EXECUTIVE SUMMARY

Background

Removal of nitrogen from wastewater is essential for the prevention of eutrophication in water courses receiving treated effluent from municipal wastewater treatment works (WWTW). However, nitrification, i.e. removal of ammoniacal nitrogen (NH_4-N) either standalone or as a precursor process step for total nitrogen removal, was not originally seen as a necessity. This meant that many existing WWTWs were only designed with provisions to remove biochemical oxygen demand (BOD) and total suspended solids (TSS) to consented limits.

Current legislative drivers such as the Water Framework Directive have ensured that new stringent consent limits for BOD and NH_4-N are now being readily applied down to smaller wastewater treatment works of any size. In recent years, this has increasingly led WWTWs serving smaller population equivalents (PE) to adopt additional energy intensive tertiary mechanically aerated processes, aimed at providing continued consent compliance. On the contrary, the UK wastewater industry has simultaneously adopted a target for reducing its carbon emissions by 26% by 2020, referenced to 1990 levels. This apparent conflict of aims, together with a recognised need to adopt a ‘sustainable development’ approach has ensured that low energy treatment technologies are now of considerable interest.

Thames Water’s Wastewater Treatment Works

Presently Thames Water Utilities Ltd (TWUL) operate and maintain a total of 350 WWTWs, of which 257 (73%) utilise trickling filters (TF) as their predominant form of biological treatment. Activated sludge is primarily adopted on the 59 WWTWs serving larger PEs with the remaining 34 WWTWs adopting a combination of TFs, activated sludge and package plant variants.

Typically, WWTWs serving small PEs of fewer than 10,000 form the vast majority of WWTWs when considering large geographical areas. Currently 78% of TWULs WWTWs are within this category, with 94% of them having TFs as their predominant biological treatment process.

Aim and Objectives

This research aims to:

- ✓ Evaluate the potential of low energy wastewater treatment processes to meet UK performance requirements, with respect to an increasingly strict regulatory framework.

The key research objectives are to:

- ✓ Provide a critical state-of-the-art literature review of TFs, and waste stabilisation ponds (WSP) in regards to process performance, modelling and potential to treat municipal wastewater serving small populations.

- ✓ Identify and assess suitable robust, low energy WWTWs utilising TFs or WSPs, typically serving populations less than 10,000. Subsequently, analyse and validate methods to improve performance of the traditional design, or process configuration.

- ✓ Assess, evaluate and where appropriate demonstrate the capability of the TFs and WSPs in relation to suitability for meeting increasingly stringent effluent quality discharge standards of NH_4-N and BOD, under a typical UK climate.

Methodology

This research firstly proposes the implementation of double filtration TFs operating in series without the requirement for constructing an intermediate settlement stage. TF process performance data is analysed and presented to demonstrate how a hypothetical offload of organic carbon (BOD) using a modern TF can enhance nitrification of the existing conventional TF. This directly challenges the current strategy of adopting energy intensive tertiary processes for enhancing nitrification on TF WWTWs serving small populations.

Secondly process performance data from 120 TF WWTWs is analysed in order to evaluate the relative nitrification performance of TF WWTWs, both with and without mechanically aerated tertiary nitrifying processes. Multivariate regression analysis is utilised to determine whether tertiary nitrifying processes act to improve process performance, or whether they contribute to NH_4-N consent exceedance. This has particular focus over two noticeably cold winter periods in the UK.

Lastly, a small decentralised facultative aerated lagoon (FAL) system with novel low energy mixing and point source aeration is investigated and evaluated. This section aims to utilise the robustness and accuracy of computational fluid dynamic (CFD) modelling techniques for describing the systems complex hydrodynamics. In conjunction with an experimental tracer study this research will determine whether the systems low energy mixing is capable of preventing hydraulic short circuiting and thermal stratification which are notorious for reduced performance in traditional WSP variants.

