Subsurface Flow

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Abstract

Subsurface flow refers to any flow below the surface of the ground which includes low flow (base flow) and quick flow (subsurface stormflow). Subsurface flow has been attracting attention as an important topic of research in recent years because of its crucial role in water cycle calculation, flood prediction, slope stability, nutrient recycling, and soil–water–vegetation exchange processes. In early subsurface flow research, trenches (or pits) combined with hydrometric approaches are the main observation techniques. In recent decades, great progress has been made on the source, pathway, and residence time of subsurface flow due to the application of tracer and geophysical techniques. However, there is yet no broad consensus on the responsible mechanisms that explain runoff processes in the

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ground. This chapter seeks to provide an overview of current research on subsurface flow. We first give a brief description of the basic concept of subsurface flow and base flow and then focus on the flow regimes, controlling factors, and monitor and model of subsurface stormflow. In the end of this chapter, future research directions are proposed.

Keywords

Subsurface flow · Subsurface stormflow · Preferential flow · Base flow · Trenching · Tracer · Geophysical methods

Terminology

In traditional hydrology, flow is divided into surface flow and subsurface flow, where subsurface flow can be divided into quick flow and low flow. In general, the quick flow refers to subsurface stormflow, and low flow refers to base flow (Fig. 1). Subsurface flow refers to any flow below the surface of the ground (WMO 2012). The flow can be saturated or unsaturated, and the flow direction can be lateral or vertical (Dunne 1990; Lin and Zhou 2008). It is part of the infiltrated effective precipitation that circulates in the ground and reaches the surface through drain channels. Subsurface flow is an important source of streamflow, contributed streamflow together with glacier runoff and overland flow (Winter 2007). The exerted role of subsurface flow has been shown to be of key importance for substantially maintaining low flow (base flow) during the rainless period, quickly responding, and contributing to quick flow (subsurface stormflow) during storm periods. The total volume of subsurface flow is the sum of base flow and subsurface stormflow (Winter 2007; Ghasemizade and Schirmer 2013).

Compared with subsurface stormflow, base flow is often viewed as a “dull” or “stable” flow. Hence, the spatial and temporal scale of the study base flow is usually larger (or longer) than the subsurface stormflow. Current research on base flow mainly focused on base flow separation methods, regression model, and influencing factors at watershed scale or year scale. However, research on subsurface stormflow is mainly focused on rainfall–runoff processes, transport mechanisms at hillslope/pedon scale, or single precipitation event scale. In the following, we will give a brief description of the base flow, then focus on rainfall–runoff processes, and mainly discuss current research of subsurface stormflow.

Base Flow

Base flow is also known as low flow, groundwater flow, percolation flow, underrun, seepage flow, and sustained flow in the hydrological literature. Base flow can be considered as subsurface flow derived from deep percolation of infiltrated water that enters the permanent saturated groundwater flow system and discharges into the
river channel especially during the prolonged rainless period (Freeze 1972; Frohlich et al. 1994). It is not the direct consequence of the rainfall event but is considered as the outflow of the groundwater reservoir feeding the river (Ghasemizade and Schirmer 2013). The base flow rate is relatively stable, generally taking the lowest flow rate of multi-year as the average value.

Base flow is an important part of assessing water resources in a watershed, especially in arid and semiarid areas. In the dry season, the base flow is the most important hydrological feature of the watershed. These streamflow characteristics can be used by watershed planners and regulators to determine water use allocations, assimilative capacities of streams, and aquatic habitat needs. It is essential that watershed planners and regulators have access to accurate and easily obtainable base flow (low flow) characteristics to make informed decisions (Stuckey 2006). At present, the research on base flow is mainly focused on separation methods, regression model, and influencing factors at watershed scale or year scale. Few studies have investigated the mechanisms which generate streamflow during inter-storm/seasonal base flow periods (Payn et al. 2012). In recent years, problems of droughts have focused attention on base flow periods and the processes sustaining water resources for both human consumption and ecosystem needs during dry spells (Lehner et al. 2006). Future research is needed to understand how base flows sustain water supplies and aquatic ecosystems. We believe that better understanding of the interacting controls on low-flow generation mechanisms can lead to better management of limited water resources (Ghasemizade and Schirmer 2013).

**Subsurface Stormflow**

Subsurface stormflow is also known as subsurface runoff, interflow, throughflow, lateral flow, transient groundwater, fast subsurface flow, or soil water flow in the hydrological literature. It was first recognized by Engler (1919) and first quantitatively studied by Hursh and Brater (1941). As an important component of subsurface
Flow, subsurface stormflow most describes runoff generation processes that discharges into the transient, near-channel wetlands that develop during the storm period and reaches the channel without entering the groundwater zone (Whipkey 1965; Genereux and Hooper 1998). Subsurface stormflow is considered to be a dominant runoff-producing mechanism in many upland environments, which determines the hydrological responses of headwater catchments to rainstorms. Subsurface stormflow has a slower drainage capacity than overland flow but a faster one than groundwater flow. It’s mainly responsible for quickly responding of streamflow during a precipitation or snowmelt event. It can lead to unexpected fast drainage of soils and transmits water to contribute to storm flow, thus delaying or even preventing the saturation of the soil and generation of saturation overland flow and determining the hydrological responses of headwater catchments to rainstorms (Weiler et al. 2005; Tromp-van Meerveld and McDonnell 2006a, b; Kienzler 2007). The essential conditions for the generation of subsurface stormflow include steep slopes and highly permeable surface soils underlain by an impermeable or semipermeable layer (Turton and Miller 1992). It often moves laterally in a downslope direction through the water-impeding layer or soil–bedrock interface. Subsurface stormflow mainly occurs in humid catchments, where the terrain is steep, the surface soil is permeable, and an impermeable soil layer or soil–bedrock interface exists near the surface (Whipkey 1965; Sloan and Moore 1984; Turton and Miller 1992). In drier climate and gentler terrains, subsurface stormflow might occur only under extreme conditions, such as high-intensity rainfall or high antecedent soil moisture (Wilcox et al. 1997). It plays a crucial role in water cycle calculation, flood prediction, nutrient recycling, sediment transport, and soil–water–vegetation exchange processes (Weiler et al. 2005; Fox and Wilson 2010; McIntosh et al. 2017).

