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Impacts of river bed gas on the hydraulic and thermal dynamics of the hyporheic zone

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ABSTRACT

Despite the presence of gas in river beds being a well known phenomenon, its potential feedbacks on the hydraulic and thermal dynamics of the hyporheic zone has not been widely studied. This paper explores hypotheses that the presence of accumulated gas impacts the hydraulic and thermal dynamics of a river bed due to changes in specific storage, hydraulic conductivity, effective porosity, and thermal diffusivity. The hypotheses are tested using data analysis and modelling for a study site on the urban River Tame, Birmingham, UK. Gas, predominantly attributed to microbial denitrification, was observed in the river bed up to around 14% by volume, and to at least 0.8 m depth below river bed. Numerical modelling indicates that, by altering the relative hydraulic conductivity distribution, the gas in the river bed leads to an increase of groundwater discharge from the river banks (relative to river bed) by a factor of approximately 2 during river low flow periods. The increased compressible storage of the gas phase in the river bed leads to an increase in the simulated volume of river water invading the river bed within the centre of the channel during storm events. The exchange volume can be more than 30% greater in comparison to that for water saturated conditions. Furthermore, the presence of gas also reduces the water-filled porosity, and so the possible depth of such invading flows may also increase markedly, by more than a factor of 2 in the observed case. Observed diurnal temperature variations within the gaseous river bed at 0.1 and 0.5 m depth are, respectively, around 1.5 and 6 times larger than those predicted for saturated sediments. Annual temperature fluctuations are seen to be enhanced by around 4 to 20% compared to literature values for saturated sediments. The presence of gas may thus alter the bulk thermal properties to such a degree that the use of heat tracer techniques becomes subject to a much greater degree of uncertainty. Although the likely magnitude of thermal and hydraulic changes due to the presence of gas for this site have been demonstrated, further research is needed into the origins of the gas and its spatial and temporal variability to enable quantification of the significance of these changes for chemical attenuation and hyporheic zone biology.

1. Introduction

The hyporheic zone (HZ), herein defined in the sense of Krause et al. [32] as the zone of groundwater–surface water mixing, has become an important and quickly evolving area of interdisciplinary research as its ecological significance and role in controlling the fate and transport of contaminants is being increasingly recognized [5,50]. The HZ is often characterized by a range of redox conditions and associated bacterial activity with anaerobic conditions potentially induced by the presence of labile organic matter, e.g. decaying vegetation and microbiota. Reducing conditions may support denitrification [40,46] and even methanogenesis [21,28,44] and may generate biogenic gases in the HZ. The importance of biogenic gas formation due to denitrification and methanogenesis in groundwater and its influence on flow and transport has been recognized in other hydrogeological settings, for example the contamination of groundwater by biodegradable hydrocarbon fuels [2] or implementation of bioremediation technologies [25]. However, we were unable to find any studies to date on the potential feedbacks of biogenic gas production on the hydraulic and thermal dynamics of the HZ.

Multi-phase flow within subsurface porous media has been examined in various studies on, for example, unsaturated zone flow, transport of immiscible non-aqueous phase liquids, air entrapment and migration in the shallow groundwater — capillary fringe [22] and air-based remediation technology, for example air-sparging [12]. Of greater relevance here though is work conducted on the formation and influence of biogenic gas bubble formation associated with contaminant biodegradation in groundwater systems, albeit not the hyporheic zone [2,25]. In the context of the hyporheic zone, the

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volume of gas present within the pore space will be determined by a complex interplay of factors including the rate of gas production and potential sites for bubble nucleation [35], rates of dissolution, and the degree of advective transport of the gas phase. Unless present in large quantities, gas is likely to be predominantly immobile within the hyporheic zone held by capillary forces. This is because considerable pressure is needed to force a bubble through a pore space and to overcome the resistance to flow offered by detached gas bubbles in capillary conduits [19,42]. Thus, although some movement of bubbles may occur if capillary forces are overcome by viscous and/or buoyancy forces, at high rates of water flow or at times of high gas production, the gas will not flow as a separate phase until the gas content is higher than the trapped gas saturation threshold. This threshold depends on, amongst other factors, the viscosity ratio, wettability, and permeability as well as the geometry of the pore space, with more poorly sorted sediments commonly having higher residual saturations [18]. The maximum residual saturation of a trapped non-wetting phase can be large, for example Fry et al. [18] summarise previous literature values indicating that trapped gas may fill over 40% of the pore space in some cases. They then demonstrate experimentally that the mechanism of gas emplacement is a significant factor in determining residual saturation. Their results indicate that exsolution due to supersaturation may lead to greater values of trapped gas than direct emplacement of gas.

