1 INTRODUCTION

This chapter introduces the concept of temperature dependent MLSS settling tests, and it highlights the lack of temperature compensation or recording for these tests. The experimental focus is established on aspects of MLSS settling, according to the objectives of the study.

1.1 Background

Biological nutrient removal (BNR) processes suffer at times from activated sludge or mixed liquor suspended solids (MLSS) settleability problems (Grady and Filipe, 2000) that disturb the BNR treatment efficiency. Short-term (diurnal) temperature variations in reactor temperature (T_r) have been observed as having an effect on MLSS settleability (Wilén *et al.*, 2006). Scherfig *et al.* (1996) showed that T_r fluctuations are very dependent on local meteorological factors, such as ambient temperature (T_a), wind, and cloud cover. Where MLSS settling properties are traditionally determined batch-wise in 1 litre (ℓ) size cylinders (Gernaey *et al.*, 1998), it is to be expected that unless special care is taken, these meteorological factors will have an effect on the sample temperature (T_s). T_s is usually not reported in batch MLSS settling evaluations that is used to represent BNR MLSS settleability (Ekama *et al.*, 1997).

Based on the temperature dependency of MLSS settling, four aspects of settling evaluations are relevant to this study. These aspects are:

1. the effects of short-term T_s variations on MLSS settling parameters,
2. the T_r and T_a variations in full-scale plants,
3. batch MLSS settling tests under operational conditions, and
4. on-line MLSS settling monitoring at a full-scale plant reactor.

On-line MLSS settling monitoring data contains semi-continuous MLSS settling profiles (Vanrolleghem *et al.*, 1996). The settling profiles form the basis for the temperature dependent MLSS settling models proposed in this study. Settling parameter predictions are subsequently possible with these T_r-based models. These settling models assist with site-specific BNR MLSS settleability management.

1.2 Experimental work

The experimental work follows three distinct stages according to the project scope. The first stage is based on temperature observations at different plant reactors to determine the extent of typical T_r and T_a variations. The second stage includes batch MLSS settling tests to determine settling parameter changes occurring during temperature variations. The final experimental stage consists of on-line MLSS settling evaluations with an automated MLSS settling meter. This stage concludes with statistical calculations to evaluate the temperature-based MLSS settling models obtained from the on-line MLSS settling profiles.

1.3 Project scope

The aim of this project is to determine theoretically and experimentally the effects of short-term temperature variations on MLSS settling parameters. The following five sections address the project scope:

- Literature review on the influence of temperature on MLSS settling (Chapter 2):

The review covers the principles and monitoring of MLSS settling, operational plant temperature conditions, as well as batch and on-line MLSS settling parameter changes related to temperature variations. The aim of the review is to identify effects of short-term temperature variations during MLSS settling, as well as techniques or models that are in use to compensate for these typical temperature variations.

- Theoretical assessment of the influence of temperature and biofloc properties changes on a discrete settling biofloc (Chapter 3):

MLSS settling velocity changes over a temperature range are calculated for water density and viscosity changes, as well as particle density, size, and shape changes. The aim of the basic theoretical assessment is to illustrate potential changes in MLSS settling over a temperature range.

- Temperature survey at plant reactors (Chapter 4):

The extent of temperature (raw sewage, reactor, ambient) fluctuations and observable relationships are established at different plant reactors over short- and long-term periods.

- Batch MLSS settling evaluation based on temperature variations (Chapter 5):

Changes in batch MLSS settling parameters are evaluated according to sample container size, reactor zone sample source, as well as typical container environments found during settling tests, based on short-term temperature variations.

- On-line MLSS settling evaluation based on diurnal temperature variations (Chapter 6):

Diurnal changes in on-line MLSS settling meter data is established, before best-fit models of settling parameters illustrate the impact of T_r inclusion in MLSS concentration-based models. Sludge volume index (SVI) relationships are correlated with the maximum settling velocity (u_max) and the time (t) to reach u_max (t_umax). Finally, simulations of 11 settling parameters with diurnal MLSS concentration and T_r variations in simplified models illustrate the extent of changes in the parameters during temperature variations.

1.4 Conclusions

The purpose of this study is to demonstrate that short-term temperature variations are an essential component of traditional MLSS settling tests. Four temperature-related MLSS settling aspects in this study comprise of a theoretical settling calculation, short- and long-term plant temperature fluctuation identification, batch MLSS settling evaluations, and on-line MLSS settleability monitoring. The development of MLSS settling models and parameter correlations that incorporate temperature concludes the project.

The development of plant specific temperature dependent MLSS settling correlations provides the opportunity to improve traditional MLSS concentration-based settling models. Specialised methods and equipment are required to capture the effects of operational plant temperature variations. Improved MLSS settling models, based on these temperature variations, will provide additional information to assist with the management and design of wastewater treatment plants.

2 LITERATURE REVIEW

This chapter reviews basic MLSS settling tests, operational temperature data, as well as batch and automated MLSS settling tests and parameters, which are applied in the experimental project stage. The purpose of this review is to identify reported correlations, or lack thereof, between MLSS settling parameters and temperature.

2.1 Background

MLSS settling has been investigated for more than 75 years in the wastewater industry (Dick and Vesilind, 1969), during which time numerous reports confirm that temperature influences aspects of MLSS settleability. Werker (2006) classifies dynamic temperature conditions as a dominant environmental factor in wastewater treatment plant processes. These temperature variations are characterised by short-term (diurnal) and long-term (seasonal) cyclic fluctuations (Baetens *et al.*, 1999) that are present at plant reactors. Makinia *et al.* (2005) modelled these fluctuations as basic sinusoidal wave profiles, which follow both cyclic daytime / nighttime and summer / winter heating and cooling stages. These temperature fluctuations lead to physical, chemical, and biological changes in MLSS (Janssen *et al.*, 2002) that will influence the settleability of the MLSS.

Ekama *et al.* (1997) consider indirect effects of temperature fluctuations on MLSS settleability, such as structural changes in biofloc, as more important than direct effects, such as liquid viscosity and density changes. The combined direct and indirect effects of short-term temperature fluctuations on MLSS settleability have not been studied in any detail (Krishna and Van Loosdrecht, 1999). Long-term temperature fluctuations effects on MLSS settling are well described, as seasonal BNR process performance variations and related MLSS settleability changes can usually be easily detected from long-term trends based on routine tests (Osborn *et al.*, 1986).

