Streams and Groundwater

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Table of Contents

1 Introduction

Streams and groundwater are absolutely vital sources of freshwater on Earth, and have huge impacts on other landscapes.

2 Streams

A stream is a flowing body of water, typically a small one.

2.1 Types of Streams

Streams are typically classified into four types based on their sinuosity, as shown in the figure. Braided and meandering rivers are the two most common types. Streams can also be classified by steam order (more on that later!), as well as being classified as ephemeral (stream sometimes dries up) or disappearing (stream sometimes dips below ground level. The stream's magnitude of the hydraulic gradient classifies its speed of flow. Lastly, streams can be classified as influent/losing if net water flow is from the steam into the groundwater, or effluent/gaining if net water flow is from the groundwater into the stream.

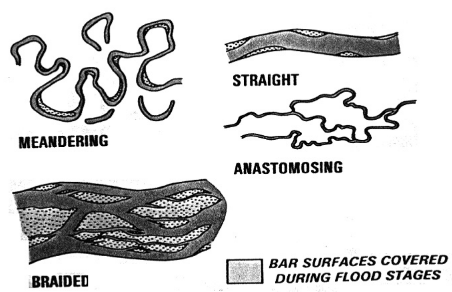


Figure 1: Four stream types based on their sinuosity, or magnitude of curvature and overall shape. (Source: University of Maryland)

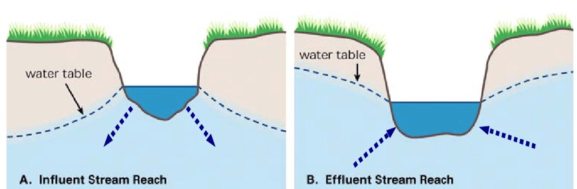


Figure 2: Influent/effluent steams (Source: Federal Interagency Stream Restoration Working Group)

2.2 Sinuosity

Qualitatively, sinuosity is a measure of how "bendy" the steam is. Quantitatively, it is the path length of the stream divided by the straight line distance. Slower, more mature streams tend to be more sinuous.

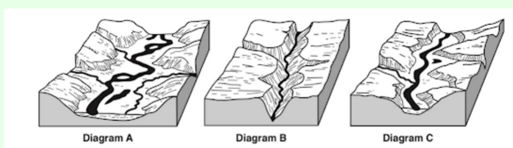
Example 2.2. Is it possible to have a sinuosity less than 1?

Solution: No, as the straight line distance is the shortest distance between any two points, so the sinuosity cannot be less than 1.

2.3 Stream Development

As a stream ages over time or develops downstream, the sediment load and channel surface undergo more erosion. Therefore, channel roughness, sediment roundness, and grading increase. Increased erosion also widens a stream channel, and allows for the development of a basin with more stream sinuosity.

Example 2.2 (USESO Open Round 2021) Refer to the following river valleys for this question.



Identify all of the following statements regarding these river valleys that are true. (*)
A. River valley A is older than river valley B
B. The stream in river valley A has the most angular sediments
C. The stream in river valley B has the highest stream discharge
D. The stream in river valley B has the greatest channel roughness
E. The stream in river valley C has the most poorly-sorted sediments

Solution: River valley A shows evidence of an older, more eroded landscape than B with its wider floodplain and greater river meandering. River valley A is more likely located in a downstream location, so the sediments should be rounder having been transported over a longer distance. The narrow landscape of river valley B suggests that it is likely to be located upstream closer to the source of the river, and discharge generally increases downstream. Channel roughness decreases downstream, so river valley B has the greatest channel roughness. Sorted sediment is more common downstream, and river valley C is an intermediate between A and B.

2.4 Base Level

Base level refers to the "ground level" of the water table the stream rests on. Structures like dams or lakes can serve as relative base levels, but the ocean is considered to be the "ultimate" or absolute base level of almost all streams, although some streams that drain into bodies of water like the Dead Sea can have lower base levels.

