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# Sorption Kinetics of Hg(II) onto *Potamogeton natans* Biomass

C. Lacher[1] and R.W. Smith[2]*

[1] *Forschungszentrum Karlsruhe, Technik und Umwelt, Institute for Technical Chemistry, Section Water and Geotechnology, Germany*
[2] *Metallurgical and Materials Engineering, University of Nevada, Reno, USA*

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ABSTRACT

The kinetics of sorption of Hg(II) from aqueous solution onto the dead biomass of the aquaphyte *Potamogeton natans* was studied. Chemical and instrumental analyses including atomic absorption, electron microscopy and X-ray energy dispersion analyses were used to elucidate sorption mechanisms. It was found that, although sorption of Hg(II) took place over the entire biomass surface, there were spots on the surface where apparent multilayer sorption of Hg(II) occurred. Kinetic studies and the construction of various adsorption isotherms confirmed multilayer sorption at least on parts of the biomass. The maximum uptake of Hg(II) by *P. natans* biomass is about 180mg/g biomass. The minimum concentration of Hg(II) in solution that can be achieved appears to be limited to about 4-5mg/l. An attempt was made to determine whether or not the Hg(II) sorbed onto the biomass could be removed by elution with an acid or a base. 

Keywords: *Potamogeton natans;* Biosorption; Mercury; Kinetics

## 1. INTRODUCTION

Mercury contamination of waters and soils is a world-wide problem (Smith, 1996; Ebinghaus, 1999; Alpers and Hunerlach, 2000; Domagalski, 2001; Lacher and Smith, 2002). Examples of contaminated soils and water in the Western United States include the Carson River system in Nevada where mercury used in the recovery of gold and silver in the vicinity of Virginia City escaped into both the Carson River and the out-wash soils. California Mother Lode Rivers also suffer from the past use of mercury in the precious metals amalgamation recovery process. Streams and reservoirs in the vicinity of former mercury mining operations such as at New Almaden, California contain elevated concentrations of mercury.

Conventional treatment includes methods such as membrane technology, precipitation, or ion exchange. However, these methods are expensive and do not work well when Hg(II) concentrations are in the range of 1-100mg/l. Using dried biomass as Hg(II) sorbent potentially offers an effective alternative method of treatment. In recent years the sorption mechanisms of heavy metal sorption onto plant biomass have been investigated (Tsezos and Volesky, 1982; Robichaud *et al.*, 1995; Chang and Hong, 1994; Lacher and Smith, 2002). Plant biomass can reversibly sorb metals. The mechanism of uptake is dependent on the composition of biomass and the solution chemistry of the metal ions.

Biosorption can be based on the following mechanisms (Volesky, 1990; Aldrich and Feng, 2000): physical adsorption, ion exchange, complexation, and surface precipitation. Metal removal by precipitation is thought to be an active defense mechanism of living biomass against highly toxic metal ions. However, the precipitation can also occur onto non-living biomass. In the latter case, the metal ions can accumulate within the diffuse part of the electrical double layer through coloumbic interaction between a negatively charged biomass and the metal cation (Schneider *et al.*, 2001). Biosorption may not necessarily consist of a single

* Corresponding author. E-mail: smithrw@scs.unr.edu

mechanism. In many sorption processes more than one of these mechanisms take place and it is difficult to distinguish between the single steps. In this work the Hg(II) uptake by the dead biomass of the aquatic plant *Potamogeton natans* was studied.

*Potamogeton* sp. (pondweed) are aquatic, lightly rooted, partly submerged plants that often grow rapidly and become pests in certain parts of the world. They often must be removed from lakes and waterways. They appear to be suitable as sorbents because of their abundance in natural environments and, also, can be cultured at a rapid rate at low cost (Schneider and Rubio, 1999). Past work (Schneider and Rubio, 1999; Schneider *et al.*, 1999) on the characterization of a closely related aquaphyte, *Potamogeton lucens*, indicates that *Potamogeton* sp. are weak cation exchangers. The species studied in this work, *P. natans*, can be found in slow moving streams, ponds and lakes in North America. A drawing of this plant is shown in Figure 1.

Figure 1. Drawing of *Potamogeton diversifolius* (*natans*) (Anon, 2001)

## 2. MATERIALS AND METHODS

### 2.1. Biological

The *P. natans* studied was obtained from a small Sierra Nevada lake near Truckee, California. The biomass was washed and dried at room temperature. Then it was ground with a blender and sieved on a 500µm sieve. The obtained <500µm particles of the biomass were used directly for the experiments.