**Flow Regimes at Different Scales**

Subsurface stormflow describes all runoff generation processes close to the soil surface that result in a stream channel hydrograph response during a precipitation event. These processes in subsurface soil may be coupled directly to flow in preferential pathways like macropores and layers or areas with high permeability. The main flow regimes in subsurface soil may be subdivided into homogeneous matrix flow (uniform flow) and preferential flow (nonuniform flow) (Green and Ampt 1911; Weiler et al. 2005). Both types of flow often occur simultaneously but have considerably different consequences for water flow and chemical leaching.

Homogeneous matrix flow (uniform flow or piston flow) refers to flow with the same velocity magnitude and direction at every point; the velocity pattern within a cross section does not change. The movement of water and solutes through the soil is relatively slow and even, while all pore spaces are sampled, obeying the convective dispersion theory, which assumes that water follows an average flow path through soil (Atkinson 1978). It has a laminar hydraulic regime, conforms to Darcy’s law, and leads to stable wetting fronts that are parallel to the soil surface. Uniform flow
includes downslope and vertical components and might occur under both saturated and unsaturated conditions.

Preferential flow (nonuniform flow) mainly refers to the uneven and often rapid movement of water and solutes through porous media, typically soil, characterized by regions of enhanced flux such that a small fraction of media participates in most of the flow, allowing much faster transport of a range of contaminants including pesticides, nutrients, trace metals, and manurial pathogens. In few cases, preferential flow can also occur in highly uniform soils in the form of unstable “fingers,” especially in coarse, single-grained, and water-repellent soils (Jarvis et al. 2016). Preferential flow and transport occur in the unsaturated zone when the vertical velocities in a small fraction of the total pore volume are much faster than the rates of lateral equilibration of water pressures and/or solute concentrations with the surrounding water-filled pores and lead to irregular wetting fronts (Beven and Germann 1982). It reflects the transport mechanism of soil water moving from homogeneous to heterogeneous; it has been acknowledged as a significant process contributing to stormflow generation in headwater catchments. Preferential flow in the vadose zone occurs on different spatial and temporal scales under a wide variety of conditions and includes several types. Each of these types of preferential flow is caused by different physical mechanisms. It comprises all phenomena, where water and solutes move along certain pathways while bypassing a fraction of the porous matrix. This physical non-equilibrium phenomenon can occur on three different scales: pore scale, Darcian scale (Fig. 2), and areal scale (Fig. 3).

On the pore scale, we can observe several types of macropore flow. Macropore flow is used to indicate preferential flow in continuous root channels, earthworm burrows, fissures, cracks, or irregular interaggregate voids created by tillage implements. Water bypasses the denser and less permeable soil matrix by using the pathway of least resistance through macropores, leading to a non-equilibrium with the soil matrix. The flow paths vary in type from individual pores to a highly connected pore network (Gerke 2006). It occurs predominantly in fine-textured soils or media with a pronounced structure. According to different formation reasons, we can divide macropore flow into crack flow and burrow flow. Crack flow refers to preferential flow along continuous cracks through an unsaturated soil profile. Cracking occurs during drying of certain duration in soils with significant clay content. Burrow flow refers to flow through channels created by soil fauna when runoff occurs (Zehe and Fluhler 2001; Allaire et al. 2009). Crack flow and burrow flow together form macropore flow.

On the Darcian scale, preferential flow can be divided into funnel flow, finger flow, and unstable flow due to the spatial variability of hydraulic properties, local surface depressions, local depressions in soil layers, water repellency, and presence of large stones. Each of these types of preferential flow is caused by different physical mechanisms (Hendrickx and Markus 2001). Funnel flow refers to a phenomenon that flow caused by redirection of water at soil textural boundaries. Funnel flow soils are usually characterized by their squat hopper geometry. It is a special case of preferential flow at the Darcian scale. It occurs when water again moves along the pathway of least resistance and can be redirected through a series of less
permeable layers embedded in the soil profile. If the underlying region is coarser, finger flow might also occur. Finger flow occurs when infiltrating water accumulates at the interface between two soil layers, usually in sandy soils, with a coarser layer underlying a finer layer, single-grained soils, or water-repellent soils (Starr et al. 1978). The water enters the subjacent layer through fingers (preferential flow paths) rather than uniformly through the entire layer (Rezanezhad et al. 2006). Finger flow might sometimes occur under the following conditions: infiltration of ponded water with compression of air ahead of the wetting front, water-repellent soils, and continuous nonponding infiltration. Unstable flow refers to unstable wetting fronts that start out as horizontal wetting fronts and, under certain conditions, break into fingers or preferential flow paths as the front moves downward, similar to rain running off a sheet of glass and breaking into streams. The occurrence of preferential
flow has always been reported in conjunction with pronounced soil structures such as earthworm burrows, root channels, or fractures. Recent numerical analyses, however, have shown that preferential flow can also occur in macroscopically homogeneous soils with spatially variable hydraulic properties but no pronounced macropore structure (Kung 1990; Hendrickx and Markus 2001).

