Synergistic wetland treatment of sewage and mine water: pollutant removal performance of the first full-scale system

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Author Contributions

Both authors have given approval to the final version of the manuscript. Both authors contributed equally: Younger on the data collection and interpretation, Henderson on statistical analysis.

Abstract

Wetland systems are now well-established unit processes in the treatment of diverse wastewater streams. However, the development of wetland technology for sewage treatment followed an entirely separate trajectory from that for polluted mine waters. In recent years, increased networking has led to recognition of possible synergies which might be obtained by hybridising approaches to achieve co-treatment of otherwise distinct sewage and mine-derived wastewaters.

As polluted discharges from abandoned mines often occur in or near the large conurbations to which the former mining activities gave rise, there is ample scope for such co-treatment in many places worldwide. The first full-scale co-treatment wetland anywhere in the world receiving large inflows of both partially-treated sewage (~100 $L.s^{-1}$) and mine water (~300 $L.s^{-1}$) was commissioned in Gateshead, England in 2005, and a performance evaluation has now been made. The evaluation is based entirely on routinely-collected water quality data, which the operators gather in fulfillment of their regulatory obligations. The principal parameters of concern in the sewage effluent are suspended solids, BOD_5, ammoniacal nitrogen (NH_4-N) and phosphate (P); in the mine water the only parameter of particular concern is total iron (Fe). Aerobic treatment processes are appropriate for removal of BOD_5, NH_4-N and Fe; for the removal of P, reaction with iron to form ferric phosphate solids is a likely pathway. With these considerations in mind, the treatment wetland was designed as a surface-flow aerobic system. Sample concentration level and daily flow rate date from April 2007 until March 2011 have been analyzed using nonparametric statistical methods. This has revealed sustained, high rates of absolute removal of all pollutants from the combined wastewater flow, quantified in terms of differences between influent and effluent loadings (i.e. mass per unit time). In terms of annual mass retention rates, for instance, the wetland system sequesters the following percentages of the key pollutants: BOD_5: 41%; Fe 89%; NH_4-N: 66%; dissolved P: 59%; total P: 46%; suspended solids: 66%. For similar wastewater chemistries, application of this type of co-treatment elsewhere could reasonably be based on the observed areally-normalized mass removal rates for the various pollutants found in this investigation.

1. Introduction

Wetland systems are now well-established unit processes in the treatment of diverse wastewater streams (e.g. Kadlec and Wallace 2009). The adoption of wetlands as unit processes in wastewater treatment is a natural development from numerous informal observations that pollutants tend to be sequestered when wastewaters flow through natural wetlands (e.g. Cooke 1994). Sewage treatment wetlands have developed substantially from modest beginnings in the mid-20th Century (Vymazal 2011). Wetland treatment was subsequently extended to landfill leachates (Mulamoottil *et al.* 1999), which often contain similar pollutants to sewage, albeit usually at higher concentrations. In the late 1980s and 1990s, independent developments in the mining industry led to the emergence of distinctive types of wetlands for ferruginous and/or acidic mine drainage (e.g. Wieder 1989; Younger *et al.* 2002), with similar systems being proposed subsequently for neutralization of extreme alkalinity in leachates arising in the steel and cement industries (Mayes *et al.* 2006).

These various types of wetland were developed by different communities of scientists and engineers, working largely in isolation from each other. Hence the system design traditions evolved essentially in parallel, with very little communication between the sewage and mine water treatment communities until the first decade of the new Millennium (Rose 2013). Even today, contact between the two communities remains sporadic, as they tend to be dealing with quite distinct pollutants: for instance, the principal parameters of concern in the sewage effluent are usually suspended solids, BOD_5, ammoniacal nitrogen (NH_4-N) and, increasingly, phosphate (P) (e.g. Vymazal 2011). In the majority of abandoned mine water discharges, the principal contaminant concern is usually iron (Fe), though pH, Al, Mn and other metals can also be of concern in the more acidic mine waters (Younger *et al.* 2002).

The limited communication between the two communities may well be leading to many missed opportunities, since polluted discharges from abandoned mines often occur in or near the large conurbations to which the former mining activities gave rise (Younger *et al.* 2002), from which large flows of sewage emanate. Furthermore, the contrasting characteristics of sewage and mine water can be expected to give rise to synergies if the two are mixed and co-treated: for instance, removal of Fe from the mine water and P from the sewage can be expected to occur by rapid precipitation of ferric phosphate solids (Dobbie *et al.* 2009). Removal of suspended solids from the sewage can be expected due to flocculation with the ubiquitous ferric sulfate complexes that develop in aerated mine waters. Removal of dissolved ferrous iron from the mine water (Batty and Younger 2002), and BOD_5 and NH_4-N from the sewage (Cooke 1994; Demin *et al.* 2002) are all favored by oxidation reactions in an aerobic system. Testing of these concepts at pilot scale by a team led by the first author gave encouraging results (Johnson and Younger 2006), and this encouraged laboratory testing by a USA-based team of the feasibility of extending the approach to co-treat very acidic mine waters with sewage (e.g. Strosnider and Nairn 2010; Strosnider *et al.* 2011a, 2011b), with a view to implementing this approach at Potosí, Bolivia (Strosnider and Nairn 2010). That work revealed that co-treatment with strongly acidic mine waters enhances the disinfection of sewage effluent (Winfrey *et al.* 2010), and results in impressive removal rates for BOD and phosphorous (Strosnider *et al.* 2011b), and zinc (Strosnider *et al.* 2013), albeit denitrification is apparently inhibited under the conditions studied (Strosnider *et al.* 2011b). Several laboratory-based studies have examined alternative co-treatment options for mine water and sewage, including activated sludge techniques (Hughes and Gray 2012, 2013), and anaerobic digestion (Deng and Lin 2013). Conceptually similar investigations have included field trials of addition of sewage to acidic mine pit lake water (McCullough *et al.* 2008). In the meantime, full-scale co-treatment of mine water and sewage has now been undertaken at the Lamesley site in the UK for more than 7 years. This paper presents a first analysis of how this, the first full-scale mine water / sewage co-treatment constructed wetland system in the world, has performed, drawing lessons for further applications of this environmental technology elsewhere in the world.

