Runoff generation

GG22A: GEOSPHERE & HYDROSPHERE
Hydrology

Definitions

- *Streamflow*
  - volume of water in a river passing a defined point over a specific time period = VxA
  - *"discharge"* *$m^3\ s^{-1}$*
- *Runoff*
  - "excess" precipitation - precipitation that is not evaporated
  - *mm depth over an area*

streamflow = runoff * area

runoff = streamflow / area

Not all runoff becomes streamflow

Definitions

- *Quickflow*
  - short-term result of precipitation
- *Baseflow*
  - slower drainage of stored water, sustaining flows through dry periods
- Runoff is shown as a *Hydrograph*, comprising short periods of sudden increasing discharge after rainfall or snow melt (*Quickflow*), separated by long periods, comprising outflow from stored water (*Baseflow*).

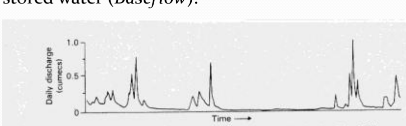


Figure 7.1 *Annual hydrograph for the Catchwater Drain, North Humberside, 1967.*

Runoff hydrographs

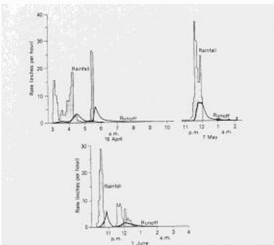


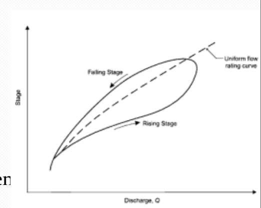
Figure 7.2 Graphs of rainfall and runoff for three storm events in Tennessee, USA (from original diagrams by Ramser, 1927).

- Only a relatively low percentage of rainfall appears as Quickflow.
- On a global scale, about 34 percent of rainfall on land reaches the oceans as runoff.

Measuring streamflow

- Volumetric gauging *(catch all the flow)*.
  - streamflow = flow velocity * flow cross-sectional area
  - runoff = streamflow / catchment area

1. Measure velocity
   - *current meter*
   - *dilution gauging*
   - *electromagnetic / ultrasound*
2. Estimate flow continuously by measuring the depth of water (*stage*) continuously, and construct a relationship between stage and flow (*Rating curve*)



Measuring streamflow

- Need to measure stage at a “controlled” site

At a weir or flume:

…or at a “stable” natural section:

Sources of runoff

- Precipitation (*P*) follows different paths to the stream:

1. Channel Precipitation (Q_p)
2. Overland Flow (Q_o)
3. Shallow Subsurface Flow or Throughflow (Q_t)
4. Deep Subsurface Flow or Groundwater Flow (Q_g)

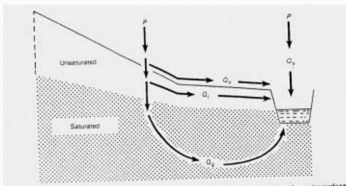


Figure 7.3 Flowpaths of the sources of streamflow: Q_p is direct precipitation onto the water surface, Q_o is overland flow, Q_t is throughflow and Q_g is groundwater flow.

The runoff process

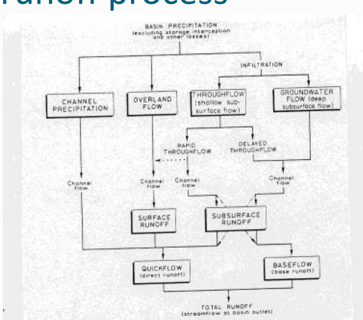
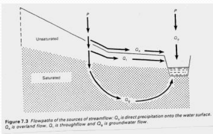


Figure 7.4 Diagrammatic representation of the runoff process

Components of runoff

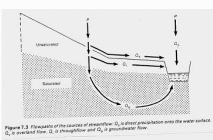
- Surface Runoff
  - part of the total runoff reaching the basin outlet by overland flow and the stream channels. May also include rapid throughflow coming to the surface some distance from the channel.
- Subsurface Runoff
  - includes delayed throughflow and groundwater flow.
- Quickflow
  - the sum of channel precipitation, surface runoff and rapid throughflow.
- Baseflow
  - comprises groundwater flow and delayed throughflow, and is defined as fair-weather runoff.

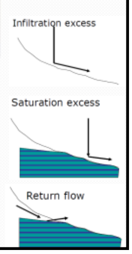
Sources of runoff



- Channel Precipitation (Q_p):
  - not all that significant
  - may be more important during a prolonged storm, or if the catchment contains lakes and swamps.

