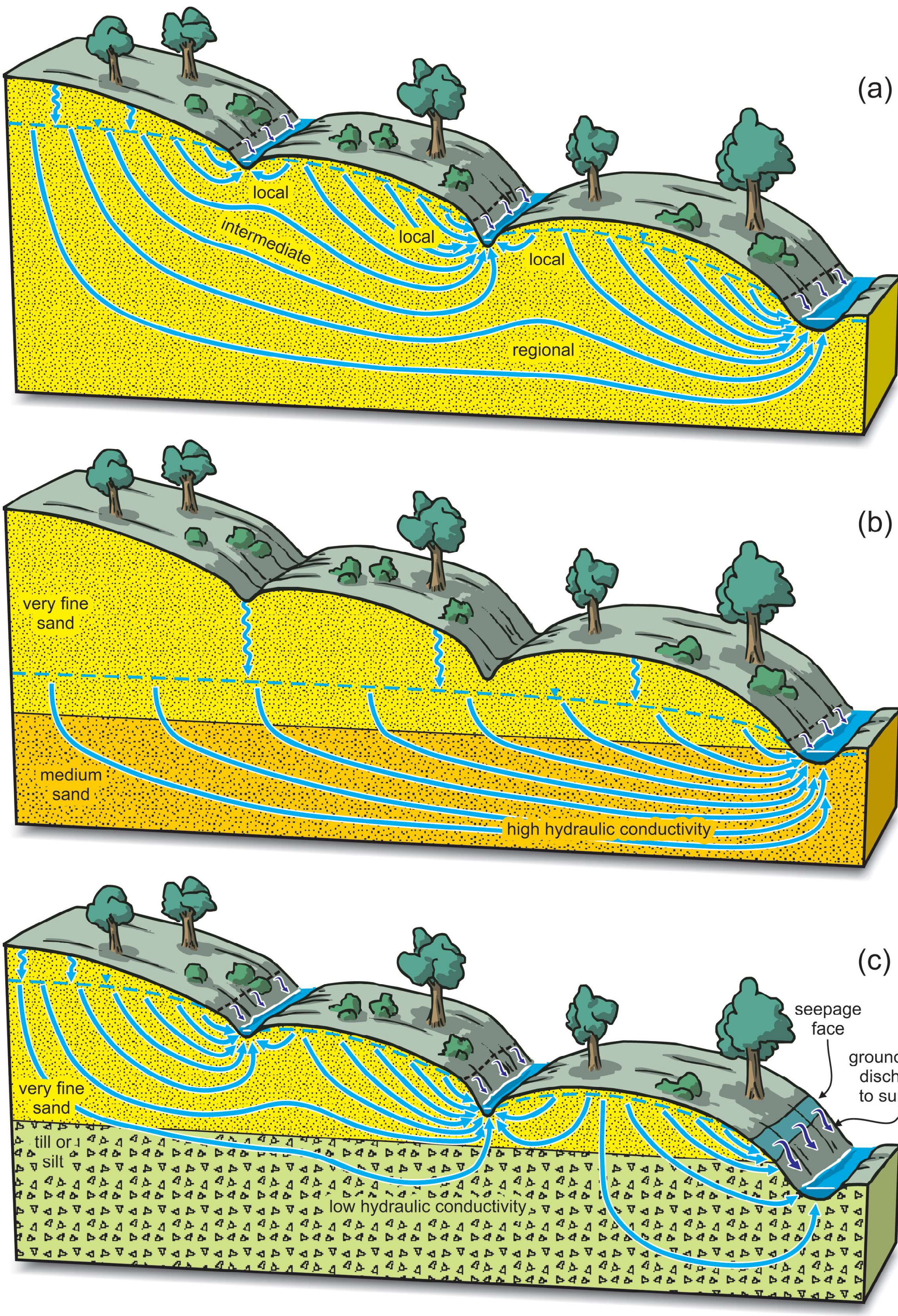


Figure 5.3 Groundwater flow systems. **(a)**in a homogeneous aquifer, **(b)** with a high hydraulic conductivity underdrain, **(c)** with a low hydraulic conductivity barrier (note same surface topography but different flow patterns).

5.2.4.1 Groundwater discharge to surface water

Because recharging groundwater ultimately returns to the ground surface within the overall flow system, groundwater discharge is a widespread form of GW-SW interactions. Although groundwater discharge is most commonly recognized as groundwater springs (see Springer and Stevens, 2009 for descriptions, sketches and photographs of spring types), it occurs more commonly as flow directly into surface water bodies.

Since groundwater flows from high potential (high water elevation) to low potential, groundwater systems produce discharge at lower elevations than at their recharge sites. One important challenge is to quantify the distribution of groundwater discharge. As discussed in Chapter 2, groundwater flow systems develop in a nested, hierarchical structure at local, intermediate and regional scales (Figures 2.17, 5.3a). The creation of these flow and discharge patterns is largely a function of the flow systems' capacity to transmit water along different flowpaths under the existing hydraulic gradients. Figure 5.3 illustrates how the subsurface geology can influence the distribution and fluxes of groundwater discharge along three flow systems with identical surface topography. In panel (a), the uppermost stream has a small recharge area contributing to its flow, whereas the middle and lower streams have much larger contributing areas which include discharge from intermediate and regional flow systems. Panel (b) shows that a more permeable underlying aquifer connected to a surface water body at low elevation can function as an effective drain for the entire flow system, resulting in dry conditions in the upper two valleys with all flow directed to the lowermost stream. In contrast, the underlying aquitard in panel (c) becomes a hydraulic barrier that limits the development of deeper intermediate and regional flow systems and results in the predominance of shallow local flow systems. The upslope recharge area contributing to the upper stream is much larger than in panel (a) and a larger seepage face develops just above the aquitard contact along the lower stream valley.

5.2.4.2 Surface water recharge to groundwater

Although less common, surface water recharge to groundwater can be a significant source of groundwater recharge, particularly where direct recharge is low or where there is a highly permeable hydraulic connection with surface water.

The required condition for surface water recharge to groundwater is a surface water level higher than underlying groundwater levels. If the ground is fully saturated beneath the surface water body, the system is considered to be fully connected and the rate of recharge will increase proportionally with the depth of the groundwater level (Brunner et al., 2009a; Brunner et al., 2009b). When the water table has dropped sufficiently to allow the development of an unsaturated zone between the surface water body and the water table (a condition that requires a "clogging" layer of lower hydraulic conductivity sediment below the surface water body), the system is considered to be disconnected and the surface water body will infiltrate the ground at the maximum rate irrespective of additional changes in groundwater levels (Brunner et al., 2009a; Brunner et al., 2009b). At intermediate groundwater levels, the system is considered to be transitional and the rate of recharge increases slowly towards its maximum value as groundwater levels decline. Therefore, knowledge about the state of

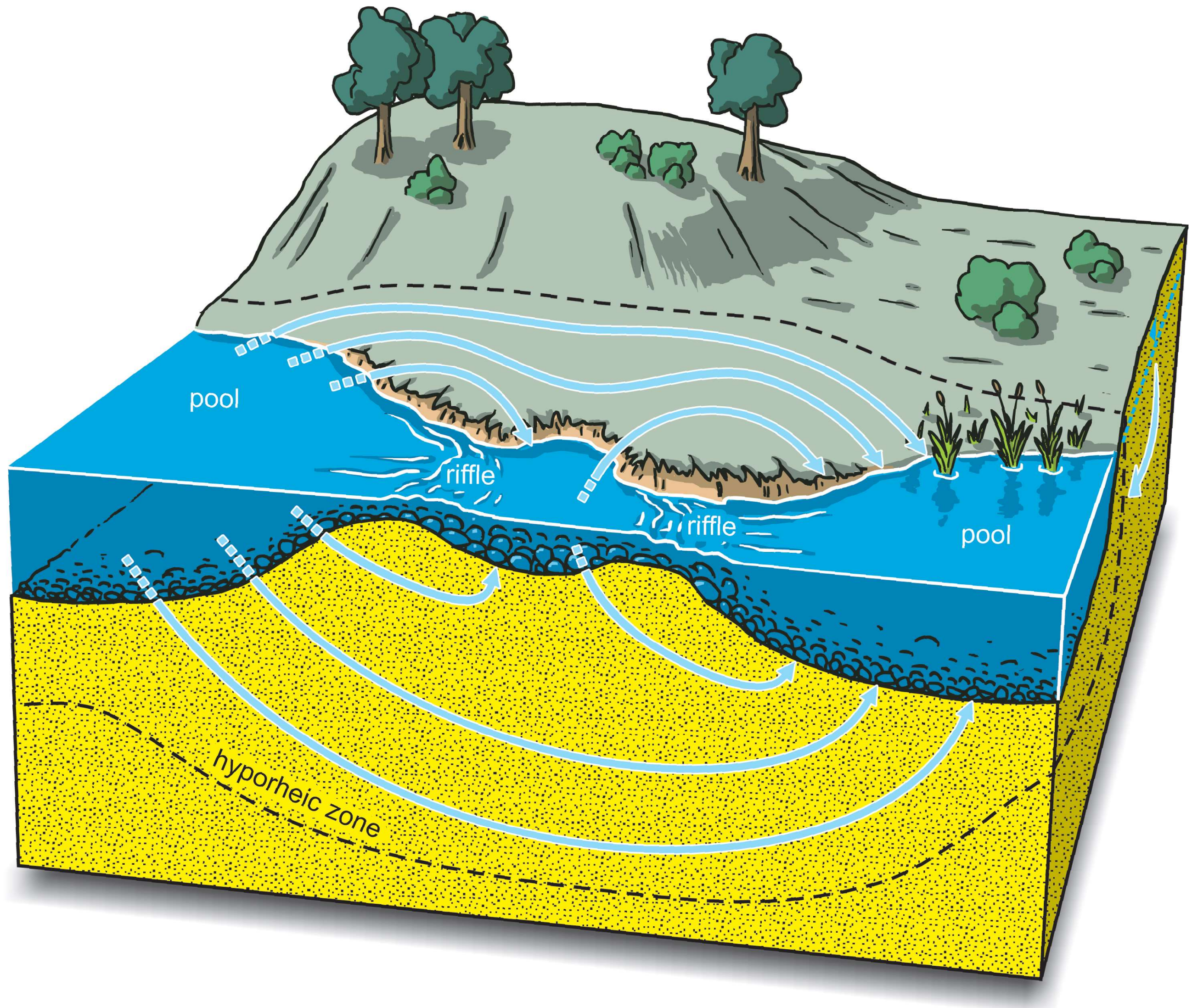


Figure 5.4 GW-SW interactions along a pool and riffle reach of a stream. The block diagram shows a longitudinal section along a pool-riffle sequence; the top of the block illustrates lateral GW-SW exchanges through the stream bank whereas the front of the block demonstrates the vertical GW-SW exchanges beneath the stream bed.

connection between a surface water body and the underlying groundwater can be useful to assess the potential effects of changes in groundwater levels (for example, due to pumping) on surface water fluxes and recharge.

