Where does the water go when it rains?

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The field studied, looking upslope

If you are studying rivers, or hazards such as flooding and water pollution, it helps to know about rainfall-runoff processes. How does rainwater move through the soil to the river? This article uses the example of a field site in western Oregon, USA to show how rainfall is converted into stream flow. Several simple but important ideas in hydrology are explored, in particular the importance of soil and slope

The site we studied is an almost flat field just outside the town of Corvallis in the Willamette Valley of western Oregon, USA. The soil is a clay loam, derived from alluvial deposits of the Willamette River. Despite the very low slope, there is no **under-drainage** (see Inset 1). This because the climate is 'wet Mediterranean': most of the rain falls between October and May, with almost none in the summer.

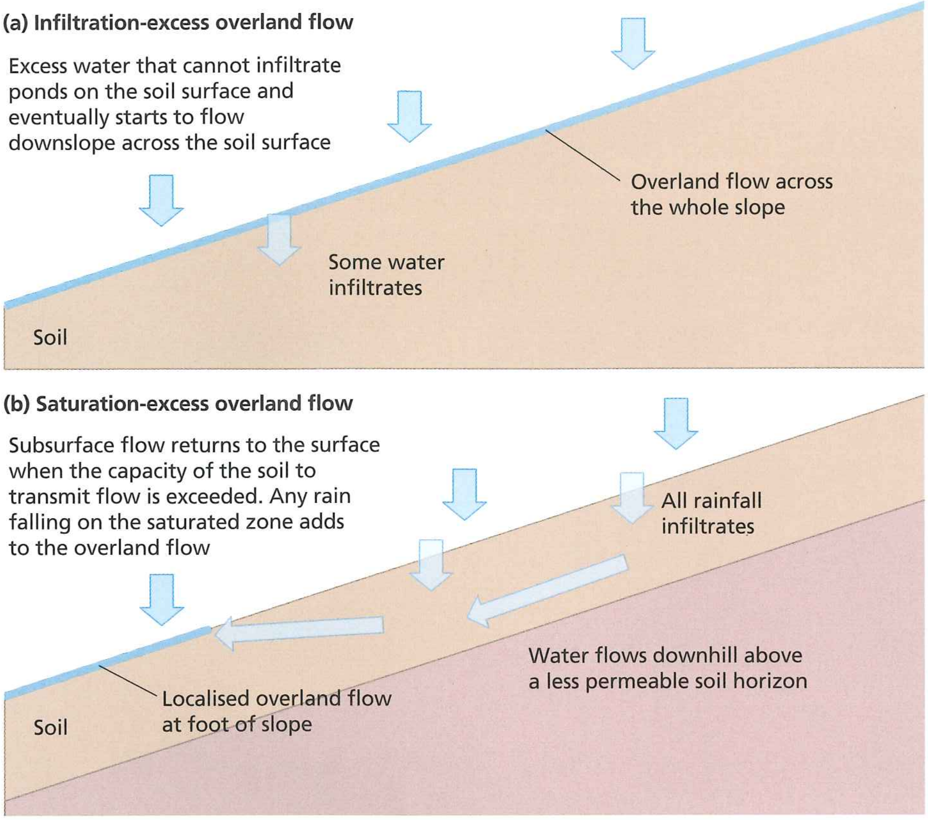

Figure 1 The differences between infiltration-excess overland flow (a) and saturation-excess overland flow (b)

Looking downslope: areas of surface saturation are clear to see

Inset 1

Draining farmland

It is necessary to install some form of drainage in order to farm land where soils have a high clay content or are prone to becoming saturated (e.g. next to a river). Undrained land can support some summer grazing, but is unsuitable for crops.

Open ditches provide one means of drainage. They help speed the removal of water from an area but do little to lower the water table within the soil. To achieve this, some form of under-drainage *within* the soil is needed.

Tile drains

The Victorians built drains by digging a ditch and installing a pipe to allow excess water to flow away. The pipe consisted of a series of unglazed clay tubes made from the same material as roof tiles. This type of drain therefore became known as a tile drain. Today, the pipe is likely to be a continuous length of perforated plastic tubing, which is cheaper and easier to install. A herringbone grid of drains is installed at approximately 10–20 metre spacing and a depth of 0.5–1 metre.

