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a0005
OVERLAND FLOW GENERATION

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s0005 Introduction

p0005 For many years, it was believed that the occurrence of surface runoff was primarily controlled by the infiltration characteristics of the ground. Specifically, runoff is generated whenever rainfall or irrigation water is applied to the ground at a higher rate than the soil's infiltration capacity. Robert E. Horton was responsible for some of the early foundational work behind this concept and hence the process is ubiquitously referred to as 'Hortonian runoff.' The synonymous term 'infiltration-excess overland flow' is also widely used, again emphasizing that surface runoff occurs when precipitation exceeds the infiltration capacity of the soil. This process is very important in many areas of the country: arid areas (where significant soil crusting and/or surface sealing occurs during rain events), in irrigated fields, in urban areas, and more generally during storms with very high rainfall intensities.

p0010 However, the Hortonian runoff concept does not meaningfully explain storm runoff in many humid regions, where the infiltration capacity of the ground is typically much greater than average rainfall intensities. Many researchers have found that the typical values published in soil surveys for disturbed samples underestimate the conductivity in the field for vegetated soils by a factor of 10 or more due to the presence of preferential flow paths in the form of worm channels and root passages. Consequently, only the most intense summer storms could produce runoff under this Hortonian runoff scenario. This is in wet times of the year, in direct contrast to stream response almost every time it rains, which means that there must be some other mechanism generating runoff.

In many regions, runoff is most commonly generated on relatively small portions of the landscape that are susceptible to becoming completely saturated. p0015
Once the soils in these areas saturate to the surface, any additional rainfall (irrespective of intensity) becomes overland flow. This process is termed 'saturation-excess overland flow.' Therefore, the propensity of an area to produce runoff is largely independent of rainfall intensity. Instead, the total rainfall amount and landscape factors such as soil depth (i.e., available water storage capacity), upland watershed area, and local topography are the important factors determining whether or not a particular area in a watershed will generate runoff. Moreover, as rainfall continues, the saturated area grows in extent, increasing the area generating runoff (hence the term 'variable source area,' VSA). This is in contrast to Hortonian infiltration-excess runoff generation, which depends on soil type (infiltration rate versus rain intensity) but is independent of position in the landscape, with the runoff generating area always the same. Examples of regions in the USA where VSA hydrology is significant include the Northeast and the Pacific Northwest, as well as forested mountain areas. It occurs also throughout the world in many similar areas.

Saturation-Excess Overland Flow s0010

Saturation-excess overland flow comes from two distinguishable sources. Rain falling on already saturated soil has no option but to run off – this case is termed 'direct precipitation on saturated areas' (DPSA). The other source, termed 'return flow,' occurs if the rate of interflow entering a saturated area from upslope exceeds the capacity for interflow to leave the area by flowing downhill through the soil. The excess interflow, thus, "returns" to the surface as runoff, hence the term. Whereas DPSA runoff only occurs during and just after a rainfall event, return p0020 flow seepage can continue as long as an interflow excess exists.

p0025 Areas prone to saturation either have a high groundwater table or hard pan (fragipan) at shallow depth. Interflow results in the formation of saturated areas at the bottom of slopes, usually in concave areas, or quickly resurfaces in seeps and ditches. Some hydrological processes observed in upstate New York, primarily the Catskill Mountains region, can serve to further elucidate mechanisms resulting in saturation. Soils in the Catskills are generally permeable (relative to rainfall intensity) and underlain by a shallow, low-permeable, restrictive layer, typically bedrock or fragipan. Rainwater easily permeates the soil and, by-and-large, runs laterally as interflow on top of the restrictive layer downslope. Many researchers have observed evidence of the accumulation of interflow water at the bottom of a slope in the Catskills during wet periods in the form of increased moisture content at hill bottoms relative to the steep parts of hills. Some common locations where saturation occurs are areas where the soil above the restricting layer is shallow, in places where the downhill topographic slope decreases such as the toe-slope of a hill, or in topographically converging areas (**Figure 1**). All three incidences are locations in the landscape where the Darcy flow capacity, or interflow capacity, is reduced either by a decrease in hydraulic transmissivity or hydraulic gradient. When interflow capacity is sufficiently restricted, the soil will saturate. During periods of enhanced rainfall, interflow will be higher and often expand the extent of saturation around saturation-prone areas; conversely, dry periods will decrease interflow and extent of saturation. This is illustrated for wet and dry seasons in **Figure 2**.