### 2.2. Chemicals

All tests were conducted with an Hg(II) bearing solution that was prepared by dissolving mercuric nitrate (Fisher Chemicals) in distilled water. The pH value was adjusted by adding nitric acid or sodium hydroxide solution (Fisher Chemicals).

### 2.3. Chemical analyses

The content of Hg(II) in solution was analyzed by cold vapor AAS (SpectrAA-200, Varian). The pH value was measured using an accumet model 50 pH-Meter (Fisher Scientific). The specific surface area of *Potamogeton lucens* determined by dye adsorption is 415$m^2$/g (Schneider and Rubio, 1999). Other properties are shown in Table 1 (Schneider and Rubio, 1999):

Table 1
Chemical properties of *Potamogeton lucens*

| | |
|---|---|
| Proteins | 21.7 % |
| Carbohydrates | 66.0 % |
| Lipids | 0.9% |
| Ash | 11.4% |
| Ion exchange behavior | Weak cationic |
| Carboxyl groups | 1.5 meq/g |
| Phenolic hydroxyl | 1.3 meq/g |

To investigate the mechanisms of the uptake, dried biomass, before and after uptake, was studied by scanning electron microscopy (Jeol JSM 848A and Kevex Sigma Software). X-ray energy dispersive spot analysis was also performed.

### 2.4. Biosorption studies

#### 2.4.1. Batch studies

Batch processes were used to study the basic uptake behavior of biomass. These tests were carried out in 125ml Erlenmeyer flasks using the ground biomass as a free suspension in water. The biomass was mixed in flasks with the prepared solutions and agitated on a mixing table. During the sorption process temperature, pH value and Eh value were noted. Once apparent sorption equilibrium was reached, the biomass was separated from solution by filtration using vacuum pump and cellulose acetate membranes with a 0.45µm pore size. Samples of the Hg(II) containing solution before and after sorption were analyzed by AAS.

#### 2.4.2. Kinetic tests

Two test series were conducted to examine the time dependence of the uptake capacity. In each series 8 flasks were filled with 100ml solution, which contained 20mg/l Hg(II) ions. 200mg of dried biomass were added to the metal bearing solution and agitated on a mixing table. Each sample was treated a different period of time with biomass to obtain the final concentration in dependence of the treatment time. After a fixed time the biomass was separated from the treated solution by a vacuum filtration. The solution was analyzed for mercury concentration. Results of these experiments were used for the power law rate expression.

#### 2.4.3. Equilibrium tests

Experiments ware carried out at the natural pH value of solutions containing various Hg(II) concentrations and using 10mg of biomass in 100ml solution. After contacting by biomass with solution for 180min, biomass was separated from solution and the solution was analyzed by AAS. These tests were used for describing equilibrium of the sorption process by the construction of Langmuir, Freundlich and BET isotherms.

#### 2.4.4. Column studies

A column of 1.3cm internal diameter and 67cm length was packed with 1g biomass. Here the particles larger than 500µm were used to keep the loss of pressure low. As the pure biomass tends to swell, the biomass was suspended with 50ml distilled water for 1 hour. Then the swollen biomass was filled in the column and fixed there with glass wool. The experiments were carried out by pumping the Hg(II) bearing solution with a concentration of 100mg/l Hg(II) to the top of the column at a flow rate of 100ml/h using a peristaltic pump. The column with equipment is shown in Figure 2. Samples of the column effluent were collected and the concentration of mercury was determined by AAS.

For desorption test the loaded biomass was treated with two different solutions: NaOH and $HNO_3$ solutions.

## 3. RESULTS AND DISCUSSION

In previous studies (Lacher and Smith, 2002), aquaphyte particles treated with an Hg(II) containing solution were viewed via a scanning electron microscope (Figure 3). The relative brightness areas in Figure 3 are a function of the molecular weight of atoms emitting the back-scattered electrons. Bright spots can be observed at certain places on the biomass. The spots are indicative of a high concentration of Hg at certain patches on the surface. X-ray energy dispersive spot analysis obtained by focusing an electron beam on one of the bright spots confirmed this high Hg concentration in the patches. Other images, showed that Hg(II) is sorbed in smaller amounts over the rest of the surface. Beside mercury, the biomass surface also contains iron, chlorine, calcium, carbon and oxygen atoms. Carbon and oxygen atoms are a main component of the biomass material, whereas chlorine, iron and calcium atoms are probably bound at the active sites of the biosorbent. These atoms could be involved in an ion exchange process.

