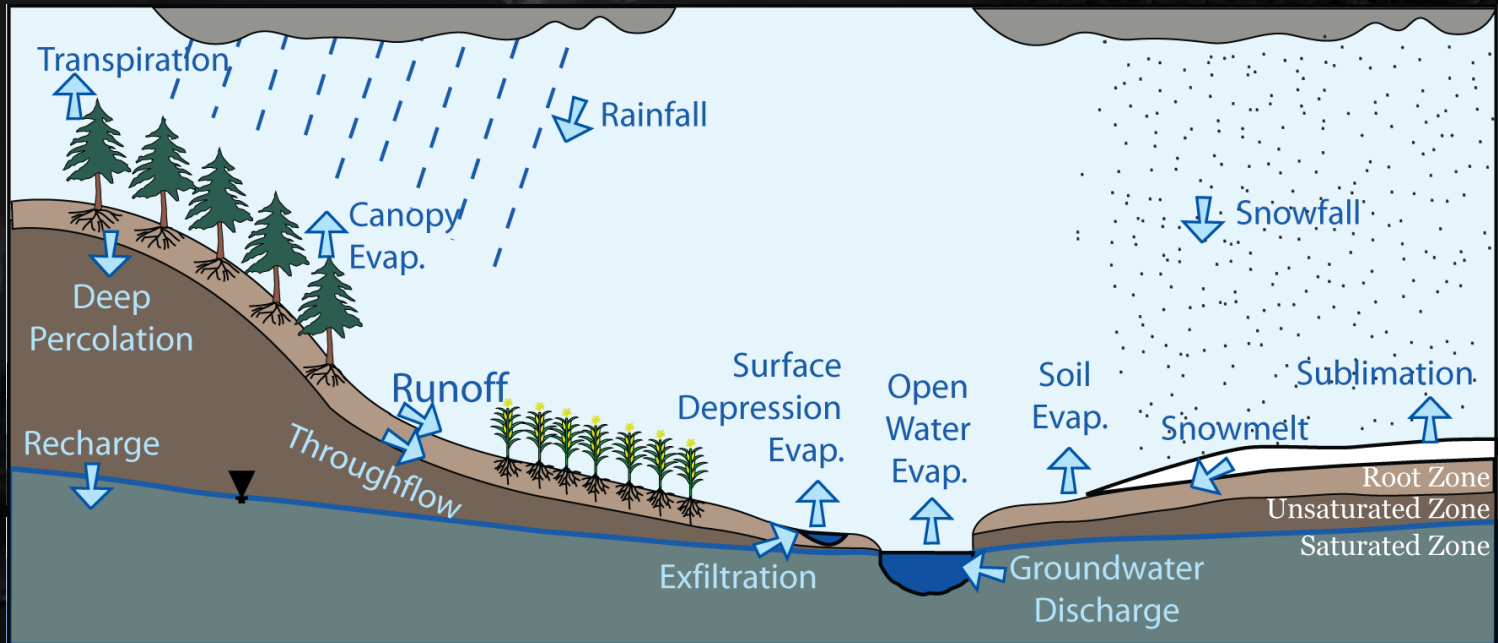


# WATS 5150 – Fluvial Geomorphology

## Watershed Hydrology



# Reading for this Module

## • CHAPTER FOUR: Catchment hydrology

### CHAPTER FOUR *Catchment hydrology*

#### Introduction: what is hydrology?

*Hydrology* is the study of water movement through the hydrological cycle. *Hydraulics* is the study of the mechanics of water flow and the impelling forces that induce sediment movement in river systems (see Chapter 5). This chapter focuses on the hydrology of catchments. Before examining the processes by which water is supplied, transferred and stored in catchments, an introduction to the global hydrological cycle is presented. Measures of discharge, and the magnitude and frequency of river flows, are considered in the second half of the chapter.

#### The hydrological cycle

The hydrological cycle is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere and the hydrosphere. Water can exist in liquid, gaseous and solid states. It is stored in various reservoirs, such as atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields and groundwater. The hydrological cycle describes the movement of water between the atmosphere, oceans and land through energy and matter exchanges as it evaporates, precipitates and flows. Water moves from one reservoir to another by processes such as evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting and groundwater flow.

At the global scale the hydrological cycle is a closed system in which water is neither created nor destroyed. Much more water in the hydrological cycle is 'in storage' than is actually moving through the cycle. Oceans are by far the largest reservoirs, holding about 97% of all water on Earth (Table 4.1). The remaining 3% is freshwater, around 78% of which is stored in ice in Antarctica and Greenland, while a further 21% is groundwater, stored in sediments and rocks beneath the Earth's surface. Freshwater stored on land in rivers, streams, lakes and soil is less

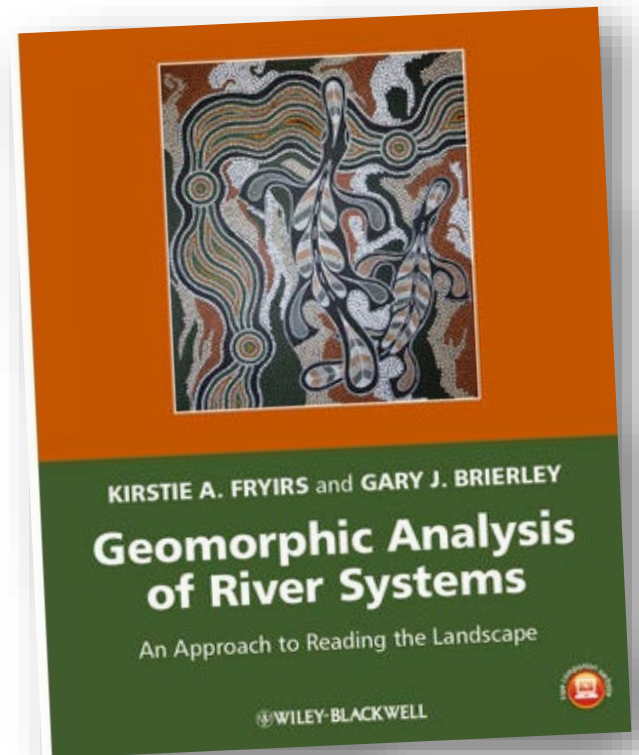
than 1% of the freshwater on the Earth and less than 0.02% of all the water on the Earth. River discharge comprises only 0.0001% of the world's water budget.

The pattern of water storage varies spatially and temporally. During colder climatic periods, water accumulation in snowfields, glaciers and ice-caps reduces the amounts of water in other parts of the hydrological cycle. The reverse is true during warm periods. During the last ice age (the last glacial maximum occurred 15 000–18 000 yr ago) glaciers covered almost one-third of Earth's land mass. As a result, the oceans were 120–150 m lower than today. During the last global 'warm spell' about 125 000 yr ago (i.e. interglacial conditions) the seas were about 5.5 m higher than they are today. About 3 million years ago the oceans were up to 50 m higher than current levels.

The *residence time* of a reservoir within the hydrological cycle is a measure of the average age of the water in that store (Table 4.2). Water stored in the soil remains there very briefly and is readily lost by evaporation, transpiration, throughflow or groundwater recharge. After evaporating, the average residence time of water in the atmosphere is about 9 days before it condenses and falls to the Earth as precipitation (global precipitable water vapour averages 25 mm, while global average annual precipitation is around 1000 mm; therefore, atmospheric water is completely recycled 40 times per year or every 9 days). On average, water

**Table 4.1** Global distribution of water

Reservoir	Volume (10 <sup>6</sup> km <sup>3</sup> )	Percentage of total (%)
Oceans	1370	97.25
Ice-caps and glaciers	29	2.05
Groundwater	9.5	0.68
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere	0.013	0.001
Streams and rivers	0.0017	0.0001
Biosphere	0.0006	0.00004



- Brierley G and Fryirs K. 2005. *Geomorphology and River Management: Applications of the River Styles Framework*. Blackwell Publishing: Victoria, Australia, 398 pp.

# Lots of Follow Up Courses @ USU

- WATS 6900 – Sed Transport w/ Open Channel Flow
- CEE 3500 – Fluid Mechanics
- CEE 3510 – Eng. Hydraulics

- WATS 4490/6490 Watershed Hydrology
- WATS 6491 Streamflow Analysis
- CEE 3430 – Eng. Hydrology

Hydrology  
(water regimes)

- WATS 5200 - Fish Habitats
- WATS 5310 – Wetland & Riparian Ecology
- WATS 6840 - Ecohydraulics
- WATS 6230 – Fish Ecology
- WATS 6860 – Beaver Restoration

Biology  
(vegetation & seedbank characteristics)

Ecology (faunal composition & evolution)

Hydraulics  
(vel & depth)

Chemistry  
(turbidity, nutrient & contaminant cycling)

## River geomorphology - character, behaviour & evolution

- WATS 4490/6490 Watershed Hyd.
- WATS 6050 – Aq Ecossystems / Water Resources Modeling
- CEE 3430 – Eng. Hydrology
- CEE 5450 – Hydrologic Modeling

Social science  
(connection & place)

- CEE 6740 – Water Quality Modelling
- WATS 4530/6530 – Water Quality and Pollution

Management  
(rehabilitation & conservation planning)

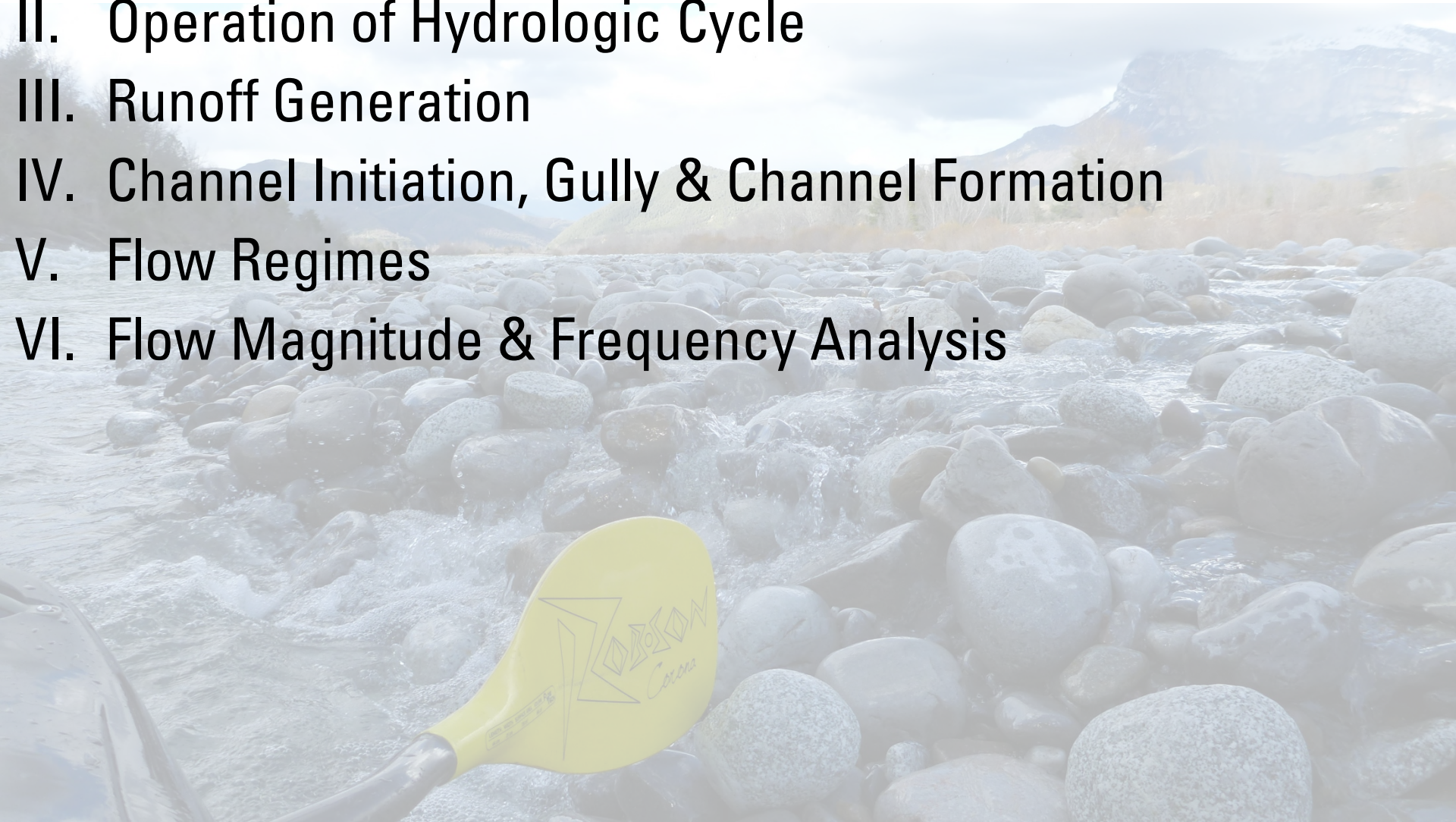
- ENVS 6320 - Water Law & Policy
- ENVS 6530 – Natural Resources Administration
- ENVS 4110 – Fisheries & Wildlife Policy & Administration

- CEE 5470 – Sedimentation Engineering
- WATS 6900 – Sediment Transport in Stream Assessment & Design
- WATS 6850 – Geomrophic Change Detection
- GEO 6800 – OSL Short Course
- GEO 6900 – Fluvial Geomorph Seminar

- WATS 5620-5625 – LTPBR Series
- WATS 5300 – Principles of Aquatic Ecosystem Restoration
- WATS 5330 – Large River Management
- WATS 5340-5350 – MRAE Capstone
- WATS 6310 – Wetland Ecology & Management
- WATS 6700 – Restoration Ecology

# Watershed Hydrology

- I. **Hydrologic Cycle**
- II. Operation of Hydrologic Cycle
- III. Runoff Generation
- IV. Channel Initiation, Gully & Channel Formation
- V. Flow Regimes
- VI. Flow Magnitude & Frequency Analysis



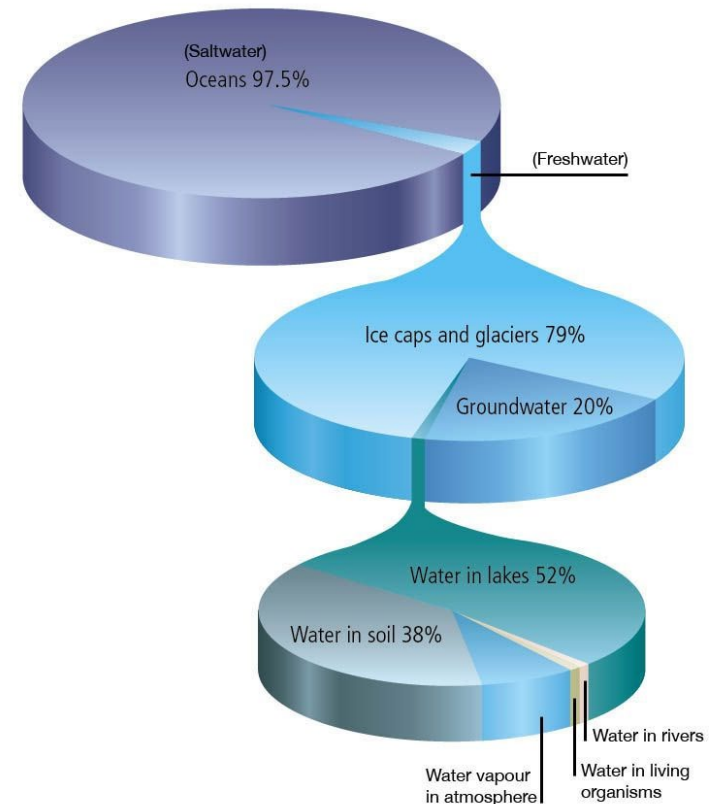
# 0.0001% of World's Water Budget Driving Fluvial Geomorphology!

At the global scale the hydrological cycle is a closed system in which water is neither created nor destroyed. Much more water in the hydrological cycle is 'in storage' than is actually moving through the cycle. Oceans are by far the largest reservoirs, holding about 97% of all water on Earth (Table 4.1). The remaining 3% is freshwater, around 78% of which is stored in ice in Antarctica and Greenland, while a further 21% is groundwater, stored in sediments and rocks beneath the Earth's surface. Freshwater stored on land in rivers, streams, lakes and soil is less

than 1% of the freshwater on the Earth and less than 0.02% of all the water on the Earth. River discharge comprises only 0.0001% of the world's water budget.

