Use of probabalistic methods for sizing a wetland to treat mine water discharging from the former Polkemmet Colliery, West Lothian, Scotland

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ABSTRACT

Following closure of the Polkemmet Colliery in 1986 and subsequent flooding, SRK predicted that mine water contaminated with iron and manganese would discharge to the River Almond with consequent major impacts.

A feasibility study was commissioned by the Coal Authority into prevention and long term treatment of the discharge. A contingency scheme involving pumping and treatment of the discharge through aeration and settlement was implemented in January - March 1998 and has successfully prevented the discharge.

One of the long term options has been surface flow wetland treatment. SRK has combined recommended wetland sizing criteria with probabilistic dilution modelling to estimate the probability distributions of iron and manganese downstream of the treated discharge.

This approach has resulted in a reduction in wetland area from about 20 Ha, calculated by more conventional means to about 10 Ha. The resulting savings could amount to between £250000 - £500000.

BACKGROUND

Polkemmet Colliery was located in West Lothian, Scotland, about 20 km west of Edinburgh. The mine closed in 1986 and was the last of a number of inter-connected mines to stop pumping water. Following closure the extensive inter-connected system of mines began to flood. The site location is shown in Figure 1 and a composite plan of the mined system is shown in Figure 2.

The two shafts at Polkemmet were capped and the rise in mine water level was not monitored until November 1995, when, as part of a study into the potential for opencast development at the site the caps were re-opened.

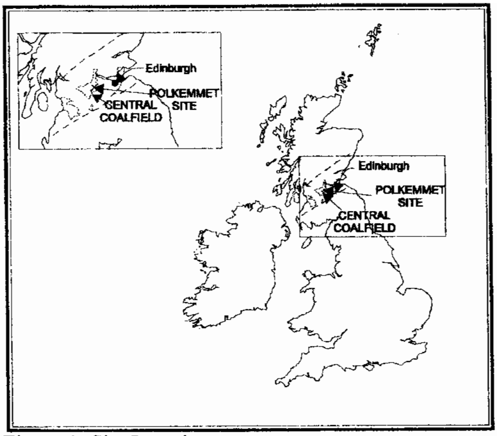

Figure 1: Site Location

At that time it was found that the water level was within 20 m of low points on the ground surface and was rising at a rate of about 0.2 m per week. Concern was raised about the potential for discharge of contaminated water and pollution of the River Almond which flows over the mined system.

Steffen, Robertson and Kirsten was appointed in December 1995 by the Forth River Purification Board (subsequently Scottish Environment Protection Agency [SEPA]) to make preliminary predictions of the timing, location, rate and quality of the anticipated discharge (Sadler and Philpott, 1998). Additional objectives were to assess potential impacts on opencast development and identify possible mitigation options, recommending further work to prepare for mitigation.

Based on background information on mining and geology, together with details of existing minewater quality and rate of rise, a simple conceptual model was developed and used as the basis of preliminary predictions which would aid in decision making. SRK predicted that the minewater would surface at one or more of three sites in the first half of 1998. The predicted and observed mine water recovery curves are plotted together in Figure 3.

The minewater was predicted to discharge at a maximum rate of 10000 m^3/day, with summer and winter flows of approximately 1500 m^3/day and 7500 m^3/day respectively. The discharge water was expected to be net alkaline (ie alkalinity > acidity) with near neutral pH and iron and manganese concentrations of 30-100 mg/l and 20-50 mg/l respectively.

As a result of the predictions made by SRK, SEPA recommended to the Coal Authority that the site be included in their national rolling programme of sites considered for remediation, despite there being no discharge to the surface at the time. Consequently, in August 1997, SRK was appointed by the Coal Authority to undertake a feasibility study into treatment of the minewater and prevention of minewater discharge to the surface. Part of the feasibility study was to develop a contingency scheme amenable to rapid implementation designed to prevent or minimise the impacts of minewater breakout if there was insufficient time to implement full scale treatment.