Surface water recharge to groundwater often occurs in topographic depressions fed by surface runoff over low-permeability or frozen soils (Hayashi et al., 1998; Hayashi et al., 2003). These depressions serve as temporary surface water storage areas that slowly recharge the groundwater beneath and surrounding them. This depression-focussed recharge may be a significant source of recharge, particularly in arid or semi-arid regions (Box 4-2) where diffuse recharge may be small. It can occur in small (10-1,000 m^2) or larger depressions such as prairie potholes, kettles lakes, ponds, and wetlands which may be either temporarily or permanently flooded.

Settings where surface runoff, streams or rivers cross into unconfined aquifers with lower groundwater levels can be among the highest intensity

GW-SW interactions, particularly in aquifers with high permeability. These interactions can occur at a variety of scales. For example, at the hillslope scale, surface runoff along a steep bedrock outcrop can infiltrate the colluvium at the base of the slope and recharge its water table. At the watershed scale, upland streams may flow onto permeable alluvial fans, terraces or coarse fluvial deposits and transmit much of the flow through the subsurface (Box 4-1, Kontis et al., 2004). Because these interactions rely on variable surface water supply, recharge will also vary significantly with time.

Surface water may also recharge groundwater as a result of human activities. These may be intentional through structures designed to increase groundwater resources or unintentional through leakage of reservoirs, unlined canals or irrigation (Bouwer, 2002, Figure 5.1). Such recharge can result in significant groundwater increase but may require treatment to minimize impairment of native groundwater quality (National Research Council (U.S.). Committee on Ground Water Recharge, 1994).

5.2.4.3 GW-SW exchange

Surface water and groundwater systems are hydraulically connected so water naturally flows back and forth between these systems in response to spatial and temporal changes in surface water and groundwater levels. In these exchanges, surface water enters the subsurface, flows as groundwater along or beneath the stream or river, mixing with existing groundwater before discharging back to the surface water at a lower elevation (Figure 5.4). These exchanges can occur across a wide range of scales. When there is a small obstruction along a streambed, currents can produce small scale pressure gradients that induce flow through sediment (Thibodeaux and Boyle, 1987). Small scale GW-SW exchange, commonly referred to as hyporheic exchange (Harvey and Wagner, 2000), can result from streambed topography, sediment heterogeneity, and is often associated with stream features, such as riffle-pool sequences or debris dams (Harvey and Bencala, 1993; Kasahara and Hill, 2006; Hester and Doyle, 2008; Käser et al., 2009). The physical break in slope at the transition between the pool-riffle boundary increases hydraulic gradients and permits more subsurface flow which, in turn, causes increased flow of surface water to the subsurface (Figure 5.4). This water flows roughly parallel to the stream along the riffle and may mix with surrounding groundwater to varying degrees. At the riffle-pool boundary, horizontal hydraulic gradients decrease to the extent that the subsurface can no longer accommodate the flow and the water is hydraulically forced to discharge back to the stream (Figure 5.4).

GW-SW exchange can also occur at a larger-scale such as surface water flowing through alluvial aquifers (Figure 5.1, Larkin and Sharp Jr, 1992; Woessner, 2000), or bank storage in response to fluctuating surface water levels (Jung et al., 2004). An important distinction between small- and large-scale GW-SW exchanges is that the large-scale GW-SW exchange may extend beyond the influence of some biological, microbiological and geochemical processes associated with the hyporheic zone. Therefore, it is sometimes important to consider the temporal and spatial scales of GW-SW exchange in the conceptualization of GW-SW interactions (Gooseff, 2010). It is also possible, in some instances, that surface water which recharges groundwater does not discharge back to surface waters but exits the groundwater flow system through evaporation or

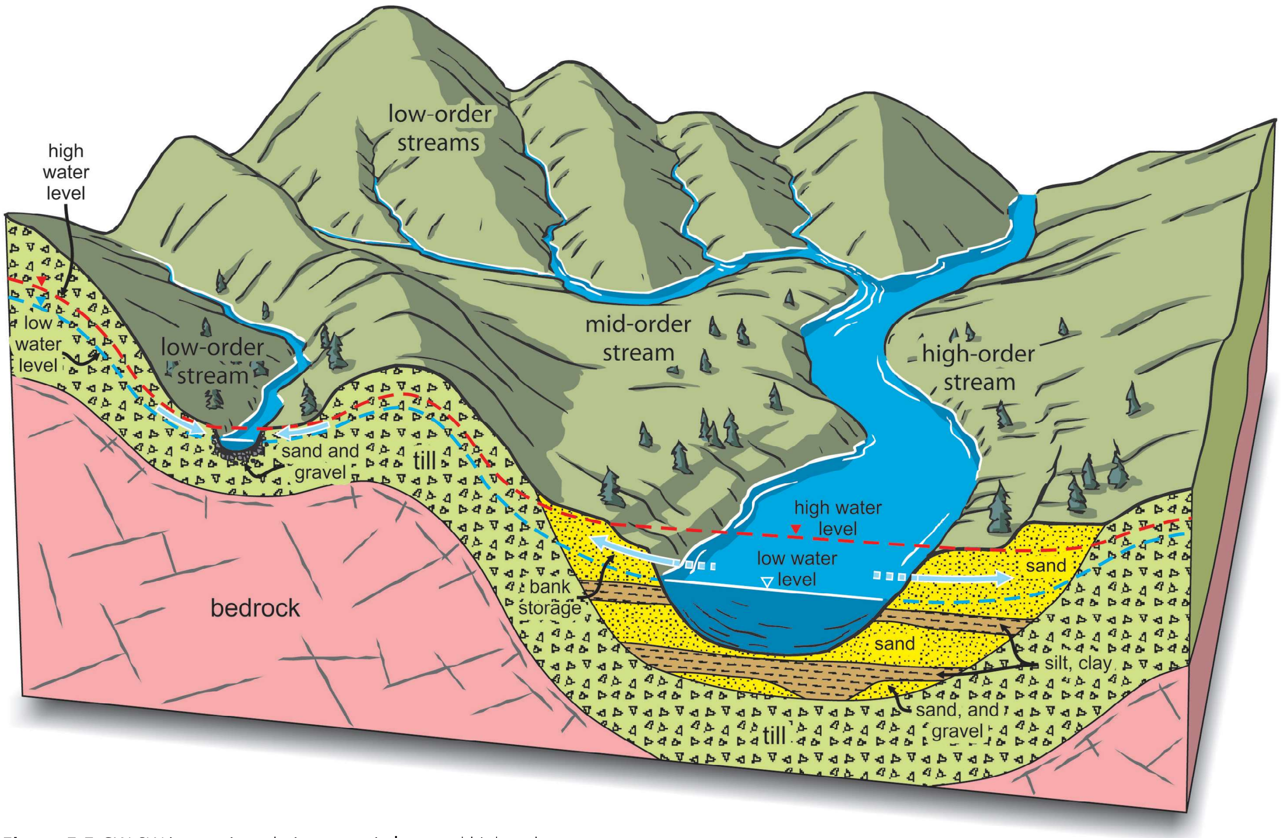


Figure 5.5 GW-SW interactions during storm in low- and high-order streams.

pumping from a well (Gooseff, 2010).

The importance of GW-SW exchange to larger-scale watershed processes may not be apparent since it generally involves a small portion of the watershed area adjacent to surface waters. However, GW-SW exchange provides a mechanism to transport organic matter, nutrients and oxygen from the stream into the hyporheic zone and enhances physiochemical and ecological processes such as nitrogen transformations and organic matter retention and metabolism that perform important watershed functions (Brunke and Gonser, 1997; Jones and Mulholland, 2000). In this manner, microscopic processes that accompany these hydrological exchanges can play key roles in macroscopic behaviour at the watershed or landscape scales (Pringle and Triska, 2000).

5.2.5 Interactions with different SW systems

The nature and significance of GW-SW interactions vary with the types of surface water bodies such as streams, rivers, ponds, lakes, reservoirs, wetlands, estuaries and oceans. Such differences are related to variability in surface water levels, groundwater flow, water chemistry, mixing and ecological dependence on groundwater.