2. Study system: Lamesley Co-Treatment Wetland System, UK

The hamlet of Lamesley is located on the edge of the Tyneside conurbation, at Gateshead, in north-eastern England (Latitude 54°54'19.3"N, Longitude 1°35'57.8"W). The site itself is in a low-lying valley floor area, underlain by more than 150m of laminated glacio-lacustrine clays of Quaternary age. Beneath the adjoining valley flanks, however, multiple seams of coal occur (Mills and Holliday 1998). , and these have been extensively mined by surface and underground methods since the late 16th Century, with the last deep mines closing in the 1960s and the last opencast site closing in the 1990s Since the last mines closed, pumping has been maintained from one of the deep mine shafts of Kibblesworth Colliery, in order to prevent uncontrolled flooding of mine-workings in the densely populated urban area of Gateshead, which would be highly likely to lead to multiple uncontrolled mine water discharges and elevated rates of hazardous mine gas emissions posing a risk to health and safety (Younger 1998). The water pumped from the shaft is of neutral pH (7.0) and brackish (conductivity ~ 4400 $\mu S.cm^{-1}$), with elevated sodium (780 $mg.L^{-1}$), calcium (162 $mg.L^{-1}$), sulphate (395 $mg.L^{-1}$), chloride (900 $mg.L^{-1}$) and alkalinity (755 $mg{\cdot}L^{-1}$ as $CaCO_3$ equivalent) (Younger 1998). Until about the year 2000, the Kibblesworth mine water contained very little dissolved ferrous iron (< 0.9 $mg.L^{-1}$), but changing patterns of groundwater movement in other flooded workings in the region resulted in this increasing to as much as 20 $mg.L^{-1}$. As the quantity of water pumped at Kibblesworth is very high (mean 276 $L.s^{-1}$; $\sigma = 85$; $n = 1422$), the total loadings of iron entering the River Team (into which the mine water was hitherto discharged without treatment) were also very high, averaging some 120 $Kg.d^{-1}$. In-channel oxidation of this ferrous iron led to extensive cloaking of the benthos with unsightly ochre (ferric hydroxide). This resulted in pressure from the environmental regulator (the Environment Agency) for treatment of the mine water.

At around the same time, increasingly stringent national guidelines on effluent limit concentrations for sewage works were beginning to bite. This resulted in pressure being put on the operators of a municipal sewage works at Lamesley to enhance the existing primary and secondary treatment steps to achieve lower concentrations of BOD_5, NH_4-N and suspended solids in the final effluent. Although not a statutory requirement in this case, the sewage works operators were also keen to achieve lower P concentrations in their final effluent, in anticipation of possible future tightening of emissions limits for this. The total flow treated at the sewage works averages 115 $L.s^{-1}$ ($\sigma = 43.4$; $n = 1422$), with recorded peak flow of 338 $L.s^{-1}$.

In 2002 the first author suggested to the separate organizations operating the mine water pump and the sewage works that they might benefit from jointly treating the effluents for which they were separately responsible. The possibility that co-treatment of their effluents using a combined wetland system was attractive on the grounds of the low energy requirement compared to other options, and the possibility that it could have ancillary benefits in enhancing avian habitats in this peri-urban area. Accordingly, a proof-of-concept study was undertaken in the summer of 2003, with construction of a small (625m^2) pilot wetland system, which was then monitored for four months. This pilot system received only about one percent of the combined sewage and mine water flows (which were mixed in the 1:3 proportion which would result from mixing the entire average flows at full-scale). The results of that brief period of testing were very encouraging (Johnson and Younger 2006), so the two organizations decided to proceed to construct a full-scale co-treatment wetland.

Construction of the full-scale wetland system commenced in 2004. The system occupies a site of some 8 hectares, although only 5.4 hectares are actually occupied by wetland cells. Water coming from the mine shaft and the sewage works is mixed in large underground header tanks, and then routed into the treatment wetlands via aeration cascades. The wetlands themselves comprise four parallel series of cells, with impermeable bunds incorporating bentonite sealants, arranged in two pairs of streams which each converge on one of two final outfalls to the River Team (Figure 1). This arrangement was designed to allow any one treatment stream to be taken out of service for maintenance, with the diverted flow being accommodated into the other still-active streams. Further aeration cascades and channels pass the flow from one wetland cell to the next. The target water depth in most of the system is in the range 15 to 50cm – a depth which has been widely found (see Younger *et al.* 2002) to be suitable for growth of the common wetland plants (*Typha latifolia*, *Phragmites australis*, and *Iris pseudacorus*), which were planted as seedlings in the new wetland cells. In a few areas, small islands and areas of deeper water (≤

1.5m depth) have been incorporated into the wetland cells, to increase the attractiveness of the system to wildlife. This has been successful, with more than a hundred species of birds regularly observed there, thirty of which are directly attributable to the new wetland habitat, together with more than twenty different species of butterfly and dragonfly, including several that are regionally endangered (Durham Biodiversity Partnership 2007).

Commissioning of the wetland system began in summer of 2005, when sewage effluent that has already been treated conventionally to secondary level was introduced to the system. Addition of the larger mine water flow was delayed until the following year to give the seedlings a chance to become well-established before flow velocities and water depths increased. Regular monitoring of influent flows, and influent and effluent water quality parameters, has been undertaken ever since by the site operators.

The wetland system was designed with sufficient freeboard to obviate the need for any reed harvesting or substrate removal for at least 25 years. Apart from occasional minor maintenance activities, e.g. to unblock internal weirs and spillways clogged with plant debris, and to repair minor bank erosion (as happened in Pond B in late 2010, for instance), the wetland is essentially left in an undisturbed state.

3. Methods

The evaluation is based entirely on routinely-collected water quality data, which the operators gather in fulfillment of their regulatory obligations. This has the advantage that it does not entail unusual monitoring procedures which would be unlikely to be replicated on similar systems elsewhere, and that it focuses on those parameters of most practical interest to wastewater engineers. All sampling and laboratory analysis techniques were carried out and certified in accordance with the UK Accreditation Scheme (UKAS), with full QA-QC measures (see UKAS 2013).

