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Groundwater–Surface Water Interactions

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13.1 Introduction

Groundwater is a fundamental natural resource for life. Understanding the groundwater–surface water interaction (GSWI) is essential to water managers and scientists. The management of one component of the hydrologic system, such as a stream or an aquifer, is only partly effective because each hydrologic component is in continuing interaction with other components. Interactions between groundwater and surface water play a fundamental role in water resource management. The movement of water between groundwater and surface water should be investigated in view of both quantity and quality aspects of water resources. The movement of water in the atmosphere and on the land surface is relatively easy to visualize, but the movement of groundwater is not. Groundwater moves along flow paths of varying lengths, from areas of recharge to areas of discharge. The generalized flow paths start at the water table, continue through the groundwater system, and terminate at the stream or at the pumped well. The source of water to the water table (groundwater recharge) is the infiltration of precipitation through the unsaturated zone. In the uppermost, unconfined aquifer, flow paths near the stream can be tens to hundreds of feet in length and have corresponding travel times of days to a few years. The longest and deepest flow paths may be thousands of feet to tens of miles in length, and
travel times may range from decades to millennia. In general, shallow groundwater is more suscep-
tible to contamination from human sources and activities because of the close proximity to the land
surface. Therefore, shallow, local patterns of groundwater flow near surface water are emphasized in
this chapter. The following are some concepts of common water resource issues where understanding
the interconnections of groundwater and surface water is fundamental to the development of effective
water resource management and policy.

The GSWI is complex. To understand these interactions in relation to climate, landform, geology,
and biotic factors, a sound hydrogeoecological framework is needed. In addition, the mechanisms of
interactions between groundwater and surface water as they affect recharge–discharge processes should
be comprehensively outlined, and the ecological significance and human impacts of such interactions
should be emphasized as well. Surface water and groundwater ecosystems are viewed as linked compo-
nents of a hydrologic continuum leading to related sustainability issues. The conceptual landscape in
this chapter shows, in a simplified way, groundwater interaction with all types of surface water, such as
streams, lakes, and wetlands and in many different terrains, from mountains to oceans. The interaction
of groundwater and surface water has been shown to be a significant concern in many of these cases.
For example, contaminated aquifers that discharge to streams can result in long-term contamination
of surface water; conversely, streams can be a major source of contamination to aquifers. Surface water
commonly is hydraulically connected to groundwater, but the interactions are difficult to observe and
measure and have been occasionally ignored in water management considerations and policies. Many
natural processes and human activities affect the GSWI. The purpose of this chapter is to present our
current understanding of these processes and activities as well as the limitations in our knowledge and
the capability to characterize them.

Modeling of GSWI requires not only knowledge of groundwater modeling but also special under-
standing of the exchange processes that occur between surface water and groundwater. In some cases, it
becomes necessary to simulate the dynamics of both surface and groundwater flows, using techniques
and softwares that are appropriate to the timescales of all flow processes.

Modeling of GSWI calls for all the same stages of development as the modeling of the groundwater
flow: conceptualization, design and construction, calibration and sensitivity analysis, and prediction
and uncertainty analysis. Each of these is discussed in this chapter with a focus on the specific require-
ments of GSWI, beyond those of groundwater flow models.

### 13.2 Federal Statutory/Regulatory/Policy with respect to GSWIs

The Victorian Government of Australia has been committed to manage water resources to support
a thriving economy, healthy environment, and growing communities [7]. The government, policy
makers, scientists, and land managers should be informed on the interactions between surface and
groundwater systems, enabling improved water resource allocation as well as river and floodplain
management.

The GSWI zone is important because 75% of the Superfund and the Resource Conservation and
Recovery Act (RCRA) sites are located within a half mile of a surface water body. Forty-seven percent
of Superfund sites have recorded impacts to surface water. Most of the RCRA sites are located adjacent
to or near surface water (presumably for ease of transportation and manufacturing). Within the last
25 years, the Clean Water Act has succeeded in cleaning up point sources in the United States, and
Environmental Protection Agency (EPA) now needs to consider nonpoint sources [29].

The Superfund National Contingency Plan offers greater detail; the RCRA relies more on program
guidance. The Superfund’s goal is to return usable groundwater to beneficial uses (current and future)
where practical. When this is not applied, the Superfund strives to prevent further migration and
exposure and to evaluate opportunities for further risk reduction. Groundwater generally is considered
“potable” if it is so designated by the state or considered so under federal drinking water guidelines.
Final cleanup levels should be attained throughout the plume and beyond the edge of any wastes left in place. The “point of compliance” for a surface water body is where the release enters the surface water [29]. Alternate concentration limits (ACLs) may be considered where contaminated groundwater discharges to surface water, in which contaminated groundwater does not lead to an increase in contaminants of surface water, where enforceable measures are available to prevent exposure to groundwater, or where restoring groundwater is “not practicable” [36]. The Environmental Protection Agency of the United States (USEPA) expects to use treatment to address “principal threats” posed by site where practical.

This guidance document describes key principles and expectations, interspersed with “best practices” based on program experience that should be consulted during the Superfund remedy selection process. These remedy selection “rules of thumb” are organized into three major policy areas:

1. Risk assessment and management
2. Developing remedial alternatives
3. Groundwater response actions

The purpose of this guide was to briefly summarize key elements of various remedy selection guidance documents and policies in one publication. The USEPA believes that consistent application of national policy and guidance is an important means by which we ensure the reasonability, predictability, and cost-effectiveness of our decisions [32]. The RCRA has similar requirements to the Superfund with respect to returning usable groundwater to beneficial uses, points of compliance for groundwater and surface water, protection of surface water from contaminated groundwater, provisions for ACLs (but without an explicit link to “practicability”), and treatment of principal threats. If current human exposures are under control and no further migration of contaminated groundwater is expected, primary near-term goals are established using two environmental indicators [35]. Surface water becomes the boundary if the discharge of contaminated groundwater is within “protective” limits.

In summary, the majority of contaminated sites have serious potential to affect surface waters. The federal framework allows for risk-based decision making (RBDM) with respect to GSWI, but we must still achieve the expectation of restoring groundwater to beneficial use and ensure discharges of groundwater to surface water are protective. Key policy issues to ponder and to pass to senior managers include [7] the following:

- How to achieve short- and long-term protection
- Where, how, and how often to measure compliance
- Whether to restore groundwater, even if it has no impact to surface water
- The diversity of surface bodies
- The relation of cleanup goals to the Clean Water Act’s National Pollutant Discharge Elimination System (NPDES) approach
- How to account for, track, and communicate total loads in watersheds

These regulatory approaches provided an improved basis for targeted and prioritized action on prevention and cleaning up of the environmental pollution. Developing these approaches, the most recent European directives and North American laws are increasingly risk based. They stress the need to assess the likelihood and magnitude of adverse effects on the wider environment and to develop more sustainable risk-management approaches that balance costs and benefits.

The Water Framework Directive (WFD) is the most significant piece of new legislation on water issues in Europe in recent decades [12]. It seeks to integrate environmental management of the different environmental compartments, such as groundwater, rivers, estuaries, and wetlands, and to set risk-based objectives to protect and improve water quality and resources. The WFD contains a timetable for implementation that includes plans to replace existing but superseded directives by 2013.
13.3 Hydrologic Cycle and GSWI

The hydrologic cycle describes the continuous movement of water above, on, and below the surface of the Earth [41]. Surface water occurs as streams, lakes, and wetlands, as well as bays and oceans. Surface water also includes the solid forms of water, snow, and ice. The water below the surface of the Earth primarily is groundwater, but it also includes soil water.

