Chapter 9

Riverine-Based Aquifers and Riparian Exchange: A Conceptual Discussion

Modreck Gomo and Joe Magner

Additional information is available at the end of the chapter

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Abstract

This chapter presents a conceptual discussion of the aquifers that typically occur along river channels and the riparian exchange of water as influenced by valley and channel type and management. Definitions of alluvial and bedrock river channel, based on literature, are provided while highlighting their general attributes and exchange options. Conceptual aquifer models occurring along alluvial and bedrock river channels are then described and presented with respect to groundwater-surface exchanges and solute fate and transport. There is theoretical reasoning to suggest that channel aquifers and concordant riparian zones can be conceptualized and classified based on valley type and the nature of the river channel hosting the aquifer. The information presented in the conceptual models can be used during desktop studies to strategically plan the optimal management for aquifer and riparian protection and restoration activities subject to anthropogenic risk. Riparian zone management is needed more so today, because basin land use in many parts of the world has advanced to the point of creating both water quantity and quality disequilibrium.

Keywords: Alluvial aquifer, alluvial river channel, bedrock river channel, groundwater-surface exchange, riparian management, ecosystem services

1. Introduction

Considerable studies exist on the geomorphologic processes governing the formation and functioning of alluvial and bedrock river channels [1–4]. However, very little effort has been devoted to the conceptual description of the influence that these river channels can have on the nature of aquifers that could develop along them given human demands related to food and water insecurity. There are several valley and channel type classifications that have been developed from a geomorphic perspective [5, 6]. We will use the Rosgen system throughout this chapter to link groundwater-surface water exchange to systems observed in nature.

"Alluvial aquifer" is a common term that is often used in reference to aquifers that generally comprise unconsolidated sediments from previous channel deposits, both current and historic (glacial past) [7–10]. However, this is also done without mention to type of the river channel hosting the aquifer. In nature, alluvial aquifers can occur along both the alluvial and bedrock river channels but with different characteristics and implications for groundwater-surface water exchange. The type of valley hosting the river channel can therefore have some influence on the development of the nature and characteristics of the aquifer system. Typically, Rosgen valley VIII encompasses the flat sand and gravel-rich sediment found with fluvial transport. In glaciated regions, Rosgen valley type IX is common; these flat valleys can have deep deposits and provide opportunities for irrigated agriculture. Besides alluvial aquifers, other riparian eco-hydrologic systems can also develop along the river channel including more lacustrine sediments: Rosgen valley type X and large deltas Rosgen type XI [6]. Slower velocities drop out fine sand and silt where there is a change in energy gradient and oxbow ponds, and wetlands can form. The lacustrine and delta valley types offer more residence time for nutrient attenuation and trapping; thus the groundwater-surface water exchanges are highly influenced by heterogeneity of the well-sorted sediments.

Riverine channel aquifers are a worldwide important source of groundwater; they are often targeted to supply water for agriculture and domestic purposes [11–16]. By nature, riverine channel aquifers exist because of regional groundwater discharge. The riverine ecosystem synthesis [17] defined the importance of a cross-sectional view of river basins across scale. Riverine aquifers play an important role on the chemical and physical functional processes that support human and aquatic life. Specifically, wetland systems form critical water storage, biotic habitat and pollutant attenuation. In order to develop appropriate investigation and management methodology that can ensure sustainable utilization of the water resources, a good conceptual understanding of such aquifers and potential implications for groundwater-surface water exchange is essential because the groundwater discharge sustains the ecosystem services present in a riparian zone.

This chapter is therefore aimed at improving the conceptual understanding of the aquifers that can occur along a river channel as influenced by the regional geology, valley type, channel type and the concordant ecosystem services that may be at risk if land use is not properly managed.