5.2.5.1 Streams and rivers

Groundwater discharge to the surface is responsible for the existence and permanence of many streams, particularly in regions with humid climates and permeable, porous substrates. However, the role of groundwater is not limited to sustaining stream flow during periods of dry weather. Numerous studies have shown the dynamic nature of GW-SW interactions during periods of storm runoff wherein shallow groundwater near the stream can make significant (and often dominant) contributions to headwater and medium sized streams (see references in Gibson et al., 2005). Rapid rises of groundwater levels adjacent to surface waters can result in rapid displacement of soil water and groundwater into adjacent surface water bodies. Such contributions have significant implications for the biogeochemical characteristics of streams. For example, the input of groundwater helps to neutralize acidic deposition in surface water and reduce its ecological impacts (Bottomley et al., 1984).

Groundwater interactions with streams and rivers are likely the most widespread and significant. They usually have the largest GW-SW fluxes among all surface water bodies due to the higher permeability of many streambeds. They have also been the primary focus of most studies on hyporheic processes (cf. Brunke and Gonser, 1997; Jones and Mulholland, 2000). Important biogeochemical processes occur in the riparian zones of stream and rivers. A notable example is the removal of nitrates derived from fertilizers or waste in riparian areas where biological processes such as denitrification and plant uptake reduce the nitrate loads to streams (Hill, 1996; Cey et al., 1999; Devito et al., 2000; Maître et al., 2003).

An important concept that is discussed more frequently in the ecological rather than hydrological scientific literature is the significance of stream order on GW-SW interactions. The river continuum concept (Vannote et al., 1980), the flood pulse concept (Junk et al., 1989) and the riverine ecosystem synthesis (Thorp et al., 2006) are a few of the models that discuss how the geomorphic, hydrological, biogeochemical and ecological roles of streams and rivers change significantly from low-order headwater streams to high-order river systems. Low-order streams usually comprise much of the watershed area and are often characterized by large cumulative inputs of nutrients, organic matter and water from terrestrial areas, higher relief, and small, discontinuous coarse fluvial deposits. High-order streams are often characterized by lower terrestrial inputs of nutrients and water, higher in-stream photosynthetic production, lower relief, and broader, thicker, finer and more continuous fluvial sediments (Figure 5.5).

Although the differences in hydrological and geomorphic processes adjacent to low- and high-order streams are recognized, there has been little attempt to synthesize the resulting variable nature of GW-SW interactions across scales. These differences are particularly evident during storms. For example, the rapid displacement of groundwater into streams during storms occurs predominantly in low-order streams (Figure 5.5) where GW-SW exchanges may remain relatively close to the stream channels. In mid- and high-order streams, rapid displacement of groundwater during storms is progressively less important. However, GW-SW exchange becomes more significant when wider and flatter valleys coupled with greater increases in surface water levels cause surface water to flow into the stream bank, known as bank storage (Figure 5.5). Although the patterns of GW-SW interactions with stream order may differ from watershed to watershed, large variability in GW-SW interactions (and their hydrological and ecological significance) is expected as water flows from headwater streams to high-order outlets. Smith and Lerner (2008) demonstrated the impact and significance of variability in geomorphic and geochemical processes occurring along a river where thicker, finer, and more organic-rich riverbed sediments of lowland

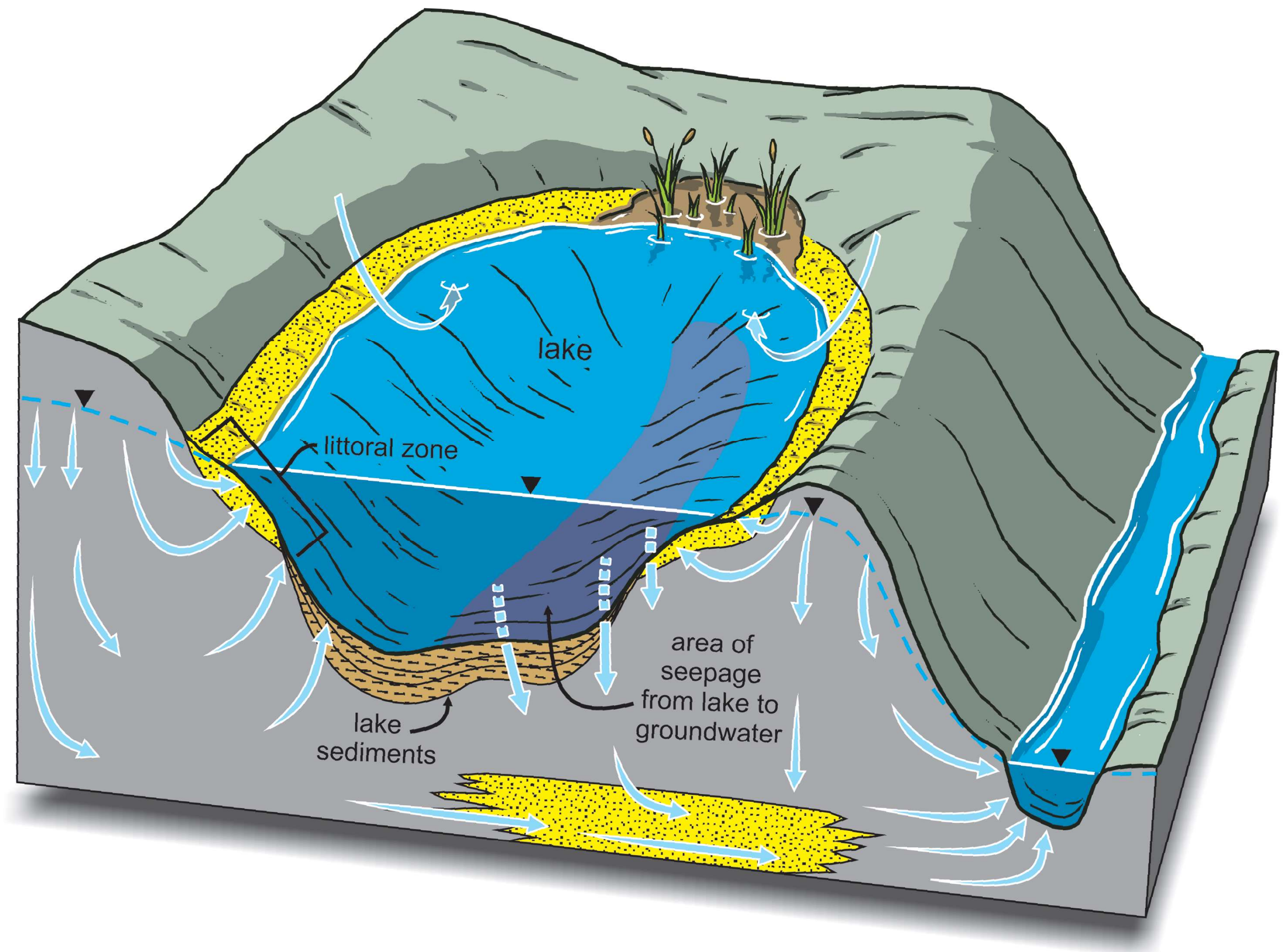


Figure 5.6 GW-SW interactions around a lake. Groundwater discharge within lakes is usually greatest near the lake perimeter and decreases rapidly with distance from the shoreline (McBride and Pfannkuch, 1975). This pattern is observed because the lake water surface is flat and the hydraulic gradient between the lake and underlying groundwater decreases with distance from shore. The distribution of groundwater discharge to lakes can also be influenced by the hydraulic conductivities of the bottom sediments in the lake basin. Lacustrine sedimentation is often composed of low-permeability, fine, inorganic and organic materials (Wetzel, 2001) that act as a physical barrier to reduce GW-SW interactions.

rivers significantly increased pollutant retardation potential as compared to upland river sediments and underlying aquitards.

5.2.5.2 Lakes and ponds

Interactions between lakes and groundwater include groundwater discharge into lakes, lake seepage into groundwater, and flow-through lakes that both receive discharge and supply groundwater systems in different areas within the same basin (Winter, 1999) (Figures 5.1 and 5.6). Groundwater inputs to lakes or ponds can occur directly through the shore or lake sediments, or indirectly as groundwater discharge to streams and/or rivers that subsequently flow into lakes. Direct groundwater discharge into lakes occurs where the adjacent water table is higher than the lake water level. Conversely, lake seepage to groundwater occurs at shorelines where the water table is lower than the lake surface (Figure 5.1). In some lake settings underlain by more permeable units, Winter (1976; 1978; 1999) demonstrated that groundwater can discharge to a lake throughout the entire shoreline, yet lake seepage to groundwater may occur

through the lake bottom (Figure 5.6).

Time scales of influent and effluent groundwater fluxes within a lake can change rapidly, within minutes, and seasonally (Sebestyen and Schneider, 2001; Rosenberry and Morin, 2004). This variability in extent and intensity of groundwater flow occurs in response to fluctuating water levels along the lake edge caused by recharge of shallow water tables or evapotranspiration from shoreline vegetation. Longer-term changes in GW-SW interactions can also result from regional changes in groundwater or lake water levels caused by climatic influences, such as drought or prolonged wet periods (Winter, 1999).

The hydrological significance of GW-SW interactions for lakes and ponds is variable due, in part, to the large range of climatic, topographic, geologic and hydrogeological settings of lake basins. In general, the intensity of groundwater-lake interactions is expected to be less than groundwater-stream interactions because of the lower permeability of lake bottom sediments and the more gentle topographic and hydraulic gradients adjacent to lakes. In most lakes, streamflow dominates water inflows and outflows; precipitation and/or evaporation may also produce significant fluxes for many lake water balances. Although direct groundwater fluxes into or out of lakes are minor in most instances, they can be significant in some settings such as prairie potholes or depressions (Box 4-2, Hayashi et al., 1998; Hayashi et al., 2003), alpine lakes (Hood et al., 2006; Roy and Hayashi, 2007; Roy and Hayashi, 2008), dunes (Winter, 1986), karst seepage lakes (Lee and Swancar, 1997) and flow-through lakes (LaBaugh et al., 1997; Smerdon et al., 2005a). In these cases, groundwater fluxes are hydrologically significant either because lake sediments are permeable and/or stream inflows and outflows are minor or ephemeral.