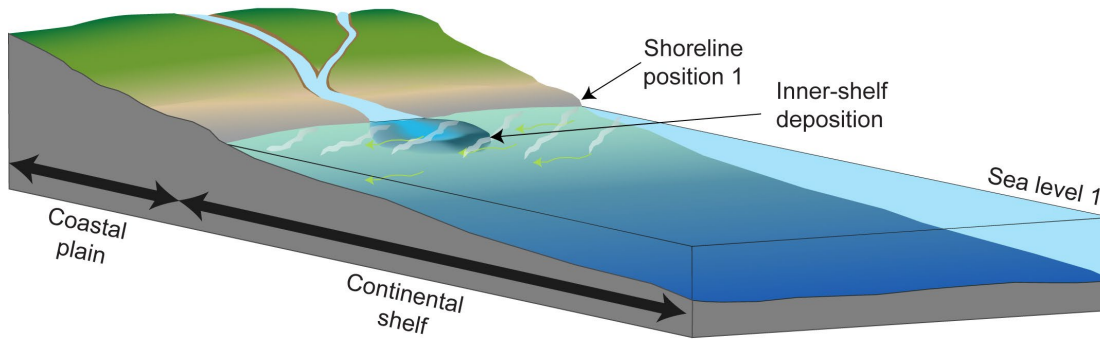
**Table 4.1** Global distribution of water

Reservoir	Volume (10 <sup>6</sup> km <sup>3</sup> )	Percentage of total (%)
Oceans	1370	97.25
Ice-caps and glaciers	29	2.05
Groundwater	9.5	0.68
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere	0.013	0.001
Streams and rivers	0.0017	0.0001
Biosphere	0.0006	0.00004

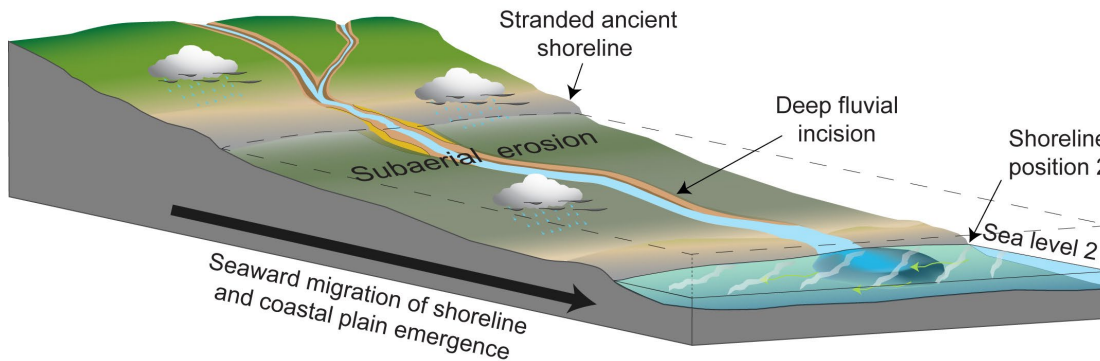


# Remember Profiles?

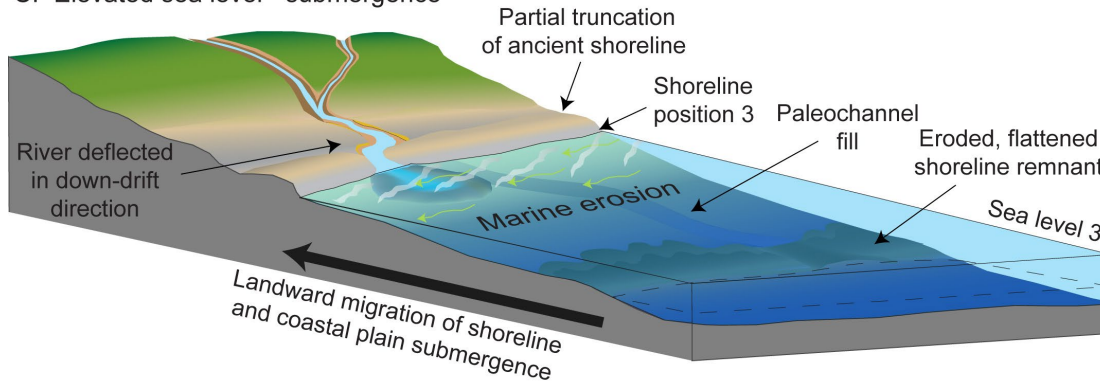
A. Initial sea level



B. Lowered sea level - emergence



C. Elevated sea level - submergence



The pattern of water storage varies spatially and temporally. During colder climatic periods, water accumulation in snowfields, glaciers and ice-caps reduces the amounts of water in other parts of the hydrological cycle. The reverse is true during warm periods. During the last ice age (the last glacial maximum occurred 15 000–18 000 yr ago) glaciers covered almost one-third of Earth's land mass. As a result, the oceans were 120–150 m lower than today. During the last global 'warm spell' about 125 000 yr ago (i.e. interglacial conditions) the seas were about 5.5 m higher than they are today. About 3 million years ago the oceans were up to 50 m higher than current levels.

- What is locked up in ice vs. ocean matters!

# Water Residence Time

---

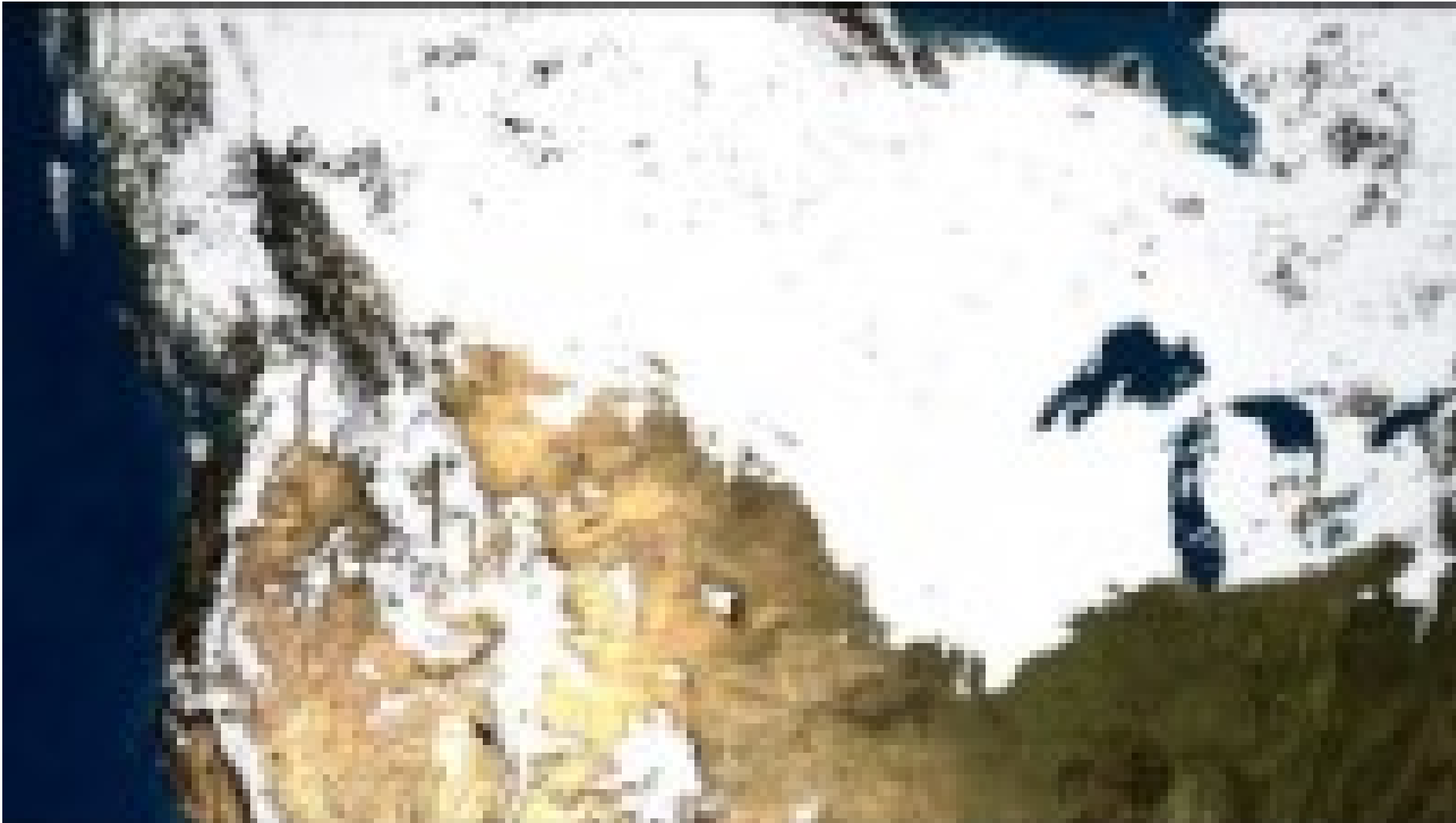
- Measure of average age of water in that store.

**Table 4.2** Average residence times of water in differing reservoirs

Reservoir	Average residence time
Oceans	3 200yr
Groundwater: deep	10 000yr
Groundwater: shallow	100–200yr
Lakes	50–100yr
Glaciers	20–100yr
Rivers	2–6 months
Seasonal snow cover	2–6 months
Soil moisture	1–2 months
Atmosphere	9 days

is renewed in rivers once every 16 days. Slower rates of replacement occur in large lakes, glaciers, ocean bodies and groundwater, where turnover can take from hundreds to thousands of years. Groundwater can spend over 10 000 yr beneath the Earth's surface. In many areas where humans are dependent on groundwater for domestic and agricultural purposes, extraction rates far exceed rates of renewal.

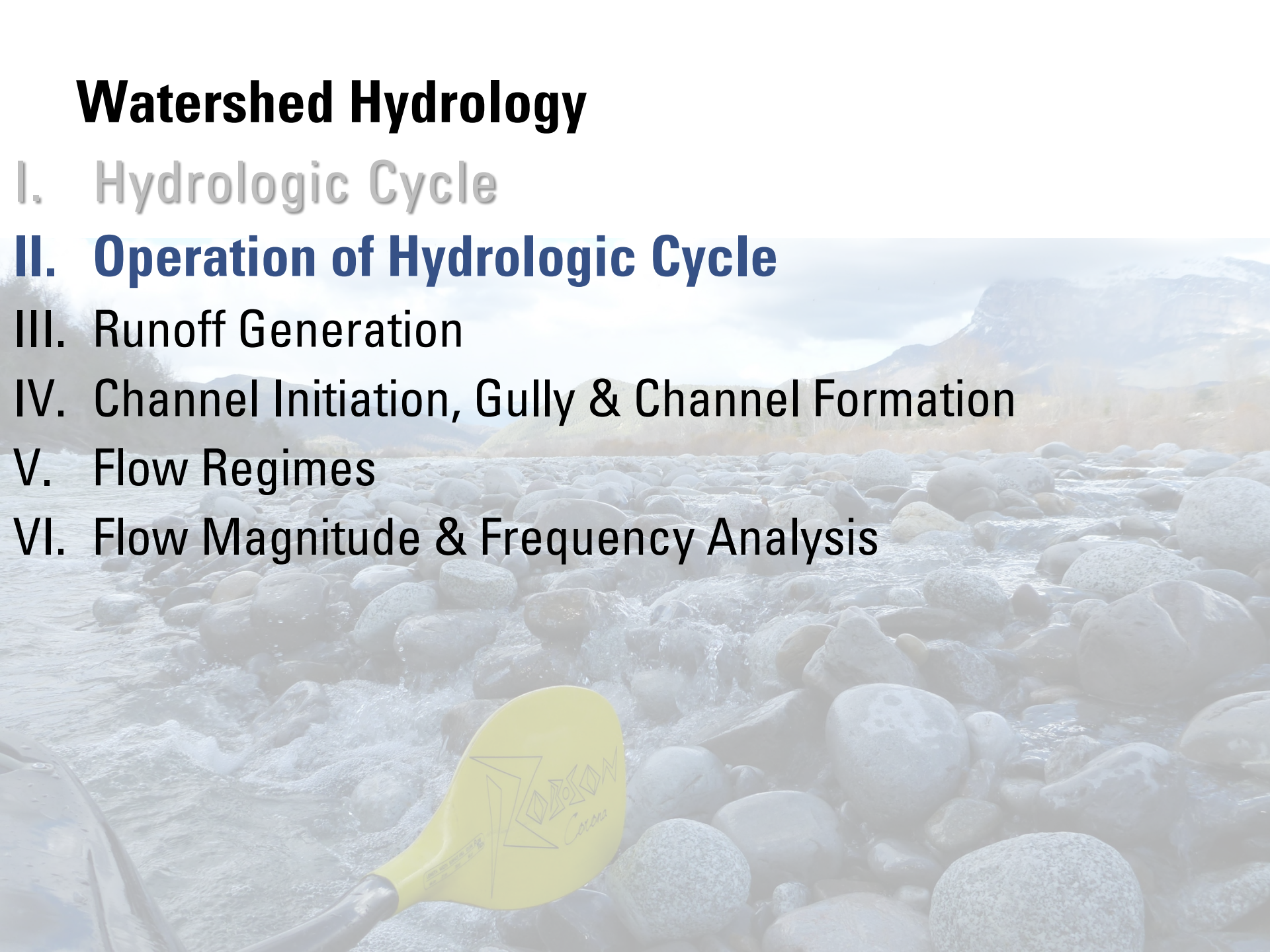
# Overview of Earth's Water Cycle





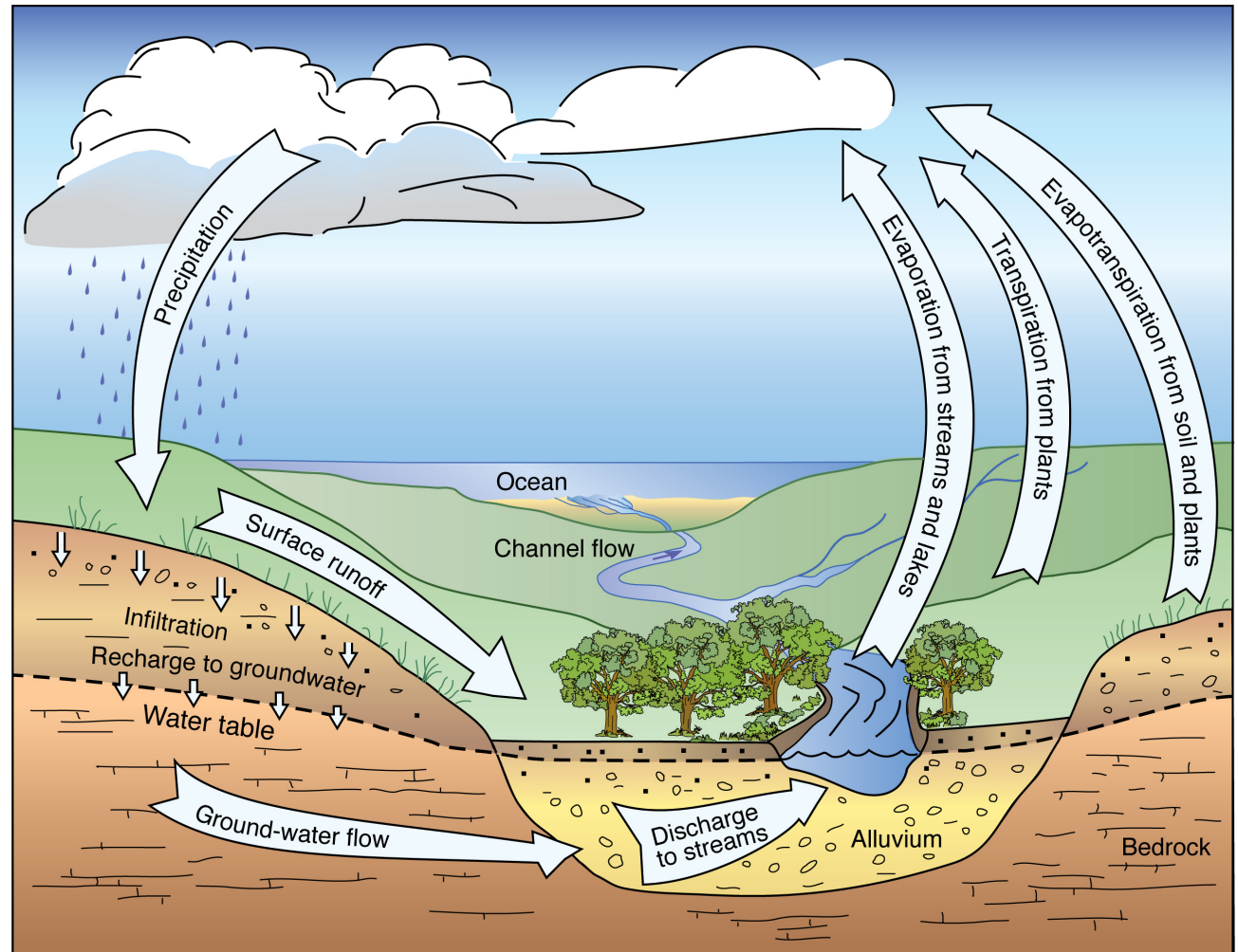
# Watershed Hydrology

- I. Hydrologic Cycle
- II. Operation of Hydrologic Cycle**
- III. Runoff Generation
- IV. Channel Initiation, Gully & Channel Formation
- V. Flow Regimes
- VI. Flow Magnitude & Frequency Analysis



# Operation of Hydrologic Cycle – A class in each process

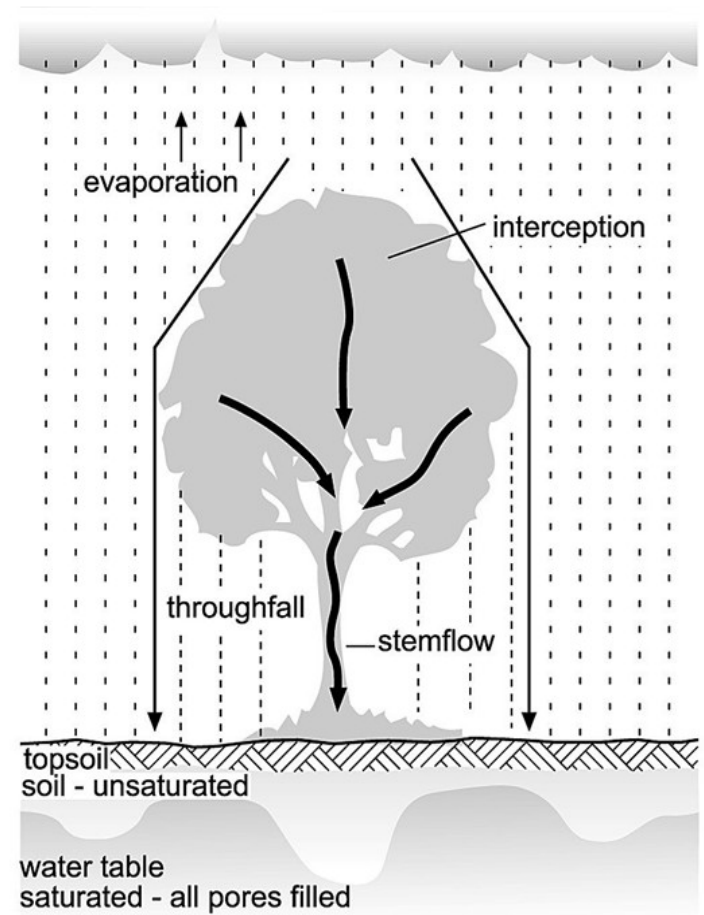
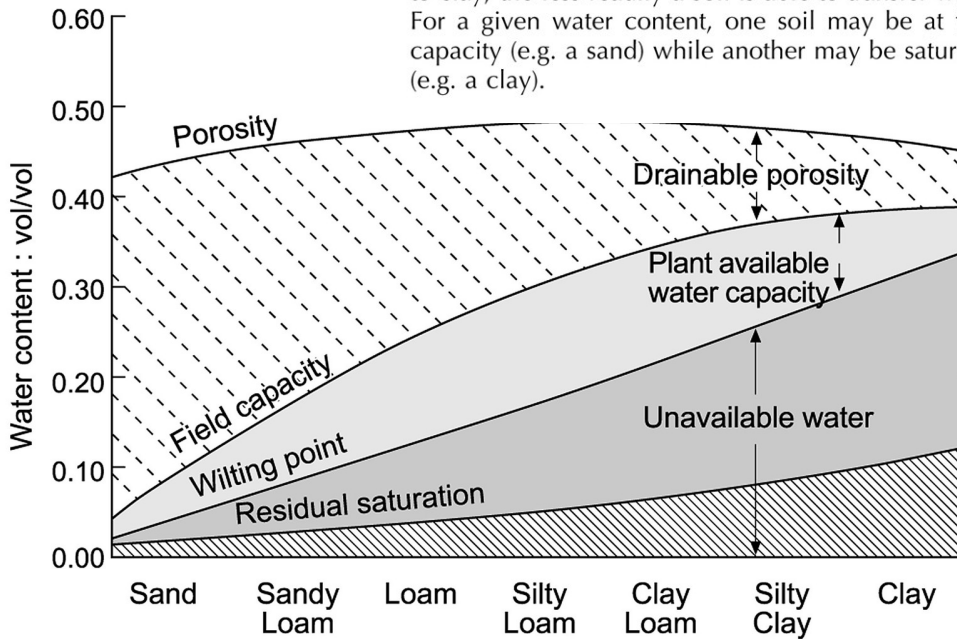
- Atmospheric Water (water vapor, droplets & crystals)
- Precipitation
- Evaporation
- Transpiration
- Interception
- Throughfall
- Streamflow
- Infiltration
- Percolation



THE HYDROLOGIC CYCLE

# Ecohydrology & Soils matter!

**Figure 4.2** Variability in soil moisture content with textural soil types. The finer the grain size, from sand to clay, the less readily a soil is able to transfer water. For a given water content, one soil may be at field capacity (e.g. a sand) while another may be saturated (e.g. a clay).



