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Modeling of gas generation from the river adjacent to the manufactured gas plant

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Abstract

Ebullition of gas bubbles through sediment can enhance the migration of gases through the subsurface and potentially effect the emission of important greenhouse gases to the atmosphere. To better understand the parameters controlling ebullition, investigations of the gas ebullition in Grand Calumet river (Indiana, USA) were conducted. We found that gas ebullition might shift and change in different vertical hydraulic gradient and temperature. The CO_2 and CH_4 flux for each site increased with increase of temperature. A comparatively simple linear relationship existed between gas flux and measured parameters ($G_F = 0.316\ T + 300.66i$, $R^2 = 0.82$). The gas flux in sand cap was more variable than that in sediment. Besides, the total field gas fluxes varied from 10 to 180 mmole m^{-2} d^{-1} for sediment and from 5 to 35 mmole m^{-2} d^{-1} for sand cap, which proved in situ sand cap could be an effective remediation. The analysis presented here has shown that gas flues and reactive transport modeling can provide effective means of investigating ebullition and quantifying gas transport.

Keywords: Gas ebullition, Sand cap, Pore water flux, Tar migration

1. Introduction

Freshwater resources pollution by various organic and inorganic contaminants such as Polycyclic Aromatic Hydrocarbons (PAHs) and other chemicals becomes a concern to the researchers. Studies were conducted to investigate the gas ebullition, PAHs contaminants and to better characterize the existing hydrologic conditions around and within a river adjacent to a former manufactured gas plant (MGP) site at Grand Calumet river, Indiana, USA.[1, 2] Surface water of Grand Calumet river indicated that tar and oil droplets migration from sediment was occurring near the former gas station. These indications were problematic, because the tar was a dense non aqueous phase liquid (DNAPL), once it was deposited in riverbed sediment, one typically would not expect it to float up from the riverbed to the water surface.

Different aspects of facilitated migration of contaminants from sediments have been investigated by many researchers, in particular the gas generation from sediment. Gas migration from sediment was found to be a function of changes in air pressure.[3] Changes in hydrostatic pressure due to changing elevation also were found at several field sites to influence rates of gas migration.[4] Sediment temperature was found to influence gas migration from sediment in Lake Sawa, Japan, on a seasonal basis.[5] Long-term trends for methane mass in water were evaluated at Onondaga Lake in New York, USA, and it was found that methane increased through the spring and summer, peaked in early fall, and rapidly decreased in late fall to winter.[6, 7]

Although ebullition was accepted as a potentially important mechanism for the fate of contaminants, no comprehensive studies have reported in literature related to the temperature and elevation effect on it. Palermo *et al.*[8] found that gas ebullition can have a significant effect on sediment stability. Ebullition was the result of a series of processes in which excess gases were generated by micro-organisms from organic matter. The gases release from contaminated sediments were generally methane (46-95%), nitrogen (3-50%), and trace amounts of hydrogen, carbon dioxide, ammonia, and hydrogen sulfide .[9] Most of the gas bubbles originate from the upper 10-20 cm of the sediment column.[10] Martens and Klump[11] reported a range of bubble sizes between 0.062 cm and 0.37 cm with a mean volume of 0.104 ml at a water depth of 7.5 m. Bubbles grew until a pressure threshold was reached as they had to build up a certain amount of buoyancy to overcome the cohesive strength of the sediment and migrate upward. Gas ebullition generally occurred episodically due to changes in pressure and water level which influenced the sediment matrix and thus affected the gas bubble release.[10] Increased hydraulic gradients, atmospheric pressure changes led to a sudden release of gas bubbles which ceases after the excess pressure is relieved. Data revealed that size of the gas bubble depended on the amount of the gas in bubbles, temperature and pressure, where temperature strongly

affected microbial activities as well as the saturation of the gas.[8] Therefore, the purpose of this study was to investigate the rate of gas ebullition and tried to build a gas ebullition model using multivariate regression analysis. In addition, understanding the facilitated migration of the NAPL process is necessary to formulate remedies to reduce the risk from the tarry sediment.

2. Materials and Methods

2.1 Gas collection and analysis

The volume of gas released from the sediment was measured using "gas tents" at five locations within Reach 6, six locations within Reach 7, and one location within Reach 5. Additionally, gas was collected from four of the sand cap test cells, with seepage meter domes in Reach 6. The test cells were installed by Purdue in 2008, and the two sand-only caps and the two sand-organoclay caps were monitored. The sediment near each of these test cells was sampled at the same time as each of the sand caps for comparisons. Fig. 1 showed the general location of gas sampling activities.

[Fig. 1]

Each gas "tent" (Fig. 2) consisted of a frame made from PVC pipe (Schedule 40, 7.6 cm ID) and PVC film (0.2 mm thickness). The area of each gas tent was 6.5 m^2 (3.05 m by 2.13 m). Each tent was held in place with 4 PVC pipes pushed into the sediment. In this way, each gas tent could move vertically as the river elevation changed by floating on the surface of the river. A closable sampling port (vent) was installed through the film near one of the corners. Upon sampling, the input port of an electric pump was attached to the port of the tent, and the output end of the pump to 0.5, 8.1, or 20.3 L Tedlar gas sampling bag. Bags in series were filled completely by squeegeeing the gas (under the PVC film) to the corner where the gas at the vent was actively pumped. To sample the gas released from the sand cap test cells and the adjacent sediment in Reach 6, seepage meter domes were placed in the sand and adjacent sediment, respectively. The area covered by a seepage meter dome was 0.3 m^2, and the port that normally would be connected to the seepage meter flow tube was capped such as all gas emitted from the sediment was collected in a gas sampling bag attached to the central pipe through a connector-valve and flexible tubing (Fig. 2). For each gas sampling event for both the gas tent experiments and the sand cap experiments, gas was collected for at least 7 days, removing (collecting) the gas every few days into the Tedlar bags to measure the volume. Gas ebullition was clearly evident, as streams of bubbles were often observed emanating from the river after a sufficient quiescent period. Alternatively, during the summer, gas release could be induced simply by disturbing the water or sediment surface with a boat oar.

