Groundwater-surface water interaction in an upland hillslope-floodplain environment, Eddleston, Scotland

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Introduction

New investigations into the integrated nature of groundwater, soil and surface water at a study site in the Scottish Borders are improving our understanding of hydrological processes in upland hillslope-floodplain environments. We present the initial results of an interdisciplinary study, which offers real potential for better understanding, mitigation and management of flood events.

The Eddleston study site is located in the Eddleston Water experimental catchment, in which work is being funded by the Scottish Government to test natural flood management techniques and an integrated catchment management approach to sustainable flood risk management. The site is upland and rural and encompasses an area of 0.2 km^2 in the Eddleston Water valley, from hillslope to floodplain. Landuse is largely improved grassland, with silage grown on the floodplain and livestock grazing on the floodplain and hillslope, and small areas of Scots pine plantations.

The study site has a complex natural character and a complex history of engineered hydrological interventions, many of which are likely to be typical of similar upland floodplain environments. As with many rivers, the channel of the Eddleston Water has been straightened, although untypically this happened at Eddleston before 1770. Later a railway embankment was built along the east side of the river, the remains of which are still present, along with a purpose built flood management levee on the eastern river bank. More recently the main road on the eastern side of the floodplain was built up as part of flood management measures. Geophysical and observational evidence points to the existence of field drains across the site. The micro-topography of the floodplain is complex, with parts of the eastern edge of the floodplain lying at lower elevation than the Eddleston Water.

Extensive characterisation of the geology, soil, hydrogeology and hydrology has been carried out by the British Geological Survey (BGS) and the University of Dundee, resulting in a detailed 3D geological model; the installation of a hydrological monitoring network; and the ongoing characterisation and conceptual modelling of the hillslope-floodplain hydrological system.

Since autumn 2011 this monitoring network has been providing detailed new dynamic data on stream flow, rainfall, soil moisture, groundwater levels, water temperature, groundwater chemistry and environmental tracers. Our understanding of the hydrological system at the Eddleston site is still evolving as data are collected and interpreted. Here we describe initial results from the study, which is enabling us to build an increasingly detailed conceptual understanding of the coupling of groundwater and surface water within the floodplain. Ultimately this will lead to improved understanding of hydrological system response to flood events.

