Using image processing for determination of settled sludge volume

Darragh Mullins, Derek Coburn, Louise Hannon, Edward Jones, Eoghan Clifford and Martin Glavin

ABSTRACT

Determination of the sludge volume index is key to describing the settling characteristics of sludge in the aeration process of wastewater treatment plants (WWTPs). The two core components of this calculation are the settled sludge volume (SSV) and suspended solids. While the measurement procedure for SSV is generally defined by national or international standards, in practice a wide variety of vessel sizes and shapes are used by operators to monitor WWTP performance. Furthermore, differences in how these tests are carried out can lead to poor data, inefficient WWTP operation and a lack of comparable metrics for WWTP operational monitoring. Thus, there is a requirement to improve operational performance of WWTPs to meet the increasingly stringent legislation regarding discharge limits. The aim of this study was to utilise a novel image-processing system (AutoSSV) to (i) determine its efficacy in describing SSV and (ii) measure and compare different methodologies for measurement of SSV. The AutoSSV system was tested using samples from various WWTPs and the results compared to those determined by standard manual measurement. Both standard and modified settlement tests were conducted on 30 mixed liquor samples, with modified settlement tests consistently resulting in lower SSV measurements. Results from the study showed a strong correlation between the SSV measurements provided by the AutoSSV system and results obtained from current manual measurement methods. The proposed technique would help to standardise the measurement in practice and increase the frequency of monitoring, particularly in small-scale rural WWTPs where there may not be permanent operators on site, and thus provide sufficient performance monitoring for efficient and effective operation.

Key words | performance and monitoring, real-time monitoring, sensors, wastewater treatment

Darragh Mullins (corresponding author)
Edward Jones
Martin Glavin
Electrical and Electronic Engineering, College of Engineering and Informatics,
National University of Ireland,
Galway,
Republic of Ireland
E-mail: *d.mullins4@nuigalway.ie*

Derek Coburn
School of Physics, College of Science,
National University of Ireland,
Galway,
Republic of Ireland

Louise Hannon
Eoghan Clifford
Civil Engineering, College of Engineering and Informatics,
National University of Ireland,
Galway,
Republic of Ireland
and
Ryan Institute,
National University of Ireland,
Galway,
Republic of Ireland

INTRODUCTION

There has been ongoing research in wastewater assessment and monitoring over the last 20–30 years highlighting the need for the development of low-cost and robust sensors that are capable of providing real-time feedback, therefore enabling operators to make informed decisions (Council of the European Communities 1991; Gitelson *et al.* 2008; Mullins *et al.* 2018). Furthermore, optimising the performance of wastewater treatment plants (WWTPs) is a key area of focus for the sector in order to meet discharge limits, set by EU legislation (European Commission 1998; Kim & Hao 2001; Fitzsimons *et al.* 2016), as well as reducing operational costs (Fernández *et al.* 2011; O'Reilly *et al.* 2011). The lack of full-time support staff for these locations often leads to infrequent measurement (Singh *et al.* 2015; Torregrossa *et al.* 2016) as well as a lack of regular historical results for comparison.

The activated sludge process is the most common type of WWTP in Ireland, though other treatment technologies exist (Fox *et al.* 2016). The solid–liquid separation, known as clarification, is a key component of the treatment process and it needs to be optimised to reduce operational costs (Christensen *et al.* 2015). Automated monitoring of the clarification process is examined in this study. While the internationally recognised 'Standard Methods' (APHA 2005) outline the procedure for measuring settled sludge volume (SVI), a component of the sludge volume index

doi: 10.2166/wst.2018.315

(SVI), in practice this is not always adhered to for day-to-day monitoring, particularly in smaller unmanned plants. There is a large variation in the SSV measurement techniques used by different plant operators and caretakers, especially in small-scale decentralised WWTPs (Hannon *et al.* 2014; Gordon & McCann 2014). A variation of the SSV measurement is widely used as an accepted measure of plant performance (Löwén & Piirtola 1998; Doherty *et al.* 2017). There are different vessel volumes, shapes and sizes utilised, e.g. settleometers and Imhoff cones, leading to difficulties in comparison of results between WWTPs. Even where compliance monitoring is performed as per regulatory requirements, there is a need for improved performance monitoring between the required reporting deadlines; the use of an automated system is one method to address this issue (Jacobsen 1999). This would allow for improved process control, rather than operating a WWTP for the worst-case scenario all of the time (Luccarini *et al.* 2010). While increased staff training may also address the lack of standardisation for measurement of SVI, this does not address the issue of data acquisition from unmanned (mostly decentralised) WWTPs.