p0030 VSA hydrology is an extension of the saturation-excess concept, recognizing that the extent of saturated areas in a watershed will expand and contract, i.e., vary temporally. The variation in the extent of saturated areas has been studied over a range of temporal scales, ranging from storm duration, hours and days, to seasons (**Figure 2**). Although the original, underlying concept for VSA hydrology was developed by the US Forest Service, the term ‘variable source area’ is often attributed to Hewlett and Hibbert. As stated above, VSA hydrology is applicable to many landscapes throughout humid regions that have undulating topography.

p0035 The VSA hydrology concept, thus, goes beyond drawing the water–soil interface boundary at the soil surface and making the simple assumption that water either infiltrates or runs off. The VSA hydrology concept includes the soil reservoir in a spatial landscape context to determine locations where the soil reservoir becomes saturated and begins to generate runoff. The soil reservoir methodology utilizes the bedrock, impermeable soil layers (relative to above layers), and/or the depth to the water table as the underlying hydrologic boundary instead of the soil surface. Thus, both hydrologic and soil water (i.e., porous media) concepts are combined to evaluate potential runoff areas in the landscape.

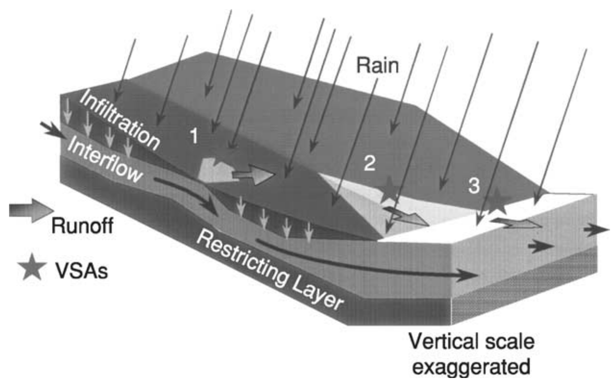

Figure 1 Incidence of saturation-excess hydrology: 1, shallow soil; 2, convergence area; and 3, decreasing downhill slope. VSA, variable source area. f0005

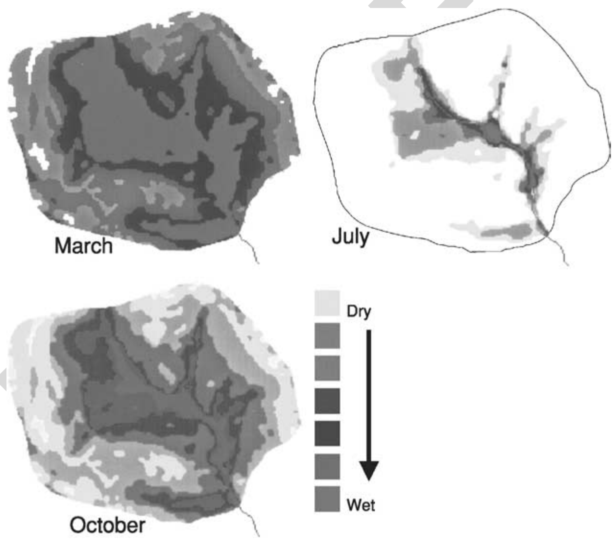

Figure 2 Seasonal changes of saturated areas (variable source areas) in a watershed in New York State. Color denotes areas more prone to saturation. f0010