Surface water bodies are hydraulically connected to groundwater in most types of landscapes; as a result, surface water bodies are integral parts of groundwater flow systems. Even if a surface water body is separated from the groundwater system by an unsaturated zone, seepage from the surface water may recharge groundwater. Because of the interchange of water between these two components of the hydrologic system, the development or contamination of one commonly affects the other. The movement of surface water and groundwater is controlled to a large extent by the physiography of an area [40]. In addition, climate change is expected to affect the hydrologic cycle. The recognition of climate change, through the effects of precipitation, air temperature, and evapotranspiration, affects the distribution of water to landscapes. Groundwater recharge, discharge, storage, saltwater intrusion, biogeochemical reactions, and chemical fate and transport may be modified by climate change. Another thing that is now known is that pollution in groundwater is a more serious situation because (1) groundwater is a major source of drinking water and (2) remediation of groundwater is much harder and much more expensive compared to that of surface water [9].

Therefore, it is necessary to understand the effects of physiography and climate on surface water and groundwater flow systems in order to understand the GSWI.

The hydrologic cycle is commonly shown by a very simplified diagram that shows only major transfers of water between continents and oceans, as in Figure 13.1.

Groundwater moves along flow paths of varying lengths from areas of recharge to areas of discharge [41]. The infiltration of precipitation through the unsaturated zone is the source of groundwater recharge. Groundwater flow systems can be of greatly different sizes and depths, and they can overlie one another. Local flow systems are the most dynamic and shallowest flow systems; therefore, they have the greatest interchange with surface water. When local flow systems are recharged, water table increases and discharges to adjacent lowlands or surface water. Local flow systems can be underlined by intermediate and regional flow systems. Water in these deeper flow systems has the longer flow paths, but they also eventually discharge to surface water. Local flow system discharges in the nearest shore, and larger-magnitude flow systems discharge to surface water further offshore [39]. Because of the different lengths and travel times of water within flow paths, the chemistry of water discharging into the surface water from different flow paths can be substantially different.

In some landscapes, surface water bodies perch at mediocre altitudes between major recharge and discharge areas. Surface water bodies commonly receive groundwater inflow on the upgradient side and have seepage to groundwater on the downgradient side. Furthermore, depending on the distribution and magnitude of recharge in the uplands, the hinge line between groundwater inflow and outflow can move back and forth across the part of the surface water bed.

The distribution of seepage to and from surface water is controlled by (1) the slope of the water table with respect to the slope of the surface water, (2) small-scale geologic features in the beds of surface water, and (3) climate [39].

Small-scale geologic features in beds of surface water bodies affect seepage patterns at scales too small to be shown in Figure 13.2.

Furthermore, seepage patterns can be influenced by the size, shape, and orientation of the sediment grains in surface water beds. In a surface water bed consisting of one sediment type, such as sand, inflow seepage is greatest at the shoreline, and it decreases in a nonlinear pattern away from the shoreline (Figure 13.3) [41].
Geologic units having different permeabilities also affect seepage distribution in surface water beds. For example, a highly permeable sand layer within a surface water bed consisting largely of silt will transmit water preferentially into the surface water as a spring (Figure 13.4) [41].

There is a two-way GSWI. One of the most commonly used forms of groundwater comes from unconfined shallow water table aquifers. These aquifers are major sources of drinking and irrigation water. They also interact closely with streams, sometimes water flowing (discharging) into a stream or lake and sometimes receiving water from the stream or lake. An unconfined aquifer that feeds streams is said to provide the stream’s baseflow (this is called a gaining stream). In fact, groundwater can be responsible for maintaining the hydrologic balance of surface streams, springs, lakes, wetlands, and marshes [11]. This is why successful watershed partnerships with a special interest in a particular stream, lake, or other surface water body always have a special interest in the unconfined aquifer, adjacent to the water body.

The source of groundwater (recharge) is through precipitation of surface water that percolates downward. Approximately 5%–50% (depending on climate, land use, soil type, geology, and many other factors) of annual precipitation results in groundwater recharge [11].
Groundwater flow paths vary greatly in length, depth, and travel time from points of recharge to points of discharge in the groundwater system. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)

Groundwater seepage into surface water usually is greatest near shore. In flow diagrams such as that shown here, the quantity of discharge is equal between any two flow lines; therefore, the closer flow lines indicate greater discharge per unit of bottom area. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)

Subaqueous springs can result from preferred paths of groundwater flow through highly permeable sediments. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)
In some areas, streams literally recharge the aquifer through streambed infiltration, called losing streams. Left untouched, groundwater naturally arrives at a balance, discharging and recharging depending on hydrologic conditions.

Integrative studies to fully understand the dynamics and importance of the groundwater/surface water interface are required that combine hydrogeology, biogeochemistry, and aquatic ecology.

### 13.3.1 Interaction of Groundwater and Streams

The interaction between streams and groundwater takes place in three basic ways:

1. Streams gain water from groundwater through the streambed when the elevation of the water table adjacent to the streambed is greater than that of the stream.
2. Streams lose water to groundwater by outflow through the streambed when the elevation of the water table is lower than that of the stream.
3. A third possibility is that streams may have no flow across their streambed if the stream water and groundwater levels are exactly equal [11].

However, this is a relatively rare coincidence that is unlikely to occur over long reaches for prolonged periods. This variability in streamflow caused by groundwater seepage is often most pronounced around the headwaters of groundwater-fed streams or in stream reaches that go periodically dry due to seepage losses. At times of low groundwater levels, surface flow may only occur due to surface flows in the upper catchment (e.g., from snowmelt) or from stormwater runoff. This flow will contribute seepage through the streambed to the underlying water table. As the water table rises due to general recharge (e.g., rainfall infiltration) to the aquifer, the losing reach may become a gaining reach as the water table rises above the streambed level. Such a change means that the point where groundwater first contributes water to the stream shifts laterally in an upstream direction.

A type of interaction between groundwater and streams takes place in nearly all streams at once, or another is a rapid rise in stream stage that causes water to move from the stream into the stream banks. This process, termed bank storage (Figure 13.5), usually is caused by storm precipitation, rapid snowmelt, or release of water from a reservoir upstream [41].

In addition to bank storage, other processes like pumping may affect the local exchange of water between streams and adjacent shallow aquifers. Changes in streamflow between gaining and losing

![Figure 13.5](image-url)  
**FIGURE 13.5** If stream levels rise higher than adjacent groundwater levels, stream water moves into the stream banks as bank storage. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)
conditions can also be caused by pumping groundwater near streams. Pumping can intercept groundwater that would have otherwise been discharged to a gaining stream or at higher pumping rates could have induced flow from the stream to the aquifer.

13.3.2 Interaction of Groundwater and Lakes

Lakes interact with groundwater in three basic methods. Lakes can receive groundwater inflow throughout their entire bed, have outflow throughout their entire bed, or possess both inflow and outflow at different localities (Figure 13.6) [41].