Information and implementation guidelines for temperature compensation, based on short-term temperature variations during MLSS settling tests, are still lacking (Wilén, 1999). The effects of these short-term temperature variations during basic MLSS settling tests, as represented by empirical settling correlations, need to be quantified and modelled accordingly.

This literature review considers the effects of short-term temperature variations on MLSS settling parameters. The review focuses on four aspects of MLSS settling tests, which are in accordance with the objectives of this project:

1. principles and monitoring of MLSS settling,
2. operational plant temperature conditions,
3. batch MLSS settling tests and temperature variations, and
4. on-line MLSS settling tests and temperature variations.

2.2 Principles and monitoring of MLSS settling

2.2.1 MLSS settling and temperature relationship

The basic ecological unit of MLSS is a biofloc (Bux and Kasan, 1994a). Inside such a biofloc, temperature variations result in physiochemical and microbiological changes (Makinia *et al.*, 2005). Gerardi (2002) recognizes that these physical and biological changes have opposite effects on biofloc settling.

On the one hand, the physical effects of a temperature increase leads to improved (faster) biofloc settling, due to lower water viscosity and density, as well as structural biofloc changes. On the other hand, bacterial activity increases at a higher temperature. Bioflocs absorb or entrap the increased production and accumulation of insoluble biological secretions, such as lipids and oils, and this leads to worse (slower) biofloc settling. Air or gas bubble entrapment, usually from denitrification of anaerobic sludge rich in nitrate (Kazami and Furumai, 2000), decreases this sludge settling velocity further.

These opposing and time-dependent temperature effects change biofloc and MLSS characteristics (Örmeci and Vesilind, 2001). Temperature variations before and during MLSS settling tests will for that reason complicate MLSS settling evaluations.

2.2.2 MLSS settling and MLSS concentration relationship

Throughout the MLSS settling process, the settling velocity of a particle or a singular biofloc depends on its individual characteristics, as well as interactions with other particles or bioflocs (Mazzolani *et al.*, 1998). Figure 2-1, adapted from Ekama (1988), illustrates in this settling process the relationship between MLSS concentration and interparticle actions or flocculation tendency. MLSS settling and liquid clarification processes are divided into four classes according to the MLSS concentration and interparticle flocculation tendency.

The top sections of the graph (Classes I and II) represent liquid clarification. Single particles settle without interparticle action during Class I, and bioflocs settle with limited interactions during Class II, governed by the flocculation tendency. Hindered MLSS settling follows, represented in the middle section of the graph (Class III) to indicate the switch to zone settling at constant and maximum velocity. The bottom section of the graph (Class IV) represents the reduced settling velocity during transition, before the final compression or thickening leads in time to a stationary settled MLSS (Dupont and Dahl, 1995).

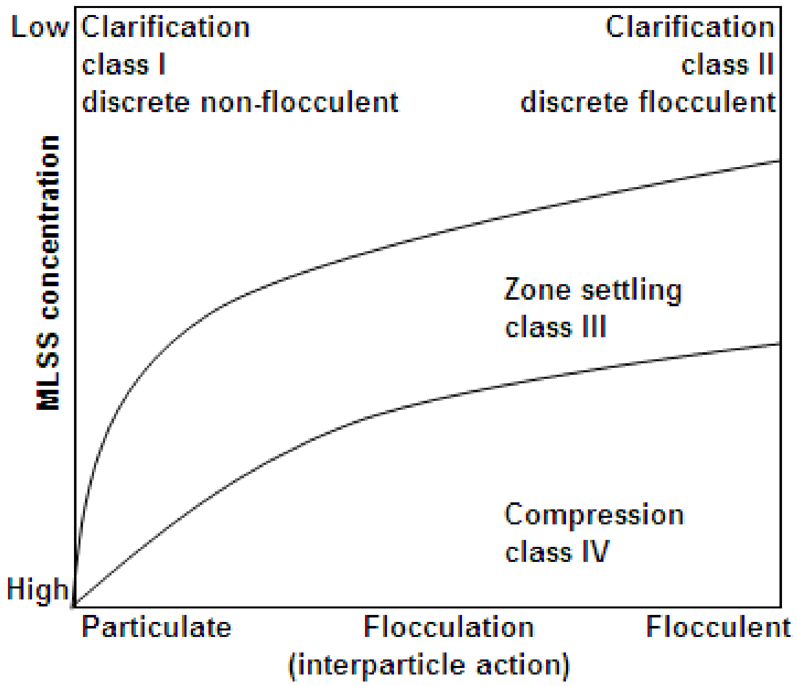

Figure 2-1 MLSS settling behaviour classified as Class I to IV according to MLSS concentration and interparticle actions

Basic mathematical equations illustrate the liquid clarification or Class I MLSS settling process, as well as the associated effects of temperature variations on settling. The resulting force of gravity and frictional shear (Catunda and Van Haandel, 1992) determines the settling velocity of individual particles. Due to the low MLSS concentration of Class I settling, the particle motion is not affected by other particles, by the settling container wall, or by turbulent currents (Kolmetz *et al.*, 2003). This particle settling in water is temperature dependent according to fundamental correlations. Class I clarification can thus be modelled from basic principles in theoretical models.

Class II to IV flocculent clarification to MLSS compression processes, at increasing MLSS concentration ranges, depend on complex forces in a matrix of interlinked bioflocs (Catunda and Van Haandel, 1992). Keller *et al.* (2002) concluded that the mechanisms of MLSS flocculation (Class II to IV) are still poorly understood. These mechanisms depend on interrelated physical, chemical, and biological factors (Jin *et al.*, 2003) that are all temperature dependent. Stypka (1998) and Biggs *et al.* (2003) confirmed that these processes cannot be presented in a fundamental theoretical model without experimental settleability tests. Class II to IV processes are thus based on empirical settling models.

The four settling classes shown in Figure 2-1 indicate that MLSS settling is dependent on two factors, (i) the MLSS concentration, and (ii) the particle flocculation tendency. Several models have been developed for general and specific use to represent MLSS settleability (Krebs, 1995). According to the literature, the MLSS concentration is the only factor considered in most of these settling models.

2.2.3 MLSS settling parameters: identification and development

Ekama *et al.* (1985) define the MLSS settling profile as the basic measurement of a manual MLSS settling test. Settling parameters that are calculated from this profile include the settled MLSS volume after 30 minutes (SV_{30}), settling indexes such as the SVI, as well as settling velocities occurring during the different stages of the settling process. The magnitude of these settling parameters that represent a well-settling MLSS depends on local plant conditions and process performance requirements.