Mole drains

On the heaviest clay soils, mole drains are installed too. A bomb-shaped metal 'mole' is pulled through the soil at right angles to the tile drain network at a depth of about 0.25 m. This forms a small channel that allows excess water to reach the tile drain. The act of moling cracks the soil and helps improve its structure. Mole drains are spaced 1–2 metres apart. They tend to last only about 10 years before they collapse and the process needs to be repeated. Tile drains may last several decades.

Land drainage is an expense for a farmer, but the investment is worthwhile if it allows a much higher rate of production. In the period after the Second World War, the UK government subsidised land drainage in order to help achieve self-sufficiency in food production. That is why floodplains today can support arable farming whereas in the past only limited animal grazing was possible.

Although the soil becomes saturated during the winter, it soon dries out during the warm growing season so that investment in under-drainage is not necessary. Open ditches provide the necessary surface drainage. The crop is grass. There is no proper channel draining this field; water simply flows along the lowest part of the field and drains to a ditch via a culvert under the adjacent road.

Infiltration

The **infiltration capacity** of a soil is the maximum rate at which water can enter the soil surface. If the rainfall intensity is heavier than the soil surface can cope with, then excess water will pond on the surface. When individual puddles fill up, they start to spill over into adjacent puddles. Eventually, the flow lines connect right across the soil surface and water starts flowing downslope and out of the field. This is **infiltration-excess overland flow** (Figure 1). In our field, the soil has a high infiltration capacity so that, despite heavy and long-lasting storms, all the rainfall can be absorbed by the soil. No infiltration-excess overland flow is generated from this field.

We shall see later on that some overland flow is generated near the bottom of the slope — but by a very different mechanism.

Concentrated surface flow at the bottom of the slope, almost a channel

Soil layers and saturation

The surface layer (**horizon**) of the soil is relatively permeable. This is the layer that has been tilled (ploughed), so the structure is open, with large pores. There is plenty of organic matter, creating a texture with lots of small aggregates, rather than large lumps. This means there are plenty of cracks and holes through which water can drain. Below the tillage layer, the subsoil is much more massive in structure. There are far fewer cracks here and so the subsoil is less permeable than the tillage layer.

This sudden decrease in permeability with depth is a crucial control on the runoff response of this slope. Without this change in soil properties, water would continue to drain downwards through the soil. Because the subsoil cannot conduct nearly as much water as the topsoil, water ponds at the base of the topsoil. Once this happens, water can start to flow sideways, downslope, towards the 'stream channel'.