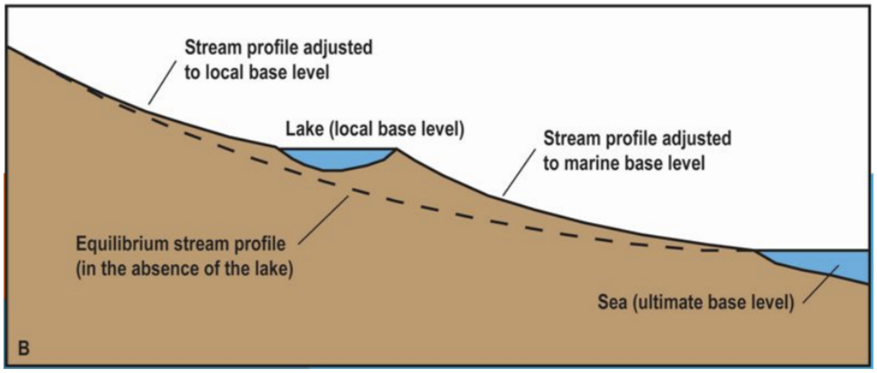


Figure 3: Local base levels reduce erosion of the stream profile. (Source: US Geological Survey)

2.5 Sediment

Streams can weather, erode, and deposit various forms of sediment. A Hjulstrom diagram allows us to determine what types of sediment it performs each of these processes on. Sediment erosion tends to happen more at higher velocity and thus near the headwaters, while deposition happens near the mouth, sometimes forming deltas. Sediment can by transported in many ways, including as suspended load, dissolved load, and bed load. It can also be transported in different ways, including rolling, saltating, and sliding. Thus, a stream channel that is made up of more easily eroded sediment will age quicker, developing into more sinuosity and wider basins.

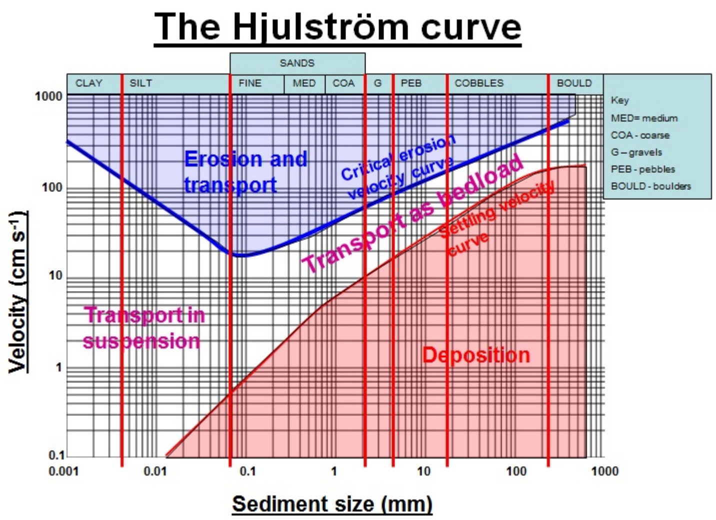


Figure 4: A Hjulstrom diagram (Source: Cool Geography)

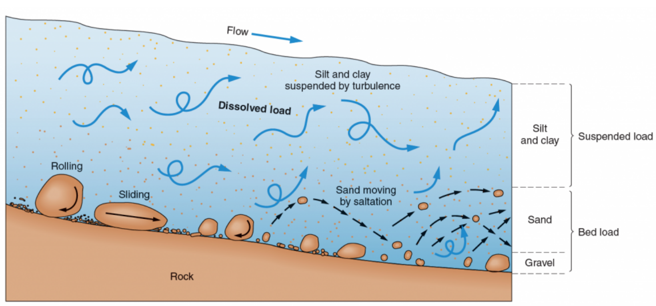


Figure 5: Types of stream load and sediment transport (Source: World Rivers)

2.6 Stream Order

Stream order is a way of classifying streams based on their number of tributaries. There are three main types of stream order classification system (although keep in mind that others exist): the Hack system, the Shreve system, and the Strahler system. The Hack system labels the main branch as 1, and tributaries get higher numbers based on how often they branch away. The Strahler and Shreve system both work by labeling the smallest tributaries as one, and combining the tributaries to make higher order streams, with the Shreve system adding the numbers, and the Strahler system increasing the order by one every time two streams of the same order combine.