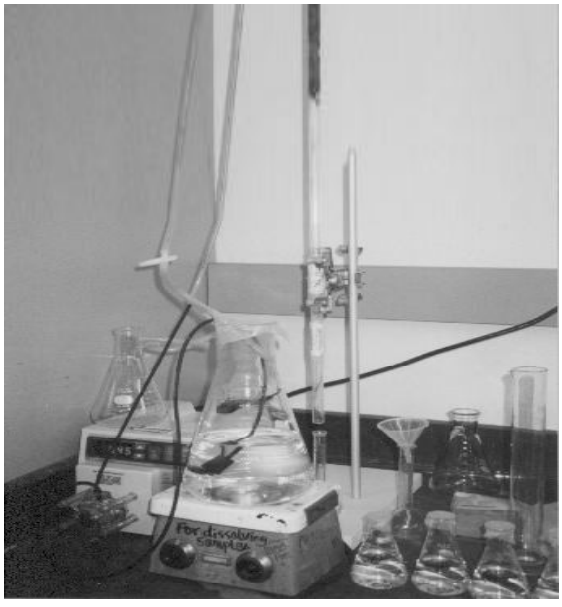

Figure 2. Sorption column used in this work

### 3.1. Sorption kinetics

In general, it is reported that equilibrium between the solid phase (biomass) and liquid phase (wastewater) for biosorption was rapidly established (Costa, A.C.A *et al.*, 1996). Information about equilibrium is very important as only in equilibrium the maximum uptake capacity can be reached. Therefore it is interesting to determine when equilibrium is established.

Another important parameter in elucidating sorption characteristics of *P. natans* is the rate of Hg(II) uptake and the maximum uptake. Therefore the uptake of Hg(II) ions by the biomass was calculated from the obtained final concentrations (Figure 4).

Most of the Hg(II) ions were sorbed within the first 30min. During this time, the Hg(II) concentration was reduced to about 60% of the initial concentration. Thus, after 30min about 89% of the maximum uptake capacity has been reached. After contacting the biomass with the solution for longer than 30min the uptake of Hg(II) ions rises slowly until the equilibration uptake is reached. The equilibrium time was determined to be about 120min.

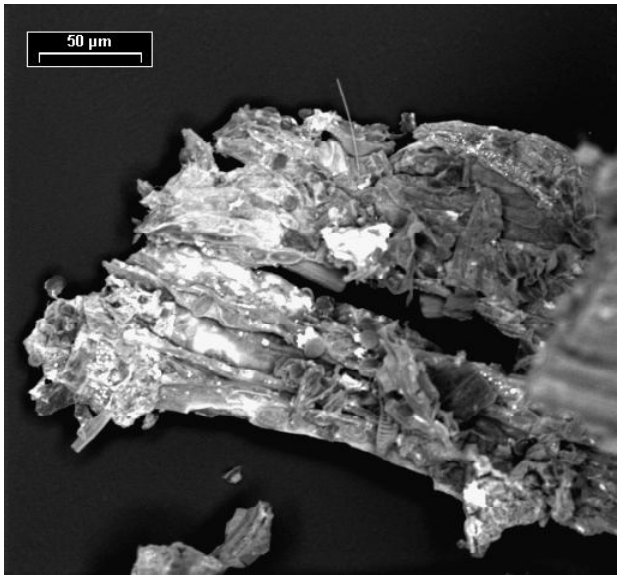


Figure 3. SEM image received by screening information based on back scattered electrons at a magnification of 350x, particle size less than 500µm (Lacher and Smith, 2002)

The plot shows that there are at least two different mechanisms involved. The first one is a rapid step, which is almost finished when the uptake slows down after 30min. The second mechanism is a slower one, as it is shown by the figure. The reason for this slower second step could be a limitation of the sorption because of slow pore diffusion or a completely different mechanism such as surface precipitation. For an industrial application it is not important to reach the equilibrium since a much longer treatment time would not result in significant higher recovery. A further problem could be the recovery of the Hg(II) ions in a following desorption process. As long as the Hg(II) ions are sorbed on the surface of biomass recovery is possible. However, if the Hg(II) diffuses into pores of the biomass the recovery would likely become more difficult.