Mixed liquor performance metrics

In activated sludge systems SVI is considered a key parameter in describing the settling characteristics of biomass in activated sludge processes and for efficient process control in WWTPs (Lee *et al.* 1983). A major element of this parameter is determining the SSV, as well as the mixed liquor suspended solids (MLSS). SSV is the measure of the volume of settled sludge in a 1 L vessel after 30 minutes and in itself is an important metric regarding sludge settleability. MLSS is the particulate mass contained in the same mixed liquor sample. SVI indicates the settleability of the biomass in the clarifier and is also an excellent indicator for the overall filamentous bacteria content of the system (Lee *et al.* 1983; Metcalf & Eddie 2003). While the settling rate of sludge is infrequently monitored, in many cases reduced rates of settling have been found to relate to poor floc morphology (Agridiotis *et al.* 2007) which in turn can cause sludge bulking and poor compaction. Alternatively, sludge that settles too rapidly leads to highly turbid supernatants in mixed liquor with a high suspended solids content (Wahlberg *et al.* 2001; Wilén *et al.* 2006). It has been argued that another parameter is required to describe sludge characteristics, such as the sludge settling rate (SSR) that can be extracted easily from standard settlement tests (Vanderhasselt *et al.* 2011). Thus, SSV (and the resultant SVI) and SSR are important parameters for controlling the recycle rate of activated sludge from the clarifier back to the biological reactors and thus ensure efficient and effective treatment.

Standard methods for determining SSV

Current practices for calculating SSV are outlined in Standard Methods, and involve a 30-minute quiescent settling in a cylindrical vessel (APHA 2005), shown in Figure 1. The SSV is measured as follows. A mixed liquor sample is placed in a 1 L cylindrical vessel, as specified in Standard Methods 2710 C. The sample settles for 30 minutes and the volume of the settled sludge, i.e. the SSV, is measured; this value is commonly referred to as SSV30. Vessel geometry has a significant impact on the SSV measurement. Sludge settling in narrow vessels is susceptible to the wall effect due to the sludge viscosity (Dick & Vesilind 1969). A settleometer is often used rather than the equivalent volume graduated cylinder (USA Blue Book, 2017). The settleometer differs in geometry, in that it usually has a much larger diameter. This larger diameter combats the wall effect and leads to increased compaction of floc (Hannon 2016). Additionally, a stirring device can be used to aid settling by minimising wall effects on the settling solids; this is known as the stirred SVI (Metcalf & Eddy 2003; APHA 2005). This stirred SSV is a key area of research for the proposed study.

MLSS measurements, also outlined in the Standard Methods, are found by filtration and drying of a mixed liquor sample and then computing the dry mass of particulate matter present. The ratio of SSV to MLSS is the SVI (Metcalf & Eddy 2003), as shown in Equation (1).

$$\text{SVI, mL}/g = \frac{(\text{SSV, mL/L}) * (10^3, \text{mg/g})}{\text{MLSS, mg/L}} \qquad (1)$$

On-site methods

While the measurement procedure for SSV is clearly defined, in practice a wide variety of vessel sizes and shapes are used by plant operators to monitor performance, with operational procedures often defined on a plant-by-plant basis. This leads to irregular results and non-comparable performance metrics between WWTPs (Gordon & McCann 2014). In an Irish context (and probably repeated elsewhere) it was found that a version of the

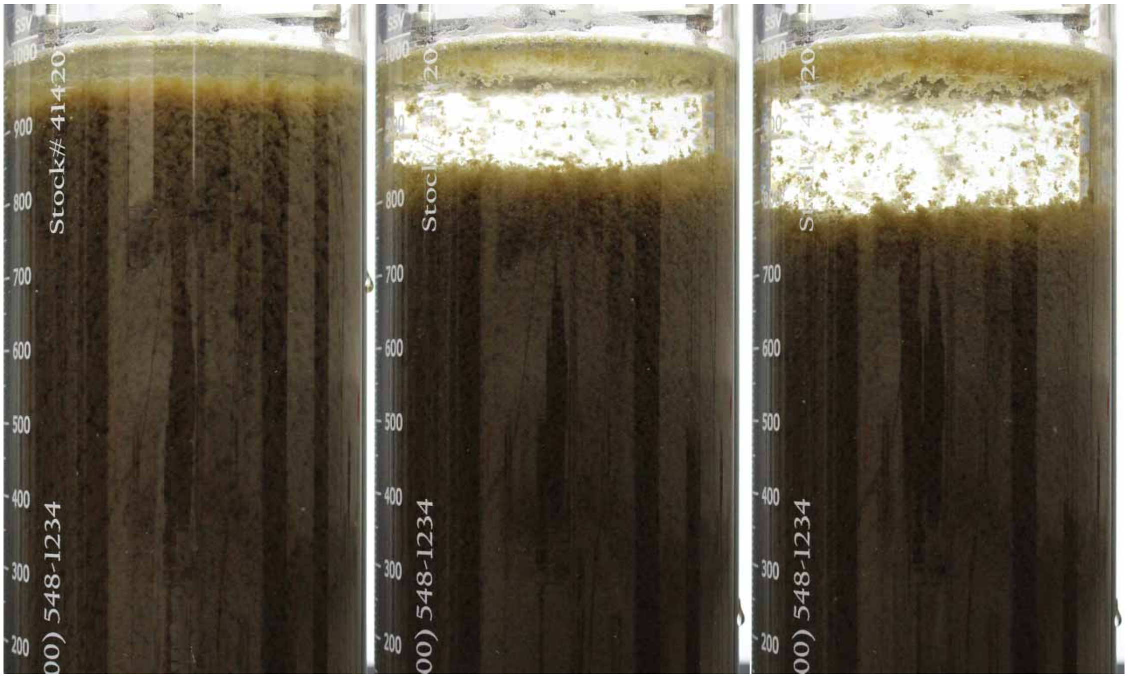

Figure 1 | Mixed liquor sample settling in a clear vessel. A floating scum layer can be seen at the top of the vessel and a non-uniform supernatant–sludge interface as the mixed liquor sample settles.