Gases were collected into gas bags and then 1ml gas was subsampled into evacuated 12 ml labco exetainers (Labco Limited, UK). The analysis was carried by using a PDZ-Europa trace gas analyzer (TGA) interfaced to a 20/20 PDZ-Europa isotopic ratio mass spectrometer (IRMS) (Sercon, Crewe, UK).

[Fig. 2]

2.2 Seepage meter

The interfacial flow measuring system consisted of a dome with flow tube and vent, circuit board, and computer (Fig. 3). The dome made by stainless steel had an OD of 61 cm, the height of 19.1 cm, and volume capacity of 28.4 L. The gas vent was a 1.27 cm diameter PVC pipe attached to the top of the dome with a bulk-head flange was of sufficient length to extend above the water surface, allowing gas to escape and water to rise within the pipe to the river's water table level. Closed-cell polyurethane foam, attached to the rim of the dome ensures a water-tight seal. The flux meter and the dome were connected directly using a flow tube. This allowed water to flow between the river and the flux meter at a volumetric rate equal to the rate across the sediment-water surface. As water flowed through the tube, the four thermocouples positioned within the tube at different positions sense the temperature change as a function of time. The volumetric flow rate in the tube was calculated from the temperature-time profile measured by the two thermocouples downstream from the heater, as described in our previous study.[1]

[Fig. 3]

Sediment at the experimental site of Grand Calumet river was composed generally of silt sized particles with high organic matter, consisting of both natural organic matter and coal-tar as reported in our previous study.[10] Fine to medium grain sand layer occurred below this organic rich top layer. Interfacial flow (Darcy flux) was measured at 7 locations (3 within Reach 6 and 4 within Reach 7), (Table S1). Measurements were made at each location between 4 and 8 times over a 15 month period. The first measurement was made near RC3 on March 28, 2011, and the last measurement was made near RC12 on May 25, 2012. On each day at each location, generally between 2 and 6 measurements were made, each requiring approximately 30 to 40 minutes, with the reported Darcy velocity being the average of all values recorded.

142 *2.3 Installation of piezometer*

143 There were fifty piezometers, gas collector sheets and eight stream gauges were installed to
144 monitor the local hydrology and gas ebullition along a 2.5 km stretch of Grand Calumet river (Fig.
145 1). Piezometers were constructed from 4.45 cm OD polyethylene pipe with 20 holes (0.95 cm diameter)
146 drilled into the pipe within 15.2 cm of the capped end. These holes were wrapped with a porous
147 geotextile and aluminum wire mesh to avoid sediment inflow and clogging. The stream gauges (i.e.,
148 piezometer at depth 0) were constructed in the same manner with the holes and screen located within a
149 60 cm segment at a sufficient distance from the capped end to assure they would be located above the
150 sediment-water interface after installation. The piezometers and stream gauges were installed
151 manually by pushing to the target depth. In the river, six piezometer clusters were installed, with each
152 cluster consisting of two piezometers pushed to depths of 1.2 and 2.4 m below the sediment–water
153 interface, and one stream gauge, each located approximately 15 cm apart. The location of each cluster
154 is shown on Fig. 1 and Fig. 3.

155 **3. Results and Discussions**

156 *3.1 Effect of gas ebullition*

157 As shown in Fig. 4, below the water surface 2.0-3.3 m organic-rich sediment layer was 0.3-0.6 m of
158 a fine to medium grain sand layer over a continuous less permeable clay layer. The sand layer was
159 extensive enough to be connected, but not evenly distributed over the site. It presented the schematic
160 of the basic hyro-biogeochemical processes occurring within the sediment as it currently existed (Eq.
161 1 and 2).

162 Active aerobic condition: $\mathrm{MAH, PAH, DOC + Nutrients} \xrightarrow{\text{Microbes, N,P}} \mathrm{CO_2} \uparrow + \mathrm{H_2O}$ (1)

163 Active anaerobic condition: $\mathrm{MAH, PAH, DOC + Nutrients} \xrightarrow{\text{Microbes, N,P}} \mathrm{CH_4} \uparrow + \mathrm{CO_2} \uparrow$ (2)

164 **[Fig. 4, 5]**

165 The measured total field gas fluxes varied from 10 to 180 mmole m^{-2} d^{-1} for sediment and from 5 to
166 35 mmole m^{-2} d^{-1} for sand cap (Fig. 5). Overall, CH_4, N_2, and CO_2 comprised 54.44 ± 8.22 %, 39.72 ±
167 8.92 %, and 5.83 ± 1.21 % (values are means ± SD) of the gas by volume, respectively. The gas
168 ebullition was higher at reach 6, reach 7 and sediment, whereas release of gas at reach 5 and sand cap

was comparatively lower. It was due to the low activity and PAHs at the sand cap layer on contaminated sediment as described by Mclinn and Stolzenburg .[3] It was clear from Figure 5b that the gas flux value of sediment dome was lower than that in sediment PVC device. The reasons were as follows: in comparison to sediment-water interface, there was gas flux in water-air interface which was decomposed by environment microbe in river water. In addition, the content of N_2 has high percentage in the air (78.12%), which solubility is 1/50 by volume. N_2 dissolved in the water could be collected with PVC device by flowing water. Analysis of simulated CH_4 transport provides a measure of the significance of ebullition as a transport mechanism. At RC7b, the total gas produced was 128 mmole m^2 d^{-1}. These large episodic releases indicated that they are commonly not coincident with short-term changes in water table elevation. Therefore many ebullition fluxes may be largely transparent to chamber- and tower-based measurements, and to methods that rely on changing water table elevation to estimate methane fluxes.[12, 13]

[Fig. 6]

As shown in Figure 6, the CO_2 and CH_4 flux for each site increased with increase of temperature. Higher temperatures in spring and summer led to higher G_F compared to fall. The relationship between CH_4 flux of sediment and water temperature was consistent with the results of Delsontro *et al.* [12]. And it was clear that the CO_2 and CH_4 flux values of sediment were higher than that in sand cap. Compare Fig. 6c with Fig. 6f, gas flux in sand cap was more variable than that in sediment. The reason maybe the complex system in sand cap. No bioturbation exists at the cap-sediment interface, and chemical migration processes are also much slower. Therefore, the upward migration of contaminants goes through the sand cap in sediment. The cap materials prevent pollutants enter into the water by adsorption, entrapment, bondage and degradation.[14-16] This function is very similar to the active cap layer or active permeable wall in the treatment of groundwater contamination.[14] Compared to the sediment, the permeability of the sand cap is better, but the volume of the gas flux is lower, which could be due to the sand cap aerobic microbial activity is higher, however, the anaerobic conditions exist in sediment, therefore the volume of gas fluxes in sediment was significantly higher than that in the sand cap (Fig. 5).