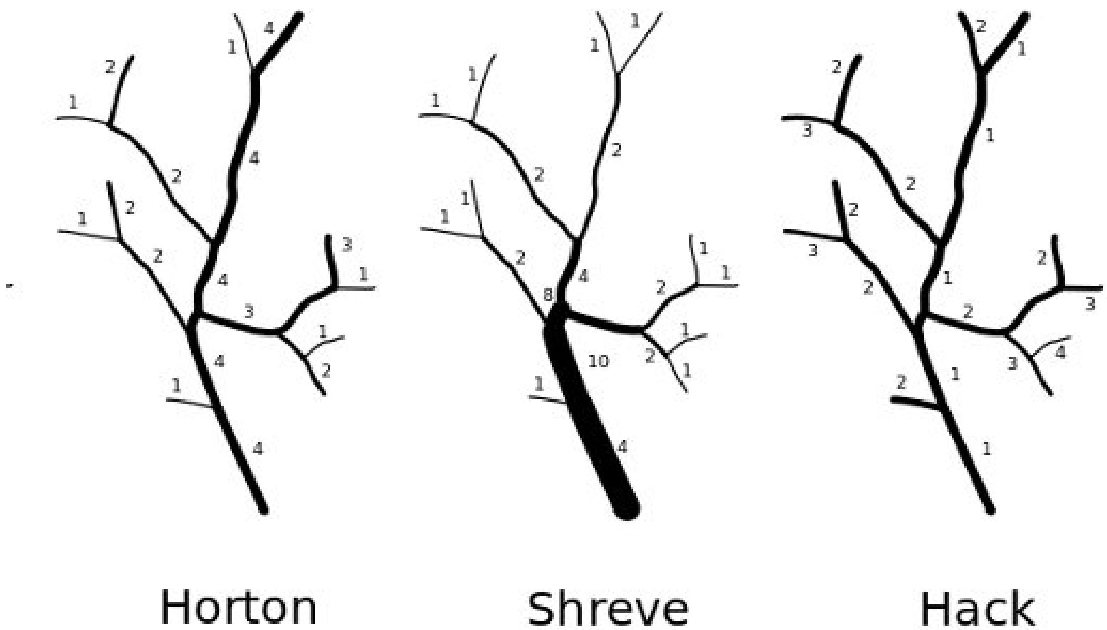


Figure 6: Stream order for the Hack, Strahler, and Shreve systems. (Source: OSGeo)

3 Groundwater

Groundwater refers to water that is stored under the ground.

3.1 Topographic Maps

Topographic maps are a good way to visualize groundwater flow by measuring the height of the water table beneath the ground surface. Groundwater flows perpendicular to contour lines, from high to low elevation. This feature of groundwater is often a good way to understand how pollutants flow. In a well, water will rise up to the levels of the water table, which can often be above the ground level, forming an artesian well.

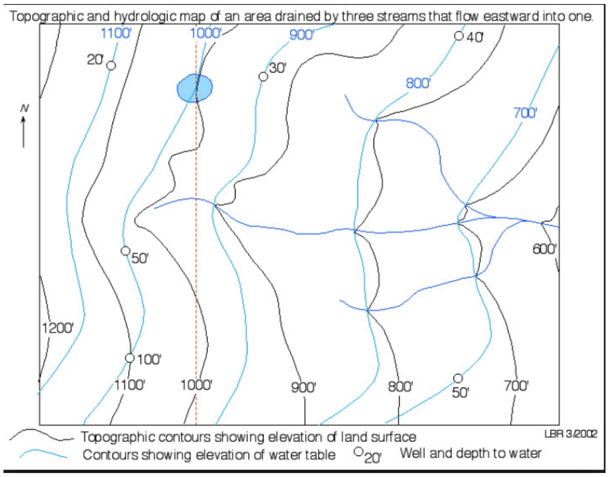


Figure 7: An example of a topographic map (Source: Arizona Geological Survey)

3.2 Groundwater Layers

Groundwater is often layered, with a surface zone of water and air, a vadose zone devoid of water below that, a capillary zone mainly of air but also of some water pulled up from the water table by capillary action, and a large saturated zone underneath it. The saturated zone is in an aquifer, or a material with high porosity (number of pores), permeability (ability of water to flow through it), and conductivity (how connected pores are). Larger sediment, especially poorly sorted sediment or sediment with large cracking, is a good aquifer. Aquitards or aquicludes hold these aquifers in, and are typically highly compressed or fine grained sediment or non-sedimentary rocks. Sometimes, an aquitard can hold water above the water table, forming a perched aquifer. There are often multiple layers of aquifer and aquatard in a region.

