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Correlating sound and flow rate at a tap

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Abstract

Laboratory tests were carried out to record the sound of water flowing through a tap and the corresponding flow rate. The results were analysed to determine a mathematical relationship between the sound signal and the flow rate. Three models, based on Fourier transforms of data in the frequency domain, were devised to estimate the flow rate of water as a function of the audible sound signal properties. The model was verified against independently recorded data from the experiments. An average error of 15% was determined when results were verified against 5 independently recorded data points. The hypothesis that actual flow rate could be estimated through the analysis of the recorded sound signal pattern was proven correct, but the accuracy of the results was relatively poor compared to mechanical meters. This study set the scene for further research into the use of microphones to assess outdoor water use.

Keywords: Water use, flow rate, sound

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1. Introduction

Water demand modelling normally involves recorded flow rates that are needed to calibrate or verify the model. With consideration for household outdoor demand modelling it is often convenient to install a water meter at the tap to measure the specific water use from each outlet. In developing countries like South Africa it is unwise to use copper water meters, since copper theft is common in poverty-stricken areas. Plastic water meters are less likely to be stolen, but are often vandalised and pose the problem of influencing consumer behaviour. For instance, consumers may reduce water use at the outside tap if a visible water meter is installed. Advanced alternatives, like

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flow trace analysis, are relatively expensive since a data logger is needed in the field at each home (once again with the potential that it may get stolen) in addition to relatively expensive commercial software.

The aim of this research was to design and test an experimental setup to assess the suitability of using recorded, audible sound at an outside tap in order to determine the corresponding flow rate of water at the tap. A mathematical relation between the recorded sound and the flow rate was sought. Subsequently the suitability of this approach in practice was tested on a small scale. Lapinski et al. [1] confirmed that sound could be used to monitor fluid flow through pipelines and similar conduits for delivering gas and oil. The hypothesis for this study was that the actual flow rate of water from the outside tap can be estimated through the analysis of the recorded sound signal of the water running through the tap.

All the experimental runs were conducted at one selected outside tap. The influence of tap shape, size and material was not investigated. Furthermore the pipe system through which the water was conveyed remained unchanged during all experiments, thus excluding possible influences of pipe material and pipe length leading to and from the tap, on the sound signal. As part of the experimental design all the recordings for this study were conducted by carefully excluding external noise, such as traffic and barking dogs.

2. Sound signal analysis

2.1. Time domain - sound intensity

The intensity or loudness of a sound can be analysed in terms of the amplitude of the sound signal in the time domain. Rumsey & McCormick [2] describe decibel as a unit that represents a logarithmic ratio between the amplitude of different signals, and the amplitude represents the power (Watt) of a signal (Ballou [3]). When working with decibels a reference point is needed - meaning that when a decibel reading is 0dB, it does not imply that there is no signal, but that the signal is at the same level as the reference in that case.

2.2. Frequency domain - signal analysis

A sound signal is a type of signal, suggesting that signal processing is relevant in order to analyse the sound signals as part of this project. Although signal processing mainly refers to the acquisition, storage, display and generation of signals, Rossing [4] stated that it also involves the extraction of information from signals. Different mathematical models are available to extract information from signals. Frequency is specific to different sounds. In order to find a correlation between sound and flow rate, the frequencies of the different sounds would have to be analysed. The Fourier series and Fourier transform are methods that could be employed to determine the frequency components of a sound signal by considering the frequency domain. The Fourier transform represents a time-based signal in terms of its frequency components, regardless of whether the time-based signal is periodic in nature. One of the differences between the Fourier series and the Fourier transform is that the Fourier transform consists of real and imaginary parts. Rossing [4] compares the Fourier transform - a continuous function of frequency - to the Fourier series, which consists of discrete frequencies.

3. Methods for flow measurement

3.1. Traditional devices

The device described in this paper could be viewed as a type of water meter - used to estimate flow measurement by analysing the corresponding sound signal. Traditional devices are available to measure water use. A water meter either measures the volume of water passing the meter or velocity of the water, which is then converted to a volume (Van Zyl [5]). Water meters are typically classified as mechanical, electromagnetic or ultrasonic meters. All of these water meters have the following four components: a sensor detects the flow; a transducer transmits the flow signal; a counter keeps record of the volume of water that passed through the meter; an indicator displays the meter reading.