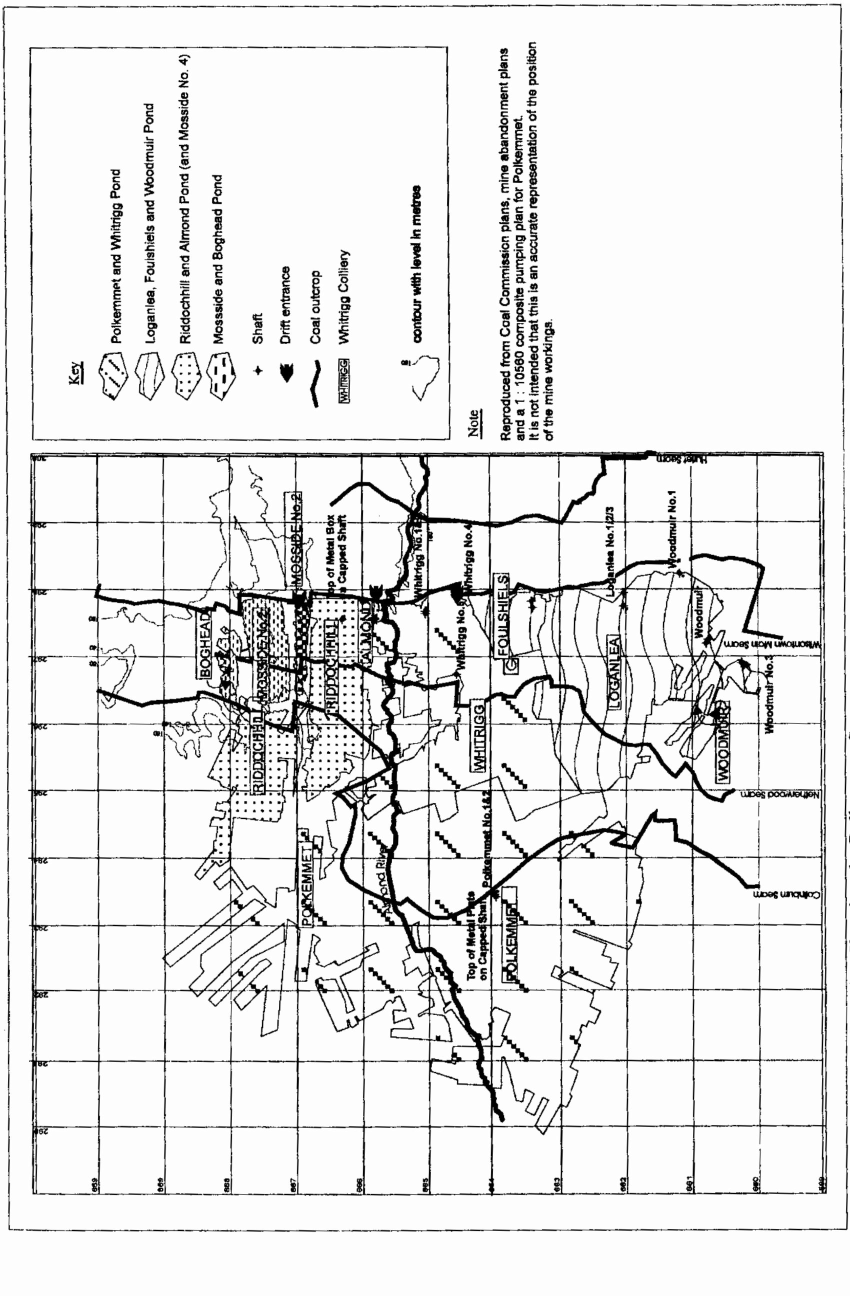

Figure 2: Composite Mine Plan Showing the Polkemmet System

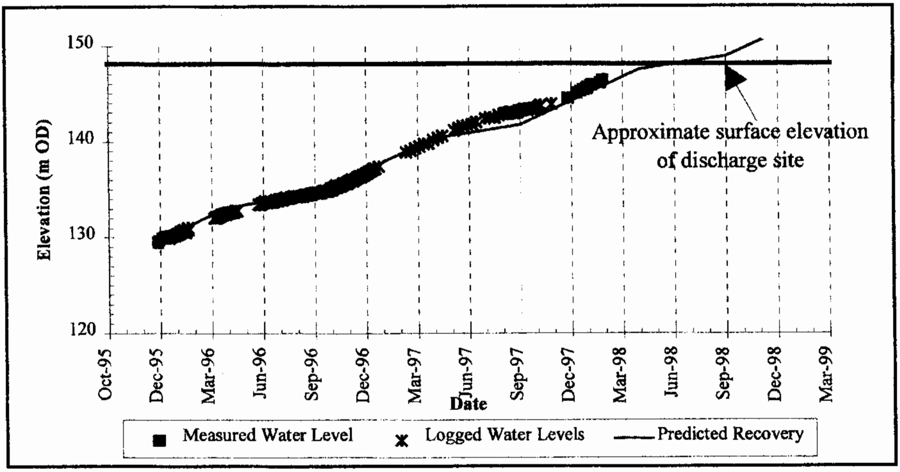

Figure 3: Predicted and actual rate of mine water rise

Short term solution

In December 1998 SRK recommended that the proposed contingency scheme be implemented since discharge was anticipated within four months leaving insufficient time for construction of more complex longer term solutions.