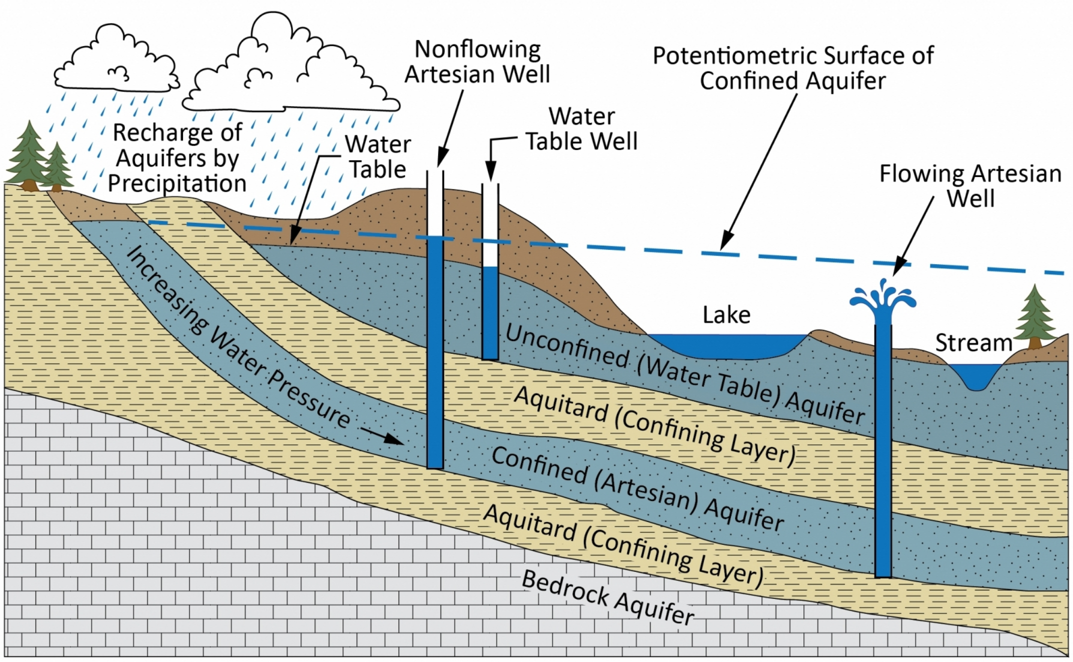


Figure 8: Diagram of groundwater layers. (Source: Utah Geological Survey)

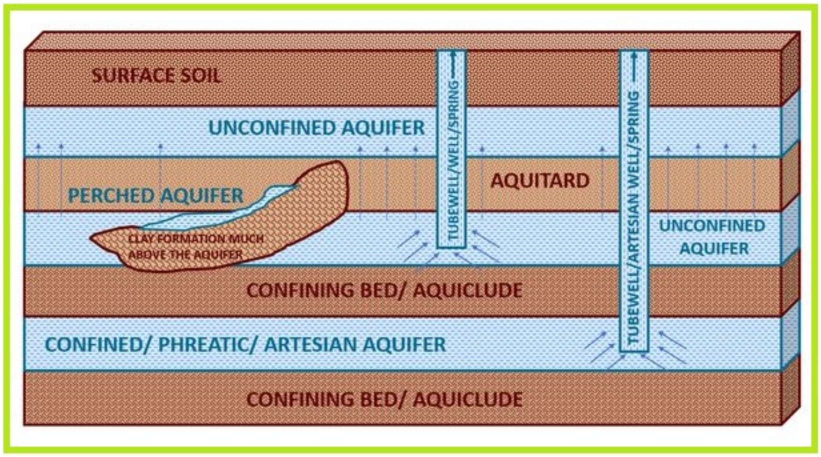


Figure 9: Properties of aquitards and aquiclude in terms of water permeability and formation of aquifers. (Source: Neenu, 2020)

3.3 Aquifers

Humans often deplete aquifers when we draw groundwater for use. Groundwater only replenishes on scales much longer than a human lifetime, so groundwater extraction is a non-renewable resource. Groundwater extraction can lead to sediment resettling and thus land subsidence.