volumetric settleable solids test is the only sludge settlement test regularly performed at most WWTPs and test frequency varied from daily to weekly (Hannon *et al.* 2014). Most commonly, the test comprised a 30-minute period of quiescent settling in an Imhoff cone, referred to as the cone test. The volume of sludge settled was then recorded in place of an SSV measurement (Hannon 2016). However, this cone test result is not comparable to the internationally accepted Standard Methods stirred SSV test (APHA 2005) that is used along with MLSS to derive the SVI parameter. Furthermore, the settleable solids test, on which the cone test is based, is recommended for dilute sludges, which are frequently not representative of activated sludge processes and thus the cone test, despite its widespread use, is of limited value (Hannon *et al.* 2014).

Furthermore, the study by Hannon *et al.* (2014) indicated that settled volume found from an unstirred settlement test is dependent on the vessel type, i.e. shape, in which the settling is taking place and that the settled volumes derived from unstirred settling in a 1 L graduated cylinder and 1 L Imhoff cone were consistently higher and showed less variation than those derived from settleometer vessels. This is an important finding as the results presented also found that the Imhoff cone is the most commonly used vessel in operational testing. Thus, an automated device/system, capable of calculating SSV as per the Standard Methods would help improve both operational monitoring as well as compliance reporting.

Proposed solution

Previous studies have presented cameras and image processing as a means of measuring the SSV30 of mixed liquor sludge (Kim *et al.* 2010, 2011). This system used a low-resolution camera (390×230) with 230 pixels along the axis of interest. The system was not developed to perform modified SSV measurements, such as the stirred SSV, and the impact of the floating scum layer formed at the air–water interface, which can affect automated sludge height estimations, was not discussed. Vanderhasselt *et al.* (2011) examined two systems using optoelectronics to determine the SSR (Vanderhasselt *et al.* 2011). The first system used a moving scanner to follow the sludge–water interface and measure the SSR (Vanrolleghem *et al.* 1996). The second system interpolated the SSR from three sludge heights during the settlement test, rather than measuring it at more regular time intervals. Vanderhasselt *et al.* (2011) noted that automated tools for measuring sludge settling can be useful, but highlighted that different systems result in different absolute values.

Our study presents a system suitable for autonomously determining the stirred SSV of mixed liquor wastewater samples from aeration tanks as per guideline Standard Methods. The system images mixed liquor in a transparent vessel, and from these images, calculates not only the SSV30 measurement with stirred settling, but also the SSR. This is achieved using a high-resolution digital camera and image processing techniques that provide a repeatable and objective measurement that could be deployed as an autonomous remote monitoring solution, particularly in remote WWTP locations, where there is currently minimal monitoring performed. This is achieved utilising inexpensive hardware, specific lighting conditions and standardised vessels to deliver a scalable and deployable system for determining SSV. Such a system could potentially replace the need for manual measurement of SSV and simplify the SVI measurement process or continue to be used as an informal metric in itself.

MEASUREMENTS AND METHODS

Sample collection

Mixed liquor samples from three municipal WWTPs (details in Table 1) located in Ireland were collected over a 7-month period. The three WWTPs received influent from a combined storm and sewer line in their municipal area. The WWTPs were selected for this case study as they provided a range of sludge types with a good spread of SSV30 values (based on historical data).

Two of the WWTPs sampled had two completely mixed aeration tanks operating in parallel (and thus independently from each other) and in those cases (TP01 and TP02) samples were collected from both tanks, identified separately (a and b) and tested. The samples were collected directly from the final aeration tanks immediately upstream of the outlet to the secondary clarifier system using a manual grab sampler A minimum volume of 25 L of mixed liquor was taken at each collection event in the same manner as the on-site operators.

Table 1 | Sampled WWTPs settlement tests

Reference	Number of settlement test samples	Design size (population equivalent)
TP01a	8	25,000
TP01b	15	25,000
TP02a	2	6,000
TP02b	4	6,000
TP03	1	4,000

Vessel specification

The apparatus requirements for Standard Methods SSV 2710 C is described as a 1 L graduated cylinder equipped with a stirring mechanism consisting of one or more thin rods rotating at no more than 4 rpm (APHA 2005). A polycarbonate settleometer vessel (USA Blue Book 1.3 L Settleometer Kit), shown in Appendix Figure A1, was used in the laboratory work to replicate the Standard Methods SSV 2710 C test vessel. While curved vessels can present problems with light reflection when imaged (shown in Appendix Figure A2), it was decided to continue using them as it provides a more comparable analogue to current measurement methods, as both vessel diameter and height are factors affecting the results of settling tests (Dick & Ewing 1967; Vesilind 1968). Settling in a flat faced vessel is more complex due to the more complex fluid dynamics in the corners of the vessel. (Appendix Figures A1 and A2 are available with the online version of this paper.)

Imaging system

An automated laboratory rig was constructed to carry out SSV and stirred SSV testing. The unit comprised two independent aluminium frames each housing two standard settleometer vessels, complete with two motors, and gearboxes for stirring.

