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A Review of the Importance of Hydraulic Residence Time on Improved Design of Mine Water Treatment Systems

F.M. Kusin

Department of Environmental Sciences, Universiti Putra Malaysia, 43400 Serdang, Malaysia

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Abstract: Hydraulic residence time is an important parameter for the design of mine water treatment systems, in particular for wetland system and settlement lagoon. Despite much investigations have been done on system hydraulic residence time, little is still known about how the residence time may relate to treatment system performance. Such an understanding will be useful for improvement of existing treatment system performance and in the design of future systems. Thus, this review attempts to explore this issue on how the assessment of system hydraulic behaviour (of which the residence time), coupled with the assessment of geochemical factors may be incorporated in future design of mine water treatment systems. Review of current design practice for mine water treatment systems in UK applications of passive treatment is also presented. Recommendation for design guidance is discussed to provide some insights into new approach for improved design of such systems.

Key words: Wetland · Settlement lagoon · Mine water · Hydraulic efficiency

INTRODUCTION

The concept of passive treatment has been applied in the UK since the early 1990s to cope with the problems associated with mine water pollution. Adoption of so-called passive treatment system for amelioration of mine-impacted waters has been recognised for the long term remediation of such discharges wherever land availability is not limiting [1]. In practice, depending upon the types of mine water (i.e. net-acidic or net-alkaline) the treatment option may require deployment of more than one of the systems in series e.g. aerobic wetland(s) following settlement lagoon(s) in most UK applications for net-alkaline, iron-rich mine water. Although passive treatment systems have operated with a high rate of success, the fact remains that the design of such units is empirically-based rather than process based [2]. There has been variability in treatment performance in terms of contaminant removal (e.g. iron) in these passive treatment systems which require a clear understanding of this removal processes. Therefore, a more precise understanding of the process mechanisms in passive systems will give greater confidence in treatment performance and allow for optimisation of system design. The link between hydraulics and geochemical factors may be important for better understanding the processes by which contaminants are treated. This is what this review attempts to present i.e. whether hydraulic and geochemical factors may govern the overall treatment system performance for such systems.

Settlement lagoons and aerobic wetlands are regarded as proven technology for passive treatment of net-alkaline, ferruginous mine waters within the UK application of passive treatment [1, 3]. However, one of the limitations of the current design practice for these passive mine water treatment systems is that hydraulic factors are not being accounted for in the design of such systems. This has significantly led to limited understanding of the hydraulic characteristics of the treatment systems which, together with the knowledge of the geochemical processes governing pollutant removal, are central in the assessment of the overall treatment system performance. Such an assessment has not been widely investigated within the UK application of mine water passive treatment. This review will provide an insight into a greater understanding on both hydraulic

Corresponding Author: Faradiella Mohd Kusin, Department of Environmental Sciences, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia. Tel: +60 389468596.

and geochemical factors that govern contaminant behaviour right from the design of such treatment systems to optimise treatment efficiency, through to improved performance over the long-term.

Overview of the Importance of Hydraulic Residence Time in Passive Treatment Systems: Hydraulic performance in passive treatment systems is often associated with the hydraulic residence time in the system [e.g. 4-6]. The time a fraction of water spends within a system may reflect the patterns of water movement across the system and the extent of treatment of polluted waters [7]. In other words, hydraulic residence time is an estimate of the average time water requires to flow completely across a water system. In order to achieve effective treatment, residence time must be greater or equal to the reaction time needed to achieve desired effluent concentration [8]. The required residence time is a function of degradation or removal rate to meet the target effluent concentration. The greater the residence time the greater the proportion of pollutant that will be removed in the system. Therefore, measurement of travel time water takes to flow through a system and its flow behaviour will essentially give an indication of the hydraulic performance of the system under which polluted water is being treated.

The relative importance of residence time as a measure of hydraulic performance of passive treatment systems, in particular within wetland-type treatment systems, has been discussed in many studies [e.g. 4, 7, 9-11]. However, within the UK Coal Authority's passive treatment sites, investigation of the actual residence time to reflect the hydraulic performance of the treatment systems has not been widely explored.

