Article:

Holden, J. (2004) Geospatial aspects of catchment hydrology. GEOinformatics, 7. pp. 22-25. ISSN 1387-0858

Geospatial Aspects of Catch

Where Water Flows into Mapping

The catchment is a fundamental unit of study in hydrology. It is normally well defined topographically, can be studied as a series of nested units (larger catchments are made of many smaller sub-catchments), and is an open system for measuring inputs and outputs of mass and energy. Catchments are usually delineated by land-surface topography and are made of hillslopes and channels. The proportion of hillslope area to channel density or total channel length may determine how efficiently water can be removed from a catchment since water in channels tends to move much more quickly than water across and through hillslopes. Thus the spatial layout of hillslopes and channels is important. This article describes some basic principles of catchment hydrology and illustrates how determining spatial factors involved is fundamental for understanding how environmental change may impact on runoff production and resulting river flow.

By Joseph Holden

Figure 1. A soil pipe outlet with coarse sediment delivered from its base.

Hillslope Runoff

Most water reaches rivers via hillslopes. Various hillslope flow pathways exist and these delay flow to different extents. Hydrological processes on hillslopes range from overland flow (OLF) through subsurface flow involving micropores, macropores and natural soil pipes, to displacement flow and groundwater discharge. The dominance of these processes varies with climate, topography, soil character, vegetation cover and land use, but may vary at one location (e.g. seasonally) with antecedent soil moisture and with storm intensity and duration. There are two possibilities for water once it reaches the hillslope; either to infiltrate into the soil or to fill up any depressions on the surface and flow over the surface as OLF.

Infiltration-excess overland flow

If surface water supply is greater than infiltration then surface flow will commence; this is called infiltration-excess OLF. In many temperate areas infiltration-excess OLF is a rare occurrence except in urban locations because the infiltration capacity of many soils is too high (i.e. water can enter the soil at a faster rate than it can rain). Infiltration-excess OLF is more likely in semi-arid areas on soil crusts and where rainfall events can be intense. Often infiltration-excess OLF will occur only on spatially localised parts of a hillslope (rather than the whole catchment) such as in tractor wheelings on arable land. This localised occurrence is known as the partial contributing area concept.

Saturation-excess overland flow

When water infiltrates it will fill up available pore spaces (gaps between solid soil particles). When all pore spaces are full the soil is saturated and the water table is at the surface. Therefore any extra water has difficulty entering the soil. Hence OLF will occur. This type of OLF is known as saturation-excess OLF. This can happen at much lower rainfall intensities than required to generate infiltration-excess OLF and can occur even when it is not raining. This might happen, for example, at the foot of a hillslope. Water draining through the soil is known as throughflow (see below). Throughflow from upslope can fill up soil pores at the slope foot and so the soil becomes saturated. Any

ment Hydrology

extra water is then forced out onto the surface to become OLF. This water is known as 'return flow' and is a component of saturation-excess OLF (the other component is fresh rainwater). Therefore saturation-excess OLF is more likely to occur at the bottom of a hillslope, or on shallow soils where there is restricted pore space for water storage. The area of a catchment or hillslope that produces saturation-excess OLF varies through time. During wet seasons, more of a catchment or hillslope will be saturated and therefore able to generate saturation-excess OLF than during dry seasons. If the catchment starts off relatively dry then during rainfall only a small area will generate saturation-excess OLF, but as rainfall continues more of the catchment becomes saturated, especially in valley bottoms. Hence a larger area of the catchment will produce saturation-excess OLF. This is known as the 'variable source area concept' and is the dominant concept in catchment hydrology. At certain times of year some parts of a catchment will provide OLF whereas at other times the same parts will not deliver OLF in response to the same-sized rainfall event. This is important for example, where surface pollutants (such as microbes attached to cattle droppings) might be delivered from a given part of a catchment or hillslope only at certain times of the year. Thus understanding such spatial processes helps us inform decision-making.