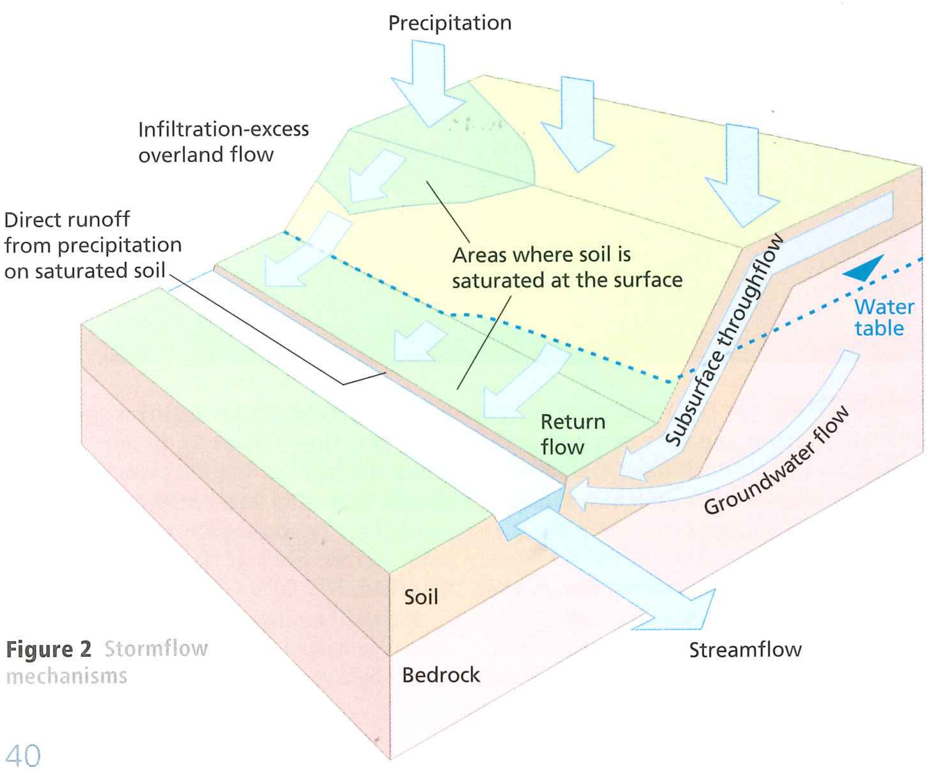

Figure 2 Stormflow mechanisms

Downwards then sideways

As described above, the only way flow in a downslope direction is generated is when a saturated layer of soil develops. At this site, this only happens at the base of the ploughed layer, because water cannot percolate into the subsoil fast enough. It does not happen at the soil surface because the permeable topsoil can absorb even heavy rain. This means water does not pond on the soil surface.

Having infiltrated the soil, the water drains vertically through the topsoil until it reaches the less permeable subsoil. Whenever the vertical drainage rate through the upper soil exceeds the ability of the subsoil to absorb this water, excess water builds up at the base of the topsoil horizon. Once this happens, water in this saturated zone begins to drain in a downslope direction.

Our simple example has provided two important rules concerning runoff processes and flow pathways on hillslopes:

- Water will continue to drain vertically through the soil until a less permeable layer is reached. If the input rate is lower than the infiltration capacity of soil layers or bedrock, water will continue to percolate downwards and the only significant lateral (sideways) flow will be from deep groundwater. However, in our case, the subsoil is a barrier to continued downward-moving soil water.

- Downslope flow can only occur once a zone of subsurface saturation has formed. In our case, soil becomes saturated immediately above the less-permeable subsoil and subsurface flow then begins in a downslope direction.

When storage capacity is exceeded

So far, we have only considered what happens in a single soil column, as water drains, first downwards, then sideways. But a hillslope is composed of lots of soil columns stacked next to each other. At the very top of the hill, there is obviously no water coming from further upslope, but as we move downslope, drainage from further upslope adds to the depth of the saturated layer of soil within the ploughed layer. The saturated zone is therefore deepest at the bottom of the slope.

This is often described as the **saturated wedge** because, if you draw a diagram to show the saturated zone getting deeper in a downslope direction, it has a triangular or wedge shape. Water flowing downslope within this saturated zone is often known as **throughflow**. At the bottom of the slope, this subsurface flow leaves the soil and enters the stream. This gives us a third rule:

- Hillslope runoff only adds to stream flow when slope drainage water reaches the stream channel. Localised soil saturation or surface ponding does not produce 'runoff'.

It rains a lot in an Oregon winter and the topsoil has limited capacity to store water. Quite quickly the combination of accumulated rainfall plus large inputs in individual storm events causes the topsoil to become completely saturated.

Q: Where does this happen first?

A: At the foot of the slope because this is where the saturated wedge is deepest, and therefore closest to the surface at the beginning of a storm.

This is why, at our site, surface saturation is found only on the lower section of the slope. It is possible that the saturated area will expand upslope if heavy rain lasts long enough. The excess slope drainage water **exfiltrates** the soil (the opposite of infiltration) because there is nowhere else for it to go. The water then flows across the soil surface. This type of runoff is known as **return flow** (Figure 2).

When it rains on to an already saturated soil, there is no possibility of infiltration — **infiltration capacity** is effectively zero. So, the rainfall directly on to the already saturated soil adds to the return flow and together they form **saturation-excess overland flow** (Figure 1).

