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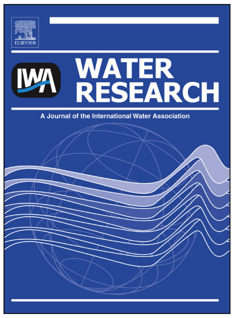

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Chemical cleaning of potable water membranes: the cost benefit of optimisation

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Abstract

A study of the variability in chemical cleaning factors on permeability recovery for potable water microfiltration (MF) and ultrafiltration (UF) systems has been carried out employing a cost model simulating plant fouling and cleaning regimes. The impact of a range of operating and cleaning factors on operating cost variation was computed using algorithms describing operational and cleaning factor relationships with permeability recovery data measured from bench scale tests on fibres sampled from full-scale operational plants.

The model proceeded through sequencing of the cleaning and backwashing operations to generate transmembrane pressure (TMP), and so head loss, transients. A number of cleaning scenarios were considered for each plant, based on employing either a threshold TMP or fixed chemical cleaning intervals. The resulting TMP profiles were then converted to operational costs. The effect of the variability in permeability recovery on annual operating costs was calculated for each of the simulations. It was evident that significant operating cost reductions were possible from optimisation of the cleaning protocol. Cost benefit varied according to facets of plant design and operation; the innate variability in permeability recovery precluded the correlation of cleaning efficacy with fouling characteristics.

Key words: membrane cleaning; factorial analysis; hollow fibre; potable water; cost benefit

SYMBOLS AND ABBREVIATIONS

(C_{min}), C	(Minimum) concentration
(P_{max}), P	(Maximum) soak period (min)
(T_{min}), T	(Minimum) temperature (°C)
$£_{op}$	Overall operational cost (GBP)
$£_p$, $£_h$, $£_c$, $£_w$	Cost of pumping, heating, chemicals, and waste (GBP)
$£_{unit}$	Unit operational cost per volume produced (pence.m^{-3})
Δh	Head difference for a column of water (m)
μ	Viscosity (kg.m^{-1}.s^{-1})
a-f	Factors in two-factorial expression for permeability recovery in Eq 2
A_m	Membrane area (m^2)
BBD	Box Behnken determination
CEB	Chemically enhanced backwash/backflush
Cf_c	Unit chemicals cost (GBP/tonne)
Cf_e	Unit electricity cost (GBP/kWh)
Cf_w	Unit waste cost (GBP/kWh)
CIP	Clean in place
CT	Capillary tubes
C_v	Specific heat capacity (kJ. Kg^{-1}.°K^{-1})
g	Gravitational constant (9.81 m.s^{-2})
GAC	Granular Activated Carbon
HF	Hollow fibres
J	flux (L.m^{-2}.h^{-1})
K_f, K_i	Final, initial membrane permeability from cleaning test (L.m^{-2}.h^{-1} bar^{-1})
K_v	Virgin membrane permeability (L.m^{-2}.h^{-1} bar^{-1})
M	Factor in two-factorial expression for permeability recovery (Eq 2)
MF	Microfiltration
N_b	Number of backflushes per year
N_c	Number of chemical cleans per year
PACL	Poly Aluminium Chloride
PES	Polyethersulphone
PP	Polypropylene
PP	Polypropylene
PVDF	Polyvinylidene difluoride
Q_b	Backwash flow rate (L.s^{-1})
Q_m	Filtration flow rate (L.s^{-1})
r	Ratio of chemical cleanant volume to membrane area
R_M, R_f	Membrane, fouling resistance (m^{-1})
R_v	Percentage permeability recovery from cleaning
$R_{v,max}$	Optimal cleaning recovery (%)
sHF	Submerged Hollow fibres
T	Average Feed Temperature (°C)
t_b	Period between backflushes, i.e. backflush frequency (min)
t_{bb}	Backflush dureation (s)
t_c	Period between chemical cleans, i.e. chemical cleaning frequency (days)
t_{cc}	Clean period (min)
UF	Ultrafiltration
V_m, V_b, V_c	Annual volumes: design throughput, backwashing, cleaning (m^3)
V_p	Net production of permeate per annum (m^3)

X_a, X_b, X_c	Proportion of fouling removed by backwashing, chemical cleaning and unremoved in Eq 4 ($m.min^{-1}$)
α	Specific Cake resistance ($m.kg^{-1}$)
ΔP or TMP	Transmembrane pressure (m H_2O, bar.g or kPa)
ΔT	Difference between ambient temperature and reagent temperature (°C)
η	Conversion efficiency (%)
ρ	Density ($kg.m^{-3}$)

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Introduction

Studies into cleaning sequencing and its impact on operating costs require experimental fouling data to provide head loss information. Whilst abundant fouling data is available, as well studies of the impact and/or optimisation of physical cleaning for fouling amelioration (Lodge and Judd, 2004; Katsoufidou et al, 2005; Smith et al., 2006, van der Ven, 2008), studies of chemical cleaning of membranes in the municipal water sector are much less common.

Early studies into optimisation of membrane cleaning qualitatively modelled the relationship between cleaning regime and recovery for single foulants (Bartlett et al. 1995). These studies were developed from Hermia's blocking model, where foulants form resistance layers (Belfort et al., 1994). Further studies into quantifying the effects of chemical cleanants have been used predominantly in food and industrial applications (Shorrock and Bird, 1998, Blanpain-Avet et al., 2004). Observations of cleaning effects with surrogate foulants in laboratory experiments show differences in cleaning effects and efficiencies for different solutions (Field et al. 2008). Dead end hollow fibre (HF) membrane cleaning studies on fibres from a single field source showed the impact of cleaning reagents to be dependent on foulant character (Strugholtz et al., 2005). Recently models have been developed investigating dynamic cleanant performance on membranes fouled with surface waters at high organic loads (Zondervan and Roffel, 2007). Economic simulations based on ultrafiltration (UF) have suggested that optimising the number of cleaning cycles does not reduce operating costs, and that cleaning should instead be optimised to control fouling (Lodge and Judd, 2004; Zondervan and Roffel, 2008b).