Cloete and Muyima (1997) specify that settling parameters of a well-settling MLSS represent a fast settling MLSS leaving a clear supernatant, combined with a stable settled MLSS at a reduced volume. The features of such a well-settling MLSS relate to the settling parameter guidelines according to four stages in the MLSS settling profile. These features are summarised in Table 2-1, as adapted from Tandoi *et al.* (2006) and Cloete and Muyima (1997).

Table 2-1 MLSS settleability criteria according to four settling stages

Settling parameter	**MLSS criterion**
Liquid clarification	SS concentration <= 15 mgSS/ℓ
Reflocculation or lag (stage 1)	Commences after few (usually 2 to 5) min.
ZSV (stage 2)	Well-settling > 3 m/hr
	Light = 2 to 3 m/hr
	Bulking < 1.2 m/hr
Transition (stage 3); Compression (stage 4)	Thickened (no excessive volume), no guideline
Stability	No rising for few (usually 2 to 3) hours
SVI	Well-settling < 100 to 150 mℓ/g
	Light = 100 to 200 mℓ/g
	Bulking > 150 to 200 mℓ/g

For a well-settling MLSS, the stage 1 reflocculation (lag) duration is about 2 to 5 minutes, followed by the stage 2 zone settling velocity (ZSV) proceeding at a constant velocity of more than 3 m/hr. There are no guidelines available for the stage 3 and 4 transition and compression stages, although the compressed MLSS volume should be concentrated to occupy a small volume. The stage 4 compressed MLSS should remain settled for a few hours, without rising or disintegrating. A clarified supernatant suspended solids (SS) concentration of less than 15 mgSS/ℓ indicates sufficient removal of SS from the clarified supernatant.

A SVI lower than about 100 to 150 mℓ/g indicates good MLSS settling, while a higher SVI indicates poor settling (Casey *et al.*, 1995). These high SVI conditions are usually, but not always, associated with a bulking MLSS (Blackbeard *et al.*, 1986). Bulking is a state where the MLSS settling velocity is low and the compression is poor (Novák *et al.*, 1993) Good MLSS settleability can be defined as a fast settling MLSS with a low SVI (Jenkins *et al.*, 1984), based on a small SV_{30}.

Bye and Dold (1998) reviewed the basic settling parameters calculation methods used to obtain settleability data. Table 2-2 lists a summary of these techniques. Three basic calculation techniques between MLSS concentration and initial settling velocity (ISV) are established by (i) direct measurement, (ii) using existing correlations based on indexes such as SVI, and (iii) using a clarifier operational chart, also based on indexes such as SVI (Hasselblad and Xu, 1996).

Table 2-2 MLSS settling parameters development techniques and use

Step	**Action**	**Method**
1	Determine MLSS concentration (X)	Standard Method 2540D (APHA, 1998) or MLSS concentration meter
2	Determine settling profile	Plot of settling volume or interface height vs. time for 30 minute duration
3	Determine SV_{30}	Read from settling profile and calculate settled volume after 30 minutes
4	Determine ISV	Read from settling profile and calculate settling velocity between 2 and 5 minutes
5	Determine ZSV	Read from settling profile and calculate settling velocity at constant slope section
6	Calculate SVI	SV_{30} / X
7	Calculate solids flux (G)	G = ZSV. X
8i	Generate flux curve directly from experimental data	G vs. X (8 to 12 MLSS samples with X range from 2 to 12 g/ℓ)
8ii	Generate flux curve from empirical equation (e.g. $V_s = v_o e^{-nX}$)	Fit ZSV and X by regression to v_o and n $V_s = v_o e^{-nX}$ with V_s and X data
8iii	Generate flux curve from correlations of SVI with v_o and n	v_o = f(SVI), n = f(SVI) $V_s = v_o e^{-nX}$ with V_s and X experimental data
8iv	Obtain G from operational chart	Read off flux by using SVI and X

Kazami and Furumai (2000) report that future MLSS settling research will be focussed to replace the flux curve experimental method (8i in Table 2-2), as the experimental procedure is based on time-consuming and laborious tests. Multiple batch settling tests at a range of MLSS concentrations (at least 8 tests from about 2 to 12 g/ℓ, Ekama *et al.*, 1985) are required to generate a flux curve. The preferred method for regular use is to apply correlations to relate MLSS settling velocity to basic measurable settling parameters, such as SVI (8iii or 8iv in Table 2-2). Vanderhasselt and Vanrolleghem (2000) caution, however, against the indiscriminate use of such correlations, as the MLSS settling velocity is influenced by factors not normally incorporated in correlations between MLSS concentration and SVI.

2.2.4 MLSS settling indexes

2.2.4.1 SVI

Mohlman, as cited by Dick and Vesilind (1969), developed the SVI in 1934 to be a basic measure of the physical properties of MLSS. The SVI test is regarded in certain circumstances as an unreliable settling measurement, as the initial MLSS concentration influences the SVI inconsistently (Catunda and van Haandel, 1992). Ekama *et al.* (1985) found SVI comparison to be most unpredictable when the MLSS samples are sourced from different plants at different MLSS concentrations, while Berktay (1998) considered the SVI as unreliable when the MLSS settleability is poor. Poor settleability is usually found in bulking MLSS (Blackbeard *et al.*, 1986) or in settled MLSS with a high SV_{30} (SV_{30} > 400 mℓ/ℓ, Ekama *et al.*, 1985). Schuler and Jang (2007a) summarised the criticism against SVI, by noting that the SVI is a composite, indirect measurement that may not be representative of the four MLSS settling classes taking place in a secondary settling tank.

These and other inadequacies of SVI are categorised in Table 2-3 as five features of the MLSS sample. These features listed in Table 2-3 indicate that SVI test results interpretation depends largely on the experimental procedures implemented for the batch MLSS settling test. The MLSS sample condition, sample modifications, container size, settling parameters required, as well as the test method, all play a role in the calculated SVI test results.

