Runoff processes -- the paths of water on the hillslopes

A schematic view of the alternative fates of precipitation on a hillslope:
Two fundamentally different runoff paths are implied by this picture:

1. **Horton overland flow (HOF)**--the movement of runoff over the ground surface where and when the rate of precipitation (the **rainfall intensity**, abbreviated RI) exceeds the rate at which the soil can absorb water (the **infiltration capacity**, abbreviated IC).

   So HOF occurs where (and when) RI > IC. The difference between RI and IC is known as the **precipitation excess**. Both terms are measured as rates (*e.g.*, inches per hour, or mm per hour).

Many factors can affect the precipitation excess at a particular site.

- Changes in RI: a function of the storm (variability of the storm intensity)

- Changes in IC: a function of the soil properties, what covers the soil, and **time**.

  --coarse-grained soils (also called **coarse-textured** soils, namely gravelly or sandy) = high infiltration capacity (many inches per hour)

  --fine-grained soil (**fine-textured** soils, predominantly silty or clayey) = low infiltration capacity (a few inches per hour, or even less)

IC is *increased* by abundant organic matter, by root holes and worm holes, by a well-developed **soil structure** (well-formed soil aggregates with cracks and spaces between them).

IC is *decreased* by the impact of raindrops, by compaction by animals or machinery, or by paving (in which case IC → 0).
In addition, most soils decline in IC over time as the soil "wets up" during a storm and (a) some of the pores become filled with water, (b) fine sediment is mobilized on the ground surface and clogs some pores, and (c) clay particles swell up from adsorbed water, blocking off some passageways.

The second of the two major runoff paths is actually more of a "family" of runoff paths:

2. **Subsurface flow (SSF)—**The movement of runoff predominantly below the ground surface. This will occur wherever the soil's IC > 0, and so takes place to some degree even when HOF is also taking place. However, we tend to reserve this term (and we see the effects of this process in the landscape) only where there is little or no HOF, and thus RI < IC.

This is the dominant runoff process in temperate humid regions, such as the Pacific Northwest, where lush vegetation has produced a porous soil structure with infiltration capacities of many inches per hour, and where the predominant storm pattern is one of long-duration low-intensity (<1"/hr) rainfall.
Four distinct (but related) **runoff processes** are defined by this picture:

- **Shallow subsurface flow** (SSSF, or "interflow")--the movement of subsurface water in a relatively shallow zone (within a few feet of the ground surface), roughly parallel to the ground surface.

- **Deep subsurface flow** (GW, "groundwater flow")--the movement of subsurface water through deeper substrata, beneath the soil zone and relatively unaffected by any but the grossest elements of the surface topography.
There is often (but not always!) a physical basis for the division of subsurface flow into "shallow" and "deep" components. Surface soils are almost always more permeable, as a result of biological activity and chemical weathering, than their parent geologic materials, and so water will move more rapidly in these upper layers and "leak" only slowly into the lower ones.

However, in soils underlain by thick deposits of very permeable material there is no "interflow" at all!

- **Saturation overland flow (SOF; also called "return flow")**—the reemergence of subsurface water that occurs where the soil layer is completely saturated and so no additional water will "fit" within it. Most common near the toe of slopes where the accumulated water collected from the entire upslope hillside is most voluminous. This is a time-dependent condition: the longer that rain has fallen, the more water will be in the soil layers, groundwater tables will rise, and a greater area will be subject to saturation.

- **Direct precipitation onto saturated ground (DP)**—wherever the ground is saturated, any rain that falls will not infiltrate even if the soil's intrinsic IC is greater than the rainfall intensity. There just isn't room for any more! This rain will run off as rapidly as if the soil's infiltration capacity were 0, but this process is not equivalent to Horton overland flow (although we can, at least locally, calculate the rate of runoff as though it were HOF).
Note how the level of the water table(s) will change during the course of a storm:
Because the predominant type of runoff (or the **runoff regime**) depends on the interplay of rainfall intensity and infiltration capacity, we can recognize regional climatic and topographic settings where each of these runoff processes should dominate:
Runoff characteristics common to the Horton overland flow regime:

1. Brief **lag-to-peak** (the time between the maximum rainfall intensity and the maximum stream discharge):

![Diagram showing rainfall intensity and stream discharge over time]

<table>
<thead>
<tr>
<th>Basin Area (mi²)</th>
<th>Lag-to-Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 min</td>
</tr>
<tr>
<td>10</td>
<td>40 min</td>
</tr>
<tr>
<td>100</td>
<td>60 min</td>
</tr>
</tbody>
</table>

2. The **runoff-producing zones** (those parts of the ground surface from which runoff will reach the stream during the course of the storm) are located wherever the infiltration capacity is lower than the prevailing rainfall intensity. In semiarid and arid climates these will be found over the entire basin. Where land-use changes have affected infiltration capacity, these areas will be found as linear features (roads and other compacted tracks) and patches (e.g., building sites) without any systematic relationship to the drainage features of the watershed.

3. **Hillslope erosion** (see next section) mainly will occur by the detachment of surface soil particles by overland flow: **sheetwash**, and **rilling** and **gullying**.
Runoff characteristics common to the subsurface flow regime:

1. Long **lag-to-peak**:

<table>
<thead>
<tr>
<th>Basin Area (mi²)</th>
<th>Lag-to-Peak (SSF)</th>
<th>Lag-to-Peak (HOF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 hr</td>
<td>20 min</td>
</tr>
<tr>
<td>10</td>
<td>4 hr</td>
<td>40 min</td>
</tr>
<tr>
<td>100</td>
<td>10 hr</td>
<td>60 min</td>
</tr>
</tbody>
</table>

2. The **runoff-producing zones** are primarily those parts of the basin where the soil is saturated up to the ground surface. These are concentrated in topographic lows, particularly at the base of long footslopes adjacent to streams, lakes, wetlands, or other perennial water bodies. Most importantly, the size of those zones will expand during the course of a storm, and also during the course of the rainy season.