The evaluation presented here is based on water quality samples and daily flow rate data from April 2007 until March 2011. This period is subsequent to the initial commissioning, so that vegetation had adjusted to the new hydraulic conditions through two full growing seasons, and the "honeymoon period" of deceptively good treatment performance observed in many new wetlands during their first year of operation (generally ascribed to initial filling of sorption sites on newly-submerged clay minerals in the wetland base and bunds; Younger *et al.* 2002) was over. During the monitoring period the mine water and sewage streams entering the wetlands were sampled 88 and 93 times respectively, and outfalls 1 and 2 were each sampled 94 times. In all cases the sampling was roughly fortnightly, with some irregularity. Each sample was analysed for concentrations ($mg.L^{-1}$) of BOD_5 (with an oxygen meter) iron (total) (by ICP-MS) NH_4-N (colorimetrically) and suspended solids (gravimetrically). For a shorter period of time, from June 2010, P (dissolved and total) were added to the analytical suite, and analysed by ICP-OES.. A cubic spline smoother (Green and Silverman 1994) was used to interpolate between sample days, with the smoothing parameter chosen by cross-validation. The inflow concentrations were applied to daily flow rates into the wetlands, for both mine water and sewage streams, in order to estimate the total mass of each pollutant carried into the wetlands through the study period. A similar calculation using the outflow concentrations was used to estimate the pollutant masses discharged through the period, assuming total outflow volume matched total inflow, and both outlets are equally used. There was no adjustment for rainfall, evaporation or any unmeasured flows, since in comparison with the very large treated flows any such effects can be shown to be negligible. The estimated total masses of pollutants taken into and out of the wetlands were converted into simple average concentrations over the period: there was no evidence of major sustained temporal trends in the data. To compare concentrations we used a generalised estimating equation approach for unbalanced longitudinal data (Diggle *et al.* 2002). We included a term for long term trend and also month-of-year as a factor variable to allow for possible seasonality. The four streams were parameterised as: mine water (MW); secondary sewage effluent (SSE); change (C) in outflow concentration compared with dilution only; and difference (D) between concentrations in the two outflows. We used robust variance estimators (Diggle *et al.* 2002) in testing C=0 and D=0.

4. Results

This wetland system has always met the regulatory emission limits set by the Environment Agency (see figures 2, 3, 4 and 5), and it is also out-performing the pilot wetland (Johnson and Younger 2006) on which its design was based (i.e. average removal rates of 89% for Fe in this system versus 60% in the pilot system; 41% BOD_5 versus 38% in pilot; 66% NH_4-N versus 20% in pilot; 59% P-PO_4 versus 20% in pilot, and 66% suspended solids versus 54% in pilot).

The data demonstrate sustained, high rates of absolute removal of all pollutants from the combined mine water / sewage flow. Average flow-weighted concentrations for key pollutants are given in Table 1, for raw mine water, raw sewage, and final effluent flow. The table also provides the expected concentrations of key pollutants in the effluent flow if there had been no retention within the wetlands. Performance can also be quantified in terms of differences between influent and effluent loadings (i.e. mass per unit time). In terms of annual mass retention rates, for instance, the wetland system retains the following percentages of the key pollutants: Fe 89%; BOD_5: 41%; NH_4-N: 66%; dissolved ortho-phosphate as P: 59%; total P: 46%; suspended solids: 66%.

For all variables there was strong evidence of outflow concentration being significantly reduced compared to inflows, after allowance for dilution. Wald (Z) test statistics for no change (C=0) were -6.93, -13.15, -9.27, -6.55, -4.16 and -6.43 for BOD_5, iron, NH_4-N, P-dissolved, P-total and suspended solids respectively. All p-values for these tests were less than 0.00001. There was no evidence of seasonal effects, but there were small but highly statistically significant reductions in concentration from the north outlet compared with south for iron (D=0.52mg.L-1, Z=7.81) and suspended solids (D=2.96mg.L-1, Z=5,74). There was no difference between outlets for any of the other variables. This is suggestive of occasional remobilisation of ochreous sediment within ponds B, especially in the final months of 2010, which are believed to relate to a period of minor maintenance works on one of the pond margins.

5. Discussion

The dynamics of pollutant removal are such that highly variant inflow concentrations are not only lowered but also substantially dampened in amplitude. All differences are highly statistically significant ($p<0.001$). Figures 2 through 5 illustrate this smoothing effect, for BOD_5, iron, total phosphorus and suspended solids. In particular, high and variable BOD_5 in the secondary sewage effluent entering the wetlands is consistently lowered and substantially damped in variability in both outfalls (Figure 2). With regard to iron, concentrations are high but variable in the mine water and generally lower (but occasionally elevated) in the secondary sewage effluent (Figure 3), whereas outflow concentrations at both outfalls are markedly lower, albeit those at Outfall no. 2 (north) are consistently higher than those at Outfall no. 1, presumably reflecting the rather lower total wetland areas encountered along treatment streams A-B and C-D that lead to outfall 2 (see Figure 1), compared to those in streams E-F-J and G-H-J that lead to outfall 1. With regard to total phosphorous concentrations (Figure 4), the decrease in concentration between the secondary sewage effluent and both outfalls is dramatic. Similar patterns emerge for dissolved phosphorus (not shown). As would be expected for an iron-rich water, the phosphorous concentrations in the mine water are consistently low, and comparable to those at the final outfalls. Ammoniacal nitrogen displays similar patterns to phosphorous (not shown). Suspended solids is the one parameter which is high in both the mine water and secondary sewage effluent, but again the outfalls from the wetlands are substantially subdued (though as for iron, the smaller treatment area leading to outfall 2 is reflected in higher peaks).

The lack of seasonal variation is rather surprising in a system in which nutrient removal is presumably biologically mediated. Two possible explanations are suggested. Firstly, the steady temperature of the mine water (it is a constant 15.8^{o}C all year round) offers a considerable buffer against cold winter temperatures. Secondly, although the concentrations of key pollutants are high enough to cause regulatory concern, they end up at the lower end of the typical concentration ranges found in wetlands, and are therefore subject to load-limiting effects on pollutant removal, so that even seasonally depressed biological processes are still sufficient to achieve quantitative pollutant removal.

As the co-treatment of mine water and sewage is generally going to be of interest to separate "problem-owners", it is appropriate to examine pollutant removal performance from the distinct perspectives of the sewage works manager and the mine pump operator. A further perspective is that of the regulator: the old adage "dilution is the solution to pollution" has long-since been ruled inadmissible in most jurisdictions, with absolute reductions of pollutant loadings being required. As we have already seen, the co-treatment wetland system meets this requirement comfortably. Nevertheless, as actual emissions limits are expressed in terms of concentrations rather than loadings, it is of interest from the regulatory perspective to assess how much of the decrease in concentrations from sewage to river, or from mine water to river, is ascribable simply to the mutual dilution of sewage and mine water. This is also what the sewage works manager and the mine pump operator would each like to know from their own perspectives. Table 1 provides the information. As would be anticipated from the loadings figures, removal rates significantly exceed those simply ascribable to dilution for all pollutants, amounting to the following percentage declines in concentration in excess of those expected from dilution alone:

- For pollutants in the mine water: iron 66%; suspended solids 61%.
- For pollutants in the sewage: BOD_5 23%; NH_4-N 40%; dissolved ortho-phosphate (as P) 21%; total P 17%; suspended solids 81%.

