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GROUNDWATER–SURFACE WATER INTERACTION AS A COMPONENT OF THE ECOHYDROLOGY OF SEMI-ARID REGIONS

J. Y. DIIWU
Alberta Research Council

ABSTRACT

The interaction of groundwater with surface water is an important process for maintaining the ecosystem. The process affects the ecology of surface water by sustaining streamflow during periods of low flow, moderates water level fluctuations of groundwater-connected lakes, and maintains wetlands which serve as habitats for a myriad of wildlife. The interaction also helps to stabilize water temperature as well as concentrations of nutrients and other organic/inorganic compounds in water. Thus, groundwater interaction with surface water helps to provide thermal refuge for aquatic species in semi-arid regions where temperatures may otherwise rise to levels that may be lethal to these species. With the growing demand for the sustainable management and utilization of natural resources, a better understanding of all components of the ecosystem, such as the linkage between groundwater and surface water, becomes imperative. This is even more relevant for the semi-arid regions where the impacts of environmental stresses tend to be more pronounced. This article is therefore intended to review fundamental concepts of the ecohydrology of the interaction of groundwater with surface water, and discuss the relevance of this interaction to the sustainable management of water resources of semi-arid regions.

INTRODUCTION

Groundwater systems are not isolated from surface water systems, but are in continuous dynamic interaction at local, intermediate, and regional scales. The degree of the interaction between groundwater and surface water depends on physiographic and climatic conditions. Irrespective of the degree of the interaction between the two systems, development and/or contamination of one ultimately affects the other, and hence the entire ecosystem [1]. An understanding of the basic principles of the interactions is therefore needed for effective management of water resources. This is even more imperative for semi-arid regions where water resource systems are highly vulnerable due to climate change and anthropogenic activities.

Interest in the relationship of groundwater with streams, lakes, wetlands, and estuaries increased in recent years due to concerns about acid rain, eutrophication, and the disappearance of coastal ecosystems as a result of development [2]. In the last two decades, attention has been focused on exchanges between near-channel and in-channel water, which are necessary for evaluating the ecological structure of streams and for designing stream restoration and riparian zone management programs. The need for a holistic approach to environmental protection has heightened the attention of ecologists, geoscientists, and watershed managers to groundwater interaction with surface water.

The partitioning of precipitation into surface runoff, infiltration, and potential recharge/discharge is highly variable in space and time in semi-arid regions. Understanding the spatial and temporal variability of these processes at a range of scales improves our ability to quantify and manage the available water resources. The recharge/discharge component which links groundwater and surface water systems has received renewed attention in the last few decades. This article is therefore intended to review fundamental ecological and hydrological concepts useful for understanding groundwater interaction with surface water, discuss the relevance of the interaction to the ecology of semi-arid regions, and provide information for further studies of this important pathway between groundwater and surface water systems.

MECHANISMS OF GROUNDWATER INTERACTION WITH SURFACE WATER

Surface and subsurface water interactions occur by subsurface lateral flow through the unsaturated soil and by infiltration into or exfiltration from the saturated zones. Also, in the case of karst or fractured terrain, interactions occur through flow in fracture or solution channels. In general, subsurface flow through porous media is sluggish. The mechanisms by which subsurface flow enters streams quickly enough to contribute to streamflow responses to individual rainstorm and snowmelt inputs are discussed in the literature [1-3]. In particular, four mechanisms that account for fast subsurface contributions to the storm hydrograph have been identified as translatory flow, macropore flow, groundwater ridging, and return flow [3].

