# Modelling the Filtration of Surface Mineral Extraction Waste Water by Reed Bed Treatment Systems

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**ABSTRACT**

The exploitation of mineral reserves can create large volumes of sediment laden waste water which must be treated before being discharged into the local water bodies. In the face of increasing pressure to improve the standard of water treatment, doubt has been cast upon the ability of conventional sedimentation lagoon techniques to meet the required discharge consents. Secondary treatment, using reed bed treatment systems (RBTS), has been proposed as part of a more robust water treatment strategy.

The ability of an RBTS to remove inert suspended solids from mineral extraction waste water was examined. A model was developed to examine the theoretical filtration efficiency of horizontal flow reed beds with and without a gravel substrate when used as a secondary or tertiary treatment method. Estimates of performance using the model indicated that both designs could reliably provide the high quality, polished effluent required. The reed bed without a gravel substrate was, however, found to be the more effective design for the filtration of inert suspended solids.

## INTRODUCTION

### Surface Mineral Extraction Waste Water

In their recent report: to the Department of the Environment: Environmental Effects of Surface Mineral Workings[1], Roy Waller Associates concluded that further research into the quality of surface water discharge was desirable. The study stated that "discharge of water with levels of suspended solids which are damaging to the receiving water course is widespread". The pollution was attributed to the inability of conventional sedimentation lagoons to be a completely reliable method for the removal of suspended solids. Alternative methods of suspended solids removal were examined and it was suggested that discharge from sedimentation lagoon systems may often need to have secondary treatment, e.g. by a reed bed treatment system (RBTS).

**Reed Bed Treatment Systems**

The use of vegetation to filter suspended solids from opencast mine waste water is widespread in the USA [2], reed beds and more elaborate wetland systems have been employed to remove heavy metals [3], [4], [5] and ameliorate acid leachate [6], [7]. The treatment of domestic sewage using RBTSs is well established in the UK and USA [8], [9]. However, there appears to be no published reference on the use of reed beds in the manner suggested by the Department of the Environment report.

The filtration of mine waste water poses particular problems because the inert mineral nature of the suspended solids means that they cannot be broken down by biochemical oxidation, as occurs during the treatment of organic effluents. Therefore, once the solids have been removed from the effluent flow, there is no biochemical action to reduce their bulk and the reed bed must rely on the composting effect of the reed litter to help immobilise the deposited material. Thus, vertical flow reed beds, designed to maximise oxidation [10], were considered inappropriate for the filtration of inert solids and attention was concentrated on the horizontal flow reed beds.

There are two main types of horizontal flow reed beds [8], [9]. Sub-surface flow reed beds are constructed with a gravel substrate, typically 0.6m in depth [11], through which the effluent is passed. Surface flow beds have no gravel substrate and all of the effluent flow is through the reed stems. A reed bed with a gravel substrate can sometimes exhibit combined surface and sub-surface flow when the hydraulic conductivity of the bed is insufficient to accommodate all of the fluid flow.

The aim of the study was to construct a model for the filtration of inert suspended solids by the reed bed types described above and thereby assess their theoretical filtration efficiencies.

## MODEL DEVELOPMENT

The following sections describe the model components and development of the theory required to carry out the simulation of their filtration performance.

When modelling the filtration characteristics of a reed bed both the bed substrate and the reed components need to be considered.

**The Bed Substrate**

It was assumed that the filtration characteristics of the bed substrate are similar to those of deep bed filters used by the sewage and water treatment industry to clarify and remove suspended solids and bacteria from waste water.

Despite their long history of use, it is not possible to derive a mechanistic model for the efficiency of a deep bed filter from a knowledge of its physical characteristics alone. Detailed experimentation is required before a mechanistic approach can be taken for any particular filter. This level of experimentation fell outside the scope of this study.

It is, however, possible to model the removal process empirically as a first order decay expressed as follows [12].

$$-\frac{\partial C}{\partial L} = \lambda C \tag{1}$$

where C is the concentration of suspended solids (mg/l)
L is the length of the filter (m)
$\lambda$ is the filter coefficient (1/m).