2. River channels

River channels can be generally classified into bedrock and alluvial channels [1, 3, 18–20]. Bedrock channels occur and flow directly through the underlying bedrock, assuming a rock material that allows fluid flow. Alluvial channels are formed in sediments previously deposited in fluvial or glaciofluvial flows and naturally pass fluids through primary pores depending on the hydraulic conductivity [21]. In nature, it is possible that along river channels, alternations could occur between alluvial and bedrock channel types as influenced by

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heterogeneity of the Earth processes. Such alternations could be in the form of mixed bedrock-alluvial [4, 22–24] and separately as an alluvial reach with specific bedrock outcrops between alluvial reaches [19, 26]. Examples of igneous bedrock outcropping occur in central Minnesota and along the Minnesota Wisconsin border in north-central USA. These systems can often have unique biotic features because of the bedrock position. Conceptual representations of bedrock and alluvial are shown in **Figures 1** and **2**. **Figure 3** shows a photo of mixed bedrock-alluvial channels taken from [27]. All of the examples shown would fit a Rosgen valley type V and/or VI depending on the geology and mountain terrain.

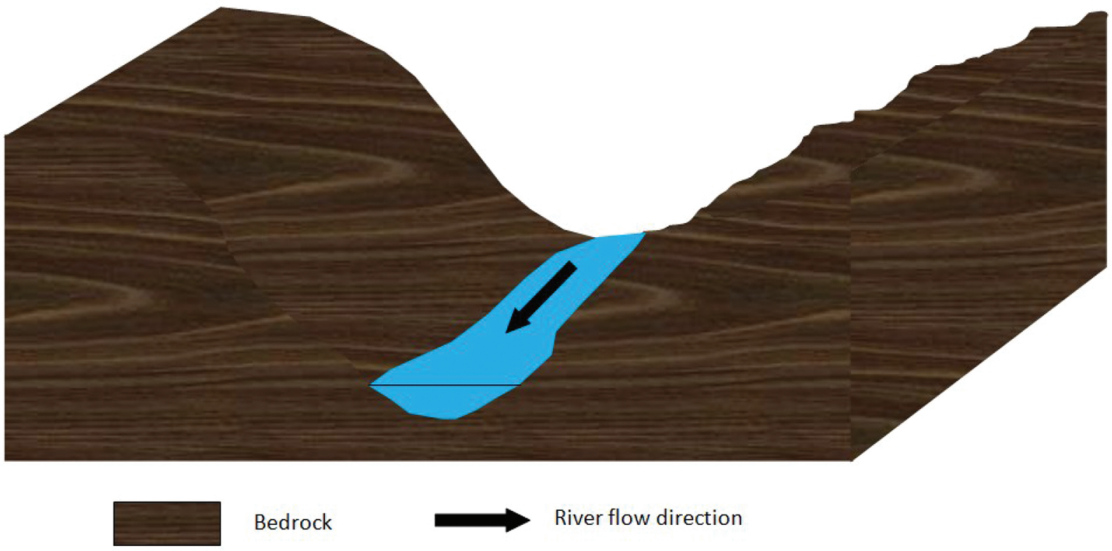

Figure 1. Conceptual representation of bedrock river channel (modified from [21]).