In the absence of detailed substrate analysis (the next phase of planned work), it is not yet possible to definitively identify the solid phase sinks for these pollutants, but experience of similar systems suggests the following fates: For iron: precipitation as ferric hydroxide (e.g. Hedin *et al.* 1994) and ferric phosphate (e.g. Dobbie *et al.* 2009); for NH_4-N: oxidation to nitrate, with subsequent reduction (in anoxic zones of bed sediment) to N_2, which then degasses to the atmosphere (e.g. Cooke 1994; Demin *et al.* 2002); for dissolved and total phosphate: sorption to ferric hydroxide and / or precipitation as ferric phosphate (Dobbie *et al.* 2009).

One potential issue is whether the high ionic strength of the mine water –and therefore the belend with sewage – might inhibit certain important microbial processes that are important in nutrient removal, particularly of NH_4-N and PO_4-P. For instance, the laboratory experiments of Strosnider *et al.* (2011b) indicate potential inhibition of denitrification in blended mine water and sewage. In that case ionic strength was also high, but in addition the mine water was initially very acidic, and this is known to be deleterious to pathogens (Winfrey *et al.* 2010), and thus possibly to other bacteria too. However, as previously noted, the mine waters treated at Lamesley are of neutral pH. On the basis of the removal rates reported here, there is no reason to suspect major inhibition of nitrifying or denitrifying bacteria by the relatively high ionic strength, which suggests that the effects observed by Strosnider *et al.* (2011b) might be more attributable to bacteria mortality during mixing with acidic waters.

Design of treatment wetlands is most frequently based on areally-normalized pollutant removal rates, typically expressed as the mass or pollutant removed from the water per unit wetland surface area per day. Substantial discussion has taken place over the suitability of this approach, not least as it implicitly assumes “zeroth-order” reaction kinetics, whereas in reality the responsible processes may well be first-order or higher-order reactions (Tarutis *et al.* 1999). In focusing on the reaction kinetics, such debates often overlook the complications arising from non-chemical processes, such as incomplete hydraulic mixing (e.g. Martinez and Wise 2003; Kadlec and Wallace 2009; Kusin *et al.* 2012), molecular diffusion into essentially immobile bed sediment pore space (e.g. Martinez and Wise 2003; Diaz-Goebes and Younger 2004; Kadlec and Wallace 2009), and physical filtration of the particulate fraction of pollutants and adsorption of dissolved pollutants by plant stems and debris (e.g. Batty and Younger 2002; Kadlec and Wallace 2009). The overall apparent removal rate is thus a reflection of a complex of hydraulic and (bio)chemical processes, for which no particular reaction-order representation is likely to be accurate. Hence many investigators continue to express the overall rate of pollutant removal as an areally-normalized mass removal rate. The relevant average figures for this study are summarized in Table 2. The observed removal rates for ammonia-N, BOD_5 and phosphorous in this system equal or exceed the relevant highest rates previously reported by Kadlec and Wallace (2009) for surface flow wetlands treating sewage only, while those for suspended solids are equivalent to the second highest rate quoted by Kadlec and Wallace (2009), i.e. 5 $g{\cdot}m^{-2}{\cdot}d^{-1}$. The iron removal rate is somewhat lower than those previously reported for aerobic wetlands treating mine water alone, however, probably reflecting the low final iron concentrations (< 0.5 $mg{\cdot}L^{-1}$), which effectively makes these wetlands “load limited” with respect to iron in terms of the criteria for wetland performance assessment outlined by Hedin *et al.* (1994). It is concluded that co-treatment of sewage and mine water using wetlands is beneficial, especially in terms of sewage treatment, wherever the two wastewaters occur in reasonable proximity.

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References

Batty, L.C., Younger, P.L., 2002. Critical role of macrophytes in achieving low iron concentrations in mine water treatment wetlands. Environmental Science & Technology 36, 3997 - 4002.

Cooke, J.G., 1994. Nutrient transformations in a natural wetland receiving sewage effluent and the implications for waste treatment. Water, Science and Technology 29 (4), 209–217.

Demin, O.A., Dudeney, A.W.L., Tarasova, I.I., 2002. Remediation of ammonia-rich mine water in constructed wetlands. Environmental Technology 23 (5), 497–514.

Deng, D., Lin, L., 2013. Two-stage combined treatment of acid mine drainage and municipal wastewater. Water Science and Technology 67: 1000-1007.

Diaz-Goebes, M., and Younger, P.L., 2004. A Simple Analytical Model for Interpretation of Tracer Tests in Two-Domain Subsurface Flow Systems. Mine Water and the Environment 23: 138-143.

Diggle, P.J., Heagerty, P., Liang, K.-Y. and Zeger, S.L., 2002. Analysis of Longitudinal Data. (Second edition). Oxford University Press, Oxford. 400pp.

Dobbie, K.E., Heal, K.V., Aumonier, J., Smith, K.A., Johnston, A., Younger, P.L., 2009. Evaluation of iron ochre from mine drainage treatment for removal of phosphorus from wastewater. Chemosphere 75, 795-800.

Durham Biodiversity Partnership, 2007. Field Notes, Issue 4. Durham County Council, Durham. 6pp,

Green, P.J., & Silverman, B.W., 1994. Nonparametric Regression and Generalized Linear Models: A Roughness Penalty Approach. London, Chapman and Hall. 184pp.

Hedin, R. S., Nairn, R. W. and Kleinmann, R. L. P., 1994. Passive treatment of polluted coal mine drainage. Bureau of Mines Information Circular 9389. United States Department of Interior, Washington DC. 35pp.

Hughes, T.A., Gray, N.F., 2012. Co-treatment of acid mine drainage with municipal wastewater: performance evaluation. Environ Science and Pollution Research International, 20: 7863-7867 (DOI: 10.1007/s11356-012-1303-4).

Hughes, T.A., Gray, N.F., 2013. Removal of metals and acidity from acid mine drainage using municipal wastewater and activated sludge. Mine Water and the Environment DOI: 10.1007/s10230-013-0218-8.

Johnson, K.L., Younger, P.L., 2006. The co-treatment of sewage and mine waters in aerobic wetlands. Engineering Geology 85, 53-61.

Kadlec, R.H.,Wallace, D.S., 2009. Treatment Wetlands (2nd Edition). CRC Press, Boca Raton. 1016pp.

Kusin, F.M., Jarvis, A.P., and Gandy, C.J., 2012, Hydraulic performance assessment of passive coal mine water treatment systems in the UK. Ecological Engineering 49: 233–243.

