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Comment on "A deterministic–empirical model of the effect of the capillary-fringe on near-stream area runoff. 1. Description of the model" by Jayatilaka, C. J. and Gillham, R. W. (Journal of Hydrology Vol. 184 (1996) 299–315)

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1. Introduction

Ragan (1968) demonstrated the rapid development of near-stream groundwater mounds in response to precipitation inputs. Since then, numerous studies have invoked the capillary-fringe mechanism to explain the ratios of conservative solutes and isotopes in channel stormflow and the apparent large and rapid contribution of groundwater to stormflow production from drainage basins (Sklash and Farvolden, 1979; Pearce et al., 1986; Sklash et al., 1986; DeWalle et al., 1988; Bathurst and Cooley, 1996). The result has been that the role of the capillary-fringe in promoting increased gravity drainage of pre-event water (water stored in a basin prior to the rainfall or snowmelt event) to stream channels has become firmly entrenched in the recent hydrologic literature (Ward and Robinson, 1990; Dingman, 1994). The paper by Jayatilaka and Gillham (1996) is another in a series of articles to advocate the importance of the capillary-fringe in basin hydrology, and presents a new deterministic–empirical model of capillary-fringe effects on near-stream hydrological processes (HECNAR). Jayatilaka and Gillham suggest that HECNAR may apply in general to the near-stream zone of humid basins underlain by shallow water-tables. However, we feel that the processes encapsulated in HECNAR are restricted to sites with severely constrained pedologic, geologic, topographic, climatic and vegetative conditions (see below), and we challenge their main conclusion that "flow processes simulated by HECNAR are consistent with the generally accepted streamflow generating mechanisms" (p. 313). Our challenge is based on the following grounds.

2. Alternative mechanisms for pre-event water contributions to stormflow

A major paradigm shift in hydrological thought has been the increased recognition that pre-event water can make a significant contribution to basin stormflow across a wide range of climatic, geologic, vegetative and land use conditions (Buttle, 1994). Evidence for these contributions has come largely from hydrograph separations using isotopic and geochemical tracers. Several papers, beginning with Sklash and Farvolden (1979) have ascribed these large pre-event fluxes to the groundwater ridging process, and by extension to the hydrological role of the capillary-fringe. Infiltration on footslopes and in valley bottoms where the

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capillary-fringe is at or near the ground surface converts the tension-saturated zone to phreatic water, and produces a water-table rise that is disproportionate to the depth of infiltrating water (Gillham, 1984). This then increases the hydraulic gradient to the channel and/or the size of the groundwater seepage face, and enhances groundwater fluxes to the stream. Sklash (1990) implied that groundwater ridging is the central model to account for rapid fluxes of pre-event water to stream channels, and this belief is apparently shared by Jayatilaka and Gillham. However, this focus on groundwater ridging ignores research indicating that rapid pre-event contributions to stormflow can originate from a range of hydrological processes, including macropore flow (McDonnell, 1990), translatory flow (Bishop et al., 1990) and kinematic waves (Nolan and Hill, 1990).

In promoting the link between the capillary-fringe, rapid water-table responses, increased groundwater hydraulic gradients towards the stream channel and observed pre-event contributions to stormflow, Jayatilaka and Gillham suggest the pre-event water is synonymous with groundwater, despite evidence to the contrary (DeWalle et al., 1988; McDonnell et al., 1991). Buttle (1994) demonstrated that the groundwater ridging mechanism may be an excellent means by which pre-event vadose water (not from the saturated zone) reaches the stream channel, since the process results in conversion of vadose water held in and above the capillary-fringe to phreatic water. This vadose water is often isotopically-heavier than groundwater or baseflow (Swistock et al., 1989; Buttle and Sami, 1992). Vertical displacement of this 'heavy' water to the phreatic zone, combined with conversion of the tension-saturated zone and the associated increase in the hydraulic conductivity of the soil, results in enhanced fluxes of this pre-event vadose water to the stream channel. Many initial isotopic and geochemical hydrograph separations assumed that large pre-event contributions to stormflow were the result of enhanced groundwater fluxes to the channel, and the capillary-fringe mechanism was proposed to explain these groundwater contributions (cf. Gillham and Abdul, 1986). Given that the associated increase in pre-event contributions to stormflow is not necessarily attributable solely to groundwater, it appears that there is a need to consider other hydrological processes when attempting to explain the results of isotopic and geochemical hydrograph separations.