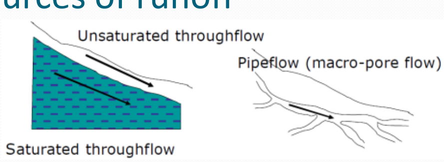
Sources of runoff





- Overland Flow (Q_o):
  - water that flows on the surface as sheetflow or in trickles.
  - Generally uncommon as most vegetation surfaces have high infiltration capacities.
  - Occurs if the ground is saturated, frozen, consolidated, or where rainfall intensity exceeds infiltration capacity.

Sources of runoff



- Throughflow (Q_t):
  - water infiltrating and moving laterally as shallow subsurface flow – through the soil, above the water table.
  - Can be unsaturated flow, but may be shallow perched saturated flow.
  - Preferential flow: rapid throughflow through pipes, highly permeable layers or boundaries within the soil

Sources of runoff

- Throughflow is favoured where lateral conductivity being greater than vertical conductivity.
  - common in perched saturated flow, when water enters the soil more rapidly than it can percolate downwards, leading to lateral escape in the direction of greater conductivity.
- Some throughflow rates are rapid, others are delayed.
- Some throughflow may not discharge directly into the stream, but comes to the surface some distance upslope, where it may contribute to overland flow and surface runoff.
- Throughflow is the most important source and component of runoff: it may account up to 85 percent of total runoff.

Sources of runoff

- Groundwater Flow (Q_g):
  - lags behind precipitation, it is a slow flow which tends to be regular, representing the discharge from a slowly changing reservoir of moisture in the saturated zone.
  - Groundwater flow represents the long-term component of total runoff and is important during dry spells.
  - Base flow is proportional to groundwater storage

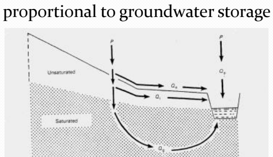


Figure 7.3 *Flowpaths of the sources of streamflow: Q_p is direct precipitation onto the water surface. Q_o is overland flow, Q_t is throughflow and Q_g is groundwater flow.*

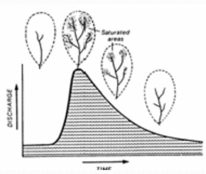
Humid temperate environments

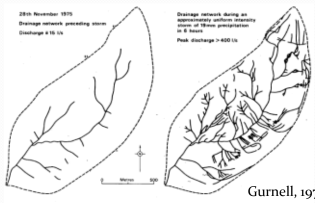
- Deep soils
- Relatively low rainfall intensities
- Infiltration excess overland flow is rare
- Area of saturation is important

- Saturation excess overland flow
- Saturated throughflow
- Pipeflow
- Increased drainage network

Dynamic contributing area

- Contributing area: “saturated” part of catchment generating quickflow
  - Extent and expansion of contributing area largely determined by topography
  - May be significant thresholds and nonlinearities



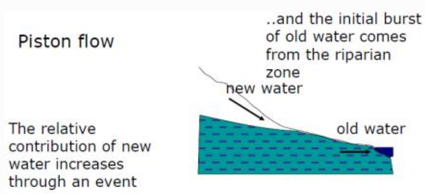


Gurnell, 1978

Fig. 7. The adjustment of the drainage network during a storm.

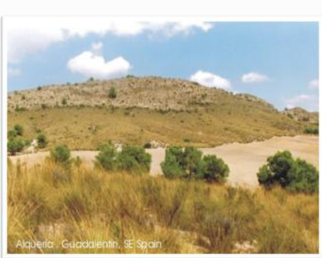
Relative contributions of different sources

- Most (>50%) quickflow is “old” water (*pre-event water),* pushed out by “new” water entering upslope.



Antecedent conditions are important

Semi-arid environments



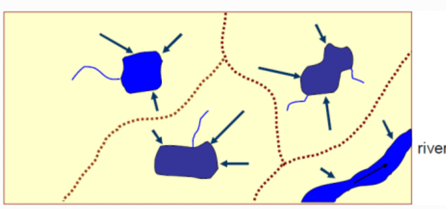
- Shallow soils
- High intensity, localised rainfall
- Infiltration excess overland flow is common
  - especially where soil forms a crust
- Not all runoff reaches the channel