Table 2-3 Reported SVI test deficiencies or limitations

Feature	**Deficiency**	**Reference**
MLSS sample condition		
MLSS concentration	SVI highly dependent on MLSS, inconsistent relationship	Dick and Vesilind, 1969
Rheological characteristics	SVI not related to yield strength or to rheological properties	Dick and Vesilind, 1969
Filaments	SVI not well related to filament number or length	Blackbeard *et al.*, 1986
MLSS sample modification		
Temperature	SVI inverse power relationship at 5 to 45°C, inconsistent relationship	Dick and Vesilind, 1969
Stirring	SVI reduces by gentle stirring, removes cylinder wall effects	Dick and Vesilind, 1969; Berktay, 1998
Dilution	SVI reduces by dilution, removes the MLSS concentration effect	Ekama and Marais, 1984
MLSS settling test cylinder		
Cylinder diameter	SVI dependent on cylinder diameter, according to MLSS properties	Dick and Vesilind, 1969
Cylinder depth	SVI dependent on cylinder depth, according to MLSS properties	Dick and Vesilind, 1969
MLSS settling parameters		
Initial settling velocity	SVI not related to ISV	Dick and Vesilind, 1969
Zone settling velocity	SVI not related to ZSV	Ekama and Marais, 1986
Settling profile response	SVI only dependent on one final point on settling profile	Dick and Vesilind, 1969
MLSS settling test method		
Batch method	Frequency of tests usually only once per day	Vanrolleghem and Lee, 2003
On-line method	Equipment not readily available for continuous and automated monitoring	Sekine *et al.*, 1989

Ignorance or confusion continues to exist regarding the most suitable procedure for the SVI test, according to the different methods and equipment used in the reviewed literature. Bye and Dold (1998) contribute this uncertainty in part to the prescribed SVI test procedure (APHA, 1998) that changed in 1980. The basic quiescent MLSS sample settling method was then modified to include slow stirring at 1 to 2 revolutions per minute (rpm) of the MLSS sample. The SVI test procedure (method 2710D; APHA, 1998) is, strictly speaking, a stirred specific volume index (SSVI) procedure, but it is designated as a SVI. This procedure further states that the T_s of the MLSS sample must be maintained at T_r during a SVI test, without providing implementation guidelines.

Table 2-4 SVI test method according to APHA (1998)

Test component	**Method**	**Remarks from literature**
Container size and type	1 ℓ cylinder	Volume and shape (diameter and height) varies
Stirring	1 to 2 rpm	Samples are unstirred or stirred
Temperature	at T_r	No T_s information or T_s compensation or control procedures for changes from T_r
Test duration	30 minutes	Standard 30-min. duration usually not changed
Container material	not stated	Material and wall thickness varies
MLSS sample source	not stated	Taken at BNR reactor outlet

A summary of the variables of the SVI test method (APHA, 1998) is provided in Table 2-4. In literature, the prescribed SVI test method modifications usually involve any combination of three of the six test components, which are (i) container size, (ii) stirring, and (iii) temperature compensation:

(i) The zone settling velocity of MLSS samples (stirred or unstirred) could be affected by the settling container size (diameter and height), depending on the MLSS characteristics. Renko (1996) concludes that a suspension with a low MLSS concentration settles faster in a small diameter cylinder, due to liquid streaming up the cylinder walls. A suspension with a high MLSS concentration settles slower in a small diameter cylinder, as a result of biofloc bridging and support. (ii) Ekama *et al*. (1985) state that gentle MLSS sample stirring reduces cylinder wall effects, short-circuiting, as well as MLSS concentration effects. The MLSS concentration effects reduce mainly due to better biofloc agglomeration during stirring (Vanrolleghem and Lee, 2003). Nevertheless, sample stirring does not completely overcome the effect of MLSS concentration, as demonstrated by Dick and Vesilind (1969) with different MLSS samples. (iii) Details of prescribed equipment and methods to compensate for temperature changes before and during MLSS settling tests are for the most part absent from the available literature.

Bye and Dold (1998) and Lilley *et al.* (1997) confirm that SVI tests for routine use are usually performed at room temperature in a laboratory, and more often than not with an unstirred MLSS sample. The continued use of the unstirred SVI at room temperature can be attributed to the simplicity and convenience of this SVI method (Schuler and Jang, 2007a), as specialised equipment and procedures for stirring and in particular temperature compensation are not readily available for routine use.

2.2.4.2 Alternative indexes

Ekama *et al.* (1985) and Daigger (1995) promote the replacement of SVI, in process design as well as plant operation and control, by alternative indexes. The most common modifications to the standard SVI include sample stirring or sample dilution, or both. A standard SVI test with sample stirring is named a SSVI. A MLSS sample dilution changes a SVI to a diluted SVI (DSVI). Ekama and Marais (1984) provide guidelines for SVI determinations at a fixed MLSS concentration of 3.5 g/ℓ (unstirred $SVI_{3.5}$ or stirred $SVI_{3.5}$), as well as a DSVI test method.

Table 2-5 Alternative MLSS settling indexes

Index name		**Procedure**
$SVI_{3.5}$	SVI at standard MLSS concentration of 3.5 g/ℓ	SVI test is performed at a fixed MLSS concentration of 3.5 g/ℓ by sample dilution
SSVI	Stirred specific volume index	Test cylinder is equipped with a slowly rotating stirring device (about 1 rpm)
$SSVI_{3.5}$	Stirred specific volume index at standard MLSS concentration of 3.5 g/ℓ	SSVI test is performed at a fixed MLSS concentration of 3.5 g/ℓ by sample dilution, 2.6 ℓ column
DSVI	Diluted SVI	Sample dilution to obtain a SV_{30} value smaller than 200 or 250 mℓ (Bye and Dold, 1998) after 30 minutes MLSS settling, 1 ℓ cylinder

These alternative settling indexes are summarised in Table 2-5 (adapted from Cloete and Muyima, 1997). The DSVI is performed in a 1 ℓ graduated cylinder, and the $SSVI_{3.5}$ in a 2.6 ℓ column. The recommended depth to diameter ratio for tall columns are prescribed at greater than 9:1, but recommended ratios for 1 ℓ cylinders are absent. Temperature compensation procedures are not supplied in the available literature for the determination of any of the alternative indexes. These settling index test procedures only address MLSS sample stirring, and in some instances the size of the settling container.

The use of alternative indexes, specifically the DSVI, can change the MLSS sample characteristics. Chaignon *et al.* (2002) caution that MLSS sample dilution for the DSVI test, with a supernatant of different ionic strength such as potable water, could lead to deflocculation. Unchlorinated secondary clarified effluent is a suitable dilution medium for the DSVI test (Jeyanayagam *et al.*, 2006). The effects of temperature changes during this MLSS sample dilution with plant effluent are not adequately addressed in available research reports. A DSVI test extends the SVI range (White, 1976), as the dilution reduces the MLSS concentration, but DSVI does not consider the MLSS compression characteristics. White, as cited by Ekama and Marais (1984), proposed the use of the $SSVI_{3.5}$ (at a fixed MLSS concentration of 3.5 g/ℓ), as the SSVI is not always independent of MLSS concentration.