Translatory flow, also known as plug flow or piston flow [4], is easily observed by allowing a soil column to drain to field capacity and then slowly adding a unit of water at the top. It would be observed that some water flows from the bottom immediately, but this is not the same water that was added at the top. *Macropore flow* is fast flow through larger noncapillary soil pores, resulting in rapid subsurface responses to storm events [5]. *Groundwater ridging* describes the large and rapid increases in hydraulic head in groundwater during storm events [6]. As a result, an increase occurs in the net hydraulic gradient toward the stream and/or the size of the seepage face, thus enhancing fluxes to the stream. The streamflow contribution induced thereby may greatly exceed the quantity of water input that induced it. *Return flow* is the discharge of subsurface water to the surface. This may result if the water table and capillary fringe are close to the soil surface, such that small amounts of applied water are necessary to saturate the soil surface completely [7]. The response of any particular watershed may be dominated by a single mechanism or by a combination of mechanisms, depending on the magnitude of the storm event, the antecedent soil moisture conditions in the watershed, and/or the heterogeneity in soil hydraulic properties in the watershed [6].

Groundwater Interaction with Streams

Large scale exchange of groundwater with surface water is controlled by the distribution and magnitude of hydraulic conductivities (both within the channel and the associated alluvial plain sediments), the relation of stream stage to the adjacent groundwater leve1, and the geometry and position of the stream channel within the alluvial plain [8]. The direction of the exchange processes varies with hydraulic head, whereas flow depends on sediment hydraulic conductivity. Storm events and seasonal patterns alter the hydraulic head and thereby induce changes in flow direction. Two net directions of flow are: the influent condition where surface water contributes to subsurface flow (losing stream shown in Figure 1), and the effluent condition where groundwater drains into the stream (gaining stream shown in Figure 2).

On one hand, variable flow regimes could alter the hydraulic conductivity of the sediment via erosion and deposition processes and thus affect the intensity of groundwater interaction with surface water [9]. During periods of low precipitation, baseflow in many streams constitutes the discharge. On the other hand, under conditions of high precipitation surface runoff and interflow gradually increase, resulting in higher hydraulic pressures in the lower stream reaches, which cause the river to change from effluent to influent condition, infiltrating its banks and recharging the aquifer. Thus, successive discharge and recharge of the aquifer has a buffering effect on the runoff regimes of rivers [9].

In *perennial* streams, baseflow is more or less continuous, whereby these streams are primarily effluent and flow continuously throughout the year. *Intermittent* streams on the other hand, receive water only at certain times of the year and are either influent (losing) or effluent (gaining), depending on the season.

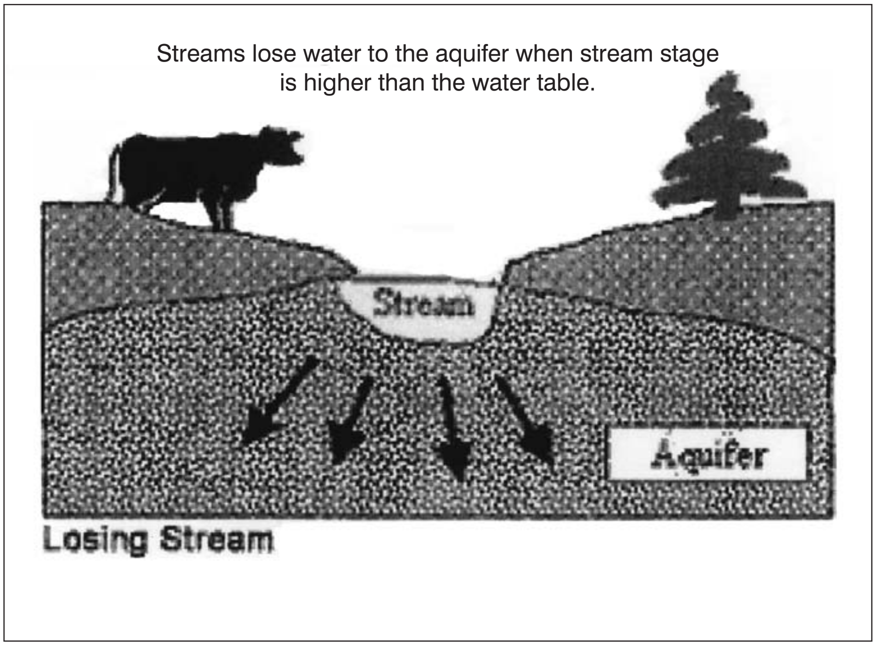

Figure 1. Schematic of a losing stream.