Although these basic interactions are the same for lakes and streams, the interactions differ in several ways [11]. The water level of natural lakes generally does not change as rapidly as the water level of streams; therefore, bank storage is of lesser importance in lakes than it is in streams [41].

Evaporation generally has a greater effect on lake levels than on stream levels because the surface area of lakes is generally larger and less shaded than many reaches of streams and because lake water is not replenished as readily as a reach of a stream. Lakes can be present in many different parts of the landscape and can have complex groundwater flow systems associated with them. This is especially true for lakes in glacial and dune terrain, as it is discussed later in an upcoming section of this chapter. Furthermore, lake sediments commonly have greater volumes of organic deposits than streams. These poorly permeable organic deposits can affect the distribution of seepage and biogeochemical exchanges of water and solutes more in lakes than in streams.

13.3.3 Interaction of Groundwater and Wetlands

GSWIs constitute an important link between wetlands and the surrounding catchment. Wetlands may develop in topographic lows where groundwater discharges. This water has its functions for ecological processes within the wetland, while surface water outflow from the wetland may provide water downstream. Wetlands may also receive inflowing surface water, which may become relatively stagnant giving rise to groundwater recharge. This transition of surface water to groundwater provides groundwater resources for human and ecological purposes further down the groundwater basin. Wetlands are present in climates and landscapes that cause groundwater to discharge to land surface or that prevent rapid drainage of water from the land surface. Similar to streams and lakes, wetlands can receive groundwater inflow, recharge groundwater, or do both. Those wetlands that get depressions in the land surface have interactions with groundwater similar to lakes and streams. Unlike streams and lakes, however, wetlands do not always get low points and depressions in the landscape; they also can be made on slopes or even on drainage divides [41].

![FIGURE 13.6](https://example.com/figure13_6.png) Lakes can receive groundwater inflow, lose water as seepage to groundwater, or both. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)
A major difference between lakes and wetlands, with respect to their interaction with groundwater, is the ease with which water moves through their beds. Lakes commonly are shallow around their perimeter where waves can remove fine-grained sediments, permitting the surface water and groundwater to interact freely. In wetlands, on the other hand, if fine-grained and highly decomposed organic sediments are present near the wetland edge, the transfer of water and solutes between groundwater and surface water tends to be much slower. Another difference in the GSWI for wetlands compared to lakes is determined by rooted vegetation in wetlands [41]. One of the significant interchanges between surface water and pore water can be made with water uptake by roots of emergent plants that results in wetland sediments because fibrous root mat in wetland soils is highly conductive to water flow.

### 13.4 Chemical Interactions of Groundwater and Surface Water

Information on the same parameters for predicting the geochemical fate of contaminants in both groundwater and surface water bodies needs to be collected. Furthermore, we also need to collect the chemical and physical information commonly used in ecological risk assessments and natural attenuation assessments to determine the dominant biological processes and the potential confounding factors in bioassays. Finally, there is a need to collect chemical information that helps locate zones where a groundwater plume or hyporheic flow is entering a surface water body. The hyporheic zone (HZ) is a region beneath and alongside a streambed, where there is mixing of shallow groundwater and surface water. The flow dynamics and behavior in this zone termed hyporheic flow is recognized to be important for GSWI. There is an overlap among these parameters, but it should be noted that the three different uses of chemical information are basically contaminant chemistry and fate, biological processes, and identification of flow paths [34].

The transport of dissolved contaminants from surface water into the subsurface through hyporheic flow or groundwater recharge from a losing stream is included in our discussion in this chapter.

#### 13.4.1 Chemical Evolution of Groundwater in Drainage Basins

The characterization, interpretation, and understanding of groundwater geochemistry are essential not only to identify groundwater quality but also to comprehend and characterize the water–rock interactions controlling the basic hydrochemistry [23].

Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with these materials. Chemical reactions that affect the biological and geochemical characteristics of a basin include acid–base reactions, precipitation and dissolution of minerals, sorption and ion exchange, oxidation–reduction reactions, biodegradation, and dissolution (specifically gases) [41]. When water first infiltrates the land surface, microorganisms in the soil have a significant effect on the evolution of water chemistry. Organic matters in soils are degraded by microbes, producing high concentrations of dissolved carbon dioxide (CO₂). This process lowers the pH by increasing the carbonic acid (H₂CO₃) concentration in the soil water. The production of carbonic acid starts a number of mineral-weathering reactions, which result in bicarbonate (HCO₃⁻) commonly, being the most abundant anion in the water [41]. Where the contact times between water and minerals in shallow groundwater flow paths are short, the dissolved solid concentration in the water generally is low. In such settings, limited chemical changes take place before groundwater is discharged to surface water.

In deeper groundwater flow systems, the contact time between water and minerals is much longer than of shallow flow systems [41]. As a result, the initial importance of reactions relating to microbes in the soil zone may be superseded over time by chemical reactions between minerals and water.

Hydrogeochemical modeling of the water draining an aquifer not only can characterize their spatial and temporal variations but can also be useful in understanding the interactions between groundwater and the aquifer matrix.
13.4.2 Chemical Interactions of Groundwater with Other Water Resources

Groundwater and surface water chemistry cannot be dealt with separately where surface and subsurface flow systems interact. The movement of water between groundwater and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems [11]. The transfer of chemicals affects the supply of carbon, oxygen, nutrients such as nitrogen and phosphorus, and other chemical constituents that enrich biogeochemical processes on both sides of the interface. This transfer can ultimately affect the biological and chemical characteristics of aquatic systems downstream [41].

Many streams are contaminated. Therefore, the need to determine the extent of the chemical reactions that take place in the HZ is widespread because of the concern that the contaminated stream water will contaminate shallow groundwater. Streams offer good examples of how interconnections between groundwater and surface water affect chemical processes [34]. Rough channel bottoms cause stream water to enter the streambed and to mix with groundwater in the HZ. This mixing establishes sharp changes in chemical concentrations in the HZ.

A zone of enhanced biogeochemical activity usually develops in shallow groundwater as a result of the flow of oxygen-rich surface water into the subsurface environment, where bacteria and geochemically active sediment coatings are abundant (Figure 13.7). This input of oxygen to the streambed stimulates a high level of activity by aerobic microorganisms if dissolved oxygen is readily available [41]. It is not uncommon for dissolved oxygen to be completely used up in hyporheic flow paths at some distance into the streambed, where anaerobic microorganisms dominate microbial activity. Anaerobic bacteria can use nitrates, sulfates, or other solutes in place of oxygen for metabolism. The result of these processes is that many solutes are highly reactive in shallow groundwater in the vicinity of streambeds.

Biogeochemical processes in the HZ affect the movement of nutrients and other chemical constituents, including contaminants, between groundwater and surface water. For example, the rate at which organic contaminants biodegrade in the HZ can exceed rates in stream water or in groundwater away from the stream. Another example is the removal of dissolved metals in the HZ [41]. As water passes through the HZ, the dissolved metals are removed by precipitation of metal oxide coatings on the sediments.

