XXXVIII
IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
Ewa Kmiecik

University of Silesia Press 2010

abstract id: **212**

topic: **2**
Groundwater and dependent ecosystems

2.3
Interactions of surface and ground waters

title: **Impacts of river-bed gas on the hydraulic and thermal dynamics of the hyporheic zone**

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keywords: gas, hyporheic zone, hydraulics, thermal dynamics, river-aquifer interaction

Highly variable redox conditions within river bed sediments can lead to the production of gas via a range of microbial processes. The water quality and ecological importance of such processes have become well known. However, the potential feedbacks of biogenic gas production on the hydraulic and thermal dynamics of the hyporheic zone (HZ) has not been widely recognized. In the context of the HZ, gas is most likely to be present as a non-wetting phase in a water-wet porous media and, unless present in large quantities, is likely to be predominantly immobile within the hyporheic zone. It is hypothesized that the presence of immobile gas within the river bed may lead to increased specific storage, decreased hydraulic conductivity and porosity, and increased thermal diffusivity. Conceptual descriptions for the presence of the immobile gas include both the trapped gas saturation and gassy sediment models described in the petroleum and soil science literature.

Using observational data from a short reach of the urban River Tame, UK, and a range of numerical and analytical models we have tested a series of hypotheses in order to quantify some of these effects for the fieldsite. Gas is present within the river bed in quantities up to around 14% by volume, and to at least 0.8 m depth below river bed. Given the indications from hydrochemical data taken from in-bed arrays of multilevel piezometers, it is thought that this gas is predominantly produced by microbial denitrification and, to a lesser extent, methanogenesis. Freeze cores from the site indicate that the carbon source for this microbial activity may be organic rich layers of sediment which have been observed to depths of several tens of cm below the river bed. Analysis and modelling of intensive hydraulic and temperature monitoring collected from the river channel and river-bed have enabled the following summary conclusions to be made for the study site:

- Gas accumulation may lead to an increased proportion of discharge of groundwater from the river banks (relative to river bed) during low flow periods in the river. During storm events the presence of 10% gas by volume in the upper part of the river bed increases the modelled capacity for flow reversal within the centre of the channel by more than 30% compared to water saturated conditions. Furthermore, the same model simulations suggest that in the presence of such volumes of trapped gas, due to the reduced effective porosity, the possible depth of such reverse flows may increase by more than a factor of 2. Figure 1 shows the difference the presence of 10% gas by volume makes to differential heads at 30 cm depth in the centre of the river bed.
- Observed diurnal temperature variations within the gaseous river bed at 0.1 and 0.5 m depth are approximately 1.5 to 6 times larger, respectively, than those predicted for saturated sediments (Figure 2). On an annual basis fluctuations are enhanced by around 4 to 20% compared to literature values for saturated sediments.

The results of the study have important implications for the hydraulic and thermal functioning of the HZ. Hydraulically, the changes in the depth and timing of mixing between groundwater and surface waters of different character will impact the biological functioning of the hyporheic zone on a range of temporal and spatial scales. Thermally, as a fundamental biological variable, such differences in the temperature regime of the river bed due to the presence of gas may be particularly significant for microbial processes and hyporheic ecology. Also, the presence of gas may 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. Quantifying the significance of these changes for chemical attenuation and hyporheic zone biology is beyond the scope of this paper.