3.2 Effect of Hydraulic Head, Darcy flux,

The piezometric head h, is a measurement of the hydraulic head at the point of measurement referenced to some standard elevation. From h values measured in the river stage (h_0), 1.2 m deep ($h_{1.2}$), and 2.4 m deep ($h_{2.4}$), piezometers at each piezometer cluster, vertical hydraulic head gradients i (m m^{-1}), were calculated by dividing the hydraulic head differences between the piezometers by the depth difference dz,

$$i_{a-b} = \frac{h_b - h_a}{dz} \quad (3)$$

Where, the subscripts a and b refer to the position within the sediment where the head was measured relative to the sediment-water interface (h_a is always river level; h_b is the head in one of the piezometers, dz =1.2 m). As shown on Figure 7, the water levels within the 1.2 piezometers were generally higher than the river elevation, over the 5 months of continuous measurement from early May to early September, 2012. The temporal changes in the gradients were minimal, except after high rainfall events when the changes in elevation of the river (h_0) was significant than the changes in water levels within the 1.2 piezometers ($p>0.05$) (e.g., see May 8th, June 17th and August 26).

The vertical Darcy velocities or specific discharges, q, measured at each river cluster position are reported in Table S1. The vertical hydraulic head gradients (i) at each respective river cluster measured manually on the same day when q was measured. Over all measurements, the range in the specific discharge (q) was 0.24 -2.53 cm d^{-1}.

Note that reported the values of the vertical change in hydraulic head (i.e.; magnitude in positive or negative head) was reflected in the corresponding seepage rates that were measured according to Darcy's Law. The vertical hydraulic conductivity, Kv (cm d^{-1}), within the top 1.2 m sediment layer is calculated by dividing q by the corresponding hydraulic head gradient, $i_{0\text{-}1.2}$,

$$K_v = q \times i_{0-1.2}^{-1} = q \times \left(\frac{dh}{dz}\right) \quad (4)$$

Where, dh is the piezometric head difference between the stream gauge and the 1.2-m piezometer, and dz is the elevation difference between the sediment-water interface and 1.2-m piezometer screen (i.e., 1.2m). The calculated values of K_v are reported in Talbe S1 with values ranging from 1.26×10^{-5} to 2.93×10^{-3} cm s^{-1}. The major advantage of the interfacial flow meter system described in this study is the ease with which it can be deployed to measure relatively low flow rates across the sediment-water boundary. Under the lowest flux condition (e.g., q=0.29 cm d^{-1} for RC11 on

5/22/2012; Table S1) discharge across the sediment-water interface through the area circumscribed by the collar was 0.49 ml min^{-1}. With an accurate addition of 3.00 ml min^{-1} with the pump, the fraction of flow due to groundwater discharge was nearly 30%, providing an accurate measurement even at this low flow rate. In some cases, measurements were made with the flow of water into the dome in alternate directions at the same arbitrary flow rate, such that the measured rate of discharge through the tube was either (a) actual flow + pump flow, or (b) actual flow - pump flow. In the latter case, the net flow direction was into the dome requiring T_m (the maximum temperature occurs at each thermocouple) to be measured at the thermocouple on the other side of the heater, nearest to the heater. In this case, the net ground water flow rate is simply the summation of two measured flow rates divided by 2, avoiding the need to accurately determine the pump flow rate.

Discharge and recharge of water from sediment had great influence on the release of gas from tar contaminated river beds. Figure 7 revealed the recharge and discharge trends on different study sites at different depth of river sediment. As shown in Fig. 7a, vertical gradient data at 1.2-2.4 m, RC6, RC5, RC7, RC8 and RC11 had higher vertical discharge, whereas recharge gradient values were found very low at these sites. The gas ebullition rate was also very high at sites where vertical gradient discharge was high. This trend indicated that release of gas also depended on the vertical gradient discharge. The possible reason for this trend might be the pressure release from the site resulted in higher release of gas. The discharge and recharge of vertical gradient rate at 0-1.2 m were not similar as that at 1.2-2.4 m. The deep sediments had high pressure that was responsible for release of gas. Increased hydraulic pressure and vertical gradient or hydrostatic pressure led to a higher release of gas bubbles which ceased after the excess pressure was relieved.

[Fig. 7]

In case of high pressure and discharge rate in sediments, the sediment layer could force newly generated gas bubbles to migrate through the available pores that resulted in breaking up larger bubbles into smaller ones. These bubbles then broke the sediment layer and flew upward according to the vertical gradient discharge trend and pressure into sediments. The size of the gas bubbles and their release rate depended on the amount of gas present in sediments, ambient temperature and pressure.

253 *3.3 Effect of Gas flux, Elevation, Tar migration*

254 **[Fig. 8]**

255 Water elevation played very important role in gas ebullition. It generated pressure in sediment that
256 was responsible for forcing gas bubbles to transport upwards. Fig. 8 showed that gas flux was
257 fluctuating according to the changes in river elevation. It revealed that the gas flux decreased as river
258 level increased. The value of gas flux collected by plastic film for sediment was highest, and the value
259 of test cell for sediment was higher than sand cap at the same time. High elevation generated pressure
260 on sediment layer or sand cap, which forced gas bubbles to move upwards. It could be also concluded
261 that sand cap were still very effective for reducing contaminant's upward flow. The impact of the gas
262 flux and seepage depended on the rate of fluxes and therefore in-situ measurements of these fluxes
263 were required.