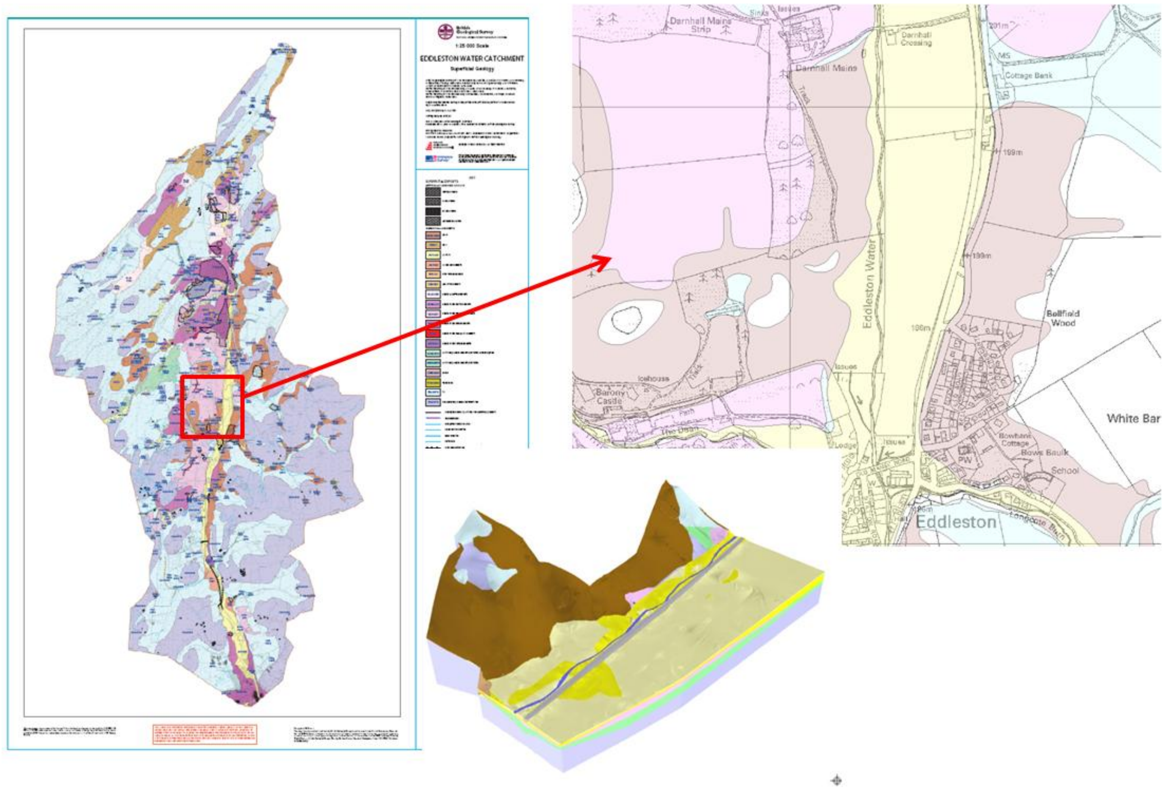


Figure 1 Location and geology of the Eddleston study site

Methodology

The Eddleston study site and the wider Eddleston Water catchment are being characterised in detail using a range of techniques. Detailed information is provided in Ó Dochartaigh *et al*. (2012).

The geology of the study site has been established by running extensive geophysical survey lines using three techniques: electromagnetic induction (EM), ground penetrating radar (GPR) and electrical resistivity tomography (ERT); geological re-mapping, using standard BGS survey techniques; constructing and logging eleven trial pits; and drilling and logging nine boreholes. The collected geological information was combined to develop a 3D geological model using the GSI3D geological modelling software (http://www.bgs.ac.uk/gsi3d/). Examples of outputs from the 3D geological model are presented in Figures 1, 2 and 5.

A network of river flow gauging stations has been established in the catchment, including two within the Eddleston study site, to monitor flow response to rainfall in the main stem and tributaries of the catchment, along with an automatic weather station and recording and storage rain gauges. River level is monitored continuously and the sites are rated to flow using measurements obtained by wading, bridge gauging and in flood conditions by Acoustic Doppler Current Profiler (ADCP).

The permeability of soils across the study site was estimated by calculating field saturated hydraulic conductivity (Kfs) from measurements using a constant head permeameter based on the Simplified Well Permeameter Procedure (Talsma and Hallam 1980). Volumetric soil water content in the improved grassland on the hillslope is being monitored using six capacitance probes (*ThetaProbes* manufactured by Delta-T, Cambridge, UK), at depths of 0.20, 0.35 and 0.6 m in two groups: one at the foot of the hillslope and one 10 m upslope. Measured soil permeability is the same for both groups. At the upslope group the hillslope has an angle of 10°, and at the lower group the hillslope is at an angle of 4°.

The hydraulic properties of the floodplain aquifers were measured by test pumping the boreholes using standard hydrogeological techniques. The hydrochemistry of the study site is being investigated by a series of water sampling campaigns and analysis of inorganic water chemistry, stable isotopes, and residence time indicators.

Hydrology and hydrogeology

The Eddleston Water is a small tributary of the River Tweed, with a largely upland catchment area of approximately 69 km^2. Base flow index along the main stem varies between 0.502 and 0.523 according to the LowFlows software, with catchment mean annual runoff estimated as 510 mm (Holmes *et al.*, 2002).