The proposed scheme involved pumping of water from the Polkemmet shaft some 5 km west of the anticipated discharge where the mine water was known to be less contaminated, followed by treatment through aeration and settlement aided by chemical dosing. A schematic cross-section through the workings showing anticipated flow paths is shown in Figure 4 and the treatment concept is illustrated in Figure 5.

The contingency scheme was commissioned in March 1998 and has succeeded in its three principal functions of preventing uncontrolled discharge of contaminated water, removing iron from pumped water and providing data on flows and quality for design of longer term solutions.

Continuous pumping at about 9000 m^3/day successfully lowered the mine water levels by 3-5 m across the system. Since this safe level has been achieved, pumping at a reduced rate of about 3500 m^3/day has been sufficient to maintain a stable water level at about 5 m below the surface in potential discharge areas.

Initially the pumped water had iron and manganese concentrations of less than 5 mg/l and less than 1 mg/l respectively. With continued pumping these levels have gradually increased and the mine water quality appears to have temporarily stabilised (May/June 1998) with iron concentrations of around 10 mg/l and manganese at about 2 mg/l.

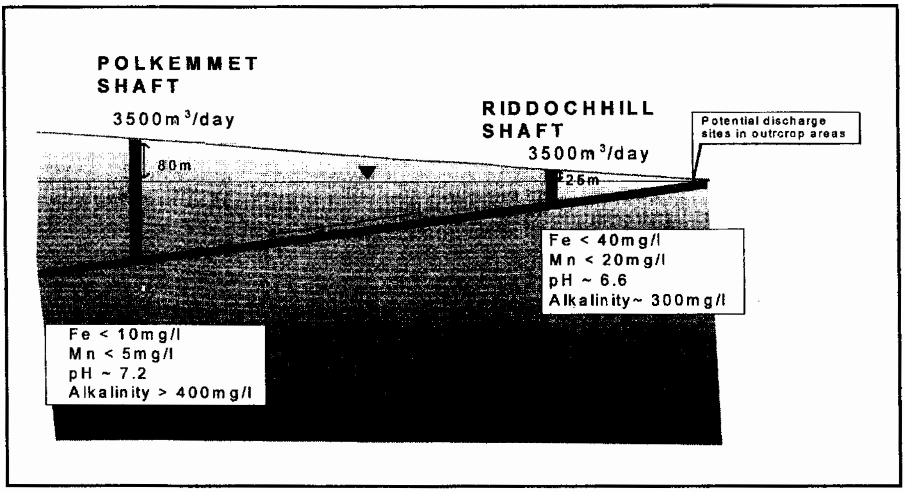

Figure 4: Conceptual model of anticipated iron and manganese removal.

