HYDROLOGY

Soil-water bypass

Hydrologists have thought of soil as a kind of giant sponge that soaks up precipitation and slowly releases it to streams. But according to new evidence the soil water used by vegetation may be largely decoupled from the water that flows through soils to streams.

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nly a very small proportion of the rain or snow that falls on a watershed drops directly into a stream. Most of the flow of the stream must be sustained by precipitation that has fallen on the soil first and been transmitted to the stream. Writing in *Nature Geoscience*, Brooks and colleagues¹ report isotopic data that show that the water occupying the pore spaces of the soil supplying the trees is quite distinct from the water that actually reaches the streams, at least in their experimental watershed in Oregon.

The transmission of rainfall to streams was originally thought to be primarily by overland runoff during storm events². Subsequent work showed that stream flow peaked during storms, even when overland flow was not observed, and that in many cases the runoff must somehow be moving to the stream through the soil itself³. Early applications of the stable isotopes of oxygen and hydrogen to tracing runoff generation demonstrated that the water expelled from the soil to the streams was not mostly from the storm precipitation, even during intense rainstorms. The runoff was instead being produced from water that had already been resident in the soil or groundwater before the storm⁴.

But, although water that precipitated before a given storm prevails in stormflow discharge, artificial tracers applied to the soil on hillslopes could be found in streams below soon after the start of heavy precipitation⁵, indicating that there is a more direct route to the river for water from severe rainfall events. Attempting to reconcile these apparently paradoxical observations has been high on the research agenda for the past 20 years.

It was recognized early on that, at a simplistic level at least, subsurface runoff on hillslopes can be divided into two categories: fast flow paths such as soil cracks, animal burrows, root channels and joint planes in bedrock, and slow paths within the surrounding soil matrix⁶. Since the discovery of this basic framework, the question has been how these types of flow paths interact with each other. In general, fast and slow pathways have been thought to represent the endpoints of an interconnected



Figure 1 Separate realms of water. Brooks and colleagues¹ present isotopic data that show — in their experimental watershed in Oregon, USA — the water stored in the soil matrix and used by trees is distinct from the water that falls during winter rainstorms and feeds the streams in the watershed. The two are linked only for the first rain after a dry summer, when the soil matrix is replenished.

continuum⁷. The hillslope system may be visualized as a discontinuous stream channel (the fast flow paths) meandering through a swampy bottomland (the soil matrix). When there is little flow most of the water in the system resides in the nearly stagnant pools, but during floods new water is pushed into the pools and old water is flushed out. This concept results in average water residence times on hillslopes ranging from a few weeks to several months^{7,8}. It also carries an implicit assumption that the history of precipitation that falls on hillsides can be inferred from the water that flows into the streams at their bases.

Surprisingly, in the watershed studied by Brooks and colleagues¹ much of the soil matrix seems to be decoupled from the fast paths that course through it. Using the seasonal variation of stable isotopes in precipitation, they show that the finegrained soil matrix is filled by the first heavy precipitation events of the autumn. The trees subsequently draw on this pool of water, but it is not replenished by the heavier series of storms that follows throughout the winter. The stream responds, although in a very muted fashion, to the changes in isotopic composition of rainfall during the winter and spring, but the soil water and tree sap do not. During the nearly rainless summer the trees suck the soil to a very dry condition, providing the capillary gradient to pull water back into the fine-grained matrix when the first autumn rains arrive.

To return to the analogy above, instead of resembling an interconnected system of stream channels and swampy pools, the hillslopes at the experimental forest in Oregon more closely resemble a stream flowing between dvked paddocks. When water in the stream first rises, water gates are opened to let in floodwater and once the paddocks are full they are closed, leaving stagnant pools trapped behind the dykes. In such a system the volume of potentially active flow should be much smaller and the average residence time longer than previously envisioned. Furthermore, the stagnant pools are dead-end roads for the water and the nutrients the water carries. They can only exit the soil by being taken up by plants. Conversely, any nutrients that are mobilized by storms after the early autumn presumably bypass the vegetation community and are flushed into the streams. Finally, since a substantial proportion of precipitation that infiltrates the soil becomes isolated from the

discharge to the streams, the composition of stream water alone is not sufficient to determine routing and residence times.