In *ephemeral* streams the groundwater level is always beneath the channel, so they are exclusively influent when they are flowing [10]. The streambed of an ephemeral stream is always separated from the aquifer by the unsaturated zone; thus it is also called a perched or discontinuous stream, shown in Figure 3. This is mostly the case for streams in arid and semi-arid regions.

Groundwater Interaction with Lakes

The hydrologic regime of a lake is strongly influenced by the regional groundwater flow system in which it is located. This interaction plays a critical role when the water budget for the lake is being evaluated. Lakes dominated by surface water typically have inflow and outflow streams, while seepage lakes are groundwater dominated. The type of interactions between groundwater and lakes are generally similar to interactions with streams. The main difference is that lakes have a much larger surface water and bed area. Furthermore, the slower flow-through rates in a lake often result in accumulations of low permeability sediments in the lake floor which can affect the distribution of seepage. As a result, the rate of seepage is often greatest around the lake margin where wave action may restrict the deposition of finer sediments [2]. The rates of groundwater inflow are controlled by watershed topography and the hydrogeologic environment [11].

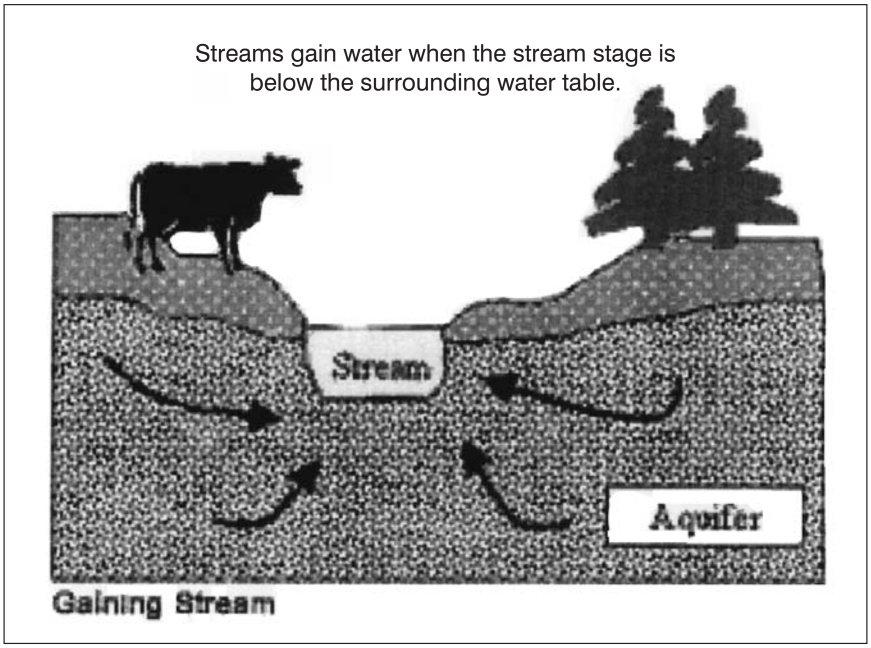

Figure 2. Schematic of a gaining stream.

Groundwater Interaction with Wetlands

Wetlands typically occur in areas where groundwater discharges to the land surface or in areas where ground conditions impede the drainage of water. For situations where impeded drainage occurs, stream depletion effects are unlikely to be significant because the layer impeding drainage is also likely to inhibit the upward transmission of any pumping effects. However, in areas where groundwater springs discharge into wetlands, the pumping from underlying aquifers can affect the amount of groundwater discharge to the wetland [2, 11].