Martinez, C.J., and Wise, W.R., 2003. Analysis of constructed treatment wetland hydraulics with the transient storage model OTIS. Ecological Engineering 20: 211 – 222.

Mayes, W.M., Younger, P.L., Aumônier, J., 2006. Buffering of alkaline steel slag leachate across a natural wetland. Environmental Science and Technology 40, 1237-1243.

McCullough, C.D., Lund, M.A., May, J.M., 2008. Field-scale demonstration of the potential for sewage to remediate acidic mine waters. Mine Water and the Environment 27: 31-39.

Mills, D.A.C., and Holliday, D.W., 1998, Geology of the district around Newcastle-upon-Tyne, Gateshead and Consett. Memoir of the British Geological Survey, Sheet 20 (England and Wales). The Stationery Office, London. 148pp.

Mulamoottil, G., McBean, E.A.., Revers, F., (editors) 1999. Constructed wetlands for the treatment of landfill leachates, Lewis Publishers / CRC Press, Boca Raton. 304pp.

Rose, P., 2013. Long-term sustainability in the management of acid mine drainage wastewaters – development of the Rhodes BioSURE Process. Water South Africa 39 (5), 583 – 592.

Strosnider, W.H., Nairn, R.W., 2010. Effective passive treatment of high-strength acid mine drainage and raw municipal wastewater in Potosí, Bolivia using simple mutual incubations and limestone. Journal of Geochemical Exploration 105, 34 – 42.

Strosnider, W.H., Winfrey, B.K., Nairn, R.W., 2011a. Novel passive co-treatment of acid mine drainage and municipal wastewater. Journal of Environmental Quality 40: 206-213.

Strosnider, W.H., Winfrey, B.K., Nairn, R.W., 2011b. Biochemical oxygen demand and nutrient processing in a novel multi-stage raw municipal wastewater and acid mine drainage passive co-treatment system. Water Research 45: 1079-1086.

Strosnider, W.H.J., Nairn, R.W., Peer, R.A.M., Winfrey, B.K., 2013. Passive co-treatment of Zn-rich acid mine drainage and raw municipal wastewater. Journal of Geochemical Exploration 125: 110-116.

Tarutis, W.J., Stark, L.R., Williams, F.M., 1999. Sizing and performance estimation of coal mine drainage wetlands. Ecological Engineering 12, 353-372.

UKAS, 2013. Schedule of Accreditation: 1181- Northumbrian Water Ltd. Issue No: 079. Issue date: 04 December 2013. United Kingdom Accreditation Service, Feltham. 47pp. (available on-line: www.ukas.org/testing/schedules/Actual/1181Testing%20Multiple.pdf; last accessed 4-2-2014).

Vymazal, J., 2011. Constructed wetlands for wastewater treatment: Five decades of experience. Environmental Science and Technology 45 (1), 61 - 69.

Wieder, R.K., 1989. A survey of constructed wetlands for acid coal mine drainage treatment in the eastern United States. Wetlands 9, 299-315.

Winfrey, B.K., Strosnider, W.H., Nairn, R.W., Strevett, K.A., 2010. Highly effective reduction of fecal indicator bacteria counts in an ecologically engineered municipal wastewater and acid mine drainage passive co-treatment system. Ecological Engineering 36, 1620-1626.

Younger, P.L., 1998. Coalfield Abandonment: Geochemical Processes and Hydrochemical Products. In Nicholson, K., Energy and the Environment. Geochemistry of Fossil, Nuclear and Renewable Resources. McGregor Science, Aberdeen. pp 1 - 29.

Younger, P.L., Banwart, S.A., Hedin, R.S., 2002. Mine water, hydrology, pollution, remediation. Kluwer Academic Publishers, Dordrecht. 464pp.

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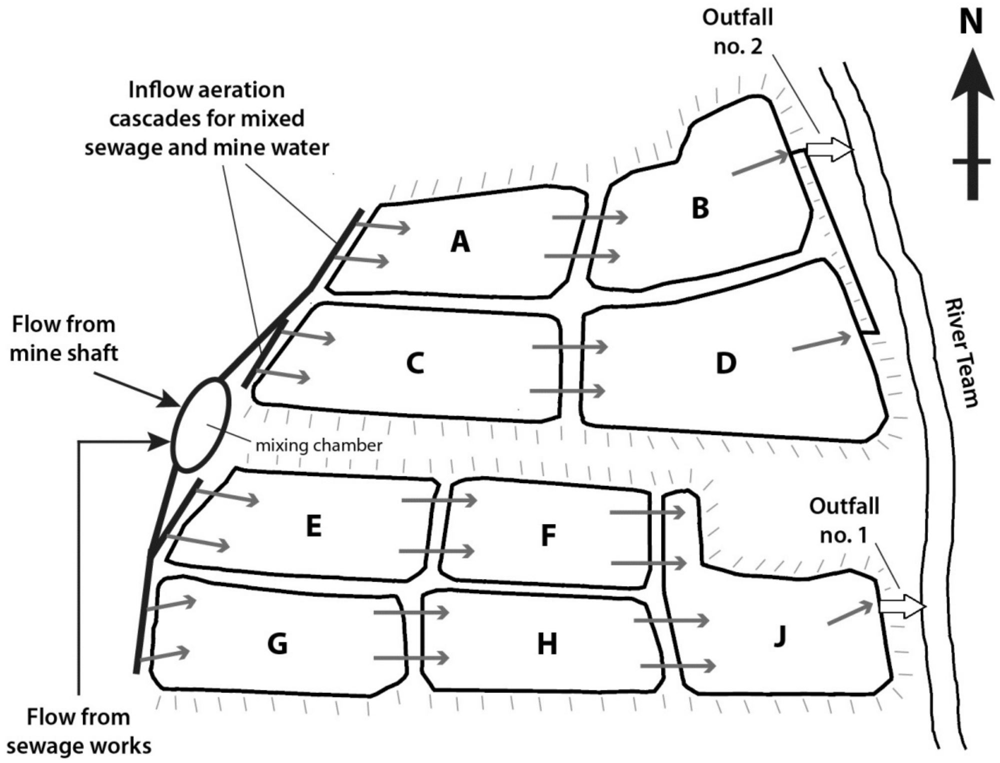
Figure 1. Sketch plan of the Lamesley co-treatment wetland for sewage and mine water. The arrows indicate directions of water movement, from the inflow aeration cascades through which the mixture of mine water and sewage enters the wetlands, to the two final outfalls to the River Team (i.e. outfall no 1 in the north, and outfall no 2 in the south). Individual wetland cells are labelled with letters, allowing recognition of the following four parallel treatment streams: (i) A – B – Outfall no. 2 (ii) C – D – Outfall no. 2 (iii) E – F – J – Outfall no. 1 (iv) G – H – J – Outfall no. 1.