On the areal scale, pipe flow is the main type of preferential flow. Funnel flow can also occur on the areal scale (Fig. 3). Pipe flow is a type of liquid flow within a closed conduit. Pipe flow might occur due to topographic depressions, calcic pipes, or karstic depressions.

The concept of preferential flow is now a hot theme in hillslope hydrology. In recent years, the hydrologic community has come to a consensus that subsurface flow is generally dominated by preferential flow of various types (Jones 2010; Lin 2010). It is a fundamentally important soil hydrologic process that controls a variety of soil physical, chemical, and biological functions.

**Controlling Factors of Subsurface Stormflow**

Subsurface stormflow is considered to be ubiquitous, especially in steep and humid catchments. However, the transport process of subsurface stormflow is very complex due to the spatial heterogeneity of the catchment and the spatial–temporal variability of precipitation distribution. Even in small catchments or hillslopes, the formation and transport of subsurface stormflow are often different because of the heterogeneity of the soil, vegetation, and topography. Many studies suggested that the occurrence and intensity of subsurface stormflow are mainly affected by a number of factors such as rainfall characteristics (amount, intensity, and duration of rainfall), soil characteristics (soil texture, soil thickness, soil structure, antecedent soil moisture, and fissures created by swell-shrink or freeze-thaw), biological characteristics (vegetation cover, plant root, animal burrow, and land use patterns), topography (slope, surface, and subsurface topography), and land use patterns.

**Rainfall Characteristics**

Rainfall characteristics (amount, intensity, and duration of rainfall) constitute a dominant control of the runoff response. Furthermore, the temporal distribution of input and patterns of evapotranspiration strongly influence the soil moisture, which represents a key factor driving hydrological processes (Jost et al. 2005; McNamara et al. 2005). Many rapid hydrological processes, such as runoff and preferential flow, are not continuous but are triggered by thresholds. The occurrence of subsurface stormflow is linked to the timing, intensity, and magnitude of rainfall events (Beven and Germann 1982). The temporal dynamics of preferential flow triggering due to between-storm and within-storm rainfall variability has been previously explored via numerical simulation approaches using synthetic rainfall time series. Many studies documented that there is a positive but nonlinearity relationship between rainfall and subsurface stormflow. Fu (2012) studied characteristics of rainfall–runoff processes in a small coastal granite catchment in the Pearl River Basin in southern China; the
results showed that a large proportion of subsurface stormflow was observed only when the precipitation amount or intensity was sufficiently large, the primary direction of rainwater movement at plot scale was vertical, and rainwater was consumed primarily by evapotranspiration and infiltration into the bedrock. Tromp-van Meerveld and McDonnell (2006a) analyzed subsurface stormflow in response to 147 rainstorms at a trenched hillslope in the Panola Mountain Research Watershed between February 1996 and May 1998. They found a clear threshold response of subsurface stormflow to total storm precipitation. For storms smaller than the precipitation threshold of 55 mm, little subsurface stormflow was observed. For events exceeding the threshold, the subsurface stormflow increased by almost two orders of magnitude compared with subsurface stormflow from storms smaller than the threshold.

Furthermore, an increase in the rainfall intensity enhances macropore flow because the soil water pressure is closer to saturation during rainfall and larger macropores conduct water. Flow in a macropore of any given size is triggered only when the pressure potential exceeds its water-entry pressure. Therefore, in addition to the rain intensity, the initial soil moisture, duration of rainfall, and saturated hydraulic conductivity of the matrix determine when macropore flow occurs. Anderson (2009) found that the subsurface stormflow velocity was most closely related to the 1-hour rainfall intensity. However, some studies showed that there is little correlation between rainfall intensity and subsurface stormflow rates (Kienzler and Naef 2008). It seems that the effect of the rainfall intensity is strongly connected to other factors and can be both highly relevant and subordinate when buffered by other controls.

**Soil Characteristics**

The physical properties and depth of the soil are very important controls of subsurface stormflow. The soil texture can affect the subsurface stormflow direction of the soil, while the thickness of the soil layer can affect the difficulty of subsurface stormflow generation. In sandy and coarse-textured soils (with predominant sand and stones), vertical flow usually dominates. In clays and fine-textured soils, there is resistance to vertical flow, and sometimes lateral or shallow subsurface stormflow occurs quickly. If the soil layer is thick, subsurface stormflow generation needs more precipitation to infiltrate the soil, and the response might be delayed. If the soil layer is thin, it’s easy for soil water to accumulate on the impermeable layer and generate subsurface stormflow.