Even where direct groundwater flux is a small component of a lake or pond hydrological budget, GW-SW interactions may still be significant to the hydrology, ecology or geochemistry of lakes, ponds or the surrounding groundwater systems. In the case of the lower peninsula of Michigan, only approximately 5% of the groundwater discharge occurs directly to the Great Lakes whereas the remaining 95% discharges to streams before reaching the lakes (Hoaglund III et al., 2002). The indirect component of groundwater discharge to the Great Lakes via streams accounts for approximately 22%-42% of the water inputs (Holtschlag and Nicholas, 1998).

The positions of lakes with respect to local and regional groundwater flowpaths can influence lake chemistry because of differences in groundwater chemistry as it evolves along different flowpaths before discharging to surface waters (Birks and Remenda, 1999; Winter, 1999). As with groundwater discharge to streams, the fate of groundwater nutrients and contaminants flowing through lake sediments is expected to be altered particularly because of the higher organic matter content of lake sediments. Therefore, there is often a need to consider the nature of GW-SW interactions even in lakes where other hydrological fluxes dominate.

5.2.5.3 Reservoirs (impoundments)

Reservoirs are frequently constructed by damming rivers; their geomorphological characteristics are intermediate between rivers and lakes (Wetzel, 2001). The shallower upstream portion of the reservoir is typically akin to the riverine zone. The deeper downstream portion of the reservoir forms the lacustrine zone. The intermediate portion in between the riverine and lacustrine zones is classified as a transitional zone (Wetzel, 2001). GW-SW interactions are also likely intermediate between rivers and lakes with more similarity to lakes due to the large area of uniform hydraulic head imposed by reservoir and lake water surfaces.

Despite many similarities between reservoirs and lakes, some differences are worth noting. Firstly, increasing water levels in the reservoir will change the spatial distribution of hydraulic gradients in the local groundwater flow system. Groundwater gradients into the reservoir will decrease or reverse, whereas hydraulic gradients between the reservoir and the downstream outlet (or aquifer) will increase, often substantially. Controlling seepage is an important design consideration, not only to reduce water losses from the reservoir, but also to prevent hazards associated with erosion of the dam or abutment by groundwater flow (Cedergren, 1989). Secondly, variations in the reservoir level are often large and can result in significant GW-SW interactions due to temporal changes in hydraulic gradients between groundwater and the reservoir. Reservoir storage and release will also influence the flow and level of the downstream river with resulting effects on the geomorphology, GW-SW interactions and ecology of the downstream river (Sawyer et al., 2009). Thirdly, dams completely change sedimentation and erosion patterns in both upstream reservoirs and downstream rivers (Collier et al., 1996) with resulting changes to sediment distribution and hydraulic conductivity patterns. In some cases, rising water levels in reservoirs can saturate permeable formations that were previously unsaturated. For instance, Smerdon et al. (2005b) gives an example of a permeable window providing a hydraulic connection between a reservoir and a buried valley aquifer in Alberta. Finally, impoundments, even small ones, through their changes to sedimentation and hydraulic exchanges can influence biogeochemical cycling in streams (Fanelli and Lautz, 2008).

5.2.5.4 Wetlands

Wetlands cover approximately 14% of Canada's land surface (National Wetlands Working Group, 1997), and occur within every hydrogeological region of Canada. There are five wetland classes — bogs, fens, marshes, swamps and shallow water — distinguished by their genetic origin and properties such as vegetation, morphology, soils, water levels, hydrology and hydrochemistry. Groundwater is an integral component of wetlands and frequently has an important role in their formation, evolution and function (National Wetlands Working Group, 1997; Winter et al., 1998; Winter, 1999; Glaser et al., 2004). A critical variable in wetlands is water level; it is a major control on hydrological, biogeochemical and ecological processes. Wetland water levels are regulated by GW-SW-atmosphere interactions both within wetlands and with their surrounding uplands, wherever present.

Wetlands occur in a wide range of hydrogeological settings which promote saturation near ground surface (Winter et al., 1998). Wetlands in groundwater discharge zones rely on inflow from local and regional groundwater systems to sustain wetland water levels. The stability of inflow depends on the extent, hydraulic characteristics and position within the flow system. Wetlands also occur in surface depressions underlain or filled with low-permeability units such as crystalline bedrock of the Canadian Shield, or clayey till in the Canadian Prairies. In these areas, surface runoff from the surrounding uplands and direct precipitation are typically the main water sources, and are therefore more variable. The role of low-permeability units is usually to limit subsurface outflow from the wetland. Although the low permeability may limit the subsurface fluxes, these fluxes may be hydrologically or geochemically important to the wetland or the surrounding upland (Berthold et al., 2004). Wetlands also develop in areas of low topographic gradient such as the Hudson Bay Lowlands where local groundwater flow systems develop within the raised bogs, and all the water is derived from atmospheric sources (Glaser et al., 2004). These wetlands are susceptible to climatic variability and fluctuating water levels (Reeve et al., 2006).

Some considerations that are relevant for GW-SW interactions in wetlands include organic soils, vegetation, geochemical processes and vulnerability to climate. GW-SW interactions often occur within wetland organic soils which influence their hydraulic and geochemical functions. The hydraulic conductivity of peat varies as a function of depth with higher permeability in the upper, poorly decomposed material and lower permeability in the deeper, decomposed peat (Letts et al., 2000). The presence of macropores formed by roots can further enhance shallow hydraulic conductivity. As a result, the dominant groundwater fluxes are often lateral exchanges near the wetland surface. The high moisture storage of organic soils is also a significant characteristic that helps stabilize water level fluctuations and increases moisture availability to vegetation.

Vegetation can have a significant influence on GW-SW interactions in wetlands. Several examples in prairie wetlands and ponds show that transpiration from surrounding upland vegetation constitutes a major water loss during dry periods and leads to groundwater flow towards transpiring vegetation (Hayashi et al., 1998; Winter, 1999).

Evapotranspiration from wetland vegetation can also influence wetland hydrology as exemplified by the rise in water table after clear-cutting forested wetlands (Dube et al., 1995). The interdependence of climate, vegetation and the water table has important ecological, hydrological and geochemical consequences for wetlands. Water table depth, its fluctuations, and geochemistry influence the vegetation that can grow; likewise, vegetation can influence the water table elevation through evapotranspiration. Many interrelated factors influence the long-term evolution of wetlands and their hydrological and biogeochemical roles. The complexity of interactions in wetland systems illustrates the difficulty in predicting effects of wetland disturbance and highlights the value of site specific assessment of GW-SW-atmosphere interactions prior to wetland alterations.

Humans rely on both natural and constructed wetlands for water quality benefits such as sediment, nutrient and pollutant removal (Johnston, 1991). Wetlands can be short and long-term sinks for various chemical elements. GW-SW-atmosphere interactions can influence the geochemical function of wetlands by their control on water levels and hydrological flowpaths, and on the biogeochemical processes related to oxidized or reduced conditions. For example, low water levels can lead to oxidation of reduced sulphur compounds stored in wetlands; these are then flushed

into surface waters when the water tables rise again (Eimers et al., 2007). As a result, increasing drought in a warming climate can cause wetlands to contribute acidity to lakes and slow their recovery from decreased atmospheric sulphur deposition (Aherne et al., 2008).

GW-SW-atmosphere interactions in wetlands are affected by climate change and may also indirectly influence climate. Wetlands are a major carbon reservoir and form the largest natural source of methane (CH4), an important greenhouse gas (Denman et al., 2007). Changes in temperature and water table depths can alter carbon cycling dynamics in several ways and result in increased or decreased carbon dioxide (CO2) and CH4 emissions from wetlands (Waddington et al., 1998; Rosenberry et al., 2006; Denman et al., 2007). Winter (2000) suggests that wetland vulnerability to climate change is variable and depends on GW-SW-atmosphere interactions. Wetlands are vulnerable to the extent that they derive their water supply from precipitation; in contrast, wetlands that obtain water from regional groundwater flow systems are least vulnerable (Winter, 2000). Consequently, bogs that receive their water supply from precipitation would be more vulnerable to climate change than fens which are sustained by groundwater. Studies of GW-SW-atmosphere dynamics in wetlands during dry and wet periods (e.g., Winter and Rosenberry, 1998) may prove useful for quantifying the effects of climate change on wetlands and the role of wetlands on carbon cycling.

5.2.5.5 Oceans and coastal areas

Research on GW-SW interactions in coastal areas has traditionally focused on assessing fresh water resources with emphasis on fresh groundwater discharge to the ocean or the impacts of groundwater pumping on salt water intrusion into freshwater aquifers (e.g., Segol and Pinder, 1976; Merritt, 1996). A more holistic perspective is emerging for which the term "submarine groundwater discharge" (SGD) is used to describe any flow of water across the sea floor, including both fresh groundwater and re-circulated sea water (Figure 5.1, Burnett et al., 2003; 2006). SGD is a unique form of GW-SW interactions that includes not only topography-driven groundwater flow, but also additional processes leading to groundwater flow and mixing, such as ocean dynamics (tides, waves, currents, storms), density gradients and geothermal gradients (Burnett et al., 2003; Wilson, 2005).