The Hyporheic Zone

The hyporheic zone, shown in Figure 4, is the region of saturated sediment where surface water and groundwater are actively mixing and exchanged [10]. Hyporheic processes occur at a variety of scales, from the small scale exchanges caused by obstacles along the stream bottom to the transit of surface water through buried paleochannels [8]. The measurement of hyporheic and riparian processes have been widely reported in the literature, even though these processes are often studied separately from groundwater-surface water interaction. Since

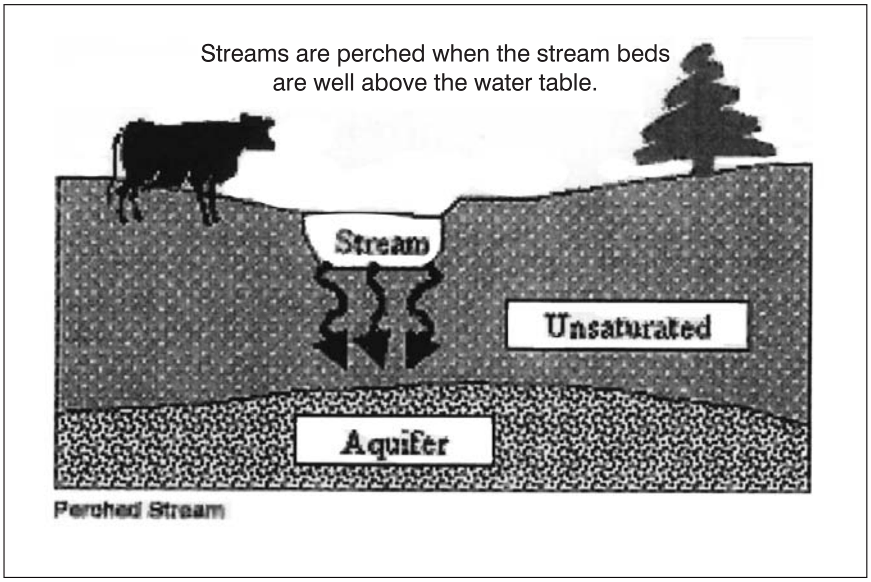

Figure 3. Schematic of a perched stream.

groundwater and hyporheic processes are not independent of one another, to be able to integrate groundwater-surface water interactions into hydrological and ecological models for application in semi-arid regions, there is a need to integrate studies on hyporheic and riparian processes with those on groundwater-surface water interactions [12].

IDENTIFICATION AND MEASUREMENT OF THE INTERACTION

The methods developed so far for measurement of groundwater-surface water interaction are extremely complex, require specialized knowledge to use them, and are resource intensive. Tools for identification of the presence of groundwater interaction with surface water range from inexpensive to resource intensive, and may be moderate to highly complex to use. First, a topographic map and aerial photo, braided channels, ancient stream channels, and dense vegetation may indicate a groundwater-surface water interaction zone. Next, vegetation type, such as cottonwood, and the presence of algae along shallow edges of waterways, may point to a groundwater-surface water interaction zone [10].

Various probes may be used to measure changes within the channel, which may indicate the points of groundwater-surface water interaction. Temperature