Figure 10: An image of groundwater extraction (Source: US Geological Survey)

4 Landscape Features

4.1 Drainage Basin

The area of land that contains groundwater experiencing a net gain and loss due to a stream is called a drainage basin. Surface topography often indicates where a drainage basin is located, as shown in the figure below. The direction of stream and tributary flow is always downhill, so net water transport can also be predicted.

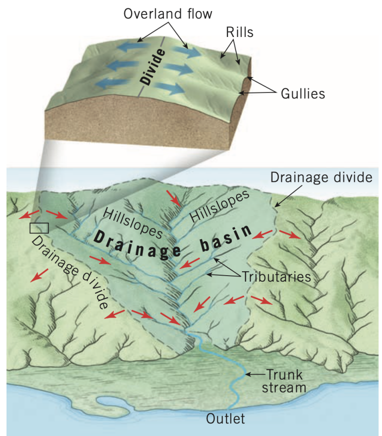


Figure 11: Surface topography of a drainage basin. (Source: Tarbuck)

4.1.1 Drainage Patterns

Drainage systems consist of interconnected networks of streams that exhibit various patterns. The specific patterns of a drainage system are primarily influenced by two factors: the type of underlying material upon which the streams have formed and/or the structural arrangement of fractures, faults, and folds in the area.

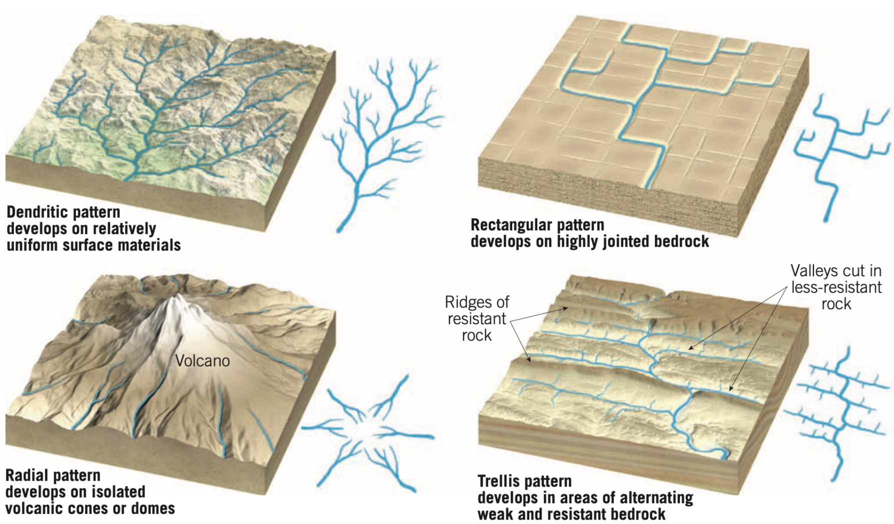


Figure 12: Various drainage patterns. (Source: Tarbuck)

4.2 Depositional Landforms

4.2.1 Deltas

Deltas are formed when sediment-laden streams enter still bodies of water such as lakes, inland seas, or the ocean. The slowing motion of the stream causes sediments to be deposited, resulting in three types of beds.

- Foreset beds are coarse particles that form layers sloping downcurrent from the delta front.
- Topset beds are thin, horizontal layers deposited during flood stage, covering the foreset beds.
- Bottomset beds consist of finer silts and clays settling away from the mouth in nearly horizontal layers.

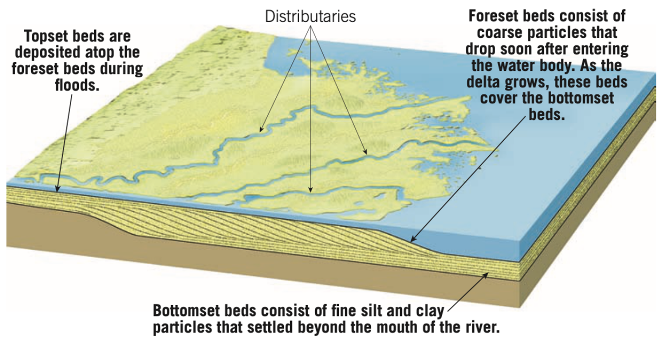


Figure 13: Depositional beds that result from delta flow. (Source: Tarbuck)

As a delta expands from the shoreline, the stream's gradient decreases, leading to sediment accumulation and the choking of the main channel. Consequently, the river seeks shorter, higher-gradient routes to reach base level, resulting in the division of the main channel into smaller distributaries. These distributaries carry water away from the main channel in different paths towards base level, giving the delta a triangular shape. The specific shape and structure of each delta depend on the shoreline configuration, wave activity, and variations in the area.