**Figure 4.1** Flow interception, stem flow and through-fall, and visual representations of the three states of soil moisture.

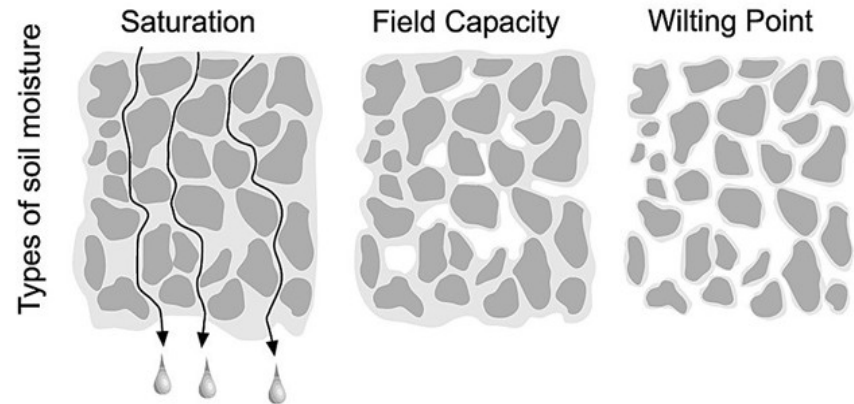


Figure 4.1 & 4.2 Fryirs & Brierley (2013)

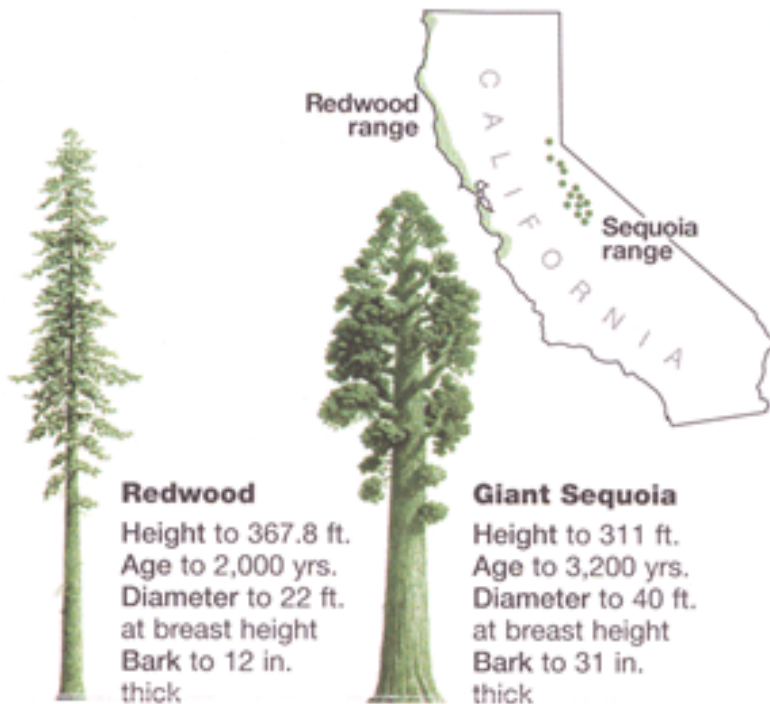
DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

# Redwood Forests

## A Hydrologic Tangent



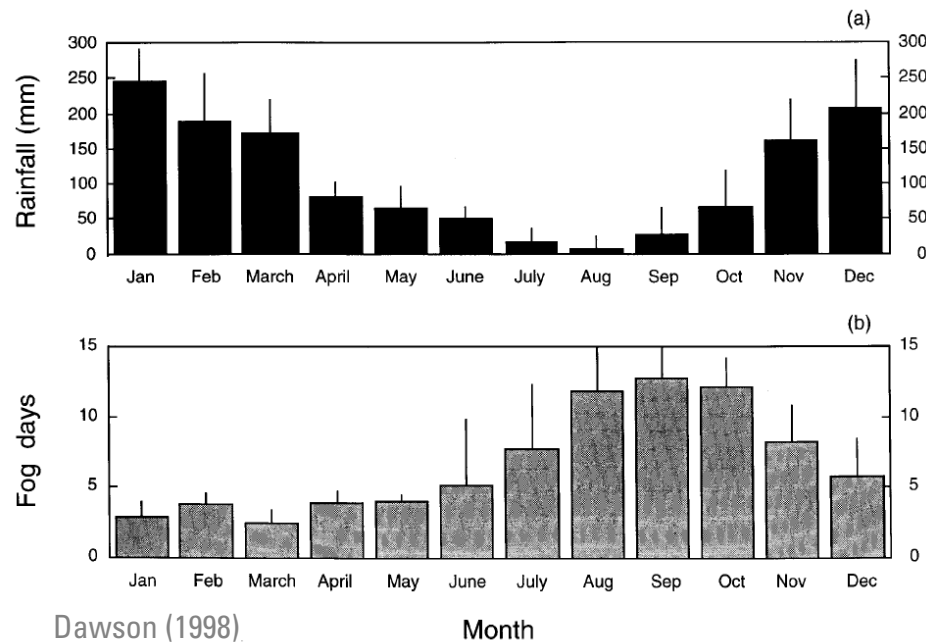
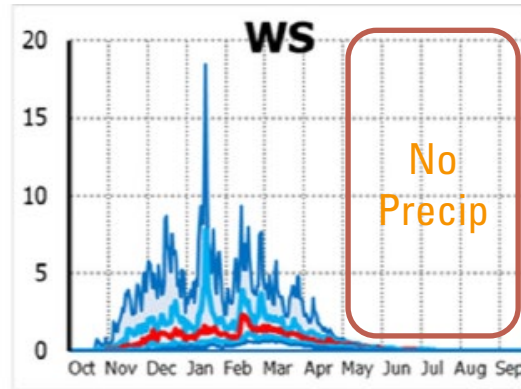
- The world's tallest trees (90 to 115 m)
- But these trees live in a region that tends to get no precip from June thru Sept.



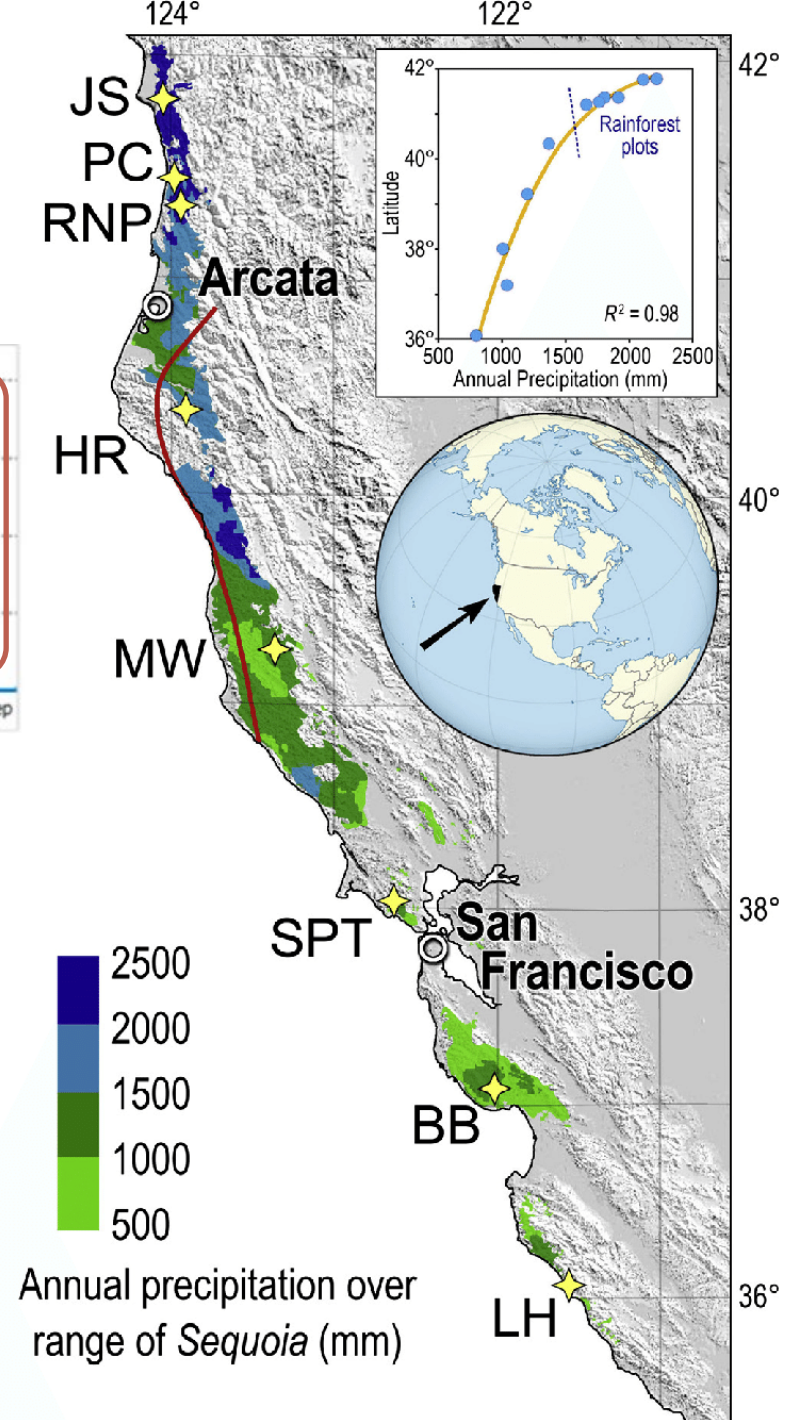
photography by  
**Susan Taylor**  
susantaylorphoto.com

# “Rain Forests” where it doesn't rain 2-5 months of year?

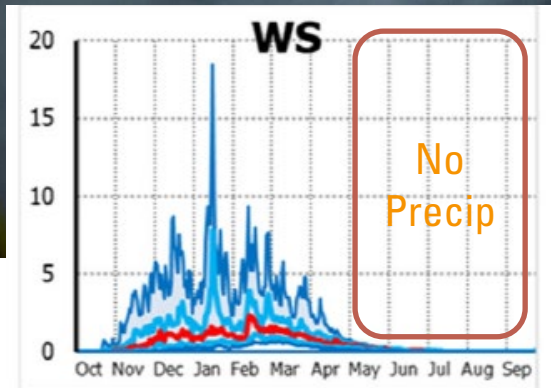
- So how do you keep such a massive, thirsty tree going in summer?



Dawson (1998)  
DOI: [10.1007/s004420050683](https://doi.org/10.1007/s004420050683)



# Coastal Fog...



**“Simple”, but not...**



# 22% to 46% of Annual Hydrologic Input from Fog!

**Table 1** The average and range of fog water input (mm) during a 12-h fog-day by different ‘collectors’, the average rainfall, fog drip and total moisture inputs to the sites occupied by different collectors, and the average percentage (and range) of the annual hydrologic inputs as fog. All data were obtained during 1992–1994 at a redwood forest site along the Klamath River near Requa, California. Fog input values are based on millimeters of fog collected for collectors of a known interception area. Input values from

different collector types can therefore be compared directly. Values for fog water input are means (SD) from seven interception or ten artificial fog collectors and the same number of 12-h ‘fog-days’. Other values are means with either SDs or ranges shown in parentheses. Values within a row with different supercripts are significantly different from one another ( $P < 0.05$ ; Students *t*-test). Differences between years were not tested (but see Table 3)

	Year		Off trees (interception)	Fog collector in the forest	Fog collector in the open
Fog water input	1992	Average	93 (21) <sup>a</sup>	55 (17) <sup>b</sup>	42 (13) <sup>c</sup>
		Range	63–128	37–73	25–71
	1993	Average	104 (26) <sup>a</sup>	62 (20) <sup>b</sup>	40 (22) <sup>c</sup>
		Range	55–132	39–70	33–69
	1994	Average	93 (21) <sup>a</sup>	60 (18) <sup>b</sup>	51 (21) <sup>c</sup>
		Range	59–130	38–66	29–60
	3-Year average		<b>98 (23)<sup>a</sup></b>	<b>59 (18)<sup>b</sup></b>	<b>46 (19)<sup>c</sup></b>
	3-Year range		55–132	37–73	25–71
Rainfall (mm)			1315 (340)	1315 (340)	1315 (340)
Fog-drip (mm)			447 (289–605)	303 (17–434)	224 (79–368)
Total (mm)			1762 (413) <sup>a</sup>	1618 (292) <sup>a,b</sup>	1540 (325) <sup>b</sup>
Annual fog input		%	<b>34 (8)<sup>a</sup></b>	<b>23 (7)<sup>b</sup></b>	<b>17 (10)<sup>b</sup></b>
		Range	22–46	13–33	6–28

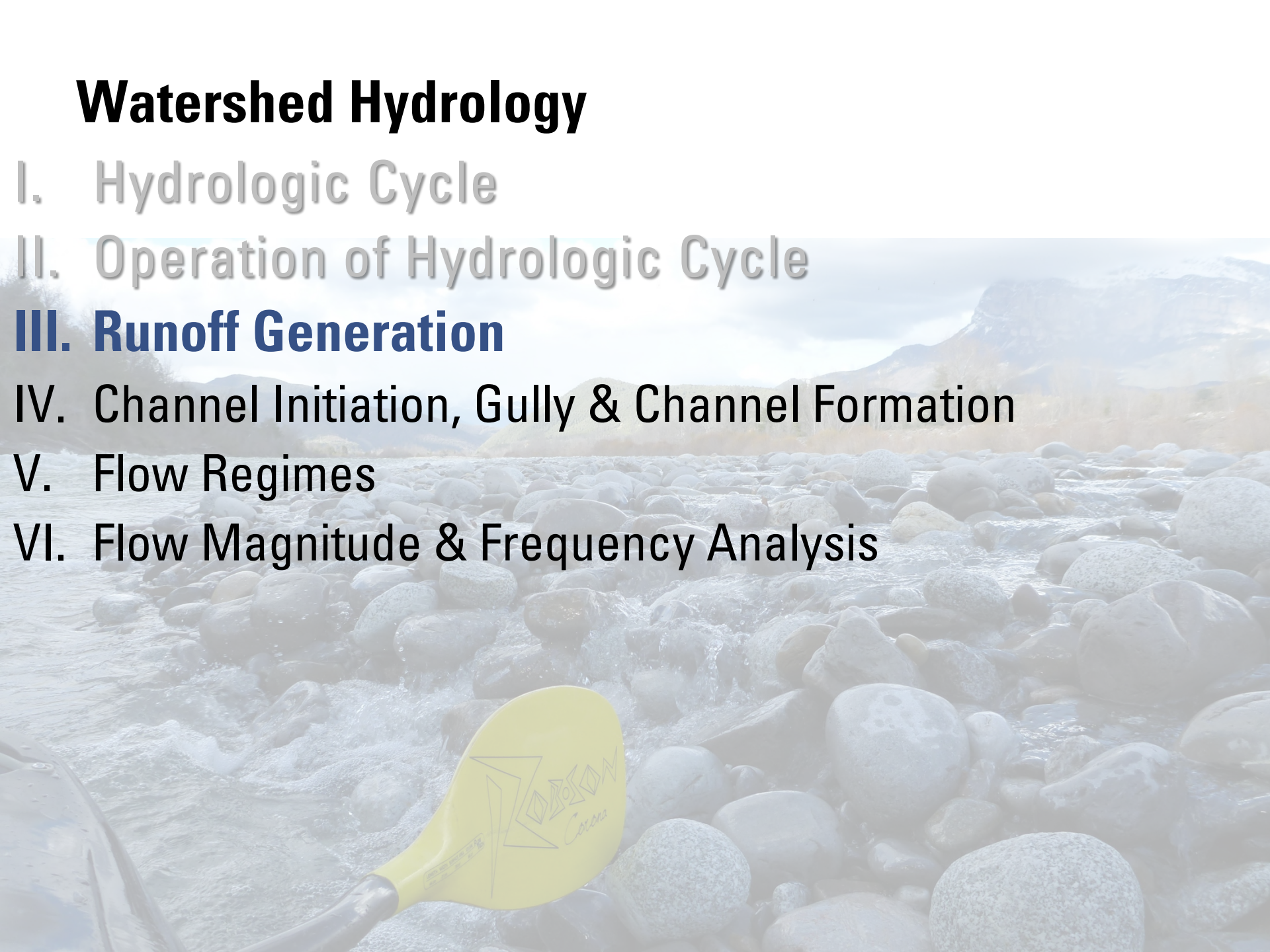
California. During the study period, 34%, on average, of the annual hydrologic input was from fog drip off the redwood trees themselves (interception input). When trees were absent, the average annual input from fog was only 17%, demonstrating that the trees significantly influence the magnitude of fog water input to the ecosystem. Stable hydrogen and oxygen isotope analyses of

the 3-year study. In summer, when fog was most frequent, ~19% of the water within *S. sempervirens*, and ~66% of the water within the understory plants came from fog after it had dripped from tree foliage into the soil; for *S. sempervirens*, this fog water input comprised 13–45% of its annual transpiration. For all plants, there



# Watershed Hydrology

- I. Hydrologic Cycle
- II. Operation of Hydrologic Cycle
- III. Runoff Generation**
- IV. Channel Initiation, Gully & Channel Formation
- V. Flow Regimes
- VI. Flow Magnitude & Frequency Analysis



# Relationship between Rainfall, Infiltration & Runoff

**Figure 4.3** Schematic representation of the relationship between rainfall, infiltration and runoff. Rain starts at time  $T = 5$  min. At this time the infiltration capacity of the soil is at its highest. At around  $T = 12$ – $18$  min the rainfall intensity is at its greatest. As water fills soil pores, the infiltration rate steadily decreases, before plateauing. The dark area represents rainfall that enters the soil via infiltration. Around this time,  $T = 18$  min, all excess rain (light grey shade) is converted to runoff. The peak in runoff at  $T = 22$  min is lagged behind rainfall because of the infiltration effects of the soil. Runoff may still occur up to 30 min after rain has ceased as soil water is contributed further down the hillslope/catchment. Modified from Dunne and Leopold (1978).

