Groundwater–Surface Water Interaction

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Groundwater and surface water, though thought to be different entities in the past, are connected throughout the different landforms of the world. The interaction between groundwater and surface water (GW–SW) is responsible for a phenomenon like contaminant transport, and understanding it helps to estimate the effects of climate change, land use on chemical behavior, and the nature of water.

groundwater–surface water interaction | gaining and losing streams | Darcy approach | water budget

1. Introduction

The interaction of the two important parts of the water cycle, Groundwater (GW) and Surface water (SW), were considered to be different entities in the past and were examined and quantified separately for a long time. With time, their profound interdependency has been explored. The interaction of GW–SW takes place in various ways in all landscapes of the earth [1]. The interaction phenomenon commences as the water enters the hyporheic zone from either of the sources. The term hyporheic is derived from Greek roots—hypo, meaning under or beneath, and rheos, meaning a stream ('rheo' means 'to flow'). Valett [2] describes the hyporheic zone as the region below streams and rivers that exchanges water with the surface sources, whereas Triska [3] defined this zone as the part beneath the surface water body containing contributions both from surface water and groundwater but has surface water greater than 10 percent of the total volume. The hyporheic zone contains high levels of organic carbon and microbes, facilitating the breakdown of pollutants from the surface or groundwater into simpler and harmless byproducts. This interaction between water, nutrients, and biodegrading organisms occurs via bio-films and is influenced by sediment quality and properties, affecting the residence time. The hyporheic zone also alters the chemical composition of incoming water and plays a crucial role in contaminant transport and stream processes.

The classification of surface water-aquifer systems is based on the degree of interaction between them, with six different types identified [4]. A gaining stream (**Figure 1**a) occurs when groundwater seeps into the stream, while for a losing stream (**Figure 1**c,d), water seeps from the stream into the aquifer. Transition-losing streams (**Figure 1**b), on the other hand, experience both sorts of interactions. Hydraulically disconnected streams have a thick unsaturated zone between the stream and groundwater, while losing and parallel connected streams (**Figure 1**e) have the groundwater table at or below the stream bed. Flow through streams (**Figure 1**f) have differing groundwater levels on either side of the stream bed. Groundwater and surface water are linked, and their interactions affect the hydrologic cycle and human life. Extraction and pollution can harm both systems, making it crucial to understand the interconnections for effective land and water management. Progress in research has emphasized quantitative and qualitative estimation of surface water-groundwater interactions to analyze phenomena in the riparian zone. In the 1960s, the GW–SW interaction between lakes and groundwater was studied to understand acid rain and eutrophication [5]. Similarly, from the 1960s through the 1980s, researchers focused more on the interaction between groundwater and wetlands, and coastal areas because the ecosystems involved were on the verge of extinction [6].

