INVESTIGATING THE ROLE OF GROUNDWATER IN CATCHMENT FUNCTIONING IN THE EDDLESTON CATCHMENT, SCOTLAND

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ABSTRACT

BGS have been investigating the role of groundwater in catchment functioning for the past 10 years in the Eddleston Research Catchment – a tributary of the River Tweed, located in the Scottish Borders. The research is part of a wider initiative funded by the Scottish Government examining the evidence for the efficacy of natural flood management and river restoration measures. Here we give a brief summary of several of the experiments undertaken: (1) exploring the coupling of an upland floodplain aquifer with the river and hillslope; (2) examining soil permeability and infiltration in different land uses and superficial geology; (3) monitoring groundwater flow and soil moisture changes underneath a forest strip; and (4) using tracers to measure the partitioning between groundwater flow, soil water and event runoff during storm events. The research experiments reinforce the importance of subsurface conditions, and in particular geology in shaping the response of catchments to rainfall. Groundwater plays an important, but often unrecognised role in mediating catchment flows, and variability in superficial geology often exerts a larger control on flooding than land use.

Key words: *groundwater, catchments, flooding, rivers, forests*

INTRODUCTION

Groundwater has long been recognised as an important part of hydrological functioning of catchments. Although early work on flood generation ignored the sub surface due to the specific environment being investigated (Horton 1933), research quickly evolved to include infiltrated water (Hursh and Brater, 1941; Dunne and Black, 1970). Much of this early focus on subsurface runoff mechanisms was on flow along the soil-bedrock interface and interflow through macropores. However, Sklash and Farvolden (1979) in their seminal paper "the role of groundwater in storm runoff", explained runoff generation processes in a completely different way. They used naturally occurring stable isotopes to show that most river water at high flows was actually 'subsurface water present in catchment soils and rocks before the rainfall event'. If the water being delivered to streams really was groundwater, the problem this raised was how such large volumes of groundwater become mobilised so rapidly. Research in the 1990s helped to address this issue further by proposing mechanisms in which soil layers near the soil-bedrock interface become saturated and then hydraulically connect during storm events of long enough duration. This process helps to mobilise old (pre-event) water towards the base of slopes through the development of a pressure head (McDonnell, 1990). This mechanism and a similar mechanism of ‘transmissivity feedback’ have helped explain the ‘old water paradox’ (Kirchner, 2006). At the scale of whole hillslopes, experiments have shown evidence for these mechanisms leading to threshold behaviour, in which whole hillsides are ‘switched on’ during events of particular rainfall intensities (McGlynn et al., 2003). This is sometimes called ‘fill and spill’ since it is not the surface topography that determines flow paths, but the subsurface topography and/or impermeable soil horizons and their role in controlling the development of saturated conditions. This significant body of research has led to a conceptual model of hillslope runoff mechanisms that includes overland flow due to infiltration excess, but emphasises flow processes within soils and bedrock.

How these conceptualisations of groundwater in catchments actually work out in practice in the temperate, post glacial environment of Northern Europe is still poorly resolved. This is due in part to the challenges of undertaking research that can identify the different flow paths through a catchment. Consequently, groundwater flow paths are still often neglected when examining or modelling flow in a catchment. This has implications for designing and implementing catchment measures which rely on increasing infiltration and catchment storage, such as flood alleviation measures, Natural Flood Management or re-afforestation. In this study we discuss recent and ongoing research in the Eddleston Research Catchment, a tributary of the River Tweed in the Scottish Borders, where we have developed several experiments to examine the role that groundwater plays in catchment functioning.

