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The emerging use of magnetic resonance imaging to study river bed dynamics

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Introduction

The characterisation of surface and sub-surface sedimentology has long been of interest to gravel-bed river researchers. The determination of surface structure is important as it exerts control over bed roughness, near-bed hydraulics and particle entrainment for transport.[1] Similarly, interpretation of the sub-surface structure and flow is critical in the analysis of bed permeability, the fate of pollutants and maintaining healthy hyporheic ecology.[2] For example, many invertebrates (e.g. mayfly, caddis) and fish (e.g. salmon) lay their eggs below the river bed surface, and rely on sub-surface flows to supply the necessary oxygen and nutrients. Whilst turbulent surface flows drive these small sub-surface flows, they can also convey sand and silts that clog the surface and sub-surface pore spaces. Reduction in sub-surface flows can starve eggs of oxygen such that larvae or juveniles do not emerge. This is particularly critical in Scottish gravel-bed rivers, as the rising supply and deposition of fine sediment (silts and sands) is contributing to the dramatic decline in wild salmon.

In order to gain a better understanding of such flow–sediment–ecology interactions in river systems, laboratory experiments are conducted using long rectangular flow tanks called "flumes", see Figures 1A and 1B. Here, traditional techniques for analysing sediment structure are typically constrained to one-dimensional (1D) or two-dimensional (2D) approaches, such as coring, photography etc. Even where more advanced techniques are available (e.g. laser displacement scanning), these tend to be restricted to imaging the surface of the sediment bed. Using magnetic resonance imaging (MRI) overcomes these limitations, providing researchers with a non-invasive technique with which to provide novel three-dimensional (3D) spatio–temporal data on the internal pore structure. In addition, the important sub-surface flows can be investigated by adding MRI contrast agents to the flowing surface water.

Magnetic resonance imaging

Magnetic resonance imaging is based on the phenomena of nuclear magnetic resonance (NMR), which was independently discovered in 1945 by Edward Purcell and Felix Bloch. Both MRI scanners and NMR spectrometers share much of the same hardware and electronics; both use a large static magnetic field, B_0, to induce a net nuclear magnetisation in the sample and pulses of radio-frequency radiation for excitation.[3] Many nuclei (such as ^{1}H, ^{13}C, ^{23}Na, ^{31}P) possess nuclear spin angular momentum and give an NMR signal, though the ^{1}H nucleus is predominantly used in MRI (mainly present in water), as it gives the highest signal and has a high natural abundance (99.9%). Due to the intrinsic nuclear spin angular momentum, the net magnetisation precesses about the static magnetic field (B_0), with the precession frequency $\omega_0=\gamma B_0$, where γ is the magnetogyric constant. In NMR spectroscopy, slight differences in the precession frequency (e.g. chemical shift, *J* coupling) give information on the position of nuclei within a molecule, hence allowing the molecular structure to be determined from the NMR spectra. In the case of MRI, additional hardware called "gradients" are used to add a small linear magnetic field gradient over the sample. In 1973, Lauterbur and Mansfield discovered that performing NMR in the presence of such a magnetic field gradient, effectively linked the precession frequency of a nucleus to its spatial position. This insight allowed the development of MRI, which has important applications in clinical diagnosis with >25,000 clinical MRI systems worldwide. However, MRI has found many other applications from psychology research using functional MRI to chemical engineering and studying transport in porous media.[4]

Fine sediment infiltration into gravel beds using traditional flumes (*ex situ* MRI)

A number of factors affect the siltation process of gravel river beds, including the grain sizes and distributions, pore