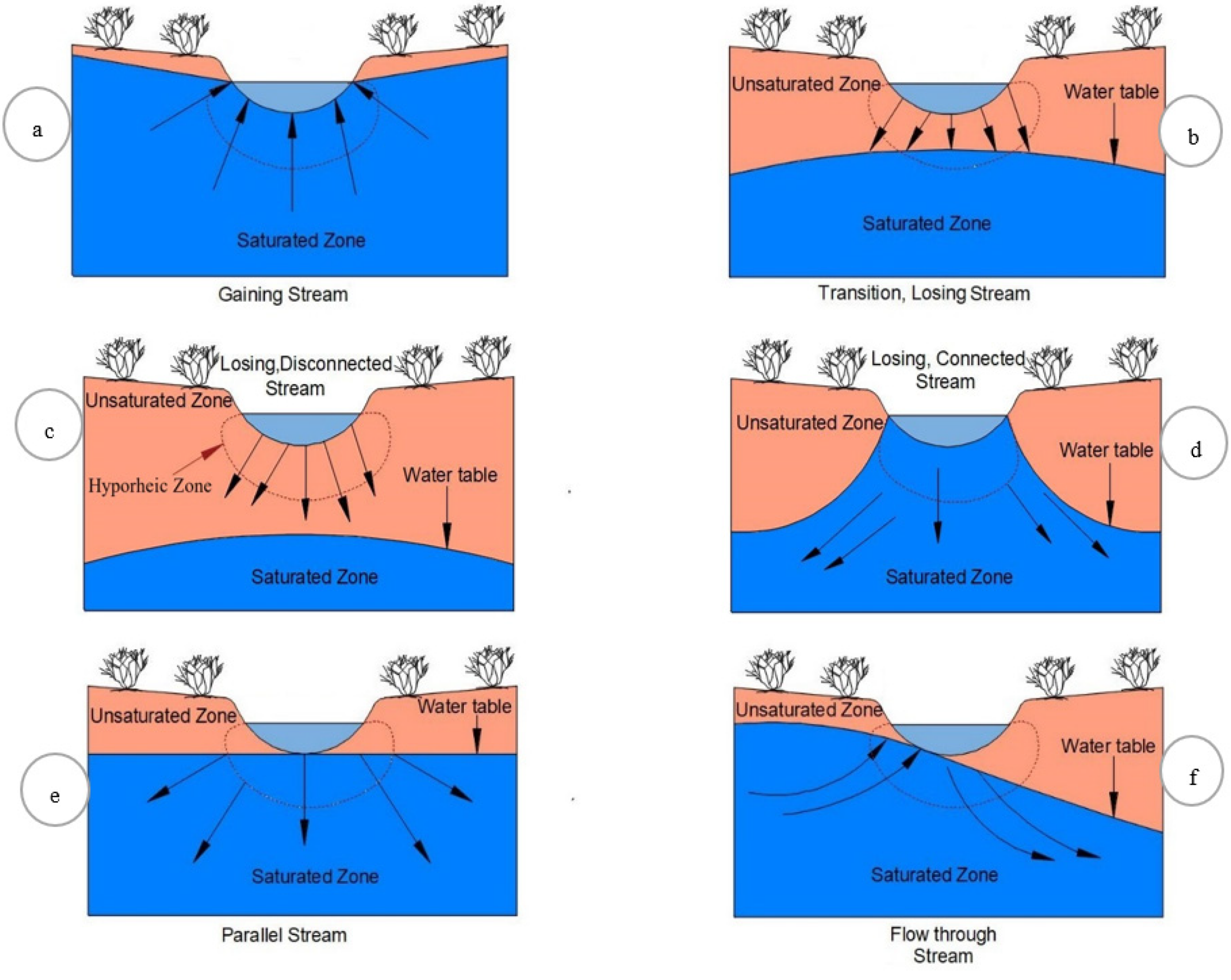

Figure 1. Different stream-water and groundwater interaction scenarios, (**a**) gaining stream, (**b**) transition-losing stream, (**c**) losing-disconnected stream, (**d**) losing-connected stream, (**e**) parallel stream, (**f**) flow-through stream. The arrows denote the directions of fluid flow.

Around the mid-1950s, in several places around the globe, groundwater pumping was found to influence the in-stream flows [7][8][9]. Seepage flux measurement in lakes and estuaries was done using a seepage meter and mini piezometers, which helped to understand the interaction of streamflow to groundwater quantitatively [10][11]. The variation of surface and subsurface water exchange over different seasons along the hyporheic area of two stream-aquifer systems was evaluated to address the variation in stream discharge and groundwater level [12]. Later, due to the increasing interest in ecological and climatic concerns, the GW–SW interaction along a river's hyporheic zone got researchers' attention [5][9]. Over time, many different methods have been developed to accomplish this task, ranging from simple continuity equations to complex modeling techniques [1][5]. One of the most straightforward ways to measure water flux and estimate GW–SW interaction is by using a seepage meter to measure water flow [11]. Heat tracers can also be utilized to determine water flux and delineate recharge zones by measuring the temperature difference between GW and SW [13]. Another popular method is the mass balance approach, which posits that any changes in the volume of a surface water body are related to its interaction with surrounding groundwater. This approach allows for the calculation of the flow between GW and SW and the linking of surface water attributes to their water source. Darcy's Law is a highly effective tool that can track and quantify GW's movement through soil and its addition to and from surface water [14]. Negral [15] used a combined approach to study GW–SW interaction in transitional wetlands, considering hydrological, geochemical, ecological, and sociological aspects. The challenge is to quantify flux and understand its spatial and temporal variation [13]. Isotope readings were used to determine if groundwater was being recharged by local rainfall and surface water sources or was recharging the river as baseflow in a catchment [14]. Grodzka-Łukaszewska et al. [16] studied GW–SW interaction in Poland using two measurement campaigns and a groundwater flow model. They measured flux, infiltration flux density, and drainage density using a seepage meter, filtrometer, and gradient meter. The model was verified using measurement data and showed a good correlation between observations and results. Grodzka-Łukaszewska [17] studied GW–SW interaction in the Biebrza River and its impact on peat habitats. They used FEEFLOW software to model interaction and measured piezometric readings and pressure differences with gradient meters. A water balance approach was used to analyze processes. Results showed that the river has a draining character and contributes only 10% to peat layer recharge. Anibas et al. [18] developed a hierarchical approach to analyze GW–SW interaction using piezometer nests, temperature tracers, and seepage meters. They used STRIVE, a 1-D heat transport model, to calculate vertical exchange fluxes at the Biebrza River. Results revealed upward water fluxes with recharge sections along the reach.