4.2.2 Natural Levees

Meandering rivers that flow through wide valleys with floodplains tend to develop natural levees on both sides of their channels. Natural levees are formed over time by successive floods. During a flood, when the river overflows onto the floodplain, the water spreads out as a broad sheet, causing a significant decrease in flow velocity. As a result, the coarser sediment in the water settles near the channel, while a thin layer of fine sediment is deposited across the valley floor. This uneven distribution creates the gentle slope of the natural levee.

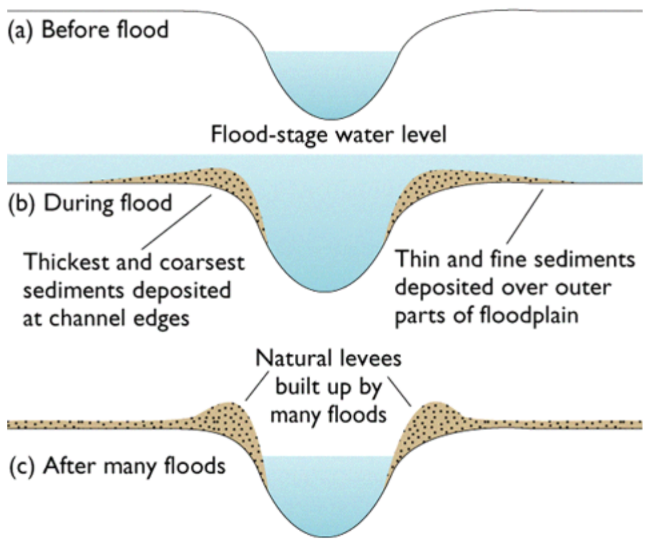


Figure 14: Natural levee formation. (Source: Tarbuck)

4.2.3 Alluvial Fans

Alluvial fans are deposits that take on a fan-shaped appearance and accumulate along the steep fronts of mountains. When a mountain stream reaches a relatively flat lowland, its gradient decreases, causing it to deposit a significant amount of sediment. While alluvial fans are more common in arid climates, they can also be found in humid regions.

Mountain streams, due to their steep gradients, carry coarse sand and gravel as their sediment load. Alluvial fans are composed of these same coarse materials, allowing water to readily soak into the fan.

In desert regions, alluvial fans often experience little to no water flow between rainy periods, leading to the presence of numerous dry channels across their surface. Therefore, in dry regions, alluvial fans grow intermittently, receiving significant amounts of water and sediment only during wet periods.

4.3 Karst Topography

Groundwater plays a crucial role in the formation of caverns and sinkholes by dissolving rock. Soluble rocks, particularly limestone, are widespread beneath Earth's surface, and groundwater acts as an erosional agent in these areas. Although limestone is mostly insoluble in pure water, it readily dissolves when in contact with water containing small amounts of carbonic acid, which is commonly found in groundwater. Carbonic acid forms when rainwater absorbs carbon dioxide from the air and decaying plants. Consequently, when groundwater encounters limestone, the carbonic acid reacts with the calcite (calcium carbonate) in the rocks, resulting in the formation of soluble calcium bicarbonate, which is then carried away in solution. The equation below depicts this reaction:

$$CaCO_3 + (H^+ + HCO_3^-) = Ca^{2+} + 2HCO_3^-$$

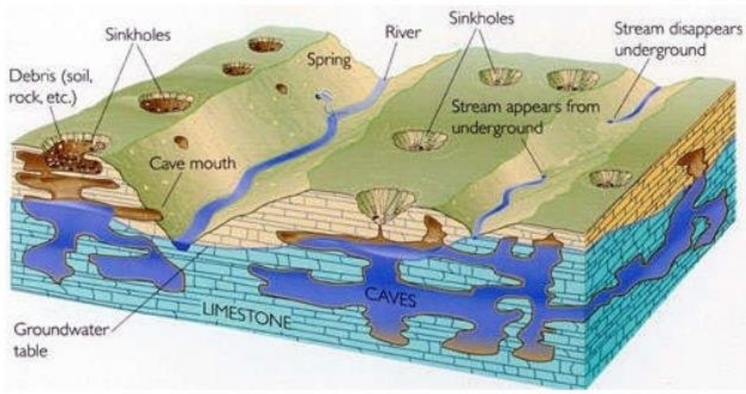


Figure 15: Development of karst topography. (Source: Tarbuck)

4.3.1 Features

Limestone caverns that form from karst reactions reflect both chemical erosion and deposition processes. Caverns form when streams downcut their valleys, causing a drop in water table elevations. Previously saturated and eroded underground passages are revealed, and a variety of karst features form, described as dripstone (travertine) deposits.