3. Failures to demonstrate the significance of the capillary-fringe to streamflow generation

We agree that the capillary-fringe mechanism is a reasonable explanation of groundwater ridging and rapid groundwater response at the sites examined by Gillham and colleagues: namely the relatively uniform Borden (Abdul and Gillham, 1984; Abdul and Gillham, 1989) and Perch Lake (Novakowski and Gillham, 1988) sands, and the fine sands and silts of a mine tailings site in Northern Ontario (Blowes and Gillham, 1988). Nevertheless, research conducted in other environments has often failed to demonstrate the significance of the capillary-fringe effect and groundwater ridging to stormflow generation. In some cases rejection of the capillary-fringe effect has been based on a failure to observe development of groundwater ridges in the near-stream zone (e.g. Bishop, 1991; Buttle and Sami, 1992); in other cases, rejection has been based on mass-balance considerations that near-stream groundwater is incapable of supplying the total pre-event water flux from the basin (McDonnell, 1990; Wels et al., 1991). Several studies in humid forested watersheds have indicated that the isotopic and geochemical behaviour of stormflow can only be explained by including water contributions from hillslopes beyond the near-stream zone. HECNAR's assumption that zone 3 (the far-stream zone) only supplies runoff to the channel via Horton overland flow ignores the potential for stormflow contributions from zone 3 via translatory flow (Bishop et al., 1990), preferential flow (McDonnell, 1990; Peters et al., 1995) or saturation overland flow in areas of thin soils or flow convergence (Ward and Robinson, 1990).

Furthermore, several studies which have advocated the capillary-fringe mechanism in humid catchments outside of the special sand-dominated situation examined by Gillham and colleagues have been proved invalid upon closer inspection. For example, the Pearce et al. (1986) and Sklash et al. (1986) studies (cited by Jayatilaka and Gillham) claimed that the capillary-fringe was responsible for observed large old water contributions to stormflow. Subsequent work by McDonnell (1990) found that the Pearce/Sklash soils showed no evidence for a capillary-fringe in the soil water characteristic curve. Rather, the soil water drainage curve was linear—preferential flow to depth and filling of storage in the lower soil horizons accounted for the rapid appearance of stored water in the stream channel. The responsibility of the capillary-fringe mechanism for stream tracer composition is now something analogous to an individual being charged with a crime: even though the person may be subsequently tried and acquitted, the only thing that people remember is the original charge—and not the fact that the person was innocent all along. In most humid watersheds, the capillary-fringe does not appear to be responsible for rapid streamflow response.

4. Limitations imposed by soil physics

Jayatilaka and Gillham state that "in humid watersheds, where shallow water-tables commonly occur in the near-stream areas, the capillary-fringe (the tension saturated zone of the soil moisture profile) extends to or close to the ground surface" (p.303). Fig. 1 shows soil water release curves for soils from three well-known humid watersheds for which we have data. None of the soils represented by the curves have tension saturated zones that extend beyond a few centimeters. Because these soils (and most soils in humid watersheds for that matter) do not maintain a discrete capillary-fringe, they will absorb some water during wetting close to saturation. Thus, they have some storage capacity, and they cannot exhibit capillary-fringe enhanced rapid water-table response. Soil physics tells us that the size of the capillary-fringe is inversely related to the saturated hydraulic conductivity of the material (Fig. 2). Therefore, the greater the propensity for capillary-fringe rise in near-stream shallow water-table environments, the less likely that rapid Darcian flux of groundwater can occur even with steepened hydraulic gradients in the near-stream zone (Zaltsberg, 1986).