Research on groundwater and surface water interaction involves interdisciplinary issues such as the use of geophysical techniques. Geophysical methods can provide information on subsurface properties such as geological, hydrological, and biogeochemical properties [19]. These methods include electrical resistivity, induced polarization, self-potential, electromagnetic induction, groundwater penetrating radar, and various seismic methods. They are helpful in determining water content, subsurface composition, clay content, permeability, and conductivity. Electrical resistivity and seismic methods can accurately determine the porosity and stratigraphy of the sub-surface [20]. The results obtained from these methods are interpreted through petrophysical models, temporal data analysis, and calibration with other methodologies, along with the most common forward and inverse modeling techniques [21]. However, there are a number of challenges like geophysical uncertainty, site-specific considerations, modifications, and the need for good and in-depth knowledge for processing and modeling the collected results to get the final quantitative interpretation. Groundwater exchange is also crucial for maintaining the ecological balance of ecosystems such as rivers, streams, and lakes [22]. This exchange influences the ecology of surface water bodies both directly and indirectly. In streams, it sustains the base flow, and in lakes, it moderates water-level fluctuations. The interaction also regulates temperature in the hyporheic zone and helps biota survive through seasonal variations. Groundwater and surface water supply nutrients and inorganic ions to each other [23][24].

2. Importance of SW–GW Interaction

Surface water and groundwater contribute to each other as a source and sometimes as a sink. The contribution of groundwater to oceans, streams, and lakes was also quantified [25]. They reported groundwater and surface water exhibit a profound interaction, with groundwater contributing almost 6% of freshwater fluxes to oceans and 35% to 55% of stream runoff. A study on 24 regions in the USA found that groundwater contributed to surface water between 14% to 90%, with a mean of 55% [1]. Later, a study demonstrated that 70% of submarine groundwater discharge flows into the Indian and Pacific oceans, unlike rivers which discharge almost half the total flux into the Atlantic Ocean [26]. The profound connection between groundwater and lakes in North America was found as groundwater nearly contributed 0% to 94% to the lakes, and lakes, too, had a contribution of 0% to 91% to the groundwater [27]. Hence, knowing about this GW–SW interaction helps us to understand their nature and extent of involvement with each other for planning water resources management. Agricultural activities, septic systems, and sewers can contaminate groundwater, which then contaminates streams and lakes through baseflow. This contamination typically includes high nitrate levels and minor contents of many other nutrients [28]. Groundwater has higher dissolved solids than surface water, which can result in the transfer of nutrients and salts to surface water resources. This has been demonstrated in Adirondack lakes in the US, which had higher base cations and metals seeping through groundwater, leading to eutrophication [29][30].