Equation (1) assumes that when the filter is clean each layer of the filter is equally efficient at removing particles and that the particles are uniformly distributed throughout a layer. At the start of filtration, Equation (1) can be integrated to give:

$$C = C_0 \exp(-\lambda L) \tag{2}$$

where $C_0$ is the initial concentration of suspended solids (mg/l).

Equation (2) describes the filtration action of a clean filter, but as the number of particles filtered from the fluid builds up, the characteristics of the filter will change, becoming less efficient Thus, as filtration proceeds, the filter coefficient for each layer of the filter will decrease [12].

There are a number of mathematical models in which $\lambda$ is a function of the specific deposit, $\sigma$, where $\sigma$ is defined as the volume of filter deposit contained in a unit volume of filter. The simplest of these assumes that $\lambda$ declines linearly with $\sigma$ [12]. As the maximum value which $\sigma$ can have is the initial porosity, $\varepsilon_0$, the model is as follows.

$$\frac{\lambda}{\lambda_0} = \left(1 - \frac{\sigma}{\varepsilon_0}\right) \tag{3}$$

where $\lambda_0$ is the initial filter coefficient (1/m).

Equation (3) states that when a filter layer is completely full of filtered sediment then no further filtration will occur in that layer and is consistent with one of the two possible results of prolonged filtration. This is that the layer filter becomes completely blocked so that no fluid flows through that layer. The fluid must then by-pass the layer in order carry on through the filter; corresponding to surface flow for a gravel bed.

The second possibility is that as the filter fills with sediment the pore spaces become constricted and the interstitial velocity increases to the point at which the rate of sediment deposition equals the rate at which it is scoured by the flow. This means that no net deposition occurs. In this case an alternative model for the decline of the filter coefficient has been proposed as follows [13].

$$\frac{\lambda}{\lambda_0} = \left(1 - \frac{\sigma}{\sigma_u}\right) \qquad (4)$$

where $\sigma_u$ is the specific deposit at which no net deposition occurs.

As with the mechanistic approach, the use of Equation (4) is impossible without the detailed experimentation required to determine $\sigma_u$.

Equations (1) and (3) were used as the basis of the gravel bed filtration model for this project because of their simplicity. The physical properties of the bed which remained to be estimated were as follows.

- the initial gravel bed porosity, $\varepsilon_0$
- the initial hydraulic conductivity, $K_0$
- the initial filter coefficient, $\lambda_0$.

**Initial Porosity**

Factors which affect the initial porosity of gravel include the size and shape of the gravel, percentage of fines and compaction. A porosity of 40% is generally accepted for a bed constructed from washed, uncompacted gravel with a diameter in the range 3 to 10 mm [14]

**Initial Hydraulic Conductivity**

Hydraulic conductivity is closely linked to porosity. For reed beds used to treat sewage it has been found that hydraulic conductivity is initially about $1 \times 10^{-2}$ m/s and, after several years use, eventually decreases to a stable $1 \times 10^{-3}$ m/s [14]. The treatment of mine waste water, however, will lead to the build up of inert solids in the bed which will not be affected by biochemical action. This may lead to the hydraulic conductivity falling well below $1 \times 10^{-3}$ m/s.

For this reason the decline of the hydraulic conductivity of the bed was assumed to be linear with the increase in the specific deposit, consistent with complete blockage of the substrate eventually occurring. Thus, as with the filter coefficient, $\lambda$, in Equation (3), the hydraulic conductivity, K, was calculated as follows.

$$\frac{K}{K_0} = \left(1 - \frac{\sigma}{\varepsilon_0}\right) \qquad (5)$$

where $K_0$ is the initial hydraulic conductivity (m/s).

It is essential to know the initial hydraulic conductivity in order to design the cross-sectional area of the bed. According to Darcy's Law for fluid flow through porous media the cross-sectional area for the bed is as follows.

$$A = \frac{Q}{Ks} \tag{6}$$

where A is the cross-sectional area of the bed ($m^2$)
Q is the flow rate through the bed ($m^3/s$)
s is the hydraulic gradient across the bed.