Freshwater SGD, like GW-SW interactions with lakes, is generally concentrated in the nearshore area and decreases with distance from shore (Taniguchi et al., 2002; Burnett et al., 2003; 2006; Martin et al., 2007). However, instances of large offshore freshwater SGD have been reported in springs and deep confined aquifers (Burnett et al., 2003). SGD also varies temporally due to hydraulic gradients on land and additional variations can result from tide, storm, wind, and current-induced gradients. Compared to lakes, coastal zones often have more permeable sediments so that nearshore SGD fluxes are expected to be higher than for lakes. Estimates of fresh SGD to the oceans have large uncertainties but range from approximately 0.3% to 16% of global river flow (Burnett et al., 2003). Significant human influences on SGD can result from activities such as groundwater pumping, construction of shoreline structures and dredging. Another concern is global sea level rise due to climate change (Meehl et al., 2007) and its impact on salinization of coastal freshwater resources.

Just as the processes and characteristics of groundwater and surface water contrast in freshwater systems (Table 5.1, Figure 5.2), the biogeochemical processes and characteristics of groundwater and seawater differ. Consequently, GW-SW interactions within coastal aquifers enhance mixing and can influence flow and water quality in fresh, brackish and salt water environments, which can be important for geological, geochemical and biological processes (Moore, 1999).

Freshwater resources and ecosystems are vulnerable to salt water intrusion. Estuaries, coastal lagoons and coastal marine ecosystems are vulnerable to variations in salinity and to inputs of pollutants, inorganic and organic carbon, but they are particularly sensitive to nutrients. Nitrogen input from groundwater appears to be a significant contributor to coastal eutrophication because concentrations in coastal groundwaters may be several orders of magnitude greater than those of receiving coastal waters (Valiela et al., 1990; Paerl, 1998; Bowen et al., 2007). One study illustrates the profound effects of nitrogen transport to coastal waters via groundwater in transforming the coastal ecosystem (Valiela, 1992). Nitrogen from groundwater increased primary production by phytoplankton and macroalgal biomass which dominated the ecosystem, increased the frequency of anoxic events, and decreased the extent of native sea grasses.

5.2.6 Interactions with different GW systems

GW-SW interactions also vary according to the nature of porosity and the dynamics of groundwater flow systems. Groundwater flow systems respond differently to spatially and temporally variable climatic, hydrological and human factors. How a groundwater flow system stores and transmits water will influence GW-SW interactions.

Because the unsaturated zone influences the storage and redistribution of infiltrating precipitation, it also has an indirect role on GW-SW interactions. The variable nature of water storage and transmission among porous, fractured and karst groundwater flow systems will generate variable GW-SW interactions.

5.2.6.1 Porous media flow systems

Groundwater flow through porous media (flow occurs through inter-granular pores) is critical in many geologic settings in Canada because much of the land surface is covered by porous sediment. Even where the sediment is thin, it often has a significant effect on water storage and transmission within a watershed. Furthermore, sediment is often present in the valleys of streams and rivers even when upland areas are predominantly bedrock. As a result, most studies of GW-SW interactions have focused on flow in porous sediments.

The dominant factor influencing GW-SW interactions in porous media settings is the grain size distribution which controls the hydraulic conductivity and can also be significant for geochemical, biological and filtration processes in hyporheic zones. The large specific yield (or storage capacity) of unsaturated porous sediments also allows for greater bank storage of surface water adjacent to rivers during floods than would a comparable stream bank composed of karst or fractured crystalline bedrock.

Two larger scale factors in porous flow systems that influence GW-SW interactions are the depth of the water table and whether the aquifer is confined or unconfined. In unconfined aquifer systems where the water table fluctuates within approximately two metres of land surface, and storage in the unsaturated zone is limited, groundwater levels increase rapidly in response to infiltration events; groundwater discharge to surface water can also respond rapidly. In this setting, most of the groundwater typically flows in local flow systems and discharges to the nearest surface water body (Figure 5.3c). In unconfined aquifer systems with deep water tables, the unsaturated zone stores most infiltration; the water table responds to large snowmelt or rainfall events and seasonal patterns of evapotranspiration and precipitation. Deep unconfined aquifer systems also tend to have longer flowpaths to surface water bodies (e.g., Figure 5.3b) and often produce groundwater levels, water chemistry and discharge fluxes that are more stable than shallow unconfined systems. Groundwater flow through confined aquifer systems is generally regulated by the flow through the confining aquitard. Consequently, discharge from these systems is expected to be sustained and more stable.

5.2.6.2 Fractured media flow systems

The nature of flow and, therefore, of GW-SW interactions in fractured geological materials can be quite variable depending on both the fracture system and the porosity of the matrix. It may vary from discrete fractures in non-porous crystalline rocks to networks of interconnected fractures in porous rocks or sediments. Whereas the latter may behave similarly in many ways to the porous flow systems described above, due to the available storage within the porous matrix, non-porous fractured rocks have little available storage and respond more rapidly to a greater depth than porous flow systems. For example, unconfined aquifers in non-porous fractured bedrock would generally have much lower available storage than a comparable unconfined granular (e.g., sand, gravel) aquifer. Consequently, groundwater levels, chemistry and discharge from a fractured bedrock aquifer would likely be more variable and the flow system would have less capacity to sustain discharge during periods of low recharge.

Although differences in near-stream GW-SW exchanges between fractured and porous media may be expected, there have been relatively few studies that investigate these exchanges and their implications specifically for fractured flow (Oxtobee and Novakowski, 2002; 2003; Praamsma et al., 2009). Fracture flow settings may have received comparatively less scrutiny due to the greater difficulty and cost of instrumentation (Praamsma et al., 2009).

5.2.6.3 Karst terrain flow systems

Karst terrain occurs in various regions across Canada (Ford, 1983) with distinctive landforms, hydrogeology and hydrology that result from the dissolution of soluble rocks to form fissures and conduits (Ford and Williams, 2007). Karst features can range widely from small fissures to extensive cave systems. Because karst systems develop as highly-interconnected subsurface drainage networks (Worthington and Ford, 2009), their hydrological and hydrogeological systems function quite differently than fractured or porous media aquifers. Although recharge, discharge and GW-SW exchange can occur in karst terrain, their rates and

processes may differ substantially. For example, groundwater discharge to surface water in karst terrain often occurs as discrete springs that result from the convergence of groundwater into subsurface conduits which function as high-permeability drains. In contrast to springs in porous media, which generally have stable flow, temperature and water chemistry, these parameters can fluctuate greatly in springs of karst terrain (Ford and Williams, 2007). Despite considerable study of surface water and groundwater systems in karst terrain (see Ford and Williams, 2007), GW-SW interactions concepts such as hyporheic zone and exchange have received little attention (Cardenas and Gooseff, 2008). Given the widespread distribution of karst terrain, the differences in hydrological and geochemical processes between karst and porous media, and the unique ecological habitats afforded by many springs, more focused study on GW-SW interactions in karst terrain appears warranted.

5.2.7 Natural and human influences

In light of the wide range of hydrological, ecological and societal issues and processes relevant to GW-SW interactions (section 5.2.2), both natural and human influences may need to be considered depending on the purpose of a given investigation. Natural factors that influence GW-SW interactions include climate, topography, hydrology, geology, hydrogeology, geochemistry, ecology, wildlife, vegetation, and permafrost. Human activities can disrupt natural factors and, either directly or indirectly, influence GW-SW interactions. Examples include groundwater and surface water withdrawal, artificial recharge, land drainage, surface water impoundment, irrigation (and irrigation canals), land use change, nutrient application, and waste water discharge. Studies of GW-SW interactions, by their nature, need to consider complex interactions and cumulative effects. General knowledge of GW-SW interactions and processes may be suitable for qualitative analysis, but dedicated study is likely necessary for quantitative analysis and assessment.

5.2.8 Spatial and temporal scales

GW-SW interactions occur at scales varying from the thickness of sediment beds (sub-millimetre to metre) to that of watersheds (> 5 km) (Hancock et al., 2005; Dahl et al., 2007). Recognition of temporal and spatial patterns and variability are important elements of any GW-SW investigation. Quantifying water fluxes, chemical fluxes and transformations, or microbiological processes involved in GW-SW interactions can be inherently difficult due to the spatial and temporal variability of natural systems even at small spatial scales such as a stream segment. For example, groundwater fluxes to a stream can vary by more than one order of magnitude on the scale of tens of centimetres due to variations in stream bed hydraulic conductivity (Conant Jr., 2004). Patterns that emerge at successively larger scales may not simply represent the cumulative effects of small-scale processes because hydrological, hydrogeological and ecological processes change across a watershed (e.g., river continuum concept and Tóth's scales of groundwater flow systems, Figure 2.17). Consequently, understanding GW-SW interactions at a watershed scale may require integration of data at various scales.

Similarly, the temporal scales of GW-SW interactions may change across a watershed as water table dynamics and storage vary. To consider the possible impacts of landscape changes on GW-SW interactions, it is important to recognize that changes to hydrological systems, particularly groundwater systems, propagate at different rates. For example, impacts from a change in recharge water quality would depend on water velocity, whereas impacts from a change in recharge or pumping rate would depend on water level changes. Therefore, the water quality and quantity impacts from a change in land use could manifest itself over different time scales.

When groundwater is removed from the flow system, either through pumping or decreased recharge, water that is captured will ultimately affect surface water (Sophocleous, 2000; Bredehoeft, 2002; Devlin and Sophocleous, 2005). This process may take many years, even centuries, depending on several parameters, including hydraulic properties, flow system change in storage and distance to surface water. Where water capture is more distal to surface water, impacts will be delayed, and occur gradually. The time required to reach a new groundwater equilibrium will also be longer (Bredehoeft, 2002). This delayed and gradual response becomes a problem for assessing potential impacts of groundwater changes on GW-SW interactions. The problem is compounded in urban areas where the cumulative effects of multiple withdrawals (or sources) that occur at different times and locations are difficult to assess. Consequently, long-term effects are often disregarded or identified as being insignificant.