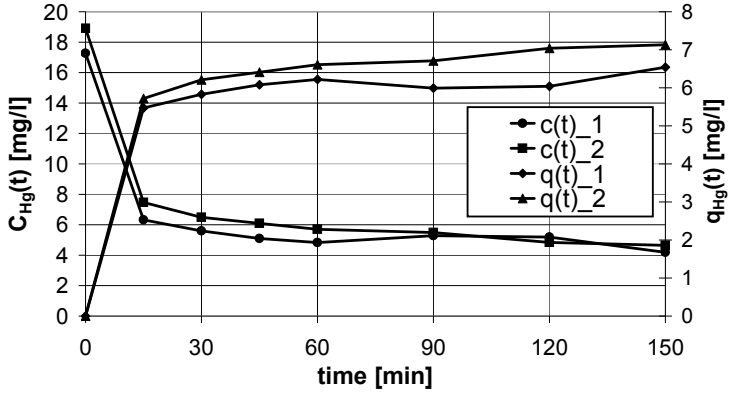


Figure 4. Concentration of Hg(II) in the treated solution as a function of time for two test series (c(t)_1 and c(t)_2) and the mercury(II) uptake of the biomass as a function of time for two test series (q(t)_1 and q(t)_2)

### 3.2. Dynamic rate equation

As any other chemical processes, the biosorption process can be described by a dynamic rate expression (Lai, 1982).

$$\frac{dR}{dt} = k^* \frac{(R_\infty - R)}{t} \quad (1)$$

where R is recovery of mercury at time t, $R_\infty$ is the total recovery of mercury by biosorption and k is a proportionality constant. Figure 5 shows results obtained from the present experimentation.

Integration of equation 1 leads to:

$$\lg \frac{1}{(R_\infty - R)} = k^* \lg t + C \quad \text{or} \quad (2)$$

$$\lg \frac{1}{(R_\infty - R)} = k^* \lg t + \lg a \quad (3)$$

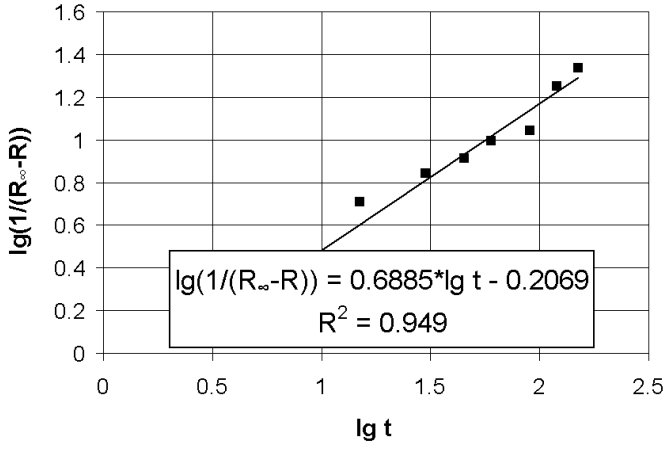


Figure 5. Calculation of the kinetics of biosorption by a power law rate expression

Parameter $R_\infty$ is the key parameter of the empirical kinetic model and describes the maximum uptake behavior of the biomass.

According to Lai, $R_\infty$ can be obtained by a trial- and- error plot of $\frac{1}{(R_\infty - R)}$ versus t on a log-log grid. The best fitting value of $R_\infty$ should give a straight line; all others will lead in curved lines.

$R_\infty$ has been found to have a value of 0.8, which means that 80% of the Hg(II) ions from solution can be recovered. Plotting lg $\frac{1}{(R_\infty - R)}$ versus lg t results in a straight line, the proportionality constant k can be determined from the slope of the curve and the intercept of the curves gives the value of lg a.

Figure 5 indicates that the proportionality constant k has a value of 0.6885 and the parameter a has a value of 0.62. The trendline has a good fit of $R^2$=0.949.

Higher values of k will lead to a steeper slope of the curve in Figure 5 and means that the reaction needs less time for the recovery than curves with smaller values of k. The values found with this method are in good accordance with the values found by Lai.

But one aspect is not considered in this expression. Biosorption aparently is controlled by more than one mechanism. The dynamic rate was created to describe a single mechanism. Although the fit is good the parameters can't be used to elucidate sorption mechanisms.