The soil architecture is also an extremely important influencing factor of subsurface stormflow. Heterogeneous soil structure leads to complex interactions among different hydrologic processes, soil moisture dynamics, and subsurface flow and solute transport (Li et al. 2018). Fissures, cracks, or channels less likely occur, nor are important, in coarse-textured soil. In fine-textured or layered soils, fissures, cracks, or channels are more likely to occur, providing possible routes for flow and largely replacing textural voids as the main paths for unsaturated and saturated flow. Noguchi (1999) found that individual macropores that make up preferential flow are typically short but can be connected through various mechanisms over
relatively long hillslope distances. Vervoort (1999) reported that preferential flow in soil profiles is related to soil structural differences (e.g., macropore flow and fractional flow) or textural differences (e.g., fingering flow and funnel flow).

The soil moisture plays an important role in the initiation and connectivity of subsurface stormflow. Many researches show that hillslope discharge was distinctly threshold-like with a nonlinear response to the soil moisture (Detty and McGuire 2010; McGuire and McDonnell 2010). Penna (2011) studied the role of soil moisture on the threshold runoff response in a small headwater catchment, and the result showed that with further increasing wetness, a moisture threshold was exceeded, resulting in a marked increase of streamflow and likely the triggering of transient subsurface stormflow on the hillslopes as suggested by the abrupt increase in runoff coefficients above the 45% soil moisture threshold and the much larger increase in runoff depth with increasing precipitation. A connection was likely established between the riparian area and hillslopes, which became hydrologically active zones. Newman (1998) found that when soils were at or near saturation (> 33% volumetric water content), a very large volume of subsurface stormflow is produced. Grayson (1997) studied the effect of the temporal variation of soil moisture on the spatial patterns of soil moisture. In their study, two spatial patterns of soil moisture were proposed. One is the lateral flow-dominated spatial pattern, and the other is the vertical flow-dominated spatial pattern. They found that the transition between two patterns likely occurs in the range of relative soil saturation of 0.6–0.8. McNamara (2005) found that the soil moisture status is related to the hillslope hydraulic connectivity: low rates of water input to the soil during winter allow dry-soil regions to persist at the soil-bedrock interface, which act as barriers to lateral flow. Once the dry-soil flow barriers are wetted, the whole-slope hydraulic connectivity is established; subsequently, lateral flow occurs, and upland soils are in direct connection with the near-stream soil moisture. Recent study showed that field capacity can be indirectly determined to indicate the potential of subsurface stormflow and quickly response to streamflow. When soil water content was above the thresholds, soil-free water content (the soil water content beyond the field capacity) started to increase. This indicated that the subsurface stormflow started to occur (Lai et al. 2018).

Furthermore, soil cracks; fissures created by seasonal drying/wetting, swelling/shrinking, and freezing/thawing; and irregular interaggregate voids form macropores in the soil due to the rainfall intensity and rates of evapotranspiration and determine the moisture budget of the soil and hillslope and affect the transport of subsurface stormflow paths and flow regimes.

**Biological Characteristics**

Biological characteristics belong to the most important factors in the process of soil formation and mainly include plant roots and macrofauna, which have an important effect on the soil structure, formation of macropores, and subsurface stormflow.

The structure is central to soil functioning because it controls water, gas, and nutrient fluxes and storage and therefore influences the activity and growth of living organisms. In return, plants, fauna, and microbes will affect the structure in complex
ways. Vegetation affects the soil structural form and stability on different scales through various direct and indirect mechanisms. At the pore scale, roots could change soil pores size and number and stabilize soil aggregates, which determine soil water storage capacity. On the Darcian scale, roots form macropores which enhance preferential flow transport. Roots of species form macropores, even in stagnic soil horizons that ameliorate poorly structured soils and enhance infiltration and drainage and ultimately aeration. Due to the enhanced infiltration of the soil, roots form macropores, which favor preferential flow transport. On the areal scale, roots could change soil structure and porosity, which affect subsurface stormflow volume and pathway. The anchorage of roots and exudation of cementing material stabilize the soil structure. Finally, as a source of C, roots and plant residues provide a food source to the microflora and fauna, which contribute to structure formation and stabilization. In return, plant-induced changes of the structure will affect plant growth, mostly by modifying the root physical environment and water and nutrient cycles (Angers and Caron 1998). Mitchell (1995) conducted an experiment to study the effect of root systems on preferential flow in swelling soil under two cropping systems. The two crops were alfalfa \textit{(Medicago sativa, L.)} and wheat \textit{(Triticum turgidum, L.)}, respectively, which provided sharply contrasting root systems; wheat possesses fine fibrous roots, while alfalfa has a taproot system. The result showed that decaying roots of alfalfa produce stable macropores, while wheat roots and earthworm \textit{(Lumbricus terrestris)} channels do not produce such stable macropores.

**Surface and Subsurface Topography Characteristics**

McGuire et al. (2005) examined surface topographic controls on residence time for seven catchments (0.085–62.4 km²) that represent diverse geologic and geomorphic conditions in the western Cascade Mountains of Oregon. The results illustrate that, compared with the area, surface topography, internal form, and structure of the basin define the first-order control on subsurface stormflow residence time. Many studies in the past assumed that hillslope flow is controlled by surface topography. However, Freer (1997) found that the flow path directions were dominant by subsurface topography. They analyze the distribution of topographic index patterns through digital terrain analysis for both surface and subsurface topography and monitor subsurface stormflow by artificial trench. The result showed that the subsurface topography (bedrock topography) is distinctly different from surficial topography and the subsurface topography (bedrock topography) has a considerable influence on local hydrological gradients and therefore the dominant flow path directions. Buttle and McDonald (2002) found that a saturated layer with thin soil may quickly develop above the lithic bedrock on forested slopes on the Canadian Shield. Haga (2005) demonstrated that saturated subsurface stormflow above the soil–bedrock interface is dominant subsurface runoff in a small catchment in the Mizugaki Research Watershed. Tromp-van Meerveld and McDonnell (2006a) proposed the fill and spill hypothesis to explain the effect of the bedrock topography on the hillslope-scale connectivity of saturated subsurface areas. These findings indicate subsurface topography of the impeding layers may play a more important role than
surface topography on storm water partitioning and redistribution in moderately sloping catchments (Du et al. 2016).