Calculation Method s0015

p0040 TOPMODEL is used most often to predict the saturated-excess overland flow. It is based on calculating a groundwater table height that, when it intercepts the soil surface, will result in runoff. In TOPMODEL, the assumption is made that the watershed is underlain by a groundwater table. This is not realistic for many mountainous areas. However, since most of the saturated areas occur near streams, this limitation is not severe as a groundwater table is present in these areas. How the water get to the groundwater is often inconsequential. An alternative method to find the saturated areas is the Soil Moisture Routing (SMR) model, a physically based, fully distributed, geographic information system (GIS) integrated code specifically designed for soils underlain by a hardpan. This model solves the water balance for cells in a square grid. What makes it different from most other models is that the spatial location of the grid cells is preserved in the landscape and water is routed by interflow from one cell to the next, resulting in the generation of saturated areas within the landscape. This model, despite its simplicity, predicts amazingly well the saturated areas in the landscape. TOPMODEL and SMR are admittedly more complicated than the popular Soil Conservation Service "Curve Number" method (SCS-CN), which was developed in the 1950s and 1960s by the USDA Soil Conservation Service (currently the Natural Resource Conservation Service). The traditional SCS-CN method is a rainfall-runoff model that was originally developed for predicting flood-flow volumes from ungauged watersheds for hydraulic engineering design. Despite the limited scope of intended application and several identified problems with the traditional SCS-CN method, it is ubiquitously used in water quality to generate the fraction of rainfall that runs off. The original model was justified by Victor Mockus, to whom the traditional SCS-CN method is largely attributed, "on grounds that it produces rainfall-runoff curves of a type found on natural watersheds." Subsequently, hydrologists have shown that the basis of the method can be described in ways that are nominally consistent with both infiltration-excess theory and saturation-excess or VSA hydrology.

s0020 Water Quality Impacts of Variable Source Area Hydrology

p0045 VSA hydrology has been shown to have significant consequences on surfacewater quality, having direct impacts on specific areas such as animal waste management, drinking water and human health, nutrient and pesticide management, pollution assessment and prevention, and watershed management. It is important that the development and implementation of the next generation of land-management practices for improving or preserving surface water quality be consistent with our most current hydrological understanding. Interestingly, many current practices aimed at reducing contaminant transport are based on Hortonian concepts. However, the effectiveness of these practices is diminished where Hortonian processes are not governing runoff generation.

Wherever VSA hydrology is a dominant process, p0050
there will be regions within a watershed that are more susceptible to producing runoff and delivering it to surfacewater bodies than other regions. These areas can be considered hydrologically sensitive areas (HSA). Recognizing the existence of HSAs allows watershed-scale water quality efforts to be focused on those areas where HSAs coincide with land uses that potentially contribute pollutants. The intersection of an HSA and a pollutant loading area is referred to as the 'critical management zone.' The most obvious best-management practice for this area would be to limit or prohibit potentially polluting activity from this region. A contrasting approach is finding methods and means of eliminating the hydrological sensitivity of the critical zones, although recent research suggests attempts to remove hydrolog sensitivity through drainage practices may simply reroute pollutants from overland flow to subsurface flow, with little reduction in concentration. In either case, the HSAs warrant primary attention when trying to preserve or improve water quality.

One example of where potential management prac- p0055
tices derived from a recognition of VSA hydrology is in direct conflict with currently mandated management practices is whether dairy operators in the New York City watersheds should spread manure on steep slopes or in flat areas. The current dogma is to avoid spreading on steep slopes and to maximize spreading in flat areas. Under Hortonian flow, steep areas might arguably produce the most rapidly moving runoff and, therefore, the greatest potential for erosion and transport of manure. However, VSA hydrology is the dominant process in these watersheds and the steep

Figure 3 Manure deposition in exactly the wrong place from a hydrologically sensitive-area standpoint (courtesy of Glenn Warner). f0015 AU:5

slopes infiltrate essentially all rainwater and drain very rapidly, resulting in almost no substantial runoff. Conversely, the flat areas, especially at the base of hillslopes, are especially prone to saturation and thus to runoff generation. **Figure 3** shows manure deposition in, from a HSA standpoint, exactly the wrong place. A manure-spreading policy that is more consistent with the recognized hydrology would promote spreading high in the watershed and minimize spreading on low, flat areas susceptible to runoff generation.

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