Such an investigation is particularly of interest to better understand the impacts the residence time (hence the flow pattern) has on the hydraulic performance of the system, which potentially have an effect on pollutant removal. This is compounded by first-order removal kinetics of some contaminants e.g. iron; removal is not only dependent on the chemical factors i.e. concentration, pH, dissolved oxygen but also the time it takes to attenuate the pollutant [e.g. 11; 12]. Understanding the actual flow patterns rather than assuming plug-flow, which is rarely the case in actual treatment systems is key to improved design and performance for such systems. Determining sufficient residence time and understanding flow characteristics of systems is vitally important in the design of passive treatment system for they dictate the sizing for optimal use of the system [13].

In a broader sense, a summary hydraulic performance of various free water surface (FWS) and horizontal subsurface flow (HSSF) wetlands in the United States, Australia, Spain and France has been presented in [31], reported from the tracer test results of these treatment systems. Irrespective of mine water or other wastewater treatment system, review of several passive treatment systems with respect to system residence time are summarised in Table 1.

As shown in the table, the actual residence time is often less than the nominal residence time. Preferential flow paths (i.e. short-circuiting with dead zones), internal obstructions such as plants and litter and incomplete mixing within a system are amongst the common factors to result in low contact time on a limited area [14]. This in turn, reflects the hydraulic efficiency of the system. It is probable that such factors may have influence on hydraulic performance of mine water treatment systems. Although review of various passive treatment systems is presented here (Table 1.1), concern is given only to settlement lagoons and wetlands as mentioned earlier.

Overview of Treatment Performance in Passive Treatment Systems in the UK: The primary objective for effective remediation in passive mine water treatment are pH correction and/or metals removal [3]. Certainly, the primary pollutant of concern in UK coal mine water discharges is iron. Aluminium, manganese and sulphates are additional pollutants in many cases [e.g. 1, 15]. Additionally, iron is the most commonly studied pollutant with respect to mine water treatment [e.g. 16, 18-20]. Treatment performance of a system is measured by assessing the extent to which the system removes the particular pollutant of concern; this is often measured as the pollutant or load removal efficiency. Treatment efficiency is simply the percentage of removal from the change in concentration of pollutant in the influent and effluent of treatment system. Load removal efficiency is the measure given as the percentage of pollutant removal by the change in pollutant loadings (i.e. concentration multiplied by flow rate) in the influent and effluent of treatment system [1, 17].

The iron removal in aerobic mine water treatment systems is principally due to oxidation of ferrous iron to ferric iron and the subsequent hydrolysis and precipitation of ferric iron to form ferric hydroxide [1].

Table 1: Hydraulic residence times in several passive treatment systems

Treatment system	Nominal residence time	Actual residence time	Comments	Reference
• RAPS • Wetland (mine water)	• 2.7-3.6 days • 7.9 days	• 4-8 days • 2-3 days	• RAPS II with higher flow rates (90-110 L/min) indicated a longer residence time compared to RAPS I with lower flow rates (30-50 L/min) • Interpretation of the mean residence time was also affected by the density of the tracer used i.e sodium chloride	[30]
• Full-scale RAPS • Pilot-scale RAPS (mine water)	• Not reported • Not reported	• 57 hours • 7.5 hours	• Breakthrough curves modelled to distinguish the dispersive characteristics between the systems • Despite the faster time to peak at the pilot-scale system, the importance of matrix diffusion in that system was not diminished	[35]
• Pilot-scale wetland • Full-scale (wastewater and agricultural runoff)	• 75 hours • 69 hours	• 53-55 hours • 60 hours	• Tracer test conducted to observe the performance of different types of tracers	[5]
• Constructed wetland, cell-by-cell • System scale (domestic wastewater)	• 5-33 hours • 2.57-60.5 hours	• 13.09-21.65 hours • 18.1-54.6 hours	• The short-circuiting experienced in the study was attributed to the non-uniform vegetation distribution, suboptimal cell shapes and variable microtopography of the wetland cells	[4]
• Constructed wetland (wastewater)	• 2.91-3.62 days	• 2.7-4.17 days	• Simulation of solute transport in the wetland systems indicated 8-47% hydraulic residence time difference from the nominal retention time	[36]
• Higher-loaded wetland • Lower-loaded wetland (dairy wastewater)	• 54.5 hours	• 27 hours • 55 hours	• Impact of organic matter accumulation on wastewater residence time was investigated • There was no direct relationship found	[37]
• Permeable reactive barrier (PRB) (colliery spoil leachate)	• 2-60 days	• 4-24 hours	• Substrate characterisation to achieve maximum addition of alkalinity and removal of acidity and metals for treatment of colliery spoil leachate	[38]