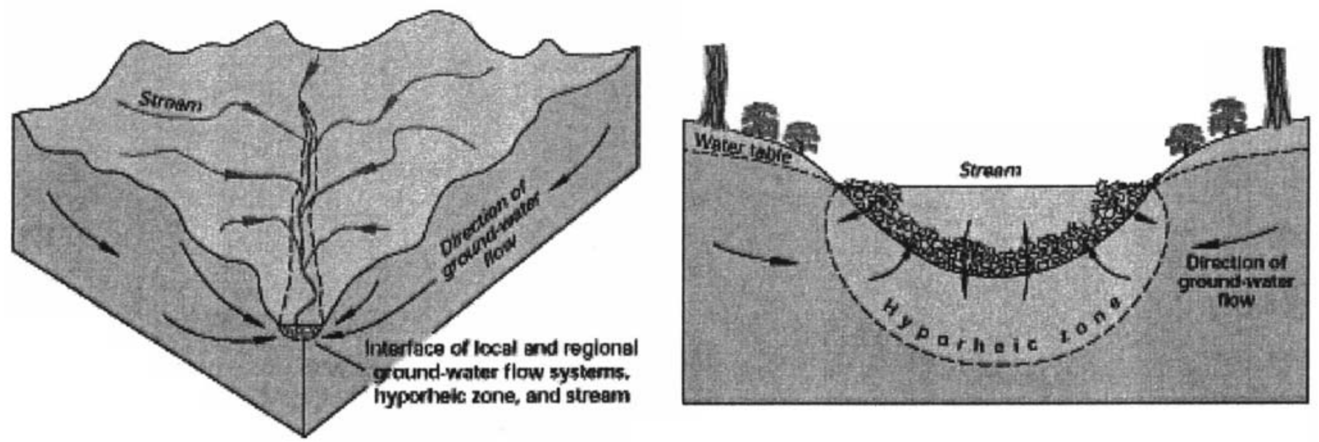

Figure 4. Interaction of the surface water system, the groundwater system, and the hyporheic zone.

probes are commonly used to indicate the influence of groundwater on surface water. Hyporheic probes may be used to measure interstitial flow rates and change in gradient. Also, the potential for groundwater and surface water to interact, which is indicated by change in hydraulic head, may be measured using minipiezometers [9].

The ability to detect and quantify patterns in groundwater-surface water interaction at nested spatial scales may be enhanced through the use of techniques complimentary to measurements using minipiezometers. In particular, accretion studies of streamflow and thermal mapping can compliment minipiezometer use and yield a more complete perspective on valley segment to reach scale patterns of groundwater-surface water interactions at smaller spatial scales [10]. This may involve the use of minipiezometers at a high sampling resolution [13], fine scale measurement of streambed temperature [10], use of seepage meters [14], digging sampling pits and performing dye injections [15], or injection of conservative tracers [10]. Any attempt to characterize patterns of groundwater-surface water interaction can benefit from a multiscale approach, as well as the use of multiple, complimentary methods.

QUANTITATIVE ANALYSIS

The flow of water on the surface and in the unsaturated and saturated zones is driven by gradients from high to low potentials. The hydraulic connection between the stream and groundwater may be direct, as shown in Figures 1 and 2. On the other hand, it may be disconnected by an intervening unsaturated zone, with streams losing water by seepage through a streambed down to a deep water table, as shown in Figure 3. The degree of connection can change over different reaches within any one stream and from time to time over the same reach.

For hydraulically connected stream-aquifer systems, the resulting exchange flow is a function of the difference between the river stage and aquifer head. A simple approach to estimate flow is to consider the flow between the river and the aquifer to be controlled by the same mechanism as leakage through a semi-impervious stratum in one dimension [16]. This mechanism, based on Darcy's law, where flow is a direct function of the hydraulic conductivity and head difference, can be expressed as:

$$q = k\Delta h \tag{1}$$

where $\Delta h = h_a - h_r$, (h_a is aquifer head, and h_r is river head/stage); q is flow between the river and the aquifer (positive for baseflow for gaining streams, and negative for river discharge for losing streams); and k is a constant representing the streambed leakage coefficient (hydraulic conductivity of the semi-impervious streambed stratum divided by its thickness). Equation (1) can be used to represent both baseflow and river discharge, even though in practice the mechanisms representing the two processes can be different.

At times of high recharge, the leakage calculated by the linear relationship in Equation (1) is much greater than would occur in practice and takes no account of water as its volume increases. For such increased resistance to flow a nonlinear relationship of the following form has been proposed [16]:

$$q = k_1 [1 - \exp(- k_2 \Delta h)] \tag{2}$$

where k_1 and k_2 are constants. In cases where the suggestion of a maximum flow rate is not acceptable, a combination of linear and nonlinear relationships of the following form has been proposed [16]:

$$q = k_1 \Delta h + k_2 [1 - \exp(- k_3 \Delta h)] \tag{3}$$

where k_1, k_2 and k_3 are constants.

In semi-arid regions where the aquifer head is lower than the river head most of the time, an exponential relationship with a maximum flow is more appropriate. Under such conditions, channel seepage is often the largest source of recharge. The magnitude of infiltration depends on a variety of factors, such as hydraulic properties of the unsaturated zone, available storage volume in the unsaturated zone, channel geometry and wetted perimeter, flow duration and depth, antecedent soilwater content, clogging layers on the channel bottom, and water temperature.