A stainless steel two-rod stirring assembly, capable of rotating at no more than 4 rpm, as per the requirements of Method 2710 I (APHA 2005) was constructed. The device shown in Figure 2 was capable of conducting simultaneous stirred settlement tests on separate samples. For this study, one of the stirring mechanisms was removed to perform simultaneous quiescent and stirred settlement tests on portions of the same mixed liquor sample.

The settleometer vessels were mounted on laboratory jacks, which were integral to the frame, and whose platforms could be raised and lowered manually to allow installation and removal of the settlement vessels and stirrer assemblies (Figure 2). A calibrated scale at the front and back housing of the settleometer rig allowed the centre of the camera axis to be determined via parallax methods, easing the need for precise alignment of the system.

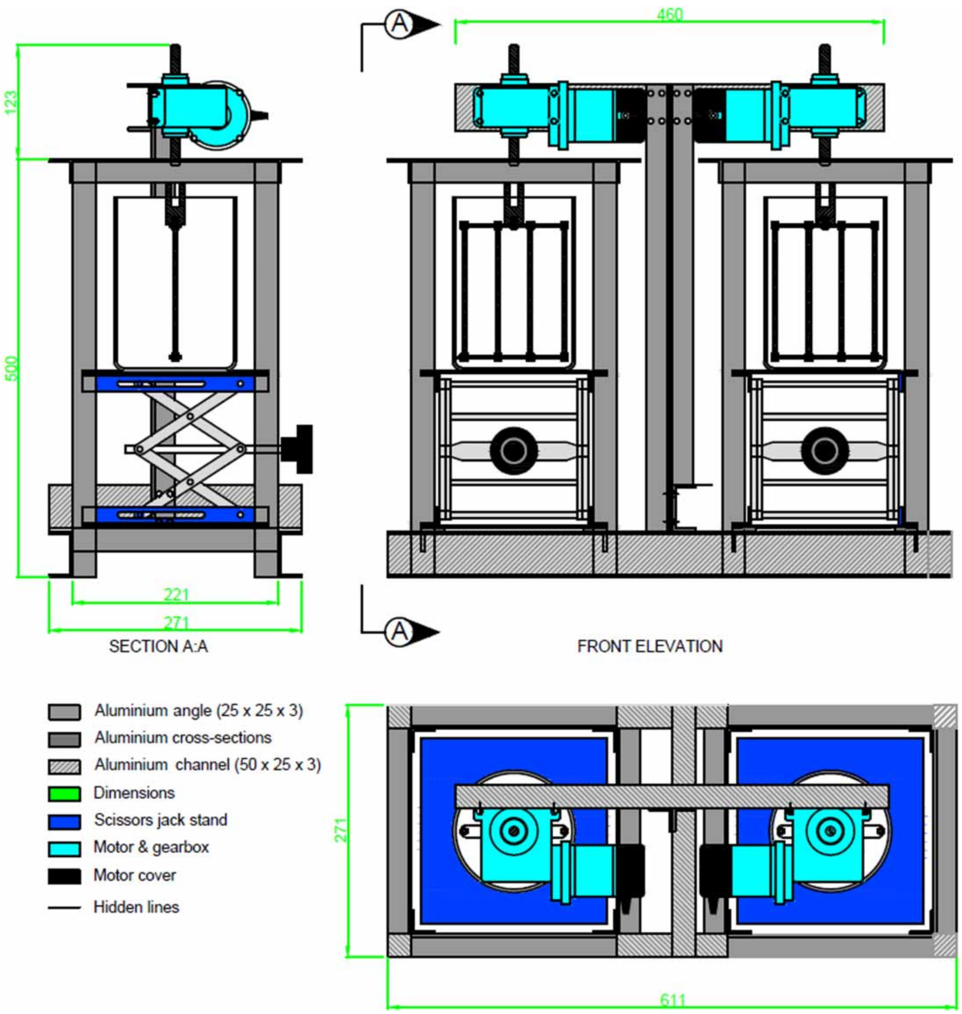

Figure 2 | Aluminium test rig for conducting SSV tests. Included adjustable jack stands, stirring mechanism and settlement vessel. Photograph of constructed rig shown in Appendix Figure A3 (available with the online version of this paper).

Camera

For this image acquisition, a commercially available DSLR Camera (Canon EOS 600D) was selected. The camera was controlled using external remote circuitry to both automate the acquisition and avoid any interference with the camera alignment and focus. This remote shutter control was triggered by the stirring mechanism attached to the motor assembly of the test rig, with one photograph taken for every revolution. The stirrer was attached to the keyed shaft of the motor via a set screw. This allowed the camera to be triggered when the spindle/paddle was in the correct orientation to not interfere with the level estimation. The camera was fixed in the portrait orientation to best utilise the size and shape of the imaging sensor relative to the vessel. When possible, additional processing features, such as automatic light balance and gamma correction, present in the camera were turned off. The camera was focused to have the front face of the vessel on the focal plane. Images were saved as $3,456 \times 5,184$ JPEGs and each AutoSSV test generated approximately 750 MB of data, including calibration images.