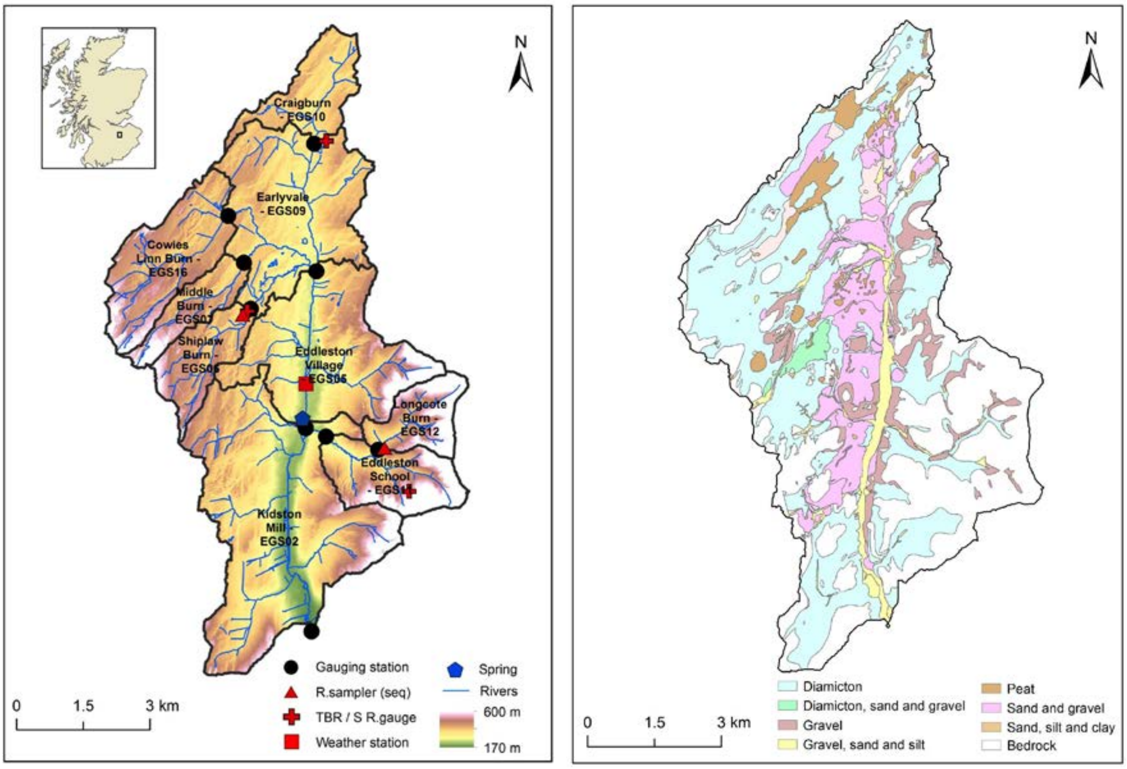

Figure 1: *The Eddleston catchment: (left) location of monitored sub-catchments, gauging stations and rainfall recorders (Peskett 2020a); and (right) superficial geology (Auton, 2011). BGS © UKRI*

THE EDDLESTON CATCHMENT

The Eddleston Water catchment (69 km^2) is a tributary of the River Tweed in the Scottish Borders, UK. The Eddleston Water flows due south and is fed by several distinct sub-catchments (Figure 1). The catchment is host to the Scottish Government’s long-term study on the effectiveness of NFM measures to reduce flood risk to downstream communities and improve habitats for wildlife. The project is a partnership initiative led by Tweed Forum (a local non-governmental organisation), with the Scottish Government, the Scottish Environment

Protection Agency (SEPA), the University of Dundee, the British Geological Survey and Scottish Borders Council (Black et al. 2021).

Catchment characteristics are typical of much of the UK uplands. Topography is in the range of 180-600 m (Figure 1), mean annual precipitation is ~900 mm, falling mainly as rainfall, and monthly mean temperatures range from 3 to 13 °C. Land cover is mainly improved or semi-improved grassland on the lower slopes, rough heathland at higher elevations and marshy ground in the hollows. Extensive coniferous plantations were established in the 1960s and 1970s in some of the western sub-catchments, with up to 90% forest cover. Forest cover in other parts of the catchment is typically mixed coniferous and deciduous woodland, concentrated along field boundaries. Soils on steeper hillsides are typically freely draining brown soils overlying silty glacial till, rock head or weathered head deposits. Towards the base of the hillslopes the ground is typically wetter and soils comprise sequences of gleyed clays and peats on sub-angular head deposits or alluvial deposits closer to the river (Soil Survey of Scotland Staff, 1970).