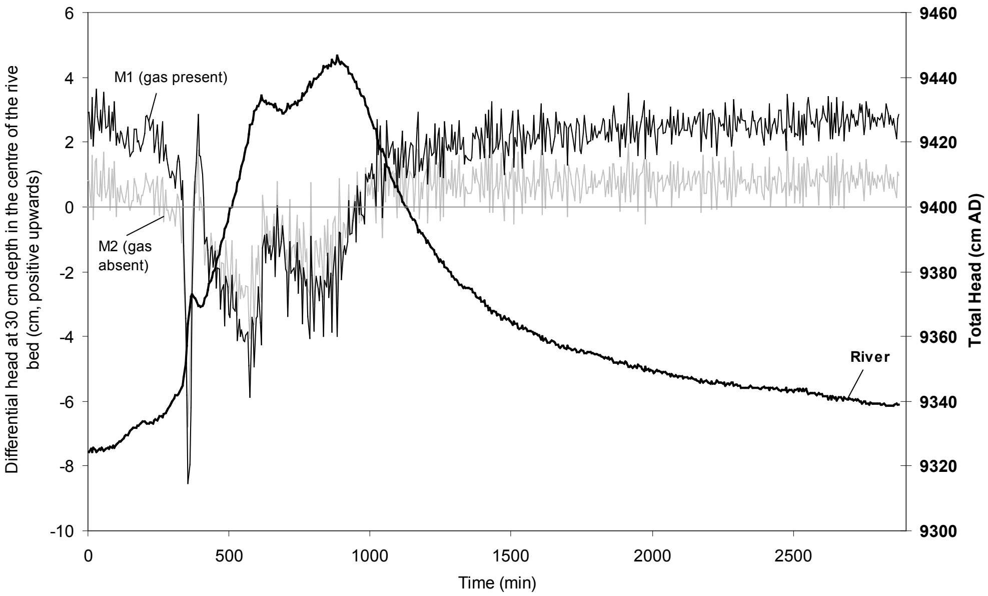
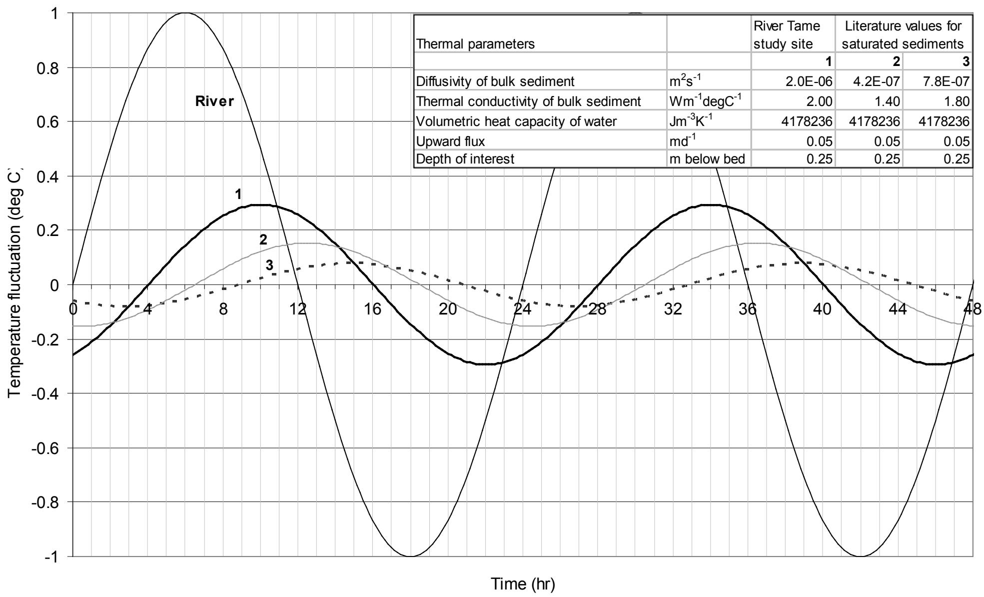


Figure 1. Comparison of modelled river bed differential head relative to head at the base of the river for simulations M1 (gas present) and M2 (gas absent), shown alongside observed river stage.



Thermal parameters		River Tame study site	Literature values for saturated sediments	
		1	2	3
Diffusivity of bulk sediment	m^2s^{-1}	2.0E-06	4.2E-07	7.8E-07
Thermal conductivity of bulk sediment	$Wm^{-1}degC^{-1}$	2.00	1.40	1.80
Volumetric heat capacity of water	$Jm^{-3}K^{-1}$	4178236	4178236	4178236
Upward flux	md^{-1}	0.05	0.05	0.05
Depth of interest	m below bed	0.25	0.25	0.25

Figure 2. Modelled diurnal river bed temperature fluctuations using a range of thermal parameters at 0.25 m depth below the riverbed.

Furthermore, the models used to test the possible changes in hydraulic behaviour due to the presence of gas have been kept highly simplified. In reality, a complex distribution of gas is likely to result in heterogeneity at a range of scales. However the data are not available to support a more complex approach at this stage and further data collection is needed.

International Association of Hydrogeologists

AGH University of Science and Technology

2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0