In order to do so, the construction of adsorption isotherms is necessary to determine these mechanisms (Sag and Kutsal, 1995). Such isotherms include the Langmuir, Freundlich and BET isotherms.

### 3.3. Equilibrium Tests

#### 3.3.1. Langmuir Isotherm

The relationship between the specific metal uptake $q_i$ and the equilibrium metal concentration $C_i$ a proposed by Langmuir can be described by the Langmuir sorption isotherm (Gadd *et al.*, 1987; Volesky, 1990; Garnham, 1997; Kapoor *et al.*, 1997):

$$q_i = \frac{q_{\max} C_i}{k_d + C_i} \tag{4}$$

where $q_{max}$ is the saturation capacity [mg/g dry weight], $q_i$ is the uptake capacity at equilibrium [mg/g dry weight], $k_d$ is the dissociation constant [mg/l], and $C_i$ is the concentration of the sorbed metal species in solution at equilibrium [mg/l].

To obtain the parameters $q_{max}$ and $k_d$, Equation 4 is transferred to the following equation, to receive the values graphically by linearisation.

$$\frac{C_i}{q_i} = \frac{k_d}{q_{\max}} + \frac{C_i}{q_{\max}} \tag{5}$$

$$k_a = 1/k_d \tag{6}$$

The Langmuir isotherm for the present data is shown in Figure 6.

When the experimental data are plotted by $C_i/ q_i$ versus $C_i$ a straight line should be obtained. The parameter $1/ q_{max}$ is identical with the slope and $k_d$ with the intercept. The strength of the bond between metal and biosorbent is expressed by the degree of association,

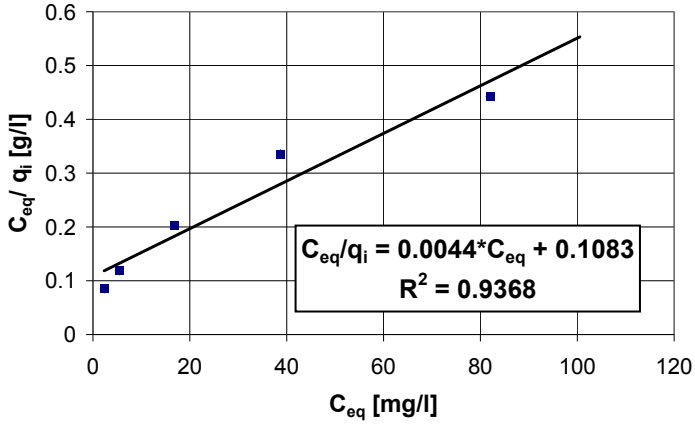


Figure 6. Calculation of the kinetics of biosorption using Langmuir isotherm (experimental results are shown as points)

With the equation, obtained by a straight line fit of the experimental data, it is possible to calculate the two parameters of the Langmuir model: $q_{max}$ and $k_d$. The first parameter, $q_{max}$, has been determined to be 227.27mg Hg/g dry weight biomass and the second parameter, $k_d$, has a value of 24.61mg Hg/l. The fit of the trendline is determined by a value of $R^2$=0.9368.

Similar values, although smaller, have been obtained by Chang, J.-S. and Hong, J. (1994) for Hg(II) biosorption of inactivated cells of *Pseudomonas aeruginosa* PU21 by $q_{max}$=105.4mg Hg/g dry cell and $k_d$=54.6mg Hg/l. This suggests that *P. natans* biomass is a better sorbent for Hg(II) and more efficient for biosorption than *P. aeruginosa* PU21.

Although the Langmuir plot indicates a reasonable fit of the present sorption data several problems exist. One is the obvious curve in the plot of Figure 6, which, again as with the data shown in Figures 4 and 5, suggests two separate sorption mechanisms, an initial rapid sorption followed by a slower mechanism. Another problem is that the Langmuir isotherm is only valid for monolayer sorption. However, the bright spots shown on Figure 3 and the dispersive spot analyses of the bright spots and other areas of the scanning electron micrograph indicate that, at least within the bright spots, multilayer sorption occurs.