The floodplain is infilled with a sequence of variable but often thick and permeable Quaternary deposits, which have a significant impact on the hydrology of the floodplain. At the study site, the Quaternary sequence comprises two interconnected aquifers: a relatively continuous layer of alluvial sandy gravel across the floodplain from near ground level to approximately 5-7 m depth; and a deeper layer of glaciofluvial gravel, from approximately 7 m to between 12-15m deep, which is largely restricted to the centre of the floodplain (Figure 2). These aquifers are largely underlain by low permeability glaciolacustrine silts and clays, and in some restricted areas by glacial till, below which is Lower Palaeozoic bedrock. In some parts of the study area the upper alluvial aquifer is overlain and/or interbedded with lower permeability alluvial silts and fine sands and/or peat. The soils across the floodplain and hillslope show a wide range in permeability, which affects water infiltration. This subject is discussed in a separate paper in this issue (Archer *et al*.).

The alluvial and glaciofluvial deposits show generally moderate permeability, with most measured transmissivity values from test pumping between 200 and 400 m^2/day (one glaciofluvial and five alluvial boreholes). Two boreholes screened in alluvium gave transmissivity values outside this range (one 50 m^2/day and one 1000 m^2/day) (Figure 2). The storage potential of the two aquifers is significant: at a conservative estimate there could be 70 to 80 Ml of groundwater stored in superficial aquifers in the floodplain just in the 400 m stretch within the study area.

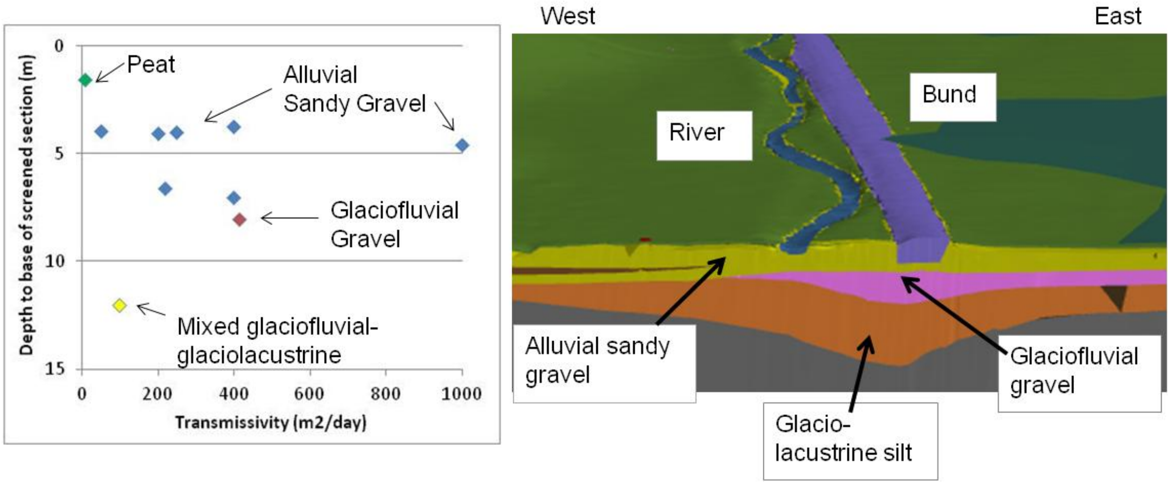


Figure 2 **Aquifer structure and transmissivity at the Eddleston study site**

Measured groundwater heads are highest at the northern edge of the study area and at the western edge of the floodplain, and are lowest close to the river at the southern edge of the study area. Heads were consistently above the adjacent river level throughout the winter period between October 2011 and end March 2012, even in high flow conditions (Figure 3). There are distinct local vertical head gradients: upward, in the area west of the river within the alluvial aquifer to the south of the study area; and downward, in the area to the east of the river, from the alluvial to the underlying glaciofluvial aquifer.

The range in groundwater levels in individual boreholes during the monitored winter period was between 0.3 and 0.95 m. Groundwater levels in all the monitored boreholes show a similar response, and also respond similarly to river level, reacting quickly to rainfall and/or river level changes (Figure 3).