Contributions to Scientific and Industry Knowledge

The initial section of this research presents the theoretical findings published in Water Environment Federations (WEF) Water Environment Research (WER) journal, entitled 'Adopting Trickling Filters as a Solution for Enhanced Nitrification', Volume 87, issue 1, January 2015. WER is an international peer-reviewed journal publishing original, fundamental, and applied research. This research paper promotes the adoption of TFs as a robust alternative treatment process for aiding the reduction of NH_4-N to provide continued consent compliance on existing TF WWTWs. This is done using empirical modelling to hypothetically simulate a prior reduction of organic carbon using a modern plastic media TF without the need to construct intermediate sedimentation. Subsequently, supporting experimental results are presented and reviewed.

The second area of research presented here is aimed at promoting TFs for sustainable and robust nitrification. This research uses statistical analysis to evaluate an extensive dataset of 120 WWTWs owned and operated by TWUL over a three year period. The objective is to demonstrate the nitrification capability of TF configurations over a wide range of NH_4-N consent limits and wastewater temperatures. The associations between final effluent temperature, ground water infiltration, excess flows, PE, and NH_4-N concentrations are investigated and reported.

Moreover, statistical analysis using generalised linear models with logistic regression is used to demonstrate the hypothesis that WWTWs with mechanically aerated tertiary nitrification processes are at higher risk of exceeding their respective NH_4-N consent limits when compared with WWTWs that adopt only conventional TF configurations. This research provides renewed confidence in TF configurations and aims to reduce reliance on energy intensive nitrification processes for providing continued NH_4-N consent compliance.

The third area of research presented here provides performance data, together with a critical CFD analysis of a FAL system with novel low energy mixing and point source aeration. FALs are an effective variant of WSP yet to receive significant attention in wastewater literature. This demonstrates the robustness and accuracy of the CFD modelling technique as a means for describing the complex hydrodynamics of full scale WSPs using experimental tracer studies, together with establishing that hydraulic short circuiting and thermal stratification can be combatted by adopting a low energy, low tech approach.

CFD modelling and practical demonstration of low energy mixing methods have yet to be undertaken on a full scale WSP serving small populations, thus making a significant scientific contribution to knowledge. Analysis of treatment performance over a three year monitoring period determines that the CFD model is proficient at simulating (within 10%) the flow characteristics in being able to successfully eliminate thermal stratification and hydraulic short circuiting. In addition, this work demonstrates the potentially detrimental effect that high rates of closed recirculation may have on the hydrodynamics of mixed WSP systems. This methodology can be used to optimise future design and construction of FAL systems when considering various locations, populations and hydraulic loading.

Trickling Filter Conclusions

This research demonstrates that TF WWTWs are capable of reliably producing high quality nitrified effluents. The empirical model predictions indicate that prior 50-80% BOD removals with a primary TF allow for further 40-70% reductions in effluent NH_4-N respectively when utilising the existing TFs. It may be concluded with reasonable confidence that this improved TF configuration can allow for compliance with a more stringent NH_4-N consent limit of 5 mg/L, compared with the current consent of 20 mg/L. This methodology can be applied to any TF WWTWs operating traditional TFs to confirm current performance, and see whether it is performing as expected.

Reduced wastewater temperatures witnessed in colder winter months directly correspond to increased effluent NH_4-N concentrations with higher counts of NH_4-N consent exceedance. Smaller TF WWTWs serving PEs of less than 10,000 are at the greatest risk of exceeding consent limits as they receive the coldest influent wastewater, together with the highest percentages of excess flow and infiltration relative to design flow. Conversely, the WWTWs serving the largest population equivalents have highest average FE temperatures, with lowest excess flow and infiltration ratios.

Multivariate regression analysis suitably demonstrates that WWTWs with tertiary NSAFs have an increased probability, and hence risk of exceeding NH_4-N consented limits in comparison to TF WWTWs without tertiary nitrifying processes. This relationship is enhanced when considering the colder winter effluent temperatures. This study demonstrates that adopting robust technology with low energy usage can reduce operational energy consumption and carbon emissions, together with maximising the longevity of existing TF assets. This will aid in reducing the wastewater industry's current dependency on mechanical aeration and highlights the potential for adopting low energy wastewater treatment processes on many UK WWTWs.