![Figure 13.7](image_url)
Lakes and wetlands have also the distinctive biogeochemical characteristics with respect to their interaction with groundwater. The chemistry of groundwater and the direction and magnitude of exchange with surface water significantly affect the input of dissolved chemicals to lakes and wetlands. In general, if lakes and wetlands have little interaction with streams or with groundwater, the input of dissolved chemicals is mostly from precipitation; thus, the input of chemicals is at least. Lakes and wetlands that have a considerable amount of groundwater inflow generally have large inputs of chemicals is minimal because in this case, single source for entering dissolved chemicals. In cases where the input of dissolved nutrients such as phosphorus and nitrogen exceeds the output, primary production by algae and wetland plants is large. When this large amount of plant material dies, oxygen is used in the process of decomposition [11]. In some cases, the loss of oxygen from lake water can be large enough to kill fish and other aquatic organisms.

The magnitude of surface water inflow and outflow also affects the retention of nutrients in wetlands. If lakes or wetlands have no stream outflow, the retention of chemicals is high. The tendency to retain nutrients usually is less in wetlands that are flushed substantially by throughflow of surface water. In general, as surface water inputs increase, wetlands vary from those that strongly retain nutrients to those that both import and export large amounts of nutrients [11]. Furthermore, wetlands commonly have a significant role in altering the chemical form of dissolved constituents.

13.5 GSWI in Different Landscapes

Groundwater and surface water interact throughout the landscape. Groundwater interacts with all types of surface water, such as streams, lakes, and wetlands, in many different terrains, from mountains to oceans. Some common features of the interaction for various parts of the conceptual landscape are described in the succeeding text. The five general types of terrain discussed are mountainous, riverine, coastal, glacial and dune, and karst.

13.5.1 Mountainous Terrain

An overview of GSWI in mountainous terrain is presented by Silar [26] and extended by Bencala et al. [4]. The hydrology of mountainous terrain is characterized by highly variable precipitation and water movement over and through the steep land slopes.

A general concept of water flow in mountainous terrain includes several pathways by which precipitation moves through the hillside to a stream. The water from precipitation moves to mountainous streams along several pathways. Between storms and snowmelt periods, most inflow to streams is commonly from groundwater. During storms and snowmelt periods, much of the water inflow to the streams is from shallow flow in saturated macropores in the soil zone. If infiltration to the water table is large enough, the water table will rise to the land surface and the flow to the stream is from groundwater, soil water, and overland runoff. In arid areas where soils are very dry and plants are sparse, infiltration is impeded and runoff from precipitation can occur as overland flow.

Near the base of some mountain sides, the water table intersects the steep valley wall some distance up from the base of the slope. These activities result in perennial discharge of groundwater and, in many cases, the presence of wetlands (Figure 13.8) [41].

Another aspect of GSWI in mountain settings is caused by the marked longitudinal component of flow in mountain valleys. The high gradient of mountain streams, coupled with the coarse texture of streambed sediments, results in a strong downvalley component of flow accompanied by frequent exchange of stream water with water in the HZ.

Favorable new methods of estimating groundwater recharge, along mountain fronts, are being developed. These methods include the use of environmental tracers, measuring vertical temperature profiles in streambeds, measuring hydraulic characteristics of streambeds, and measuring the difference in hydraulic head between the stream and underlying aquifer.
Water extraction facilities have to be protected against erosion and are often placed near the stream or even in the streambed as not much space is available [15]. Therefore, low pumping rates and short residence times of the bank filtrate are typical for mountainous regions.

The geochemical environment of mountains is quite diverse owing to the effects of highly variable climate and many different rocks and soil types on the evolution of water chemistry. Geologic materials can include crystalline, volcanic, and sedimentary rocks and glacial deposits [41]. During heavy precipitation, much water flows through shallow flow paths, where it interacts with microbes and soil gases. In the deeper flow through fractured bedrock, longer-term geochemical interactions of groundwater with minerals determine the chemistry of water that eventually discharges to streams. The baseflow of streams in mountainous terrain is derived by drainage from saturated alluvium in valley bottoms and from drainage of bedrock fractures.

13.5.2 Riverine Terrain

In some landscapes, stream valleys are small and they usually do not have well-developed flood plains. However, the major rivers have valleys that often become increasingly wider at the downstream. Terraces, natural levees, and abandoned river meanders are common landscape features in major river valleys, and wetlands and lakes are normally associated with these features [15]. Riverine alluvial deposits range in size from clay to boulders, but in many alluvial valleys, sand and gravel are the predominant deposits, offering high yields of well fields adjacent to the river.

For larger rivers that flow in alluvial valleys, GSWI usually is more spatially diverse than it is for smaller streams. Groundwater from regional flow systems discharges to the river as well as at various places across the flood plain (Figure 13.9). If terraces are present in the alluvial valley, local groundwater flow systems may be associated with each terrace, and lakes and wetlands may be formed because of

**FIGURE 13.8** In mountainous terrain, groundwater can discharge at the base of steep slopes (left side of valley), at the edges of flood plains (right side of valley), and to the stream. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)
this source of groundwater [41]. At some locations, such as at the valley wall and at the river, local and regional groundwater flow systems may discharge in close proximity. Furthermore, in large alluvial valleys, significant downvalley components of the flow in the streambed and in the shallow alluvium also may be present.

For a river, GSWI is often described as of gaining or losing conditions. Rivers can exhibit both gaining and losing conditions in different reaches or at different times of the year within the same reach. Long losing stretches cause the extensive redox zones to develop and have a higher microbial activity within this zone compared to that of a zone under gaining conditions, since the nutrient-poor groundwater enters the river in the gaining stretches [15].

Chemical reactions including dissolution or precipitation of minerals commonly do not have a significant effect on water chemistry in sand and gravel alluvial aquifers because the rate of water movement is relatively fast compared to weathering rates. On the other hand, sorption and desorption reactions as well as oxidation/reduction reactions related to the activity of microorganisms probably have a greater effect on the water chemistry in these systems. As in small streams, biogeochemical processes in the HZ may have a significant effect on the chemistry of groundwater and surface water in larger riverine systems [41]. The movement of oxygen-rich surface water into the subsurface, where chemically reactive sediment coatings are abundant, causes increased chemical reactions relevant to the microorganisms' activity.

### 13.5.3 Coastal Terrain

Coastal terrain extends from inland scarps and terraces to the ocean. This terrain is characterized by low scarps and terraces that were formed when the ocean was higher than present time such as streams, estuaries, and lagoons that are affected by tides; ponds that are commonly associated with coastal sand dunes; and barrier islands. Wetlands cover extensive areas in some coastal terrains.

GSWI in coastal terrain is affected by discharge of groundwater from regional flow systems and from local flow systems associated with scarps and terraces (Figure 13.10), evapotranspiration, and tidal flooding. The local flow systems associated with scarps and terraces are caused by the configuration of the water table near these features. Where the water table has a downward break in slope near the top of scarps and terraces, downward components of groundwater flow are present, and where the water table has an upward break in slope near the base of these features, upward components of groundwater flow are present [41].
Evapotranspiration directly from groundwater is widespread in coastal terrain. The land surface is flat and the water table generally is close to land surface. Therefore, many plants have root systems deep enough to transpire groundwater at nearly the maximum potential rate. The result is that evapotranspiration causes a significant water loss, which affects the configuration of groundwater flow systems as well as how groundwater interacts with surface water. In the parts of coastal landscapes that are affected by tidal flooding, GSWI is similar to that of alluvial valleys affected by flooding. The principal difference between the two is that tidal flooding is more predictable in both timing and magnitude than river flooding [41]. The other significant difference is in water chemistry. The water that moves into bank storage from rivers is generally fresh, but the water that moves into bank storage from tides generally is brackish. Estuaries are a highly dynamic interface between the continents and the ocean, where discharge of freshwater from large rivers mixes with saline water from the ocean. In addition, groundwater discharges to estuaries and the ocean, delivering nutrients and contaminants directly to coastal waters. However, few estimates of the location and magnitude of groundwater discharge to coasts have been made.