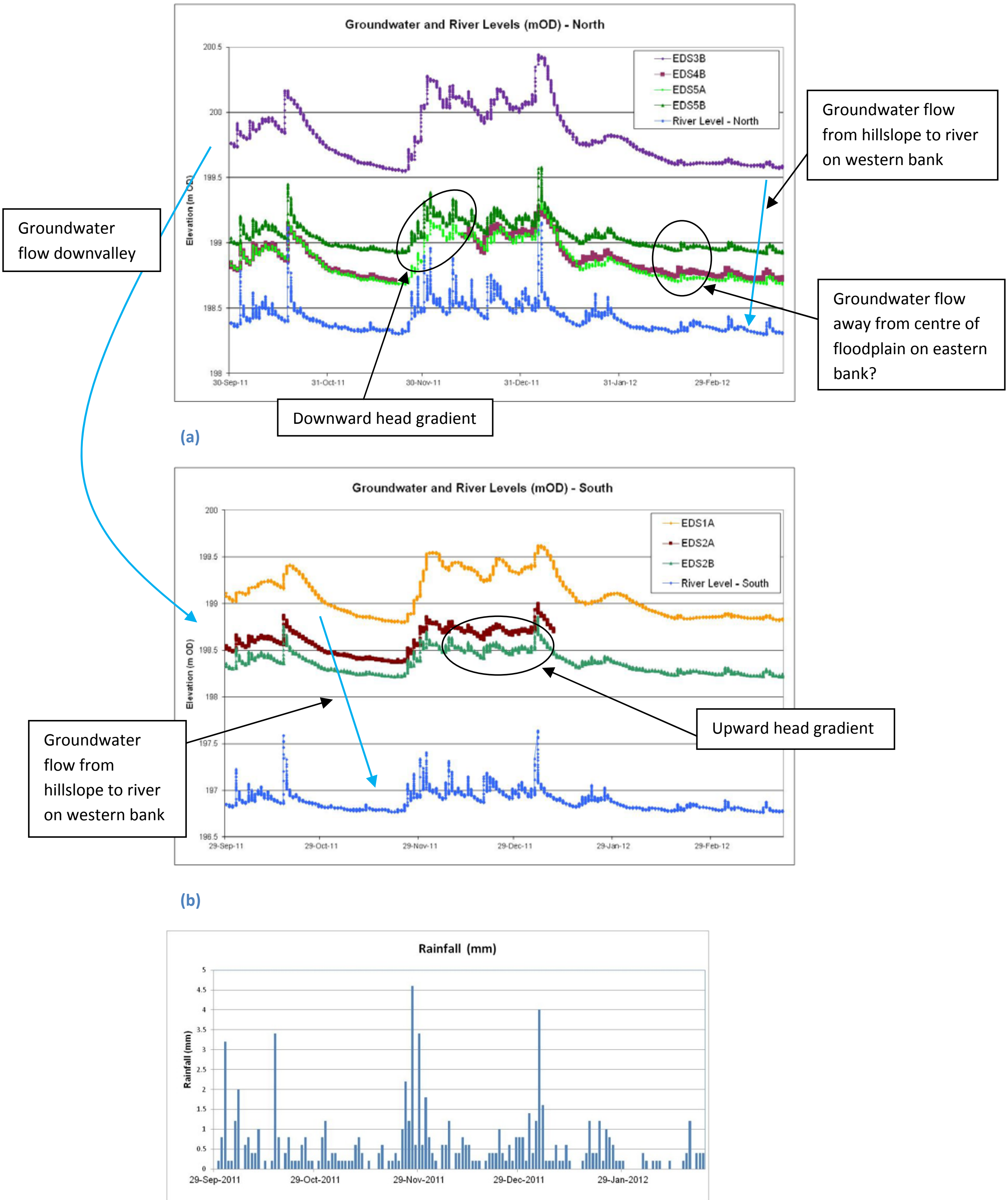


Figure 3 Groundwater and river levels and rainfall (a) at northern end and (b) southern end of the study area