**Initial Filter Coefficient**

The estimation of $\lambda_0$ was carried out by using the following relationship between fractional suspended solid removal and volumetric load for reed bed treatment systems [15].

$$\ln R = -(0.000784Q + 0.260) \tag{7}$$

where R is the fraction of suspended solids removed by the whole bed
Q is the volumetric load (l/day/$m^2$).

Equation (7) was derived from the suspended solids removal from organic effluents of 25 RBTSs around the United Kingdom.

The suspended solids removal by reed beds from organic waste is not a completely mechanical process. Removal is aided by the biochemical oxidation of the waste which would not occur for the inert solids of mine waste water. Many secondary treatment reed bed, however, are mostly anaerobic [16] and under these conditions over 60% of the organic waste cannot be oxidised, rendering them practically inert [17]. Thus, Equation (7) was considered to be a useful estimate for the initial filter coefficient.

Equating R with $C/C_0$ for the whole length of the bed, Equation (2) can be rearranged as follows.

$$R = -\frac{C}{C_0} = \exp[-\lambda_0 L] \tag{8}$$

When combined with Equation (7) and rearranged, Equation (8) gives the initial filtration coefficient for each metre of the bed as follows.

$$\lambda_0 = \frac{0.000784Q + 0.260}{L} \tag{9}$$

Thus, knowing the volumetric load and length of the gravel bed, it was possible to estimate the initial filtration coefficient using Equation (9). Once this had been done, Equations (1) and (3) were iterated over time to give the fraction of suspended solid filtered from the fluid and the corresponding reduction in the filter coefficient.

## The Reeds

The stems and dead straw of a reed bed act as a filter when there is surface flow through them. This will occur when the reed bed is designed specifically to allow this or when the hydraulic conductivity of the bed substrate is insufficient to allow complete sub-surface flow.

Tollner, Barfield, Haan and Kao [18] presented a model for the filtration of homogeneous sediment by rigid media representing the stems of a vegetation filter strip as follows.

$$\frac{s_i - s_o}{s_o} = \exp\left[-1.06\times10^{-3}\left(\frac{v_m R_S}{\nu}\right)^{0.82}\left(\frac{L v_s}{v_m d_f}\right)^{-0.91}\right] \qquad \textbf{(10)}$$

where $s_i$ is the input sediment load per unit width (kg/m/s)
$s_o$ is the output sediment load per unit width (kg/m/s)
$v_m$ is the mean flow velocity (m/s)
$R_S$ is the spacing hydraulic radius (m)
$\nu$ is the kinematic viscosity of the fluid ($m^2$/s)
L is the bed length (m)
$v_s$ is the deposition velocity of the sediment particles (m/s)
$d_f$ is the depth of flow (m).

The spacing hydraulic radius, $R_S$, is a characteristic length derived from the depth of flow and reed stem spacing. It is defined as follows.

$$R_S = \frac{s_s d_f}{2d_f + s_s} \qquad \textbf{(11)}$$

where $s_s$ is the spacing of the reed stems (m)

The spacing hydraulic radius was used as an alternative to the conventional hydraulic radius and substituted into the Manning Equation for turbulent channel flow as follows.

$$v_m = \frac{1}{n} R_S^{\frac{2}{3}} S^{\frac{1}{2}} \qquad \textbf{(12)}$$

where n is the Manning channel roughness coefficient
S is the slope of the bed.

The Manning Equation, Equation (12), was required in order to calculate the velocity and depth of flow from knowledge of the mean flow volume. This was achieved by iterating Equations (11) and (12) with the flow continuity equation defined as follows.

$$q_w = v_m d_f \qquad \textbf{(13)}$$

where $q_w$ is the mean flow volume per unit width ($m^2/s$)

This model, derived by Tollner *et al.*, was verified and extended to steady-state and unsteady flow with large homogeneous and non-homogeneous sediment loads [2], [19], [20]. [21].

## RESULTS AND DISCUSSION

The model was run with initial suspended solids concentrations of 30 and 100 mg/l. This was to provide a comparison of the filtration performance of the reed beds with and without gravel substrate over typical effluent suspended solid concentrations for secondary treatment. 30 mg/l represents a typical discharge consent for a sedimentation lagoon system discharging into a high quality water body whereas 100 mg/l is typical of a less sensitive discharge.