Factorial analysis using analysis of variance has been shown to identify and optimise cleaning with proprietary reagents, specifically on spiral wound ultrafiltration and reverse osmosis membranes fouled from wastewater recovery duties (Chen et al., 2003). Recent chemical cleaning optimisation studies based on hollow fibre UF and MF (microfiltration) membranes sampled from full scale potable water treatment plants have quantified optimum permeability recovery from chemical cleaning of hollow fibre (HF) and capillary tube (CT), respectively representing shell-side to lumen-side and lumen-side to shell-side flow, submerged and pumped membranes (Porcelli et al, 2009ab). The method for these latter studies was based on three factorial analyses using a response surface methodology, Box Behnken Determination (BBD), and has yielded algorithms quantifying the variation in permeability recovery from cleaning as a function of the key cleaning parameters of concentration (*C*), temperature (*T*) and soak period (*P*). The experimental method (Porcelli et al, 2009a) has allowed optimum values of *C*, *P* and *T* to be identified for membranes pertaining to a range of plants, cleaning protocols, operating conditions and feed qualities (Porcelli et al, 2009b).

In the following paper the results from a cost model based on the simplest representation of fouling, as resistances in series (Belfort et al., 1994; Zondervan et al., 2008), are presented based on previously published data (Porcelli et al, 2009b). The model has been applied to four full-scale, established MF/UF potable plants selected to provide a range of membrane material types and configurations, water sources, pre-treatment, fouling conditions and corresponding operation and maintenance conditions, with the latter particularly relating to the chemical cleaning regimes.

Methodology

Sampled membrane plants

Cost models for a number of cleaning operational scenarios were built from cleaning factor relationships generated from permeability recovery data from laboratory cleaning optimisation tests (Porcelli et al, 2009ab). Figure 1 shows the information flows to a transient headloss (ΔP) or Trans Membrane Pressure (TMP) model built from site and laboratory data. The factorial algorithms from cleaning experiments allowed four cleaning scenarios to be explored for four membrane potable water treatment sites (A-D, Table 1) with another four scenarios for variation in operational strategy, yielding 64 data in all. Operational costs over a year were calculated from energy and chemicals consumption and waste generation.

Table 1 Operational and membrane data from Sites A-D

Figure 1 Cleaning variation cost model methodology

The HF membranes sampled from the primary stage of each of the four sites were polyethersulphone (PES) ultrafiltration; polypropylene (PP) pumped system microfiltration and polyvinyldiethylene (PVDF), with one site having a submerged configuration and the other pumped. Modules were extracted in a fouled state, prior to on-site backwashing and chemical cleaning, and transported wet to the laboratory. Storage and autopsy of the modules and permeability testing and chemical cleaning efficacy of the extracted fibres was as described in Porcelli et al (2009a).

Generation of cleaning parameter algorithm

A bespoke rig was constructed to measure permeability at constant head of ultrapure water (Porcelli et al, 2009a). Permeability was recorded before and after cleaning to allow calculation of permeability recovery ($\%R_v$) according to:

$$\%R_v = 100(K_f - K_i)/(K_v - K_i) \qquad (1)$$

where K_i and K_f are the measured initial and final permeability in L.m^{-2} h^{-1}. bar^{-1}, and K_v is the virgin membrane permeability.

Fouled fibres extracted from modules taken from full-scale potable water membrane plants were rinsed before assembly into bench scale modules for cleaning and recovery measurement (Porcelli et al, 2009ab). Fifteen trials were conducted in total, and $\%R_v$ measured for a range of values of C, P and T (Table 2). The data were then used to generate site-specific algorithms from least square optima based on a two factorial model (Porcelli et al., 2009b). The aim was to quantify the responses for each factor.

A 2^{3-1} experiment with fifteen tests varying factor conditions was performed to a response surface Box Behnken design (Myers et al. 1989). Cleaning parameters were varied in the matrix in equal proportions, with the central points of each parameter repeated three times. The factorial multipliers (Table 3) from the computed responses from the *CPT* ranges given in Table 2 generated two-factorial expressions specific to each plant:

$$\%R_v = M + a{*}\mathrm{C} + b{*}\mathrm{P} + c{*}\mathrm{T} + d{*}\,\mathrm{C.P} + e{*}\mathrm{C.T} + f{*}\mathrm{P.T} \qquad (2)$$

Table 2 Cleaning factor ranges for BBD experiments

Table 3 Factorial algorithm components for sites A, B, C and D

Cost model basis and operation.

Using the algorithms determined from the cleaning response experiments (Table 3) a simple cost model was built to compute the impact of the cleaning factor envelope for each site. An

Excel spreadsheet time incremented fouling while sequencing optimised recovery from backwash and cleaning operations, generating a TMP transient from the Darcian relationship:

$$R_M + R_f = \frac{\Delta P}{\mu . J} \tag{3}$$

where R_M and R_f are the membrane and fouling resistance, ΔP the TMP, μ the viscosity and J the flux. Foulant deposition was assumed to follow the resistance in series model (Belfort et al. 1994) which can be used for sequencing cleaning cycles in dead end membrane systems (Zondervan et al., 2008a) :

$$R_f = \alpha (X_a + X_b + X_c) \tag{4}$$

where X_a, X_b and X_c are the proportions of the resistance from foulants, contributing to the overall specific cake resistance α, which comprise cake deposits which completely removed by backwashing (X_a), pore deposits removed by chemical cleaning (X_b) and non removable (X_c) (Huang et al. 2009). The factor X_b was iterated such that the model permeability recovery replicated the experimentally determined value represented in the two factorial *CPT* algorithms summarised in Table 3. Historical TMP decline data from the full-scale plants (Fig.2) were used to estimate the average annual rate of foulant build up between backwashes and chemical cleans in place (CIPs) for the MF plants (B, C and D) and chemically enhanced backwashes (CEBs) for the UF plant (A).