HECNAR assumes a homogeneous and isotropic porous medium. This simplifies the modelling aspects, and may well describe the field sites where the capillary-fringe effect has been demonstrated; however, it does not apply to the environmental situations we are familiar with: variations in texture and porosity with depth, distinct soil horizons, and the presence of macopores which can induce preferential flow are the norm in most humid basins rather than the exception. Jayatilaka and Gillham acknowledge the role of macopores only so far as to suggest that their presence may delay the rapid water rise in the near-stream zone expected as a result of the capillary-fringe effect. It seems more likely to us that the heterogeneity in soil water content–matric potential relationships introduced by macropores would make development of an extensive capillary-fringe in the near-stream zone highly improbable (Germann, 1990).

5. Rapid water-table responses in the absence of a capillary-fringe

Jayatilaka and Gillham subdivide a drainage basin into 3 zones: the near-stream zone, where the capillary-fringe effect results in a rapid water response to precipitation inputs; the intermediate zone, where the

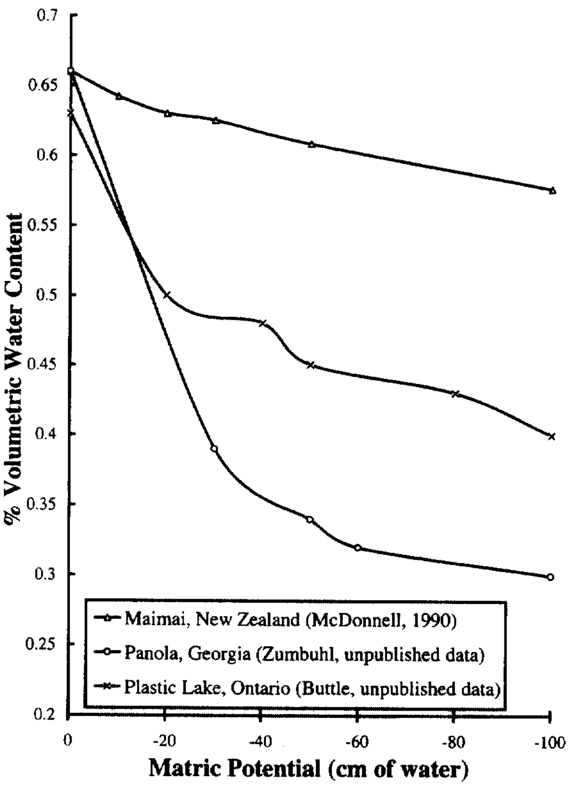

Fig. 1. Soil water release curves for Maimai, New Zealand (yellow brown earths), Panola, Georgia (sandy loam), and Plastic Lake, Ontario (B horizon podzol).

water-table rise is greater towards the stream as a consequence of downslope increases in soil water content at a given depth in the soil profile; and the far-stream zone, where the water-table response to precipitation is muted and lagged relative to the first two zones because infiltrating water may not reach the water-table during the course of the event. However, water-tables may develop and rise rapidly in response to precipitation inputs in humid watersheds despite the lack of capillary-fringe. Fig. 3 shows the water-table responses from two studies that have reported capillary-fringe (Heliotis and DeWitt, 1987; Sklash and Wilson, 1982). Also plotted are data from a humid watershed where soils do not display a capillary-fringe and where tensiometric information exists to record water-table response to inputs (McDonnell, 1989). Water-table response is similar in studies with and without a capillary-fringe, and the generally accepted theory of shallow groundwater recharge in humid watersheds is that bypass flow to depth may cause rapid and large water-table responses to incoming precipitation (Germann, 1990).

6. Alternative models of streamflow generation

Jayatilaka and Gillham's statement that "predictions in watersheds could be substantially in error if the transient flow system caused by capillary-fringe mechanisms is not adequately accounted for" (p.302) is at odds with the simulation of stormflow hydrographs and flow pathways using such topographically-based models as TOPMODEL (Robson et al., 1992). These models do not consider the capillary-fringe effect explicitly; nevertheless they have been applied successfully to a much wider range of environmental conditions than the sites that have provided evidence for a capillary-fringe effect.