Daigger (1995) cautions that there is not sufficient reference data available to develop improved empirical correlations for these alternative indexes, when compared to the large collection of available SVI data. Operational and research reference data in the literature is generally related to SVI (Mines and Horn, 2004), with fewer case studies using alternative indexes. The effects of temperature variations on these alternative settling indexes are not readily available in the literature. The alternative settling index interpretation depends accordingly on experimental conditions, as is applicable to SVI.

2.2.4.3 Future SVI use with settling parameters

Akça *et al.* (1993) confirm that SVI is still a useful and a valuable indicator of MLSS settling and thickening characteristics. Several South African treatment plants perform SVI tests as the only routine indicator to monitor MLSS settleability (Casey and Alexander, 2001). SVI is also extensively used in various modelling applications. MLSS settling characterization that precedes MLSS settling model selection is often based on SVI (Vanrolleghem *et al.*, 2003), due to SVI data and model availability. Such SVI-based models are used in several applications, amongst others to predict settleability failures (Banadda *et al.*, 2005). Recently, Martínez *et al.* (2006) developed a case-based reasoning tool for MLSS separation, and SVI is included as a quantitative indicator of MLSS settleability. The simplicity of the SVI test is the main reason for its continued extensive use in these various operational and modelling applications (Akça *et al.*, 1993), despite all the publicised shortcomings.

Table 2-6 Experimental conditions for SVI use in settling parameter correlations

Parameter	**Cylinder size**	**T_r, T_s, T_a**	**Stirred**	**Reference**
Minimum ZSV	1 ℓ	Unknown	No	Bhargava and Rajagopal, 1993
Sonification time	1 ℓ	Unknown	Unknown	Bień *et al.*, 2005
Tank bottom SS concentration	1 and 2 m tall columns	Unknown	Unknown	Kazami and Furumai, 2000
Tank average SS concentration	1 ℓ	Unknown	1 rpm	Kim *et al.*, 1997
Biological and physico-chemical parameters	Unknown	Unknown	$SSVI_{3.5}$	Sponza, 2004

Several SVI-based parameter correlations, as summarised in Table 2-6, are used for operational process control, design and modelling. SVI is correlated in five different applications, as listed in Table 2-6, to settling velocity, sonification time (ultrasonic floc disintegration time), settled and suspended MLSS concentration, and biofloc properties. SVI is included as an independent variable in all of these correlations, but once again without any temperature related reference information.

2.2.5 SVI and settling velocity correlations

MLSS settling proceeds through different settling velocities (Zhang *et al*, 2006a) during a 30-minute test period. Discrete, zone settling, and compression settling velocities are three separate processes taking place. The zone settling velocity is considered as a key parameter, due to its use in design and operational MLSS settling control.

Most empirical ZSV models include MLSS concentration as the only independent variable, although a variety of mathematical expressions with calibrated constants are used (Smollen and Ekama, 1984). The exponential Vesilind function is the most widely used model, and it links the maximum MLSS settling velocity (the ZSV) to the MLSS concentration (Grijspeerdt *et al.*, 1995) as follows:

$$V_s = v_o.e^{-n.X}$$

where V_s represents ZSV, X represents the initial MLSS concentration, and v_o and n are MLSS-specific settling constants.

The MLSS settling constants v_o and n define settling characteristics (Daigger and Roper, 1985). These constants require calibration to reactor process conditions and MLSS properties for each individual plant reactor (Bergh, 1996). The ZSV is also named constant- (Bhargava and Rajagopal, 1993), hindered- (Dupont and Dahl, 1995), highest- (Gernaey *et al.*, 1998), relative- (Bergh, 1996), or maximum settling velocity (Lynggaard-Jensen and Lading, 2006). The v_o constant is also named initial settling velocity (Lynggaard-Jensen and Lading, 2006). The use of numerous terms indicates that detailed experimental MLSS settling information is required to ensure parameters are interpreted correctly.

Catunda and Van Haandel (1992) found that parameter values that characterise MLSS settleability exhibit considerable oscillations around average values. This noticeable scatter in experimental settling results is frequently reported (Kristensen *et al.*, 1994). Daigger and Roper (1985) found likewise a great deal of experimental settling data scatter, and they had to separate SVI data in four SVI ranges to improve correlations.

Table 2-7 Experimental conditions for SVI use in settling velocity correlations

Parameter	**Empirical equation**	**Reference**	**Cylinder**	**T_r, T_a, T_s**	**Stirred**
Settling velocity, V_s	$V_s = 7.80e^{-[0.148 + 0.00210.(SVI)] .X}$	Daigger and Roper (1985)	1 ℓ	Unknown	1 rpm
Settling velocity, V_s	$V_s = (17.4e^{-0.00581.SVI} 3.931). \exp(-(-0.9834.e^{-0.00581.SVI} + 1.043).X)$	Härtel and Pöpel (1992)	Not stated, equation was compiled from various data sources		
Settling velocity, V_s	$V_s = (28.1\ (SVI)^{-0.2667}). \exp(-(0.177+0.0014.SVI).X)$	Akça *et al.* (1993)	Not stated, equation was compiled from various data sources		

Empirical correlations between ZSV and SVI attempt to make MLSS settling predictions easier. The SVI-based settling velocity correlations listed in Table 2-7 illustrate the additional uses of SVI in MLSS settling correlations, as well as the continued lack of temperature related reference data.

None of the previous studies explicitly addresses temperature fluctuations as a possible contributing factor to variations in the empirical MLSS settling correlations results. The extent of temperature variations under operational and laboratory test conditions must be determined to consider the possible impact of temperature on MLSS settling.

2.3 Operational plant temperature conditions

2.3.1 Overview

Various T_r models have recently been developed. Wells *et al*. (2005) describe several model improvements to allow plant designers and operators to predict reactor and plant effluent temperature variations. These models are developed in order to design treatment plant structures to avoid low T_r conditions, or to reduce the heat load from the final effluent discharge to rivers during cold winter months (Makinia *et al.*, 2005). These T_r-based model developments are for the most part unrelated to MLSS settleability, as correlations between modelled T_r fluctuations and MLSS settleability variations have not been considered in the available literature.