Semi-arid environments

- Where infiltration capacity is:
  - **Low** - runoff depends on rainfall intensity
  - **High** - runoff depends on rainfall volume
- Antecedent conditions *not important*
  - But proportion of rainfall going to runoff depends on location of rainfall relative to different surface characteristics

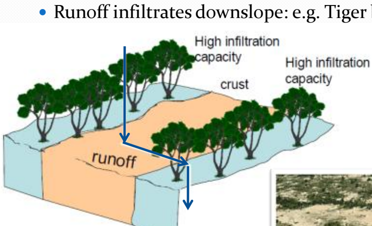
Semi-arid environments

- Not all runoff becomes streamflow:
  - "Disorganised" drainage in flat areas – e.g. Sahel
  - Water evaporates or recharges long-term groundwater



Semi-arid environments

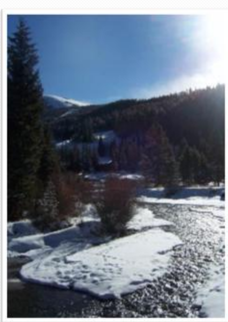
- Not all runoff becomes streamflow:
  - Runoff infiltrates downslope: e.g. Tiger bush, Sahel



Semi-arid environments

- Water recharges groundwater along the river bed
  - "Transmission loss"
  - At the extreme, rivers may disappear completely

Snow-dominated environments



- Precipitation stored as snow during winter
  - Water released as snowmelt
  - Either infiltrates or runs off
    - Partly dependent on whether the soil is frozen
  - Water table may rise into snowpack and cause rapid melting

Contribution of overland flow to runoff

- The **Horton Hypothesis**:
  - partition of runoff into
    - (a) overland flow
    - (b) infiltration with gradual groundwater flow
- The infiltration capacity of the soil is important in this hypothesis.

The Horton Hypothesis

- During the part of a storm (t) when rainfall intensity (i) exceeds infiltration capacity (f), there will be an excess of precipitation (P_e) which will flow as overland flow (Q_o).

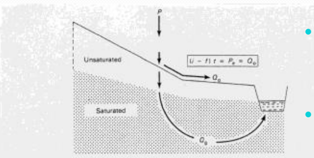


Figure 7.5 *The response of streamflow to precipitation: the Horton hypothesis.*

- If the rainfall intensity does not exceed infiltration capacity of the soil, there will be no overland flow.
- This type of overland flow resulting from high rainfall intensity has been referred to as **Hortonian Overland Flow**.

The Horton Hypothesis

- It has been suggested that infiltration capacity (f) would pass through a cycle for each storm:
  - Infiltration capacity is greatest at the start of a storm.
  - It decreases rapidly after the first hour and the declines only very slowly for the remainder of the storm.
  - Infiltration capacity then recovers slowly after the end of the storm.

The Horton Hypothesis

- If rainfall intensity is…
  - **High**: may exceed infiltration capacity and generate overland flow relatively quickly.
  - **Moderate**: may not generate overland flow early on, but does so after infiltration capacity has declined.
  - **Low**: may not generate Hortonian Overland Flow at all.
- In the Horton Model, it is likely that in a sequence of closely-spaced storms, only the later ones may generate overland flow (and therefore more Quickflow) compared to the early storms.

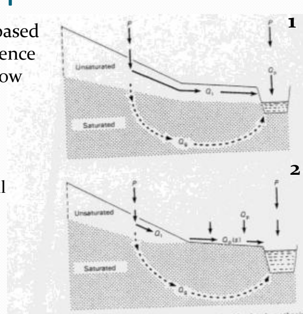
The Horton Hypothesis

- The rainfall intensity has to exceed infiltration capacity.
- Lower infiltration capacities, such as from compact soil, favours Hortonian Overland Flow.
- The Horton Model is most likely to apply to conditions of sparse vegetation cover, especially in arid and semi-arid environments, where crusts develop at or near to the surface.

The Hewlett Hypothesis

- The Hewlett Hypothesis: based on the general lack of evidence for widespread overland flow in many environments.

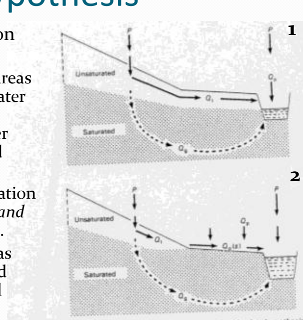
1. Onset of storm event:
   - Across the catchment, all precipitation infiltrates into the soil.



igure 7.6 The response of streamflow to precipitation: the Hewlett hypothesis

The Hewlett Hypothesis

2. After prolonged infiltration and throughflow:
   - The shallow water table areas near to the streams and later the lower slopes become saturated due to the water table rising to the ground surface.
   - In saturated areas, infiltration is zero - *Saturated Overland Flow* ($Q_o(s)$) is generated.
   - Only saturated areas act as sources of Quickflow, and increase in size as rainfall continues.