Lighting

The light source comprised several strips of broadband white LEDs, configured to provide optimum contrast between the background and the sludge column for layer profiling as well as the scum layer. LED strips were placed on the two vertical uprights between the vessel and the camera, as well as another strip on the upper horizontal strut between the two. This placement ensured a uniform illumination of the front face of the vessel and minimised the amount of reflections on the curved face. Due to the shape of the vessel, there was a tendency for reflections to originate from the centreline of the settleometer. To address this, all other light sources in the area were turned off during data recording. A card was placed behind the settleometer with respect to the camera to reduce light scatter from this direction.

Operating procedure

Both quiescent and stirred settlement tests were carried out as follows. The test vessel was filled with a mixed liquor sample and placed into the test rig, using the alignment pins on the platform to ensure correct position. The stirring paddle was then placed into the vessel and attached to the motor shaft (the paddle and motor shaft were keyed to ensure correct alignment.) The platform was then raised such that the 500 mL marker was in line with the centreline of the camera lens. The camera was then manually focused such that the fiducial markers at the front of the test rig were in focus, thus locating the front of the vessel on the focal plane.

For volume calibration, the vessel was imaged once with graduations facing towards the imaging sensor. The graduations were then rotated out of the field of view so that they did not interfere with the subsequent image processing. Prior to commencing the 30-minute SSV test, the sample was manually agitated to ensure homogeneity. The stirring motors were then switched on and the test and imaging began. For control results the height of the sludge–supernatant interface was recorded manually at 1-minute intervals for the first 5 minutes and at 5-minute intervals thereafter for the remainder of test duration. After the SSV estimation process was complete, the platform was lowered, and the stirring paddle removed. The vessel was then removed from the test rig and the sludge sample disposed of. The vessel was then thoroughly cleaned for the next test. The test procedure was repeated for 30 mixed liquor samples.

Processing the results

The central algorithm developed for this system employed an adaptive threshold of the captured images to estimate sample layers and corrected for parallax effects on the volume estimates. The pixel values of vertical line profiles through the centreline of the settleometer were used to assess the settlement of the sludge column. This was also used to measure the thickness of the scum layer formed on top of the sample. The measurement was obtained by determining the high to low dip in light intensity associated with air to top of liquid meniscus, then the low to high as the profile transitioned to the main volume of liquid.

Use was also made of fiducial and graduation markers on the flask to perform real-world coordinate calibration and image de-rotation correction as required. The reference image (image with graduations facing towards the image sensor) was loaded and several points of reference were found from which to measure. These are shown in Table 2.

The centreline of the vessel in the Y direction was found by drawing a line between the front and back fiducial markers on the test rig structure and choosing the height at which there was no parallax error. The X direction was considered as the vertical centreline of the vessel. A configuration file was then written to store these parameters for each AutoSSV test. The image acquisition rig had multiple independently adjustable components (vessel stand, motor assembly, and camera); therefore there were minor differences in alignment between subsequent tests. The final settled sludge height and settling rate were then determined for each sample collected.

Image processing algorithm

The image processing involved a number of stages as follows:

HSV colourspace

The image was converted from the RGB (red, green, blue) colour space to the HSV (hue, saturation, value) space and the V (value) channel extracted. The V channel provided the best contrast between the dark sludge and clear supernatant. From the initial calibration, each image was

Table 2 | Points of reference for image processing

Reference parameter	Description
Angle	Angle rotated to ensure vertical sections through vessel are parallel with sidewall.
X center	Centre point of vessel volume in X direction.
Y center	Centre point of vessel volume in Y direction.
Y 1,000 mL	Height of 1,000 mL marker in Y axis.
Y 100 mL	Height of 100 mL marker in Y axis.

rotated such that the vessel walls were vertical (or as close as possible).

Extract the line profile

The algorithm plotted the series of profiles and marked the level estimates as shown in Figure 3. An intensity profile was extracted for a pixel column, along the axis of the vessel, through the volume starting at the maximum level at the top of the sample and running to 0 mL. Due to the curved face of the vessel, a single section was chosen, rather than a wider region of interest. Due to parallax, the top of the settling sludge was not seen as a horizontal line; therefore averaging across the width of the vessel was not possible. As these were single line profiles, they were found to be inconsistent due to the inhomogeneity of the sludge caused by the floc composition. This is a challenge with this type of imaging and, in general, median-based filters are effective at removing impulse noises in digital images with small signal distortion (Sun & Neuvo 1994).