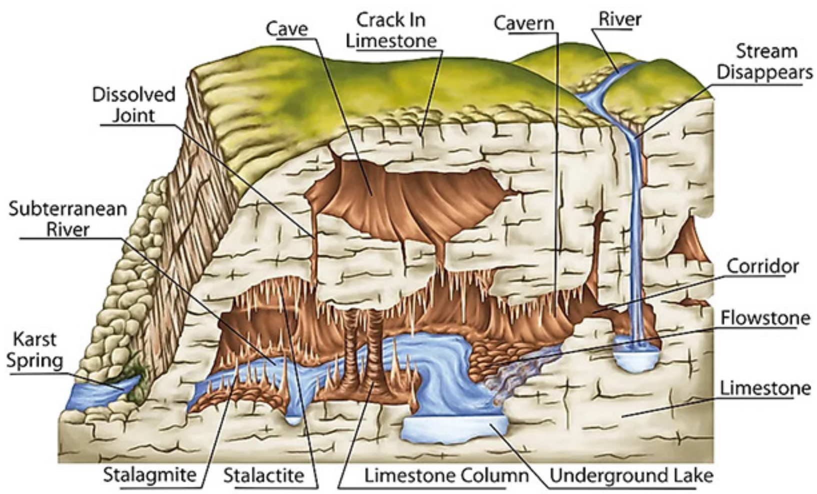


Figure 16: Stalactites and stalagmites are the most common karst depositional features formed from drip limestone. (Source: Tarbuck)

5 Groundwater/Stream Calculations

There are two key equations for groundwater and stream flow: Darcy's Law and the Manning-Chezy Equation.

Darcy's law is a way of calculating the flux or amount of volume moved per unit time of groundwater. The equation for Darcy's law is:

$$Q = VA = KA\frac{h}{L} = -KA\frac{dh}{dL}$$

where K is the hydraulic conductivity, L is the length, A is the area, V is the velocity, and h is the hydraulic head which is typically equivalent to height.

The Manning law is a way of calculating the flux for a stream. The equation for metric units is:

$$Q = VA = (\frac{1}{n})R_h^{2/3}AS_0^{1/2}$$

where R_h is the hydraulic radius or area divided by wetted perimeter, which is just the length of the cross section that is in touch with the round as unblocked, S_0 is the hydraulic gradient or slope of the channel, and n is Manning's coefficient, which depends on the characteristics of the channel bed.

The equation for imperial units (feet, pounds, etc.) is:

$$Q = VA = (\frac{1.49}{n})R_h^{2/3}AS_0^{1/2}$$

and is often used in the United States.

Chezy's law, a simpler version of the Manning equation, is:

$$Q = VA = CA\sqrt{R_h S_0}$$

where C is Chezy's coefficient, which depends on channel roughness.

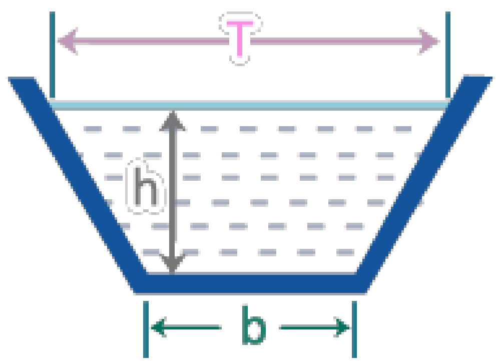


Figure 17: Example calculation of area and wetted perimeter for a stream. The wetted perimeter here is $b + 2\sqrt{h^2 + (/fracT - b2)^2}$ (Source: EasyCalculation)

6 Conclusion

With our amazing new knowledge and mathematical tools, we are ready to analyze streams and groundwater, and start a lifelong journey into hydrology!