Bedrock throughout most of the catchment is comprised of Silurian poorly permeable well-cemented, poorly sorted sandstone greywackes (Auton, 2011). Extensive glaciation during the last glacial maximum has affected the superficial geology and soil types (Ó Dochartaigh et al., 2019). The western part of the catchment has extensive, thick and poorly permeable glacial tills (often >5 m thick) (Aitken et al., 1984) but with some highly permeable glacio-lacustrine sands and gravels in isolated areas (Figure 1). The centre of the catchment has extensive alluvial and head sand and gravel deposits (up to 20 m thick) overlying bedrock or glacial till.

EXPERIMENT 1: INFILTRATION

The first groundwater experiment undertaken on the catchment was to investigate the influence that land use, and in particular forestry has on soils permeability and infiltration (Archer et al. 2013). Figure 2 shows the experimental set up and some of the results, which are represented as runoff. The results show the importance of broadleaf woodland in increasing soil permeability and therefore infiltration when compared to neighbouring grassland. There was also a relationship with the age of woodland, with infiltration greatest in oldest forests, most likely due to the deeper organic layer and presence of coarse roots. However, there was no statistical difference in soil permeability between 40 year old plantation and neighbouring grassland. When examining only the grassland sites, superficial geology was the main control on soil permeability, and therefore infiltration to groundwater.

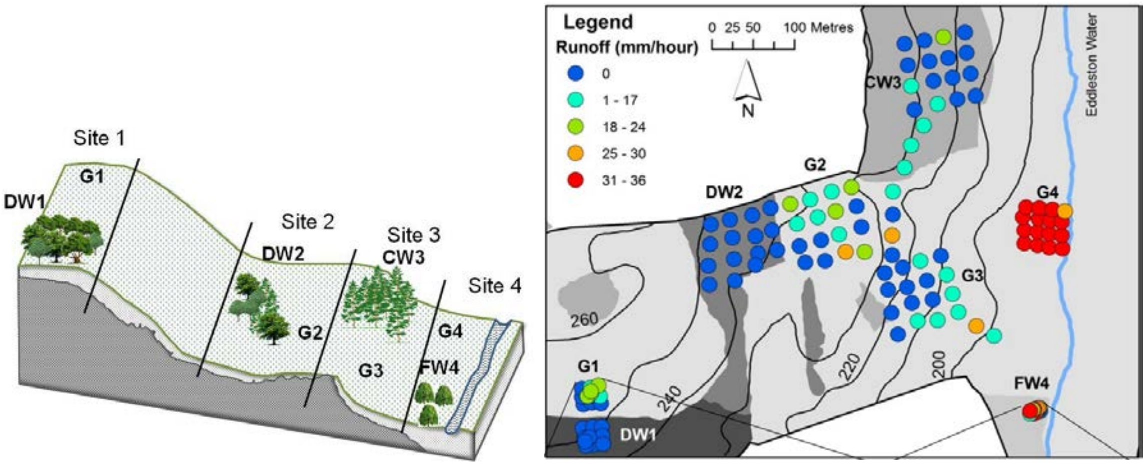

Figure 2: *Estimated runoff for grasslands and different types of forestry at the Darnhall observatory in Eddleston. G1-4 sites are improved grassland, DW1 is 500-year-old broadleaf woodland, DW2 is 180-year-old broadleaf woodland, CW3 is 45-year-old conifer plantation, and FW4 is floodplain woodland (Archer et al, 2013). Reprinted from Journal of Hydrology, 497, 208–222 © 2013, with permission from Elsevier* https://www.sciencedirect.com/journal/journal-of-hydrology