In summary, we do not dispute the contention that the capillary-fringe effect may have an important role in streamflow generation *under certain conditions* (our italics). However, we feel that the claims made by Jayatilaka and Gillham for the widespread operation of this process are too sweeping, and that the role of the capillary-fringe effect in enhancing groundwater fluxes to the stream channel during precipitation

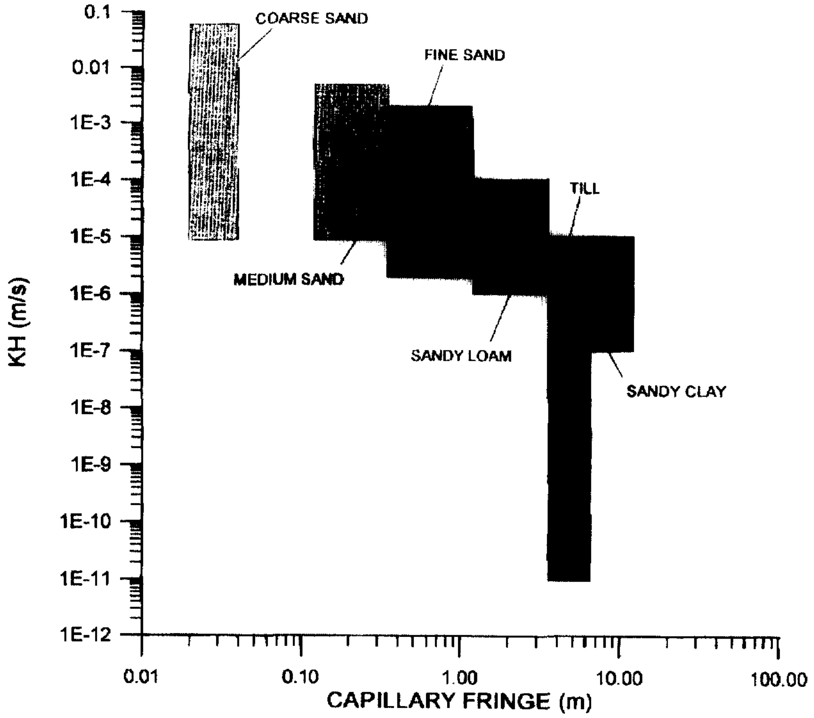

Fig. 2. Envelopes encompassing relationships between height of the capillary-fringe (from Zaltsberg, 1986) and saturated hydraulic conductivity (K_H) (from Freeze and Cherry, 1979 and Domenico and Schwartz, 1990) for various geologic materials.

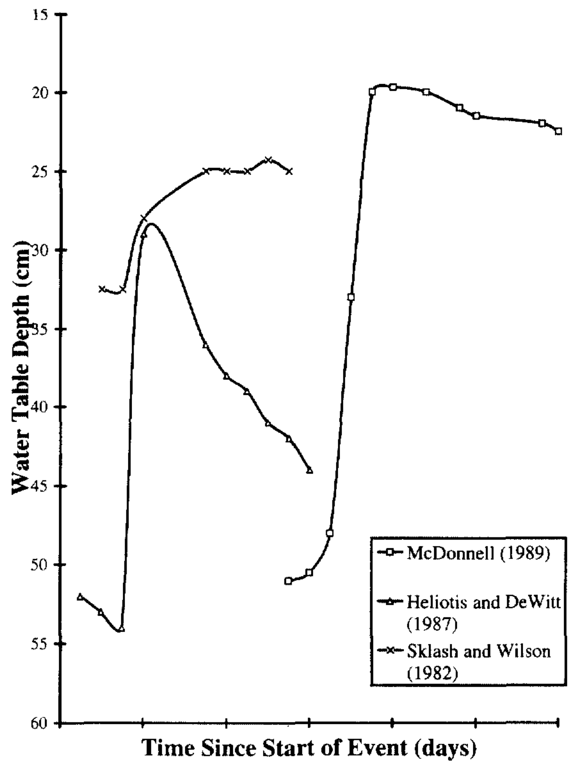

Fig. 3. Depth to water-table versus time relationships from Heliotis and DeWitt, 1987, McDonnell, 1989, and Sklash and Wilson, 1982.

needs to be considered in light of hydrometric, isotopic and geochemical evidence to the contrary. Thus, we disagree with Jayatilaka and Gillham's main contention that "the flow processes simulated by HECNAR are consistent with the generally accepted streamflow generating mechanisms" (p.313).

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