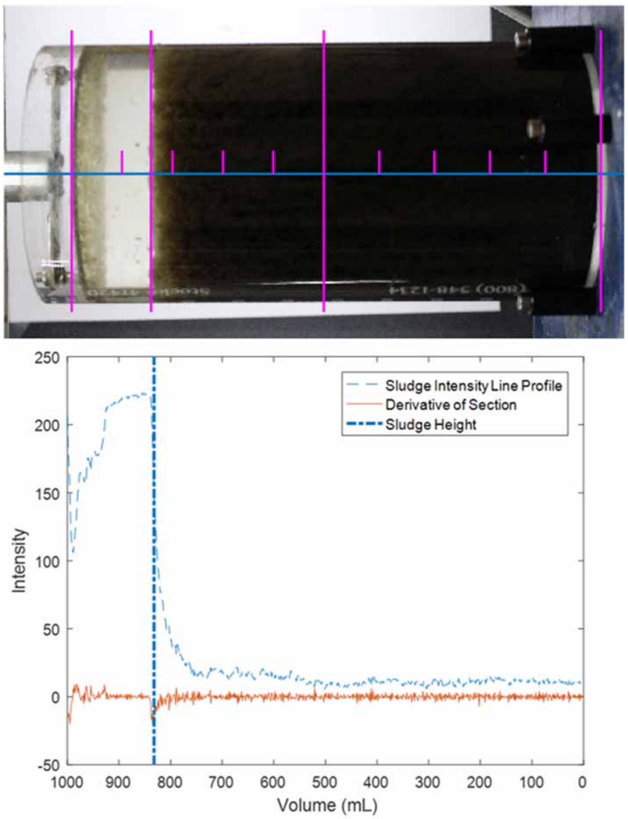

Figure 3 | Image of partial settlement after 3 minutes. Graduated scale overlaid on vessel, with 100 mL divisions. Sludge height also marked. Plot of vertical section through mixed liquor sample and its derivative shown below it. Sludge water interface marked on both plots.

Differentiate the line profile

To find the sludge–supernatant interface, the inflection points of the section profile were found from the profile's derivative. Figure 3 shows additional negative peaks at the air–water interface. To combat this only transition regions, where the signal derivative dropped below the threshold (T) equal to 0.1 times the minimum signal derivative, were logged. The value of 0.1 was chosen as it indicates the significant peaks in the profile derivative that are sudden drops in intensity along the profile. A sharp drop can be seen at the beginning of the intensity profile, which can be attributed to the edge of the floating scum layer present at the air–water interface. In some cases, this is the most significant negative peak of the derivative; therefore a small threshold value was required. This threshold value of 0.1 was determined iteratively from a small subset of the acquired data. The inflection points' coordinates were used to estimate the liquid meniscus and settled sludge layer.

Find the inflection points

A state machine was used to find the coordinates of the inflection points. Each point $X(i)$ of the profile was compared to the threshold (T) and if $X(i) < T$ the state output was **True**, otherwise the state output was **False**, where i is the index of each point along the section profile, measured from the air–water interface down. The purpose of the state machine is to find the location of the lowest inflection point corresponding to the sludge–water interface. The truth table for the state machine is shown in Table 3.

The processes in each state are outlined as follows:

- Enter Region: start point is defined as index of $X(i)$.
- In Region: no change, proceed to $X(i+1)$.
- Leaving Region: end point is defined as index of $X(i)$
- Out of Region: no change, proceed to $X(i+1)$.

From the output of this state table, the index of the negative peaks of the derivative of the section profile were identified, thus locating the supernatant–sludge interface.

Table 3 | Truth table for state machine that locates inflection points intensity profile

$X(i)$	$X(i-1)$	State
0	0	Out of Region
0	1	Enter Region
1	1	In Region
1	0	Leaving Region

In the case of multiple peaks that satisfy the threshold conditions, the largest index value is chosen to be the peak of interest.

Convert to sludge height

For each image processed a plot of the section profile was generated with the sludge height marked, as shown in Figure 3. The location of each inflection point (in pixel values) corresponds to a sludge volume in millilitres. In the initial calibration, the location of the 100, 500 and 1,000 mL fiducial marks were defined. Using these marks, the sludge volume was interpolated. For each image, the sludge level was computed in millilitres and this value was logged along with the timestamp. From this log of settlement levels, a settlement curve was generated. The final image (taken 30 minutes from the start of the test) provided the SSV30 measurement.

Collection of mixed liquor samples from WWTPs was the major source of labour with this analysis. The image collection time was dependent on the settling test, i.e. 30 minutes. Data processing time was minimal with this system; an entire image set could be processed in 20 minutes. This processing time could be overlapped with the settlement test, such that each image was processed as it was taken, thus reducing the total time required.

RESULTS

Statistical analysis of manual vs AutoSSV

The results from the image processing were output as a sludge height in pixels. This value was then scaled to a value for sludge volume in millilitres using the 100 mL and 1,000 mL marker points, defined in the config file, as points of reference for calibration.

The results of this analysis are presented in Figure 4; the full table of results are included in Appendix Table A1 (available with the online version of this paper). A correlation was found between the two measurement techniques for the SSV30 measurement. Computing Pearson's R showed an average $R = 0.99$ with a p-value <0.01, suggesting the results are significant. Similarly, using Lin's concordance correlation coefficient (CCC) an average correlation of 0.99 was observed. A strong linear correlation (Pearson's R) does not always indicate agreement between two datasets; as an additional check, Lin's CCC was also computed, it being a measure of agreement for variables with continuous data

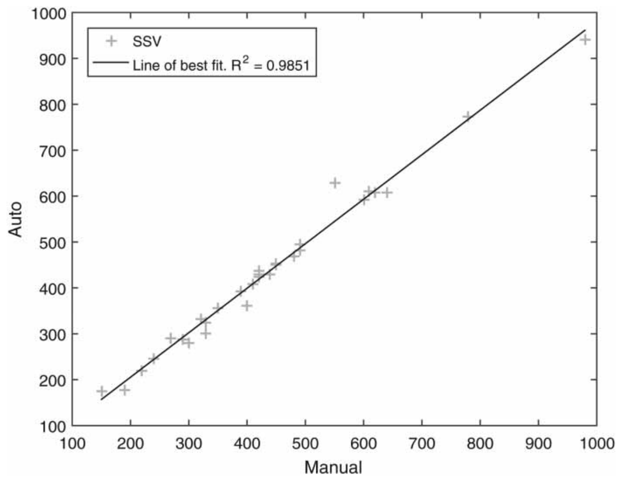

Figure 4 | Scatter of SSV30 results, manual vs Auto, with line of best fit.

that compares the distance between the line of best fit of the datasets (Lin 1989). A high value of Lin's CCC indicates the correlation line is near to $y = x$; therefore, no calibration is necessary for both measurements providing similar values.