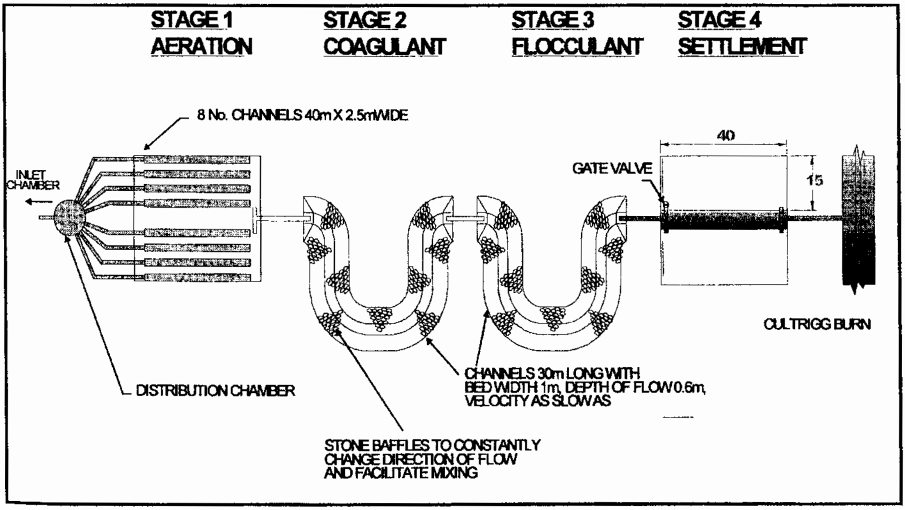

Figure 5: Polkemmet mine water treatment system

Long term solutions

The contingency scheme has been designed and constructed as a short term emergency measure. Some aspects of the scheme may be included in more long term solutions, but it is likely that for long term treatment a more passive system of treatment will be employed. Since the minewater is net alkaline and iron is the main contaminant which requires removal, the minewater is amenable to treatment in a surface flow wetland system (Hedin et al, 1994).

The principal mechanisms employed in such a system are oxidation of ferrous iron to ferric, hydrolysis of the ferric iron, flocculation of ferric hydroxide precipitates and settlement. It is difficult to quantify the relative importance of the above factors and the rates of each process to provide a processed based means of sizing wetlands. Consequently most wetland designers use the 'rule of thumb' sizing criteria developed by the US Bureau of Mines (Hedin et al, 1994). For net alkaline minewaters, the wetland sizing criteria for compliance with local regulatory standards are the removal of 10 $g/m^2/day$ of iron and 0.5 $g/m^2/day$ of manganese. These removal rates apply sequentially with iron removal followed by manganese removal.

The above rates of removal are often applied directly to the maximum or mean discharge characteristics. Based on the above removal rates and assumed mean discharge characteristics at Polkemmet of:

flow rate	3500 m^3/day
iron concentration	40 mg/l
manganese concentration	20 mg/l

the wetland area required would be :

$$\frac{3500 \times 40}{10} + \frac{3500 \times 20}{0.5} = 16\,800 \text{ m}^2 \text{ (16.8 ha).}$$

The flow rate above is reasonably well known, but since the ultimate discharge water quality is not known values have been taken which are considered at the high end of the likely range for the mean. In applying this approach, no account has been taken of the impacts on the receiving water course, and therefore many designers are probably being over conservative.

For the long term solution at Polkemmet, SRK consequently applied a Monte Carlo risk simulation approach to wetland sizing to take account of dilution in the receiving water course and anticipated variability in discharge and receiving water course characteristics. This approach enables the wetland to be designed to achieve River Quality Objectives (RQO) in the receiving water course. In this case the RQO's for iron and manganese are mean concentrations of 2 mg/l and 1 mg/l respectively.

The standard dilution equation (Connelly et al, 1994) was adapted to estimate downstream receiving water quality following wetland treatment as follows:

If $(Q_D C_D) - (WR \times A) > RC$:

$$C_R = \frac{(Q_D C_D) - (WR \times A) + Q_I C_I}{Q_D + Q_I}$$

and:

If $(Q_D C_D) - (WR \times A) < RC$:

$$C_R = \frac{(Q_D \times RC) + Q_I C_I}{Q_D + Q_I}$$

Where:

Q_D	=	Discharge flow rate
C_D	=	Discharge concentration
WR	=	Wetland removal rate
A	=	Wetland area
RC	=	Residual Concentration i.e. 2 mg/l for iron and 1 mg/l for manganese
C_R	=	Resultant downstream concentration
Q_I	=	Upstream flow rate
C_I	=	Upstream concentration

The 'if' statement simply means that the wetland cannot remove iron or manganese to below a residual concentration. In this case it has been assumed that RC is equal to the RQO. This is a reasonable conservative assumption since it is very difficult to settle the finest particulates from suspension.

Each of the parameters above is a variable, however and will either vary independently or inter-dependently with other variables. In addition to the actual variation that will occur there is considerable uncertainty regarding certain of the values and ranges attributable to each parameter. The equations have therefore been solved using the probabilistic simulation package @Risk (Palisade Corporation, 1997a) which solves the equations through Monte Carlo simulations to produce a probability distribution for the downstream metal concentration. For each input a distribution was defined, and a correlation matrix which defines relationships between variables was established.

Where real or synthesised data, which were considered to represent the probability distribution of the variable, were available, the programme Best Fit (Palisade Corporation 1997b) was used to assign the most appropriate distribution. Where this data was not available, a normal or lognormal distribution was assigned based upon experience and judgement. Summary statistics for the distributions are presented in Table 1. Input distributions for all parameters are illustrated in Figure 6.