Many wetlands exist along streams, especially slow-moving streams. Although these riverine wetlands commonly receive groundwater discharge, they are dependent primarily on the stream for their water supply. Wetlands in riverine and coastal areas have especially complex hydrologic interactions because they are subject to periodic water-level changes. Some wetlands in coastal areas are affected by very predictable tidal cycles. Other coastal and riverine wetlands are more affected by seasonal water-level changes and by flooding. The combined effects of precipitation, evapotranspiration, and GSWI result in a pattern of water depths in wetlands that is distinctive.

Hydroperiod is a term commonly used in wetland science that refers to the amplitude and frequency of water-level fluctuations. Hydroperiod affects all wetland characteristics, including the type of vegetation, nutrient cycling, and the types of invertebrates, fish, and bird species present [41]. The driving force of these interactions is the yearly flood season giving rise to extensive groundwater recharge. The infiltrated flood waters are transported as groundwater to wetland islands bordering the river delta channels driven by the evaporative force of island plants [25].
13.5.4 Glacial and Dune Terrain

Glacial and dune terrain is characterized by a landscape of hills and depressions. Although stream networks drain parts of these landscapes, many areas of glacial and dune terrain do not supply runoff to an integrated surface drainage network [15].

A common conception is that the lakes and wetlands that are present in topographically high areas recharge groundwater and that the lakes and wetlands that are present in low areas receive discharge from groundwater.

However, the lakes and wetlands underlain by deposits having low permeability can receive discharge from local groundwater flow systems even if they are located in a regional groundwater recharge area. As an overall result, in glacial and dune terrain, local, intermediate, and regional groundwater flow systems interact with lakes and wetlands. It is not uncommon for wetlands that receive recharge from local groundwater flow systems to be present in lowlands and for wetlands that receive discharge from local groundwater flow systems to be present in uplands (Figure 13.11).

Lakes and wetlands in glacial and dune terrain underlain by highly permeable deposits commonly have groundwater to seepage on one side and seepage to groundwater on the other side.

Transpiration directly from groundwater has a significant effect on the interaction of lakes and wetlands with groundwater in glacial and dune terrain [41]. Transpiration from groundwater has perhaps a greater effect on lakes and wetlands underlain by low-permeability deposits than in any other landscape.

The hydrologic and chemical characteristics of lakes and wetlands in glacial and dune terrain are determined to a large extent by their position with respect to local and regional groundwater flow systems [41].

13.5.5 Karst Terrain

A type of landscape that needs special attention is the areas underlain by limestone and dolomite. These landscapes, referred to as karst terrains, normally have fractures and solution openings that become larger with time because of dissolution of the rocks.

Karst terrains are characterized by closed surface depressions of various sizes and shapes known as sinkholes [41].

Water moves at different rates through karst aquifers; it moves slowly through fine fractures and pores and rapidly through solution-enlarged fractures and conduits.

Typically, karst terrain forms where water has dissolved and eroded soluble bedrock particularly carbonate rocks such as limestone and dolomite and gypsum, by enlarging cracks into underground conduits that can enlarge into caverns and sometimes collapse to form sinkholes.

**FIGURE 13.11** In glacial and dune terrain, local, intermediate, and regional groundwater flow systems interact with lakes and wetlands. It is not uncommon for wetlands that receive recharge from local groundwater flow systems to be present in lowlands and for wetlands that receive discharge from local groundwater flow systems to be present in uplands. (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)
Collapse sinkholes usually occur progressively. For example, the process of collapse has been shown in Figure 13.12.

The dissolution of limestone and dolomite guides the initial development of fractures into solution holes that are diagnostic of karst terrain. Perhaps nowhere else is the complex interplay between hydrology and chemistry so important to changes in landform. Limestone and dolomite weather quickly, producing calcium and magnesium carbonate waters that are relatively high in ionic strength. The increasing size of solution holes allows higher groundwater flow rates across a greater surface area of exposed minerals, which stimulates the dissolution process further, eventually leading to the development of caves. The development of karst terrain also involves biological processes [41].

Microbial production of carbon dioxide in the soil affects the carbonate equilibrium of water as it recharges groundwater, which then affects how much mineral dissolution will take place before solute equilibrium is reached.

**FIGURE 13.12** Process of collapse sinkholes. (a) Water works its way through the “vadose” zone above the water table through joints and cracks in the limestone bedrock. The slightly acidic water erodes the carbonate-rich rock. (b) Small passages grow into caverns as water continues to dissolve and carry away rock. (c) If the cavern ceiling grows thin enough, or it otherwise cannot support the weight of the rock and soil above, it collapses into a sinkhole. (From Karst and Coastal Landscape, Forms and processes of collapse sinkholes, www.caves.org/conservancy/mkc/about_karst)
Chemical process for calcium–carbonic acid equilibrium is included in the following phases:

Finally, carbonic acid is produced, which dissolves calcium carbonate [28]:

\[
\begin{align*}
\text{H}_2\text{O} + \text{CO}_2 & = \text{H}_2\text{CO}_3 = \text{H}^{+} + \text{HCO}_3^{-} \\
\text{CaCO}_3 + \text{H}_2\text{CO}_3 & = \text{Ca}^{2+} + 2(\text{HCO}_3^{-})
\end{align*}
\]

Water movement in karst terrain is especially unpredictable because of the many paths groundwater takes through the maze of fractures and solution openings in the rock. Because of the large size of interconnected openings in well-developed karst systems, karst terrain can have true underground streams.

Water chemistry is widely used for studying the hydrology of karst aquifers. Extensive tracer studies and field mapping to locate points of recharge and discharge have been used to estimate the recharge areas of springs, rates of groundwater movement, and the water balance of aquifers [41]. Variations in parameters such as temperature, hardness, calcium/magnesium ratios, and other chemical characteristics have been used to identify areas of groundwater recharge, differentiate rapid- and slow-moving groundwater flow paths, and compare spring flow characteristics in different regions.

13.6 Delineation and Field Technology of the Hyporheic Zone

The term hyporheic is derived from Greek roots hypo, meaning under or beneath, and rheos, meaning a stream (rheo means to flow). It is a middle zone bordered by the surface water of the stream or river above and by the true groundwater below. Although it receives water from both of these sources, the relative strengths of input depend on the configuration of the bed materials and interstitial flow paths and on the prevailing hydraulic heads. These heads vary spatially and seasonally to alter hyporheic habitat volume and to produce ragged-edged boundaries to the zone [37].

Some common themes in the definitions of the HZ in the literature are as follows:

- It is the zone below and adjacent to a streambed in which water from the open channel exchanges with interstitial water in the bed sediments.
- It is the zone around a stream in which fauna characteristic of the HZ (the hyporheos) is distributed and alive.
- It is the zone in which groundwater and surface water mix [27].