An indication of the significance of each of the flow and bed design characteristics was obtained by varying each in turn as described in Table I.

**TABLE I:** Ranges of flow and bed characteristics examined.

| Variable | Standard | Range |
|---|---|---|
| length(m) | 100 | 50 - 200 |
| width(m) | 100 | 50 - 200 |
| area($m^2$) | 10 000 | 2 500 - 40 000 |
| depth(m) | 0.6 | 0 - 1.0 |
| flow($m^3$/day) | 1 200 | 300 - 1500 |
| initial porosity* | 0.4 | 0.25 - 0.45 |
| reed spacing(m) | 0.03 | 0.03 - 0.50 |
| particle size(m) | $1 \times 10^{-5}$ | $1 \times 10^{-6}$ - $1 \times 10^{-4}$ |
| hydraulic gradient | 0.01 | 0.005 - 0.03 |
| initial hydraulic conductivity (m/s)* | 1 000 | 500 - 2 500 |

Notes: *Reed bed with gravel substrate only.

The model predicted that, with the correct design characteristics horizontal flow beds with and without gravel substrate can both provide satisfactory filtration performance over a wide range of flow conditions. The bed without substrate, however, was shown to give much higher filtration performance than that with a substrate (Figures 1 and 2).

This large difference in filtration performance was attributed to the fact that the gravel bed was substantially less able to filter suspended solids than the reeds stems. Thus, for example, as the area of the bed with gravel substrate was increased, a greater proportion of the effluent flow was able to pass through the gravel and the filtration performance of the bed was reduced (Figure 2). The change in filtration performance with width, depth, flow, initial porosity and hydraulic conductivity and hydraulic gradient were similarly linked to the proportion of the total flow passing through the gravel bed.

The filtration performance of the surface flow reed bed was greatly affected by the mean suspended particle size (Figure 3) and little affected by the spacing of the reeds (Figure 4). These results indicate that the primary filtration mechanism is not interception by the reed stems but increased sedimentation caused by the effluent flow being spread out and slowed down across the surface of the plot.

## CONCLUSION

The deficiencies in the operation of primary and secondary treatment sedimentation lagoons identified in the Department of the Environment report must be addressed by the mineral extraction industry if it is not to fall foul of the increasingly stringent discharge regulations. Surface flow reed beds may prove to be a practical and cost effective solution.

The model indicated that, when used as a secondary or tertiary treatment method, an entirely surface flow reed bed is the most efficient configuration for the filtration of inert suspended solids and is capable of producing a very high quality polished effluent. The gravel substrate of the sub-surface flow reed bed greatly reduces its filtration performance making it less effective.

The model also raises the intriguing prospect of designing a non-biological filtration system based on the stem arrangement of the reed bed. This system, whilst less environmentally desirable, may have advantage of reduced construction and maintenance costs.

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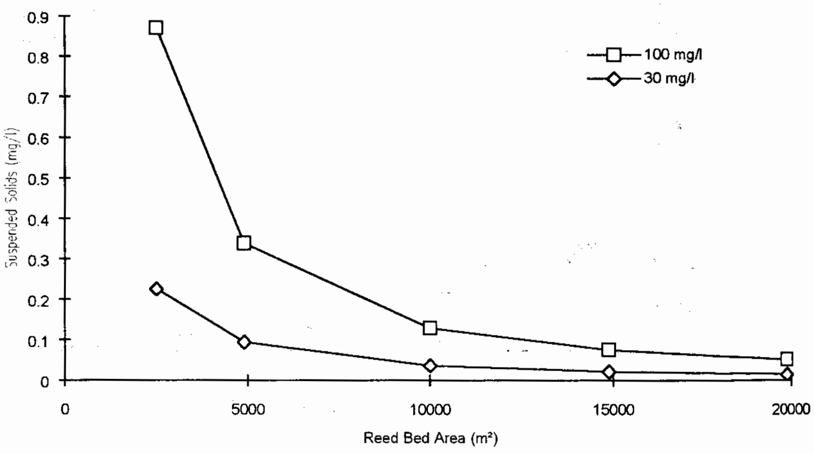