A two-sample T-test yielded a P-value <0.9 in favour of the null hypothesis that the results of the automated and manual SSV were equivalent. Comparing the error of the results, using the manual measurement as the reference, there was an average error of 3.7% across the entire dataset of SSV30 values between the manual and the automated measurements.

Sludge settling rate

To examine the robustness of the system, the SSV30 dataset was extended by considering the intermediate SSV height measurements as SSV30 measurements. Manual and automated system measurements were examined at select intervals in the settling process, every minute for the first 5 minutes and every 5 minutes subsequently, yielding 10 points of comparison between the two methods. The results of this analysis are shown in Figure 5.

As can be seen from the results, there was a high level of agreement between the manual and automated system. However, there were several cases where the scum layer at the top of the sample was erroneously selected, by the algorithm, as the top of the settling sludge–supernatant interface. A line of best fit was applied and both Pearson's R and Lin's CCC computed, with the results shown for each sample in Table 4. Despite the outliers (seen in Figure 5), caused by the floating scum at the top of the sample, many of the correlation results were greater than 0.9 between both methods, with an average value of 0.94 and 0.91 for Pearson's R and Lin's CCC respectively. The p-value was <0.001 indicating

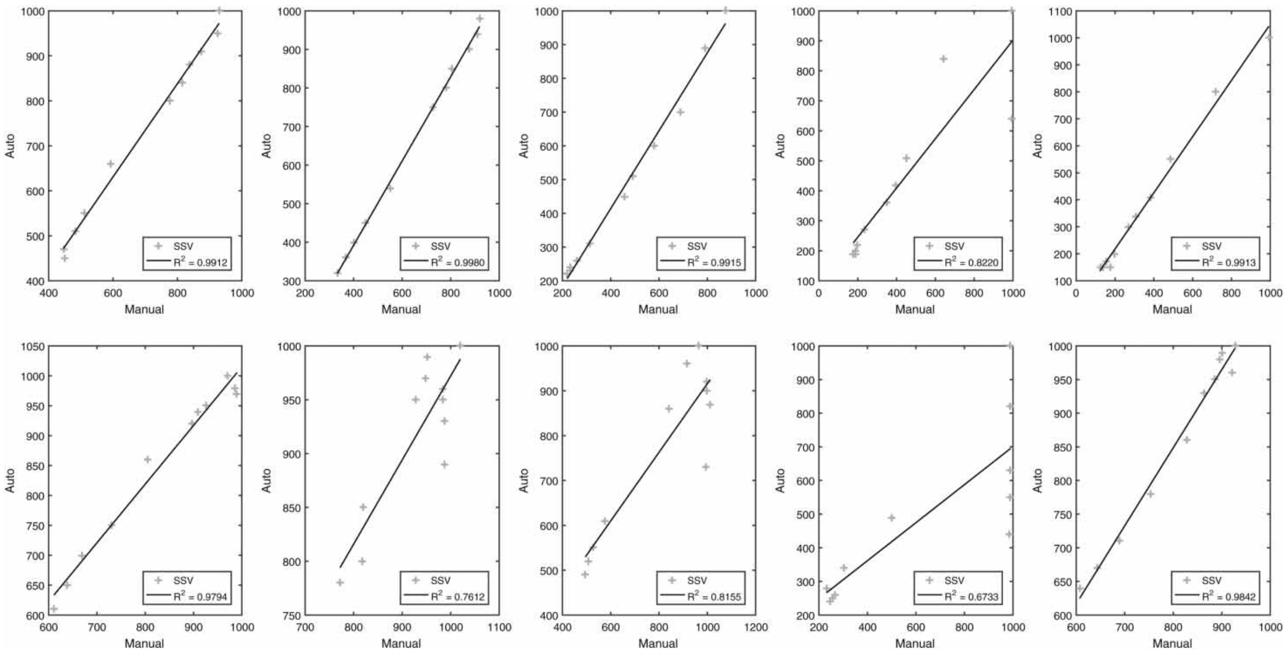

Figure 5 | Plots of sludge height over time for 10 mixed liquor samples.

Table 4 | Summary of results

Measurement	*n*	*R*	*P*-value	R^2	T-test *P*-value	Lin's CCC
SSV30	30	0.99	< 0.01	0.985	0.66	0.99
Incremental sludge height	100	0.94	< 0.001	0.88	0.91	0.91

the results are significant. A two-sample T-test yielded a *P*-value <0.91 in favour of the null hypothesis that the results of the automated and manual stirred SSV were equivalent.