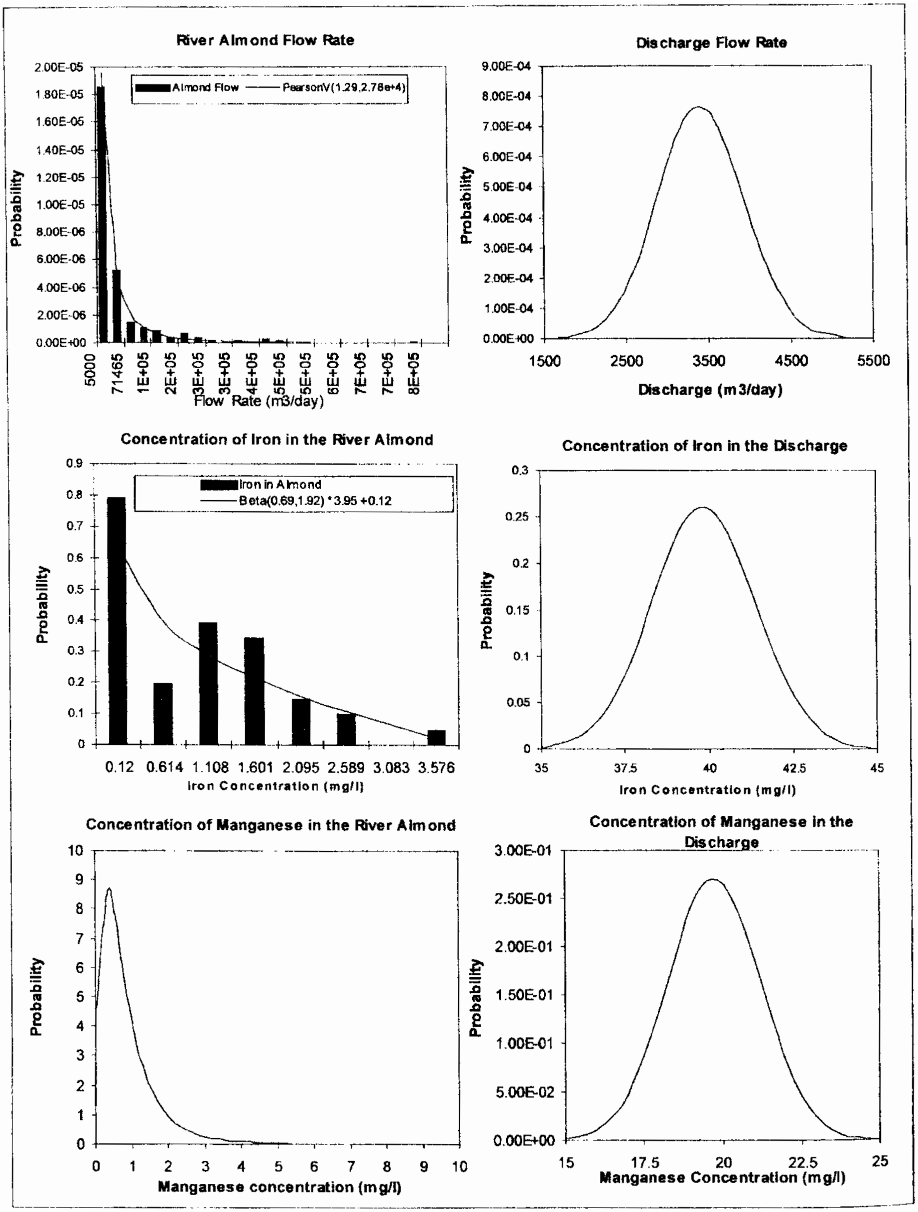

Figure 6: Input Distributions For All Parameters

Table 1: Summary Statistics For Input Parameters

Variable		Iron		Manganese	
Upstream Flow	(Q_I)	Pearson5	(1 29 27800)	Pearson5	(1.29 27800)
Upstream Quality	(C_I)	Beta	(0 69 1 92)*3 95+0 12	Lognormal	(0 1 0 08)
Discharge Flow	(Q_D)	Normal	(3456 522)	Normal	(3456.522)
Discharge Quality	(C_D)	Normal	(40 1 5)	Normal	(40 1 5)
Wetland Removal Rate	(WR)	10		0 5	
Residual concentration	(RC)	2		1	

The bases for assigning distributions to the various parameters are summarised below:

Q_I Based on long term records of flows in the River Almond and estimated using Bestfit.