In addition, the position of the measurement site on a hillslope is also a major factor determining the amount of subsurface stormflow observed. The distance from the divide is related to the amount of flow accumulated from the upslope, and the slope gradient helps to determine the rate of flow. Both the slope-profile convexity or concavity and the convergence or divergence of flow lines in plan also influence the flow rates. These topographic factors interact with the soil factors already discussed; the two sets are related via the soil catena concept and produce complex areal patterns of subsurface and overland flow.

**Land Use Pattern Characteristics**

Land use can change the infiltration and soil hydraulic conductivity by altering soil surface conditions and modifying the soil structure; it affects the total macroporosity, size distribution of large pores, and also their continuity (Jarvis 2007). Different land use systems and management practices affect not only the types and abundance of macropores but also the potential for subsurface stormflow. For example, the long-term use of organic amendments in arable farming produces organic-rich topsoils that can become water repellent under dry conditions and therefore are prone to fingering (Vanderborght et al. 2001). Undisturbed soils have a much higher infiltration capacity than soils in agricultural land. Heavy machinery used in agriculture exacerbates soil compaction, particularly at depth, via the development of plow pans. These compacted, dense layers have a significantly higher bulk density and lower total soil porosity than the soil directly above or below and frequently become preferential zones of runoff generation (Burt and Slattery 2005).

**Monitoring of Subsurface Stormflow**

Subsurface stormflow has been observed to substantially contribute to hillslope and catchment runoff. However, the direct observation of the occurrence and distribution of subsurface lateral flow on hillslopes has been difficult because of the complexity of nonuniform flow and the lack of appropriate means to directly observe flow pathways and their dynamic changes. Trenching, tracer, and geophysical techniques are three primary methods for the characterization and detection of subsurface stormflow networks that have been reported in the literature.

**Trenching**

In early subsurface stormflow research, physically based direct field observations, such as trenches (or pits), combined with hydrometric data were used extensively for hillslope investigations and subsurface stormflow measurements. Trenching is a method used to investigate lateral subsurface stormflow processes, where soil is excavated from the surface to a certain depth or to bedrock; the lateral flow is monitored in a cross section of the hillslope (Whipkey 1965). This conventional method is used extensively in hillslope investigations and is the only direct means of
measuring subsurface stormflow. It is one of the most representative methods and might be the most intuitive and accurate method to study hillslope runoff processes. Many other methods need to be verified with trenching measurements. To understand the rainfall–runoff transformation, much advancement has been made through the use of trenches on experimental hillslopes (Freer et al. 2002). Trench studies can be used to identify subsurface stormflow sources, groundwater–stream water relations, and the role of macropores and preferential flow in subsurface stormflow generation (Tromp-van Meerveld and McDonnell 2006b). Trench studies have also demonstrated that a variety of subsurface stormflow pathways are involved and important in controlling and transporting hillslope contributions to streams. Graham (2010) used an instrumented (trenched) 0.5 ha hillslope in the southern tier of New York State, USA, to provide new insights on how variable source areas and associated flow pathways form and combine to connect rainfall with downstream water flow across a hillslope. The results showed that near-surface runoff in the upper 10 cm of the soil profile significantly contributes to the event and pre-event water (37%–62%) during storm events with wet antecedent conditions and large rainfall amounts. However, deeper subsurface water from below the fragipan layer significantly contributes (33–71%) to the total discharge from the hillslope during events with dry antecedent conditions. Thus, increasing subsurface saturation decreases the vertical percolation of water through the fragipan and the depth to the lateral subsurface stormflow occurrence; lateral flow increasingly occurs atop instead of below the fragipan layer.

Tracer Methods

In the past few decades, tracers have provided the best new insights into the age, origin, and pathway of subsurface stormflow transport. They have been widely applied in hydrological studies because of their ability to provide more detail about some of the underlying processes that control the chemical and physical behavior of elements and compounds in the natural environment. The ability to study widespread effects has generally made naturally occurring tracers more useful and more environmentally accepted than artificially introduced tracers and also more applicable to a broader range of geochemical problems (Gibson et al. 2005).