Discussion

There were a few challenges associated with this system. As shown in the supplementary material, Appendix Figure A4, the layer of floating scum at the top of the mixed liquor did, on occasion, interfere with the measurement of the settling sludge–supernatant interface. This was caused by less dense particles in the sample that gradually rose to the top as the rest of the sludge settled. Also, in two or three cases, a large amount of sludge rose to the top of the vessel part way through the settling test as shown in Appendix Figure A5. However, in situations where a significant amount of sludge floated on the top of the sample, the SSV30 results are unlikely to be significant as this is generally an indicator of much greater issues with the treatment process. The system presented here could easily be used to detect such problems and would be particularly effective in WWTPs without permanent on-site operators. Equally, there are situations with high sludge content samples that effectively do not settle after 30 minutes, and therefore deliver no measurable result. (Appendix Figures A4 and A5 are available with the online version of this paper.)

Previous systems that examined SSV extracted an intensity profile and computed the slope from the origin to each point on the profile, i.e. 229 calculations per image collected. The maximum slope was assumed to be the sludge height. This previous method does not account for thick floating scum layers at the top of the vessel. The proposed system uses an improved adaptive threshold to narrow down the points of interest from the derivative to fewer negative peaks of interest and then chooses the most significant.

Existing image-based systems for performance monitoring cannot examine the stirred SSV (Kim *et al.* 2011). Stirred settling has been a requirement of the Standards Methods 2710 C since 1980 and thus should be included as part of an automated SSV measurement system.

A camera-based system has advantages; for example this one could self-diagnose its state of calibration because an empty vessel could be imaged and then the vessel clarity or cleanliness could be compared with previous tests and either cleaned or compensated for in the algorithms.

Future work

There are some potential areas for future work that could ensure this imaging system would be more robust in an on-site environment. The inclusion of blackout material around the test rig would improve the comparability between tests. While all artificial environmental light sources were turned off, the incident daylight was not completely removed from the system. Condensation on the vessel surface was also found to have an obscuring effect on the automated SSV measurements; it may be desirable to operate the camera in a dehumidified enclosure to guard against the impact of condensation as well as to ensure that moisture does not have any long-term adverse effects on the camera. Minor discrepancies were present in samples that settle to less than 200 mL after 30 minutes. In these cases, the stirrer created a hollow in its wake that led to a non-uniform settled sludge surface. Since the camera was positioned at the midpoint of the vessel, it had a view down on this surface. Therefore, the volume was slightly under- or overestimated – depending on the intensity of the image in this area. Perhaps the camera could be situated below the midpoint to reduce the parallax at the bottom of the vessel, thus reducing the error in this area. However, this would increase the parallax error at the top of the vessel. A non-linear scale between pixel height and volume would be required to estimate SSV.

A feasibility study with lower-end hardware could be undertaken by examining the effects of compression on the images. The DSLR camera used for this study is above the required specification. The limits of scaling and compression could be examined to find the minimum required specification for the imaging system.

For this study, all sample handling was conducted manually. For a practical implementation of the proposed system, a reliable automated sampling system would be required. This could present additional challenges in terms of equipment maintenance and cleaning. A laboratory-scale study would prove a suitable test case.

CONCLUSIONS

The energy usage of WWTPs must be reduced going forward; improvements in operational monitoring using low-cost and robust sensors can reduce this energy usage by allowing real-time feedback and thus more efficient process management. In this paper, an automated method of determining SSV using image processing is proposed. Studies have found that compliance with SSV measurement techniques outlined in Standard Methods (or equivalent guidelines) is poor. Replacing the manual procedure with a system based on image processing provides both objectiveness and repeatability by reducing the requirement for human intervention, which also reduces cost of monitoring.

Results have shown that it is possible to determine SSV with a high level of accuracy using image processing. Control tests as per the accepted Standard Methods were utilised to determine the accuracy of the proposed system; Lin's CCC = 0.99 with an average error of 3.7% from the manual measurements. There was a clear correlation between the two methods, not only for the SSV30 measurements, but also for the incremental sludge height measurements taken during the settling phase, Lin's CCC = 0.91.

In future, it is envisaged that the turbidity of the supernatant could also be examined, as it is indicative of effluent turbidity. From the work conducted previously (Hongve & Åkesson 1998; Mullins *et al.* 2018), it is known that infrared light is required for this analysis, as the dissolved organic matter present absorbs broadband white light in different ways. Also, the camera used for this analysis was unsuitable for viewing IR light, as like most consumer cameras it contains an infrared–ultraviolet cut filter.

Several significant benefits have been identified. The proposed system has the advantage of being automated if combined with a sample collection system. This could be used to provide a simple performance metric that could be remotely monitored on a more frequent basis than is currently performed.

As discharge regulations become more stringent, performance monitoring is becoming increasingly important. Implementing the proposed SSV system could reduce manpower requirement, improve monitoring frequency for WWTPs and potentially reduce energy usage and increase WWTP efficiency.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding from the European Union's Horizon 2020 programme under grant number 689817 (INNOQUA), the Enterprise Ireland

Commercialisation Fund (Grant Number: CF2332) and the College of Engineering and Informatics PhD scholarship.

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First received 19 February 2018; accepted in revised form 2 July 2018. Available online 12 July 2018