   They are known as **Variable Source Areas**—they are the "source areas" for runoff, and (unlike the runoff-producing areas under the HOF regime) they "vary" in size during the course of a single storm and during the changing seasons.

3. In areas where the subsurface flow regime predominates, **hillslope erosion** will reflect the movement of saturated soil masses—**creep**, **landslides**, and other modes of **mass failure** (next section). Locally there may be some detachment of surface soil particles by overland flow, as with HOF, but these areas are normally limited in size and quantitatively not very important.
Note that, in general, surface flow paths (Horton overland flow and saturation overland flow) move water rapidly and efficiently to channels--so even temporary increases in rainfall intensity are clearly reflected by increases in stream discharge. In contrast, subsurface flow paths move water only slowly, with much diffusion of any temporary peaks in the rainfall intensity and some losses to deeper groundwater systems. The channel response to a burst of rainfall thus may be weak or entirely absent.

Note also that the water chemistry of the runoff where subsurface flow paths predominate may be very different from that where Horton overland flow occurs: fewer surface contaminants, more opportunities for filtration by the soil, but also a much greater contribution from the groundwater chemistry.
Other hydrologic relationships in watershed:

**Lag-to-peak in a small basin**

![Graph showing discharge and rainfall over time, highlighting lag-to-peak in a small basin.]

**Lag-to-peak in a large basin**

![Graph showing rainfall, average infiltration rate, flood runoff, and base flow over time, highlighting lag-to-peak in a large basin.]

*Figure 23.13 Four days of flow of Sugar Creek, Ohio, illustrate passage of a flood on a stream draining 310 square miles. (After Hayt and Langbein, Floods.)*
Figure 10-2  Inflow and outflow hydrographs for the valley bottomlands and the channel of the Delaware River above Port Jervis, New York, during the hurricane flood of September 1938. The drainage area is 3076 sq mi. The inflow hydrograph represents the computed time distribution of water provided from the basin to the valley bottomlands. The outflow is the measured flow in the channel and shows the attenuation of peak due to storage in the valley and the channel. The shaded area represents the volume of water stored in the channels and valley floors of the catchment before the peak outflow occurred. (From H. K. Barrows 1942, EOS, American Geophysical Union Transactions, vol. 23, pp. 483–488. Copyrighted by American Geophysical Union.)
(a) Translation only

(b) Reservoir only

(c) Actual channel
Basin Size & Hydrologic Response
Storm Size & Hydrologic Response
II. Erosion processes—the paths of sediment on the hillslopes

Basic framework: the sediment budget

"A sediment budget is a quantitative statement of relations between sediment mobilization and discharge, and of related changes in storage. Construction of a sediment budget requires: a) identification of sediment sources/storage elements and quantification of the volume, particle-size distribution, residence time, and changes in storage of sediments in each element; b) identification of erosional processes and understanding of their controls and linkages; and c) measurement of the magnitude and frequency of sediment mobilization and frequency of sediment mobilization by each process."

(Lehre, Collins, and Dunne, 1983, Z. fur Geomorphologie supp. 46)

There are three fundamental elements in our analysis of sediment budgets:

1. **Sediment production**—how much sediment, and what kinds of sediment, are detached from the hillsides; by what processes does that production occur?

2. **Sediment yield**—how much of the "produced" sediment actually arrives in the stream channel? How much remains in medium- or long-term storage on the hillsides above the channel? Is their a segregation of sizes between that which is delivered and that which is stored?

3. **Sediment delivery**—the ratio of sediment yield and sediment production; can range from <10 percent for large basins with gentle topography to >95 percent for small basins with steep slopes.

A graphical overview of a sediment budget is presented on the following page:
Often, only a scant fraction of this "total" picture is necessary to find the answers to the questions before you. However, appreciation of the overall context is critical to be sure that what you are measuring or estimating is in fact the most important element of the physical processes actually occurring!
Sediment Production

Two major categories: surface erosion and mass failures. Their relative importance at a site is strongly related to the overall topography and runoff regime:

1. **Surface erosion**—the detachment of surface soil particles.

   Major processes: *rainsplash, sheetwash, and rilling and gullying*.

   What primarily determines the rate of surface erosion?

   --slope
   --soil texture and structure
   --rainfall intensity
   --vegetation
The second major family of sediment-production processes:

2. Mass failures--the downslope movement of soil (or other geologic materials) under their own weight, i.e. not transported by the medium of running water.

Major processes: creep, treethrow, landslides, debris flows

What primarily determines the rate of mass failures?

--slope
--soil texture and structure
--vegetation
--daily, weekly, and seasonal rainfall quantities
--groundwater levels
--local surface-water concentrations

**Sediment yield and sediment delivery**--the amount of the "produced" sediment that actually arrives in the stream channel, and the fraction of the originally detached sediment represented by that amount that enters the channel.

How is sediment yield determined? Normally, by measuring the amount of sediment being carried by the stream or river itself (suspended sediment loads, to be discussed in a later section). Thus the measured sediment yield will also include any sediment eroded from the bed and banks of the channel itself, even though this material was not "produced" from the hillslope except perhaps in the long-distant past.

Typical measured values\(^1\) of sediment yield are 10's to 100's of tonnes/mi\(^2\)/year. Values may vary with the size of the drainage basin; they are also highly dependent on land use.

\[^1\] 1 ton/acre = 640 tons/mi\(^2\) \(\approx\) 2 tonnes/hectare