For each of the four sites the model generated the classic TMP "saw-tooth" transient (Fig. 3) through appropriate scheduling of backwashing and cleaning and adjustment of R_f to match reported site conditions. Following every backwash X_a was returned to zero whereas both X_a and X_b were returned to zero following a chemical clean. Chemical cleaning was initiated in the model either at fixed time intervals or on reaching a threshold TMP. The pore fouling X_b component was iterated such that the permeability recovery ($\%R_v$) equalled the experimentally-determined value generated from Equation 2 for each site (Table 3). The model provided a TMP transient over a one-year period as a function of cleaning efficacy, which in turn was a function of the *C*, *P* and *T* values for optimum recovery in each plant's experimentally-derived cleaning performance algorithms. The model's recovery was iterated to replicate the optimal cleaning conditions and scenario driven operational costs calculated.

Figure 2 Example SCADA analysis for flux decline TMP Vs Time: 9/07 to 4/08: Showing the annotations for a MF module on plant B.

Figure 3 Typical model output TMP transient, Site A, highlighting an hourly backwash and a cleaning events. Profile is for 2 days of operation (day 31 through 33 of 365).

Model input data from plant operation

Operational variables used to generate the TMP profiles for each site are given in Table 4. The annual design throughput volume (V_m) includes volumes for backwashing (V_b) and cleaning (V_c), such that net permeate production rate is:

$$V_p = V_m - (V_b + V_c) \tag{5}$$

The rate of fouling and the backwash and chemical cleaning intervals, which respectively relate inversely to the number of backwashes (N_b) and cleans (N_c) performed annually, determine the mean TMP. N_b and N_c also determine the volume of water wasted, the total energy demanded for cleaning (primarily for heating) and the chemical demand. Hence, whilst increasing the cleaning frequency maintains a higher TMP, this is to some extent offset by the decreased production and pumping energy demand from membrane "downtime" and reagent heating.

For each plant the model parameter values (Table 4) were collected from site and plant design information. The specific cake resistance and fouling rates were determined by iteration of the variables separately to replicate the average flux decline rate as reported from site data over an annual cycle.

Scenarios

Four cleaning scenarios based on *CPT* variation were computed for each site. These represented the optimum permeability recovery ($R_{v,max}$), as determined from the bench-scale tests (Porcelli et al, 2009b), plus three other scenarios representing ranges of *CPT* variation: minimum cleanant concentration (C_{min}); maximum soak period (P_{max}) and minimum (ambient) temperature (T_{min}). These were used in the algorithm (Equation 2) along with the design and operation data (Table 4) to generate the TMP transient. Results for the four cleaning scenarios are given in Table 5.

Table 4 Design and operational variables, Sites A-D

Table 5 Cleaning factors for *CPT* variation, Scenarios I-IV, for Sites A- D

Each of the four cleaning scenarios was run for four operational strategy variations based on fixed high-level and low level threshold TMPs and chemical cleaning intervals. The average TMP, and thus the pumping energy demand, was thus dictated by the cleaning frequency and permeability recovery. Table 6 gives the operating envelopes for the four operational strategies adopted for modelling each site, for which four the *CPT* scenarios were applied.

Table 6 Operational "Strategies" 1-4 for Sites A-D

Operating cost calculations

Determination for operational costs ($£_{op}$) in for each of the sixteen scenarios (Figure 3) on the four sites were expressed in GBP from the individual costs of pumping energy ($£_p$), heating ($£_h$), chemicals ($£_c$) and waste ($£_w$), using the baseline cost factors given in Table 7:

$$£_{op} \quad = \quad £_p + £_h + £_c + £_w \qquad (6)$$

Table 7 Baseline cost factors

Pumping energy costs were derived from the flow rate Q_m, the average TMP and the mechanical and electrical power conversion efficiency η (Table 7), with the total water production modified for loss of product through downtime and backwash:

$$£_{op} = \frac{Cfe}{\eta}.\Delta P_{avg}\left[Q_m\left(31.5x10^6 - \left(N_c.t_{cc}\right) - \left(Nb.t_{bb}\right)\right)\right] \qquad (7)$$

where Cf_e is the unit cost of electrical energy, t_{cc} and t_{bb} the cleaning and backwash durations, and Q_b the backwash flow. Heating costs are proportional to the summation of the gross energy required to heat the cleaning solutions (kWh), and is therefore a function of the difference ΔT between the ambient temperature and the reagent temperature:

$$£_h = \frac{Cf_e}{\eta}\left(\frac{C_v \Delta T (V_c \rho)}{3600}\right) \qquad (8)$$

where C_v is specific heat capacity (4.2 kJ.Kg.K^{-1}), ρ is the density and V_c the volume of cleanant, which is a function of the membrane area A_m and the number of chemical cleans. The cleanant volume per clean was taken from site chemical usage data from which the ratio r of chemical cleanant volume to membrane area ratio was derived (Table 4).