We can add two more rules:

- Soil depth and slope angle are the main controls of hillslope runoff. In our case, a shallow topsoil and a low slope angle produce a very particular runoff response: a mixture of throughflow and saturation-excess overland flow.
- Soils tend to be wettest nearest the channel so these areas produce most storm runoff. The area contributing water to the stream varies in size during storms as the amount of water reaching the bottom of the slope builds up. The contribution area also expands seasonally. It is small or non-existent at the end of a dry summer and much bigger at the end of a wet winter. The area producing surface runoff is known as a **variable source area**.

Implications

Water quality

Water flowing through the soil can leach nutrients such as nitrate. Water flowing over the soil surface can erode mineral soil particles, including material attached to these particles such as organic matter or phosphate, another nutrient. Despite the low slope angle, erosion by flowing water is still possible, especially in the 'channel' at the bottom of the field where flow velocities will be highest.

Floods

Once soil moisture has been recharged, there is little or no space for additional water to be stored in the soil. Additional rainfall has to run off into local stream channels. Thus, any heavy fall of rain in a wet period is likely to generate high flows in local streams. Downstream, the combined effect of this happening in small tributary basins produces floods on the main river.

Landslides

There is no risk of a landslide at this site. The slope angle is far too low. A saturated soil is weaker than a dry soil, so on a much steeper slope, the soil is likely to slip once it becomes saturated. In steep terrain, landslides often result from heavy rain.

Questions for discussion

1 Explain why **infiltration-excess overland flow** and **saturation-excess overland flow** are generated from very different parts of a catchment.

2 For an area you know well, describe the range of runoff-generating processes that will happen during heavy rain. This exercise is equally applicable to an urban area as to a rural catchment. Note that although urban areas tend to have more impermeable surfaces, they still have plenty of areas where water can infiltrate.

You can find a PowerPoint presentation about runoff processes and hydrographs, and a quiz on flooding, on this issue's GeographyReview*Online*.

Jeff McDonnell directs the Institute for Water and Watersheds at Oregon State University, USA. **Greg Hancock** (University of Newcastle, Australia) and **Tim Burt** (Durham University, UK) were visiting fellows at IWW in 2010. Tim spotted this field site while on a bike ride — it's always worth keeping your eyes open.

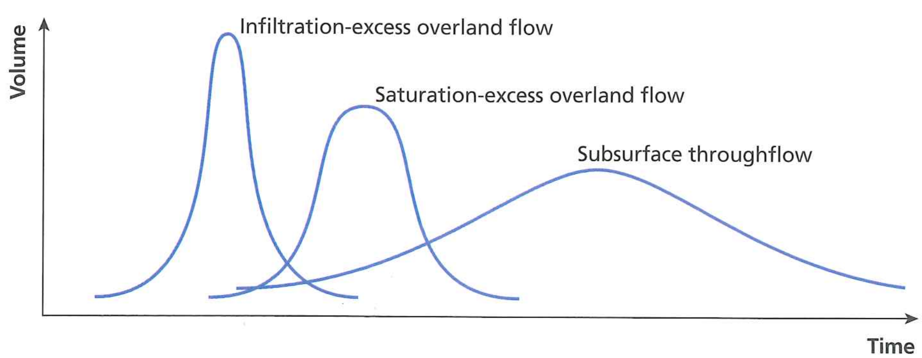

Figure 3 Hydrographs for three components of stormflow. Note how peak discharge, time to peak and total amount of runoff (area under the curve) vary between the three mechanisms

Key points

- If rainfall is heavier than the soil surface can cope with, excess water ponds on the surface and may eventually flow downslope towards the nearest stream.
- Water which infiltrates the soil continues to drain vertically until a less permeable layer of soil is reached.
- Wherever there is any restriction on vertical drainage, the soil becomes saturated immediately above the less-permeable layer and subsurface flow then begins in a downslope direction.
- Soil depth and slope angle are the main controls of hillslope runoff production.
- Soils tend to be wettest nearest the channel so these areas produce most storm runoff.