264 Pore water flow through the sediments was presumably driven by piezometric head gradients that
265 varied in time due to hydrologic processes. In estuaries, the effects may exhibit shorter time responses
266 due to tidal fluctuations which can create short term variations in the head differences. The highest
267 groundwater discharge corresponds with periods of low water level and could potentially even reverse
268 direction. In the Grand Calumet river, reported measurements of seepage rates ranged from 0.24 to
269 2.53 cm d^{-1}. The groundwater seepage phenomenon could indirectly affect the stability of sediments
270 by altering the consolidation rates in the sediment and changing the bulk density, and thus the erosion
271 resistance. Simon and Collision [12] stated that in addition to the advective flow induced shear stresses
272 on cohesive stream beds, another mechanism contributing to the detachment of cohesive aggregates is
273 upward-directed seepage forces. The range of groundwater fluxes reported in the literature varied
274 significantly, which depended on the sediment type of the bed and other characteristics of the site.
275 Spatial and seasonal variations in the sites where seepage measurements were collected also affected
276 the ranges. Since a vertical upwards gradient of greater than one implied a quick condition, the bed
277 should not be stable due to seepage effects. One possible explanation was that non-Darcy flow through
278 channels may be responsible for the primary transport of pore water through the sediments. This
279 preferred flow would change many aspects of sediment resuspension and mass transfer of
280 contaminants, which should be carefully considered for relevance at a particular site. Experimental

investigations studying seepage effect should be performed considering the possibility of channel formation.

3.4 Linear Regression Analysis Describes Gas Ebullition

A comparatively simple linear relationship existed between gas flux and measured parameters, as shown by multivariate regression analysis:

$$G_F = 0.316\ T + 300.66i,\ R^2 = 0.82 \quad (5)$$

Where G_F is molar gas flux (mmole m^{-2} d^{-1}), T is pore water temperature (℃) and i represents the vertical hydraulic gradient (m m^{-1}).

Under the recharge direction, there would be no relationship between gas flux and vertical hydraulic gradient. As shown in Fig. 7 and Fig. 8, all of vertical gradient data had higher vertical discharge and recharge gradient values were very low in our studies. It indicated that the release of gas also depended on the vertical gradient discharge. As shown in Fig. 9b, Methane flux increased as the vertical hydraulic gradient (discharge) went up. The results were consistent with the previous trend described by Huls and Costello.[17] In previous studies, if the discharge rate was high, gas ebullition was also high, which could affect the erosion rates.[18]

[Fig. 9]

Exploratory factor analysis was performed to assess the robustness of this regression. There were few studies reported in literature related to the temperature and gas flux. However, there were rare in the literature about the parameters of G_F, sediment temperature, and vertical hydraulic gradient. Moreover, no gas ebullition model was reported on the relationship between the vertical hydraulic gradient and the gas flux in the field. There were two models available in the literature corrected to gas fluxes [19]. The model results were converted from a volumetric basis assuming that the top 1 m of the sediment at the field sites is ebullition active to provide a consistent comparison to the measured G_F values and the regression. Both literature models predict substantially higher G_F than those observed in the field. As shown in Fig. 9a, the calculated gas flux matched the measured values better (R^2 = 0.82). Comparison of previous research, these two parameters were able to predict G_F better than all the other measured parameters, explaining 82% of the variation (Fig. 9a). The choice of model for estimating volume of gas within the soil at the bog site depends on the elasticity of the

309 semipermeable, semiconfining layers that allow an interval of overpressured sediment to exist at
310 depth. Rosenberry *et al.*[13] provided a gas ebullition model based on barometric efficiency, this model
311 is not sensitive to the difference between porosity and volumetric moisture content of the sediment.
312 Since the Grand Calumet river has a substantially overpressured interval at depth, it may be
313 reasonable to prefer the overpressuring (or hydraulic head) model over the barometric efficiency
314 model.[13] Beckwith and Baird[20] carried out a laboratory column study using time domain
315 reflectometry probes that indicated a gas content between 5% and 10% by volume. These methods
316 do not provide a direct, in situ measurement for gas volume. The methods described above are based
317 on a destructive/invasive sampling methodology. Sediment samples were collected from peatlands,
318 some of which had been dewatered by natural or man-made causes.[13] They were also instantaneous
319 measurements. Methods used in this paper are noninvasive and nondestructive. In addition to
320 providing an in-situ measure of gas volume, methods presented here provide continuous data,
321 allowing the response of gas volume at different site to be related to climatic drivers. There is no
322 paper reported that the difference between air-water interface and sediment-water interface gas
323 collection.

324 Gas bubbles from sediment of the tar deposit were generated by anaerobic degradation of organic
325 matter, consisting of organic material in the riverbed (sawdust and other detritus), as well as low
326 molecular weight (LMW) PAHs in tar, as discussed by Godsy *et al.*.[21] Compounds which may be lost
327 from the sediments due to gas ebullition could include mono-, di- and trichlorobiphenyl congeners,
328 toxaphene and other semi-volatile environmentally persistent organic compounds. Tar migration to
329 surface water was mostly observed in those areas where both ebullition and tarry sediment were
330 observed. Whereas, ebullition occurred only in a portion of the tar deposit in which the water was
331 relatively shallow and sufficient organic matter in the sediment. It is well known fact that ebullition
332 is a dynamic equilibrium among the degradation of organic carbon, water depth, and sediment
333 strength, such that no one parameter will control gas bubble generation.[13] It could be concluded from
334 the results that gas ebullition increased with Darcy flux and the temperature. The possible reason
335 could be the microbial growth increased with temperature increasing.[10] Microbial activity also
336 increased the amount of gas levels leading to formation of new gas in deep sediments.[10] So gas

production was higher in current study due to the increase in Darcy flux, temperature and microbial growth in contaminated river sediments, which is inconsistent with previous results.[12, 22] The final phase of bubble or contaminant transport from sediments was bubble ejection from the sediments, movement through the water column, and released to the atmosphere. Based on the studies, it was apparent that the transport of sediment-associated organic compounds by way of sediment bubbles may be an important pathway. It should be considered in toxic chemical management plans and models for the Great lakes basin. It was a mechanism by which in place sediment pollutants may be recycled within the basin and could also represent a pathway whereby contaminants could be transported outside of the basin.