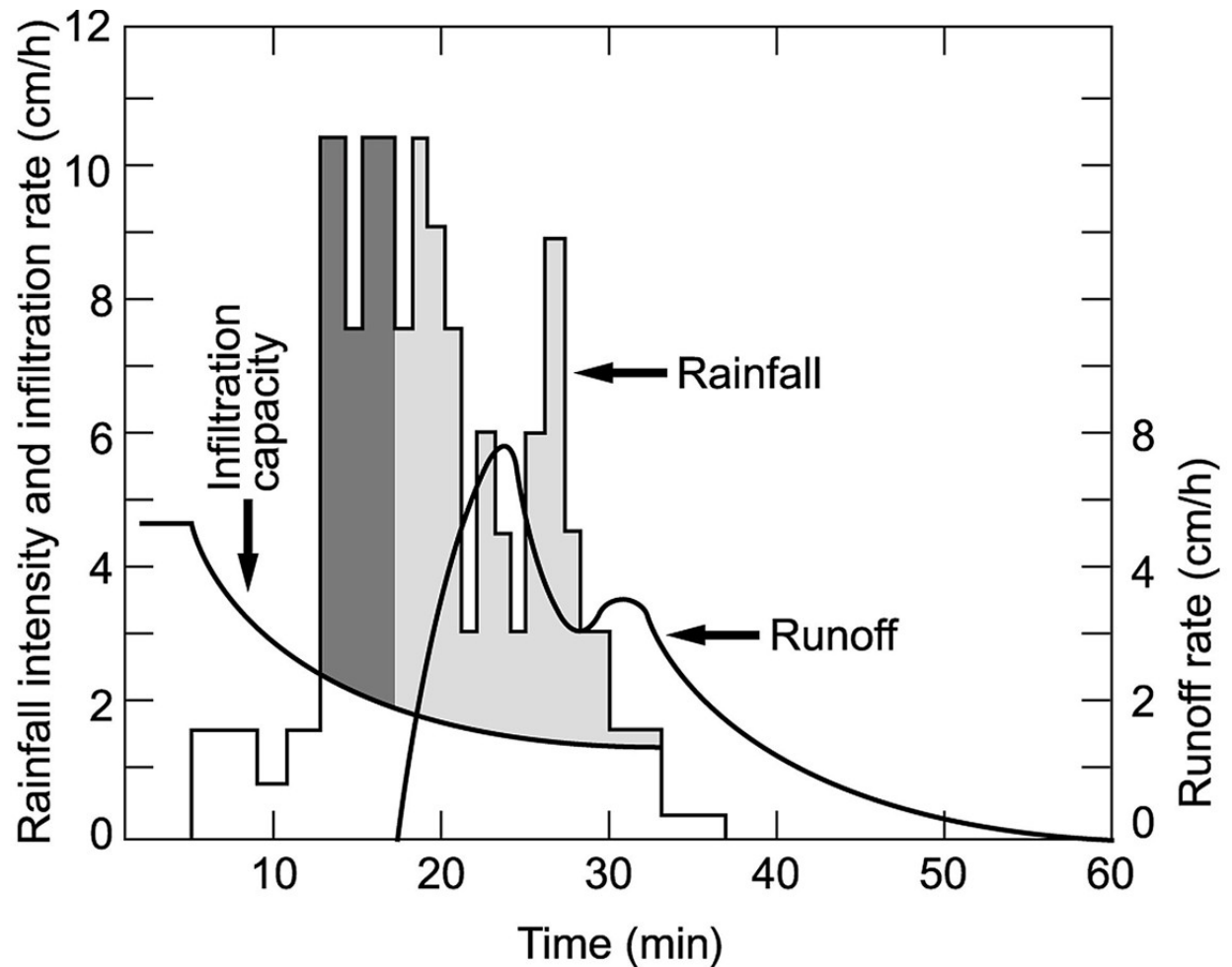


Figure 4.3 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

# Runoff Generation Mechanisms

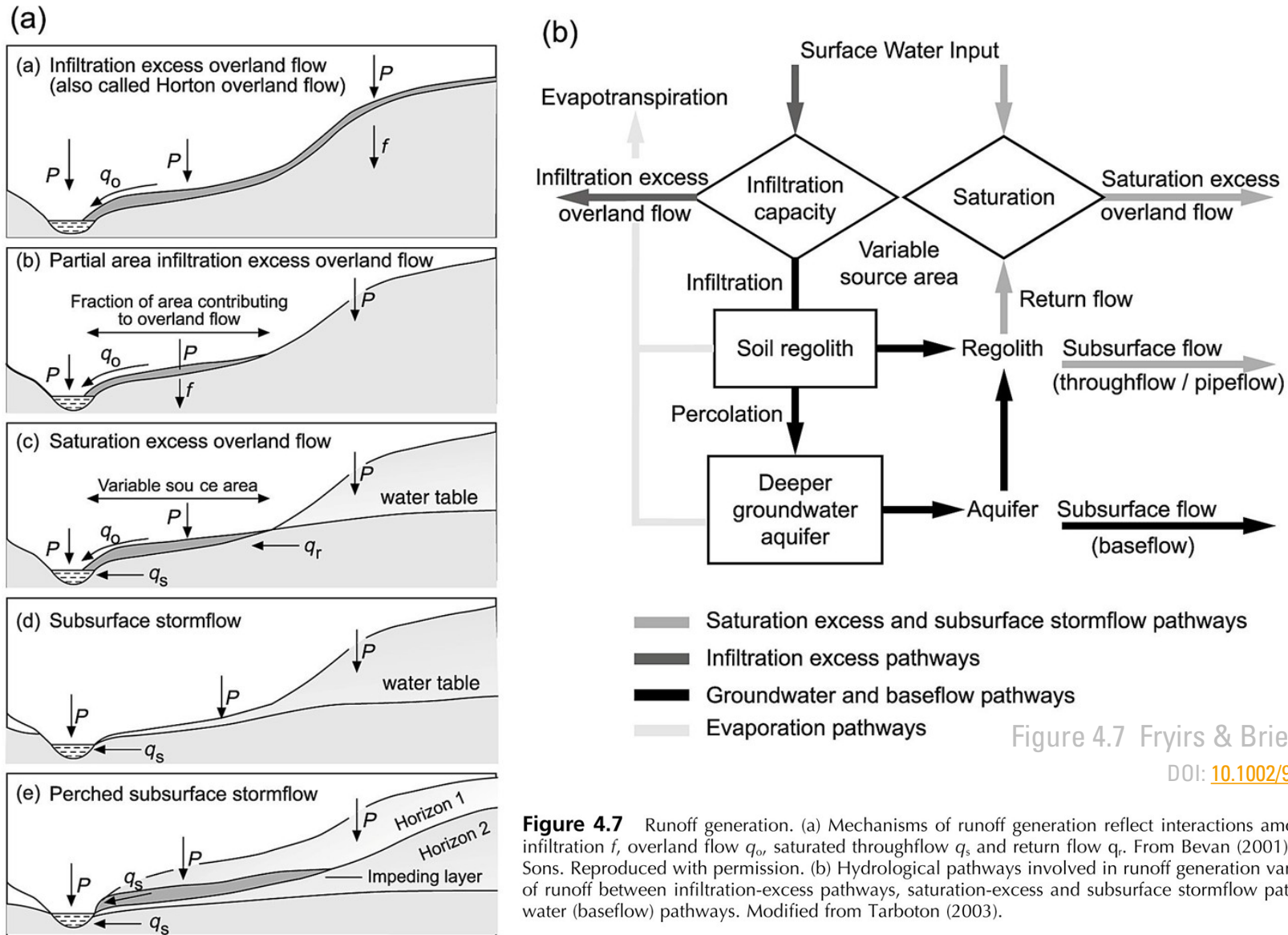


Figure 4.7 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

**Figure 4.7** Runoff generation. (a) Mechanisms of runoff generation reflect interactions among precipitation  $P$ , infiltration  $f$ , overland flow  $q_o$ , saturated throughflow  $q_s$  and return flow  $q_r$ . From Bevan (2001). © John Wiley and Sons. Reproduced with permission. (b) Hydrological pathways involved in runoff generation vary for different types of runoff between infiltration-excess pathways, saturation-excess and subsurface stormflow pathways and groundwater (baseflow) pathways. Modified from Tarboton (2003).

# Return Flow

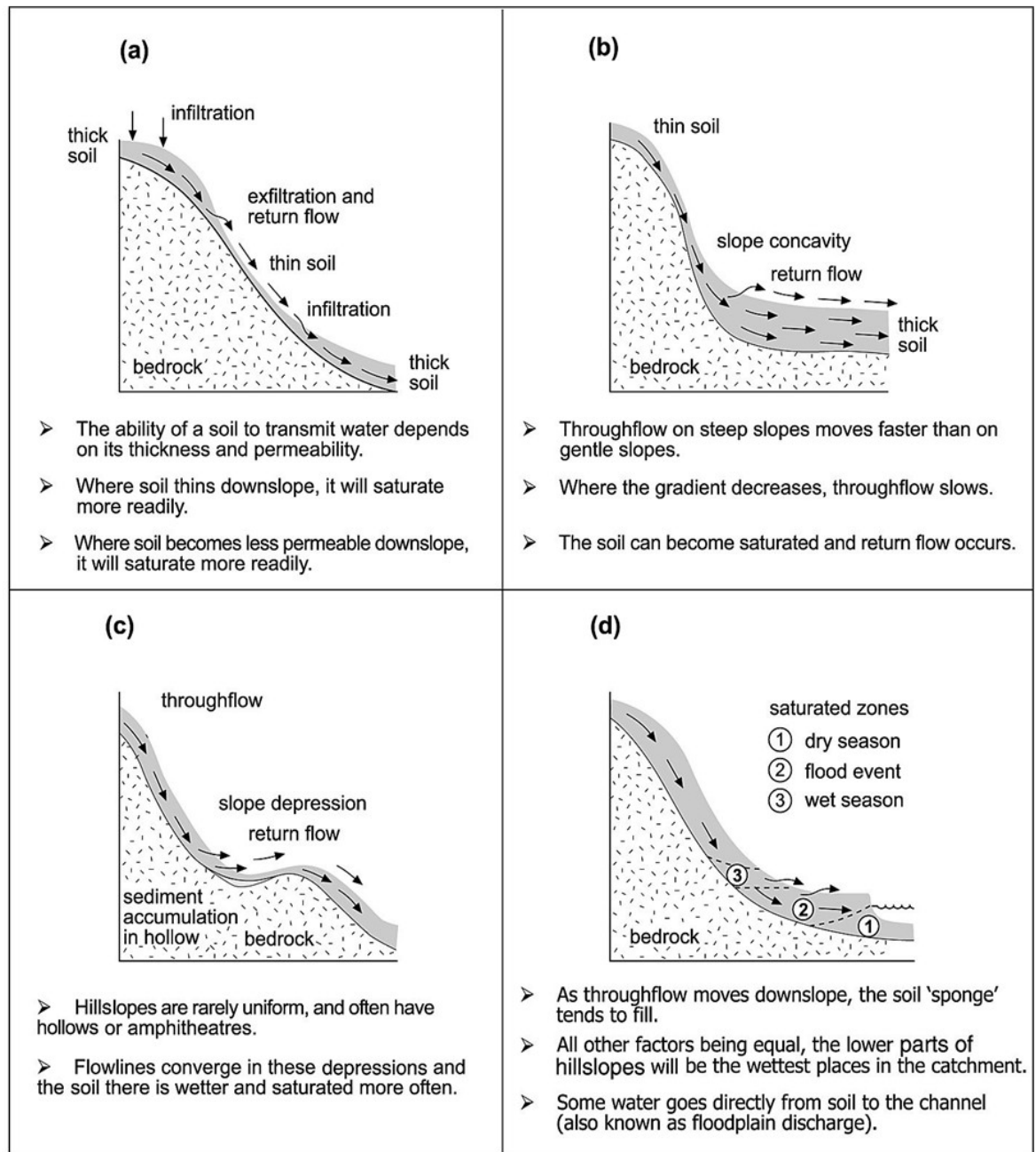
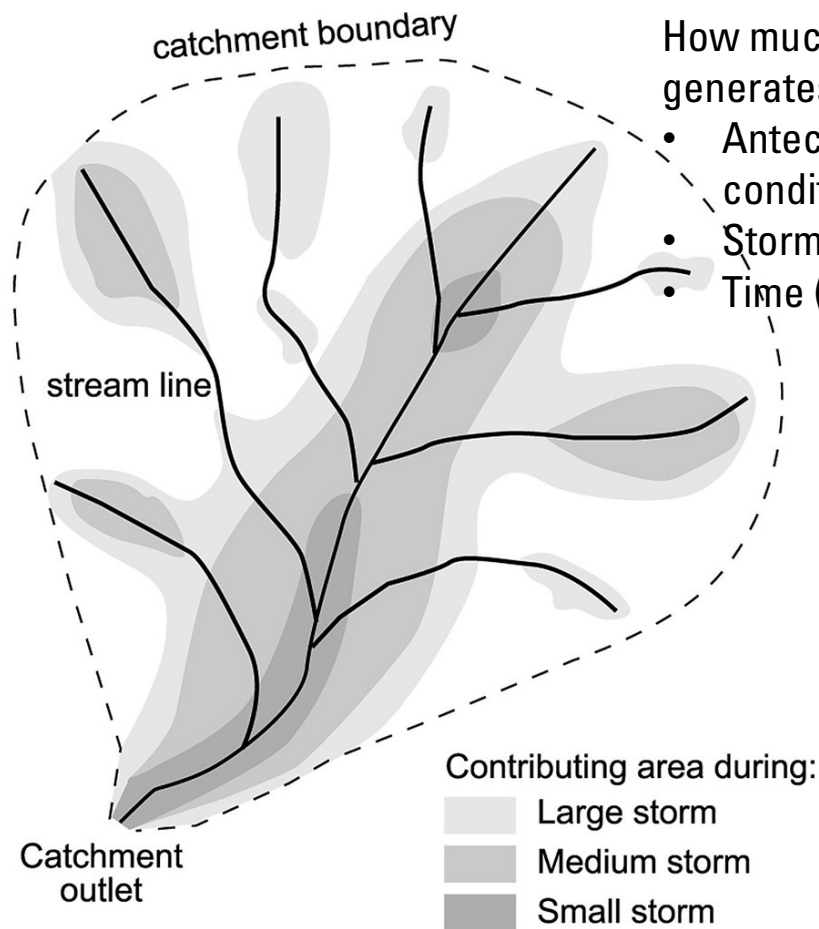


Figure 4.5 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

**Figure 4.5** Forms of return flow. Return flow occurs where throughflow is forced back to the soil surface (exfiltrated) when it is saturated. Four scenarios are shown: return flow associated with (a) changes in soil thickness, (b) soil concavities, (c) hollows and (d) saturated zones on valley bottoms.

# Variable Source Area Concept



How much of catchment generates runoff is a  $f(?)$ :

- Antecedent soil moisture conditions
- Storm size
- Time (in event)

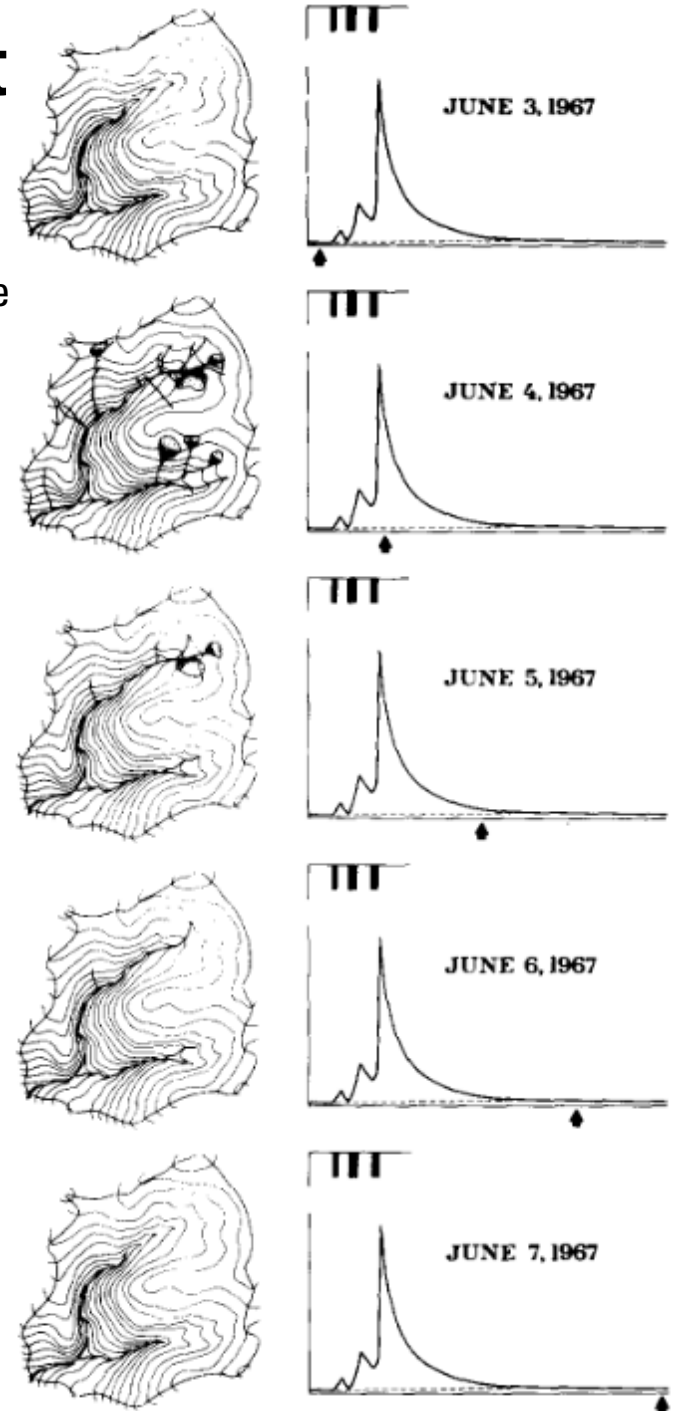
**Figure 4.6** The partial area model of runoff generation. During small storms only small areas of the catchment are saturated and generate runoff. However, as storm size increases (either more rain falls or rain lasts longer), the total area that contributes water via various forms of runoff increases.