Figure 1: Filtration performance of reed beds without a permeable substrate

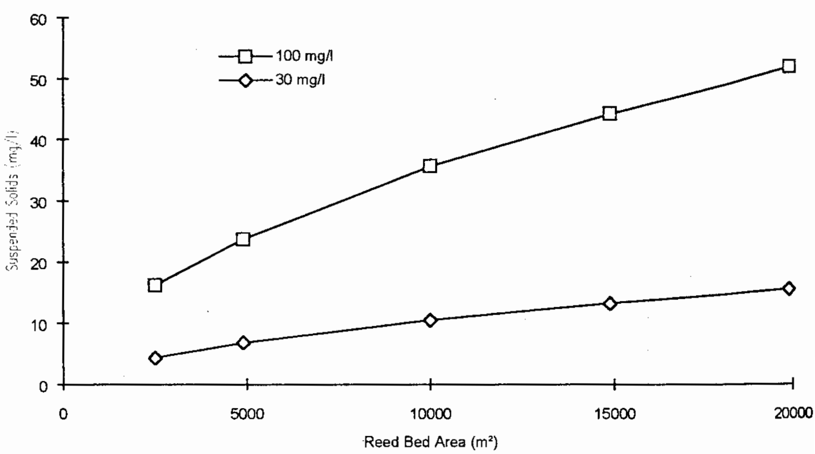


Figure 2: Filtration performance of reed beds with a permeable gravel substrate

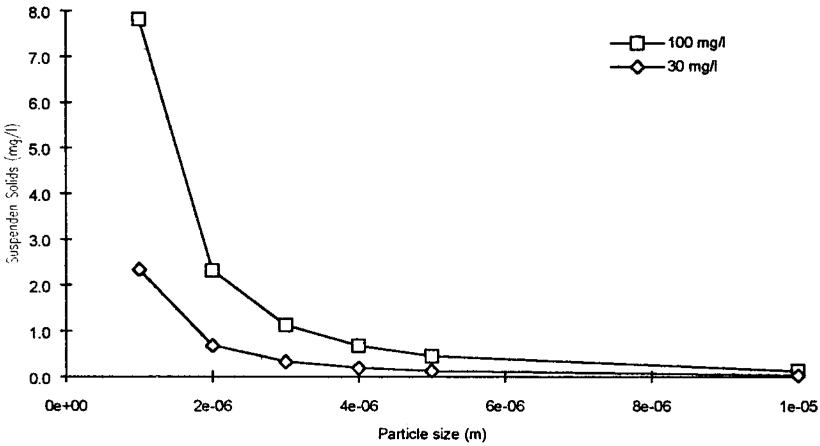


Figure 3: The effect of suspended particle size on the filtration performance of reed beds without a permeable substrate.

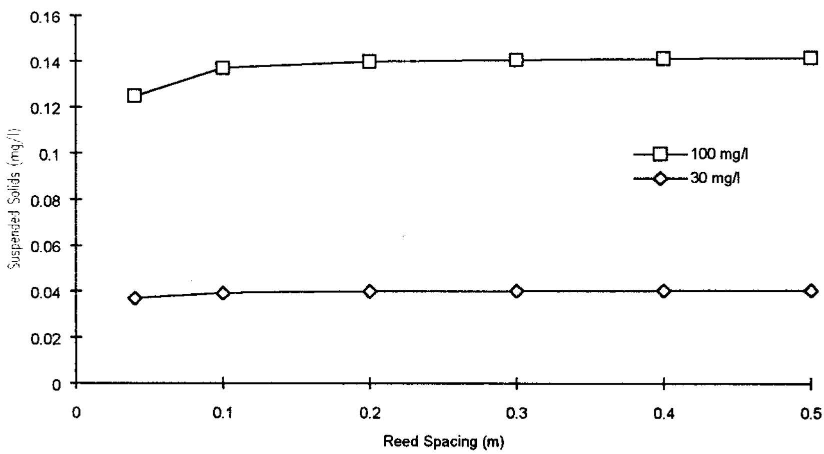


Figure 4: The effect of reed spacing on the filtration performance of reed beds without a permeable substrate.

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