Tracer methods mainly include isotope, geochemical, and dye tracers. Isotopic tracing techniques are of particular interest in hydrological studies. They were introduced into catchment hydrology research in the 1960s as tools complementary to conventional hydrologic methods to address questions with respect to where water goes when it rains, what pathways it takes to the stream, and how long the water resides in the catchment (McDonnell 2003). Stable isotope tracers mainly refer to oxygen-18 ($^{18}$O) and deuterium ($^{2}$H or D). Hydrogen/oxygen isotopes and mixing models are often used to separate stormflow into its event and pre-event components as time source components to determine the temporal origin of subsurface stormflow. The identification of these runoff components is achieved through the use of stable isotopes; thus, these models are also referred to as isotope hydrograph separations (Inamdar 2011). Pre-event water is the main source producing the stream hydrograph peak instead of Hortonian overland flow that was first truly proven through isotope
hydrograph separations. Compared with isotope tracers, geochemical tracers are utilized for hydrograph separations from geographic sources. These mixing models can be referred to as geochemical hydrograph separations (Genereux and Hooper 1998). In the 1990s, Christophersen and Hooper (1992) introduced a multivariate statistical analysis method and dramatically increased the interest in using geochemical tracers to identify subsurface stormflow sources. They used a suite of tracers (e.g., cations, anions, and silica) for mixing models, which is referred to as end-member mixing analysis (EMMA). Subsequently, chemical tracers and non-conservative isotope tracers became an effective tool for the identification of subsurface stormflow paths and resident times because of their “active” characteristics and composition changes due to the reaction between water and soil. The use of geochemical and isotopic tracers has proven to be a valuable aid in field research integrating process understanding on larger spatial scales (Buttle 1994). Moreover, tracer data, when combined with simple hydrological flow models, provide a means of estimating subsurface stormflow sources, pathways, and residence times (McGuire et al. 2002; Weiler and Naef 2003; McDonnell 2003).

Dyes are important tracers for the investigation of subsurface stormflow movement. Dye tracers have provided clues about the hydrological cycle and subsurface stormflow and transport processes. They are important tools to assess the flow pathways of such contaminants with respect to groundwater contamination often originating in the vadose zone. Dye tracers, followed by destructive sampling, have long been used by hydrologists and soil scientists to identify vertical subsurface stormflow paths and flow networks on the pedon scale. However, this method also has great limitations. The experimental procedure is complicated. It is often difficult to observe clear staining traces in the soil after long-distance transport of the dye solution when applying dye tracers to large-scale water transport studies. Therefore, it is necessary to find a better stain to trace the soil flow.

**Geophysical Methods**

Traditional methods have largely been destructive or based on the interpolation between point-based measurements (Sidle et al. 2001; Freera et al. 2004). As a result, transient phenomena or the spatially varying occurrence of subsurface preferential flow could not be easily and precisely determined. In recent years, with the increasing use of nondestructive microscopic imaging techniques in the laboratory (such as X-ray computed tomography, CT; and nuclear magnetic resonance, NMR), widespread use of noninvasive geophysical and remote sensing methods (such as ground-penetrating radar, GPR; electromagnetic induction, EMI; and electrical resistivity tomography, ERT), and growing arrays of sensor networks for in situ real-time monitoring (such as soil moisture and temperature monitoring networks), new opportunities emerged to better document and understand the preferential flow occurrence and its networks. Only based on such technological breakthroughs, we can determine detailed network-like flow and transport dynamics for new types of hydrologic models (Lin 2010).

On the pore and core scales, CT has been widely used to directly characterize the quantity, morphology, and continuity of macropores and related vertical preferential
flow networks (Luo et al. 2008). Three-dimensional visualization and quantification of soil macropores have been performed by synthesizing a series of two-dimensional CT images (Pierret et al. 2002). Sequential scans with and without a tracer allow the determination of active flow networks. Pierret (1999) applied medical CT to isolate the macropore domains from the soil matrix and monitored the solute transport within an intact soil column. Luo (2008) showed that connected macropore networks could extend throughout soil columns with a diameter of 10 cm and length of 30 cm. However, the CT methods are limited to laboratory studies using intact soil cores or columns.

On the Darcian to areal scales, geophysical methods, such as GPR (Holden 2004), EMI (Zhu et al. 2010), and ERT (Ward et al. 2010), have been used to observe subsurface stormflow networks in situ. The GPR refers to a range of electromagnetic techniques designed primarily for the location of objects or interfaces buried beneath the Earth’s surface or located within a visually opaque structure (Daniels 1996). Electromagnetic waves are transmitted to detect changes of physical properties within the shallow subsurface; GPR has become a popular geophysical tool for the detection of subsurface features (Poisson et al. 2009). It can be applied either directly or indirectly to map lateral preferential flow in situ. Direct GPR is an effective method to monitor real-time subsurface stormflow dynamics. Indirect GPR can be used to identify subsurface cavities (such as soil pipes and macropores). Lateral preferential flow pathways can be inferred from the hydrological connectivity of lateral subsurface pipes or macropores (Guo et al. 2014). Overmeeren (1997) tested GPR against capacitance probes and showed that this technology accurately measures the volumetric subsurface water content without excavation or other disturbances. Yoder (2001) used both EMI and GPR to identify locations in an agricultural field, where soil and bedrock features were conducive to promoting lateral preferential flow, although measurements of actual water fluxes or stores were not carried out. Gormally (2011) used GPR technology to detect and map the three-dimensional structure of subsurface lateral macropore networks at a Mid-Atlantic riparian wetland field study site. The results showed that the temporal and spatial variations of the stream discharge and nitrate flux are due to preferential flow mechanisms. Depth-weighted soil electrical conductivity (EC) measurements obtained using various EMI meters have been widely used to map different soil and hydrologic properties (James et al. 2003; Sherlock and McDonnell 2003; Robinson et al. 2009). Zhu (2010) demonstrated that repeated EMI surveys are useful in capturing the dynamics of soil moisture change and related subsurface stormflow paths in the landscape. The results indicated a significantly higher EC in areas close to subsurface stormflow paths on an agricultural hillslope, especially during wetter periods. Ward (2010) used ERT in a combined tracer and monitoring approach to identify subsurface stormflow paths in the hyporheic zone in a first-order stream meander in the Leading Ridge Watershed in central Pennsylvania. They applied a salt tracer to stream water and used ERT to monitor fluxes through an abandoned stream bend. The above-cited studies show the potential of geophysical techniques in probing the subsurface and parameterizing subsurface stormflow networks. Further work is needed to both
identify new geophysical methods and determine how spatial and temporal resolution limitations of EMI and GPR can be surmounted to pinpoint subsurface stormflow networks.