Surface water sources can also contaminate groundwater in several cases. A study in Chennai, India, reported that high concentrations of toxic elements in the groundwater were found in areas where surface water was heavily contaminated with toxic elements [31]. Bear studied the intrusion of ocean water and salts into groundwater, which can lead to the contamination of other surface water bodies [32][33]. Singh found that heavy metals, as well as calcium, sulfur, and nickel, were present in higher concentrations in groundwater near the Buddha Nullah River, Ludhiana, India, with high TDS and BOD levels [34]. Maeng showed that organic micropollutants from pharmaceuticals can deteriorate water quality in areas where they are discharged, with further effect on supply water quality [35]. Li found that anthropogenic ions (Na^+, Cl^-, NO_3^-) and nutrients intrude into groundwater along the Fenhe River in the Jinci karst system in China [36]. Prakash found higher concentrations of trace elements like Al, Cr, Fe, Pb, and Zn near the Bay of Bengal in India than away from it [37]. Guevara-Ochoa [38] demonstrated that climate change can modify groundwater levels and reverse GW–SW flow in some reaches of streams, causing variations on a monthly, seasonal, or annual basis. Abdelhalim [39] found similar results with experiments on the river Nile, showing that climate change decreases both surface water and groundwater levels.

3. Mechanisms of GW–SW Interaction

Surface and subsurface water interact through water infiltration from the surface to the subsurface water table or exfiltration from the saturated zones, as well as the lateral flow of water in the subsurface zone that emerges into a surface water body. Sophocleous [5] demonstrated how karst terrain has these interactions occurring through flow in fracture channels. For a general soil profile, Beven [40] identified four mechanisms by which subsurface flow contributes to streamflow in a brief period, in addition to surface runoff from a single rainstorm input. The mechanisms are: (a) translatory flow, (b) macropore flow, (c) groundwater ridging, and (d) return flows.

Translatory flow, also known as plug flow or piston flow, is a lateral flow in which the water stored in the voids of soil structure before the storm is displaced by the percolated rainfall water, hence forming a component of subsurface storm flow. It may be called lateral flow if old water is displaced by precipitation input. Translatory flow in a lab is simulated by taking a soil column, letting it drain to field capacity, and adding water at the top [41][42].

Macropore flow is the type of flow in which there is a continuous flow from the soil surface to the groundwater table, not getting trapped or losing water in the intermediate soil profile. This flow occurs through connected and disconnected macropores, soil pipes, soil cracks, random holes formed by soil fauna, and desiccated roots [43]. Macropore flow consists of ‘old’ or ‘pre-event’ water, which has a quick subsurface contribution. When the water flow under pressure greater than or equal to atmospheric pressure, which means either water is inside the saturated zone or there is a ponding state at the surface of the earth, it enters a large non-capillary pore [44].

The third phenomenon is groundwater ridging, in which the rapid increase of hydraulic head near the stream causes a substantial contribution from groundwater to the stream. Above the groundwater table exists a capillary fringe zone with water held under surface tension. During a storm, this fringe gets destroyed just by adding a small amount of water into this zone, so the water rises to the top of the fringe. In this process, water pressure inverts from negative to positive. Due to the water level rise near the stream, the net hydraulic gradient increases or the seepage face causing more significant groundwater discharge to the stream, and thus induced discharge from the groundwater to the stream may be higher in quantity than that the input water that triggered the process [5].

The fourth phenomenon, Return Flow, is an extension of Groundwater Ridging, which occurs when the water table and capillary fringe are very near to the soil surface, and even a minimal amount of percolated water will cause the capillary to break. Hence pressure inverts from negative to positive with the water table rise. Still, this saturated soil will start discharging water from the subsurface to the surface directly, which is termed Return Flow. According to Beven [40], the contribution area of return flow depends upon the closeness of the capillary fringe to the surface. It shows expansion if this area is close to the surface.

Apart from the mechanism suggested by Beven [40], another predominant phenomenon for the interaction is Induced Riverbank Flow. When water is pumped from a well, it creates a pressure gradient that induces flow from the river to the well, which leads to groundwater recharge. This induced recharge process enhances the interaction between the river water and groundwater, affecting the hydrodynamics and chemistry of both systems. Understanding the role of induced riverbank flow is important for designing and operating riverbank filtration systems that rely on this interaction to provide safe and reliable drinking water [45]. The same concept has been explored by Rossetto et al. [46]. They have used multidisciplinary methods like hydrodynamics, hydrochemical, and numerical modeling to evaluate the change in recharge from the Serchio River to the aquifer due to the building of the Riber Bank Filtration infrastructures along the river. They established that the pumping wells alongside the river are being fed through the river and that the use of induced recharge would drastically increase the river water level up to 1.5 m. Zu et al. [47] studied the water supply safety of riverbank filtration wells under the impact of surface water-groundwater interaction. They have also shown that long-term pumping may impact the efficiency of riverbank filtration wells.