2.3.2 Modelling temperature variations

Makinia *et al*. (2005) present reviews of several dynamic T_r models that predict temperature fluctuations in full-scale reactors. Several energy contributions of heat gains and losses that influence this T_r are summarised in Table 2-8, according to model components provided by Gillot and Vanrolleghem (2003) and Makinia *et al*. (2005).

These T_r models illustrate the extent of temperature variations possible at a treatment plant. Table 2-8 indicates that, although the raw sewage plant inlet temperature (T_{raw}) component is the largest single contributor to T_r, the combined site-specific conditions have a larger influence on T_r. The contribution of energy components can change on a short- and a long-term basis, according to local conditions. For example, cloud cover and shading have a direct effect on the contribution from solar radiation (Scherfig *et al.*, 1996).

Table 2-8 Typical range of energy contributions to influence T_r

Energy transfer phenomena	**Temperature change [°C/day]**
Significant energy contributions:	
Sensible heat (inflow)	0.5 to 3.5 decrease or increase
Solar radiation	0.5 to 2.5 increase
Surface evaporation	0.5 to 2.5 decrease
Process energy (exothermic biochemical reactions)	0.5 to 2.0 increase
Atmospheric radiation	0.5 to 1.0 decrease
Insignificant energy contributions:	
Precipitation (rain / snow on surface)	<0.2 decrease or increase
Mechanical energy (aerators / mixers)	<0.1 increase
Geothermal energy (basin wall convection / conduction)	<0.05 decrease or increase

An overview of temperature data for raw wastewater, reactors, secondary settling tanks, as well as the surrounding environment (ambient), provide an indication of the expected range of operational temperature variations. These variations will contribute towards the change from T_r to T_s during batch MLSS settling tests, as well as temperature-based MLSS settling changes in reactors and secondary settling tanks.

2.3.2.1 Ambient temperature

Observations by Banks *et al.* (2003) confirm that short-term T_a fluctuations follow diurnal sinusoidal wave profiles. These T_a profiles are mirrored, with a lag period, by changes in temperatures of affected water bodies, such as plant T_r. There will be damping effects present in these T_r profiles with increased depth, if the reactor content is not well mixed.

Sinusoidal wave profiles are also present in long-term (seasonal) T_a changes, as illustrated in Figure 2-2. The meteorological data for Johannesburg, South Africa, provides an average diurnal T_a fluctuation of 12°C, based on monthly averages over a 30-year period (South African Weather Service, 2007). The average fluctuation moves from an average daily minimum of 10°C to an average daily maximum of 22°C, as illustrated in Figure 2-2. The lowest and highest recorded T_a is -8°C and 35°C respectively, as measured in winter (June) and summer (January).

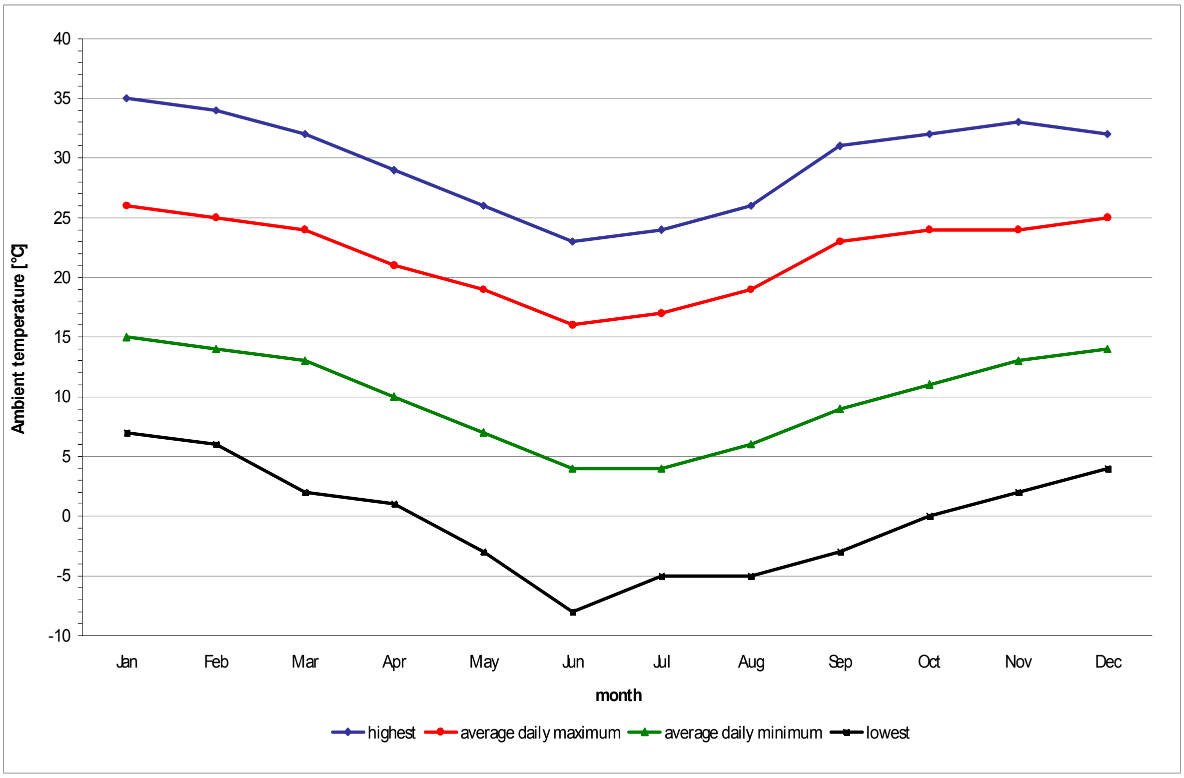

Figure 2-2 Annual T_a profiles for Johannesburg, South Africa

2.3.2.2 Raw wastewater temperature

There is limited information available about the short-term and long-term changes in T_{raw}. These T_{raw} variations are due to cyclic domestic water uses and industrial processes, with additional contributions from industrial process unit shut-downs and start-ups (Morgan-Sagastume and Allen, 2003), as well as seasonal climate changes. Short-term meteorological conditions should also influence T_r, but this could not be confirmed from the available literature. T_{raw} variations are plant specific, but T_{raw} data is usually not required for plant performance monitoring.