3.2. Sound-based flow measurement

Some types of microphones are in fact vibration sensors; vibration sensors were included in this review and it was noted that previous studies investigated the relationship between vibrations and flow rate (Safari et al. [6]; Kim et al. [7]). Kakuta et al. [8] employed a condenser microphone as vibration sensor to record the vibrations, while the flow rates were measured at the same time and presented a mathematical relationship between flow rate and sound pressure (vibration fluctuation), which could be used to estimate the flow rate. The relationship was verified with an experiment. The recorded sound signal was processed to determine an output sensor index relating to "sound pressure". Kakuta et al. [8] reported that an increased flow rate corresponded to increased sound pressure. Evans et al. [9] determined that flow rate can be estimated if the signal noise (measured in mV) is related to the flow rate of water. A piezoelectric accelerometer was used to record the vibration of water flowing through a pipe. The recorded vibration signal was analysed in the frequency domain and the signal noise was also analysed directly. Evans et al. [9] found it easier to establish a mathematical relationship between flow rate and sound when the signal was analysed in terms of signal noise. Another conclusion drawn by Evans et al. [9] was that the diameter and the material type of the pipe influences the relationship between sound and flow rate.

Fogarty et al. [10] reported that a microphone sensor was used to identify water use of the following different end-use sources: 100% of clothes washer usage; 95% of dishwasher usage; 94% of showers; 88% of toilet flushes; 73% of bathroom sink activity lasting ten seconds or longer; 81% of kitchen sink activity lasting ten seconds or longer. Their study involved implementing microphone sensors at each of these water use points in a household. Record was taken of the number of times a water point was actually used. The recordings by Fogarty et al. [10] were analysed according to the duration of disruptions in the sound signal. The statistics above were obtained relating the actual number of uses to the number of uses identified from the recorded audible sound signal. The work by Fogarty et al. [10] confirmed that sound could be used to obtain an indication of the water use. Hu et al. [11] used a single-point sensing technique for water-use activity recognition by attaching an accelerometer sensor to the main water pipe in a house to detect vibration of the pipe. The signal was processed in an activity recognition system. Four water-use activities, namely bathing, toilet flushing, cooking and clothes washing were classified by the system and experimental results showed that the system could recognize about 70% of those water-use activities.

4. Experimental setup and procedure

4.1. Sound recording

After selecting an appropriate and convenient outdoor tap, a hosepipe was connected to the tap in order to divert the water away from the tap. This was necessary to physically remove the noise of splashing water from the sound recorder. A Schaller Oyster 10/84 pickup (typically used for an acoustic guitar) was used as a passive piezo microphone, mounted under the tap. A sticky flexible plastic material was supplied with the Schaller pickup and was used to connect the pickup onto the base of the tap. The purpose of the plastic material was to reduce vibration noise that might have been caused due to poor contact between the guitar (tap in this case) and the pickup base. The pickup was then secured to the tap using black duct tape in order to fix the pickup to the tap and was also used to prevent possible water damage. The Cakewalk SONAR X1 LE software program was used in conjunction with a Roland Duo-Capture USB audio interface, allowing for a sampling rate of 44100Hz.

4.2. Volumetric flow rate measurement

Despite the availability of various flow meters it was decided to measure the flow rate volumetrically, to ensure accuracy at relatively low flow rates. Firstly, three litres were accurately measured and marked off on the side of a transparent plastic container. Since the experiments were conducted at night, torches were set up. During the experimental runs video clips were taken of the water flowing into the bucket. Afterwards, the videos were analysed and the times noted to derive the flow rate. Before the experimental runs were done, the accuracy of the flow measuring method was determined. Firstly, the tap was opened and adjusted to a relatively low flow rate. After the water ran for a while to achieve a constant flow rate, the flow rate was measured ten times. The process was repeated for a medium and high flow rate. The average flow rates and standard deviations for the low, medium and high flow rates are summarised in Table 1. The standard deviations were small percentages of the average flow rates in all cases and the flow rate measurement system was considered sufficiently accurate.

Table 1 : Statistics for testing the accuracy of volumetric flow rate measurement.

	Low	Medium	High
Minimum flow rate (L/s)	0.0267	0.149	0.290
Maximum flow rate (L/s)	0.0283	0.161	0.308
Mean flow rate (L/s)	0.0276	0.156	0.301
Standard Deviation (L/s)	0.00056	0.00401	0.00605

4.3. Experimental procedure

Each series of tests comprised six measurements, called readings. Six different flow rates, increasing in magnitude with each iteration, were measured and recorded. Such a series of six readings was called a run. Each run produced six sets of corresponding sound signals and flow rates. A reading was done in the following manner: the plastic container was placed on a level surface and the video camera was set up; the sound recording was started; the tap was opened and water was allowed to achieve a constant flow rate; the video recording was started; after the bucket was filled to the three litre mark, the sound and video recordings were stopped and all files stored.