HZs in sediments adjacent to streams are usually defined as one of the three ways [22]. In the geochemical definition, an HZ must contain at least 10% surface water. This surface water delivers nutrients, including dissolved organic carbon (DOC), to hyporheic sediments. The influx of nutrients from surface waters is reflected in the biological definition, in which the presence of macroinvertebrate riverine fauna delineates the HZ. This faunal population is distinct from typically subterranean species. The hydraulic definition includes a return of hyporheic water (and solutes) to surface water, encompassing hydrologic flow paths that begin and end in the stream [14].

The majority of authors in the freshwater ecology literature emphasize the importance of the HZ as a dynamic ecotone. For example, Boulton and Foster [5] describe the HZ as “an active ecotone between surface and groundwater,” in which water, nutrients, and organic matter exchange occurs as a result of hydraulic and chemical gradients, topography, and sediment lithology.

To the hydrogeologist, the HZ is a part of the groundwater system. The conventional definition of groundwater is “water beneath the surface of the ground in the saturation zone and in direct contact with the ground or subsoil” (Council of the European Community [27]).

The HZ is a 3D aquatic interstitial ecotone formed within the mixed substrate particles that comprise the bed of a natural, running water channel (Figure 13.13).
This chapter adopts a conceptual definition of the Environment Agency’s concentration on the attenuation of pollutants at the groundwater–surface water interface [31].

Water-saturated transitional zone between surface water and groundwater is an ecotone with hydraulic and biogeochemical gradients in which there is often mixing of the respective waters, and as a habitat for living organisms, it can play an important and protective role for both surface and groundwater [27]. It is often characterized by the presence of dense microbial communities (relative to a typical aquifer population), variably high organic matter concentrations, and a faunal assemblage distinct from both stream channel and true groundwater.

The most important ecological parameters and services that cause groundwater–surface water interface are as follows:

- Controlling the flux and location of water exchange between stream and subsurface
- Providing a habitat for benthic and interstitial organisms
- Providing a spawning ground and refuge for certain species of fish
- Providing a rooting zone for aquatic plants
- Providing an important zone for the cycling of carbon, energy, and nutrients
- Providing a natural attenuation zone for certain pollutants by biodegradation, sorption, and mixing
- Moderating river water temperature
- Providing a sink/source of sediment within a river channel [32].

Hyporheic sampling techniques roughly fall into four categories (Table 13.1). Unfortunately, virtually all of these samplers have limitations. For example, well digging cannot be used in midstream and is not very quantitative, freeze cores may drive organisms away as they form, mechanical corers may have depth or substrate particle size limitations, and artificial substrates may fail to reestablish natural sediment profiles and/or detrital components [34]. Further, many of these samplers have neither been evaluated in more than one location nor evaluated against each other.
Major pathways of water movement through riparian areas are as follows: (1) groundwater flow, (2) overland flow and shallow subsurface flow from adjacent uplands, and (3) in stream water sources such as overbank flow, bank storage, and hyporheic exchange. Streambeds and banks are unique environments because they are where groundwater that drains much of the subsurface of landscapes interacts with surface water. “Hyporheic exchange” is the term given to the process of water and solute exchange in both directions across a streambed [38]. The direction of seepage through the bed of streams commonly is related to abrupt changes in the slope of the streambed or to meanders in the stream channel (Figure 13.14). This process creates subsurface environments that have variable proportions of water

TABLE 13.1  Four Main Categories of Hyporheic Samplers

<table>
<thead>
<tr>
<th>Main Categories</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digging of small wells</td>
<td>In the exposed (above water) areas of gravel bars and stream margins to reach the water table and then straining the interstitial water so exposed through a fine-mesh net</td>
</tr>
<tr>
<td>Freeze cores</td>
<td>That use chemicals such as liquid nitrogen, liquid carbon dioxide, or a mixture of “dry ice” (crushed solid carbon dioxide) and acetone or alcohol to freeze the substrate around a standpipe driven into the bed</td>
</tr>
<tr>
<td>Mechanical corers</td>
<td>That, when driven into the bed, either isolate a sample of the surrounding substratum and its fauna for subsequent removal or suck up interstitial water and organisms from a desired depth</td>
</tr>
<tr>
<td>Artificial substrate samplers</td>
<td>That involve placing a sterilized portion of natural streambed into perforated containers that are sunk into the bed and then removed after a desired period of colonization</td>
</tr>
</tbody>
</table>

13.6.1 Hyporheic Exchange

Surface water exchange with groundwater in the HZ is associated with abrupt changes in streambed slope (a) and with stream meanders (b). (From Winter, T.C. et al., Groundwater and surface water: A single resource, U.S. Geological Survey Circular 1139, p. 79, 1998.)
from groundwater and surface water. Depending on the type of sediment in the streambed and banks, the variability in slope of the streambed, and the hydraulic gradients in the adjacent groundwater system, the HZ can be as much as several feet in depth and hundreds of feet in width. The dimensions of the HZ generally increase with increasing width of the stream and permeability of streambed sediments.

Because of this mixing between groundwater and surface water in the HZ, the chemical and biological characters of the HZ may differ markedly from adjacent surface water and groundwater [41]. Although most works related to hyporheic-exchange processes have been done on streams, processes similar to hyporheic exchange also can take place in the beds of some lakes and wetlands because of the reversals in flow caused by focused recharge and transpiration from groundwater near surface water, as discussed earlier. Therefore, it is not enough to know only the relationship of surface water to groundwater flow systems and to small-scale seepage patterns in surface water beds, because hyporheic-exchange processes also can be important in some types of landscapes [38].

13.6.2 Chemical Processes in the Hyporheic Zone

Chemical and microbial substances in the environment are subject to a range of physical, chemical, and biological processes that often act to decline concentration and mass. Within the subsurface environment, processes that act to degrade pollutants or retard their movement through soils or aquifers are named “natural attenuation” processes [30]. The U.K. Environment Agency [31] has defined natural attenuation within groundwater systems as:

The effect of naturally occurring physical, chemical and biological processes, or any combination of those processes to reduce the load, concentration, flux, or toxicity of polluting substances in groundwater.

For natural attenuation to be effective as a remedial action, the rate at which those processes occur must be sufficient to prevent polluting substances entering identified receptors and to minimize the expansion of pollutant plumes into currently uncontaminated groundwater. Dilution within a receptor, such as in a river or borehole, is not natural attenuation [31].

Natural attenuation processes are commonly considered as part of the assessment of risks associated with contaminated groundwater or soils.

Metals and other nondegradable cations are normally attenuated as a result of sorption onto clay minerals and oxides and/or hydroxides, complexation, and precipitation of insoluble metal compounds.

The conditions present in the HZ, such as steep chemical (e.g., redox) gradients; dynamic exchange of oxygen, carbon, and nutrients from the stream channel; a dense microbial and invertebrate community; and potential for elevated water temperatures (both relative to aquifer conditions), mean that attenuation processes may be more rapid in hyporheic sediments than in aquifer sediments [27]. However, the residence time in the HZ is likely to be small relative to that in an aquifer.

Cycling of diffuse pollutants plays a significant role on natural attenuation in hyporheic region. Nitrogen, along with carbon, oxygen, hydrogen, and phosphorus, is the most important element in living matter.