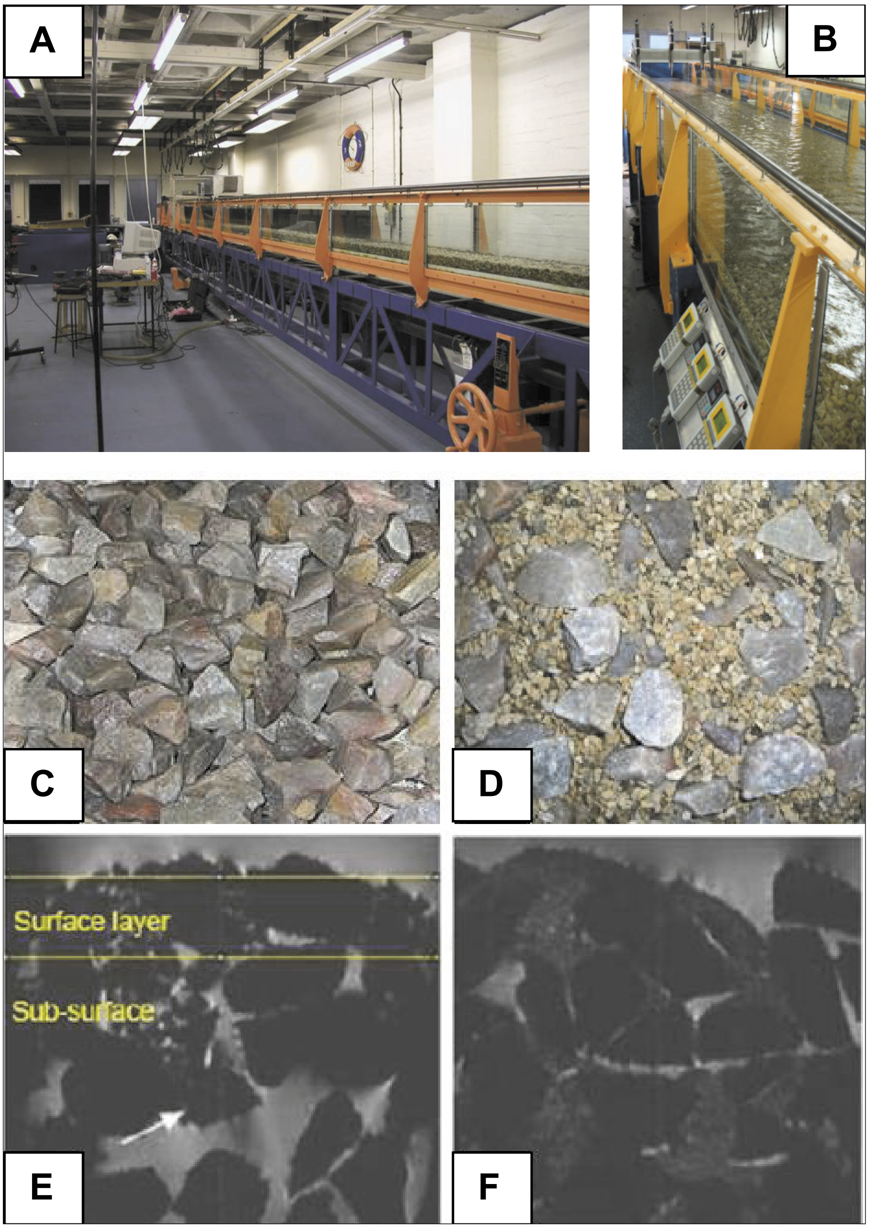

Figure 1. A,B Large traditional re-circulating hydraulic flumes (15 m long × 0.45 m deep × 0.3–1.8 m wide). C shows surface photographs of the initial coarse gravel bed. D shows the gravel bed after deposition of the fine sediment from the flowing water. High resolution *ex situ* MRI was performed on blocks of the river bed. E Cross section MRI showing fine gravel only infiltrating the upper few layer of the bed. F Whereas, the finer sand resulted in deeper infiltration affecting more pore spaces. (Haynes *et al.* 2009)

size, turbidity, local pore structure and near-bed flow velocities and turbulence. In order to better understand the effect of fine sediment siltation on river bed structure we performed a series of large flume experiments. Here, a coarse gravel bed was laid of rose-quartz lithology 17 mm grain diameter. Rose-quartz was used due to its low heavy metal content, reducing image distortion in the MRI. The channel was inclined at a 1 : 200 gradient with water flowing at 7.7 $L s^{-1}$; at this flow rate the coarse gravel framework itself is immobile. Experiments were then conducted by feeding fine gravels (2.4 mm diameter) and sands (0.5 mm diameter) into the flow for a fixed time period.[5] The water transported and redistributed these fine sediments, which eventually settled and infiltrated the coarse gravel bed. At the end of each experiment, sections of the bed were indirectly (i.e. external to the margins of the sample area) frozen with liquid nitrogen and cut into blocks for *ex situ* MRI imaging. These blocks were imaged on a 7-Tesla Bruker Biospec system using a 3-D rapid acquisition relaxation enhanced (RARE) scan at 300 µm isotropic resolution (echo time 11 ms, RARE factor 8, repetition time 5000 ms, bandwidth 200 kHz, volumetric field of view of 104 × 80 × 104 mm, scan time per sample was 21 hours). Figure 1 shows example surface photographs and cross-sections from the high resolution 3D MRI dataset, these MR images highlight the distinct infiltration behaviour for beds subject to different feed grain sizes. The sands resulted in deeper infiltration affecting all pore spaces, whereas the fine gravel resulted in infiltration of only the upper few layers of the bed to form a coarse near-surface "seal". Also, data show that there is considerable spatial variation in the accumulation of fines; some regions are completely or partially filled, while others remain empty.[6] This significantly affects local river bed void ratio and permeability, crucial for the sub-surface hydraulic conductivity responsible for the free exchange of oxygenated water and removal of metabolic waste within the hyporheic habitat.