Table 2: Treatment performance of the UK mine water treatment system

Type of treatment system	Location	Average Influent Fe	Average Effluent Fe	Removal efficiency (%)	Reference
Treatment of net-alkaline waters					
Aerobic wetland	Lambley, Northumberland	3.8	1.6	58	[24]
	Whittle, Northumberland	20.8	1.7	92	[24]
	St Helen Auckland, County Durham	3	0.3	90	[21]
	Edmondsley, County Durham	27	0.1	99	[21]
Settlement lagoon	Acomb, Nothumberland	34.1	5.05	85	[24]
	Whittle, Northumberland	28.6	21.6	24	[24]
Surface catalysed oxidation of ferrous iron (SCOOFI)	Kimbersworth, County Durham	1.43	0.41	85	[12]
Treatment of net-acidic waters					
Reducing and alkalinity		40	<10	>75	[22]
producing system (RAPS)	Bowden Close, County Durham	20	3	85	[21]
Compost wetland	Quaking Houses, County Durham	4.55	2.5	45.4	[13]
		10	1	90	[21]
Permeable reactive barrier	Shillbottle, Northumberland	100	25	75	[21]
		>800	~10	98	[23]
		>300	~10	95	[39]

These are given in the following equations [19].

Oxidation: $Fe^{2+} + ¼ O_2 + H^+$ _ $Fe^{3+} + ½ H_2O$ [1]

Hydrolysis: $Fe^{3+} + 2H_2O$ _ $FeOOH_{(suspended)} + 3H^+$ [2]

Settling: $FeOOH_{(suspended)}$ _ $FeOOH_{(settled)}$ [3]

Studies on iron removal within UK's Coal Authority mine water treatment systems have been reported by many authors [e.g. 13, 12, 21-25]. A summary of the treatment performance for iron in several mine water treatment systems in the UK is presented in Table 2. As seen in the table, irrespective of the treatment system types, iron removal efficiency varies greatly from as low as 24% to as high as 99%. The lowest iron removal was found in a settlement lagoon while the highest removal was found in an aerobic wetland. It is therefore interesting to recognise what factors contribute to such variations.

[1] have presented a summary of constructed wetland systems performance in the United States, given in the metric of a commonly used treatment system performance measure, the area-adjusted removal rate. This treatment performance metric was derived from the zero-order kinetics for pollutant removal [19]. The removal rates (in unit $g/m^2/d$) varied greatly from one treatment site to another (e.g. iron removal ranged between 0.5 and 42.7 $g/m^2/d$. This variation in iron removal rates can be associated with different chemical characteristics of the different sites and may also be attributable to the hydraulic factors in the systems and hence assumption of the zero-order kinetics may not be appropriate in such situations. This highly variable treatment performance may reflect the first-order kinetics (concentration-dependence) for iron removal that provides one of the bases for the recommended design formula by [18]. [26] has also shown the concentration-dependence nature for iron removal (both iron oxidation and settlement) in a passive treatment scheme consisting of a series of ponds and aerobic wetland in Pennsylvania, United States. On the other hand, the influence of hydraulics on treatment performance cannot be ruled out [1, 11, 27]. Therefore, it is important to know whether there is a link between geochemically determined processes and system hydraulic performance (i.e. hydraulic residence time). Such an assessment will improve the understanding of the processes with respect to current design practice and for optimisation of the system design.

As noted earlier, the hydraulic flow behaviour through a mine water treatment system is a significant measurement of system hydraulic performance. However, its relationship to pollutant removal has not been widely assessed. It is believed that greater hydraulic efficiency (i.e. longer residence times) should result in an improved rate of pollutant removal. Most of the previous studies (not only in mine water) put their emphases on the interpretations of residence time as a sole means for characterising hydraulic behaviour of the systems rather than developing the link between hydraulic and geochemical factors governing treatment system performance [e.g. 5, 28, 29, 30]. Much could be gained from such as an assessment on the effect of different hydraulic flow patterns as they relate to treatment performance efficiencies of the mine water treatment systems.