Chemical costs were assumed as delivered with no supplementary handling costs. The volumes used in tonnes per annum were calculated based on the volume used per CIP/CEB event over the year:

$$\pounds_c = Cf_c \, C \, N_c \, V_c \qquad (9)$$

where Cf_c is the reported UK unit chemicals cost in £/tonne (IChemE, 2002) adjusted to 2008 values from government data (NSO-UK, 2008). A common notional waste disposal route was assumed based on backwashing and cleaning waste volumes which were converted to energy demand using a common waste energy cost factor Cf_w, adapted from (Zondervan and Roffel, 2008) and based on waste neutralisation and returning to the head of works:

$$\pounds_w = Cf_w \, (((N_c \, V_c) + (Q_b N_b t_{bb})) \, \rho \, g \, \Delta h) \, / \, \eta \qquad (10)$$

The cost variation in contribution from each cost group was compared for the different CPT envelope responses ($R_{v,max}$, C_{min}, P_{max}, T_{max}). By converting total operating costs to relative costs per cubic metre of water produced it was possible to compare costs across the different sites. The deviation from the optimum cleaning scenario for each of the operational scenarios could also be compared.

Results

Costs for each site were categorised according to headloss pumping, cleanant heating energy, chemical consumption, backwash pumping and waste treatment. These are presented as percentage of total operational costs, indicating the differences that each operational “Strategy” provides, in Table 6. The operational cost of each operational “strategy” at optimal permeability recovery are shown in Figure 3; where error bars indicate the minimum and maximum operational costs according to different CPT envelope “scenario” responses (I $R_{v,max}$, II C_{min}, III P_{max}, and IV T_{max}). The percentage component contribution to the operating cost, based on optimum cleaning recovery, is given in (Table 8) for a number of cleaning “scenarios”. It can be seen that the cost associated with the TMP headloss represents the primary component in all cases and that, despite optimisation of cleaning, there is significant variation in calculated operational costs.

Figure 4 Chart showing how optimal cleaning recovery (Rv_{max}) influences relative costs/m^3 of water for a variation in operational scenario (1-4, Table 6) The error bars show how this varies across the cleaning factor envelope (II-IV, Table 5).

Table 8 Percentage contribution to operational costs based on optimum cleaning protocol (I) for the four sites and the four operational scenarios

The influence of the cleaning factor envelope variations on the unit cost (Figure 4) shows the relative cost variation across the ranges of recovery attained from the four cleaning scenarios applied to the four operational "strategies" chosen for the four sites. The calculated variation in the plant life operating costs for each of the "scenarios" (Table 9) includes data for cash flow using a discount rate of 10% and a 15 year plant life. For all the models the range of variation from treatment factors is seen to have cost implications which vary with operational strategy. The MF membrane sites (B, C, D) indicate increasing costs under optimal cleaning conditions as the "strategy" proceeds from a high fixed TMP (1) to a long fixed interval cleaning cycle (4). For the UF plant (Site A) the wider range of costs for a fixed low TMP "strategy" indicates that frequency of cleaning operations together with the optimisation of the cleaning factors has the largest impact on operational costs.

Figure 5 Chart showing relative operational costs (p, or £ x 0.01, per m^3) for the four cleaning factor "scenarios" (Rv_{max}, C_{min}, P_{max}, T_{max}) for each of the four Operational Scenarios (1-4) on Sites A-D.

Table 9 Difference between best and worst case operational costs with cleaning factor envelope for sites A-D for each of the operational scenarios 1-4: (*i*) operational cost savings from variations in cleaning factors, with (*ii*) the equivalent capital cost for 15 year amortisation period at 10%.

Discussion

Evidence provided from the analysis (Figs. 3-4, Table 9) indicates a significant impact of both the plant operating protocol (i.e. the basis chosen for applying the chemical clean) and the degree of optimisation of the chemical clean (i.e. the attainable permeability recovery and energy/consumables expenditure) on overall operating costs. For example, for Plant C the spread of the unit operating costs ($£_{unit,}$ in pence per m^3) arising from operation across the range of the cleaning "scenario" ranges (maximim to minimum *CPT* values) is calculated to be as high as 0.2 pence.m^{-3} above an optimum of 0.3p.m^{-3} for a strategy of less frequent CIPs (Fig. 4). If the operating "strategy" is changed to more frequent CIPs the operating costs decrease by around 10% and its cost variation for operation across the *CPT* envelope is reduced by a third. As the cleaning "scenario" is changed, the impact of the cleaning envelope is also changed, with the largest impact - from 0.08 to 0.23 pence.m^{-3} as measured for Plant D (a submerged MF plant) on changing from operation at fixed high threshold TMP to operation at less frequent CIPs (Fig. 5). Moreover, there is a distinct difference in the pattern of behaviour between the UF plant (Plant A) and the microfiltration plants (Plants B-D), according to Figure 4.

It has previously been observed (Zondervan and Roffel, 2008) that optimisation of cleaning cycles has little impact on the lifetime cost, based on models built for a UF plant scenario with varied cycle time for a particular set of parameter data. The current study, conducted across a range of plants, showed the cleaning response to vary greatly. This variation yielded changes in annual operational costs, relating primarily to energy and consumables, ranging from below £20k to over £170k for a UF plant challenged with pre-treated groundwater (Table 4, Site A). This has implications regarding existing and proposed control strategies for backwash frequency and cleaning cycle control based on neural networks (Veerapaneni et al., 2004, Oh et al., 2004) based on cleaning efficacy attained on site. Such approaches, using heuristic data for feedback control, are necessarily constrained by the operating envelope used on site, whereas the approach used in the current study allows a much larger envelope to be explored and the optimum cleaning conditions precisely identified, though the approach is constrained by the necessity for ex-situ tests.