Throughflow

If water infiltrates into soil several things can happen:

- It can be taken up by plants and transpired (or be lost from the soil by evaporation).
- It can continue to percolate down into the bedrock
- It can travel laterally downslope through the soil or rock – this is called throughflow.

In fact most water reaches rivers by throughflow, through the soil layers or through bedrock. Throughflow can both maintain low flows (baseflow) in rivers by slow subsurface drainage and can also contribute to peak flows (stormflow) through its role in generating saturation-excess OLF. There are different ways water can move through soil and this effects the timing of water delivery to the river. Soils are not uniform deposits as they have cracks and fissures within them. Water can move through the very fine pores of soil as matrix flow, or it can move through larger pores called macropores (macropore flow), or even larger cavities called soil pipes (pipe flow).

Matrix flow

Flow through the soil matrix is controlled by soil type (e.g. texture) and saturation. Sandy soils allow faster water movements through them than clay soils. Even after a long drought most soils contain some water which suggests that the forces involved must be very strong. A combined attraction of the water molecules to each other and the water to the soil particles means that water is held in soil against the force of gravity. This is known as capillary water and it will move within the soil from wet to dry areas. Thus it is possible to map the likely movement of soil water across the hillslope if there is a sufficient spatial array of instruments.

Macropore flow

Macropores are pores larger than 0.1 mm in diameter and can promote rapid, preferential transport of water and chemicals through the soil, not only due to their size but also because they are connected and continuous over sufficient distances to bypass agriculturally and environmentally important soil layers. Therefore if a field has many macropores, surface fertiliser applications may get washed through the macropore channels and may not enter the main part of the soil. Macropores can be formed by soil fauna, plant roots, and cracking resulting from a dried soil. They may not take up much space but can still play a large role in throughflow; studies in upland peat catchments by the author have indicated that 30 % of throughflow moves through macropores.

Pipe flow

Natural soil pipes are cavities greater than 1 mm diameter that are continuous in length such that they can transmit water, sediment and solutes through the soil and bypass the soil matrix. Soil pipes are created by a range of processes including animal burrows and turbulent flow through macropores. Pipes can be up to several metres in diameter (see Figure 1) and several hundred metres in length and occur in a broad range of environments. Often pipes can erode to form large gullies. Pipes may transmit a large proportion of water to the stream in some catchments (10 - 40 % of discharge in peat catchments). Sometimes it is difficult to detect soil pipes where they have not collapsed and are several metres below the surface. However, the author has used geophysical techniques such as ground penetrating radar as shown in (see Figure 2) to allow mapping of subsurface pipes and their hydrological connectivity. The pipe networks can be complex and provide rapid connectivity of water, sediment and solutes coupling distant parts of hillslopes with stream channels.

Groundwater flow

Groundwater is water held below the water table (in soils and rock) and has, to some extent, already been discussed in the sections above. Groundwater may be a large store of water, but in order for it to be available to supply river flow the holding material (rock or soil) needs to be not just porous but permeable (i.e with connecting pores). Layers of rock sufficiently porous to store water and permeable enough to allow water to flow through them in economic quantities are called aquifers. Sometimes aquifers can be confined between impermeable rock layers (aquitards) and are only open for recharge and discharge at certain locations.

Impact of Runoff Processes and Land Management on Streamflow

Knowledge of runoff mechanisms and their controls is important for determining catchment response to a precipitation event. The amount of precipitation that reaches the river channel can vary from almost 100 % (in some urban areas) to less than 5 %. Changes in catchment management (or land use) such as urbanization, ploughing, afforestation, deforestation and artificial soil drainage can alter hydrological flow paths, affecting the timing, volume and quality of water reaching the river channel. There is always a lag between precipitation and peak river discharge. This lag time is affected by hillslope runoff processes. Catchments dominated by infiltration-excess OLF have the shortest lag times and the highest peak

Figure 2. Mapping soil pipes using ground-penetrating radar. The instrument is transported or wheeled across the surface and can detect soil pipes that are several meters below the surface.