Runs 1 to 3 were recorded on the night of 19 September 2014, runs 4-5 on 23 September 2014 and 6-10 on 3 October 2014. The ten runs with 6 readings each resulted in a total of 60 recorded sound signals and corresponding flow rates. Visual inspection of the recorded sound signals confirmed spikes at the beginning and end of each water use event. These spikes are induced by external mechanical noise while opening and closing the tap. It was considered appropriate to select only the representative period of the sound signal between these spikes for frequency analyses. The recorded sound signals were thus manually cropped as schematically illustrated in Figure 1 to isolate each water use event. Five random data sets (readings) were extracted and kept aside for verification purposes. The remaining 55 readings were subsequently analysed to derive an estimation model.

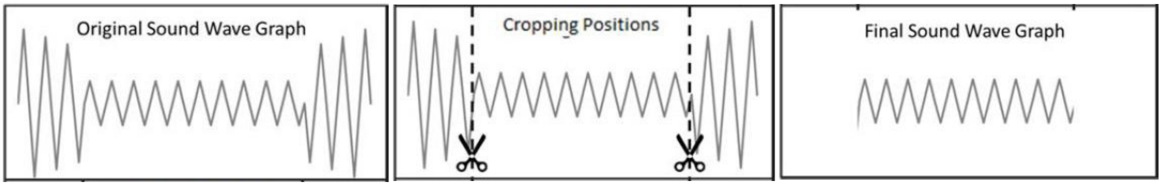


Figure 1 : Schematic cropping of sound signals for each water use event.

5. Analysis and Results

5.1. Simple analysis of sound signal in the time domain

Analysis of the sound signal in the time domain provided insight into the flow rate in the following basic ways:

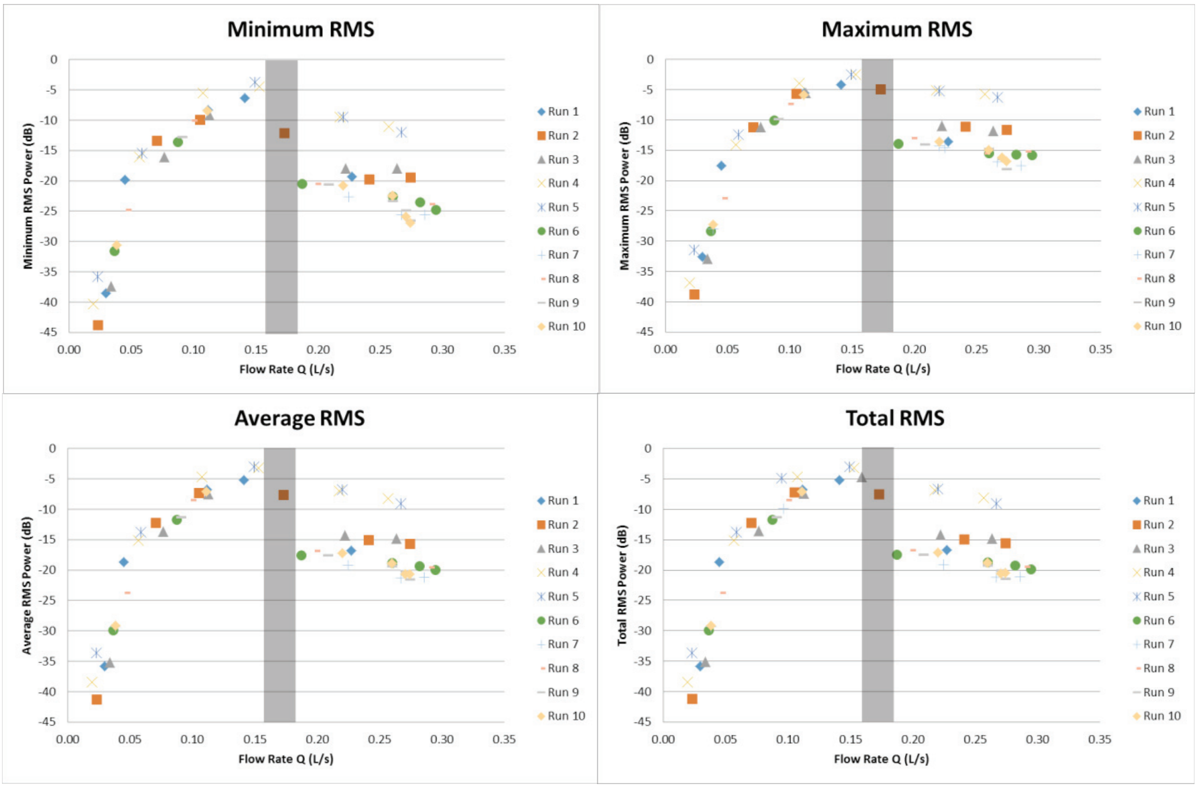
- It was possible to determine whether the tap was open or closed at any point in time