Conclusions

The effects of actual variable cleaning recoveries for different membrane fibres fouled on full scale plants were appraised using a simple fouling model to generate a transient TMP trend with variable backwash and cleaning cycles. The effect of cleaning factor "scenario" variations on recovery from experimental data was incorporated into the model along with plant operating "strategies", and the model used to quantify their impact on operating cost. The study revealed:

- Differences in cleaning factor performance, as determined by the values for the cleanant concentration *C* and cleaning temperature *T* and soak period *P*, were significant and have a bearing on the design of a process, and in particular the range of operating flux which determines the fouling rate and so cleaning cycle times.

- Optimisation of permeability recovery has a measurable impact on operational costs, with the difference in annual operating cost between the most and least optimal chemical clean being as little as £5 to as high as £74 p.a. per l/s of flow depending upon the plant operating protocol.

- The extent of the operational cost reduction for an optimal cleaning regime is dependent on both the operational strategy, with respect to the basis for scheduling the chemical cleans, and the membrane type (ultrafiltration vs. microfiltration) and/or configuration (hollow fibre vs. capillary tube).

Results indicate that the innate variability in cleaning efficacy appears likely to eclipse any possible correlation of permeability recovery with fouling characteristics. Clearly this aspect demands further study, given the wealth of scientific information on fouling mechanisms and linked with foulant physicochemistry and biochemistry.

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Table 1 Operational and membrane data from Sites A-D

Site	*Water Type*	*Membrane*[1]	*Config.*[2]	*Pre-treatment*
A	Groundwater: single borehole. pH = 7.1, turbidity <5 NTU	UF - PES	CT	Coagulation (PACl 4 mg L^{-1}), clarification, GAC, pre-chlorination
B	Upland surface-impounded reservoir. pH = 6.9, turbidity = 0.71 NTU	MF - PP	HF	Microstrainer (30 µm)
C	Upland surface-impounded reservoir. pH = 5.5 – 5.8, turbidity < 2 NTU	MF - PVDF	HF	pH correction, pre-coagulation (PACl 2 mg L^{-1}), primary pressure filtration, pre-chlorination, 2nd stage pressure filtration
D	Groundwater: single borehole. pH = 7.1. turbidity < 0.2 NTU	MF - PVDF	sHF	Microstrainer, pre-chlorination

[1] PES = polyethyl sulphone; PVDF = polyvinylidene difluoride; PP = polypropylene

[2] Configuration: (s)HF = (submerged) hollow fibre; CT = capillary tube

Table 2 Cleaning factor ranges for BBD experiments

Site	*Cleaning agent*	*Strength (C, mol.L^{-1})*	*Soak Time (P, min)*	*Temperature (T, °C)*
A	NaOH	0.050 – 0.175	30 – 90	10 - 40
B	NaOH	0.188 – 0.405	30 – 90	5 - 35
C	Citric acid	0.003 – 0.009	30 – 90	5 - 35
D	NaOCl varied then H_2SO_4 at pH 2.0, 15°C, 60 min	0.001 – 0.002	30 – 90	5 - 35

Table 3 Factorial algorithm components

Site	*M*	*a*	*b*	*c*	*d*	*e*	*f*
A	34.577	-65.346	0.019	-0.156	0.379	1.716	0.000
B	9.463	-3.830	0.042	0.187	0.029	0.127	-0.005
C	125.822	-55.799	-0.950	-2.587	0.435	2.124	0.014
D	29.755	-0.078	-0.151	0.540	0.001	0.001	-0.014

Table 4 Design and operational variables

Model variable		*Site:*	*A*	*B*	*C*	*D*
Design throughput	Q_m	$L.s^{-1}$	417	752	62.5	440
Membrane area,	A_m	m^2	17640	20092	2806	11192
Clean water resistance,	R_m	m^{-1}	2.5	2.5	1.25	2.5
Design flux,	J	$L.m^{-2}.h^{-1}$	109	68	80	142
Backwash flux; rate	J_b	$L.m^{-2}.h^{-1}$	250	60	120	60
Backwash interval	t_b	minutes	55	60	60	60
Backwash duration	t_{bb}	seconds	50	20	20	20
Cleaning interval	t_c	days	*Variable*			
Cleaning duration	t_{cc}	minutes	*Variable*			
Cleanant Ratio	R	$m^3.m^{-2}$	1.83E-04	1.53E-03	1.53E-03	1.53E-03
Average Feed °C	T_f	°C	10.0	10.4	6.0	6.0
Cake fouling rate, as a function of (Equation 4): *from d(TMP)/dt data,*						
Cake deposits	X_a	$m.min^{-1}$	1.01.E+01	7.40.E-02	2.50.E+00	2.50.E+00
Pore deposits	X_b	$m.min^{-1}$	2.01.E-01	6.89.E-06	2.33.E-02	2.33.E-02
Non Removable deposits	X_c	$m.min^{-1}$	6.89.E-06	1.15.E-03	5.00.E-09	6.89.E-06
Specific cake resistance	α	m^{-2}	1.43.E-03	8.66.E+00	1.25.E-03	1.25.E-03

Table 5 Cleaning factors for *CPT* variation, Scenarios I-IV,for Sites A- D

			CPT VARIATION SCENARIO			
			I	**II**	**III**	**IV**
SITE A			**$\%R_{v,max}$**	**C_{min}**	**P_{max}**	**T_{min}**
Caustic Soda	**C**	*$mol.L^{-1}$*	0.175	0.050	0.175	0.175
	P	*minutes*	89	89	30	89
	T	*°C*	37	37	37	10
	R_v	*%*	52.0	36.0	35.8	24.4
SITE B						
Caustic Soda	**C**	*$mol.L^{-1}$*	0.405	0.188	0.405	0.405
	P	*minutes*	30	30	90	30
	T	*°C*	35	35	35	10
	R_v	*%*	14.8	13.5	10.4	8.4
SITE C						
Citric Acid	**C**	*$mol.L^{-1}$*	0.009	0.009	0.009	0.003
	P	*minutes*	90	30	90	90
	T	*°C*	35	35	10	35
	R_v	*%*	97.0	78.0	35.0	28.0
SITE D						
Hypochlorite	**C**	*$mol.L^{-1}$*	0.002	0.002	0.002	0.001
	P	*minutes*	30	90	30	30
	T	*°C*	35	35	5	35
	R_v	*%*	26.6	26.6	16.1	5.6