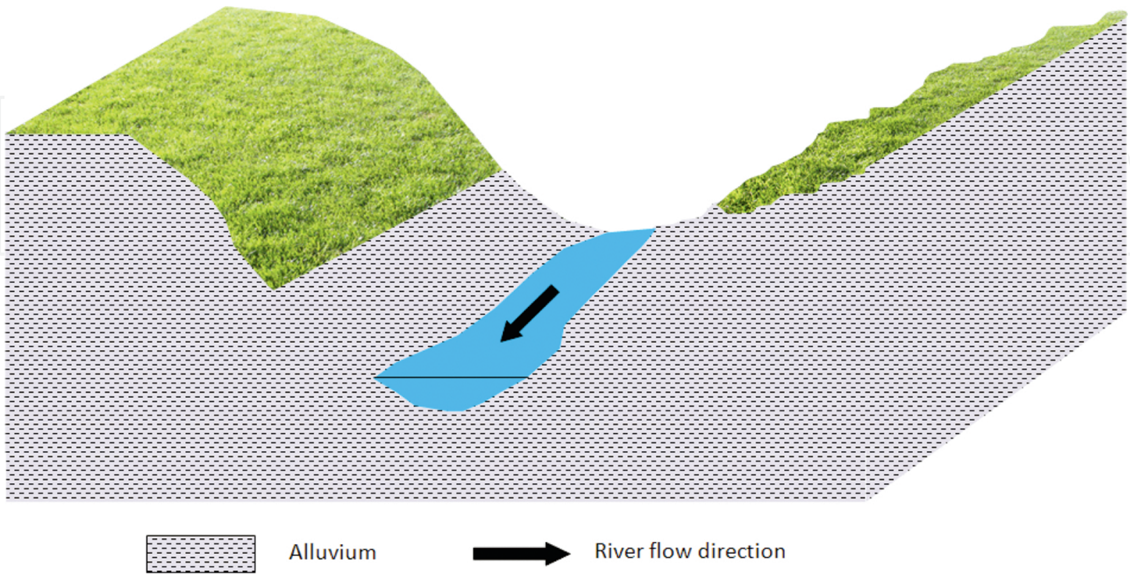

Figure 2. Conceptual representation of an alluvial river channel (modified from [21]).

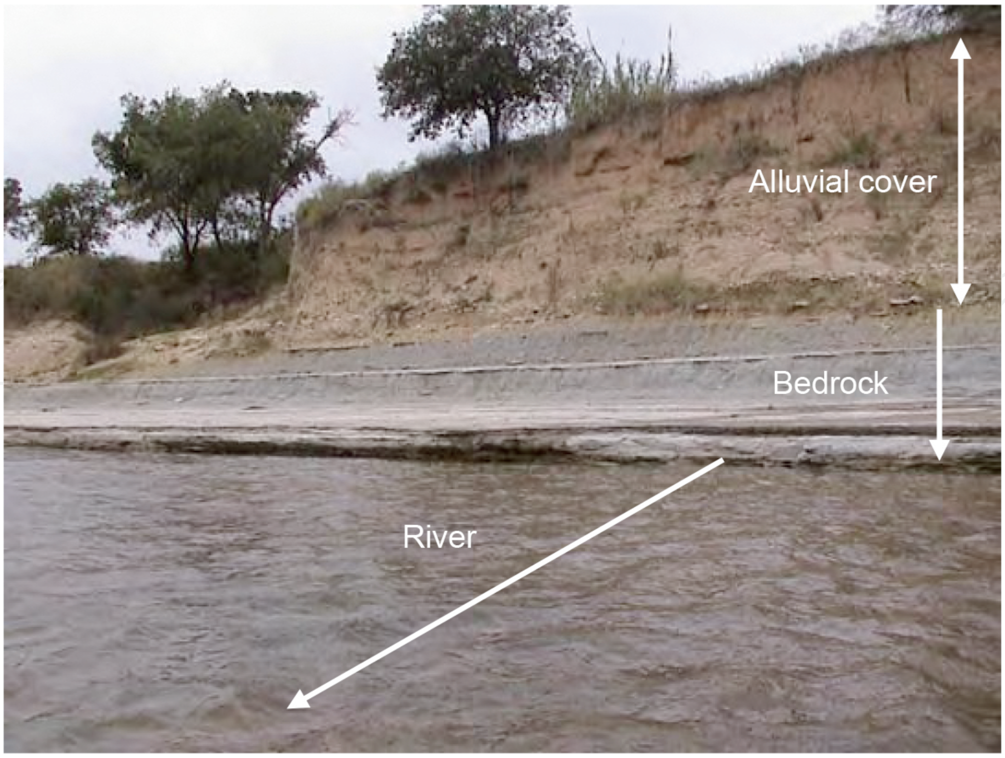

Figure 3. Photo of a mixed bedrock-alluvial channel (taken from [27]).

A key distinction between the figures above is directly related to hydraulic conductivity. **Figure 1**, where the channel is set in bedrock, is primarily unidirectional; little, if any, bank storage of high-stage water can occur unless the properties of the rock allow for fluid flow. In contrast to **Figure 1**, the channel shown in **Figure 2** is multi-directional; groundwater can resurge and flood water can be stored in the alluvium. The channel in **Figure 3** can provide a limited amount of bank storage, but only high stages and only under sustained high stage.