If the findings of Brooks and colleagues can be generalized, they will require substantial revision of the accepted conceptual models for runoff generation and biogeochemistry on hillslopes. A much more compartmentalized system incorporating wetness-dependent interconnectivity will have to be used in models, and nutrient flow-paths will consequently be diverted. But the extent to which the findings can be generalized is uncertain. Hints of similar behaviour have been published for semiarid hillslopes in the southwestern United States⁹. However, many climate regimes do not have such pronounced seasonal disparities in water availability and the soil matrix may exchange with the fast flow paths on a more frequent basis. Also, many geological settings may not produce soils that are sufficiently fine-grained to absorb infiltration when dry and then resist it when wetted up. Even this mechanism for retention is hypothetical and detailed soil-physics and tracer studies are necessary to confirm it.

Despite numerous questions that remain to be answered, the results of Brooks and colleagues¹ are intriguing and open a new way towards a better understanding of the fate of water in the landscape. Fred M. Phillips is at the Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801, USA.

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EARTH'S INTERIOR

Intraplate upwelling



The pre-Columbian Sinagua people, who occupied the land of present-day northern Arizona until about 1425, probably witnessed the final burst of volcanism in the San Francisco volcanic field. At some point between AD 1064 and 1150, Sunset Crater formed through the last eruption in this landscape dominated by more 600 volcanoes. Unusually, the volcanoes are located well within the interior of the North American plate.

The causes of volcanism in the middle of tectonic plates are hotly debated. Intraplate volcanism, away from obvious magma sources such as spreading ocean ridges or subducting plate margins, could result from upwelling of an anomalously hot mantle plume that impinges on the Earth's uppermost rigid layer. Yet many features of the San Francisco intraplate volcanic field (and others) do not fit the mantle-plume hypothesis. A variety of non-plume mechanisms to generate intraplate volcanism have been proposed. One example is so-called lithospheric drips, where a block of cooler, dense rock sinks from the Earth's uppermost layer, generating a return upward flow of buoyant, hot, mantle material. Another possible mechanism is edge-driven convection, where the variable thickness of a tectonic plate creates relief on the boundary between the rigid lithosphere and the underlying ductile asthenosphere, enhancing small-scale convection and driving mantle upwelling.

Both of these mechanisms require density contrasts — either between the brittle lithosphere and the ductile asthenosphere or within the asthenosphere itself — to produce enhanced convection and upwelling of hot mantle rock. Yet, many examples of intraplate volcanism are not associated with density heterogeneity. Clinton Conrad, at the University of Hawaii, and his research team propose a mechanism that results in enhanced upward mantle flow without this requirement (*Phys. Earth Planet. Inter.* doi:10.1016/j.pepi.2009.10.001; 2009). Using numerical modelling they show that viscosity variation alone can induce increased upwelling, if subject to shear motion, in a mechanism they call sheardriven upwelling.

Viscosity contrasts can occur in the same locations as density contrasts. Variable thickness along the base of the highly viscous lithosphere can form an indented cavity that fills with less viscous asthenosphere. Alternatively, pockets of lower viscosity asthenosphere can form within normal asthenosphere owing to anomalies in thermal patterns, melting, or volatile or fluid content. The low viscosity cavities or pockets are exposed to a velocity shear that is generated by the relative motion between the convecting mantle and the overlving tectonic plates. Conrad and colleagues' numerical modelling results indicate that, under this imposed shear, viscosity variations within a cavity or pocket can generate increased mantle upwelling of up to ~1 cm yr⁻¹, causing partial melting and the generation of magma that erupts as surface volcanism.

The idea of shear-driven upwelling provides a neat alternative to existing models for volcanism where it is least expected. Whether it was indeed responsible for the generation of the San Francisco volcanic field remains to be shown.

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