Table 6 Operational "Strategies" 1-4 for Sites A-D

SITE	*STRATEGY*			
	1 Fixed maximum TMP - HIGH ΔP_{max}, kPa	2 Fixed maximum TMP - NORMAL ΔP_{max}, kPa	3 Fixed # of cleans - SHORT t_c, days	4 Fixed # of cleans (t_c) - LONG t_c, days
A	50	45	0.5	1
B	150	120	14	28
C	70	40	14	28
D	90	60	14	28

Table 7 Baseline cost factors

Cost Factor	*Value*
Power supply efficiency (η)	0.60[1]
Pumping and heating energy (Cf_e, £/kWh)	0.10[2]
Waste treatment energy (Cf_w, £/kWh)	0.25[4]
Chemical cleanant cost (Cf_c, £/tonne)[3]	
Citric acid	900[3]
Caustic soda (NaOH), 50 wt%	60[3]
Chlorine	130[3]

[1]Rishel, 2002; [2]Holden, 2008; [3]IChemE, 2002: 2002 data indexed to 10/2008 from UK national Statistics Office Annual Variation Tables, NSO-UK, 2008. [4] Based on Zondervan 2008a

Table 8 Percentage contribution to operational costs based on optimum cleaning protocol (I) for the four sites (A-D) with four operational scenarios (1-4)

SCENARIO	*SITE % Scenario Contribution*			
	A	B	C	D
Scenario 1 Fixed maximum TMP- HIGH				
Headloss pumping	75.2	97.2	89.5	96.4
Cleanant heating energy	18.2	1.9	6.1	2.6
Chemical consumption	0.3	0.1	1.8	0.1
Backwash pumping	1.8	0.2	0.7	0.2
Waste treatment energy	4.5	0.6	1.9	0.6
Scenario 2 - Fixed maximum TMP – LOW				
Headloss pumping	49.7	95.1	72.9	91.6
Cleanant heating energy	44.9	3.9	19.4	7.2
Chemical consumption	0.7	0.2	5.6	0.4
Backwash pumping	1.3	0.2	0.6	0.2
Waste treatment energy	3.4	0.6	1.5	0.6
Scenario 3 Fixed number of cleans- SHORT t_c				
Headloss pumping	57.7	95.8	74.7	92.9
Cleanant heating energy	36.5	3.2	17.9	6.0
Chemical consumption	0.6	0.1	5.2	0.3
Backwash pumping	1.5	0.2	0.6	0.2
Waste treatment energy	3.7	0.6	1.6	0.6
Scenario 4 Fixed number of cleans - LONG t_c				
Headloss pumping	73.2	97.8	87.5	96.5
Cleanant heating energy	20.3	1.3	7.7	2.6
Chemical consumption	0.3	0.1	2.2	0.1
Backwash pumping	1.8	0.2	0.7	0.2
Waste treatment energy	4.4	0.6	1.8	0.6

Table 9 Difference in GBP between best and worst case operational costs with cleaning factor envelope for Sites A-D for each of the operational scenarios 1-4: (*i*) operational cost savings from variations in cleaning factors, with (*ii*) the equivalent capital cost for 15 year amortisation period at 10%

Site:	***A***		***B***		***C***		***D***	
Scen.	***i***	***ii***	***i***	***ii***	***i***	***ii***	***i***	***ii***
1	7,532	*55,487*	3,531	*26,015*	1,103	*8,123*	11,865	*87,409*
2	23,386	*172,274*	6,347	*46,754*	1,664	*12,256*	19,402	*142,931*
3	9,254	*68,170*	26,838	*197,710*	1,412	*10,403*	27,796	*204,766*
4	2,690	*19,817*	34,897	*257,075*	1,833	*13,503*	32,423	*238,850*

i Saving in £ per annum between worst and best case operational cost with cleaning factor CPT variation.
ii Annual operational savings in £ as capital amortised for 15 yrs at 10%