flows. This is why urbanisation can lead to increased flood risk downstream. If throughflow in the matrix dominates on hillslopes then the lag time will be long and peak flow low. There may even be two river discharge peaks caused by one rainfall event. This might occur where the first peak is saturation-excess OLF dominated (with some precipitation directly in the channel). The second peak may be much longer and larger and caused by subsurface throughflow accumulating at the bottom of hillslopes and valley bottoms before entering the stream channel. Throughflow may also contribute directly to storm hydrographs by a mechanism called piston or displacement flow. This is where soil water at the bottom of a slope (old water) is rapidly pushed out of the soil by new fresh infiltrating water entering at the top of a slope. Climate change and land management may alter infiltration, soil saturation, soil structure and vegetation and the dominance of particular runoff processes. In some locations flooding has increased due to changing precipitation regimes and land management. Many solutions have involved building taller levees or embankments, or straightening and clearing river channels (rather than tackling the problem on the hillslopes). However, the flood waters have to go somewhere and these practices often lead to worse flooding; sending water quickly through the river system reduces the downstream lag time and increases the flood peak. Floodplains function as a temporary water store reducing the flood peaks downstream. However, demand for building/farming on floodplains means that less area is available for water storage. Thus flooding in lowland areas is an increasing problem as water is brought downstream more quickly and in greater quantities than ever before.

Case Study – Upland Drainage in the Yorkshire Dales

The idea that 'upstream matters' is important because it makes us think about spatial processes. Even within an upland headwater, the impact of a management activity may be very different depending on the location. The following case study provides an example. Floods have been more common on the River Ouse, at York, UK since the 1940s. Analysis of the rainfall record showed minimal change. Hence land management change is a likely causative factor. Many parts of the upland Yorkshire Dales were drained by ditches in the 1940s in order to improve grazing and game bird habitat by lowering water tables. Two main hillslope hydrological changes are likely:

There is increased water storage capacity within the soil (as a drained soil can store more fresh rainfall). Therefore peak flows would be reduced and lag times increased. This, on first impression, should result in a decrease in flooding. The ditches now provide new channels for fast moving water to reach the stream. Instead of water moving as OLF through vegetated terrain or as throughflow in the soil matrix the water is able to move much more quickly as OLF within drainage ditches directly linked to streams. Thus the flowpaths for hillslope water will be reduced. Before ditches had been dug, precipitation that landed on a hilltop would have to move across the entire length of the slope (e.g. ~200 m) to its base before reaching the stream. After drainage the same precipitation now only needs to travel a short distance (e.g. ~10 m) from the hilltop to a ditch before it is then rapidly channelled away. There are two conflicting processes; the first reduces the hillslope flood peak and increases the lag time and the second has the opposite effect. However, the first process may also lead to increases in flood peaks. This is because of spatial processes. Where a hillslope that once produced a flood peak 30 minutes after rainfall, following drainage it now produces a flood peak 60 minutes after rainfall due to the extra storage capacity available in the drained soil. While the flood peak from this hillslope is lower than it was before drainage, its timing now corresponds to when the main river channel has its flood peak. Such synchronicity leads to an overall increase in the main channel flood. Clearly the effects will depend on where in the catchment land management change takes place as this determines the impact of changing the timing of water delivery to the main channel. In addition, the effects of ditching can result in small-scale irreversible changes to hillslope processes. Lowered water tables in organic soils such as those in the Yorkshire Dales can result in soil shrinkage and cracking. These cracks provide new routes for water (as macropore flow) which then enlarge into soil pipes. This leads to an interesting problem. If we block ditches in an attempt to ameliorate flooding, this may lead to more water (from blocked ditches full of water) travelling to the stream via newly created soil pipes on ditch walls. Subsurface pipe erosion (and resulting gully development) might ensue. Thus change to hillslope processes brought about by land use change may not be simply reversible just by reverting back to the original land use. We must therefore think very carefully about impacts of land use change within a catchment before those changes are implemented.

Dr. Joseph Holden (j.holden@leeds.ac.uk), is Professor at the School of Geography, University of Leeds in the UK.