Wahlberg *et al.* (1996) demonstrate the extent and influence of unique plant specific T_{raw} variations with a case study. An average winter T_r reduced subsequently in spring by 2°C, from 10.3°C to 8.3°C, due to the colder snowmelt inclusion in a wastewater plant inflow. A guideline for industrial effluent contributions to sewer networks limit the maximum discharge temperature to 45°C (IWPC, 1977), although T_{raw} was at that stage not related to T_r.

2.3.2.3 Reactor temperature

The long-term average T_r fluctuation for design calculations in South Africa has been approximated as 8°C (WRC, 1984), based on a minimum and maximum T_r of 14 and 22°C respectively. Osborn *et al.* (1986) reported the same seasonal T_r measurements, of 14 and 22°C, for a plant in Johannesburg. Long-term T_r variations of up to 13°C have been detected in European plants, such as 7 to 20°C for the Klaby plant in Sweden (Ingildsen, 2002), as well as 9 to 22°C for the Katwoude plant in the Netherlands (Janssen *et al.*, 2002). These long-term T_r fluctuations are subject to individual plant conditions and seasonal meteorological conditions.

Psychrophilic, mesophilic, and thermophilic bacteria function in low (0 to 15°C), medium (15 to 40°C), and high (40 to 75°C) temperature ranges respectively (Droste, 1997). No single organism will grow over all three temperature ranges, although MLSS bacteria can tolerate short-term exposure to high temperatures (Archibald and Young, 2004). Temperature exerts a selective pressure to create medium- to long-term microbiological population shifts (Erdal, 2002). Most municipal wastewater treatment plants operate in the psychrophilic or lower mesophilic temperature range, while industrial effluent plants such as pulp and paper mills operate in the higher mesophilic or thermophilic range (Archibald and Young, 2004). Long-term MLSS settleability evaluations outside the operational T_r range can therefore produce inconsistent settling test results, to some extent due to microbial population shifts.

Bubble or diffused air aeration reactors have higher T_r than comparable surface aeration reactors, due to the addition of warm compressed air that can reach 85°C at source (Maqueda *et al.*, 2006). Pitman (1991) observed that a plant with a bubble aeration system produced MLSS with excellent settling properties, at maximum 60 mℓ/g DSVI, against DSVI values of up to 300 mℓ/g at two nearby plants equipped with mechanical surface aeration systems. Parker (2004) contributed this kind of improved settleability to the superior air and dissolved oxygen (DO) distribution of bubble aerators. The influence of higher T_r in bubble aeration reactors on MLSS settleability is not well documented in the available literature.

Scherfig *et al.* (1996) observe frequent T_r drops of 2 to 3°C over a few days when winter weather patterns in Europe change rapidly. The diurnal T_r fluctuation is in the range 0.5 to

1.0°C (Makinia *et al.*, 2005). The temperature change from the reactor inlet to outlet is reported at about -1.0 to 0.5°C in winter, compared to 0.5 to 1.5°C in summer. These T_r variations are once again subject to individual plant conditions.

2.3.2.4 Secondary settling tank temperature

The formation of concentration and thermal density currents in secondary settling tanks are created by SS concentration and temperature differences (De Clercq *et al.*, 2003). These temperature differences are as small as 0.2°C. Taebi-Harandy and Schroeder (2000) experimentally confirmed these small temperature differences, as well as related settleability changes. The MLSS inflow from the reactor, the MLSS in the settling tank, the return activated sludge (RAS), the clarified effluent from the tank, as well as the top surface effluent layer, all exhibit different temperatures that can be related to T_a (Tadesse *et al.*, 2004). Density currents cause short-circuiting (Kim *et al.*, 2003) as MLSS inflow moves over dead space (when warmer and lighter) or under dead space (when colder and heavier) inside a secondary settling tank.

Denitrification in a secondary settling tank is regulated by the NO_3^- / NO_2^- concentration and the sludge residence time (Azimi and Horan, 1991). There is furthermore a correlation between temperature and the denitrification rate, as the buoyancy of gas bubbles increases by 15% for a MLSS temperature increase of 10°C (Ekama *et al.*, 1997). Sarioglu and Horan (1996) determined that the gas bubble size is dependent on temperature. At lower temperatures (<15°C), the small gas bubbles result in a critical nitrogen concentration (rising sludge) of 13 to 16.5 mgN/ℓ that decreases to about 8 to 13 mgN/ℓ at higher temperatures. Settled MLSS stability is therefore temperature dependent.

Solar radiation (Schutte, 2006) and changing wind patterns (Van Der Walt, 1998) create diurnal temperature changes in secondary settling tanks. Kim *et al.* (2006) modelled the effect of these diurnal temperature fluctuations on MLSS settling flow patterns. A positive heat flux is created by daytime solar radiation once T_a is about 2°C warmer than the tank MLSS influent. This temperature increase results in density currents and cascading flow patterns. Conversely, a negative heat flux is created by nighttime and winter surface cooling once T_a is 2°C cooler than the tank MLSS influent. This temperature decrease results in buoyant flow, a surface current and significant short-circuiting. Jokela and Immonen (2002) studied the impact of the lower winter water temperatures (3 to 12°C) on activated sludge clarification in a chemical-industry wastewater treatment plant. They observed sludge settling deterioration and ultimate sludge carry-over during variable and lower temperatures. These results confirm the general hypothesis of the direct link between MLSS settleability and temperature.

The temperature dependent MLSS settling process in a secondary settling tank is simulated by manual batch MLSS settling tests. For these tests, the temperature impact on MLSS samples in containers will vary according to procedures and equipment used.

2.4 Batch MLSS settling tests and temperature variations

Batch MLSS settling tests should preferably be carried out on-site as soon as possible after a MLSS sample is collected (Ho *et al.*, 2006). The immediate testing of MLSS samples ensures the sample is fresh (Ekama, 1988). Wilén (1999) recommends that T_s is as close as possible to T_r during settling tests, as storage (specifically at 4°C) results in a reduction in microbial activity and a larger tendency of the MLSS to deflocculate. Neither T_s nor T_a is as a rule regulated or monitored during batch MLSS settling tests. Research reports mention occasionally that a settling test is performed at a laboratory or room temperature (Chaigon *et al.*, 2002). Constant room temperatures are in such cases assumed, if not specified (Grijspeerdt and Verstraete, 1997; Hercules *et al.*, 2002).