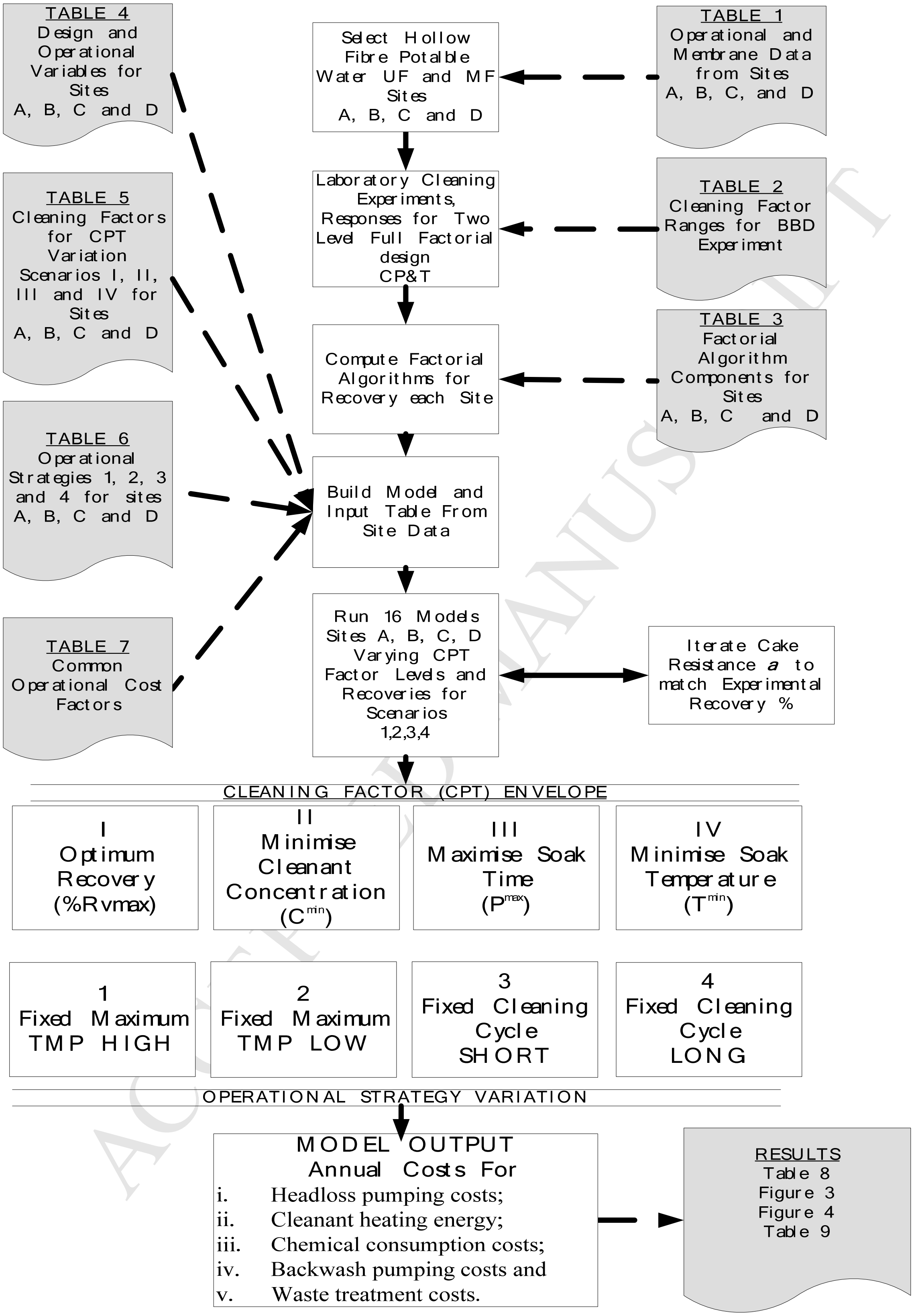

Figure 1 Cleaning variation cost model methodology

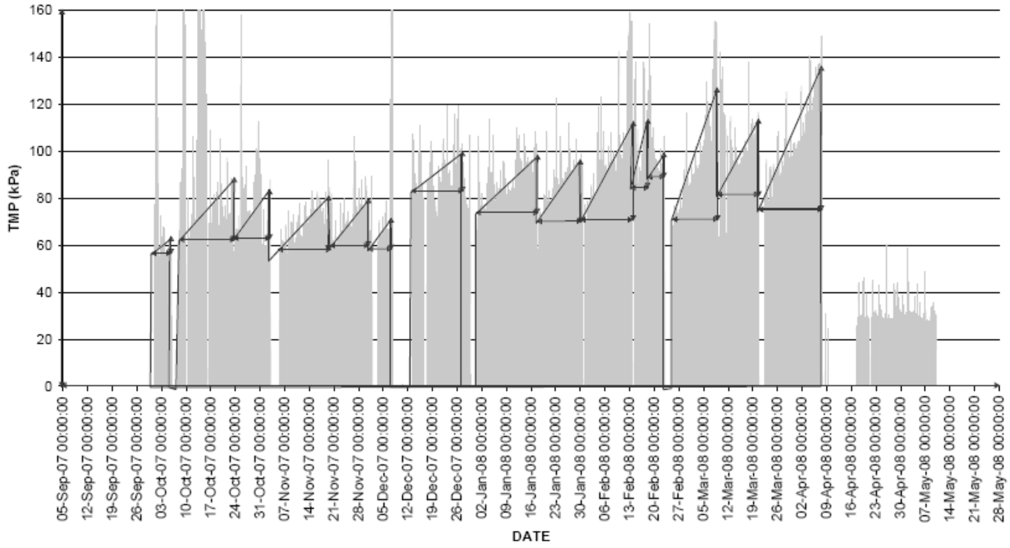

Figure 2 Example SCADA analysis for flux decline TMP Vs Time: 9/07 to 4/08: Showing the annotations for a MF module on plant B.

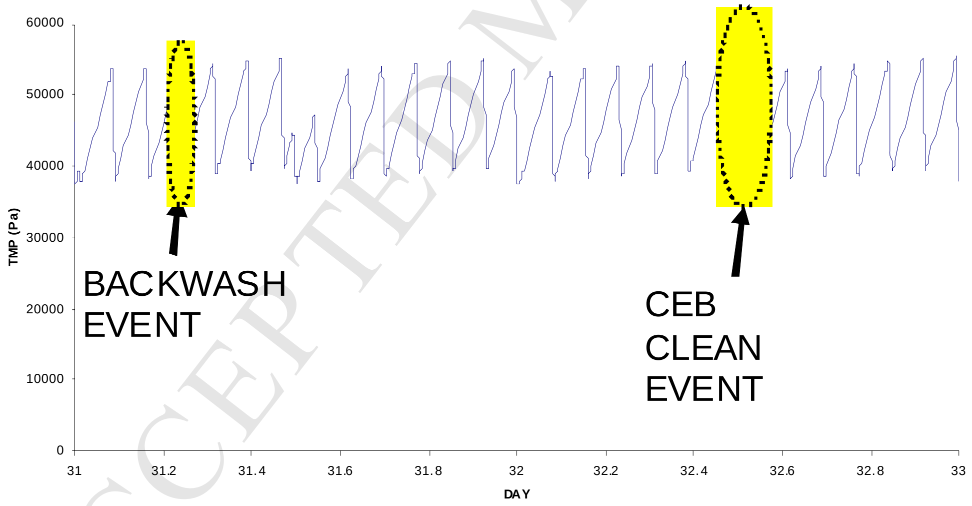

Figure 3 Typical model output TMP transient, Site A, highlighting an hourly backwash and a cleaning events. Profile is for 2 days of operation (day 31 through 33 of 365).