13.6.2.1 Dissolved Organic Nitrogen

Nitrogen is a vital component of proteins and nucleic acids and contains around 10% of the dry-weight mass of bacteria [8]. Bacteria, fungi, algae, and plants assimilate nitrogen as nitrate, $\text{NO}_3^-$, or ammonium, $\text{NH}_4^+$. Dissolved organic nitrogen (DON) is usually rare in pristine aquatic environments, and in consequence nitrogen is often the limiting variable in biological productivity. Most nitrogen is bound to organic matter and is not bioavailable. Nitrogen assimilation is generally via mineralization of $\text{NH}_4^+$, which can be taken up or converted into nitrate by bacteria.

Nitrate is recognized to be the most important pollutant of groundwater being produced mainly from agriculture activities, because the excessive levels of nitrate are dangerous for human life and environment. Treatment of contaminated water is also hard or sometimes impossible [10]. Therefore, investigating nitrate pollution in groundwater has been found very necessary.
13.6.2.2 Dissolved Organic/Inorganic Phosphorus

There is an extensive literature on phosphorus dynamics in lakes, wetlands, streams, and marine environments but relatively little on the HZ or aquifer environments [22].

Phosphorus, P, is often a limiting nutrient in aquatic systems and is subject to complex processes that control its speciation, sorption, and fate. In aquatic systems, P may be present in a number of forms. It is usual to classify P into dissolved and particulate forms, which can then be further subdivided [27]. Dissolved P is either dissolved inorganic P (DIP), which is generally bioavailable, or dissolved organic P (DOP), which includes colloidal organic P (generally unavailable to biota until it is converted into DIP).

13.6.2.3 Dissolved Organic Carbons

The quality, or chemical and physical character, of DOC affects the degree to which it is transformed by biological and chemical processes [14]. In turn, the DOC quality affects microbial ecology, metal mobilization in streams, and anthropogenic organic contaminant solubility.

HZs play a significant role in stream nutrient and DOC processing. As a source of organic carbon, DOC is both consumed and produced by biota in streams and HZs and can be a limiting factor in ecosystem metabolism [14]. DOC transformative processes, considerably microbial processing and photodegradation, can occur in the stream channel, but HZ nutrient processing is so significant in riverine DOC metabolism that HZs have been dubbed “the river’s liver” [13] and are generally considered a sink of DOC. GSWI serves as a “control point” for nutrient fluxes with a variety of terminal electron accepting processes active in HZs such as denitrification, iron and sulfate reduction, and methanogenesis [42]. In semiarid catchments with highly variable hydrology, DOC export and biogeochemical activity can be controlled by the degree of connectivity between groundwater and surface water [14].

13.7 Field Methods for Determining GSWI

Measuring GSWI is an important component for integrated river basin management. Numerous methods exist to measure these interactions, which are applied either in the aquifer, in the surface water, or in the transition zone itself. The methods differ in resolution, sampled volume, and the timescales they represent. Often, the choice of methods constitutes a trade-off between resolutions of heterogeneities and sampled subsurface volume. Furthermore, the measurement scale on which a selected technique operates may have a significant influence on the results, leading to differences between estimates obtained from a grid of point measurements and estimates obtained from large-scale techniques. Therefore, a better representation of the local conditions including the effects of scale on measurement results can be achieved by conducting measurements at multiple scales at a single study site. Attention should be paid to distinguish between groundwater discharge and hyporheic-exchange flow. Small-scale flow measurements in the shallow streambed may not suffice to make this distinction, so that additional measurements to identify the water source are necessary.

Approaches that should be considered while developing a conceptual model are as follows [2]:

- Hydrologic approaches are used at a regional scale, over periods of years, and perhaps with a focus on long-term yield and water supply. Rainfall runoff is simulated at the land surface and discharge is computed in networks of rivers and streams. The level in a river or stream is estimated from discharge using a stage discharge or rating curve, and this level is used to compute exchange flows between surface water and groundwater.
- Hydraulic approaches are used at a more local scale, over periods of days and weeks, and perhaps with a focus on flood management. These approaches are based not only on conservation of volume (mass) but also on conservation of energy or momentum, either in 2D in plan or in 1D. They assume a single layer of surface water, with constant head and velocity throughout the water
column in 2D or throughout the cross-sectional area in 1D. Hydraulic approaches are often used to simulate flow in river and stream channels and also on flood plains.

- Hydrodynamic approaches are used in deep or density-stratified water bodies, like mine-pit lakes or tidal estuaries. These approaches are also based on conservation of mass, energy, and momentum. They are applied in 3D or 2D in vertical section, and take into account vertical gradients in head and velocity.

### 13.7.1 Observable Qualitative Indicators of Groundwater Discharge to Surface Water

Various approaches and techniques to measure the GSWI have been studied.

The most common indicators are seeps and springs, infrared mapping, aquatic plants, phreatophytes, unique sediment zones such as mineral precipitates, water color, odor from contaminants, and mapping of lineaments in fractured-rock settings [34].

New techniques to measure regional groundwater discharge such as thermal remote sensing and using noble gases have been developed [16].

Observation of seeps and springs is relatively straightforward if the flow rates are high. In fractured-rock landscapes, mapping of lineaments can be useful if the fractures are open. Groundwater flow concentrated in the fractures enters surface water bodies as springs. In settings where seepage rates are low, it is easier to observe seeps during colder times of the year when groundwater and air temperatures are considerably different, because the water vapor above seeps is visible [34]. The difference in temperature between groundwater and surface water also makes infrared mapping a useful reconnaissance tool, especially in midsummer when the difference in temperatures of groundwater and surface water is at a maximum.

Some chemical constituents dissolved in anoxic groundwater precipitate upon contacting oxygenated surface water. For example, iron and manganese oxides are common indicators of seep areas. Contaminated groundwater commonly has color and odor. Water color and odor from contaminants can be used as an indicator of groundwater inflow, especially if the inflow consists of the contaminated water [34].

Aquatic plants can be indicators of groundwater discharge. In addition to aquatic plants, upland phreatophytic plants near a surface water body are indicators of the presence of groundwater at shallow depths.

Benthic organisms can be indicators of groundwater discharge to surface water. Numerous examples of the relationship of organisms to water flow and chemistry are provided by studies of the HZ beneath streams.

Thermal remote sensing is based on the principle that in shallow groundwater systems, upward fluxes of deep groundwater discharge reduce seasonal temperature variation in layers close to and at the surface. The analysis of satellite-acquired surface thermal data has the potential for estimation of groundwater discharge [3].

This section explores opportunities to apply widely available remotely sensed thermal data to delineate groundwater discharge zones. The approach is based on two fundamental principles:

1. Temperature is a reliable tracer of GSWI.
2. Remotely sensed thermal data may be used to delineate shallow objects with contrasting thermal properties.

The approach does not intend to inspect an absolute temperature at the ground surface. Rather, it is expected that the thermal signature within groundwater discharge zone is likely to be weak, potentially masked by stronger thermal anomalies associated with vegetation, exposure related to topography (mainly slope and aspect), soil type, and meteorological conditions preceding and at the time of remotely sensed data acquisition. Therefore, the approach was focused on defining [3].
• Criteria for image selection when the thermal signatures associated with groundwater discharge zones are most evident
• Adequate image processing targeting to reduce the effect of the aforementioned factors
• Validation of the methods in a data-limited environment

13.7.2 Direct Measurement and Calculated Flow of Water between Groundwater and Surface Water Using Physical Data

Methods for directly measuring the flux of water between groundwater and surface water include the use of seepage meters, minipiezometers, temperature profiles in the sediments, heat-flow meters, hydraulic properties of sediments determined from cores, and direct contact resistivity probes [34].