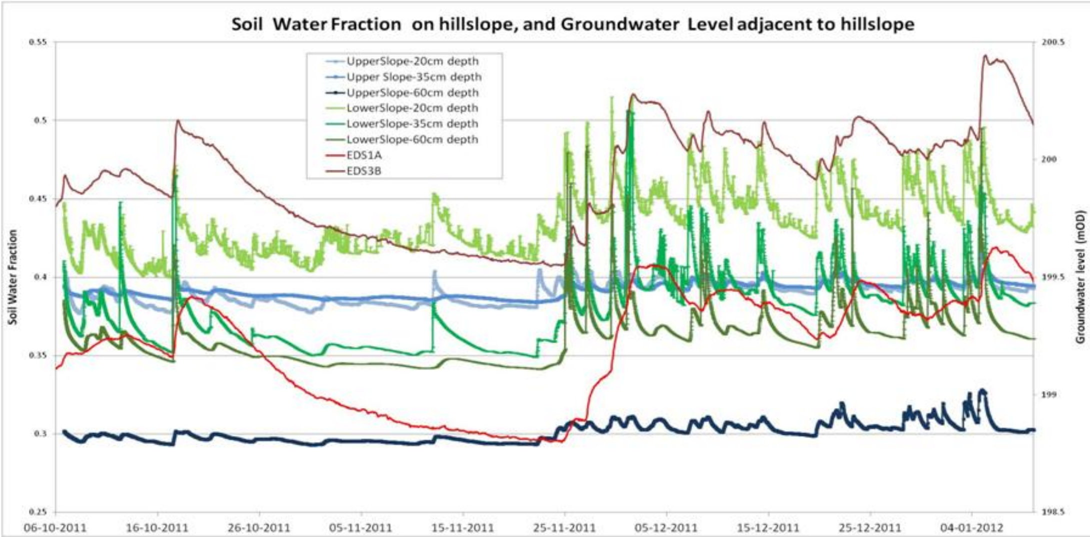
The groundwater head distribution indicates there are two lateral components to groundwater flow through the floodplain: one down-valley, sub-parallel to the river; and one cross-valley from the western edge, where the floodplain appears to be connected to the hillslope, eastwards towards the river. The relative magnitude of these two components has not yet been established. There is little indication of significant groundwater flow from the eastern side of the floodplain towards the river: on the contrary, there is some evidence from groundwater heads of flow in the opposite direction (Figures 3 and 5). Parts of the eastern side of the floodplain are lower in elevation than the river, and there is geophysical evidence for buried field drains in this area which lead away from the river towards a sub-surface drain which runs southwards to discharge into the Eddleston Water at the southern edge of the study site. It may be that a component of shallow groundwater in the eastern part of the floodplain is being transferred away from the river locally via these engineered drains. The floodplain topography suggests that this component of flow occurred naturally before field drainage was installed, but to what degree is uncertain. Further monitoring may help increase our understanding of this process, which is likely to be relevant to local flooding.

The vertical head differences between adjacent boreholes indicate additional complexity in groundwater flow, and probably reflect internal heterogeneity, and perhaps stratification, within the alluvial aquifer as well as between the alluvial and glaciofluvial aquifers. Importantly, the groundwater head monitoring data indicate that groundwater is likely to be discharging to the river throughout the year, and may contribute a significant volume to river discharge.

In relation to ground level, groundwater levels through the winter ranged from artesian to a maximum of 1.4 m below ground level. The surface discharge of groundwater from the shallow alluvial aquifer (less than 4 m deep) appears to cause localised groundwater flooding in at least one part of the floodplain on the eastern side and some 100 m from the river. Artesian conditions also occur in a borehole at the base of the hillslope on the western edge of the floodplain.