4. Scales of GW–SW Interactions

Tóth [48] introduced the term Groundwater Flow Systems for the classification of groundwater, which is a set of aquifers having similar characteristics that exhibit a definite pattern to the flow of water through them (**Figure 2**). For an area of a few hundred square kilometers with a mild slope and lower-order outlet stream, Tripathi [49] divided the flow scales into local, intermediate, and regional for unconfined groundwater systems. Winter [1] demonstrated that similar flow systems classification is effectively applicable to groundwater systems with confined aquifers. Tóth [48] stated that the scales that come into the picture for a particular case depend upon local and regional geomorphology. Local flow systems depend upon the local slope of an area and diminish or even get extinct if the regional slope is increased, which caters to the formation of other flow systems. In local systems, discharge fluctuates widely, and water flux has higher penetration depth and residence. The hydrologic properties also change according to the scale of the flow. Groundwater and surface water interaction highly depend on the scale through which their interaction occurs [50].

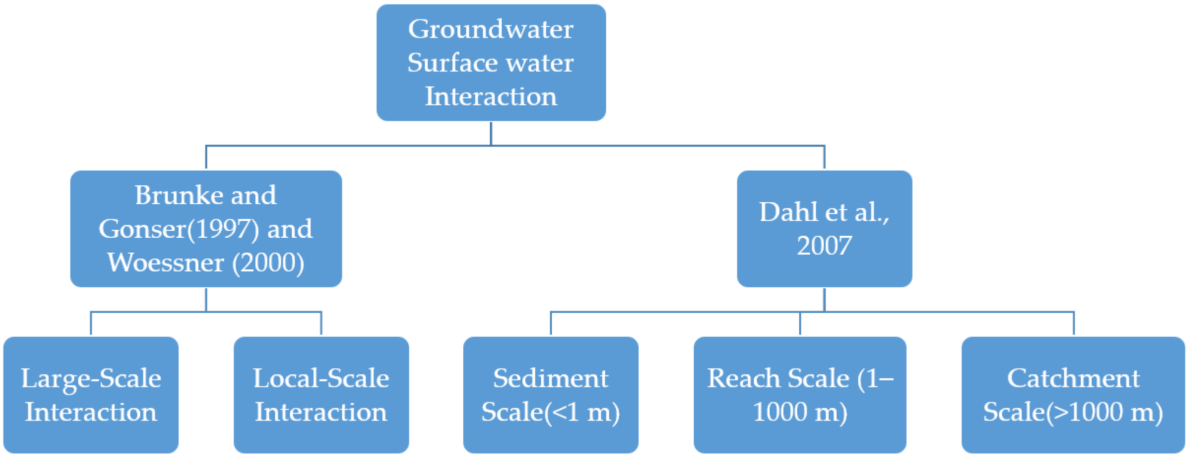

Figure 2. Different groundwater–surface water interaction scales studied through different approaches [50][51][52].

As shown in **Figure 3**, the interactions were distributed into different sets according to the scale of their interaction. The scales of GW–SW interactions were separated into two types [51][52], namely large-scale and local-scale interactions. Large-scale interaction was used when the whole of the catchment was actively participating in the interaction process, whereas local-scale interaction was used when only the hyporheic zone was influencing the interaction process.