MRI compatible flume (*in situ* MRI)

In order to take full advantage of MRI, we constructed a re-circulating flume through the MRI scanner, thus allowing serial *in situ* imaging of sedimentary processes and sub-surface flows.[7] For the flume to be compatible and safe within a high magnetic field (7 Tesla) environment it needed to be constructed of non-ferrous material, i.e. Perspex® [poly(methyl methacrylate)] and aluminium. In addition, the size of the flume was restricted by the bore of the MRI system (15 cm diameter) to a 3 m long rectangular cross-section 6.2 cm deep × 9.3 cm wide. This apparatus allowed us to non-invasively image *in situ* a time-series of deposition and infiltration processes specific to fine sedimentation, see Figure 2. In addition, we investigated the sub-surface flows

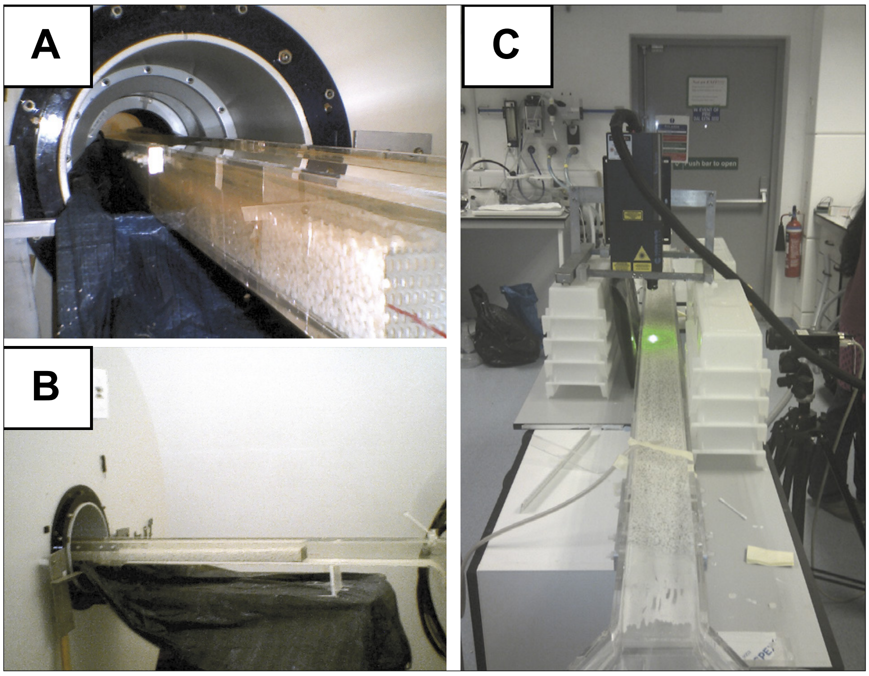

Figure 2. A Photograph of the 3-m long MRI-compatible open-channel flume within the bore of the MRI system. B Side view photograph shows the channel was initially covered with a coarse Dolomite gravel bed. C Shows the flume assembled outside the MRI for particle image velocimetry of the above surface flow.

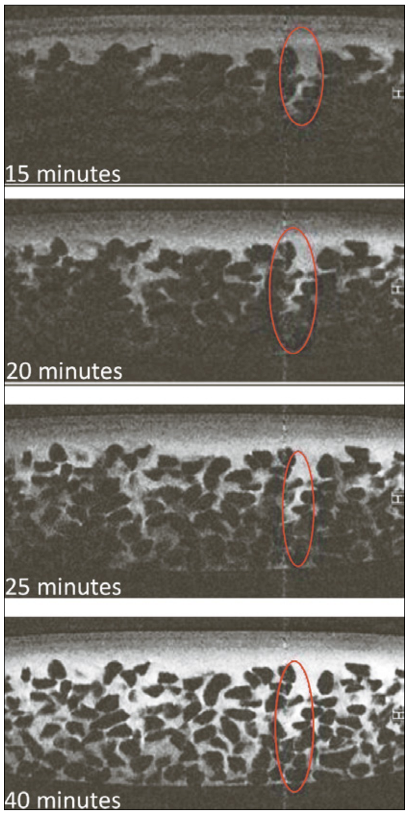

Figure 3. Shows serial T_1 MRI imaging, including the effect of adding a Gadolinium contrast agent to the water inflow reservoir. Slowly the Gadolinium contrast agent penetrates, from the surface flow to deeper into the gravel bed. This appears as increased signal on T_1 weighted MRI. This give an indication of, for example, sub-surface flow exchange, penetration flow velocity and depth, pore connectivity. Rapid penetration of flow through a wide and well-connected surface pore is highlighted in red.

by adding a Gadolinium contrast agent [Gd DTPA (diethylenetriaminepentaacetate)] to the water reservoir. Figure 3 shows serial T_1 MRI imaging; slowly the gadolinium contrast agent penetrates from the surface flow to deeper into the gravel bed. This appears as increased signal on T_1 weighted MRI, giving a measure of sub-surface flow exchange, penetration flow velocity and depth, pore connectivity etc. Moreover, the flume was constructed in three sections, this allowed it to be dismantled and re-built outside the MRI for particle image velocimetry (PIV) experiments of flow hydraulics over the imaged bed, see Figure 2C.

Summary

We have demonstrated that MRI can be used for structural analysis of sediments, both *ex situ* and *in situ* within experimental flumes. The MRI compatible flume allows for serial 3-D high-resolution imaging of the infiltration process and for visualisation of sub-surface flows. In addition, following serial MRI the flume can be removed from the MRI scanner and rebuilt, thus allowing for coupling with "traditional" PIV and laser surface scanning of the same bed. Being able to use MRI to analyse such complex natural processes in 4-D (time and space) now provides an exciting opportunity to unravel a plethora of processes relevant to wider environmental science.

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