EXPERIMENT 2: FLOODPLAIN AQUIFERS

A second investigation was undertaken in the Darnhall floodplain, just north of Eddleston Village (Figure 1) to examine how groundwater in small upland floodplains interacted with the river and adjacent hillslope (Ó Dochartaigh et al., 2019). Detailed geophysical surveys using a variety of electrical methods, and trial pits and site investigation boreholes were constructed to develop a 3D geological model. Ten piezometers were then carefully sited, tested and monitored to characterise the 3D groundwater behaviour within the floodplain. Nine years of monitoring of groundwater, rainfall and river flow shows how the geological structure of the floodplain affects groundwater within the floodplain and mediates the interaction between the hillslope and river flow (Figure 3). Groundwater levels respond strongly to river stage for approximately 100 m distance from the river. However in the floodplain hillslope interface groundwater levels respond more slowly and continue to rise for several days after rainfall maintaining high (artesian) water levels for weeks – sustained by subsurface flow from the hillslope. Permeable solifluction deposits facilitate this sub surface coupling (Figure 3).

Adjacent to the river channel, the river generally loses water to the aquifer, and re-emerges just south of the study area in a wetland. During high river flows, the water levels rise rapidly in the floodplain, and then groundwater discharges back to the river in the following days as the river stage falls and the groundwater gradient changes.

The chemistry of the groundwater is impacted by the geological structure, with pockets of reducing groundwater associated with higher base metals, increased dissolved carbon and evidence of nitrate reduction associated with the presence of silts and peat.

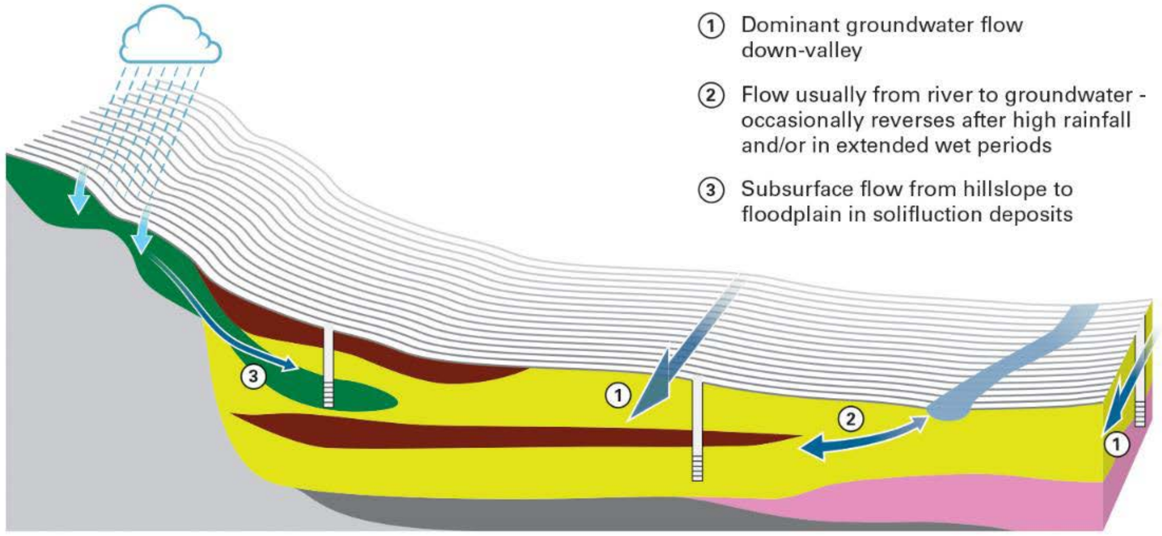

Figure 3: *Conceptual model of the groundwater flow at the Darnhall observatory in Eddleston (Ó Dochartaigh et al. 2019). Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/)*