### 3.3.2. Freundlich Isotherm

Another equation for isothermal adsorption is the Freundlich isotherm. The Freundlich model is empirical in nature and was developed for heterogeneous surfaces (Kapoor *et al.*, 1997). The Freundlich isotherm can be given by (Sag and Kutsal, 1995):

$$q_i = K_F * C^{\frac{1}{n_F}} \tag{7}$$

where $q_i$ is the equilibrium uptake capacity [mg/g dry weight], $C_i$ is the concentration of the species i at equilibrium [mg/l] and $K_F$ and $n_F$ are the Freundlich constants. $K_F$ is an indication of the sorption capacity of the sorbent in [g/g dry weight] and $1/n_F$ represents the sorption intensity. If $n_F$ is less than unity the forces between the surface layer are attractive and if $n_F$ is greater than unity the forces are repulsive which also means that sorption is favorable. Usually, experimental values of $n_F$ are greater than unity. The advantage of the Freundlich model is that it can be easily linearised by plotting lg $q_i$ versus lg $C_i$. The linearisation is given by:

$$\lg q_i = \lg K_F + 1/n_F \lg C_i \tag{8}$$

A straight line should be obtained where the slope is equal to $1/n_F$ and the intercept represents lg $K_F$. A plot of the present data in the form of a Freundlich Isotherm yields Figure 7.

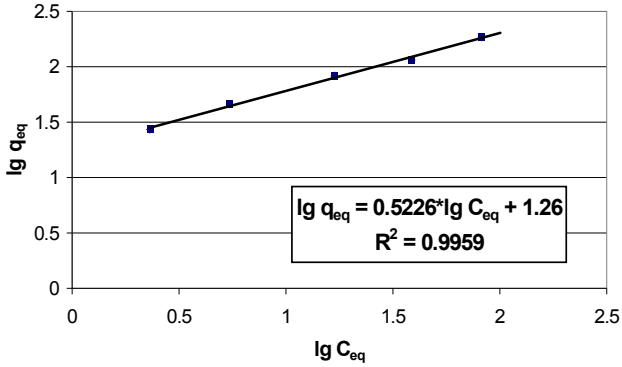


Figure 7. Calculation of the kinetics of biosorption using Freundlich sorption isotherm (experimental results are shown as points)

A fit of the model for the experimental data tends to smooth out the data because of the log-log plot. However, the excellent fit suggests that at least two separate sorption mechanisms exist. The parameters of the Freundlich model are, n and $K_F$. The parameter n has in this case a value of 1.91, that is conform with the demand n>1 to have repulsive forces between the surface layer. The adsorption capacity, $K_F$, has a value of 18.20mg/g. This value of n is similar to values which have been found in other experiments. Mishra (1995) found that Hg(II) uptake by

*casein* can be described by Freundlich isotherm with the parameters n=1.068 and $K_F$=21.00g/g dry weight. The equation of Freundlich fits the obtained data very well, with $R^2$=0.9959. The Freundlich model may fit better than the Langmuir because of the obvious roughness of the sorbent's surface. The model, however, also assumes monolayer coverage.

To describe a multilayer adsorption at the sorbent surface the BET isotherm is used. A further assumption of the BET model is that a layer need not be completely formed before the next layer is already started. Also it has been assumed that the Langmuir isotherm applies to each layer and therefore the model is reduced for a monolayer sorption to the Langmuir model. Finally it has been assumed that each layer has an equal energy of adsorption.

### 3.3.3. BET Isotherm

The BET isotherm is given by the following equation (Kapoor *et al.*, 1997):

$$\frac{C_i}{C_s - C_i} = \frac{1}{BQ^0} + \left(\frac{B-1}{BQ^0}\right)\left(\frac{C_i}{C_S}\right) \tag{9}$$

where $C_s$ is the saturation concentration of the metal ion [mg/l], $C_i$ is the equilibrium concentration of the metal ion [mg/l], $Q^0$ is the amount adsorbed per unit weight of biomass for monolayer biosorption [mg/g], and B is a constant relating to the energy of interaction with the surface. To obtain the parameters of this model a plot of $C_i/(C_s-C_i)$ versus $C_i/C_s$ is used. The slope of the straight line gives the value of $(B-1)/BQ^0$ and the intercept gives the value for $1/(BQ^0)$. Then the parameters B and $Q^0$ can be calculated by the given values.

This model is unlike the former ones since it is based on a multi-layer sorption. The resulting isotherm is presented in Figure 8.