ECOLOGICAL SIGNIFICANCE

In semi-arid regions where intense runoff occurs in relatively short periods of time, closed topographic depressions of varying sizes are filled by runoff to form ephemeral ponds or wetlands. *Playas* in arid and semi-arid regions are some examples of such ephemeral ponds [9, 10]. As the water level in a pond occupying a depression rises in response to input from overland flow and streamflow, water flows from the pond to groundwater where the adjacent groundwater level is lower than the pond. The period of standing water in the depression, called the *hydroperiod,* affects the species richness of aquatic invertebrates, amphibians, and their predators. From a study of 22 wetlands in various climatic regions, it has been found that amphibian species richness increased with increase in the duration of standing water in the wetlands, but no significant relationship between species richness and wetland size has been found [17]. In semi-arid regions, intense runoff coupled with high evapotranspiration produces wetlands with intermediate duration of interaction with groundwater. This is crucial for biodiversity because such wetlands maintain high productivity by periodic drying, which results in routine recycling of organic materials and nutrients [10, 17].

The hyporheic zone, as shown in Figure 4, is a mixture of surface water and groundwater, and so has physical and chemical characteristics considerably different from stream water. The zone is therefore an ecotone between the surface environment characterized by light, high dissolved oxygen, and temperature fluctuation and the groundwater environment characterized by darkness, less oxygen, and stable temperature [11]. Invertebrates living in the hyporheic zone exploit the groundwater environment to varying degrees. Some species spend their entire life cycle in the hyporheic zone, while others spend their egg and larval stage in the zone, and then move to the surface environment to spend their adult life. A third category of species uses the hyporheic zone only to seek protection from unfavorable situations [11]. The food web of the hyporheic zone is fueled by the heterotrophic microbial communities which depend on dissolved oxygen provided by surface water exchange, particulate organic carbon, and dissolved organic carbon in nutrient-rich groundwater. The microbes provide food for grazers, which in turn provide food for invertebrate predators. Dissolved organic carbon stored in the hyporheic zone can serve as a food source when it is not readily available in surface water, and therefore has a crucial influence on the metabolism of the fluvial ecosystems [9].

The hyporheic zone provides a number of ecologically important services. When surface water recharges groundwater, there is opportunity for organic pollutants and detritus to become trapped in the sediment. The bacteria may then catalyze reactions that could change the chemicals into less toxic forms or into available nutrients. For instance, in contaminated aquifers many bacterial micro-organisms residing in groundwater and sediment interstices can aid in groundwater remediation by degradation and denitrification [9]. During floods, excess water that enters bank storage may percolate to recharge groundwater or may re-emerge at a different location in the watershed and at a different time. These diversions allow the onslaught of water into streams to be delayed by days, weeks, or even months and thus mitigates the effects of flood flows [2, 9]. The interaction of groundwater with surface water within the hyporheic zone also has a thermal service. Since groundwater temperatures remain relatively constant, the water that discharges tends to be cooler than surface water in semi-arid regions. The hyporheic zone therefore serves as a thermal refuge for fish and other aquatic species in semi-arid regions. The zone also serves as a habitat for micro-organisms, macro-invertebrates, fish and wildlife; provides flow augmentation; refugia for endangered aquatic species under conditions of increased fragmentation and degradation of aquatic habitat; and food source for fish in surface water ecosystems and organic matter for microbial activity in groundwater ecosystems [2]. Surface water moving into groundwater is one of the ways in which micro-organisms may colonize groundwater environments. The presence or absence of certain groundwater species may indicate the location of groundwater-surface water interaction zones and a decline in the diversity of groundwater species may indicate a decline in water quality [11]. Groundwater invertebrates and micro-organisms are an important food source for fish, and so the interaction of groundwater with surface water, which determines the availability of such organisms, has the potential to affect the viability of native fish populations [11].