EXPERIMENT 3: GROUNDWATER UNDER A FOREST STRIP

The impact of forest strips on infiltration and groundwater flow through hillslopes was examined on a hillslope on the main stem of the Eddleston Water 3 km south of Eddleston Village (Figure 1). Two 60 m long transects were instrumented with shallow piezometers (2.5 m deep) and soil moisture probes (0.15 and 0.6 m depth), one through a 27 year old forest strip and the other on improved grassland (Peskett et al. 2020b). Repeat ERT surveys were also undertaken along the surveys approximately every 6 weeks. In the parallel transects soil and groundwater dynamics were recorded up slope, midslope (which encompassed the forest strip in the forested transect) and downslope (Figure 4). The monitoring identified significant differences in sub-surface moisture dynamics underneath the forest strip: drying of the forest soils was greater, and extended deeper and for longer into the autumn compared to the adjacent grassland soils. However downslope of the forest, soil moisture dynamics was similar in the forest and grassland transects and no significant effect was recorded 15 m downslope of the forest. Groundwater levels in the forest strip were persistently deeper than the grassland and this effect was observed downslope of the forest strip. However, during the wettest conditions, the monitoring indicated upslope-downslope water table connectivity beneath the forest (Figure 4) with response times similar for grassland and the forest transect. This research suggests that fragmented forest strips may have little impact on groundwater connectivity within a catchment during wet periods, although further research in a variety of different geological environments is needed.

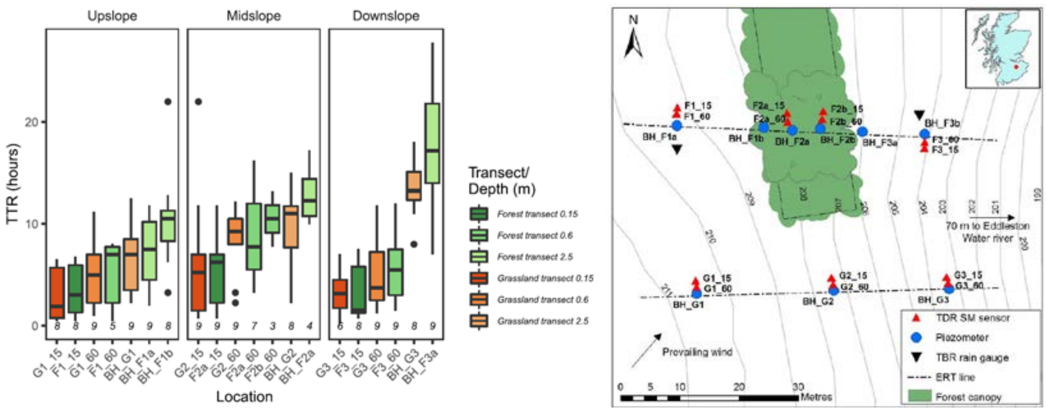

Figure 4: *Time to response from the start of rainfall (TTR) for uplsope, midslope and downslope for the forest strip and grassland transects for the 9 wettest events where the monitoring network responded to rainfall. G refers to grassland strip, F for forest, BH is piezometer and 15 and 60 refer to soil mositure at 15 cm and 60 cm respectively. In each domain shallower sensors respond quickest to rainfall. Groundwater response time increases with distance down slope, but with no statistical difference between the grassland and forest strip (Peskett et al. 2020b). Reprinted from Journal of Hydrology, 581, 124427 © 2020, with permission from Elsevier* *https://www.sciencedirect.com/journal/journal-of-hydrology*

EXPERIMENT 4: GROUNDWATER FLOW DURING STORM EVENTS

Detailed monitoring was undertaken over a two year period, 2015-2017 of three sub-catchments, Middle Burn, Shiplaw and Longcote (Figure 1) to determine the proportion of surface rainfall runoff, soil water and groundwater in streamflow during a storm event. Detailed fieldwork was undertaken during storm events to monitor temporal variability in stable isotopes ^{2}H and ^{18}O in rainfall and streamflow, and Acid Neutralising Capacity (ANC) in streamflow (Peskett et al., 2020a). These data, along with weekly baseline monitoring over the 2 year period were used to separate hydrographs into three component parts: event runoff, soil water and groundwater. The three sub-catchments had different characteristics, Middle Burn and Shiplaw had similar geology but Middle Burn had a much higher proportion of plantation (spruce) forestry (94% Middle Burn compared to 41% in Shiplaw). The geology for Longcote was different – with little superficial geology cover and mostly fractured Silurian bedrock close to surface – and had negligible forest cover. An example of the results for one of the storms is shown in Figure 5.