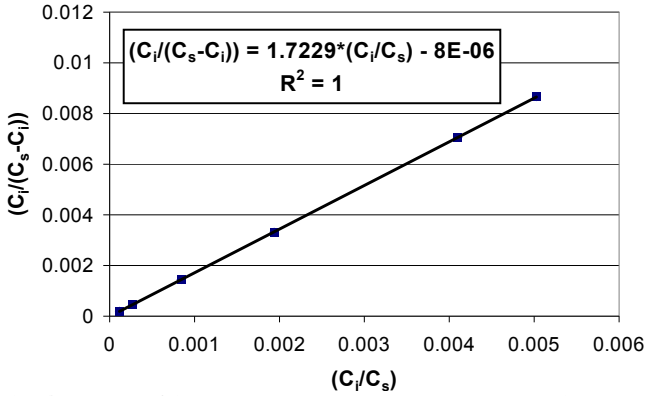


Figure 8. Calculation of the kinetics of biosorption using BET sorption isotherm (experimental results are shown as points)

It can be seen, that the BET fits the data best $R^2$=1. Thus, the characteristic parameters of the BET isotherm are determined as: B=-215361.5 and Q°=0.58042 [mg/g dry weight]. A comparison with other literature data is not possible since there are no values given in literature for the biosorption process. The BET isotherm shows a fit of $R^2$=1. However, the initial Hg(II) concentration, which has been used for the experiments, is far from saturation concentration. The difference between saturation and initial concentration is so huge that finally a straight line is obtained may contain little information about mechanisms involved. However, the good fit is consistent with multilayer sorption, especially when compared to the poorer fit of the Langmuir plot.

All isotherms describe the obtained experimental data well. Although the fit of the Langmuir isotherm is the poorest in comparison of all three models and has serious obvious flaws, it may be used for practical calculations of the sorption process. This isotherm describes the maximum

uptake capacity with a value of $q_{max}$=227.27mg Hg/g dry weight, which is consistent with actual experimentation.

### 3.4. Column studies

To study the properties of *P. natans* for industrial application, column studies were conducted. A typical result for the column studies is shown in Figure 9.

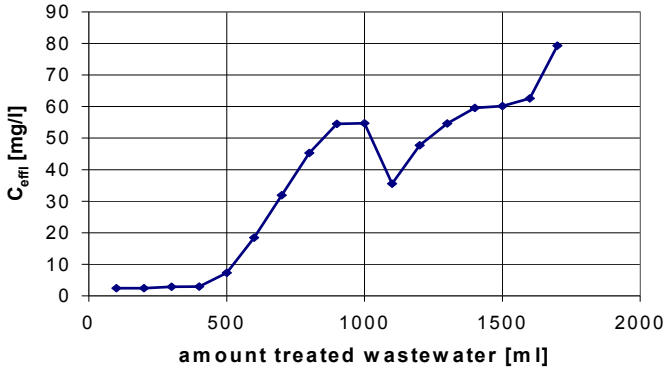


Figure 9. Fixed bed column treatment of a 100mg/l Hg(II) containing solution

The breakthrough couldn't be reached in this test, although a highly concentrated solution was taken. The breakthrough curve showed the typical 'S' shape until 900ml of solution had been treated. The steep decrease after 1000ml treated solution takes place because the experiment has only been conducted during day and rested during nights. After the first day, most of the active sites had been already occupied. While the experiment was resting at night the ions which were bound on the surface had a possibility to diffuse to unoccupied active sites inside the porous structure of the biomass. When the experiment started the next day again, more active sites on the surface had been free than the day before. This explains why the biomass could sorb more ions as at the end of the last day.

### 3.5. Desorption

The desorption solution fulfills two different functions (Wang, 1995). First the sorbed metal ions must be stripped from the binding sites to regenerate the biosorbent for the next cycle. Secondly it should provide an eluate from which the valuable metal ions if present can be recovered. For the desorption test the loaded biomass was treated with two different solutions: NaOH and $HNO_3$ solutions. Other authors have reported that biosorption of Hg(II) ions is a pH independent process (Butter *et al.*, 1998) and suggest use of mercaptoethanol (Gadd, 1990) as a desorption eluant. However, the results of this work showed that there is a pH dependence of Hg(II) sorption and desorption.