3. Conceptual models of river channel aquifers

3.1. Bedrock river channel aquifers

A bedrock river channel can potentially host different types of aquifer systems; however, hydrogeological characterization will require differing approaches, tools and techniques. Aquifers that could be formed in concert with bedrock channels will mainly consist of (a) alluvial cover, (b) fractured/weathered bedrock, (c) porous-bedrock aquifer, (d) alluvial cover overlying fractured/weathered bedrock aquifer, (e) alluvial cover overlying porous-bedrock aquifer and (f) all alluvial sediment. In all these examples, the valley type will be defined by the regional geology; steep mountainous systems will have little to no groundwater exchange except where alpine terraces and deltas form.

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3.1.1. Alluvial cover aquifer

This can occur on a mixed bedrock-alluvial river channel. In this instance, the bedrock is an aquitard while the overlying alluvial covers have sufficient porosity and permeability to respectively store and allow movement of groundwater (**Figure 4**). Depending on the river stage elevation, there could be direct or indirect hydraulic exchanges between the groundwater in the alluvial cover aquifer and surface water in the river.

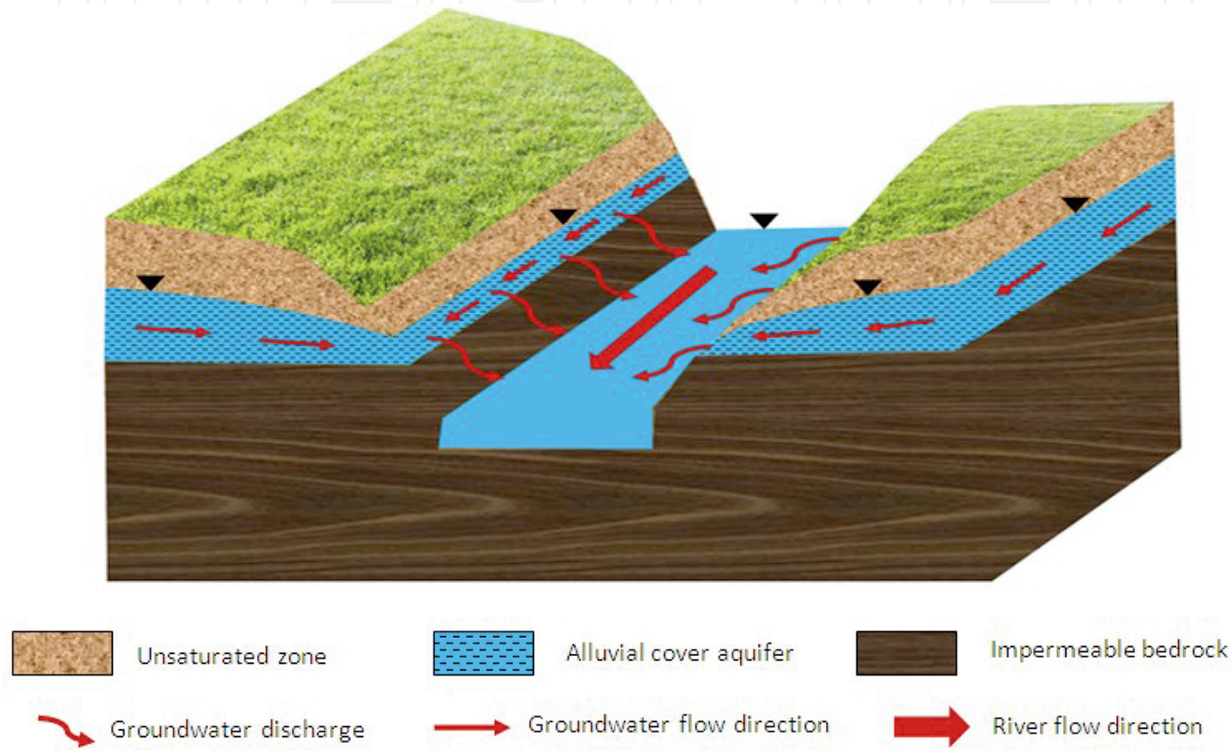

Figure 4. Conceptual representation of an alluvial cover aquifer on a mixed bedrock-alluvial river channel.