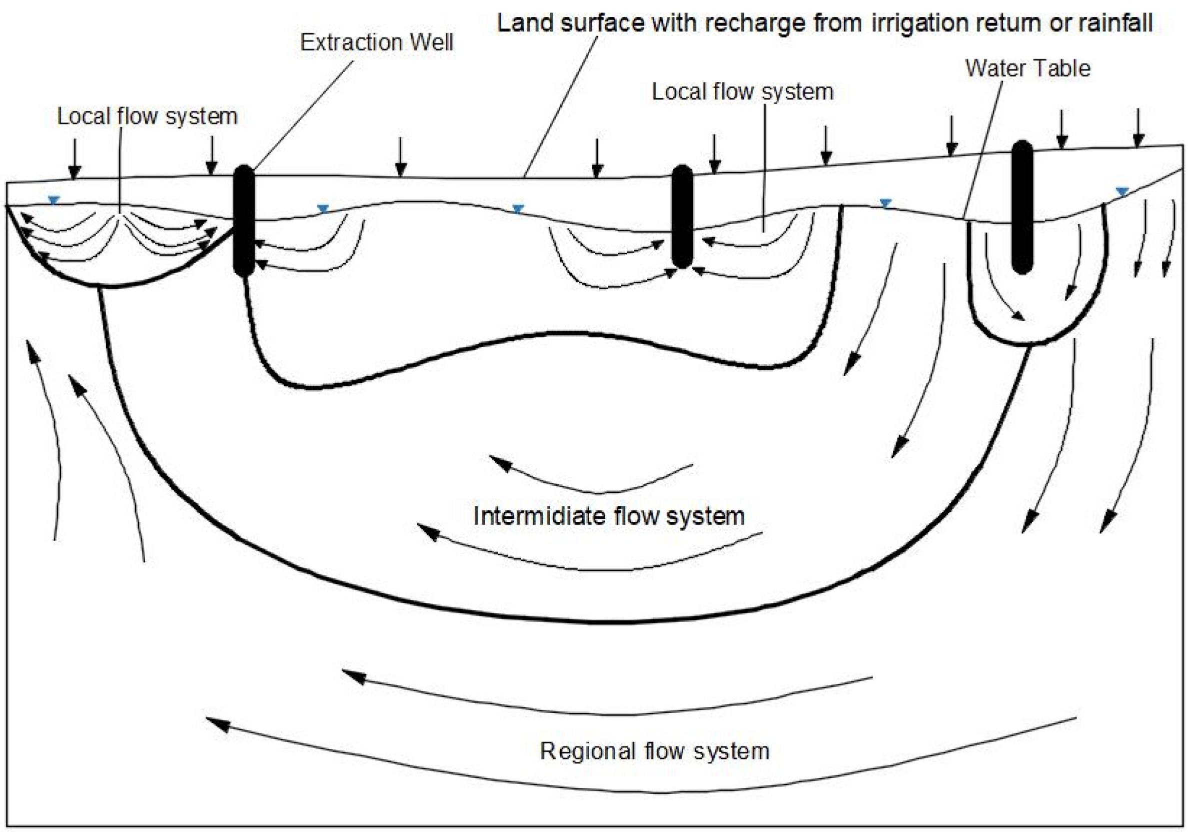

Figure 3. Groundwater flow systems: Local, Intermediate and Regional, as described by Tóth [48].

Dahl [50] divided the groundwater and surface water interaction into three sub-areas according to the scales, the first being the sediment zone within 1 m depth, the reach zone covers a depth of up to 1000 m, and a catchment zone is concerned with a depth of more than 1000 m. These scale divisions further resemble the hierarchic classification of groundwater flow systems. The hyporheic zone correlates to the sediment scale, whereas the local flow system corresponds to the reach size and the regional flow system to the catchment scale. The most commonly encountered interaction scales are given below:

(a) Large-scale Interaction

On a regional or local scale, the interaction between groundwater and surface water depends on the position of the water body respective to groundwater flow systems, anisotropy of the soil system underneath and hydraulic conductivity variations of the groundwater system, arrangement of the water table, and depth of concerned water body.

Groundwater flow depends on the water table elevation relative to surface water-bed elevation. However, it has been observed that sometimes, even with a higher water table elevation, surface water discharges water to groundwater. The local groundwater flow system boundary controls these processes. Winter [53] suggests that seepage through a streambed occurs when there is no continuous local groundwater flow system boundary or stagnation point under the surface water body. There is no seepage if there is a continuous local groundwater flow system boundary or a stagnation point (**Figure 4**). The head difference between the surface water body and a stagnation point determines the amount of seepage.