Figure 4.6 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

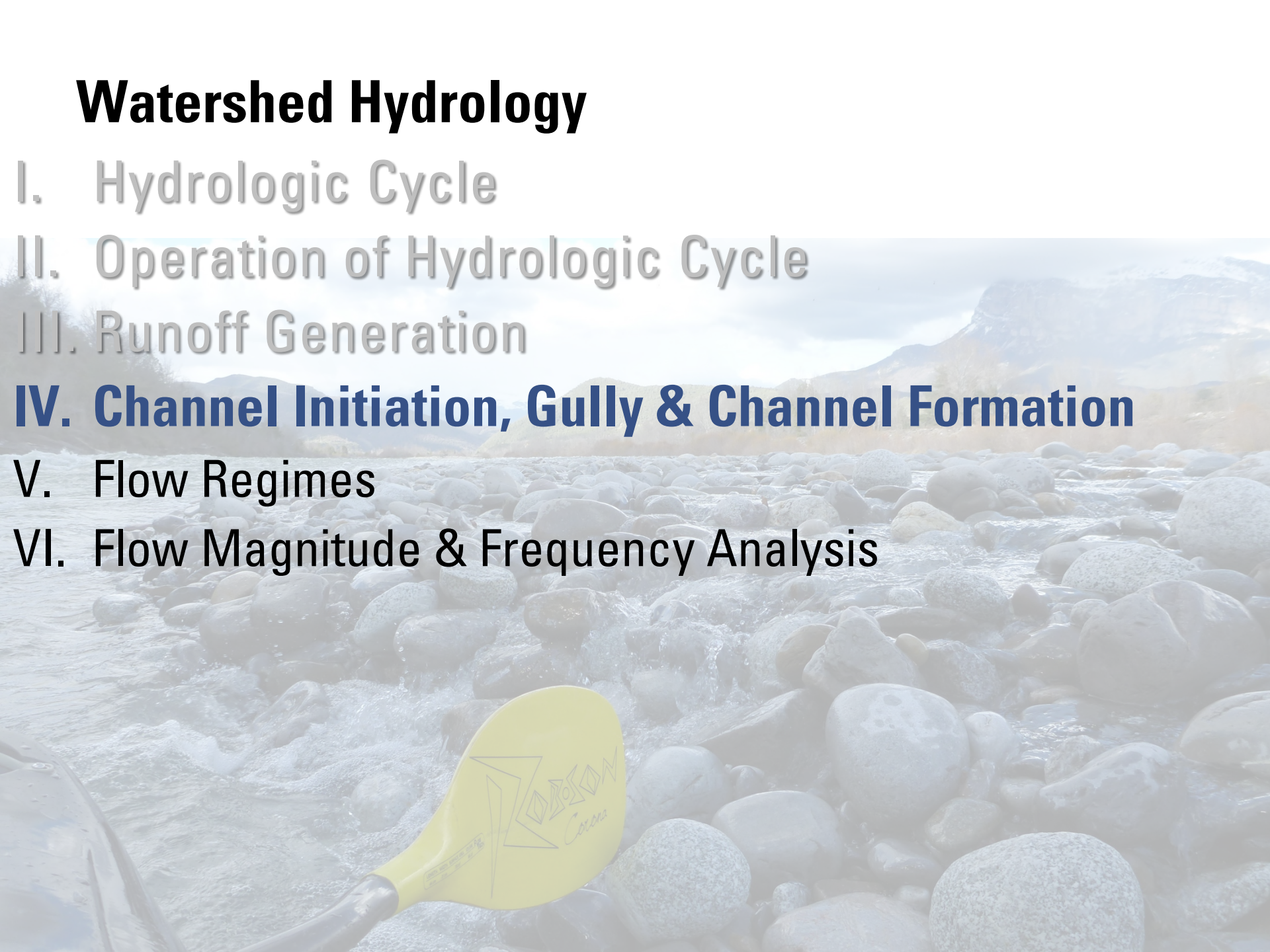
Bernier (1985)

DOI: [10.1016/0022-1694\(85\)90055-1](https://doi.org/10.1016/0022-1694(85)90055-1)

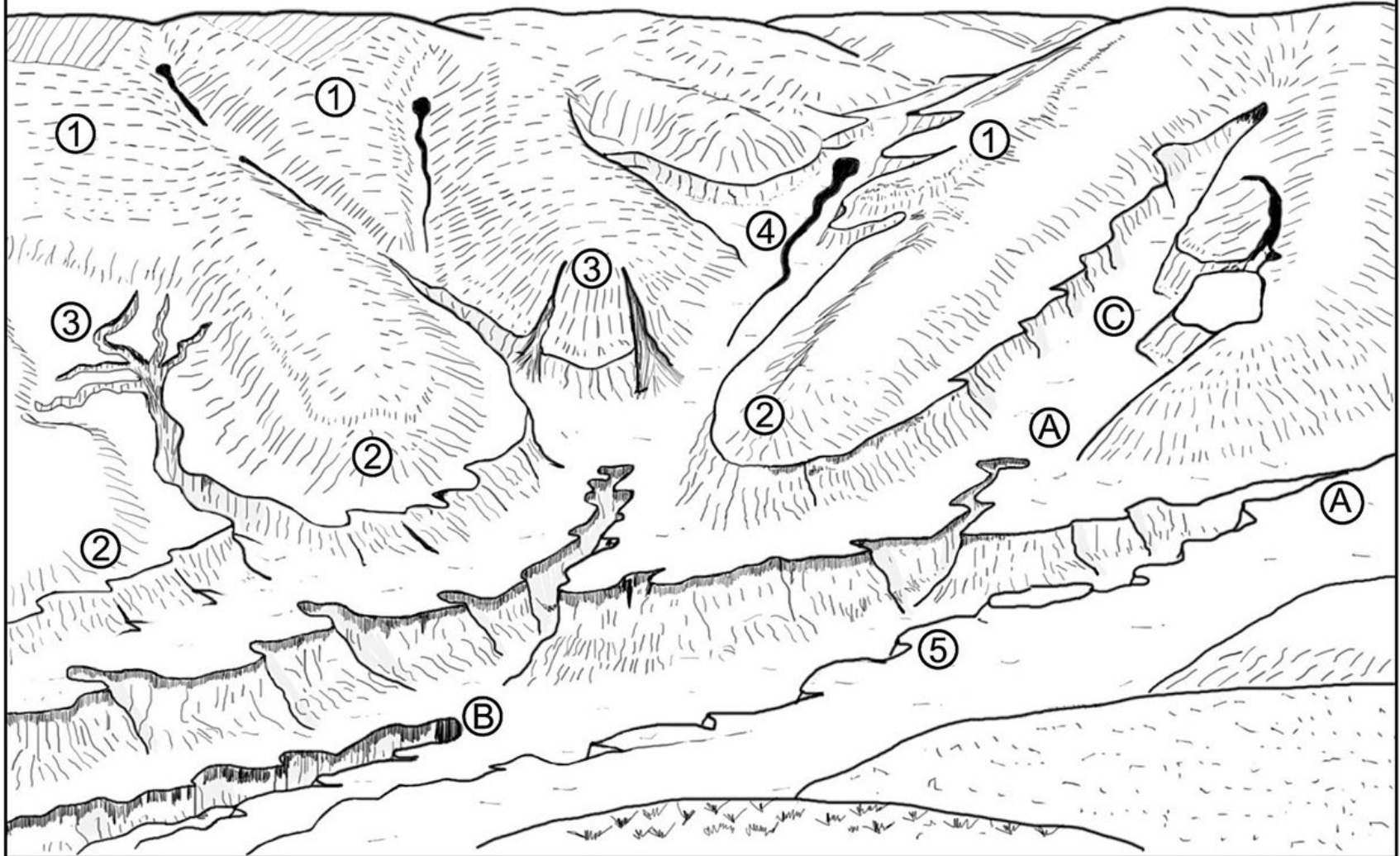


# Watershed Hydrology

- I. Hydrologic Cycle
- II. Operation of Hydrologic Cycle
- III. Runoff Generation
- IV. Channel Initiation, Gully & Channel Formation**
- V. Flow Regimes
- VI. Flow Magnitude & Frequency Analysis



# Channelized Flow Paths



## Types of drainage lines

- ① interrill ② rill ③ gully ④ incised channel - discontinuous  
⑤ incised channel - continuous

## Incised channel forms

- Ⓐ primary headcut Ⓑ secondary headcut Ⓒ intact valley fill

Figure 4.8 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

# Channel Incision & Cut-Fill Cycles

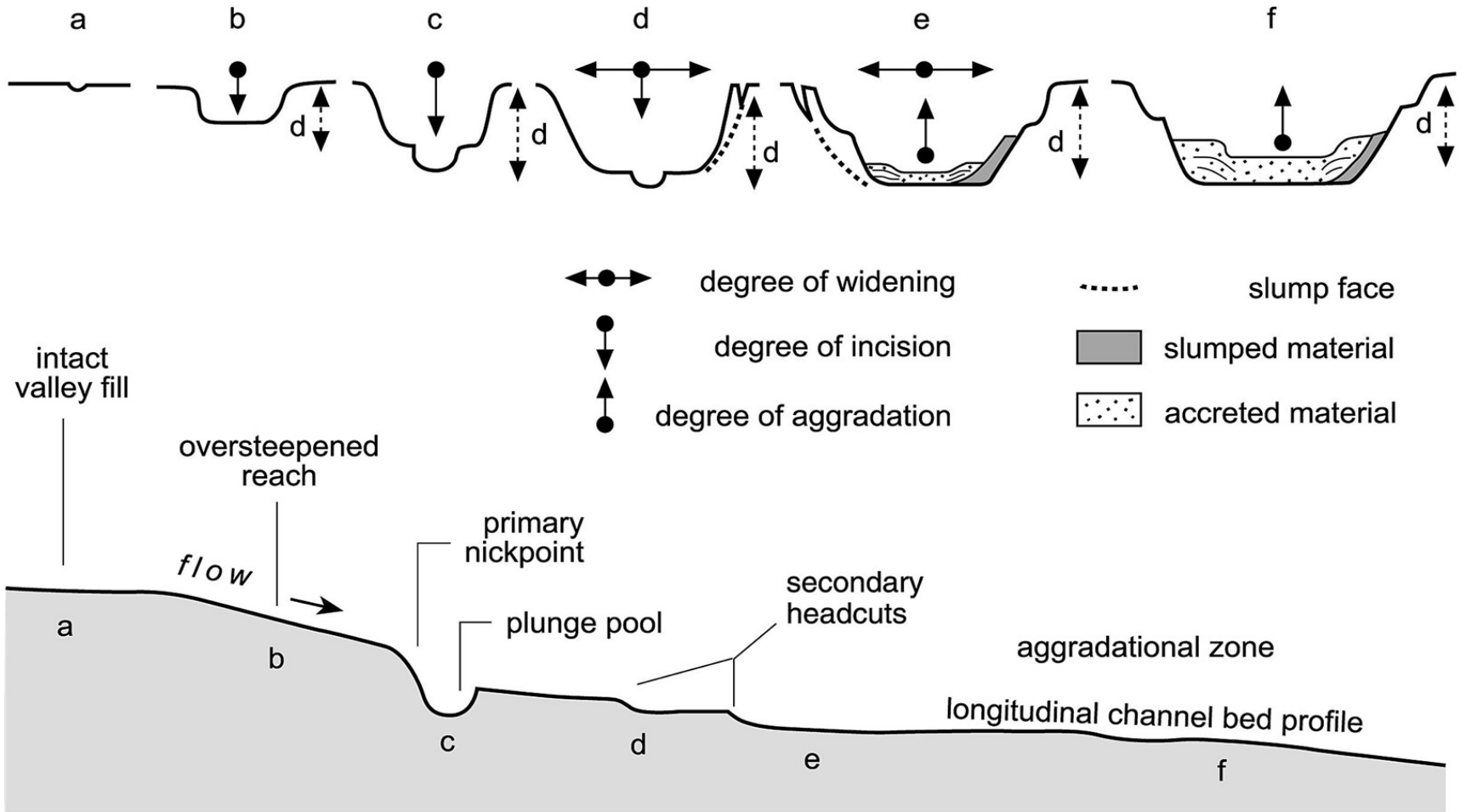
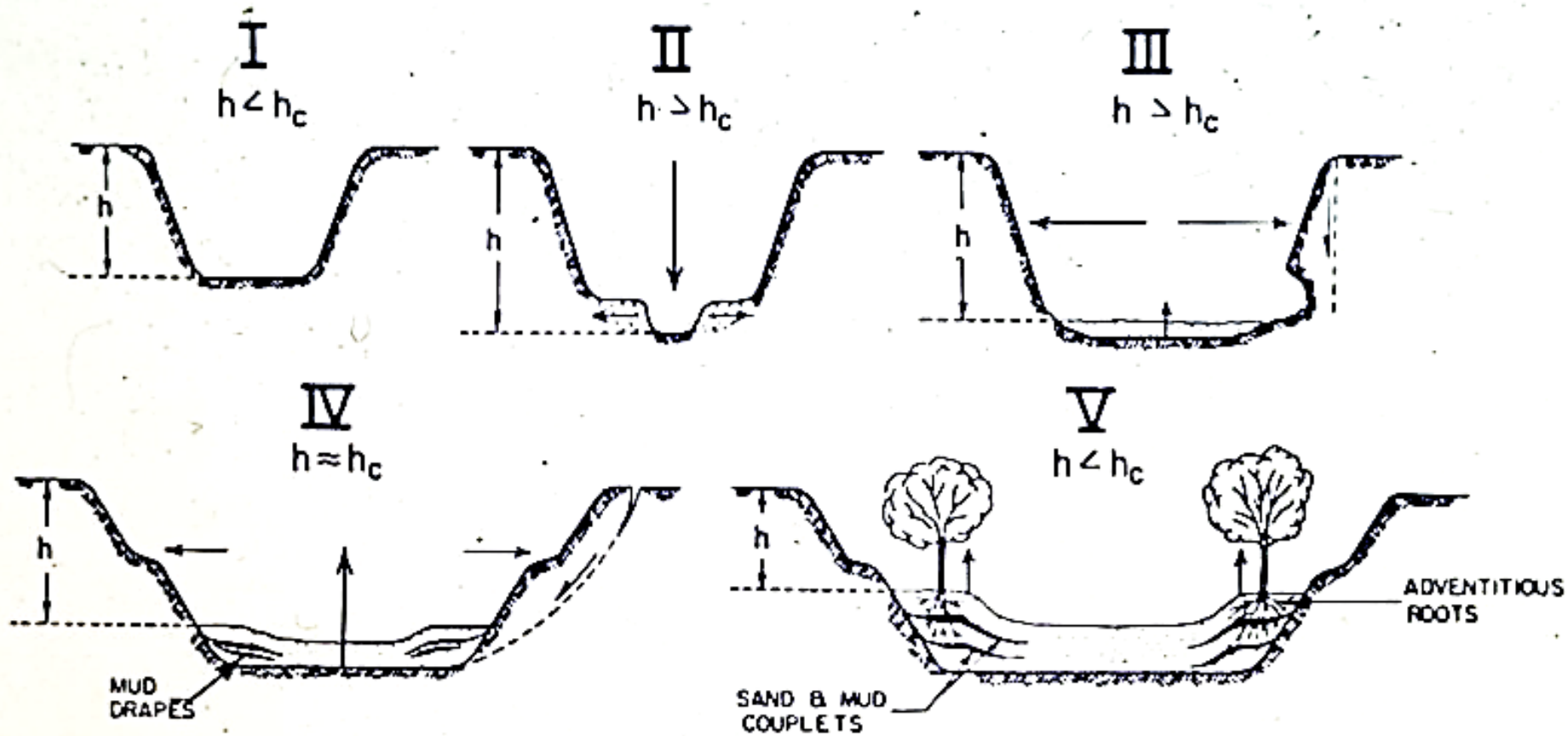