ANTHROPOGENIC IMPACTS AND WATER RESOURCE SUSTAINABILITY

Valley bottoms in semi-arid regions often serve as desirable areas for grazing and agriculture because of continuous availability of soilwater in the unsaturated zone and hence green pasture throughout the year. While these areas have the ability to introduce the cooling effects of groundwater to surface water and continuously make soilwater available in the unsaturated zone, they are also easily degraded by mismanagement. Grazing and agriculture may cause accelerated erosion and soil compaction in the valley bottoms, thus leading to permanent loss of such vital components of the ecosystem in semi-arid regions [11].

In semi-arid regions, crop production requires consumptive use of large quantities of water. Water, which is already scarce, must be shared among several consumptive as well as non-consumptive uses. Consequently, society faces serious water management problems. The decline of groundwater levels due to over-pumping ultimately results in reduced baseflow, which would have discharged into surface water to sustain aquatic life during periods of low flow. At sufficiently large pumping rates, these declines induce flow out of the body of surface water into the aquifer, and this leads to streamflow depletion. As discussed in a previous section, groundwater–surface water interactions are also important in situations of groundwater contamination by polluted surface water, and in situations of degradation of surface water by discharge of saline or other low quality groundwater. Information on groundwater–surface water interaction in semi-arid regions is therefore important for the sustainable management of water resources in those regions.

RESEARCH NEEDS

An understanding of the near-channel and in-channel exchange of water, solutes, and energy is an important key to evaluating the ecological structure of stream systems and their management. Despite the recent increase in research on groundwater–surface water exchange, there are still many related processes that are not well understood. The relative importance of variables affecting the activity of the hyporheic zone at sediment and reach scales over time is unclear, and the spatial and temporal dynamics of groundwater discharge and recharge along active channels in varying geomorphic settings needs to be further investigated [2, 18]. Whereas surface-hyporheic exchanges and water residence times are known to be important regulators of subsurface biochemical transformations, the manner in which these parameters vary across streams and under different climatic conditions, such as semi-arid regions, is not yet known [12].

The effect of heterogeneity on water fluxes in general, and specifically between groundwater and surface water, is still a major challenge. The hydraulic properties of stream and lake beds control the interactions between groundwater and surface water systems, but these properties are normally difficult to measure directly. The primary limitation has so far been the difficulty of spatially defining the hydraulic properties and heterogeneities of a stream and lake beds. Streambed clogging and stream partial penetration are factors which are important as heterogeneity. All these factors need to be considered during analytical treatments of groundwater–surface water interactions [12]. Moreover, the relative importance of streambed clogging, stream partial penetration, and heterogeneity under semi-arid conditions needs to be further investigated [19].

At the current state of research, most techniques and models developed for groundwater–surface water interaction were based on information from humid regions [2]. There is therefore a need to revise such techniques and models utilizing both in-situ and remote sensing observations from semi-arid regions. These techniques also need to be coupled with Geographic Information Systems (GIS) technology and statistical analysis to study groundwater–surface water interactions in semi-arid regions in a multidisciplinary and multiscale approach.

CONCLUSIONS

Knowledge and information on groundwater–surface water interaction at local, intermediate, and regional scales is essential not only for water resource management, but also for the sustainable management of ecosystems. Several examples have been presented in the literature on how exchange between groundwater and surface water affects interface ecology, and how biological communities affect groundwater–surface water interaction under a range of environmental conditions. Studies investigating the advantages of the interaction have also been reported in the literature. However, there are still many gaps in our understanding of the processes involved in groundwater–surface water interaction, and the environmental implications of such interaction. The boundaries between hydrological and ecological research are gradually disappearing, yet a need remains for closer collaboration between these traditionally distinct disciplines and among researchers working in different climatic regions, so that research results may be pooled and applied to the benefit of the global environment, such as for the sustainable management and utilization of water resources.

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Direct reprint requests to:

J. Y. Diiwu
Alberta Research Council
250 Karl Clark Road
Edmonton, Alberta,
Canada T6N 1E4
e-mail: diiwu@arc.ab.ca