However, by definition a bedrock river channel must be cut into bedrock and flow through the bedrock, which implies that the river stage will always be within the impermeable bedrock. When the river stage is within the bedrock, it can therefore not be in direct hydraulic contact with top alluvial cover aquifer. The most likely form of groundwater-surface water exchange would occur as groundwater discharge at the contact plane between alluvial cover and impermeable bedrock (assuming the hydraulic gradient in the alluvial cover aquifer is towards the river).

Under the conditions assumed in **Figure 4**, the river will gain water from the alluvial cover aquifer; thus, it represents a groundwater sink. However, when groundwater is being abstracted from a well drilled into the alluvial cover aquifer, the cone of depression cannot extend beyond the river; thus, the river could act as an impermeable/no flow hydraulic boundary. A schematic showing how the river channel of an alluvial cover aquifer acts as a no flow boundary to the cone of depression created by a pumping well drilled into the aquifer is presented in **Figure 5**.

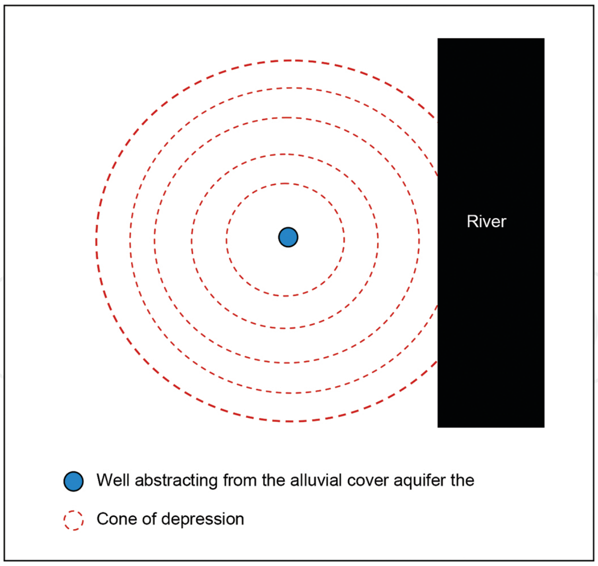

Figure 5. Schematic showing how the river channel of an alluvial cover aquifer acts as a no flow boundary to the cone of depression created by a pumping well drilled into the aquifer.

Abstracting groundwater from the alluvial cover aquifer would therefore not draw water from the river or cause the ingression of river water into the aquifer because the two are not hydraulically connected. This however does not mean that abstraction from such an aquifer cannot negatively affect the river. Indirectly, abstraction from the alluvial aquifer will effectively reduce the discharge into river, which could also impact negatively on the functioning of the riparian and river ecosystems. A flatter valley type is required such as a Rosgen IX formed in glaciofluvial sediments. An example of this system can be found in flat outwash plains of central Minnesota (USA) near adjacent to the Mississippi River.

3.1.2. Alluvial cover and bedrock aquifer

It is possible that the bedrock underlying the alluvial cover aquifer can have sufficient properties to allow storage and movement of water, thus making it also an aquifer. This could occur in form of (1) porous-bedrock aquifer (**Figure 6**), (2) fractured/weathered bedrock aquifer (**Figure 7**) or both. When the bedrock is also an aquifer, the groundwater resource would then occur and flow in both the alluvial cover and underlying bedrock aquifer. Since the river flows only through the bedrock, only the bedrock aquifer can be in hydraulic contact with the river water thereby presenting the opportunity for direct groundwater-surface water exchanges. Porous bedrock most often consists of weakly cemented sandstone. Finer-grained or compacted sandstones will allow a limited about of groundwater movement, but not enough to be considered a viable aquifer. Nevertheless, fine-grained bedrock can weather and develop fracture networks allowing for secondary porosity. If the sedimentary rock is carbon based, the bedrock can enlarge by dissolution. Carbonate bedrock aquifers can be extensively developed with cave networks with rapid pipe-like hydraulic conductivity; these systems are referred to as karst and exist in selected locations throughout the world [28]. More commonly, carbonate aquifers have smaller fractures (1–10 cm) that function similar to porous media flow.