5.2.9 Methods of investigation

Traditional field hydrological and hydrogeological methods to study GW-SW interactions include the use of piezometers, seepage metres, natural or artificial chemical tracers, water chemistry, water temperatures, stream hydrographs, and incremental stream discharge measurements (Harvey and Wagner, 2000; Kalbus et al., 2006). Methods used in ecological and microbiological studies include various approaches to identify and enumerate macro- and micro-organisms including the use of DNA, microcosm, mesocosm or solute injection experiments that quantify microbial activity or nutrient retention (e.g., Barton, 2006; Griebler and Lueders, 2009; Ibisch et al., 2009). The scale of measurement varies from point values to the entire watershed. Given the spatial variability in GW-SW interactions (section 5.2.8), methods must be selected for the appropriate scale of processes being studied.

Another approach to investigating GW-SW interactions is to develop models that use mathematical formulations of processes to simulate several components of the groundwater, surface water or biogeochemical systems. Models vary widely in the issues they address, in processes stimulated, in the assumptions required, in the way GW-SW interactions are represented, and in the numerical approaches used to solve the mathematical equations (Tellam and Lerner, 2009). Models help address the problem of integrating spatially variable processes and properties (Gauthier et al., 2009); they can also provide insight into regional, long-term and/or cumulative effects on GW-SW interactions (e.g., Sulis et al., 2011). Models, however, generally have relatively high data requirements to allow appropriate calibration.

A significant advance has been the development of physically-based models that fully integrate subsurface and surface flow (VanderKwaak, 1999; Panday and Huyakorn, 2004; Therrien et al., 2005; Jones et al., 2008; Brunner and Simmons, 2010). In these models, the GW-SW interfaces are not boundary conditions and the GW-SW interactions are controlled by the models' representations of the processes and parameters. One application of such a model to a watershed revealed the importance of better characterizing evapotranspiration to improve transient stream simulations (Li et al., 2008). Another model implementation incorporated thermal transport modelling to consider GW-SW-atmosphere interactions on temperature distributions (Brookfield et al., 2009). Although these integrated models will likely provide significant insight into GW-SW-atmosphere interactions, they require extensive data sets that are not widely available. The cost, effort and difficulty of collecting sufficient site-specific data may limit the application of such sophisticated GW-SW models in most watersheds.

5.3 GW-SW INTERACTIONS IN CANADA

5.3.1 Research and data

An extensive amount of research has contributed to an increased understanding of GW-SW interactions from studies both in Canada and worldwide. Much of the knowledge about GW-SW processes has accumulated gradually from independent studies from a number of different disciplines addressing a broad range of issues. Better understanding of GW-SW interactions has seldom been the main goal of research studies, yet has been required to improve the grasp of the issue of interest. For example, understanding nitrogen dynamics from uplands through riparian zones and into streams has required a better understanding of the hydrological and biogeochemical interactions between surface water and groundwater (Hill, 1996; 2000). One ongoing challenge is to integrate fragmentary knowledge of GW-SW interactions from many disciplines into a more holistic understanding of interrelated processes.

One research approach that has fostered better multi-disciplinary understanding of GW-SW interactions has arisen from long-term research catchments where hydrological and geochemical mass balances and ecological monitoring are combined with process-oriented research. In Canada, long-term catchment-scale research has addressed issues such as lake eutrophication and acidification (e.g., Dillon et al., 1987; Jeffries et al., 2003; Schindler et al., 2008; Yan et al., 2008), land or forest management practices (Foster et al., 2005; Mallik and Teichert, 2009), climate change (Schindler, 2001; Eimers et al., 2004) and the cycling of toxic contaminants (Hall et al., 2005). By design, these research programs have contributed towards a multidisciplinary understanding of interacting natural processes in which GW-SW interactions are often significant.

Although much has been learned about GW-SW interactions from independent studies and catchment-scale research, additional insight has been gained more recently by specifically targeting GW-SW exchanges and related processes (Harvey and Wagner, 2000). The number of studies of this nature is increasing in Canada, and many have been focused at relatively small spatial scales (e.g., Conant Jr., 2004; Kasahara and Hill, 2006; see Hayashi and Van Der Kamp, 2009). At larger-scales, integrated or coupled groundwater and surface water models are being used to incorporate the effects of GW-SW interactions when considering issues such as climate change (Scibek et al., 2007; Gauthier et al., 2009; Sulis et al., 2011). More studies specifically focussed on GW-SW exchanges are needed across a wider range of geographic scales (e.g., pool-riffle to river basin scales): these studies would benefit greatly from an approach that combines field research and modelling. The concept of classifying and mapping GW-SW interactions across multiple scales is also relatively recent (Dahl et al., 2007). Additional investigations in the development of classification, mapping and field techniques can provide key data on the nature of GW-SW interactions to support scientific analysis and decision making.

To date, there has been no detailed examination of data available regarding GW-SW interactions in Canada. With respect to water-related data for sustainable groundwater management, however, an expert panel found that data collection has failed to keep pace with demands over the past 20 years (Expert Panel on Groundwater, 2009). This report also indicated large discrepancies in groundwater monitoring data collected countrywide. A survey of Canadian groundwater professionals revealed insufficient groundwater data and the need for integrated groundwater and surface water monitoring data (CCME, 2010). A recent evaluation of the Canadian surface water hydrometric network concluded that almost all Canadian main watersheds do not have adequate hydrometric networks (Mishra and Coulibaly, 2010). Therefore, it is expected that the type, amount and distribution of surface water, groundwater and ecological data available for watersheds across Canada varies considerably and is usually inadequate for assessment of GW-SW interactions. Watershed- and site-specific data of GW-SW interactions is often insufficient to make informed decisions about land and water use on the watershed scale. Even in watersheds, where surface water and groundwater dynamics are reasonably well characterized, data specifically on GW-SW interactions is usually sparse. Most existing groundwater flow models have insufficient data to validate GW-SW fluxes and their distributions. To manage surface and groundwater resources in an integrated manner will require a greater effort in systematic and integrated data collection of groundwater, surface water, and GW-SW interactions, in addition to better data analysis, interpretation and reporting.

5.3.2 Conceptual models in Canadian settings

Despite the scarcity of data and interpretations on GW-SW interactions in Canada, there is the need to consider these interactions in numerous applications such as assessment of environmental impacts of development, predictions of climate change impacts or water resource development planning. Consequently, as part of the overall study area conceptualization, it is often necessary to develop a conceptual model of GW-SW interaction (either explicitly or implicitly) based on available data. Conceptualization of these interactions can be critical to establishment of boundary conditions for surface water and groundwater models. A key element of conceptual model development is the application of useful generalizations (LeGrand and Rosen, 2000). Few conceptual models of GW-SW interaction have been developed explicitly; more detailed generalizations and conceptual models applicable to specific settings are needed (e.g., Woessner, 2000 for a fluvial plain setting). Development and testing of such generalizations and conceptual models will advance current understanding of processes where specific data on GW-SW interactions is limited. In effect, the proposed solution to the problem of large variability in GW-SW interactions and insufficient data is to build conceptual models of type environments that can be applied to site specific situations. This approach is commonly used by geologists in the form of facies models (Walker, 1992) and is finding increased application by hydrogeologists (LeGrand, 1970; Anderson, 1989).

In Canada, the large number of variables influencing GW-SW interactions (e.g., geology, topography, hydrology and climate) and their variability may influence applicability and usefulness of such generalizations and conceptual models. For example, some generalizations about GW-SW interactions in permafrost environments may be broadly applicable across northern Canada; by contrast, a conceptual model of GW-SW interaction for an alluvial fan would only be applicable to that specific setting.

Much has been learned about GW-SW interactions from a wide range of studies in various disciplines. Various elements of the results can be integrated to begin development of generalizations about GW-SW interactions in regions where little data exists specifically on GW-SW interactions.

Following are three brief examples where integrating the existing literature allows for consideration of the nature and key controlling factors of GW-SW interactions in specific Canadian settings.

5.3.2.1 Permafrost

The presence of permafrost, seasonally frozen ground (otherwise known as the active layer), and a low-precipitation regime dominated by snow accumulation distinguishes both surface water and groundwater flow regimes in the permafrost hydrogeological region. As a result, the nature and some of the key factors controlling GW-SW interactions in northern Canada are expected not only to differ when compared to areas with similar physiography farther south, but also to be more complex because of the additional interactions between the hydrological and thermal regimes.

Permafrost or perennially frozen ground is a key factor controlling GW-SW interactions because frozen ground has very low permeability, and behaves hydraulically as an effective aquitard (Sloan and van Everdingen, 1988). Permafrost continuity and thickness control development of groundwater flow systems and appear to affect the nature and intensity of GW-SW interactions. One useful classification of groundwater in permafrost regions is based on its position relative to the permafrost (see Chapter 15, Tolstikhin and Tolstikhin, 1977; Sloan and van Everdingen, 1988): a) suprapermafrost water above permafrost in the active layer and taliks (perennially unfrozen ground), b) intrapermafrost water within the permafrost, and c) subpermafrost water beneath the permafrost (see also Figure 15.6). Interactions between subpermafrost groundwater and surface water in the continuous permafrost zone are limited to areas where open taliks allow a hydraulic connection across permafrost (e. g., beneath large lakes). These settings are not well studied yet, therefore their significance is not fully known. As a first approximation, it is assumed that these fluxes are generally small since even large rivers in continuous permafrost can cease to flow after freeze-up (Woo, 1986). Interactions between suprapermafrost groundwater and surface water are more widespread but occur during the period of active layer development and are limited to shallow depths. In areas of discontinuous permafrost, there is more opportunity for GW-SW interactions caused by hydraulic connections between subpermafrost aquifers and surface waters. Discharge sites are sometimes indicated by the presence of springs, open water in the winter, and icings (aufeis) formed by the freezing of groundwater discharge (van Everdingen, 1974). Significant differences in winter baseflow yield between rivers in continuous (approaching 0 mm/year) and discontinuous (30–160 mm/year) permafrost highlight the significant role of permafrost continuity (Williams and van Everdingen, 1973; Sloan and van Everdingen, 1988).