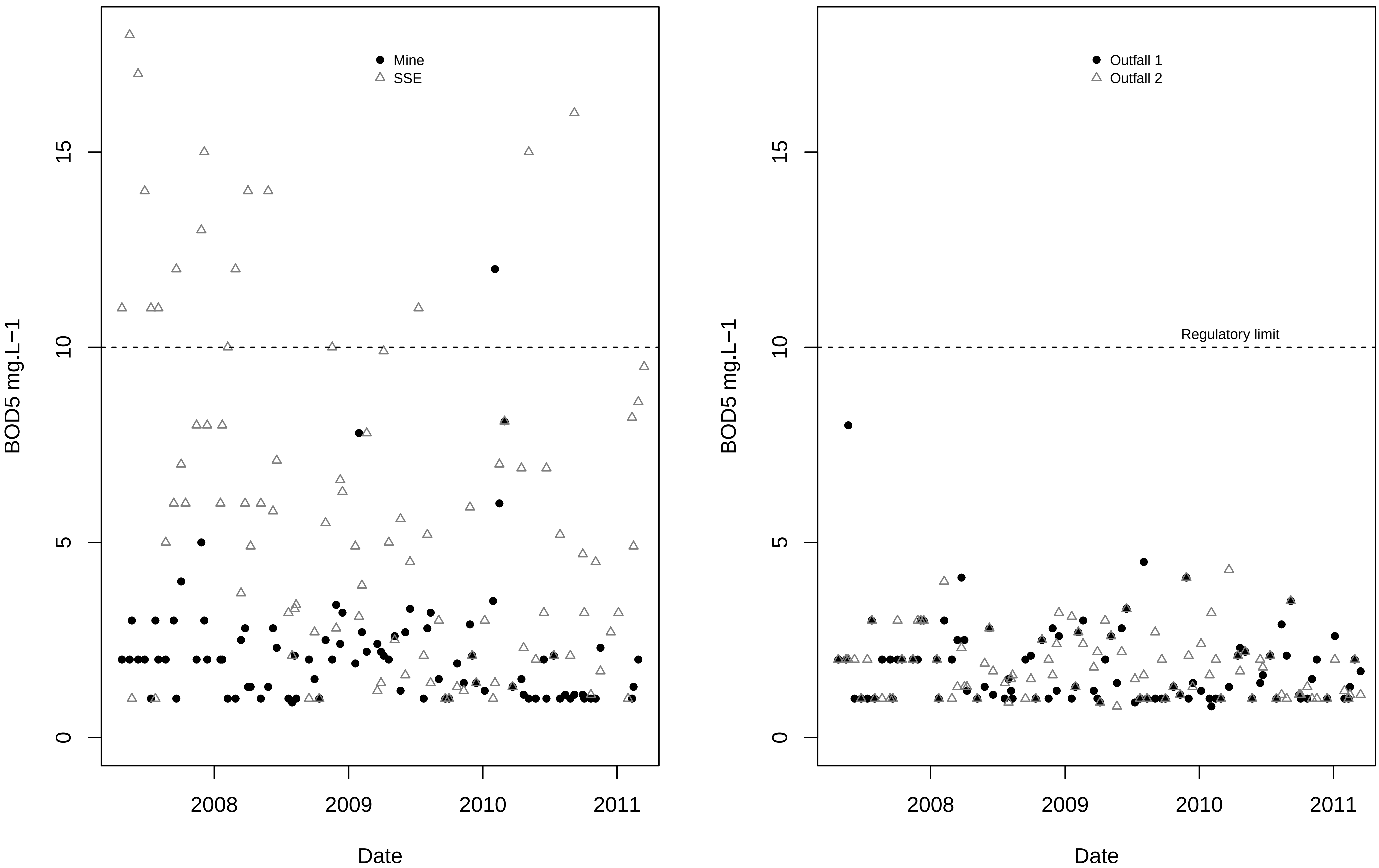
Figure 2. Sample concentrations ($mg \cdot L^{-1}$) of BOD_5 into and out of the wetlands, from April 2007 until March 2011. Left plot: raw mine water (MW) and secondary sewage effluent (SSE). Right plot: Outfalls nos. 1 and 2 (see Figure 1).

Figure 3. Sample concentrations ($mg \cdot L^{-1}$) of iron into and out of the wetlands, from April 2007 until March 2011. Left plot: raw mine water (MW) and raw secondary sewage effluent (SSE). Right plot: Outfalls nos. 1 and 2 (see Figure 1).