In case of NaOH as a desorption solution, an Hg(II) recovery of 64% was obtained. This may not be sufficient. In addition, the high pH value leads to a loss of color of the biomass, which indicates a destruction of the biomaterial. With $HNO_3$, however, a recovery of 80.7% can be obtained and the desorbed Hg(II) solution is highly concentrated. Thus, it should have sufficient metal concentration for a recovery process. No attempt was made to reuse the biomass for additional loading and elution cycles. Although the Hg remaining on the biomass may significantly reduce Hg(II) uptake in subsequent cycles, the problem may not be serious if a steady state loading and elution sequence is set up. Additional experimentation is required to explore this possibility. Other possible eluants such as mercaptans should also be studied.

## 4. CONCLUSIONS

This work shows that dead *P. natans* biomass can be efficiently used as sorbent for Hg(II) because it is a natural occurring biological material that is sometimes an invasive aquatic pest. If it must be cut from ponds and waterways for various reasons, it may be obtained for very little cost, perhaps mainly for transportation costs. *P. natans* biomass also can be cultured at rates up to100kg/ha/day (Schneider *et al.*, 1999). It has also been shown that this biomass is highly suitable for Hg(II) recovery from wastewater and has an uptake capacity of over 200mg Hg(II) per g dry biomass. Furthermore, *P. natans* biomass is a particularly good sorbent for removing Hg(II) from very dilute solutions.

The time dependence characteristics showed that this sorption process consists at least of two different mechanisms. The first is a very rapid step leading to an uptake of about 90% of the maximum uptake followed by a second, much slower, step. Also, it has been shown that the pH value of the treated solution is important for the uptake capacity. An optimum uptake was reached at a pH value of 9-10 (Lacher and Smith, 2002). The initial Hg(II) concentration of the wastewater is also a factor affecting the uptake capacity. With an increasing initial Hg(II) concentration the uptake capacity also increases. At the same time the percentage removal decreases. SEM studies showed clearly that Hg is sorbed all over the surface of a biomass particle. However, certain bright spots (Figure 3) were observed on the biomass surface that contained much larger concentrations of Hg. These high Hg spots may be due to surface HgO precipitation, perhaps on particularly active sites. Such surface precipitation may involve exceeding the solubility of HgO within the electrical double layer because of the increase in Hg(II) in the diffuse part of the double layer due to coulombic effects (Schneider *et al.*, 2001; Dzombak and Morel, 1990). The second, slower, step may involve diffusion into pores on the biomass surface. All of these steps probably involve some manner of ion exchange. It also should be noted that solid $Hg(OH)_2$ is not stable and spontaneously coverts to HgO. In addition the dead biomass may reduce Hg(II) to Hg(I) and/or $Hg^0$.

Column studies were conducted to test *P. natans* for application in wastewater treatment. Although a reduction of uptake capacity in the packed bed column was observed, the biosorbent still had good uptake properties. Because biomass tends to swell upon wetting, the biomass was mixed with distilled water before it was packed in the column. A porous bed was obtained which could be treated with wastewater without a high pressure drop.

For regeneration of biomass NaOH and $HNO_3$ solutions have been tested. Desorption of Hg from the biomass with the NaOH solution produced a green colored concentrate which indicates a damage to the biomass. A $HNO_3$ solution was a more effective eluate, and 81% of the sorbed Hg could be recovered.

## ACKNOWLEDGEMENT

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## LIST OF SYMBOLS

| | |
|---|---|
| B | constant, relating to the energy of interaction with the surface [-] |
| $C_{eq}$ | concentration of the sorbed metal species in solution at equilibrium [mg/l] |
| $C_i$ | concentration of the sorbed metal species in solution [mg/l] |
| $C_S$ | saturation concentration of the metal ion [mg/l] |
| k | reaction velocity constant, using power law rate expression [1/min] |
| $k_d$ | dissociation constant [mg/l] |
| $K_F$ | Freundlich constant, indicating sorption capacity [g/g dry weight] |
| n | order of reaction, using power law rate expression [-] |
| $n_F$ | Freundlich constant, representing the sorption intensity as 1/nF [-] |
| $Q^0$ | amount adsorbed per unit weight of biomass for monolayer sorption [mg/g] |
| $q_{eq}$ | uptake capacity of the biomass referring to the metal species at equilibrium [mg/g dry weight] |
| $q_i$ | uptake capacity of the biomass referring to the metal species [mg/g dry weight] |
| $q_{max}$ | saturation capacity [mg/g dry weight] |
| r | reaction velocity [mg/(l*min)] |