4. Conclusion

There is no paper reported that the difference between air-water interface and sediment-water interface gas collection. Hydraulic head gradients and temperature data can be used to estimate volumes of gas bubbles in sediment. Results showed that a comparatively simple linear relationship existed between gas flux and measured parameters ($G_F = 0.316\ T + 300.66i$, $R^2 = 0.82$). Methods used in this paper are noninvasive and nondestructive. In addition to providing an in-situ measure of gas volume, methods presented here provide continuous data, allowing the response of gas volume at different site to be related to climatic drivers. In addition, these results had implications for capping design in ebullition-active sediment sites, which proved in situ sand cap could be an effective remediation for tar contaminated. The analysis presented here has shown that gas flues and reactive transport modeling can provide effective means of investigating ebullition and quantifying gas transport. Further work along this modeling using different sites and gas production rates will lead to a better understanding of the controls on toxic chemical by way of sediment bubbles.

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Figure captions

Fig. 1 Locations of gas sampling activities. RC6 (top) is near the Hohman Avenue Bridge and the railroad bridge is evident by the change in surface topography over the river.

Fig. 2 Schematic of sand cap test cell and photograph of gas collection tent at RC3, with gas evident under the PVC film.

Fig. 3 Schematic of field implementation of the seepage meter system.

Fig. 4 Possible pathway for sediment contaminant transport by gas bubble ebullition.

Fig. 5 Quantity of gas released at different locations, CH_4, N_2, and CO_2 comprised 54.44 ± 8.22 %, 39.72 ± 8.92%, and 5.83 ± 1.21 % (values are means ± SD) of the gas by volume, respectively.

Fig. 6 Gas flux in sediment and sand cap. Plot of gas flux versus temperature.

Fig. 7 Comparative graph of the percent of time under discharge conditions with the percent of time under recharge conditions for the seven river clusters with data loggers.

Fig. 8 Fluctuation of gas flux according to the changes in river elevation and gradient.

Fig. 9 Comparison of measured versus model predicted gas flux. The upper Fig (a) compares measured gas flux values to regression predicted gas flux (dashed line represents 1:1 slope). The lower Fig (b) compared Methane flux values versus the vertical hydraulic gradient (Discharge) values.

Figures:

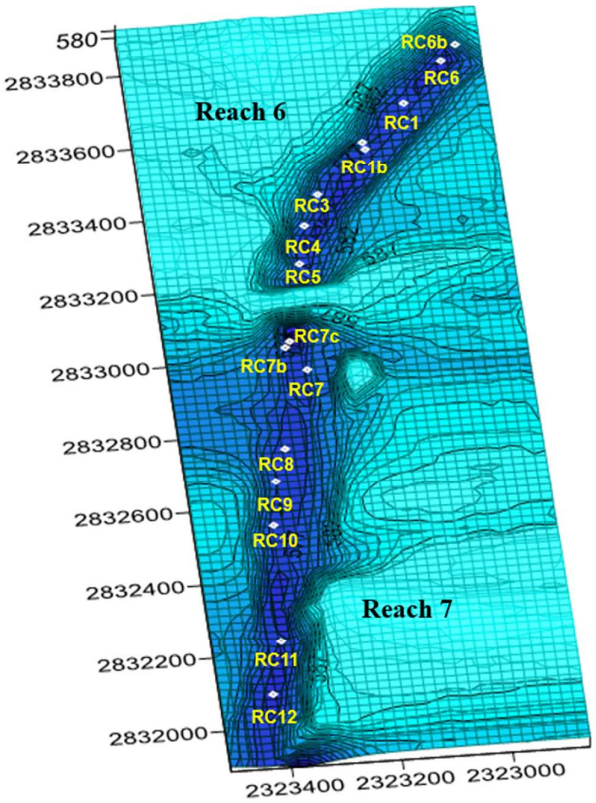


Fig. 1

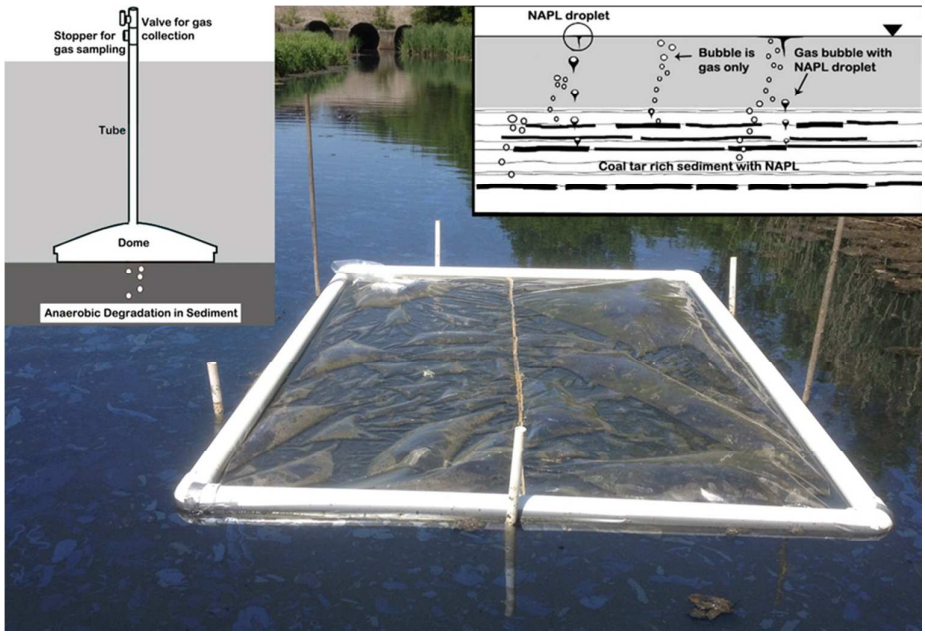


Fig. 2

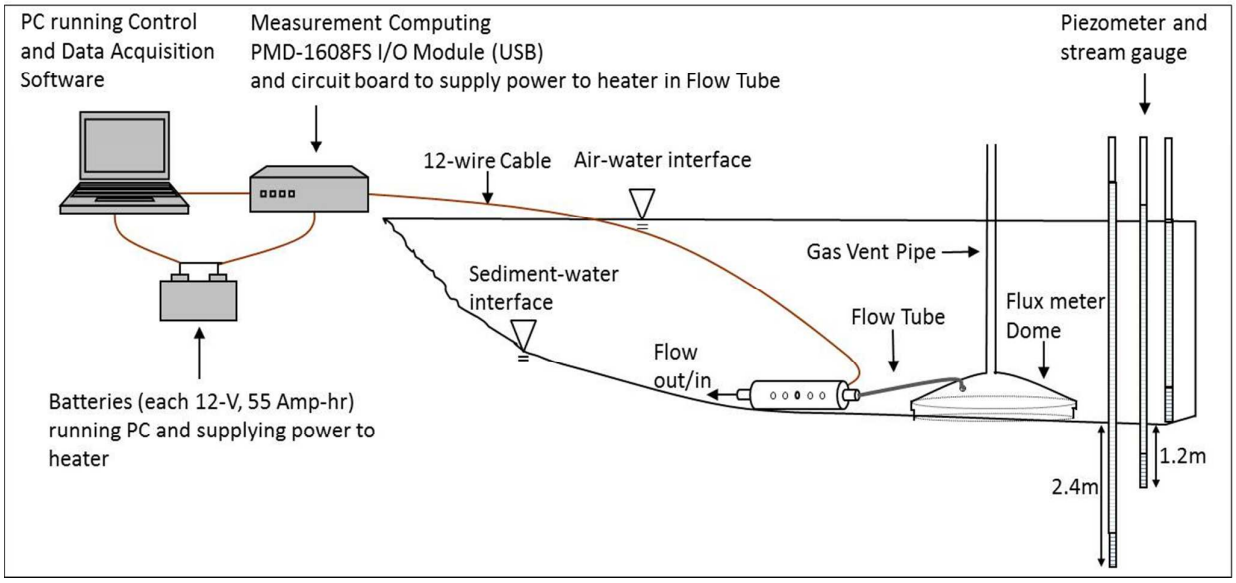


Fig. 3