Design and Sizing Options for Mine Water Treatment Systems

Design and Sizing of Passive Mine Water Treatment Systems: Design and sizing of passive systems should ideally be based on the reaction rates of pollutant removal processes as they relate to both the geochemical and hydraulic conditions [1]. According to [31], there are three ways of estimating performance and sizing of treatment wetlands/ponds. This could either be based on pollutant and hydraulic loading of the system, adoption of first-order removal models, or the use of regression equations that link several treatment performance parameters. To date, sizing tools for wetlands treating mine water discharges within the UK Coal Authority's mine water treatment systems is still based on zero-order removal rate, which subsequently gives the area required for the system. The use of estimated retention time has also been widely applied to the design of settlement lagoons [3]. The use of the zero-order removal model, also known as the area-adjusted removal method, for sizing of mine drainage treatment systems has been recommended by [15]. Despite being widely used for mine water treatment system design, criticisms of the use of this method have been fundamentally because it takes no account of pollutant concentration effects on the removal rate [17, 31].

Adoption of a first-order removal model that considers the effect of pollutant concentration on the rate of removal is likely more reliable for sizing of wetlands treating mine water discharges [17]. However, it should be noted that the first-order removal model is in fact derived from the assumption of plug-flow system, which is rarely the case in actual mine water treatment wetlands and lagoons. Therefore, [14] extended the applicability of first-order removal based on several assumptions including the plug-flow. On the other hand, [27] criticised the use of first-order expressions for the design of sewage treatment wetlands, reasoning that the plug-flow assumption does not apply for such systems and that the contaminant removal processes differ between the fast- and slow-moving zones within a wetland. [11] investigated the applicability of first-order removal for a wetland treating agricultural and urban runoff and found poor fits of the model to most of the observed data. The reason for this is that the seasonal variations greatly affected the ideality of the flow i.e. causing non-ideal flow patterns during summer and fall, thus affecting the extent of treatment received by the pollutants. [11] have shown that the use of first-order removal formula based on [17] may result in four times larger system area for an aerobic wetland than if designed using the area-adjusted removal formula (although this may vary from site to site). This reflects the fact that acquiring such a large land area needed particularly in the UK where land availability is limited is often of issue [21].

Therefore it is possible that the use of relative reaction rate for pollutant removal according to, for example a tanks-in-series model would be a better option for the design and sizing such systems [e.g. 32]. This approach does take account of the flow pattern across a system, in addition to the first-order kinetics for iron removal. However, use of first-order removal formula requires a reliable removal rate constant value to appropriately design the systems. This is what this review attempts to suggest that the use of first-order removal model that also takes account of flow pattern effect would be an alternative to improved design of mine water treatment system. In order to assess this, measurement of both hydraulic factor (residence time) and geochemical factor (pollutant removal) governing the performance of mine water treatment systems has to be evaluated. This is somewhat related to the work done by [33, 34], whereby the hydraulic performance of such systems has been presented through detailed flow-pattern modelling approach.

Summary: Current design practice for aerobic wetlands treating net-alkaline mine waters in UK applications are based on the zero-order kinetics for pollutant removal i.e. the commonly used area-adjusted removal as recommended by [19]. Lagoons are design to allow nominal 48 hours of retention time. However, there have been limited studies that investigate the effectiveness of the use of these methods in UK applications. A knowledge that iron removal under aerobic conditions follows first-order kinetics model for pollutant removal has been the basis for a recommended alternative method for the design of such systems (i.e. first-order removal model by [17]). Both of these approaches are based on the plug-flow assumption, which is not the case in real systems. An increasing knowledge of the hydraulic behaviour (e.g. flow pattern across a treatment system) requires a better understanding of the hydraulic factors relating to treatment system performance. Such an assessment has not been widely explored in UK mine water treatment systems. The extent to which actual systems deviate from an ideal flow pattern is the subject matter to be explored. It is therefore interesting to assess the conditions under which mine water treatment systems perform well in terms of hydraulic efficiency and efficient rates of contaminant removal. This in turn, could help evaluate the appropriateness of current and alternative system sizing methods in light of the new insights gained.

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