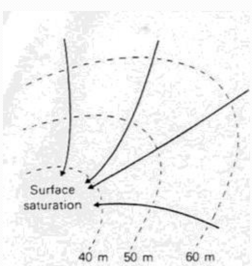


igure 7.6 The response of streamflow to precipitation: the Hewlett hypothesis

The Hewlett Hypothesis

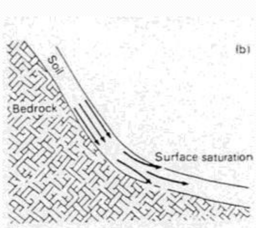
- The original model implied that the saturated areas would be connected to the stream channels.
  - Other areas in a catchment (in addition to contiguous channel side areas) may also have saturated overland flow, such as areas of throughflow convergence.
  - Do these areas also contribute to Quickflow?

The Hewlett Hypothesis



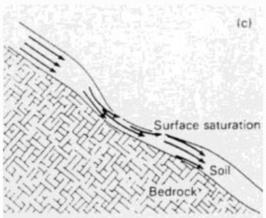
1. Slope Concavities in Plan:
   - convergence leads to rates of flow being greater than the transmission capacity of the soil
   - leads to flow emergence at the surface in the centre of concavities.

The Hewlett Hypothesis



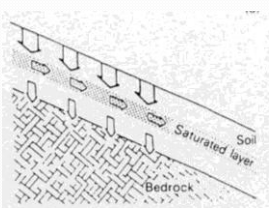
2. Slope Concavities in Section:
   - Subsurface flow rates are proportional to the hydraulic gradient.
   - If the hydraulic conductivity of the material is uniform, water will enter a concavity faster than it can leave.
   - Water emerges at the surface.

The Hewlett Hypothesis



3. Areas of Thinner Soil:
   - where water holding and transmission capacities are low.

The Hewlett Hypothesis

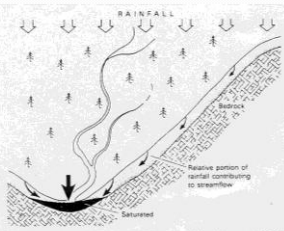


4. Perched Water Tables:
   - layers of temporary saturation due to reduced hydraulic conductivity with depth.
   - Mostly removed as throughflow, but it could reach the surface.

The Hewlett Hypothesis

- Concavities, areas of thinner soil and perched water table build up may provide a source of quickflow.
  - Other routes may be through animal burrows, root channels and other soil pipes.

The Hewlett Hypothesis



.9 The relative contributions of rainfall to streamflow (from an original 1961a)

- No overland flow, all rainfall infiltrates.
- In the upslope areas of a catchment, rainfall recharges the soil moisture store for future baseflow.
- In the lower slope, throughflow and, to a lesser extent, channel precipitation provide most of the quickflow.

The Hewlett Hypothesis

- The role of groundwater in storage and storm runoff:
  - In flat drainage basins, groundwater is a major component of total storage.
  - In steeper basins, soil moisture is the larger storage zone.

The response of stream flow to precipitation

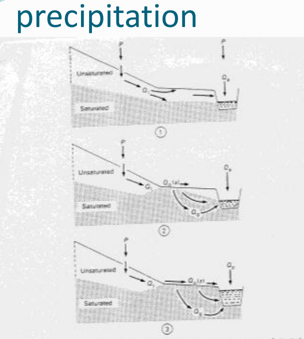


Figure 7.10 The response of streamflow to precipitation: an integrated view. Q, includes ... flow and pipeflow

1. Water infiltrates and moves as throughflow.
2. Convergence and infiltration in the lower slopes leads to saturation and groundwater recharge.
3. This creates overland flow and a groundwater component to the storm hydrograph.
4. A groundwater ridge develops and merges to form a wider area of surface saturation.

The Horton Model vs. the Hewlett Model

- The Hewlett Model accommodates a broad range of field observations of runoff.
  - Precipitation is generally able to infiltrate, but where slope material or vegetation has been altered, widespread overland flow may occur during high-intensity storms.
- Hortonian Overland Flow does occur in certain environments, especially in semi-arid and arid climates.