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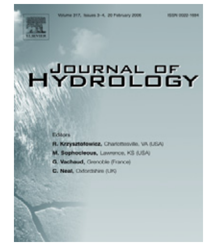

Hydrological connectivity of upland-riparian zones in agricultural catchments: Implications for runoff generation and nitrate transport

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Summary This paper addresses the issue of *hydrological connectivity* between discrete units of the landscape, notably, upland and riparian zones, and its implication for runoff generation and chemical transport. It presents results based on a field experiment carried in Susannah Brook catchment in Western Australia, during which measurements of relevant physical and chemical parameters were carried out using a sampling strategy that enabled us to capture the complete cycle of hydrological connection and disconnection over the entire hillslope. The results show that the upland and riparian zones respond to rainfall events almost independently and differently, and remain disconnected from each other for much of the year. During a 2–3 month period in mid-winter, however, a shallow groundwater system becomes established all the way across the hillslope, providing a direct hydrological connection between the two zones, enabling not only down-slope transport of fresh water but also nitrates that had previously accumulated in the upland zone. Associated with the establishment of connectivity is a sharp increase in the hydraulic gradient that drives shallow subsurface flow to the stream. These results have important implications for the modelling of runoff generation and nutrient export. The lack of connectivity for much of the year precludes the use of models that assume that the shallow subsurface flow system is connected all the way up the slope, and that hydraulic gradient is equal to local topographic gradient. The findings relating to hydrological

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connectivity also have important ramifications for Cl^- and NO_3^- transport and export. The complex internal dynamics of flow, transport and reaction, and their dependence on hydraulic connectivity, must be explicitly captured if we are to develop predictive models that remain accurate as well as internally consistent.

Introduction

New advances in hillslope and catchment hydrology have been made recently by considering explicitly the *hydrological connectivity* of discrete units of the landscape. The hydrological connection, via the subsurface flow system, between the riparian (near-stream) zone and the upland zone (also known as hillslope) occurs when the water table at the upland-riparian zone interface is above the confining layer (Vidon and Hill, 2004). Hydrological connectivity has become the focus of research in small, forested catchments with the acknowledgement of the importance of the partitioning of the landscape into these two contrasting units, on catchment hydrological and hydrochemical responses. Non-linear responses and threshold behaviour in catchment-scale runoff production (Devito et al., 1996; Buttle et al., 2004), various mechanisms of rapid delivery of pre-event water (McGlynn et al., 2002; McGlynn and McDonnell, 2003a), dissolved carbon dynamics (McGlynn and McDonnell, 2003b) and nutrient transport (Stieglitz et al., 2003), constitute a few examples of this phenomenon. These previous studies have also highlighted the important role played by the development of a shallow saturated local subsurface flow system (SSLFS) in contributing to this hydrological connectivity. Thus the need for improved understanding of how SSLSF develops and evolves in time and space constitutes a challenging problem in hillslope and catchment hydrology.

Shallow groundwater flow (ephemeral or continuous) can occur in transient local flow regimes particularly in small headwater forested and agricultural catchments. Its development depends upon the rainfall and/or snowmelt regime, unsaturated zone thickness, permeability, and the presence of an impeding layer (bedrock or clay). It has been documented that catchments with local groundwater flow systems show contrasting seasonal patterns of water table fluctuations and spatial connection. Many studies have found that the depth of permeable soils in the unsaturated zone constitutes a first order control that determines the ephemeral or continuous nature of shallow subsurface flow systems. Devito et al. (1996) were the first to emphasize the occurrence of both ephemeral and continuous upland-wetland connections in headwater, forested wetlands in the Canadian Shield. Using hydrometric data they identified that till depth of more than 1 m exerted an important control in determining the nature of the subsurface flow system that impacted in wetland water levels and surface hydrology. Following this study, Vidon and Hill (2004) presented a conceptual model of riparian zone hydrology for glacial till and outwash landscapes in Ontario (Canada) based on the upland permeable sediment depth and the topography of both riparian and upland zones. Soil depth and bedrock topography have also been identified as important controls in catchments with shallow soils. McGlynn et al. (2002) showed that bedrock depressions within the Maimai catchment in New Zealand can store significant volumes of old groundwater that can be delivered to the streamflow when they become hydrologically connected to the stream. Similarly, Buttle et al. (2004) found, in catchments within the Canadian Shield, that groundwater storage in depressions within riparian zones needed to be hydrologically connected in order to generate substantial runoff from slope positions, including, at catchment scale. Antecedent conditions also play an important role in determining when the hydrological connection occurs. While upland and riparian zones for ephemeral SSLFS in shallow soils can occur over the course of a few rainfall events (McGlynn and McDonnell, 2003a), longer time-periods may be required for continuous SSLFS to develop in deeper soils (e.g., till or laterite).

Historically, there has been a paucity of effort in monitoring these shallow subsurface systems in sufficient detail, which in some cases has led to many misconceptions about them. As a result, two important aspects of their dynamics in space (length scale) and time (time scale) have been under-estimated. First, in hillslopes studies, water levels have usually been measured over short length scales (from 5 to 50 m) and generally at valley bottom positions. These limited measurements have helped to perpetuate the idea that groundwater levels are parallel to the ground surface with little change in the hydraulic gradient to drive water down-slope (Buttle, 1989). This also constitutes one of the key assumptions in distributed topographically driven hydrological models such as TOPMODEL (Beven and Kirkby, 1979; Sivapalan et al., 1987). The second aspect relates to the time scales associated with its temporal dynamics. Shallow groundwater levels have been monitored using only coarse time intervals, generally daily, which could only record an apparently smooth response with little diurnal variation, and consequently no response over a short time scale such as a rainfall event. New insights into SSLFS dynamics in space and time have recently been presented. For example, using detailed shallow groundwater data (2–4 h time intervals) and at different positions within a hillslope, Seibert et al. (2003) found that the steady state assumption did not hold for the entire hillslope as there appeared to be different temporal trends in water level responses (i.e., moving in opposite directions) between the upland and riparian zones. Non-steady behaviour was observed in water levels at positions upslope located at more than 50 m from the streamline. Short-term dynamics in water tables levels (i.e., 15 min) in riparian zones have also provided insight of the important role of SSLFS in generating runoff during rainfall events (Burns et al., 2001).

Many Western Australian (WA) catchments with lateritic soils present both ephemeral and continuous SSLFS as characteristic features, which are the result of a deep highly