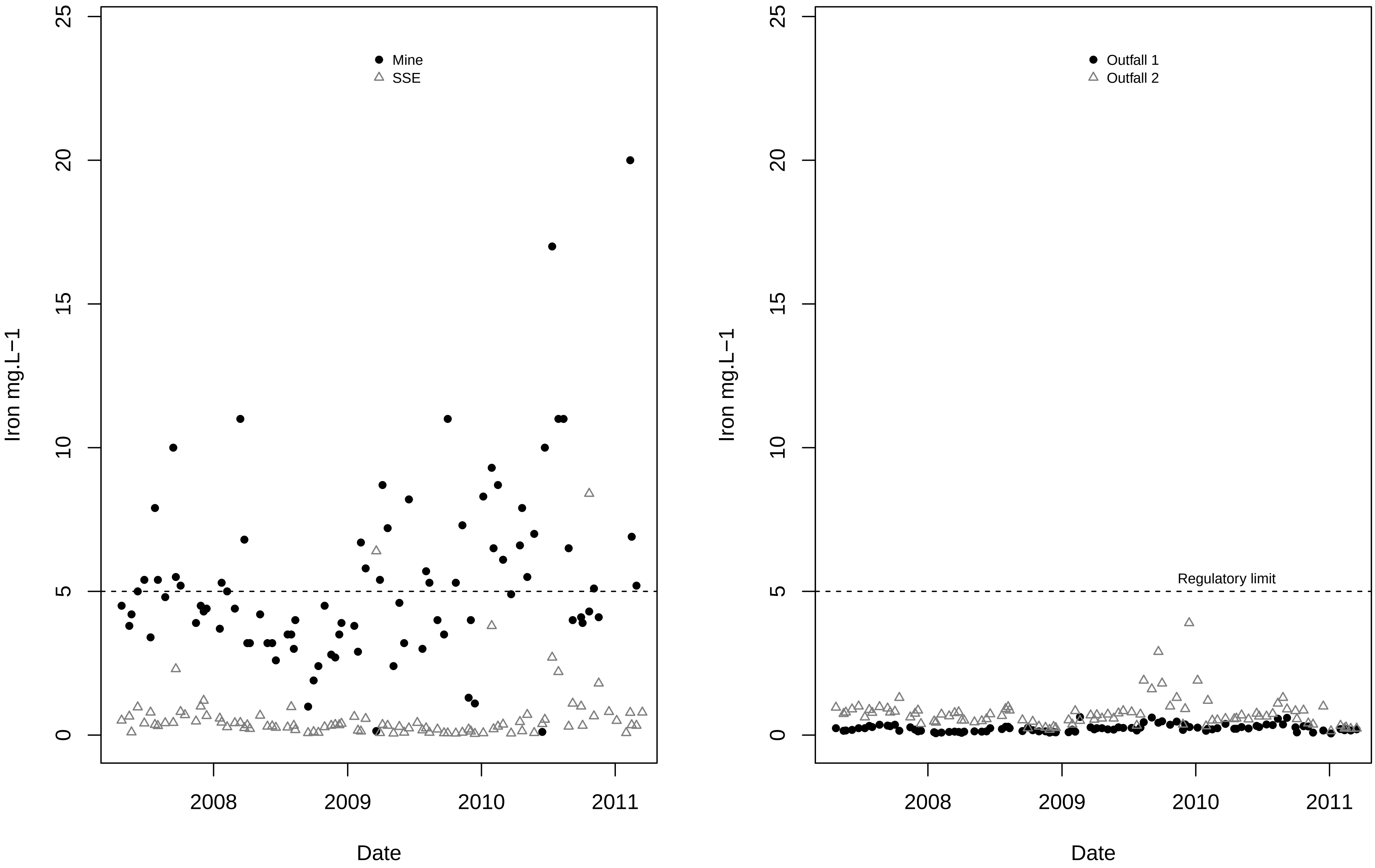
Figure 4. Sample concentrations ($mg \cdot L^{-1}$) of total phosphorus into and out from the wetlands, from June 2010 until March 2011. The left hand plot shows the total P concentration in the mine water (MW) and the secondary sewage effluent (SSE).

Figure 5. Concentrations of suspended solids (mg·L^{-1}) into (left plot) and out of (right plot) the wetlands, from April 2007 until March 2011.

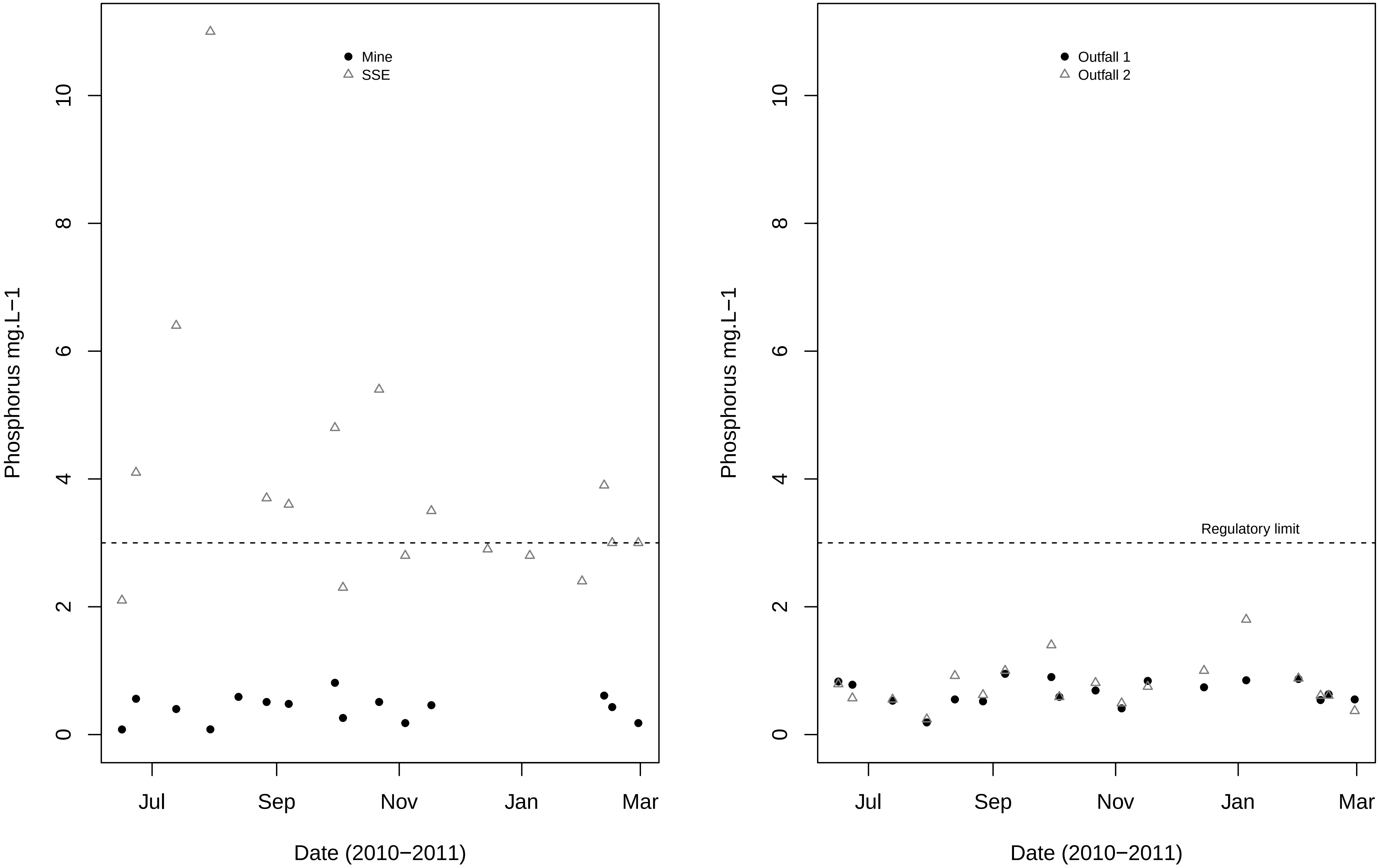

Outfall
no. 2
N
Inflow aeration
cascades for mixed
sewage and mine water
A
B
C
D
Flow from
mine shaft
mixing chamber
River Team
E
F
Outfall
no. 1
G
H
J
Flow from
sewage works