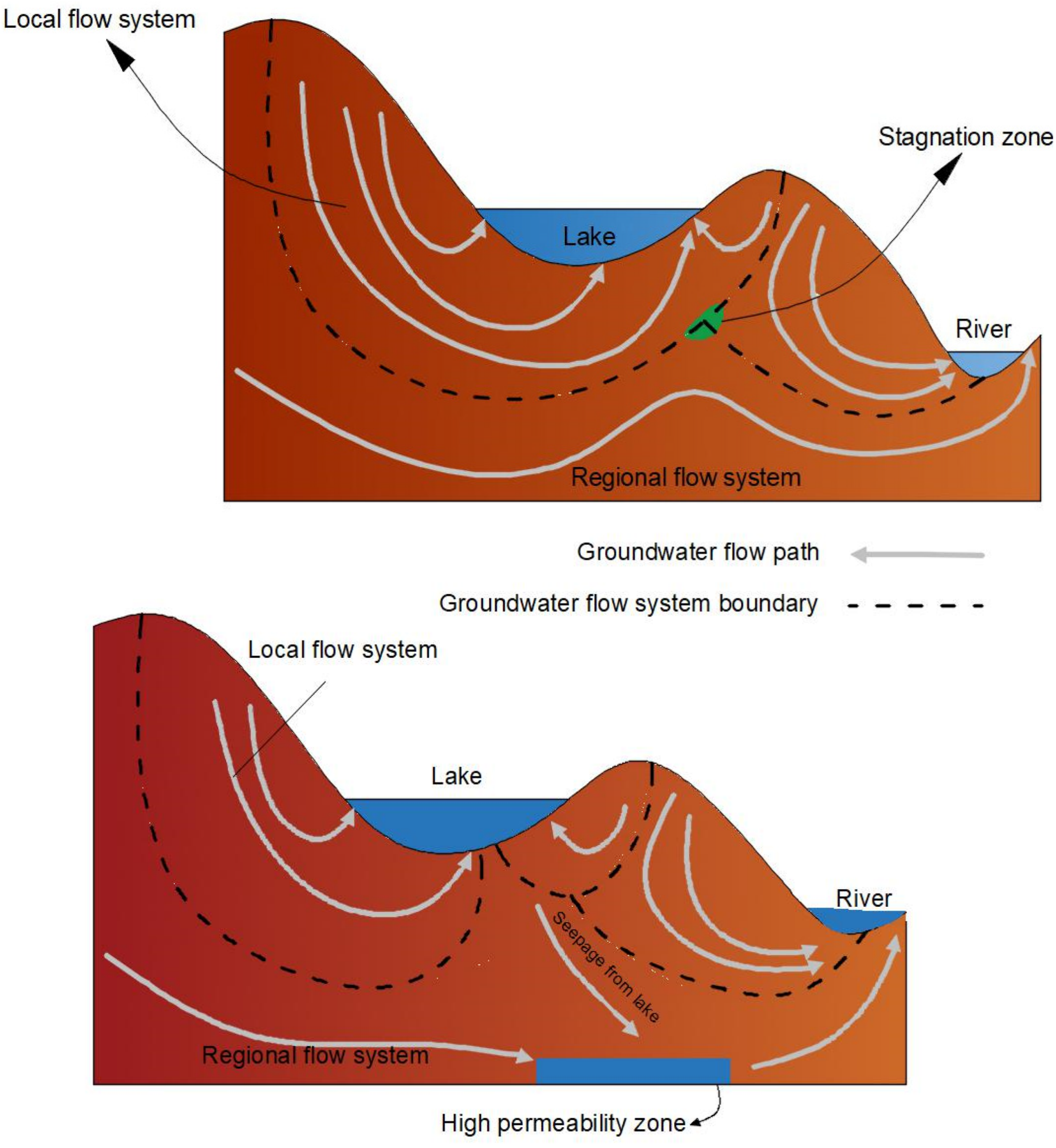

Figure 4. Conditions for seepage to occur from a surface water body with respect to groundwater flow system boundary.