Typical Rosgen valley types found in these systems are VI (fault-controlled valleys) and VII (dissected fluvial slopes); these systems can be observed in Pennsylvania, USA.

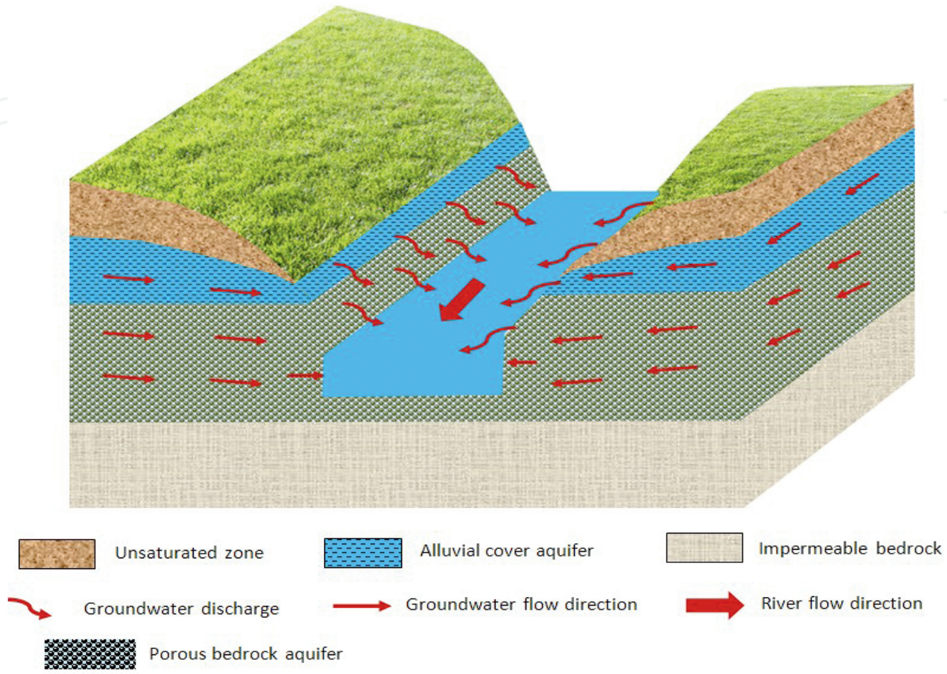

Figure 6. Conceptual representation of alluvial cover and porous-bedrock aquifers on a bedrock river channel type.