Great achievements have been made in hydrology due to the application of tracer and geophysical techniques. However, each method has advantages and disadvantages. It is necessary to clearly research objectives and design experiments together with the advantages and disadvantages of various methods. In general, trenching is the only direct means of measuring subsurface stormflow. Many other methods need to be verified with trenching measurements. However, trenching has the disadvantage of (1) destroying the soil architecture, interrupting the hydrograph, distorting the net of the hydraulic potential on the slope, and altering the water flux and (2) only collecting saturated subsurface stormflow. Tracer-based approaches have the advantage of providing more process-based information about temporal and geographic sources of runoff which do not disturb the hydrologic system (Weiler and Naef 2003). But affected by different instruments and operating methods, there is a high variability in test results. Recently, geophysical technology has been widely used for its nondestructive and easy-to-measure features. Geophysical technology also can measure 2D or 3D network of soil architecture or subsurface stormflow. However, the technology still has the following disadvantages: first, it requires special expertise and interpretation often difficult, and, second, instruments are usually very expensive. Finally, instrument parameters and results need to destructive sampling test (Allaire et al. 2009).

Model Simulation

Models are convenient and useful tools in subsurface stormflow quantitative simulation and hypothesis formulation (Weill et al. 2011). Subsurface stormflow models mainly include the following types: Darcy–Richards model, two-domain model, dual-porosity model, kinematic wave model, two-phase model, stochastic model, and numerical model.

The Darcy–Richards model is based on the continuum principle of soil water movement (also called equilibrium principle) and Darcy’s law. The Darcy–Richards model studies the subsurface stormflow from a microscopic point of view and cannot directly determine the flow discharge in the soil profile at the outlet section of the slope. Based on the degree of simplification of the Richards equation in the solution process, it can be divided into one-dimensional, two-dimensional, and three-dimensional models. The Darcy–Richards model has a high precision; however, it is difficult to predict and forecast the flood of rainstorms due to the complexity of the solution process (Sloan and Moore 1984).

The two-domain model assumes that the soil consists of two domains, one representing the soil matrix and the other one representing the macropores in the soil. Depending on the different transports of water and solutes in the two domains and the exchange of water and solutes between the two domains, the two-domain model can be divided into the following types: dual-porosity model, kinematic wave
model, and boundary layer flow theory. The dual-porosity model considers the macropore domain and matrix domain as pore systems, each of which is considered to be a homogeneous medium with the properties of individual flow and solute transport. It assumes that both water flow and solute transport can be described by two equations, which are coupled using a term characterizing the exchange of fluid or solutes between the two pore regions. The system consists of two flow velocities, two pressure heads, and two water contents and solute concentrations (Gerke and Genuchten 1993). The kinematic wave theory was first discussed by Lighthill and Whitham and has been widely applied to a variety of hydrological processes such as overland flow, channel flow, base flow, unsaturated flow, macropore flow, furrow flow, and preferential flow. It is a simplified description of complex flow processes, mathematically expressed by the law of conservation of mass through the continuity equation and a flux–concentration relationship. The theory includes the theory of continuous wave formation, theory of shock wave formation, and theory of continuous wave formation from shock waves (Singh 2001).

The two-phase model was first discussed by Hosang (1993). The model divides the generation of preferential flow into two stages. The first phase represents times of redistribution and low infiltration, which does not generate preferential flow. Times of heavy infiltration, inducing preferential flow, are handled by the second phase. The Richards equation is applied to both phases as the governing flow equation, and preferential flow is allowed by increasing the hydraulic conductivity of the soil during the second phase. The two-phase model is simple and easy to understand.

The stochastic model uses the stochastic mathematical method to describe the transport of preferential flow. Because macropores are randomly distributed in the soil, the stochastic model can be used to better describe the transport of water and solutes in the soils with macropores. In the numerical model, the flow paths through which the water and solutes flow are essentially in vertical direction, with gravity being the main driving force. The various flow paths are considered to be connected to each other or grouped together. The pore size groupings are established by introducing a piecewise linear conductivity function. It consists of a number of lines tangent to the conductivity function in the “Darcy flow region,” with the slope of each consecutive tangent line always being an integer multiple of the preceding line. Macropores are simulated by adding one or more pore groupings above the region, where Darcy’s Law is valid (Steenhuis et al. 1990).

**Connecting Subsurface Stormflow with Ecohydrology Processes**

There is an increasing recognition of connecting aboveground ecohydrology and belowground subsurface stormflow in recent years (Li et al. 2009). The ecosystem structure influences the spatial and temporal dynamics of water flowing across the terrain surface and subsurface. Hydrology influences the rates of transport, deposition, and recycling of inorganic materials, which, in turn, influence the spatial and temporal dynamics of ecosystem processes. Thus, detailed studies of subsurface
stormflow can help us to better understand ecohydrological processes (Pcovich 2005).