Figure 4.9 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

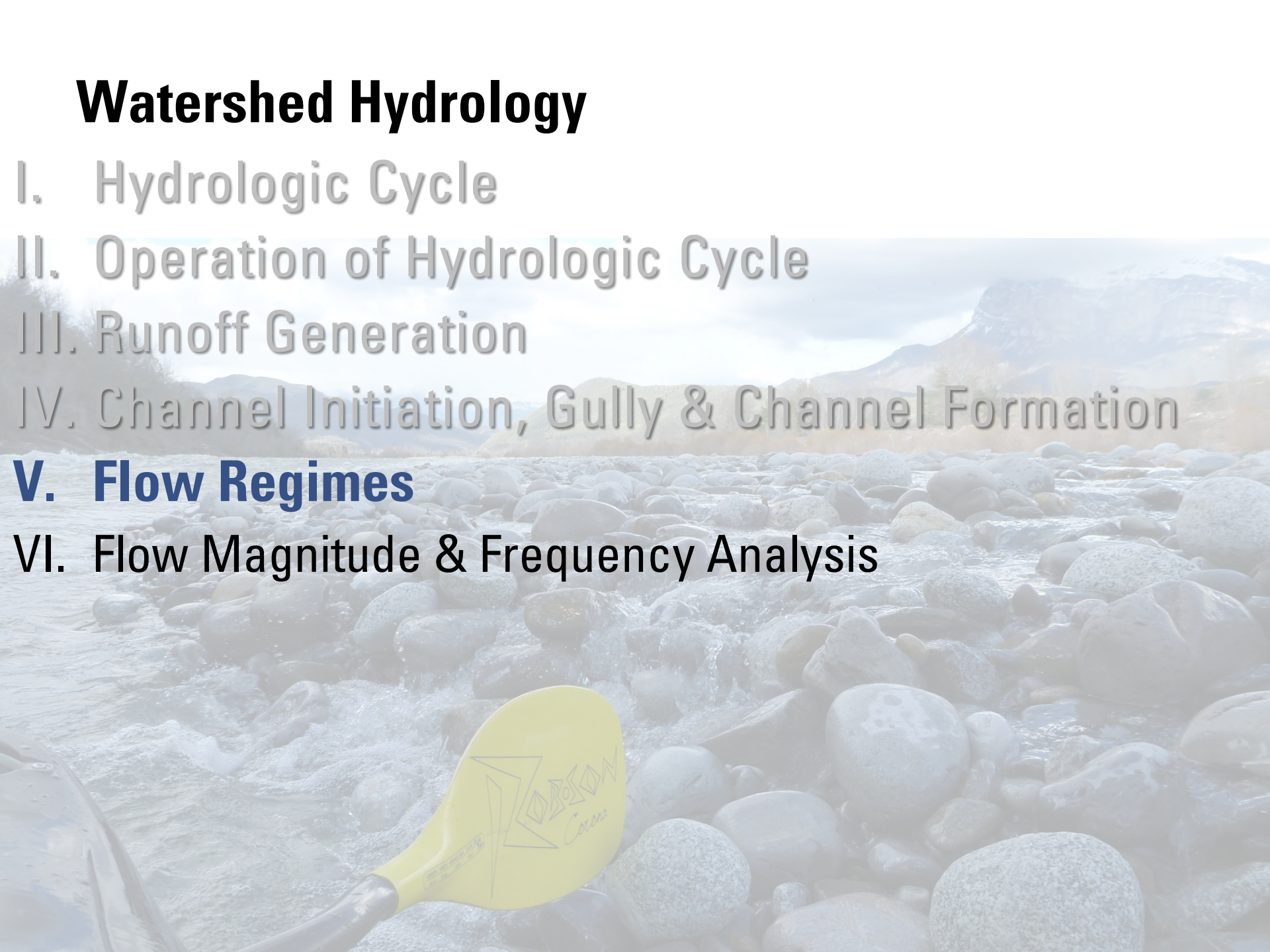


## Stages in the Channel Evolution Model

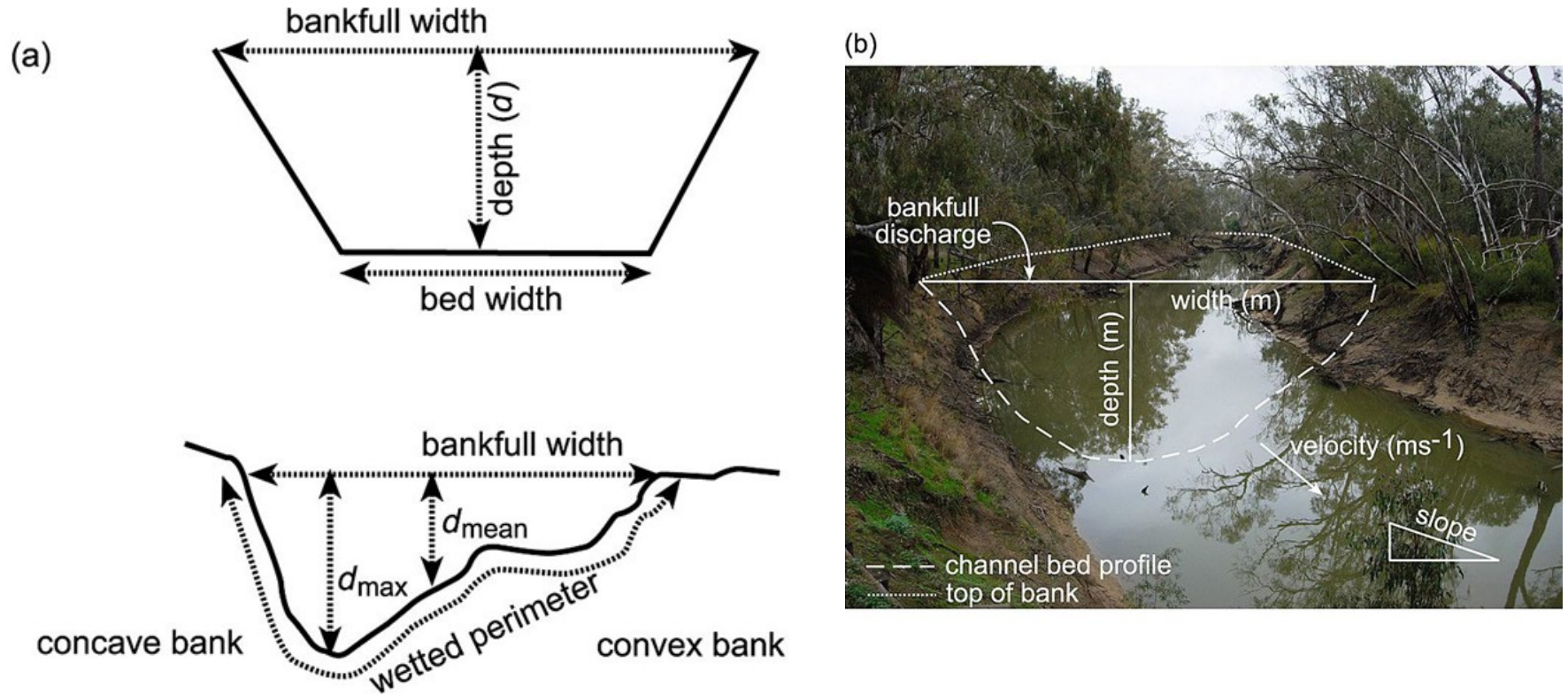


# Watershed Hydrology

- I. Hydrologic Cycle
- II. Operation of Hydrologic Cycle
- III. Runoff Generation
- IV. Channel Initiation, Gully & Channel Formation
- V. Flow Regimes**
- VI. Flow Magnitude & Frequency Analysis



# Channel Cross Section

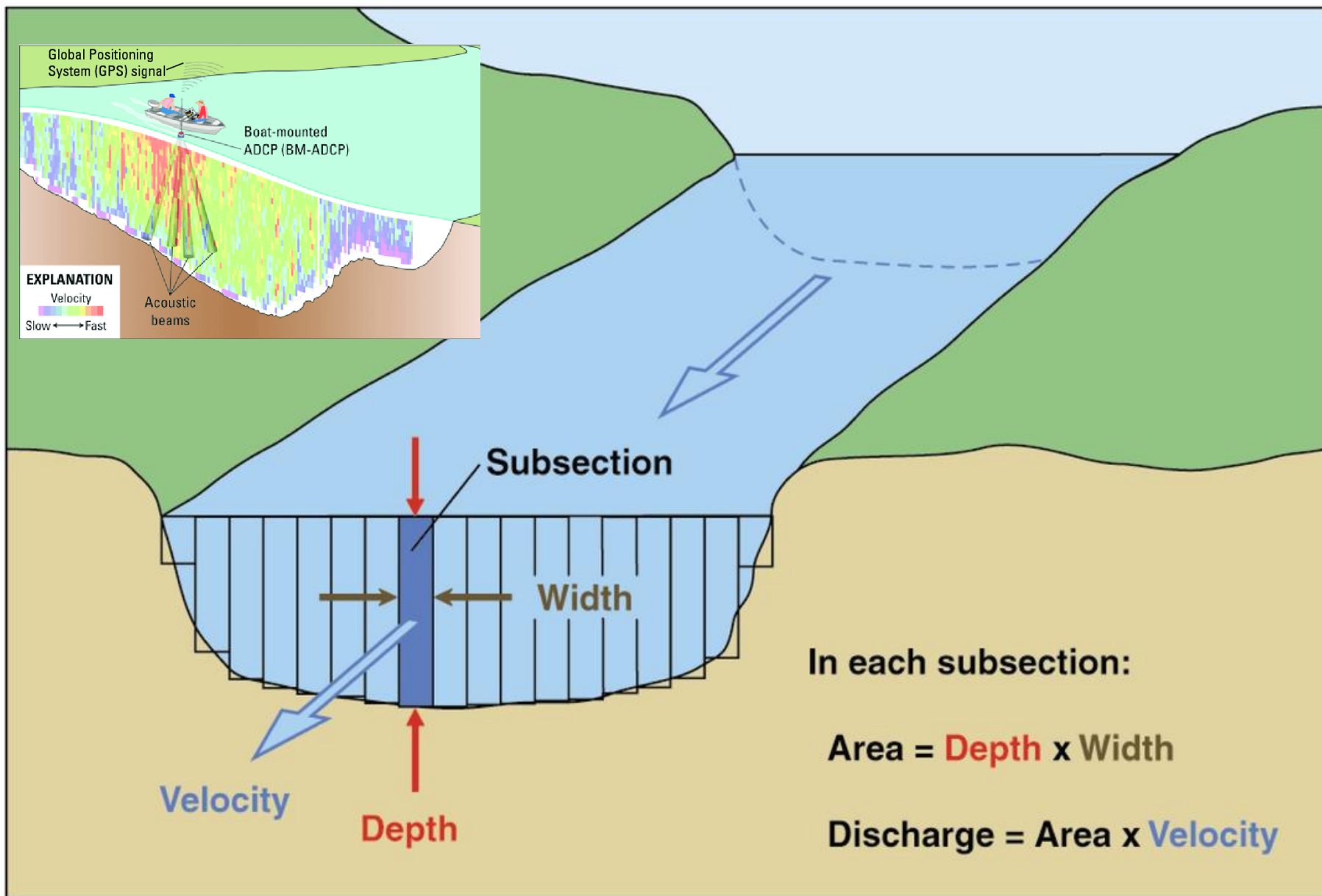


**Figure 4.11** Discharge measurement in a channel cross-section  $d_{mean}$  is the same as  $y$  in the hydraulic radius equation. Photograph: Campaspe River, Victoria (K. Fryirs).

Figure 4.11 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

# $Q = A V$



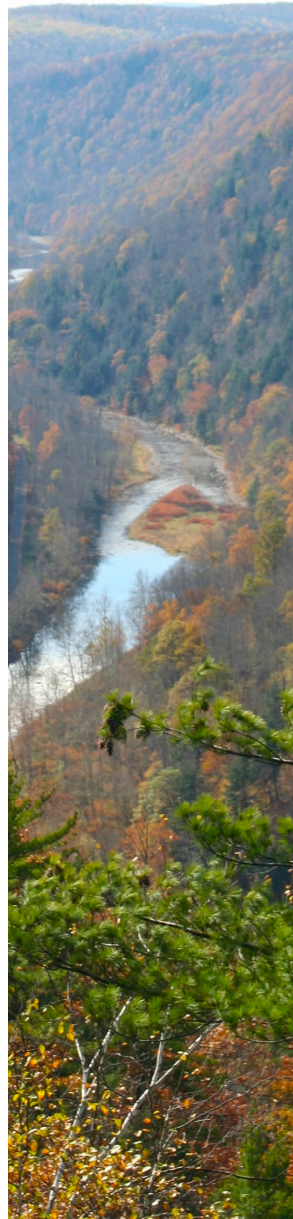
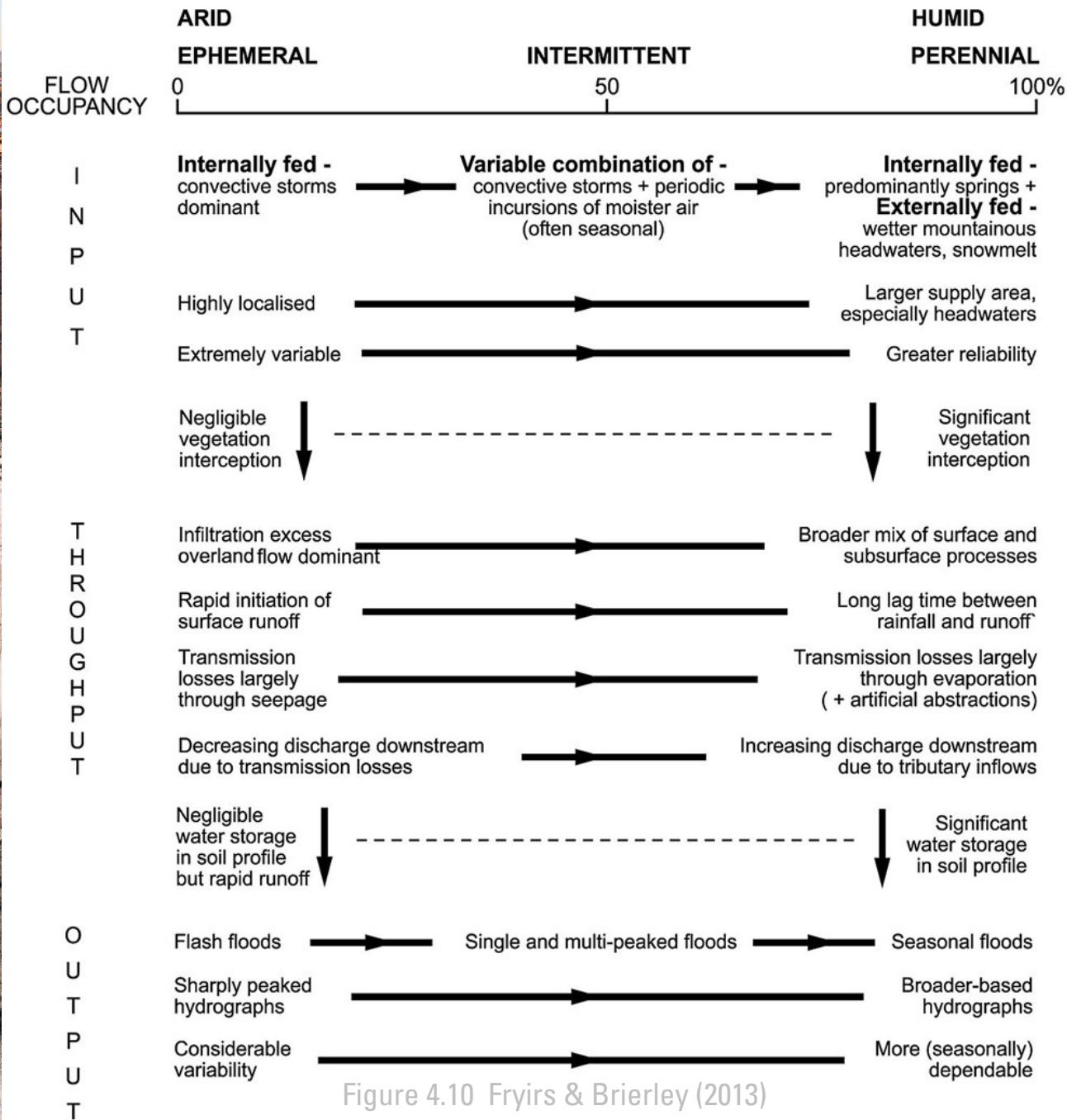


Figure 4.10 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

# A Flash Flood



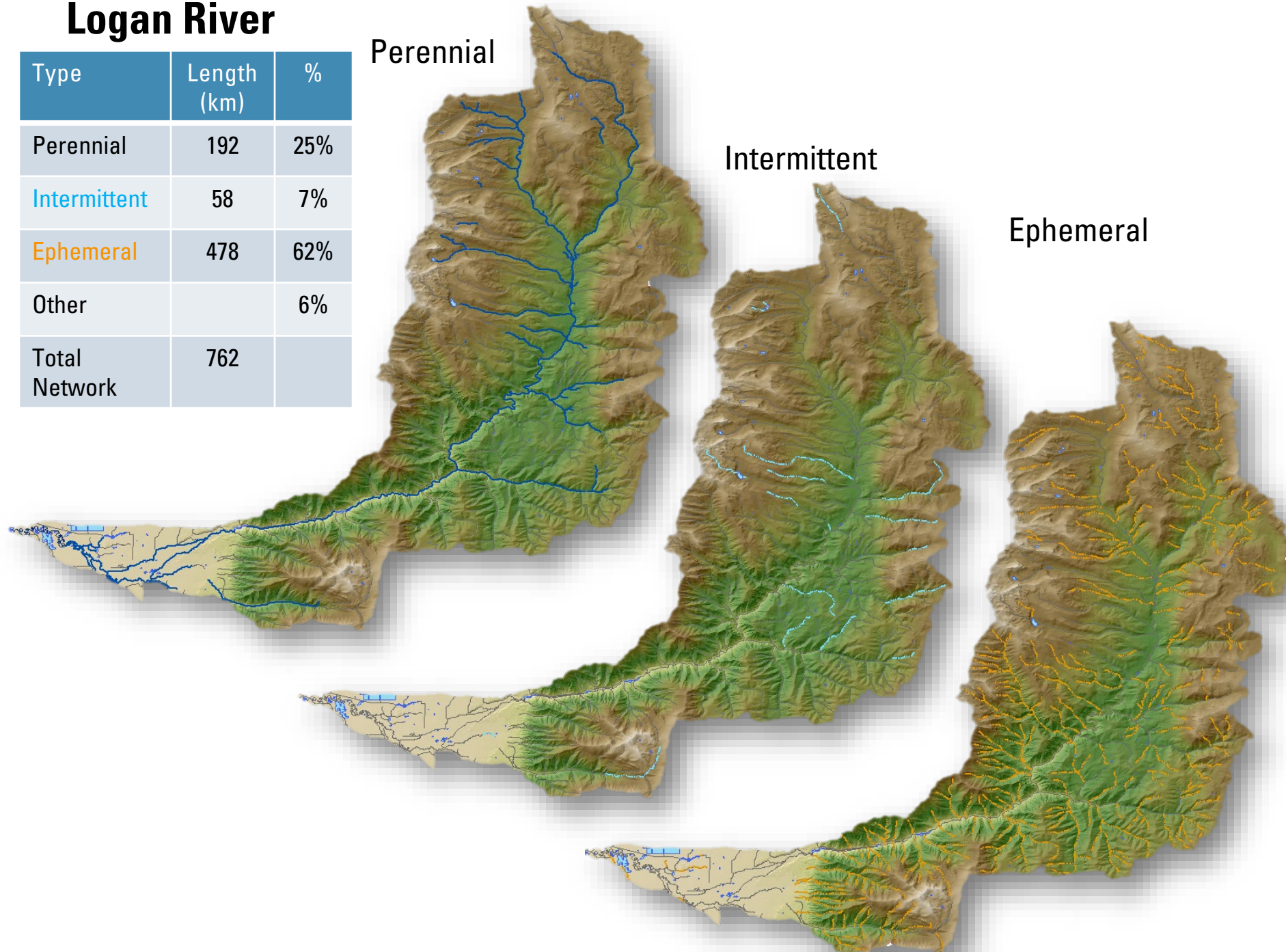
# Logan River

Type	Length (km)	%
Perennial	192	25%
Intermittent	58	7%
Ephemeral	478	62%
Other		6%
Total Network	762	