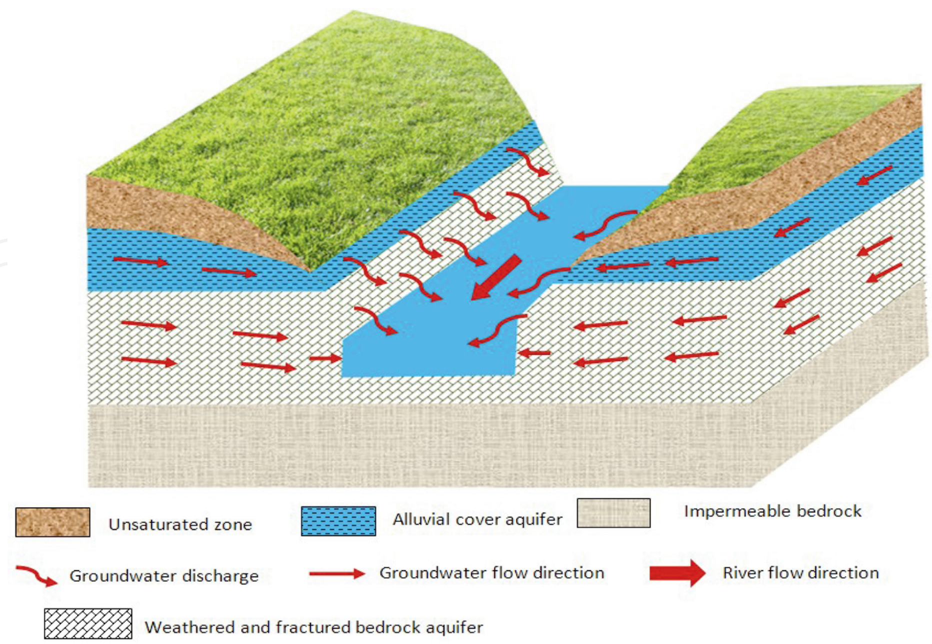

Figure 7. Conceptual representation of an alluvial cover and fractured-bedrock aquifers on a bedrock river channel type.

Depending on the permeability of the formation separating the alluvial cover and bedrock aquifer, the two could behave as hydraulically connected or separate systems. The aquifers will behave as hydraulically connected systems when the separating geological formation is permeable to allow vertical exchanges between the aquifer systems. In this situation, abstracting from a well drilled into the alluvial cover aquifer could also draw water from the deep bedrock aquifer through vertical leakage and potential draw from the river. The bedrock aquifer can also receive its recharge through the overlying alluvial cover aquifer. Ref. [29] observed deep fractured bedrock aquifer that derived 80–100% of its recharge during stressed (pumping) conditions through vertical and horizontal flow from the overlying deposits.

When the geological formation between the alluvial cover and bedrock aquifers is at least semi-impermeable, the two aquifers will hydraulically behave as separate systems. Because of the impermeable confinement, the bedrock aquifer will not receive recharge from the overlying alluvial cover aquifer and water held in the alluvial material will move laterally toward the river and resurge as a spring. In this scenario, abstracting from one aquifer would also not directly affect the other aquifer, since they are not hydraulically connected; however, abstraction from the bedrock aquifer could create a gradient and draw water from the river because of the hydraulic connectivity. Depending on connectivity between the river and the aquifer, river base-flow could be adverse and drive failure of ecosystem services. When abstracting from the bedrock aquifer system, the river potentially represents a recharging hydraulic boundary; this is more common when aquitards or semi-impermeable layers limit upland recharge. This is because when the cone of depression of a high-capacity well expands into the river, the river acts as a source of water for the aquifer (recharge boundary). Due to this groundwater-surface water exchange effect, direct transfer of pollutants can occur between the river and bedrock aquifer, which could negatively affect the water quality. Investigation of groundwater-surface water exchanges is therefore an important issue in this channel aquifer model.

3.2. Alluvial river channel

3.2.1. Alluvial aquifer

In an alluvial aquifer channel, typically a Rosgen VIII broad flat valley type, groundwater occurs and flows in the alluvium deposits (**Figure 8**). The river almost always flows within the sediments; thus, it is generally in hydraulic contact with the alluvial aquifer thereby presenting the opportunity for direct groundwater-surface interaction between the two reservoirs. The aquifer can therefore be recharged from the river or resurge into the river. Groundwater abstraction from the alluvial aquifer can draw water from the river if the cone of depression expands to the river. Pollution can also be transported from one resource to the other during the exchanges. In a Rosgen type XI (delta valley type), the valley slope may result in a losing river channel if the regional water table has dropped below the alluvial bed. An example of this type of riverine system can be found along the eastern front of the Rocky Mountains in Montana (USA) where snow-melt drops down from higher elevations into the delta in May/June but fails to fully flow east because of the drier climatic regime. Groundwater-surface water

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exchange is an important facet of this aquifer model; one that demands extensive evaluation before anthropogenic development.