Large-scale field assessment methods such as hydrograph separation, temperature modeling, and water and solute mass balance also exist where hydrograph separation will overestimate regional groundwater discharge. Thermal modeling of temperature to determine groundwater inflows to streams has potential. Water and solute mass balances work well but can be difficult to apply in complex catchments.

Seepage meters are chambers that are set on the bed of a surface water body. Direct measurements of water flux across the groundwater–surface water interface can be realized by the use of seepage meters. Bag-type seepage meters as proposed by Lee [21] consist of a bottomless cylinder vented to a deflated plastic bag. The cylinder is turned into the sediment, and as water flows from the groundwater to the surface water, it is collected in the plastic bag. To measure the flux, the valve is opened, and the change in water volume in the bag over a given period of time is a measure of flux per that period of time. Seepage meters are perhaps the most commonly used devices to determine the collected volume, the cross-sectional area of the cylinder, and the collection period from which the seepage flux can be calculated. In case of surface water seeping into the sediment, a known water volume is filled into the plastic bag [17]. These bag-type seepage meters have been used extensively in lakes, estuaries, reservoirs, and streams (Figure 13.15) [19].

Minipiezometers are widely used to determine the hydraulic gradient from hydraulic head measurements. Installed in the streambed, piezometers deliver information whether a stream reach is gaining or losing by a comparison of piezometer and stream water level [17]. If the water level in the piezometer is higher than that of the stream, this indicates groundwater flow into the stream, and vice versa. To determine water flux, the hydraulic conductivity of the sediments needs to be determined as well as the cross-sectional area of the flux.

![Figure 13.15](image)

Temperature profiles measured in the transition zone carry information on whether groundwater is discharging to the surface water or surface water is infiltrating to the groundwater [6]. Heat transport in groundwater is a combination of advective heat transport (i.e., heat transport by the flowing water) and conductive heat transport (i.e., heat transport by heat conduction through the solid and fluid phase of the sediment) [17].

Lapham [20] used sediment temperature data to determine flow rates and hydraulic conductivity of the sediments based on fundamental properties of heat transport. Heat-flow meters, consisting of a heating element and a ring of temperature sensors, placed at a distance from the heater, have been used to measure the rate and direction of water movement through sediments [20].

### 13.7.2.1 Calculated from Streamflow Data and Analysis

By stream discharge data or groundwater flow nets, the quantity of water moving between groundwater and surface water can be determined.

The most direct method for determining groundwater inflow or stream losses to groundwater is to make stream discharge measurements at different locations along a stream. The flow net approach is probably the most common method used for determining the GSWI. The term flow net is used broadly herein as any calculation of groundwater flux, including simulation models, that makes use of a network of wells for determining hydraulic gradients, estimates of hydraulic conductivity of the geologic units and sediments, and cross-sectional area of the interface of groundwater and surface water [17]. The accuracy of the values is related to the quantity and quality of the hydrogeologic data and the grid spacing that is justified by these data.

### 13.7.3 Indicators of Flow between Groundwater and Surface Water Using Chemical Data

Tracer-based hydrograph separation using isotopic and geochemical tracers provides information on the temporal and spatial origin of streamflow components [17]. Stable isotopic tracers, such as stable oxygen and hydrogen isotopes, are used to distinguish rainfall event flow from pre-event flow.

Devices for collection of water samples for determination of the chemical characteristics of water passing through sediments consist of two basic types: (1) collection at the sediment–water interface and (2) collection at various depths in the sediment by inserting a device into the sediments [34]. By calculating mass balances of the constituents, the flux of water can be quantified. Isotopes of some elements, such as nitrogen and radon, are particularly useful because in some cases a specific contaminant source can be identified. Isotopes of water are among the most useful because they are part of the water molecule itself and are not subject to modification by chemical reactions [34]. The age of groundwater can be determined by analyzing for tritium and chlorofluorocarbons, which are useful for identifying groundwater flow paths.

The analytical results of the chemical analysis and the statistical parameters such as minimum, maximum, and mean of the geochemical data and hydrochemical data can be compared to current conditions [24].

A list of required parameters and tools for determining GSWI is as follows:

- Semipermeable membrane devices
- Drag probes for temperature, conductivity, and gamma anomalies, useful in lakes, estuaries, and large rivers to determine zones of groundwater discharge
- Piezometers and minipiezometers
- Dye tracers of groundwater and streamflow
- Bead pipes (ceramic beads)
- Walk river bed with a hand auger
- During low flow, note odor and visual observation
- Photoionization detector (PID)
• Passive diffusion samplers
• Analyze bubbles of gas (marsh or lake setting)
• Multilevel samplers
• Seepage meters
• Cores (solid analysis and visual)
• Field chemistry with spectrometer (nitrate, ammonia)
• Chemetrics for sulfides
• Differential global positioning system (GPS)
• Velocity meter
• Tidal stage
• Multilevel wells
• Everything on screening tools list [38]

13.7.3.1 Sampling at the Sediment–Water Interface
Devices that have been developed for sampling water at the sediment–water interface include drag probes, seepage meters, diffusion bags, bubble collectors, and biosensors [17]. Of these devices, seepage meters are the only ones that actually collect a water sample large enough to be analyzed in the laboratory for many constituents.

13.7.3.2 Sampling at Depth in Sediments
Devices that have been developed for sampling or measuring water chemistry at depth in sediments consist of (1) multilevel samplers that are driven into the sediments and (2) probes through which individual samples can be drawn from any depth or a constituent measured but can then be driven deeper to collect samples at other specific depths [17].

13.8 Summary and Conclusions
Recently, due to rapid increase in population and shortage of suitable water, assessing groundwater quality has become an important issue in groundwater studies of the area. For these reasons, a qualitative evaluation of groundwater has been proposed as a basic prerequisite for efficient groundwater resource management. It is important to note that increased knowledge of geochemical evolution of groundwater in the regions could lead to improved understanding of hydrochemical systems, leading to sustainable development of water resources and effective management of groundwater resources.

The overall goal of this chapter was to provide an opportunity for statement scientific and technical backgrounds to discuss the importance of the groundwater/surface water transition zone and help regulators better understand environmental issues relating to the connections between groundwater and surface water.

This chapter provides an overview of the way that GSWI is conceptualized and the methods to design and construction of models that include GSWI. Each of the development stages such as modeling, calibration, and sensitivity analysis was discussed in this chapter with a focus on the specific requirements of GSWI, beyond those of groundwater flow models.

Attention should be given in order to distinguish between groundwater discharge and hyporheic-exchange flows. Small-scale flow measurements in the shallow streambed may not suffice to make this possible; therefore, additional measurements to identify the water source are strongly recommended. Long-term air entrapment affecting runoff and water table observations should be investigated. The application of thermal remote sensing to delineate groundwater discharge zones and coupling the models to optimize the flooding system is necessary to deal with current needs. Groundwater recharge during spring thaw in view of quality and quantity and bank filtration as a managing tool for GSWIs could be also the other research topics of interest.
References