A separate TF observational study has been included to the appendix, which aims to address the detrimental effect of moss that accumulate on the upper layers of TF media. This moss can clog media leading to surface water ponding and reduced performance due to a number of factors. This study observes the effect of replacing the upper portion of the conventional stone media, with a capping layer of cross flow structured plastic media. This study demonstrated that plastic media is able to effectively reduce the onset of moss growth. However, to ensure moss does not become an issue, it is recommended that the media be placed in small sections so that it can be periodically flipped once moss begins to form on its exposed surface. This has great potential to reduce operational expenditure associated with the cleaning of traditional media.

Waste Stabilisation Pond Conclusions

Correctly designed WSP systems are highly robust, easy to operate and maintain with high removals of TSS, BOD. The Roundwood Aero-Fac® WWTW has satisfied the discharge consent requirements, producing a good quality final effluent with average BOD, COD, TSS & NH_4-N of 4.4mg/L, 58.6mg/L, 12.9mg/L and 5.2mg/L respectively. The removal rates are impressive with average BOD, TSS & NH_4-N removals of 95.2%, 76.4% & 65.5% respectively.

This research is unique as it provides a critical CFD analysis of a novel completely mixed FAL system, designed for serving small populations. This is the first comprehensive CFD analysis undertaken on low speed, low energy mixed FALs, designed for serving small populations. This research demonstrates the ability of CFD modelling to accurately simulate decidedly complex hydraulic flow patterns within WSP systems.

CFD analysis of the system determined that novel low energy mixing together with bubble lift point source aeration is capable of providing a hydrodynamic profile highly proficient at preventing thermal stratification. The CFD model is proficient at simulating (within 10%) the flow characteristics. Post processing demonstrates the lagoon cells to be completely mixed. In addition, this work investigates the potentially detrimental effect that high rates of closed recirculation may have on the hydrodynamic flow characteristics of small mixed WSP systems.

NOMENCLATURE

1-D	One Dimensional
2-D	Two Dimensional
3-D	Three Dimensional
%	Percent
95%ile	Ninety Fifth Percentile
98%ile	Ninety Eighth Percentile
^{o}C	Degrees Celsius
£	Pound (British Sterling)
®	Registered Trademark
T	Hydraulic Residence Time (days)
τ_s	Wind Induced Shear Stress at Water Surface
ρ	Density of Water (1000 kg/m^3)
ρ_a	Density of Ambient Air (1.225 kg/m^3)
ρ_z	Density of Water at Depth z (g/cm^3)
μ	Dynamic Viscosity of Fluid (kg/m.s)
µg	Microgram (1×10^{-9} kg)
$\sum$	Sum of
.	90.0% Statistical Significance
*	95.0% Statistical Significance
**	99.0% Statistical Significance
***	99.9% Statistical Significance
a	Y-Intercept
A_o	Surface Area of Lagoon Cell (cm^2)
A_z	Surface Area at Height z (cm^2)
AMP	Asset Management Program
ANER	Ammoniacal Nitrogen Exceedance Ratio
AS	Activated Sludge
ASF	Aerated Sand Filter
AWSL	Anglian Water Services Limited

b	Gradient
BC	Boundary Condition
BOD	Biochemical Oxygen Demand
BOD_5	Five Day Biochemical Oxygen Demand
BOD_f	Filtered Biochemical Oxygen Demand
CAPEX	Capital Expenditure
C_D	Drag coefficient (1×10^{-3} dimensionless)
C_o	Influent Concentration
C_e	Effluent Concentration
CFD	Computation Fluid Dynamics
CFSP	Cross Flow Structured Plastic
CSTR	Continuously Stirred Tank Reactor
CTF	Conventional Trickling Filter
CTFP	Conventional Trickling Filter Process
COD	Chemical Oxygen Demand
COD_f	Filtered Chemical Oxygen Demand
CO^2	Carbon Dioxide
CO^2Eq	Carbon Dioxide Equivalent
d	Day
dp	Decimal Place
DF	Double Filtration
DO	Dissolved Oxygen
DPM	Dispersed Phase Model
DWF	Dry Weather Flow
e^{-k}	BOD Exponential Decay Function
E	Multivariate Analysis Estimate
EA	Environment Agency
EC	European Commission
EF	Expected Flow
EFR	Expected Flow Ratio
EngD	Engineering Doctorate
EU	European Union

