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Near-stream soil water–groundwater coupling in the headwaters of the Afon Hafren, Wales: Implications for surface water quality

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Summary Hard-rock acid headwater catchments typically exhibit a rapid streamflow response and concomitant rapid mobilisation of soil-derived solutes, such as aluminium, into the aquatic environment during storm events. The rapid stream responses are paradoxically associated with pre-event water dominating the storm hydrograph, however the sources and mechanisms by which 'old' water enters the stream channel and interacts with the soil horizons are still poorly understood. To investigate these processes a detailed and novel field study was established in the riparian zone and lower hillslopes of the Hafren catchment at Plynlimon, mid-Wales. This study showed that shallow bedrock groundwaters discharge into the stream channel. Pressure wave propagation in response to recharge further upslope caused a rapid displacement of shallow groundwaters up into the soils in the near-stream hillslope. A lateral fast flow horizon transported water down slope as interflow at the soil–bedrock interface such that the upper soil horizons remained largely unsaturated. Only where there was a discontinuity in the lateral fast flow horizon was water forced up as an ephemeral spring discharge at the soil surface. At this site, the major zone of soil water–groundwater coupling was in a narrow (20–25 m) strip next to the stream channel. The zone of soil water–groundwater interaction next to the stream channel is likely to depend on the nature of the lateral flow pathways and the hillslope characteristic. This study has shown the importance of the near-stream environment as a locus for soil waters that are bedrock groundwater derived; these groundwaters dominate processes in the deepest soil horizons from where soil components such as aluminium are sourced. Understanding these physical processes is fundamental for understanding upland catchment functioning and has important implications for solute transport modelling and for

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the sustainable management of surface water systems and stream ecology in these headwater regions.

Introduction

Acidification of upland catchments in the UK in response to anthropogenic pollution has been an issue of concern over the past few decades (Donald and Gee, 1992). With increasing catchment acidification comes increased mobilisation of ecologically toxic constituents, such as aluminium, from the soils into the aquatic environment (Harriman and Morrison, 1982; Rowell, 1994). The impact on fish populations and aquatic ecology has been severe (Harriman and Morrison, 1982; Ormerod et al., 1987; Stoner et al., 1984). In order to understand the catchment response to this kind of pollution, it is fundamental to understand the mechanisms and flow pathways involved in streamflow generation, especially with respect to the movement and interaction of water with soil horizons.

Traditional simple rainfall-runoff models fail to describe complex headwater streamflow generation processes; this is highlighted by their inability to model surface water quality responses to storm runoff (Neal et al., 1988). Simplistic models, which assume the bedrock geology is watertight below the soils, are also unable to explain the dominance of pre-event water in the storm hydrograph observed at a number of upland study sites (Genereux and Hooper, 1998). For example, studies in the headwater catchment of the Afon Gwy (River Wye) in mid-Wales, identified rapid flow through soil pipes as an important pathway in transporting water and solutes such as aluminium to the stream channel during storm response (Chapman et al., 1993; Muscutt et al., 1993). The source of this water was long assumed to be new rainfall, however Sklash et al. (1996) used stable isotopes to show that the pipe flow during storm events was overwhelmingly older pre-event water. At Llyn Brianne, a forested headwater catchment in central Wales, although flows were thought to be surface generated above an impermeable bedrock, water balance studies showed that the catchment was not watertight (Soulsby, 1992). Deeper flow paths in the lower soils were considered to be an important influence on stream water chemistry. Soulsby (1995) identified storms where runoff generation was dominated by the displacement of 'old' pre-event water. These results were consistent with earlier work by Robson and Neal (1990) but the source of this pre-event water was thought to be in the deeper soil horizons (Robson et al., 1993).

The paradox between 'old' water dominance and rapid runoff responses to rainfall has required the presence of an 'old' water store which can easily be displaced into the stream channel. Near stream or riparian saturation has been observed in a number of studies. Work at Maimai, New Zealand, showed the importance of stored water in generating storm runoff (Pearce et al., 1986; Sklash et al., 1986). Runoff was found to be dominated by displacement of pre-event water from the riparian soil horizons (McDonnell, 1990; McGlynn and McDonnell, 2003), though conceptually the bedrock geology was still assumed to be impermeable (McGlynn et al., 2002). Similarly, Chappell et al. (1990) and Fiebig et al. (1990), independently described upland saturated riparian zones in upland mid-Wales where displacement of soil water could account for the stream chemistry. The importance of riparian saturation has also been recognised elsewhere (Katsuyama et al., 2005; Wenninger et al., 2004). In laboratory and field experiments, Abdul and Gillham (1984, 1989) showed how the zone of tension saturation near the stream channel could very rapidly initiate the discharge of pre-event water into the river.

The focus of the search for an 'old' water source for streamflow storm response has been limited to saturation observed in the riparian soil horizons; the source of this water has been assumed to be lateral throughflow above an impermeable bedrock. In these studies, the term 'groundwater' is used to refer to saturation in the soil horizons perched on a supposedly impermeable bedrock. The concept of a deeper bedrock groundwater resource (extending down to many 10s of metres depth) has been poorly understood and consequently often ignored. Soil water—groundwater interactions in the riparian zone and lower hill slopes are likely to be very different from those interactions occurring in the mid-slopes or interfluves in an upland catchment. This is because the near-stream valley bottom areas represent areas of bedrock groundwater upwelling and discharge to surface waters. Whilst saturation in soils can technically be termed groundwater, in this paper the term groundwater refers specifically to the saturated horizons within the bedrock. It is used simply to differentiate between soil and bedrock saturation; the authors accept that there is a dynamic continuum between soil water and groundwater and that groundwater is not a single homogenous body but a complex system whose physico-chemical characteristic will vary both spatially and with time. Bedrock groundwater *can* rise into the soils causing saturation however, the flow pathways, residence times and water chemistry are wholly different to rainfall-derived perched saturation in the soil horizons. Detailed field observations of these processes are limited and the origins of near-stream saturation in the soil horizons have not been clearly defined.

The presence of deep bedrock groundwater has been observed in upland Wales (Neal et al., 1997). The role of this groundwater in streamflow response at Plynlimon was first highlighted by Shand et al. (1997) who used strontium isotopes to show that the river waters lie on a mixing line between bedrock groundwater and rainfall. Work in upland Scotland is also beginning to recognise the importance of