Most research reports disregard the requirement to create uniform temperature conditions throughout the MLSS settling container content. Tchobanoglous *et al.* (2003) caution against T_s variations inside large settling columns. For this reason, Clements (1976) insulates settling columns with polystyrene to minimise changes to T_s. Simon *et al.* (2005) specifies a maximum 2°C difference between T_s and T_a to minimise the effects of convection on samples during MLSS settling. These references appear to be the only reports in the available literature to address the control of T_s inside settling containers.

Different types and sizes of containers are used for batch MLSS settling tests. Tchobanoglous *et al.* (2003) describe these containers as 1 or 2 ℓ graduated cylinders or 2 ℓ settlometers (usually wider than 2 ℓ graduated cylinders), as well as larger settling columns. These columns vary in size, from 1.8 m (Bye and Dold, 1999) to 3 m (Clements, 1976) tall. The basic 30-minute batch MLSS settling test in such a container is the short-term simulation of reactor MLSS settleability. The reactor MLSS settles subsequently in a downstream secondary settling tank.

2.5 On-line MLSS settling tests and temperature variations

It is not realistic to measure MLSS settling in an operational secondary settling tank (Forster and Dallas-Newton, 1980), as the liquid / MLSS interface blanket height changes according to the hydraulic load on the settling tank. An *in situ* MLSS settling test approach is recommended, which suggests on-line MLSS settling measurements at the reactor. Rasmussen and Larsen (1997) state that such semi-continuous on-line methods can identify variations in MLSS settling properties that are not easily detected with batch settling tests.

Vanrolleghem and Lee (2003) find the scarcity of on-line instrumentation for MLSS settling monitoring in wastewater treatment plants surprising. They blame this monitoring deficiency on the lack of fundamental insights in the determination of MLSS settling factors. Grijspeerdt *et al.* (1995) recognise that specific research from the early 1990s attempts to develop reliable on-line MLSS settling sensors. This technological progress results in the development and implementation of novel sensors, suitable for aspects of on-line settleability monitoring and control.

2.6 Summary

The MLSS settling process depends on the MLSS concentration and the flocculation tendency of SS particles. The flocculation tendency is governed by complex physical, chemical, and biological interactions. Temperature has opposite effects on these physical and biological changes, and MLSS settleability changes are therefore difficult to predict.

Several parameters represent the MLSS settleability, with SVI still regarded as the most widely used parameter, in spite of several limitations. Alternative indexes have been developed, but SVI is still preferred for routine and modelling use, mainly due to the simplicity and convenience of the experimental test procedure. The lack of reported temperature data in MLSS settling test results, although required by standard methods, suggests that temperature compensation is not performed during these experimental procedures.

Existing plant temperature models include energy components that contribute to create site-specific T_r profiles. These T_r profiles usually mirror with lag short- and long-term T_a fluctuations. MLSS settling is very sensitive to meteorological conditions at full-scale secondary settling tanks. It is obvious that these conditions, specifically temperature, wind, and sunshine, will have a similar significant influence on batch MLSS settling test results. Inadequate information was found in the available literature on the use of batch settling equipment with temperature compensation facilities to manage changes from T_r to T_s, due to the influence of T_a.

Automated MLSS settling meters are suitable equipment for on-line MLSS settleability evaluations. Surprisingly, the reported on-line settling meter applications over diurnal T_r fluctuations excluded temperature-based settling models. On-line monitoring of MLSS settling during these diurnal temperature fluctuations provides as a result an opportunity to correlate possible relationships between MLSS settling parameters and temperature.

2.7 Conclusions

The review of the literature, relating temperature to MLSS settling, indicates that there is a lack of reported MLSS settling data subject to short-term temperature fluctuations. The following conclusions are based on the literature survey:

- Unhindered single particle settling can be represented by theoretical equations. The temperature variation effect on particle settling velocity can be calculated from these equations. Hindered MLSS settling requires though empirical correlations that are developed from experimental data. Unhindered or hindered MLSS settling correlations that incorporate T_s or T_r are not available from the literature survey.

- MLSS settling parameters are determined from basic batch MLSS settling tests, based on standard methods that require the implementation of temperature compensation. Details of methods or equipment suitable for temperature compensation are not obtained from the literature survey.

- Reactor temperature models are available for short- and long-term temperature fluctuation simulations. The literature survey indicates that MLSS settling aspects are not incorporated in these reactor temperature models.

- SVI is still the most prevalent settling index used by operators, although the deficiencies, amongst others a significant temperature reliance, has been reported for more than 75 years. T_r recordings and T_s compensation procedures during batch MLSS settling tests are absent from the reported literature. Suitable settling equipment details, to compensate for short-term temperature effects, are also not readily available.

- Numerous settling models provide relationships between SVI and MLSS settling velocity. It appears from the literature survey that temperature compensation is absent from these MLSS settling models.

- A small number of on-line MLSS settling meters have been developed and successfully tested in pilot and full-scale reactors. These settling meters have, however, not been utilised to identify MLSS settling parameter relationships based on short-term temperature fluctuations.

MLSS settling dependence on temperature variations are sufficiently demonstrated in the literature survey to merit proceeding with the rest of the research program, as represented by the research aims.

2.8 Research aims

The purpose of this study is to demonstrate that short-term temperature variations are an essential component of traditional MLSS settling determinations. Consequently, this research focuses on four aspects, owing to their relevance to MLSS settling tests and monitoring, combined with the identified lack of operational temperature information from the literature survey:

- The theoretical impact of temperature on unhindered biofloc settling will be calculated. The changes in unhindered biofloc settling velocity over a temperature range will illustrate the extent of possible MLSS settling velocity changes due to temperature variations.

- The magnitude of short- and long-term temperature variations will be established with an operational plant survey. Significant T_r variations will confirm the need to determine the impact of T_r fluctuations on MLSS settling parameters.

- Batch MLSS settling tests will establish the sensitivity of settling parameters to environmental conditions. The extent of settling parameter variations will indicate if the current lack of temperature compensation or reference temperature data in MLSS settling tests require future equipment and procedure improvements.

- On-line MLSS settling evaluations will be conducted to establish the effect of diurnal T_r fluctuations on MLSS settling parameters. The temperature-based settling parameter correlations will be compared to traditional MLSS concentration-based correlations to evaluate the impact of T_r inclusion. T_r-based settling parameter modelling will be based on best-fit and simplified curve-fitting procedures to illustrate the effects of short-term T_r variations on MLSS settling.

The above-mentioned four main research aims are individually addressed in the subsequent four chapters.