The discharge, infiltration, and residence times of subsurface stormflow are all influenced by the ecosystem. Aboveground vegetation and surface flow networks appear to have a close connection to belowground root and subsurface stormflow networks. Vegetation can be considered as a key link connecting aboveground and belowground. The actual pathways from rainfall to streamflow usually involve a combination of surface and subsurface stormflow, and many of them are related to biological factors including the canopy, stem, and root. Aboveground, vegetation canopies can redistribute incident precipitation and affect the vertical and horizontal spatial distribution of water within the plant community by interception, stemflow, and throughfall. Belowground, plant root systems create networks of subsurface stormflow and thus can alter subsurface stormflow and nutrient transport paths in the vadose zone. Subsurface stormflow can occur in channels formed by dead or decaying roots, channels formed by decayed roots that are newly occupied by living roots, and channels formed around live roots (Ghestem et al. 2011). The subsurface stormflow volume, flow paths, and residence times can affect the sediment transport, nutrient cycling, and biological productivity and ecosystem dynamics. Li (2009) confirmed that root channels are the preferred pathways for most stemflow water moved into the soil and stemflow is conducive to concentrate and store water in the deeper layers of the soil profiles, creating favorable soil water conditions for plants to survive droughts under arid conditions.

Recently, a study on global warming, plant growth seasons, and terrestrial carbon sinks has highlighted the importance of the terrain and deeper subsurface geophysical structure in controlling plant water availability (Hu et al. 2010). Hu (2010) used observations of stable hydrogen isotopes (δD) of snow, rain, and extracted xylem water from three dominant tree species. The results showed that the trees relied heavily on snowmelt, even late into the growing season. By coupling the model, they found that the annual forest carbon uptake highly depends on snow water; the annual gross primary productivity was estimated to be 67%, 77%, and 71%, respectively, depending on snowmelt. Their isotope results suggest that rain events typically hydrate only the upper soils and rarely reach depths between 30 and 35 cm; however, all three dominant tree species access water deeper than 35 cm. They suggested that the lower reliance on summer rain could be attributed to two reasons: (1) the trees were tapping into a deeper and more consistent water source during the growing season; and (2) the rain events were too small to penetrate deeply into the soils. They then suggested that global warming induces longer growing seasons, which could lead to less carbon sequestration in a subalpine forest because of less available snowmelt resources. Precipitation patterns and temperatures have been affected by global climate change. Changes in climate factors, such as precipitation patterns and temperature, will in turn affect the runoff patterns (surface and subsurface flow), the plant water use sources, and the dynamics of vegetation. This provides new insights into the mutual feedback mechanism of the subsurface stormflow and ecohydrological processes.
Some studies suggested that the patterns in crop development are often directly related to lateral and vertical changes in soil texture, causing changes of the available water and resource supply for plant growth. Hence, better detection, delineation, and quantification of the subsurface variability are needed (Rudolph et al. 2015). Rudolph (2015) used multi-receiver EMI data and large-scale multi-temporal and multispectral satellite imagery in conjunction with selected ERT transects and conventional soil sampling to investigate the lateral and vertical changes of soil properties that influence the spatial and temporal variability of crop performance in arable fields [satellite-derived leaf area index (LAI) patterns]. For the first time, the LAI patterns with better crop performance in large-scale multi-temporal satellite imagery were interpreted by proximal soil sensor data; a higher water storage capacity and increased correlations between the large-offset EC data and subsoil clay content and soil profile depth imply that the subsoil is mainly responsible for better crop development in drought periods along the buried paleo-river structure; and stagnant water in the subsoil indicates that this paleo-river structure still plays an important role in subsurface hydrology.

**Future Research Directions**

Subsurface flow research aims to address questions about the flow source, pathways, resident times, dominant control factors, and deciphering runoff mechanisms across diverse hillslopes and catchments. Current research and challenge of subsurface flow are mainly focus on (1) subsurface flow (preferential flow) initiation condition, (2) observation methods for the detection and quantification of preferential flow, (3) first-order control of flow generation, (4) thresholds and nonlinearity of the subsurface flow process, (5) transit time distribution and pathway, and (6) interactions among hydraulic conductivity distributions, subsurface topography, soil architecture, and subsurface flow transport processes.

Up until recently, it has been difficult to derive general hydrologic principles from single research studies within intensively studied small basins. Future research of subsurface flow will need to focus on the following aspects: first, we need to continue process-based field experimental observations to better understand subsurface flow transport processes; second, we need to combine tracers, geophysical or other new techniques (such as GPR, CT, or laser spectrometer technologies), to obtain high-precision and systematic field datasets in time and space, especially from different types of catchments and environments, to better characterize the soil architecture and hydrological process; third, we need to extract commonalities from multiple different well-instrumented sites to define the first-order controls of subsurface stormflow generation, flow paths, and residence time; and fourth, we need more stringent tests of models; assess the uncertainty of the model; capture the mechanisms of subsurface stormflow transport processes, transport paths, resident times, key thresholds, hysteresis, and other nonlinearity behaviors through high-precision and systematic field datasets to test old hypotheses; formulate new
hydrologic theories; and provide feedback for catchment water resource management and prediction.

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