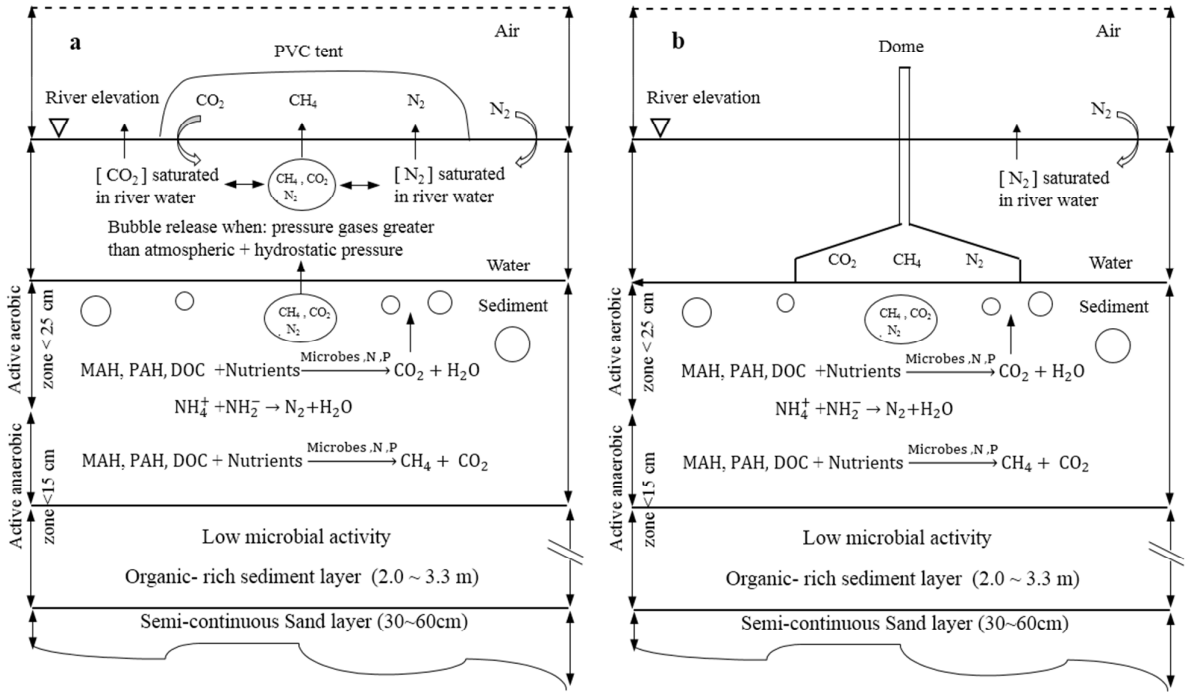


Fig. 4

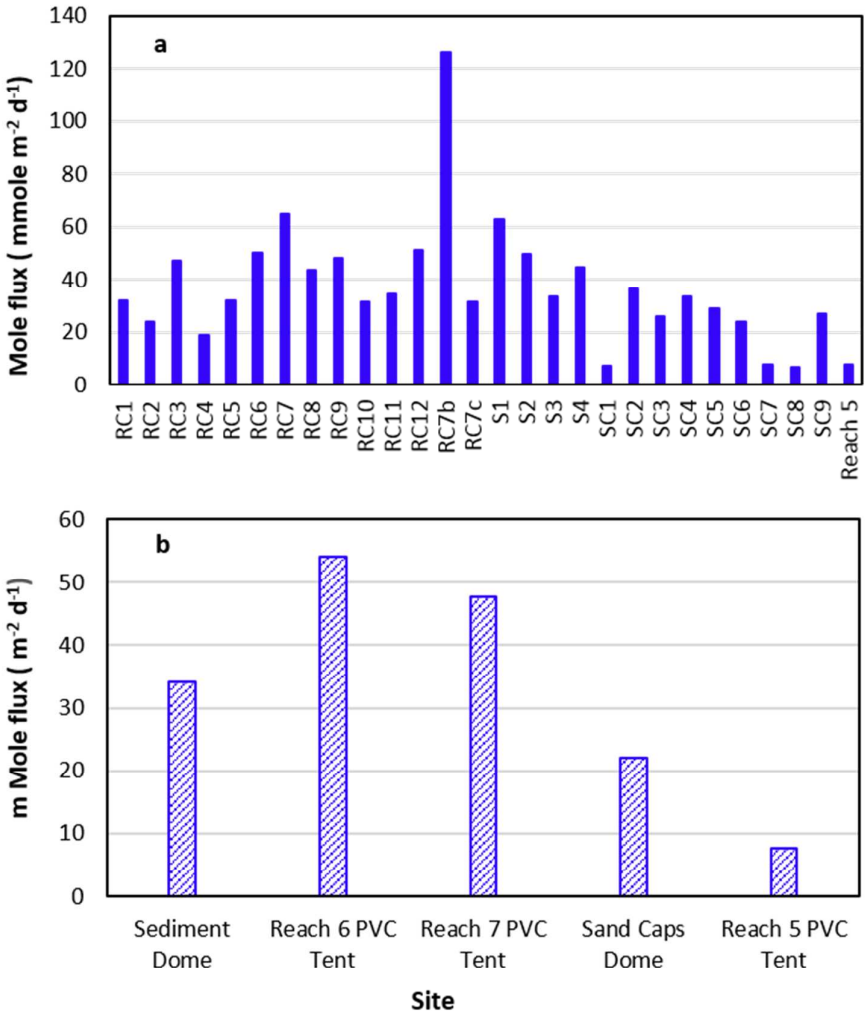


Fig. 5

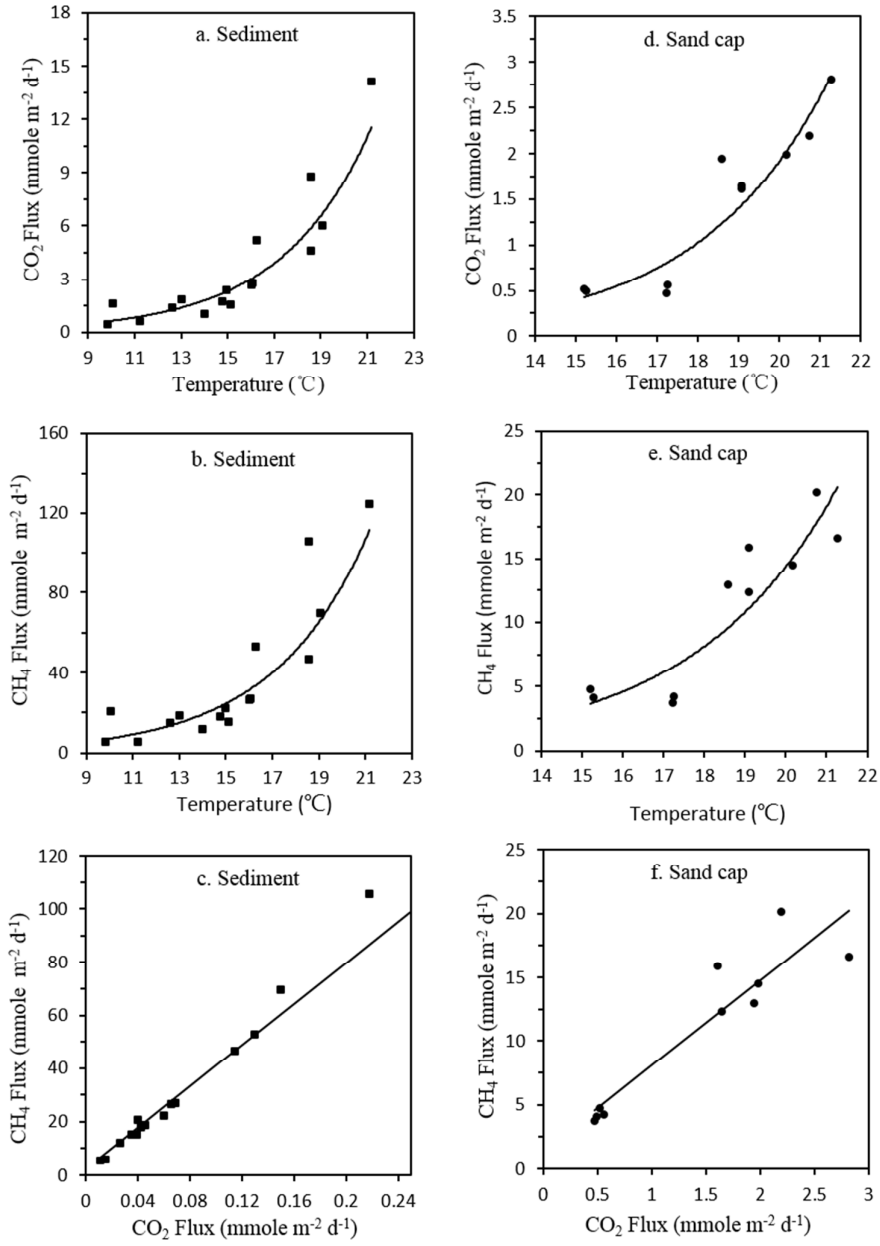
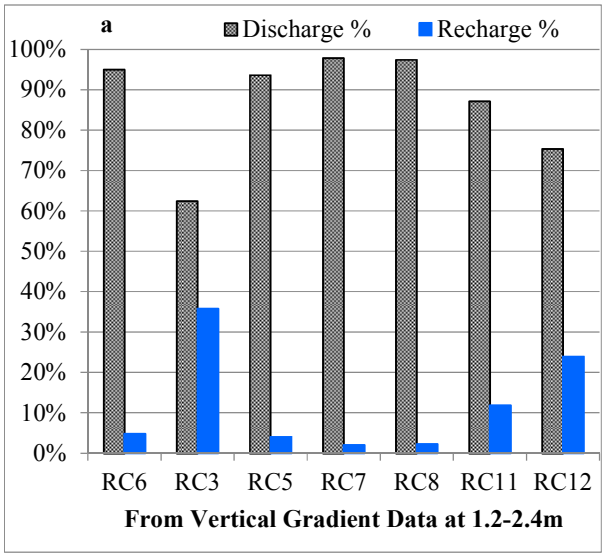