The results of this survey soon to be published (Peskett et al., 2021) indicate that pre-event water stored in soil and groundwater is an important component of stream discharge during storms for these small catchments (<10 km^{2}). Geology and soil type appeared to exert a stronger control on the fraction of event water compared to the extent of plantation forest cover – demonstrating the importance of the hydrogeological environments in flood generation.

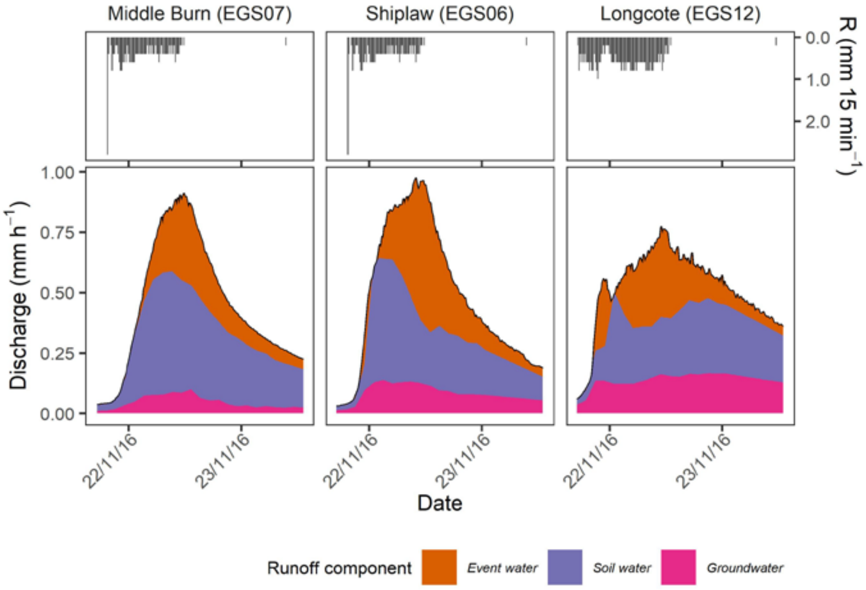

Figure 5: *Three-component hydrograph seperation based on stable isotopes in streamflow and rainfall and ANC in streamflow relative to baseflow conditions. Much of the streamflow comprises pre-event water stored in the catchment, with the greatest proportion soil water (Peskett et al. 2020a). The Longcote catchment with limited glacial till, and more bedrock exposed, shows a slower response during storm events and a greater proportion of groundwater within streamflow.*

CONCLUSIONS

Ten year of research in the Eddleston Research Catchment has highlighted the importance of groundwater in catchments. Monitoring groundwater in poorly permeable upland catchments is challenging and a range of techniques are required, from detailed site characterisation and monitoring to integrating methods using tracers. Below are some of our findings.

- Soil type and superficial geology exert a strong control on infiltration to groundwater, with broadleaf forests increasing infiltration and also deepening groundwater levels. Coniferous plantations had a less demonstrable impact on infiltration to groundwater.
- Shallow groundwater flow through hillslopes is significant during wetter periods, and responds more slowly than soil water (hours - days) to heavy rainfall, but can persist longer (days – weeks) when activated. Groundwater connectivity appears not to be disrupted by fragmented forest strips. However, more research is required to observe how this changes with antecedent conditions.
- Pre-event water stored in soil and groundwater comprises a significant component of stream flow during storms, and for the headwaters monitored was >50%. The hydrogeological conditions of the catchment appear to exert strong control on this proportion, with a higher groundwater proportion, and longer delays in fractured bedrock compared to sub-catchments with low permeability superficial deposits.
- Groundwater in small flood plains helps to mediate the coupling between hillslope and river, providing a buffer to the connectivity. Higher river levels during flood events are propagated through the floodplain, reversing river/groundwater gradients after river levels recede. Elevated groundwater levels at the floodplain edge due to hillslope flow have been observed in the Eddleston and elsewhere (MacDonald et al. 2014).

Building on the long term monitoring and multidisciplinary study at the Eddleston has helped uncover some groundwater behaviour, with much more still to discover. The investment in characterising and monitoring the catchment makes it an ideal location for future research.

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