EXP	Exponential
FAL	Facultative Aerated Lagoon
FE	Final Effluent
FET	Final Effluent Temperature
FL	Facultative Lagoon
g	Acceleration due to Gravity (ms^{-2})
GHz	Gigahertz
GLM	Generalised Linear Models
GMP	Great Meadow Pond
GWI	Ground Water Infiltration
HLR	Hydraulic Loading Rate
h	Hour
ha	Hectare
HRT	Hydraulic Residence Time (days)
IR	Infiltration Ratio
IV	Irrigation Velocity
k	BOD Removal Coefficient
Km	Kilometre
Kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
L	Litre
L_{Re}	Characteristic Linear Dimension (m)
Li	Lithium
LiCl	Lithium Chloride
Ltd	Limited Company
Log	Logarithmic
m	Meter
M	Mass of Lagoon Cell Water
m^2	Square Meter
m^3	Cubic Meter
MBBR	Moving Bed Bio-Reactor

MCERTS	Monitoring Certification Scheme
mg	Milligram
mg/L	Milligrams per Litre
n	Number of Tanks in Series
NH_4-N	Ammoniacal Nitrogen
NO_2	Nitrite
NO_3	Nitrate
NSAF	Nitrifying Submerged Aerated Filter
NTF	Nitrifying Trickling Filter
ou_E	European Odour Unit Concentration
OLR	Organic Loading Rate
OM	Operation and Maintenance
OPEX	Operational Expenditure
p	Pence (British Sterling)
PE	Population Equivalent
PETRO	Pond Enhanced Treatment and Operation
PO_4	Soluble Reactive Phosphorus
Pr(>t)	Probability Outside Confidence Interval
PST	Primary Settlement Tank
Q	Flowrate
R	Multivariate Statistical Software Program
RE	EngD Research Engineer
RAM	Random Access Memory
RBC	Rotating Biological Contactor
Rcmdr	R Commander Extension
RTD	Residence Time Distribution
s	Second
S	Schmidt Stability (g-cm/cm^2)
SAF	Submerged Aerated Filter
SRT	Stimulus Response Technique
SS	Suspended Solids
SSA	Specific Surface Area

SSSI	Site of Special Scientific Interest
Std.Dev	Standard Deviation
SF	Single Filtration
SR	Sludge Recirculation
t	Hydraulic Residence Time (HRT)
't'	Confidence Range (within 95%ile)
t_{50}	Time for 50% Tracer Recovery
TF	Trickling Filter
TFP	Trickling Filter Process
TIS	Tanks-in-Series
TN	Total Nitrogen
Tn	Nominal Retention Time (Volume/Flowrate)
TON	Total Oxidised Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
TWUL	Thames Water Utilities Ltd
U_{∞}	Wind Velocity (3m Elevation) (m/s)
USA	United States of America
UK	United Kingdom
UWWTD	Urban Wastewater Treatment Directive
v	Max Velocity Relative to Fluid (m/s)
WEF	Water Environment Federation
WER	Water Environment Research
WFD	Water Framework Directive
WSP	Waste Stabilisation Pond
WWTW	Waste Water Treatment Works
X	Independent Variable Coefficient
Y	Dependant Variable Coefficient
z	Height Above Base of Lagoon Cell (cm)
z'	Stratified Centre of Volume above Base (cm)
z_g	Mixed Centre of Volume above Base (cm)
Z_m	Maximum Depth of Lagoon Cell (cm)

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FIGURES