Work is ongoing to investigate the complex relationship between soil water dynamics on the hillslope, groundwater in the floodplain, and an adjacent wetland area where groundwater discharges via a spring year-round. Measurements of grassland soils at the Eddleston study site (Archer *et al*., this issue) show very low sub-surface soil permeability and indicate that sub-surface flow in the soil may be an important hydrological component, for example in providing recharge to the floodplain aquifers via inflow from hillslope soils. Unlike river and groundwater levels, soil water content on the hillslope does not appear to respond directly to large rainfall events, but does vary significantly in response to smaller events, to which groundwater levels and river levels do not react (Figure 3, Figure 4). This perhaps indicates that soil water storage in the catchment buffers smaller volumes of rainfall infiltration, and that water transfer to the saturated aquifer and/or the river only occurs above a rainfall threshold. Initial soil water monitoring provides further evidence of soil water flow (Figure 4). At the upslope soil water sensors, the shallower soil layers at 0.2 and 0.35 m depth remain near saturation with little fluctuation, while the deeper soil at 0.6 m has significantly lower water content. The downslope sensors, in contrast, show large soil water fluctuations down to 0.6 m. Soil on the lower slope may be receiving inflows of water under pressure from further upslope, and possibly laterally from the floodplain.

(a)



(b)

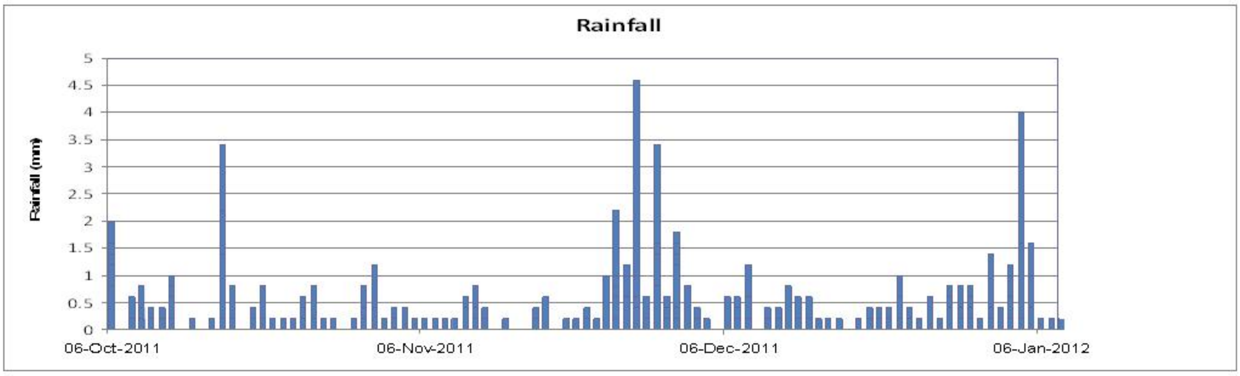


Figure 4 (a) Soil water content on hillslope and groundwater levels in boreholes adjacent to hillslope; (b) daily rainfall