Fig. 6



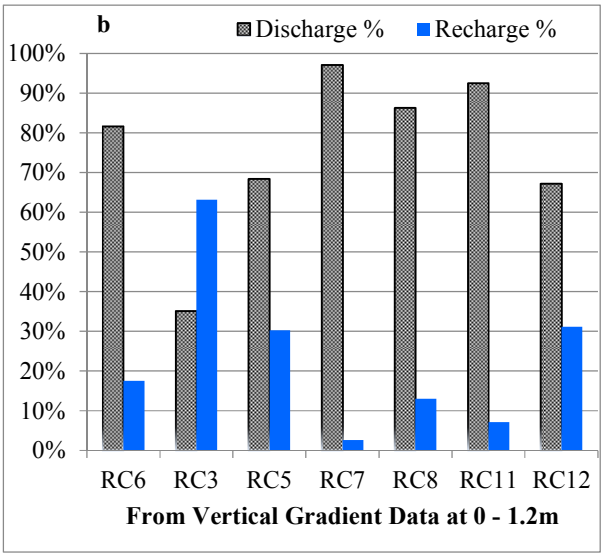


Fig. 7

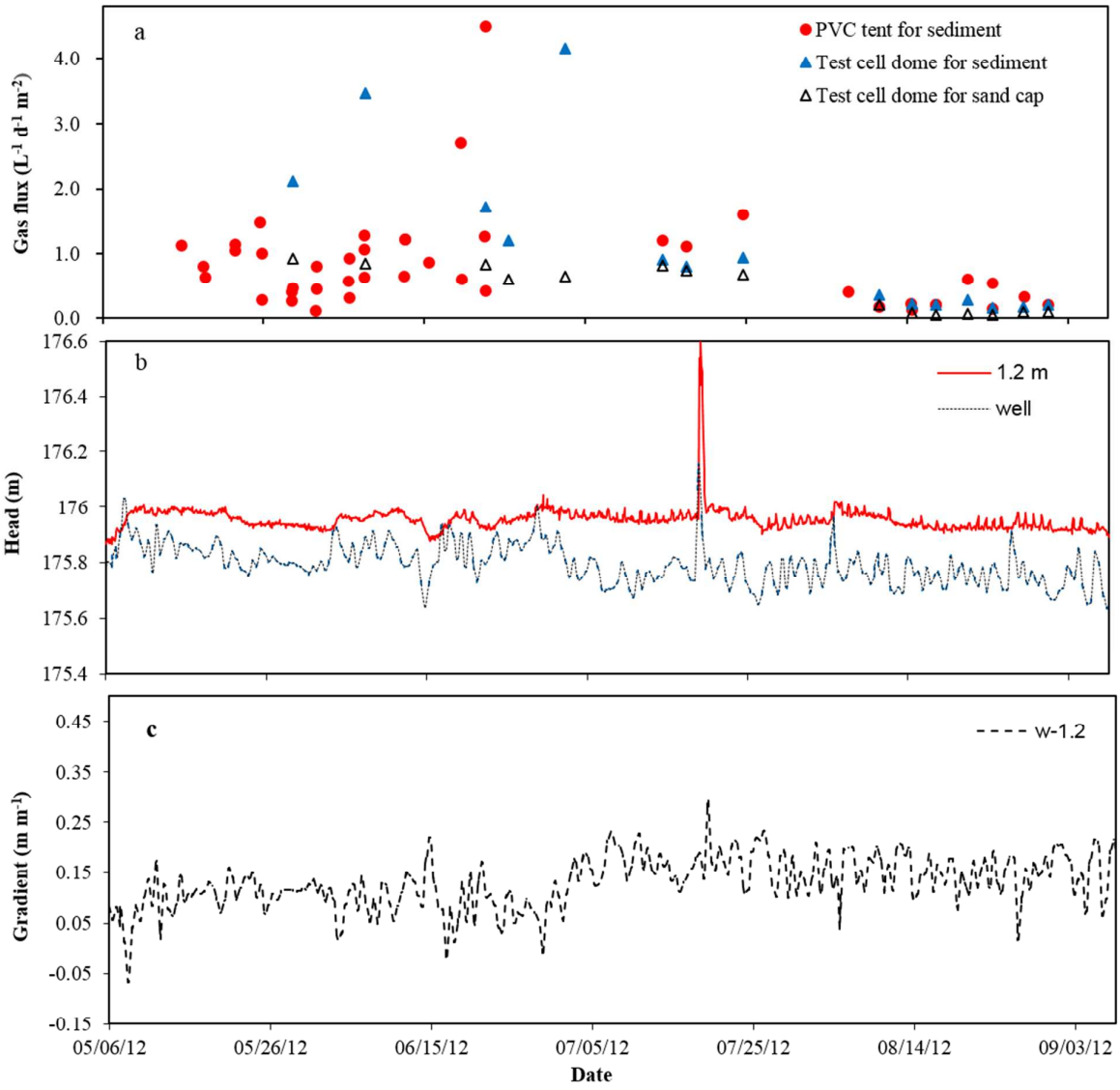


Fig. 8

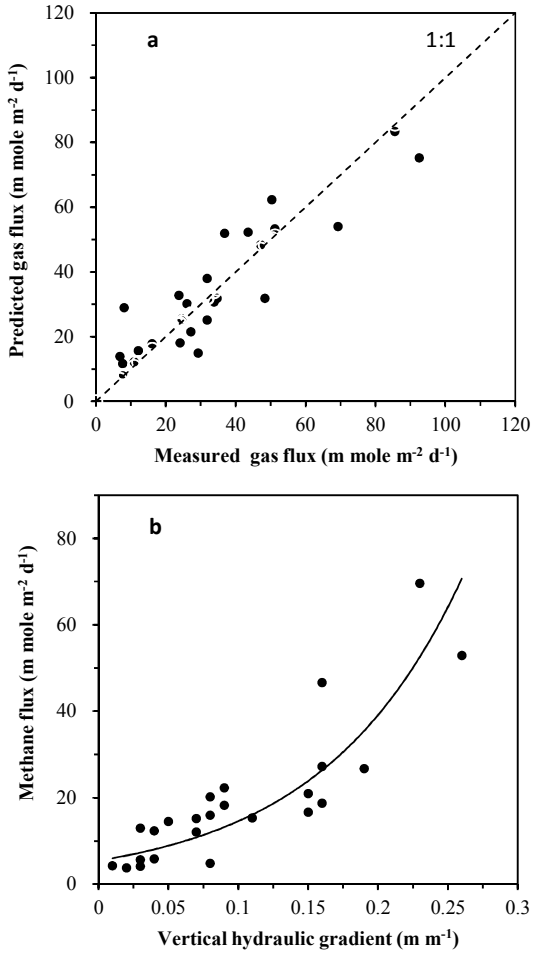


Fig. 9