Q_D Based on the pumping rate needed to stabilise minewater levels and historical variability of minewater recovery rate.

C_I Based on historical water quality records for the River Almond. For iron the distribution was estimated using Bestfit. Since manganese data was limited the maximum measured value was used as a conservative approximation to the mean. The distribution was assumed to be lognormal and an arbitrary variance of 0.08 was selected.

C_D Based on analytical results of samples taken from workings and geochemical modelling. There is considerable uncertainty associated with this parameter, but it is anticipated that once water quality has stabilised there will be limited variability. To take account of uncertainty whilst maintaining conservatism, a mean value at the high end of the potential range has been selected. A normal distribution with standard deviation of 1.5 has been selected based on experience.

It is assumed that the values of WR and RC are constant.

Correlation coefficients between distributions are presented in Table 2. The positive correlation between Q_D and Q_I must exist since both are flows dependent to some degree on rainfall and weather conditions. Based on experience of correlation between baseflow and total flow in streams, a value of 0.5 was selected for this correlation.

The positive correlation between Q_I and C_I (Fe) is based on the historical data sets. This positive correlation probably occurs because higher suspended solids loads are mobilised during higher flow periods and there may be a greater proportional contribution from adjacent mine sites during these periods. In the absence of sufficient data it has been assumed that manganese behaves similarly.

Table 2: Correlation Matrix For Simulation

Variable	Q_I	C_I Iron	C_I Manganese	Q_D	C_D Iron	C_D Manganese
Q_I	1	0.55	0.55	0.5	0	0
C_I Iron	0.55	1	0	0	0	0
C_I Manganese	0.55	0	1	0	0	0
Q_D	0.5	0	0	1	0	0
C_D Iron	0	0	0	0	1	0
C_D Manganese	0	0	0	0	0	1

Using the above distributions and correlations the modified dilution equation was solved for C_R with the value of A (wetland area) being varied until acceptable distributions of downstream concentrations of iron and manganese were achieved. In each case the target was for a mean of 0.1mg/l less than the mean RQO.

It was found that acceptable distributions were achievable for iron and manganese with wetland areas of 1.1 Ha and 8.7 Ha respectively. The total requirement would therefore be about 9.8 Ha. The predicted downstream distributions for iron and manganese for these wetland areas are shown in Figures 7 and 8 respectively.

The 9.8 Ha area compares favourably with the areas of about 17 Ha obtained by the more straight forward deterministic methods and has the advantage that probability distributions for receiving water quality have been predicted. Further, such predictions can then be compared with the River Quality Objective and used to support applications for discharge consent for the wetland.

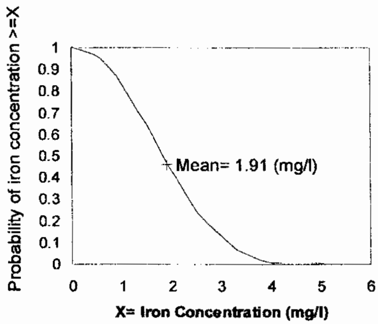

Figure 7: Downstream iron distribution following wetland treatment (1.1Ha)

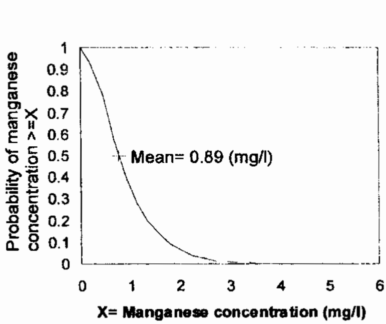

Figure 8: Downstream manganese distribution following wetland treatment (8.7Ha)

CONCLUSIONS

The reduction in wetland area from 20-9.8 Ha was achieved by progressing from the inherently conservative sizes obtained with minimal evaluation to the more realistic designs achieved by more rigorous evaluation. This represents a minimum financial saving of approximately £500 000, for an additional expenditure on evaluation of less than £5000.

In the UK where good data sets are often available for receiving water courses, this kind of approach is clearly cost effective. However, even where data is less readily available, the savings are likely to justify significant data collection programmes and modelling efforts to synthesise the data and optimise water treatment designs.

ACKNOWLEDGEMENTS

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