Another key factor controlling GW-SW interactions in the permafrost hydrogeological region is the seasonal dynamics of the active layer. Seasonal ground freezing and thawing results in seasonal variations in groundwater recharge, flow, storage and flowpaths in suprapermafrost groundwater. The varying frost depths and water tables significantly influence subsurface flowpaths and rates (Quinton and Marsh, 1999). Understanding the thermal regime is crucial because it can affect GW-SW interactions differently than in non-permafrost areas. Thermal regimes differ based on slope aspect and position, moisture content, surface vegetation and thermal properties, leading to both spatial and temporal differences in suprapermafrost groundwater flow and overall water balances (Carey and Woo, 1999; Quinton and Carey, 2008).

Similarly, thermal regime of surface waters and their hyporheic zones are important factors affecting GW-SW interactions. Both the depth of permafrost and the seasonal freeze and thaw cycles influence hydraulic and geochemical functions within the hyporheic zone. Whereas some surface waters can maintain taliks and perennial flow beneath them, others will freeze and effectively shut off hyporheic flow. Usually, larger and deeper water bodies, such as lakes, are more likely to maintain unfrozen hyporheic zones. By contrast, the hyporheic zones of small streams or peatlands are more frequently

within the active layer, and contract and expand seasonally as they freeze and thaw. Consequently, the depth of thaw and hyporheic flow will be quite uneven along streams due to variable thermal conditions or GW-SW exchange (Zarnetske et al., 2008; Brosten et al., 2009). However, groundwater flow modelling predicts that a deepening subsurface thaw under warming climatic conditions only affects hyporheic exchange to a threshold depth (Zarnetske et al., 2008).

Despite increased research in the Arctic to assess the multiple impacts of climate change and geotechnical problems on infrastructure, Woo et al. (2008) note the dearth of groundwater research on intrapermafrost and subpermafrost aquifers within the last decade, and have identified the need for well-integrated process studies of ground and surface water hydrology. Only recently have studies specifically considered GW-SW exchanges in the hyporheic zones of Arctic rivers (Edwardson et al., 2003; Greenwald et al., 2008; Zarnetske et al., 2008). These studies have found that biogeochemical processes in the hyporheic zone of Arctic streams transform nutrients, such as N and P, and may be as important as similar processes in temperate zones (Edwardson et al., 2003; Greenwald et al., 2008).

The permafrost hydrogeological region is currently undergoing significant changes in permafrost and hydrological conditions (White et al., 2007; Woo et al., 2008). Both Walvoord and Striegl (2007) and St. Jacques and Sauchyn (2009) detected long-term (>30 years) increases in winter discharge from streamflow records in the Northwest Territories, Yukon and Alaska . They propose that these changes could be attributed to increased groundwater contributions from permafrost thaw. Such changes are intimately linked to permafrost degradation via various interrelated processes (Chapter 15, White et al., 2007; Woo et al., 2008). Climate impacts on permafrost to alter groundwater flow systems and their interactions with surface water (Michel and Van Everdingen, 1994; Bense et al., 2009). GW-SW interactions can also have a role in the degradation of permafrost and the hydrological impacts of climate change due to heat transport by recharging groundwater or GW-SW exchange. Despite the significant potential impacts of climate change and GW-SW interactions to northern hydrology, there is little research on groundwater flow systems and GW-SW interactions in the permafrost hydrogeological region of Canada.

Thermal regime is a key element of the conceptualization of GW-SW interactions in permafrost settings, and this conceptualization is more complex because it must consider both the hydrological and thermal regimes. For example, thermal modelling can be used to estimate the dimensions of lakes that might have open taliks in the zone of continuous permafrost (e.g., Cumberland Resources Limited, 2005) and thus predict where deep subpermafrost groundwater may interact with surface water. Suprapermafrost groundwater fluxes and flowpaths are closely linked to the seasonal freezing and thawing of the active layer and are highly variable both spatially and temporally. Subpermafrost groundwater contributions are expected to be more constant on a seasonal basis, but may increase in the long term as a result of permafrost degradation.

5.3.2.2 Permeable glacial sediment

Many areas of high groundwater discharge are associated with permeable glacial deposits such as eskers, kames and kame terraces, interlobate moraines, subaqueous fans, ice marginal deltas and outwash. These landforms occur in all hydrogeological regions of Canada and have the potential for significant GW-SW interactions. Groundwater discharge is commonly the dominant and most extensive type of GW-SW interaction in these settings although GW-SW exchange can also be significant at a local scale. Even though conceptualization of GW-SW interactions may differ according to landform, some generalizations are possible.

First, permeable glacial landforms often have a positive topographic expression that includes elevated areas of groundwater recharge such that a groundwater flow system develops on the scale of the landform. Typically, groundwater discharge is concentrated at the edges of landforms where there is a rapid change in slope that reduces hydraulic gradients. Sometimes where there is a decrease in sediment thickness or permeability that forces groundwater to discharge (e.g., Gerber and Howard, 2002).

Second, higher recharge rates in these settings sustain higher groundwater discharge and baseflow to perennial surface waters which maintain more constant flow, water levels and geochemical conditions than ephemeral surface waters. Due to the permeable nature of glaciofluvial sediment, headwater streams with perennial flow can develop even in watersheds of only a few square kilometres.

Third, GW-SW interactions are more intense where higher-permeability units are connected hydraulically with surface waters. The wide range of permeability in glacial landscapes and the extensive

distribution of lower-permeability units such as till and fine grained glaciolacustrine or glaciomarine sediment results in preferential groundwater flow in these more permeable units. Groundwater discharge rates and fluxes per unit area in the Oak Ridges Moraine area are highest in areas where permeable sediments are in hydraulic connection with surface waters, and lowest in areas where surficial sediments are till or fine grained glaciolacustrine (Hinton, 1995; Hinton et al., 1998; Hinton, 2005). The continuity of low-permeability units can also affect GW-SW interactions at the scale of a stream reach. In an intensive study along a 60-m reach of a river, Conant (2004; Conant Jr. et al., 2004) mapped large differences in groundwater fluxes and contaminant concentrations over distances of a few metres in riverbed sediments composed of fluvial sands. Areas of highest discharge measured only a few square metres in size and corresponded to localized breaches in the underlying unit, which was formed of silt, clay and peat.

Similarly, variability in GW-SW interactions may also result from variability within permeable glacial landforms. Each type of landform has characteristic distributions of sediment facies that result in characteristic horizontal and vertical patterns of hydrostratigraphy (e.g., Anderson, 1989). For large and complex landforms such as the Oak Ridges Moraine in southern Ontario, the strata are typically deposited in a sequence beginning with proximal sands and gravels progressing into finer, more distal sediment (Barnett et al., 1998). Localized areas of high groundwater discharge within permeable portions of the Oak Ridges

Moraine are consistent with such facies variations (Hinton et al., 1998). In summary, GW-SW interactions in permeable glacial settings are expected to show significant spatial variability as a result of the depositional patterns of sediment facies, the larger scale stratigraphic sequence of high- and low-permeability units and the topographic expression of these landforms.

5.3.2.3 Mountains

Mountainous areas, such as within the Cordillera, Appalachian and portions of the Canadian Shield regions, include a particularly wide range of geologic, topographic and climatic conditions, and the nature, distribution and intensity of GW-SW interactions are highly variable. In upland mountainous areas, it appears that shallow subsurface flow may play a significant role in GW-SW interactions. A review of GW-SW interactions in alpine and subalpine watersheds draws attention to the important contributions of groundwater to surface water, primarily, as very shallow subsurface flow through soils or shallow sediment. Secondarily, as groundwater flow through shallow fractured bedrock or thicker, less permeable sediment adjacent to surface water (Roy and Hayashi, 2007). Recent studies of one alpine watershed in the Rocky Mountains demonstrated that local scale deposits of coarse unconsolidated sediments (in this case talus and moraine) along drainage pathways can result in significant GW-SW interactions which impact hydrological response and water quality (Roy and Hayashi, 2008, 2009). Similarly, limited terrace deposits in the Mirror Lake watershed of the White Mountains, New Hampshire significantly influenced water chemistry and groundwater and surface water fluxes along a mountain stream (Winter et al., 2008). These examples suggest that localized presence of permeable sediment can result in significant GW-SW interactions even within watersheds where groundwater fluxes through the bedrock are relatively minor.

Stream valleys draining upland areas are subject to intense GW-SW interactions. GW-SW exchange is enhanced at the reach scale (connecting tributaries between streams and rivers) by changes in stream topography (Figure 5.4, Harvey and Bencala, 1993). The higher permeability of alluvial deposits at the watershed scale can become a preferential groundwater flowpath of mountain watersheds, providing a significant portion of the total groundwater flow to the valley below (Smerdon et al., 2009). Topographic and geologic conditions of the valley-margin position occupied by alluvial fans are conducive to all three types of GW-SW interactions (Houston, 2002; Woods et al., 2006; Blainey and Pelletier, 2008). The apex or head of an alluvial fan is usually characterized by coarse sediment, a high hydraulic gradient, and a source of surface water (Blair and McPherson, 1994) — conditions that permit significant surface water recharge as an upland river crosses a fan (Figure 5.1). GW-SW exchange also occurs at the landform scale when recharged surface water flows as groundwater through the fan, discharging back to the surface near its base (Woods et al., 2006; Smerdon et al., 2009). Additional factors affecting the GW-SW interactions in alluvial fans are the extreme variability in flow from upstream (Houston, 2002; Smerdon et al., 2009) and the heterogeneity in geologic and hydrogeological facies (Blair and McPherson, 1994; Weissmann and Fogg, 1999; Fleckenstein et al., 2006). The heterogeneity contributes to significant variability in surface water distribution infiltration to the fan, and the resulting low flow conditions of the river (Fleckenstein et al., 2006).