The literature describing gas accumulation within soft sediments is also relevant and shows that growing bubbles, rather than simply filling existing pore space, may also deform the sediments. A useful summary is given by Boudreau [3] indicating that, although the mechanics of uncemented soft sediments during bubble growth are not widely understood, bubbles within muddy cohesive sediments are likely to grow either by fracturing or by re-opening existing fractures. Within soft sandy sediments bubbles tend to be spherical suggesting that the sand acts fluidly or plastically in response to growth stresses, and that bubble rise in such sediments as a result of buoyancy forces can be accomplished by sediment displacement [3].

Although large accumulations of gas are not found in all river beds, the volume of gas present may be significant in some cases and is likely to be highly variable spatially and temporally. This paper begins by developing the theory necessary for understanding the effects of such accumulated gas on the hydraulic and thermal dynamics of a river bed. It then introduces a study site in which accumulations of river bed gas have been observed. The final section tests three hypotheses through data analysis and modelling. The three hypotheses are as follows:

Hypothesis 1. Accumulations of biogenic gas may increase the specific storage and reduce the hydraulic conductivity of the river bed significantly enough to lead to more prolonged flow reversals during storm events, and hence may enhance HZ mixing.

Hypothesis 2. The effective porosity of the river bed may be reduced such that the unreactive transport of solutes through the HZ may be significantly modified.

Hypothesis 3. The thermal properties of the river bed may be altered to such an extent by the presence of gas that the propagation of daily and annual temperature cycles is significantly enhanced.

2. Theoretical development

Theoretical aspects concerning the effect of gas on hydraulic and thermal properties of porous media are now outlined based on existing literature, and extended in relation to the dynamic setting of the hyporheic zone. We examine the effects on specific storage, relative hydraulic conductivity, effective porosity and thermal diffusivity.

2.1. Specific storage

As pressure (p) in the river bed sediments varies, for example due to changes in river stage, water will move in and out of compressible storage. For saturated sediments, the specific storage (S_s) has been defined as follows [17]:

$$S_s = \rho g(\alpha + n\beta) \tag{1}$$

where ρ = water density, g = acceleration due to gravity, n = total porosity, α = compressibility of the sediment matrix and β = compressibility of water.

However, where a gas phase is present, we propose that Eq. (1) may be modified as follows:

$$S_s = \rho g(\alpha + (n-m)\beta + m\gamma) \tag{2}$$

where γ is compressibility of gas, and m is the fraction of bulk volume that is gas filled pore space.

The isothermal bulk modulus of an ideal gas is equal to pressure and relatively insensitive to typical near surface temperatures. In most hyporheic zones, gas compressibility will therefore be in the range 5×10^{-6} to 1×10^{-5} m^2/N for pressures of 2 to 1×10^5 Pa respectively. This is several orders of magnitude greater than either water (around 4.4×10^{-10} m^2/N at 25 °C) or sandy gravel or rock matrices (around 1×10^{-8} to 1×10^{-10} m^2/N [11]).

In addition to the compressibility effect, changes in pressure will also lead to changes in the volume of dissolved gas according to Henry's law. Assuming instantaneous equilibrium between the gaseous and liquid phases and neglecting the partial pressure of water (which is small in this context), it can be shown [26,57] that a first order approximation for the additional specific storage term is as follows:

$$S_{sg} = \frac{\rho g n}{pH} \tag{3}$$

with the Henry's law constant defined as:

$$H = \frac{C_v}{C_w} \tag{4}$$

where C_v and C_w are the concentration of gas in the gas and liquid phases respectively, p is pressure.

Combining Eqs. (2) and (3) gives a first order approximation for calculating the S_s of sediments containing gas and water mixtures as follows:

$$S_s = \rho g(\alpha + (n-m)\beta + m\gamma) + \frac{\rho g(n-m)}{pH} \tag{5}$$

2.2. Relative hydraulic conductivity

It is well known that the presence of a non-wetting phase (e.g. gas) can reduce the relative hydraulic conductivity, K_r, of a wetting phase (e.g. water). A useful summary for the soil science and petroleum literature is given by Fry et al. [18] indicating that K_r may range from 63 to 4% for gas filling 4 to 43% of the pore space. Furthermore, their laboratory experiments showed that the van Genuchten–Mualem [55] model of the unsaturated conductivity function gives a good approximation for fine to coarse sands containing trapped gas bubbles. The relevant van Genuchten–Mualem equation is as follows:

$$K(s) = K_{sat}s^{0.5}\left(1-\left(1-s^{n/(n-1)}\right)^{(n-1)/n}\right)^2 \tag{6}$$