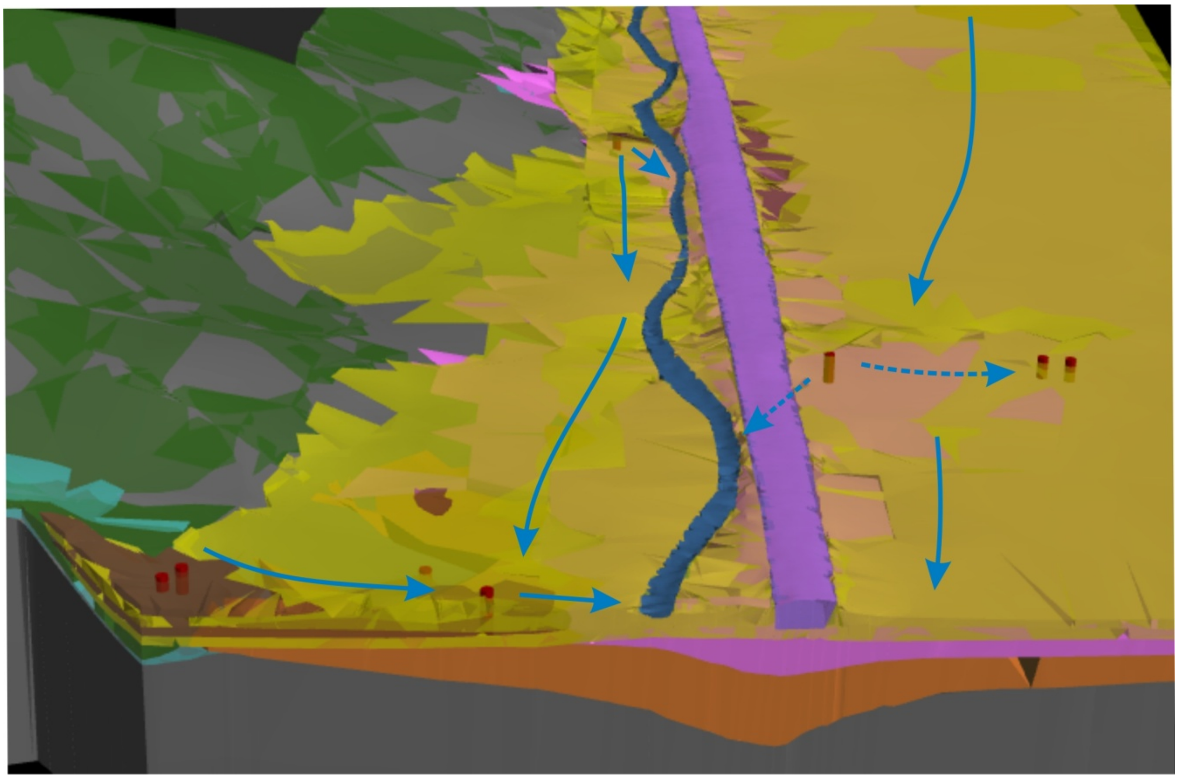


Figure 5 Inferred groundwater flow directions through the Eddleston study area

Groundwater in the Eddleston floodplain shows relatively large temperature fluctuations. When unaffected by local active recharge, groundwater temperature at depths of greater than approximately 1 m tends to approximate to the annual average air temperature and to change only gradually, by generally less than a degree or two, throughout the year. By contrast, the temperature in most of the Eddleston boreholes varied by between 2.5 and 4.5 degrees Celsius over the winter (Figure 6), which indicates a relatively strong connectivity with surface water. The nature of this connectivity appears to be complex. Some of the boreholes appear to show a greater sensitivity to rainfall events than others, but the controls on this response are not clearly groundwater depth, aquifer type, and/or proximity to the river and/or hillslope. The groundwater temperature response to individual rainfall events is different in different boreholes; and it is not yet clear to what degree groundwater temperature is responding to direct rainfall recharge and to the impact of the river.