- (b) Hyporheic interaction or sediment scale interaction

The interaction between the surface water bodies and the water stored in the sediment directly underneath the water bodies is termed the Hyporheic Interaction (**Figure 5**). This interaction accounts for the local water infiltration from the streambeds and stream sides to the aquifer underneath and vice versa. In addition, a stream may have localized zones of infiltration and exfiltration even though the overall effect may be reversed [51][52]. According to

Woessner [51], the highly localized flow systems are mainly controlled by surface-water-bed topology and sediment hydraulic conductivity variation beneath the stream bed.

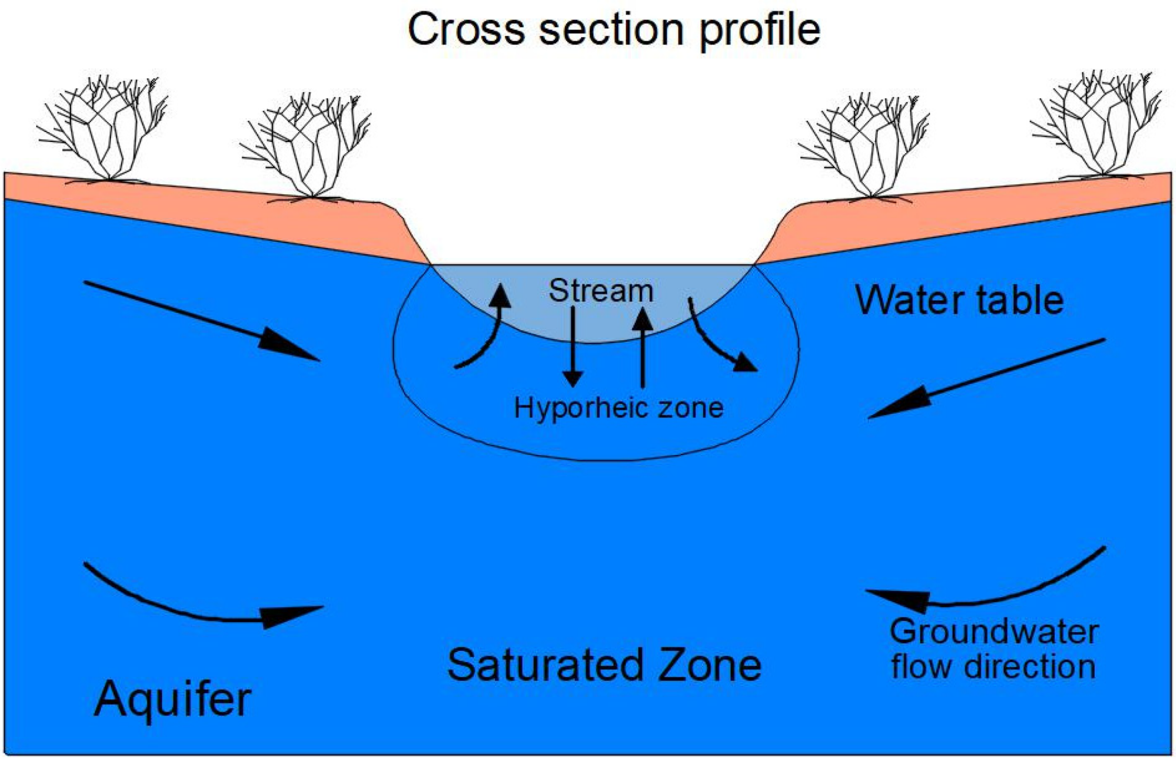

Figure 5. Processes occurring in the Hyporheic Zone. The black arrows represent the fluid flow directions.

Harvey and Bencala [54] showed that the interaction between a stream and underlying sediments is influenced by bed convexity and concavity. Due to the stream bed convexity, downwelling of the stream occurs while upwelling of the hyporheic and deep waters occurs due to concavity. The water enters through the riffles, the convex part, and exits through the pool area, the concave part of the stream bed. Cardenas [55] found that stream water enters the deposits through the upstream portion of a meander and moves back to the stream through the downstream portion of the meander, influenced by the factor channel sinuosity. Woessner [51] demonstrated that the hydraulic conductivity of stream bed sediments affects the depth of mixing of surface water and groundwater, with heterogeneous bed sediments increasing the depth of mixing to 1.5 m underneath the streambed compared to 0.7 m with homogenous bed sediment.

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