Perennial

Intermittent

Ephemeral



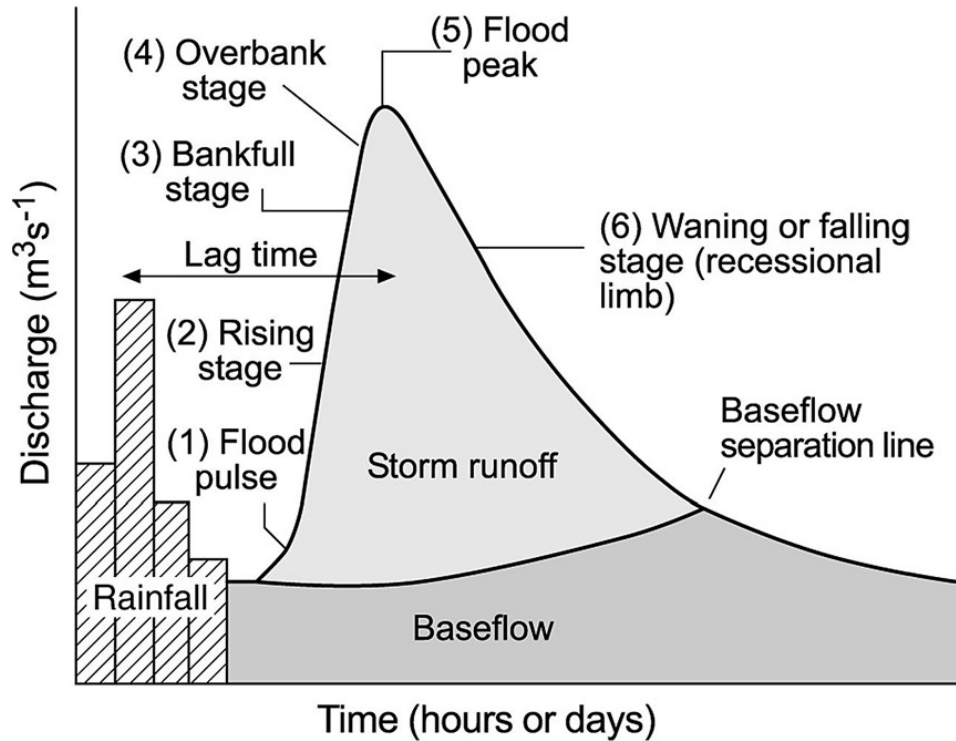
# Watershed Hydrology

- I. Hydrologic Cycle
- II. Operation of Hydrologic Cycle
- III. Runoff Generation
- IV. Channel Initiation, Gully & Channel Formation
- V. Flow Regimes
- VI. Flow Magnitude & Frequency Analysis**

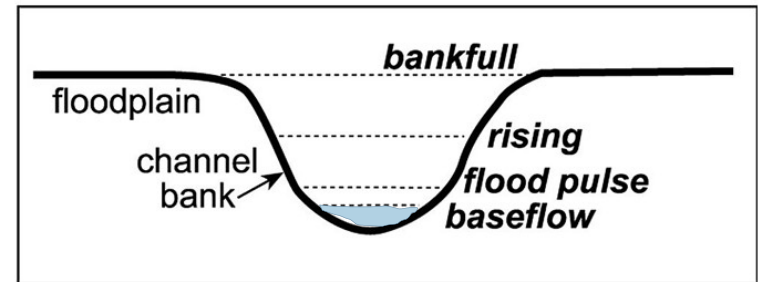




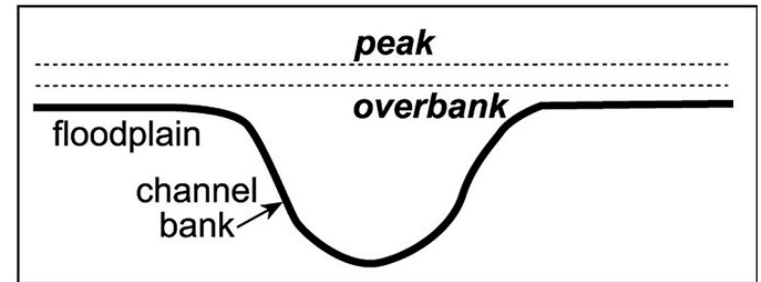
# Flow Stages of Hydrograph



within channel flows



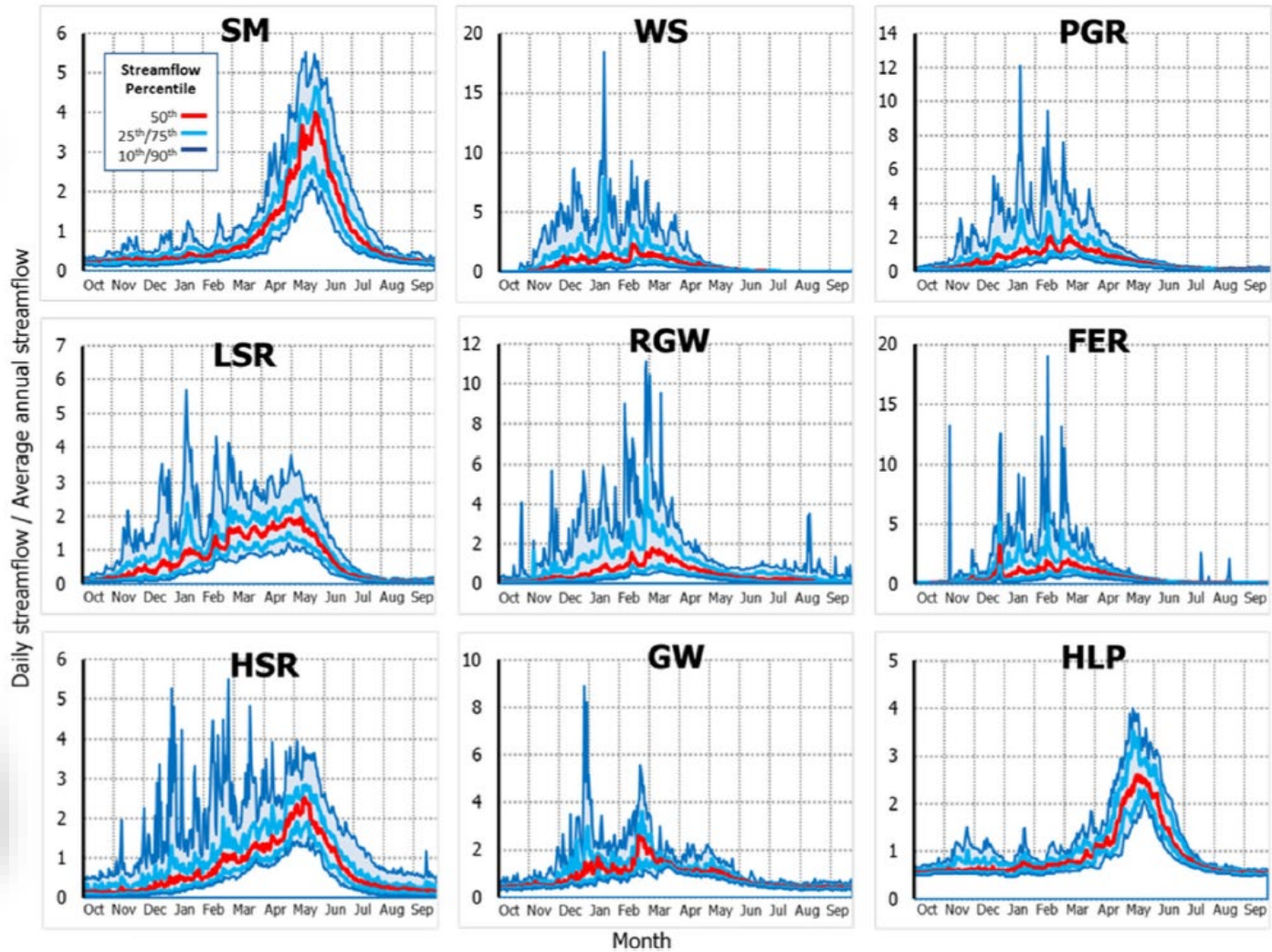
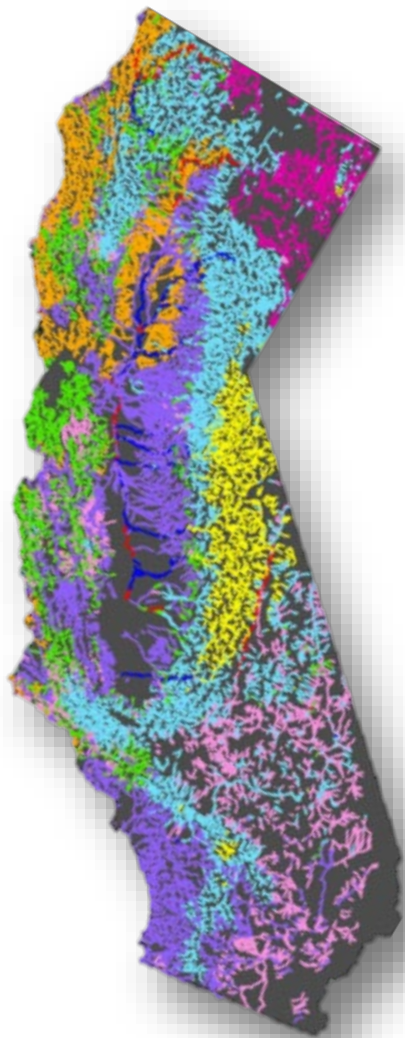
overbank flows



- Baseflow
- 1. Flood Pulse
- 2. Rising Limb (stage)
- 3. Bankfull Stage
- 4. Overbank Stage
- 5. Flood Peak
- 6. Recession Limb
- Baseflow

Figure 4.12 Fryirs & Brierley (2013)

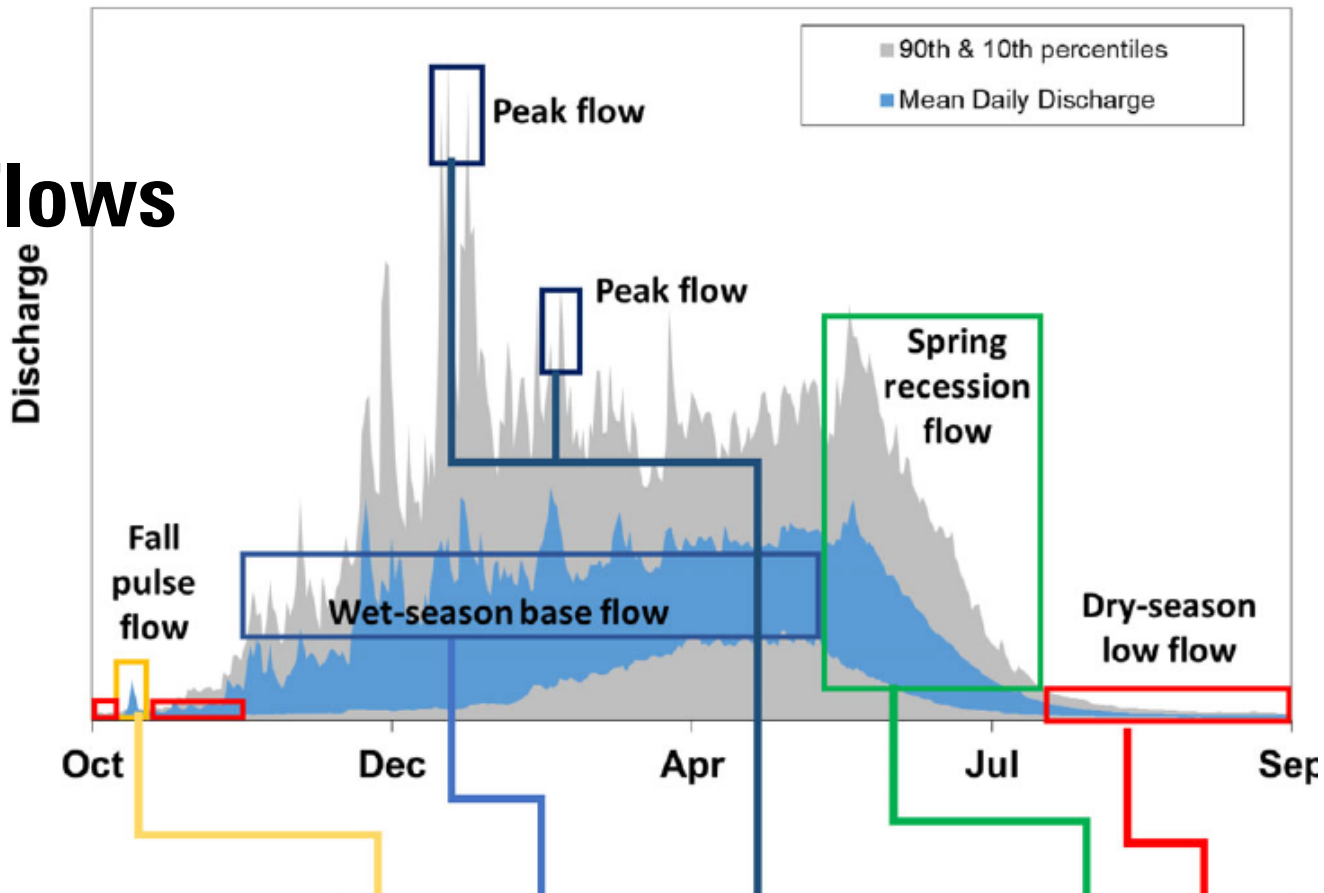
DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)



### Stream Class

- (SM) Snowmelt
- (HSR) High-volume snowmelt and rain
- (LSR) Low-volume snowmelt and rain
- (RGW) Rain and seasonal groundwater
- (WS) Winter storms
- (GW) Groundwater
- (PGR) Perennial groundwater and rain
- (FER) Flashy, ephemeral rain
- (HLP) High elevation, low precipitation

# Functional Flows

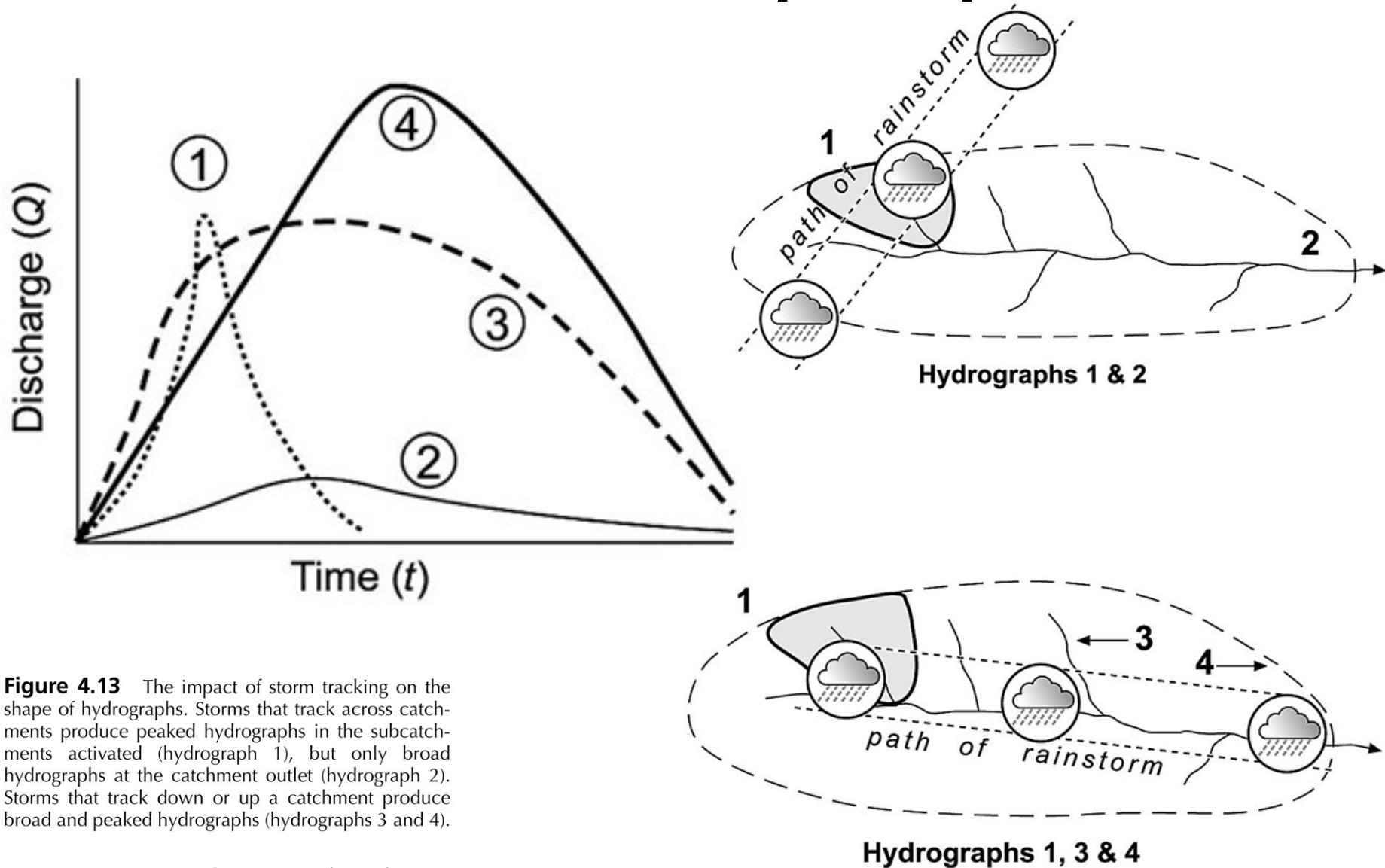


	Functional Flow Components				
Flow Characteristics	Fall Pulse	Wet Baseflow	Peak Flow	Spring Recession	Dry Low Flow
Magnitude	X	X	X	X	X
Timing	X	X	X	X	X
Duration		X	X	X	X
Frequency			X		
Rate of Change				X	X

Figure 2 Yarnell et al (2019)

DOI: [10.1002/rra.3575](https://doi.org/10.1002/rra.3575)