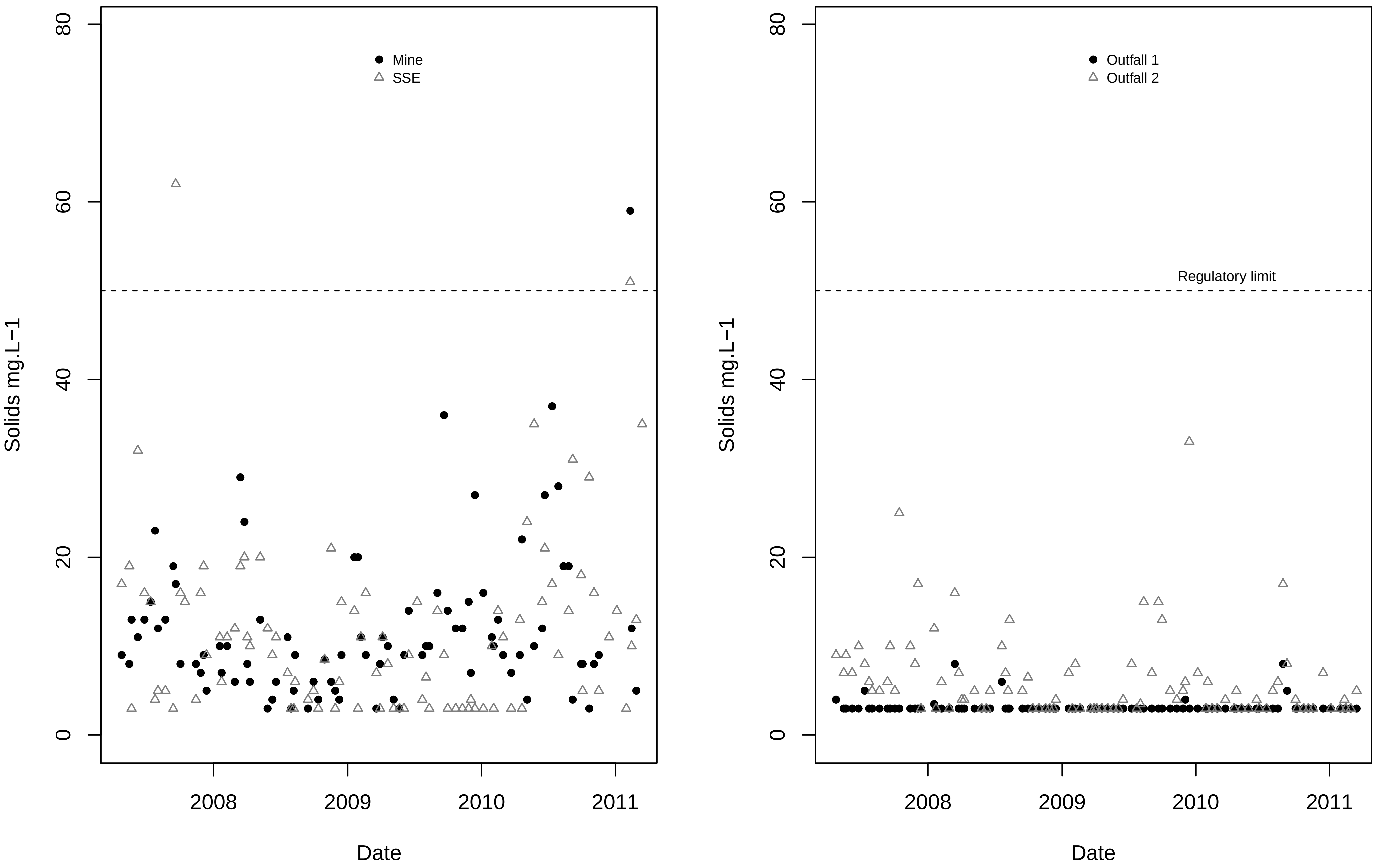


Mine
SSE
Outfall 1
Outfall 2
Regulatory limit
BOD5 mg.L−1
Date
0
5
10
15
2008
2009
2010
2011



Mine
SSE
Outfall 1
Outfall 2
Regulatory limit
Iron mg.L−1
Date
0
5
10
15
20
25
2008
2009
2010
2011


Mine
SSE
Phosphorus mg.L−1
0
2
4
6
8
10
Jul
Sep
Nov
Jan
Mar
Date (2010−2011)
Outfall 1
Outfall 2
Regulatory limit
Phosphorus mg.L−1
0
2
4
6
8
10
Jul
Sep
Nov
Jan
Mar
Date (2010−2011)



Mine
SSE
Solids mg.L−1
Date
Outfall 1
Outfall 2
Regulatory limit
Solids mg.L−1
Date
0
20
40
60
80
2008
2009
2010
2011

Table 1. Flow-weighted average concentrations (mg·L^{-1}) of key pollutants in the raw mine water (MW) and secondary sewage effluent (SSE), compared with the concentrations in the final effluent from the co-treatment wetland system which would result if mutual dilution of MW and SSE were the only process operative ("expected"), versus the actual concentrations observed, which clearly reflect substantial net immobilization of pollutants.

Pollutant	MW	SSE	"Expected" (i.e. by dilution only)	Actual (observed)
BOD_5	2.04	5.5	3.06	1.8
Iron	6.05	0.62	4.46	0.49
NH_4-N	0.6	1.39	0.83	0.28
P (dissolved)	0.32	3.04	1.08	0.44
P (total)	0.49	3.91	1.45	0.79
Suspended solids	14.46	10.99	13.44	4.55

Table 2. Areally-normalized mass loadings ($g \cdot m^{-2} \cdot d^{-1}$) for the Lamesley co-treatment wetland system with respect to key pollutants delivered in secondary sewage effluent (SSE), which predominantly contributes BOD_5, NH_4-N, P-dissolved and P-total, and mine water (MW), the main source of Fe. (The net removal rate is simply the difference between the mass loadings entering and leaving the wetland for each of the pollutants). Literature relevant to the final column is: [a] Kadlec and Wallace (2009); [b] Hedin *et al.* (1994).

	Loading from SSE	**Loading from MW**	**Total loading entering wetland**	**Total loading leaving wetland**	**Net removal rate (this study)**	**Relevant maximum removal rates reported in literature**
BOD_5	1.048	0.936	1.985	1.171	0.814	0.8[a]
Fe	0.119	2.775	2.894	0.320	2.574	10[b]
NH_4-N	0.264	0.277	0.541	0.182	0.359	0.35[a]
P-diss	0.533	0.142	0.675	0.277	0.398	0.25[a]
P-total	0.687	0.218	0.904	0.489	0.415	0.25[a]
Susp. solids	2.096	6.630	8.726	2.952	5.774	10[a]