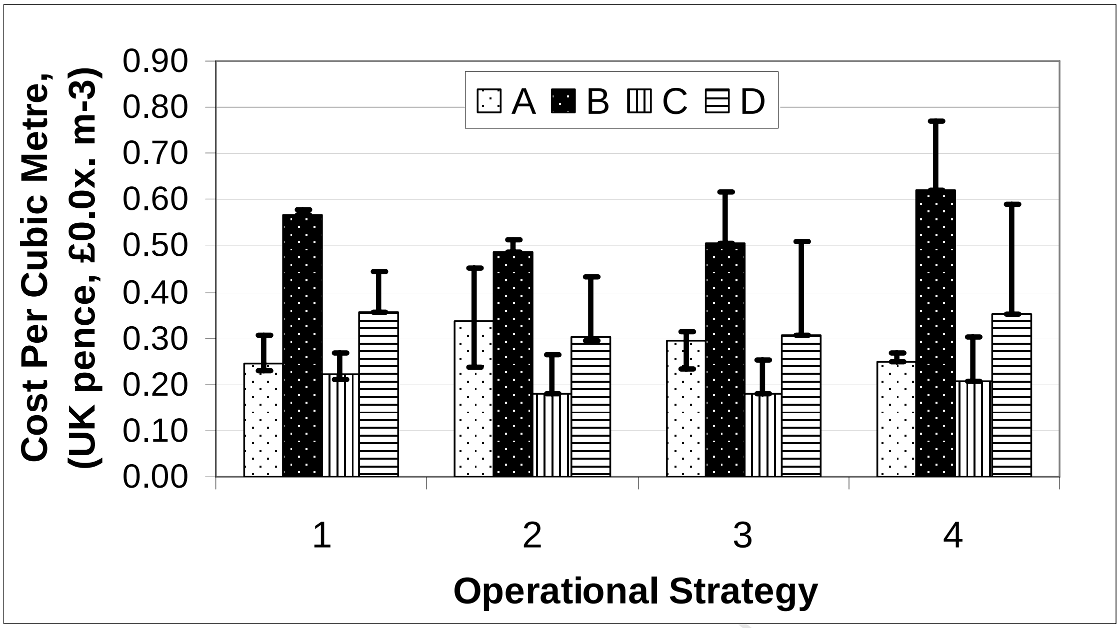

Figure 2 Chart showing how optimal cleaning recovery (Rv_{max}) influences relative costs/m^3 of water for a variation in operational strategy (1-4, Table 6) The error bars show how this varies across the cleaning factor envelope (II-IV, Table 5).

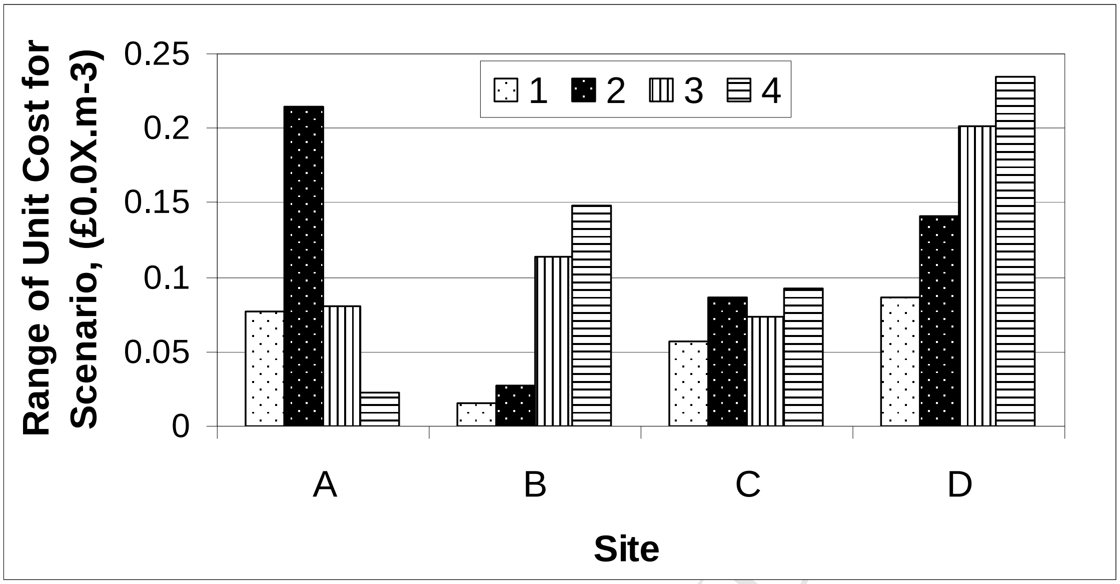

Figure 3 Chart showing relative operational costs (p, or £ x 0.01, per m^3) for the four cleaning factor scenarios (Rv_{max}, C_{min}, P_{max}, T_{max}) for each of the four Operational Scenarios (1-4) on Sites A-D.