# Storm-Tracking & Hydrograph Shape



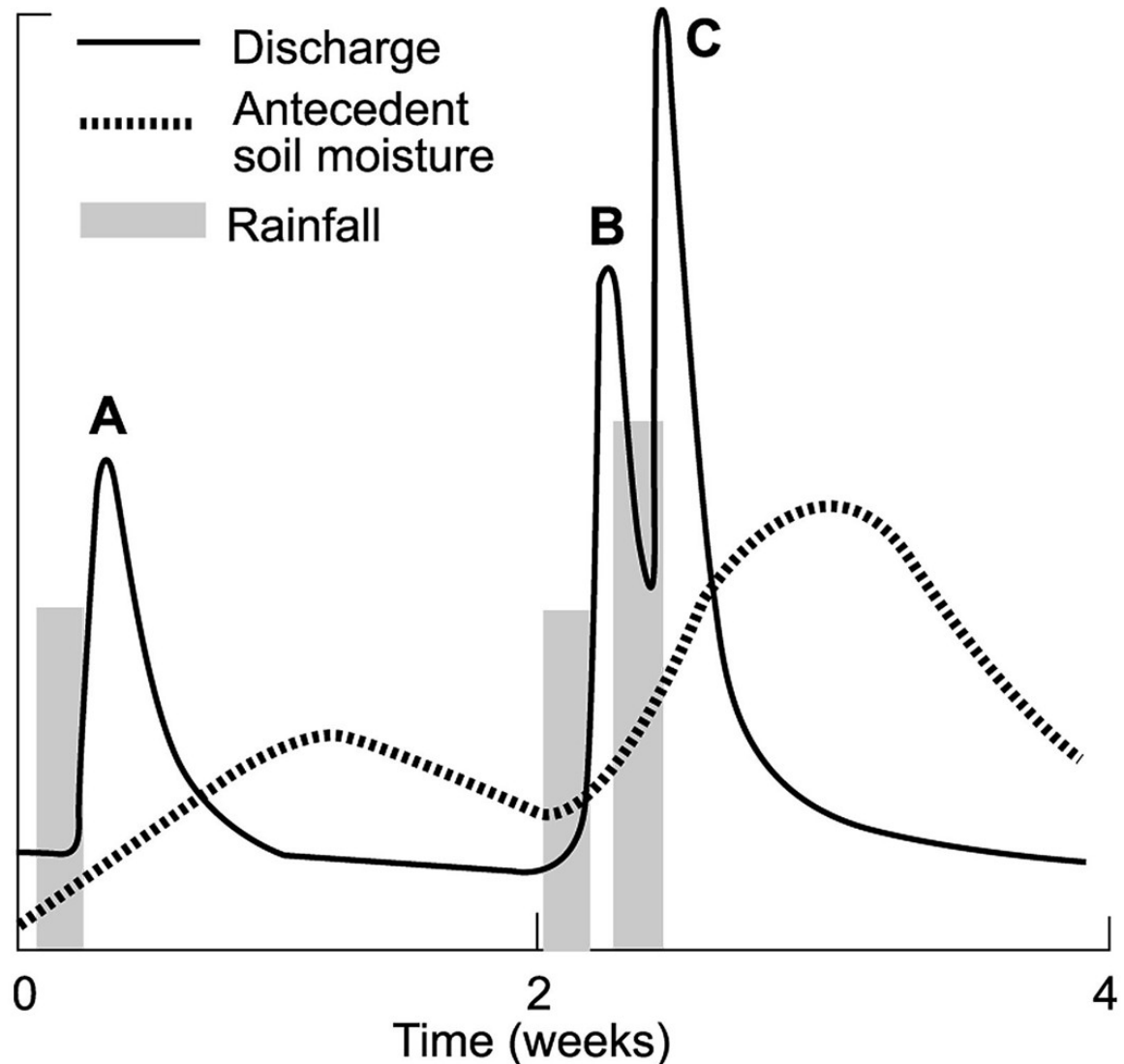
**Figure 4.13** The impact of storm tracking on the shape of hydrographs. Storms that track across catchments produce peaked hydrographs in the subcatchments activated (hydrograph 1), but only broad hydrographs at the catchment outlet (hydrograph 2). Storms that track down or up a catchment produce broad and peaked hydrographs (hydrographs 3 and 4).

Figure 4.13 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

# Flood Sequencing & Antecedent Soil Moisture

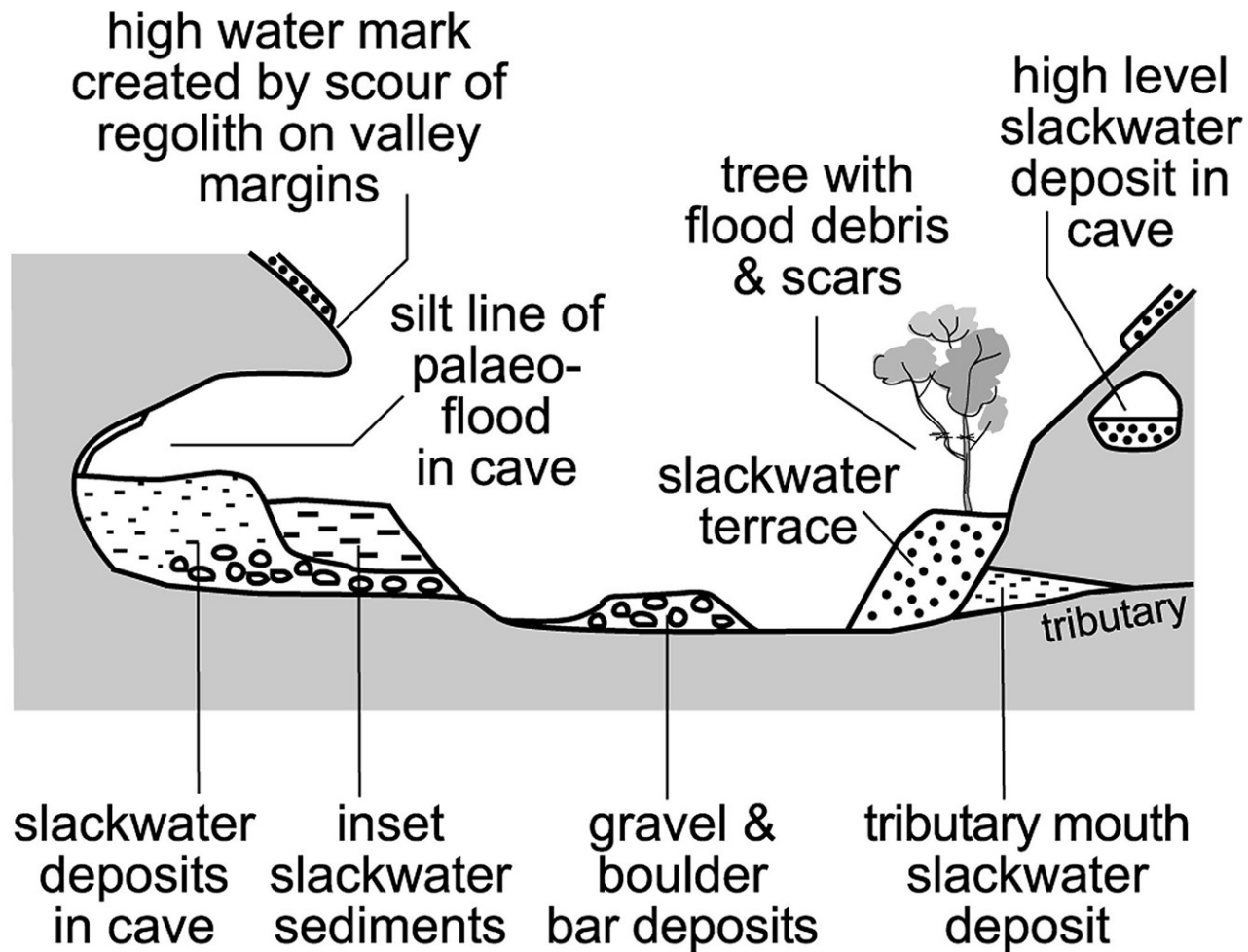
- Storm 1 & 2 equal
- But Flood A & B different!



**Figure 4.14** The role of flood sequencing and antecedent soil moisture on the magnitude of hydrographs. Rain onto a dry catchment (low antecedent moisture) will only produce a small-magnitude flow. However, recurrent rain or rain onto already wet and saturated catchments will produce large-magnitude flows with multiple peaks. This reflects ongoing inputs of rain and the activation of various forms of runoff from different parts of a catchment.

Figure 4.14 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)



*Geomorphic Analysis of River Systems: An Approach to Reading the Landscape*, First Edition. Kirstie A. Fryirs and Gary J. Brierley. © 2013 Kirstie A. Fryirs and Gary J. Brierley. Published 2013 by Blackwell Publishing Ltd.

**Figure 4.15** Slackwater deposits found in elevated situations that are not recurrently reworked can be used to reconstruct high-flow stages of past events. Modified from Baker (1978). © Elsevier. Reproduced with permission.

# Ecological Benefits of Overbank Flows



Overbank flows are important every now and then to water floodplain trees such as river red gum and black box

Low flows keep the river bed and lower banks wet, helping to maintain plants such as ribbonweed, eelgrass and common reeds



Freshes prompt native fish such as Australian grayling or golden perch to migrate and spawn



Low flows create pools of slow moving water that provide protection for young fish and shrimp to feed and grow



High flows wet stream benches and water vegetation higher on the bank, providing an increased range of habitat for bugs and shrimp



Overbank flows improve soil quality as river silt fertilises the floodplain. Carbon in leaf litter and soil flows from the floodplain to the river providing food for bugs and fish

OVERBANK FLOW

HIGH FLOW

FRESH

LOW FLOW

CEASE TO FLOW

*Sometimes low flows are referred to as 'baseflows'.  
Sometimes high flows can be 'bank full' flows.*

*Note: This is not an exhaustive representation of flows nor benefits.*



Rivers cease to flow from time to time. Sometimes this is an important part of the natural flow regime. Other times, environmental water can be used to provide refuge pools for fish in dry river sections.

# What is a 100 Year flood event?

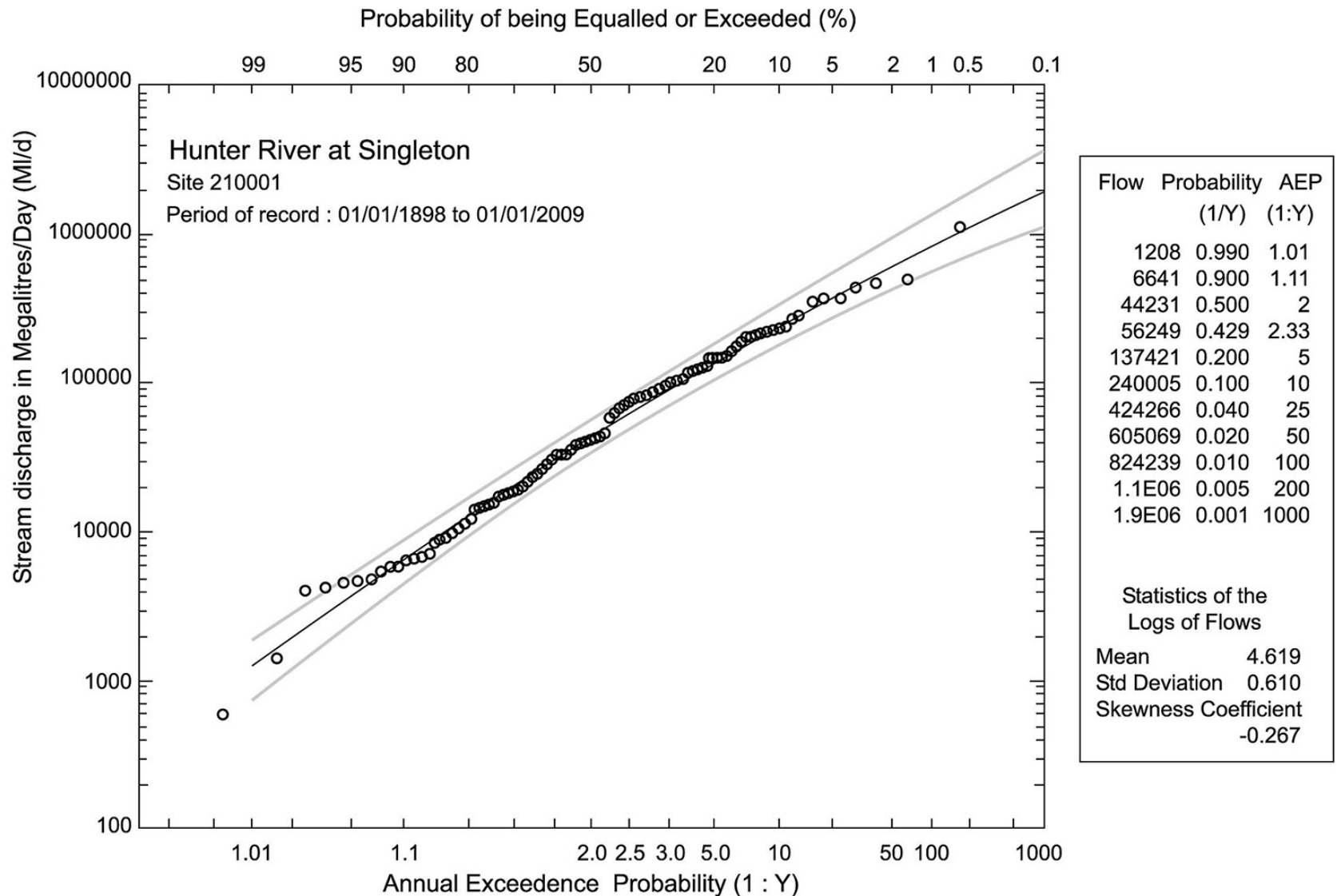


Figure 4.16 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)

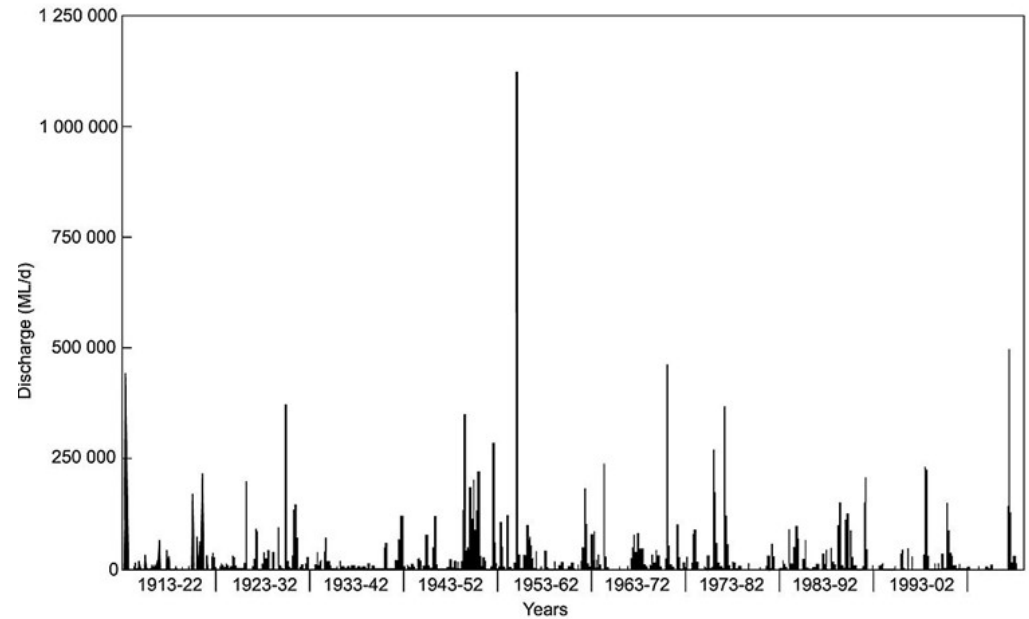
**Figure 4.16** The Log Pearson III graph of flow magnitude–frequency relationships for the Hunter River at Singleton, NSW, Australia. Extracted from the NSW Office of Water Pinneena database for gauged streams.



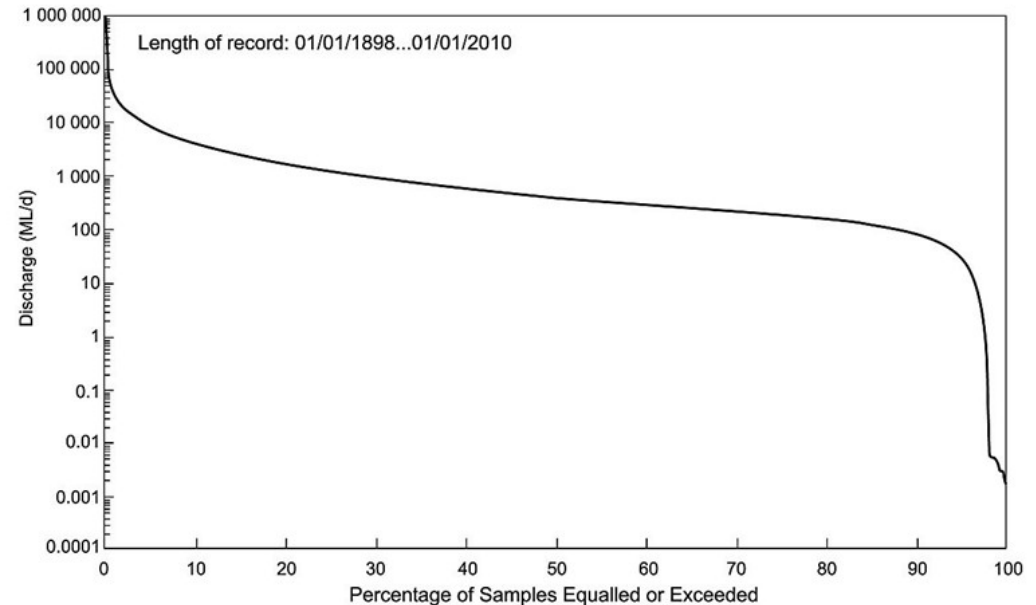
# Flow Duration Curve

- Get a time series of flows.
- Calculate the

(a) Time Series Plot for the Hunter River at Singleton



(b) Flow Duration Curve for the Hunter River at Singleton



**Figure 4.17** (a) Time-series plot showing the history of floods for the Hunter River at Singleton, NSW, Australia. (b) Flow duration curve used to determine the amount of time flows of different magnitude are exceeded for the Hunter River at Singleton, NSW, Australia. Extracted from the NSW Office of Water Pinneena database for gauged streams.

Figure 4.17 Fryirs & Brierley (2013)

DOI: [10.1002/9781118305454](https://doi.org/10.1002/9781118305454)