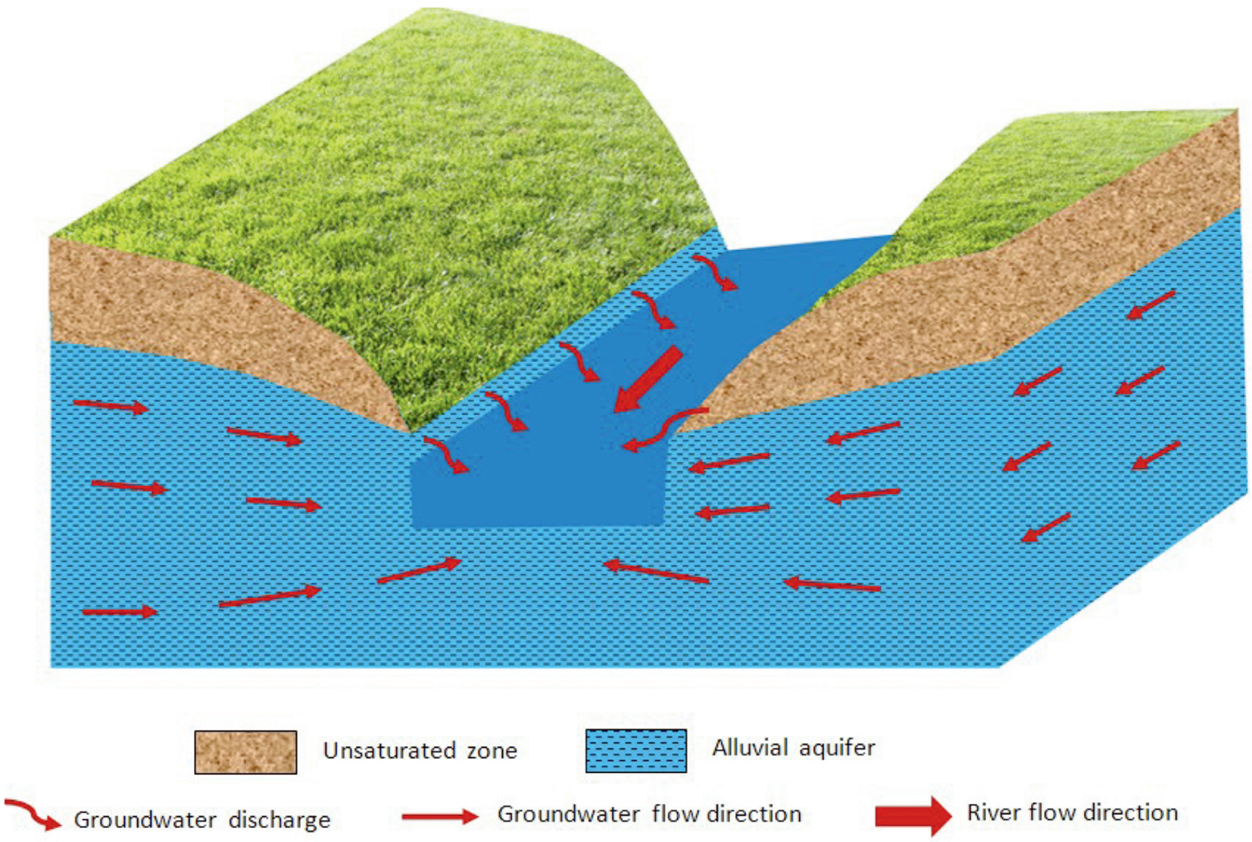

Figure 8. Conceptual representation of an alluvial aquifer on an alluvial river channel.

4. Conclusions

We have presented conceptual models of aquifers that could occur on river channels as influenced by the valley and stream type. A classification that conceptually splits channel aquifers based on the river and valley type has been presented to illustrate possible management concerns. The classification would split aquifers that can occur along a bedrock river channel into (a) alluvial cover aquifer, (b) fractured/weathered bedrock, (c) porous-bedrock aquifer, (d) alluvial cover overlying fractured/weathered bedrock aquifer, (e) alluvial cover overlying porous-bedrock aquifer and (f) alluvial.

The information presented in the conceptual models can be used during desktop studies to strategically plan the optimal management for aquifer and riparian protection and restoration activities subject to anthropogenic risk.

Author details

Modreck Gomo[1] and Joe Magner[2*]

*Address all correspondence to: magne027@umn.edu

1 University of the Free State, Bloemfontein, South Africa

2 University of Minnesota, St. Paul, MN, USA

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