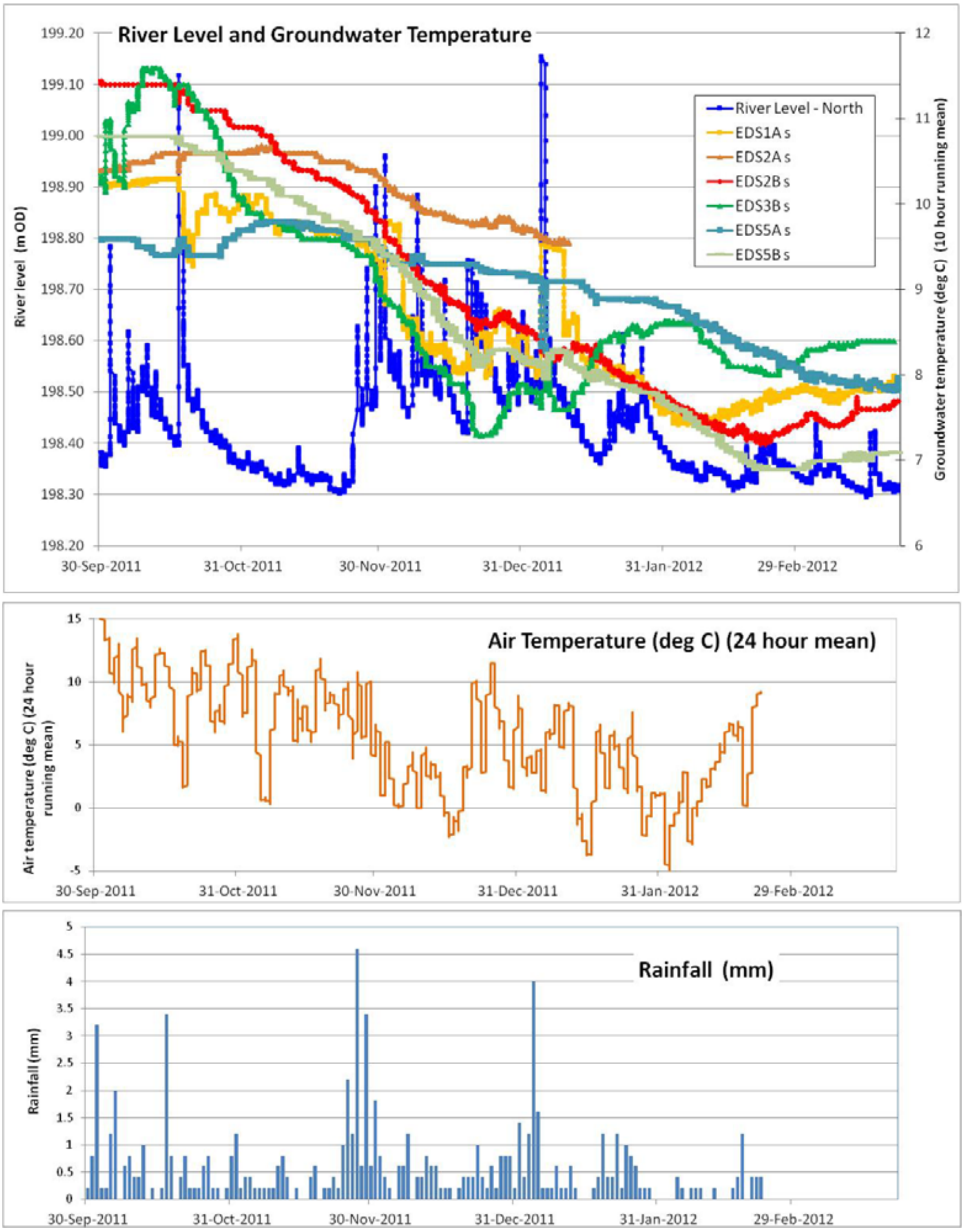


Figure 6 Groundwater and air temperature plotted against river level and daily rainfall

Conclusions

This short paper describes preliminary results from an integrated study into hydrological processes in an upland hillslope-floodplain system. Groundwater plays a significant role in this environment. The evidence to date indicates that there are complex coupled relationships between rainfall, river flow, soil water and groundwater, linked to heterogeneity in soil permeability and aquifer structure and transmissivity as well as to wider catchment processes, climate, land use, and drainage engineering. Monitoring of climate, river and groundwater levels and soil water is continuing, and targeted field campaigns have already been carried out to collect data on groundwater and surface water chemistry, stable isotopes and residence time. Integration and interpretation of these data is ongoing to investigate the complex hillslope-floodplain processes in more detail and to provide process underpinnings for flood management initiatives within the catchment.

Acknowledgements

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