Similar interactions can also occur in valley fill aquifers receiving recharge from upland streams. Water balance estimates for 12 valley-fill aquifers in the glaciated northeastern United States indicate that upland runoff provides from 31% to 93% of the total groundwater recharge (Kontis et al., 2004). Small upland tributaries will occasionally go dry on a seasonal basis in areas where they enter large valleys which absorb all the runoff. Recharge amount from larger upland streams and rivers often depends on the streambed hydraulic conductivity of the streambed and the relative water levels between surface water and groundwater. Groundwater pumping from valley-fill aquifers can also induce recharge into an aquifer when groundwater levels fall below that of the stream (Kontis et al., 2004). Surface water recharge to valley-fill aquifers ultimately discharges back to surface water at lower elevations, which is usually the main river in each valley (Kontis et al., 2004).

A key element of GW-SW interaction conceptualization in major valleys is the transient recharge of alluvial aquifers from rivers during high stages, and subsequent groundwater discharge as river stage declines (Box 4-1, Scibek et al., 2007). Although the process is analogous to bank storage, this type of GW-SW exchange can occur on a scale from hundreds of metres to several kilometres because of the down-valley component of groundwater flow. An additional control on GW-SW interactions in major valleys is aquifer continuity; aquifers are usually bounded by valley walls which can cause them to narrow or pinch off, forcing groundwater discharge into the river (SRK Consulting Inc., 2003). From these examples, it is apparent that, although permeable sediments may cover only a relatively small proportion of the area in mountainous regions, they are predominantly located in valleys adjacent to surface waters where more intensive GW-SW interactions can occur.

5.3.3 Summary of GW-SW interactions in Canada

GW-SW interactions are important in all hydrogeological regions of Canada, regardless of intensity. Better understanding of groundwater, surface water and their interactions in regions with greater reliance on groundwater is needed to manage water resources and their dependent aquatic and ecological habitats sustainably. Even in geographic areas where groundwater resources are traditionally considered of lesser importance (e.g., Canadian Shield and permafrost regions), GW-SW interactions may be significant with respect to water quality issues (e.g., lake eutrophication and acidic deposition) and climate change impacts (active layer and permafrost dynamics). Despite limited groundwater fluxes through glacial till and crystalline bedrock, the geochemical significance of these subsurface fluxes can be substantial. In the absence of carbonate minerals, weathering of silicates is the main source of alkalinity through groundwater flow and discharge (Aravena et al., 1992).

Although GW-SW interactions are not well studied in most Canadian watersheds, conceptual models could provide insight into key processes likely to be important within a specific setting. Conceptual models for GW-SW interactions are yet to be developed for most Canadian watersheds. Such models will remain fragmentary unless integrated with multidisciplinary studies of groundwater, surface water and GW-SW interactions.

5.4 CONCLUSIONS AND FUTURE CHALLENGES

Nevertheless, significant progress has been made in the study and understanding of GW-SW interactions both in Canada and globally. We have better knowledge of the hydrological exchanges between groundwater and surface water and the biogeochemical and ecological processes that occur in riparian and hyporheic zones. Canadian research has made, and continues to make, important contributions to the understanding of GW-SW interactions. However, our knowledge with regard to watershed- or site-specific GW-SW interaction processes across Canada remains limited. The Canadian landscape is vast, with many factors influencing GW-SW interactions over a wide range of spatial and temporal scales; these factors are also undergoing transformation as a result of climate change and changes in land use. Improved understanding of GW-SW interactions will be necessary if Canadians wish to make informed decisions that lead to sustainable use of our water and aquatic resources. Considerable challenges remain for both the scientific community and decision makers in Canada. These include

- improving the integration of knowledge from various disciplines to advance conceptual understanding and quantitative prediction of impacts (e.g., ecological impacts of hydrological or hydrochemical changes; Hunt and Wilcox, 2003)
- coupling of detailed field-based data and modelling at the watershed scale to test and validate conceptual and numerical GW-SW models and the processes they represent
- incorporating greater consideration of atmospheric processes in GW-SW interactions (National Research Council Committee on Hydrologic Science, 2004)
- considering the cumulative and long-term effects of climate change, water use and land use on aquatic and groundwater-dependent resources (Schindler, 2001)
- compiling and analyzing existing data to provide preliminary interpretations of GW-SW interactions at large watershed scales (Ivkovic, 2009)
- conducting more systematic investigations of GW-SW interactions in specific regions or settings where current knowledge is insufficient (e.g., permafrost areas, urban areas)
- recognizing that sustainable development of water resources is inherently linked to GW-SW interactions since sustainability limits are often defined for ecological or social impact criteria which thresholds are attained before hydrological limits for water resources are reached (Alley and Leake, 2004)
- developing policies that recognize the central role of GW-SW interactions in the protection of aquatic, riparian and wetland ecosystems (e.g., EU Water Framework Directive (see Dahl et al., 2007))
- increasing the use and accountability of adaptive management in which there is ongoing data collection and analysis to facilitate a flexible decision-making process (Maimone, 2004)
- continuing support for intensively studied watersheds across the country wherein conceptual knowledge is advanced, methodologies are developed, and the resultant knowledge is fed into integrated management of GW-SW resources. Such studies require both the dedicated effort of scientists and water managers and a long-term financial commitment from funding agencies. In effect, we need adaptive management and the integration of emerging scientific

knowledge into watershed management. This need is greatest in watersheds where land use is intensifying (e.g., urbanized or urbanizing areas and areas of agricultural or industrial intensification) so that continued monitoring and focused studies can be used to assist in this management. Such catchments will provide opportunity for all parties to become involved in administration of watershed and demonstrate to the public what can be accomplished by effectively integrating science information into local decision making

These challenges require greater interdisciplinary collaboration between scientists, closer interaction between scientists, water managers and policy makers, and wider site-specific data and analysis of those areas where decisions may influence long-term water and aquatic resources. (Tellam and Lerner, 2009, have outlined some of these issues in the context of developing management tools for the river-aquifer interface.)

Another broader, more significant challenge is raising public awareness of the interconnection between land use and its impact on water and aquatic resources. Protection of aquatic and water resources is not simply a question of protecting riparian areas; it also requires effective management of terrestrial components of the watershed. Recognition of this interconnection is necessary before the public becomes more willing to support land management policies for the protection of water resources.

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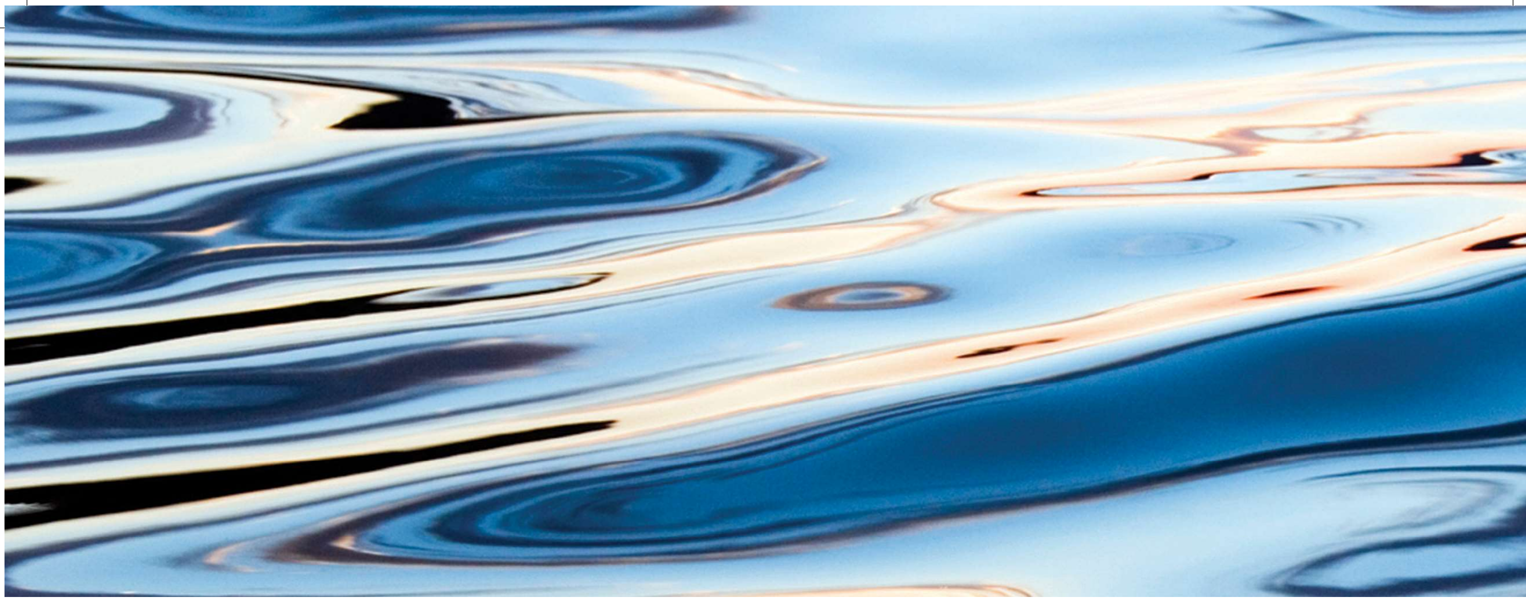

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