- Based on sound spikes recorded during opening and closing it was possible to identify whether the tap was being opened (noise after the spikes) or closed (the sound after the spikes is silent, with noise before the spikes).
- The time of day for each tap use event as well as the water use event duration could be determined, provided that the microphone-recorder is linked to an automatic clock.

In addition to the basic - and somewhat obvious - information that could be extracted from the sound signal, as mentioned above, this study set out to link the sound signal to the corresponding flow rate. In order to relate the sound signal to flow rate it was necessary to firstly analyse the sound signal in terms of its amplitude, and secondly to investigate the frequency domain.

5.2. Sound signal amplitude analysis

The amplitude of the sound signals were analysed using the Cool Edit Pro statistical analysis function. The following parameters were given by the software: peak amplitude (dB); minimum root mean squared (RMS) value (dB); maximum RMS value (dB); average RMS power (dB) and total RMS power (dB). The average RMS power, measured in decibels, was determined using a sine wave with a 50 millisecond (ms) window width. This means that the sound signal graph was divided into sections of 50ms lengths during the analyses. All the available statistical parameters were plotted against the corresponding flow rates, for all the experimental runs. The four most notable results are presented in Figure 2. The shapes of the four graphs are quite similar.



Minimum RMS

Maximum RMS

Average RMS

Total RMS

Figure 2 : Results of sound signal amplitude analyses.

The grey areas on the graphs once again indicate a possible discontinuity between 0.16L/s and 0.18L/s. From the graphs above, it is clear that the peak amplitude cannot be used to uniquely describe flow rate from the sound signal.

The shapes of the graphs are identical and any of these graphs could thus be used for the analysis. For further analysis the average RMS graph was used to find a correlation between sound and flow rate.

5.3. Selection of frequency modes from sound signal

The frequency domain was used to investigate patterns in the available information. This was achieved by plotting the Fast Fourier Transform (FFT) of the sound signals using MATLAB. The MATLAB output produced a symmetrical graph around 22050Hz over a frequency domain of 44100Hz (sampling rate of recording equipment). Only one side of the symmetrical graph had to be analysed, thus the frequency axis was cut at 22500Hz to enable a clearer analysis of the FFT graphs. The FFT graphs of the sound signals of all the readings were meticulously inspected and methodically assessed to identify peaks on the FFT graph - and note corresponding frequencies. Frequencies (frequency ranges) at which peaks were noticed in all the graphs were lifted from the data set. The selected frequency modes were subsequently noted for further analysis, but the notable peak at 50Hz was excluded because it was considered to be linked to electrical interference (in South Africa 220V power is supplied to homes at 50Hz). Five modi were selected for further investigation, shown in Table 2.

Table 2 : Frequency modi lifted from FFT of each sound signal.

Modus	Frequency rage corresponding to FFT-peak (Hz)	Representative value used as plotting position (Hz)
1	131 - 231	181
2	379 - 618	499
3	1265 - 1933	1599
4	6321 - 9676	7999
5	10700 - 11 010	10855

The peak amplitude of each modus was determined and could be plotted against the flow rate for each run. Five different scatter graphs showing peak amplitude versus the corresponding flow rates could now be plotted. Four of the results are reported in Figure 3. The grey areas on the graphs indicate a possible discontinuity for flow rates between 0.16L/s and 0.18L/s. The result for Modus 5 (not shown) was similar in shape to Modus 4. Harmonic repetitions of frequencies were identified during the analyses, for example, Modus 5 reported peaks at almost double the frequencies of Modus 4.

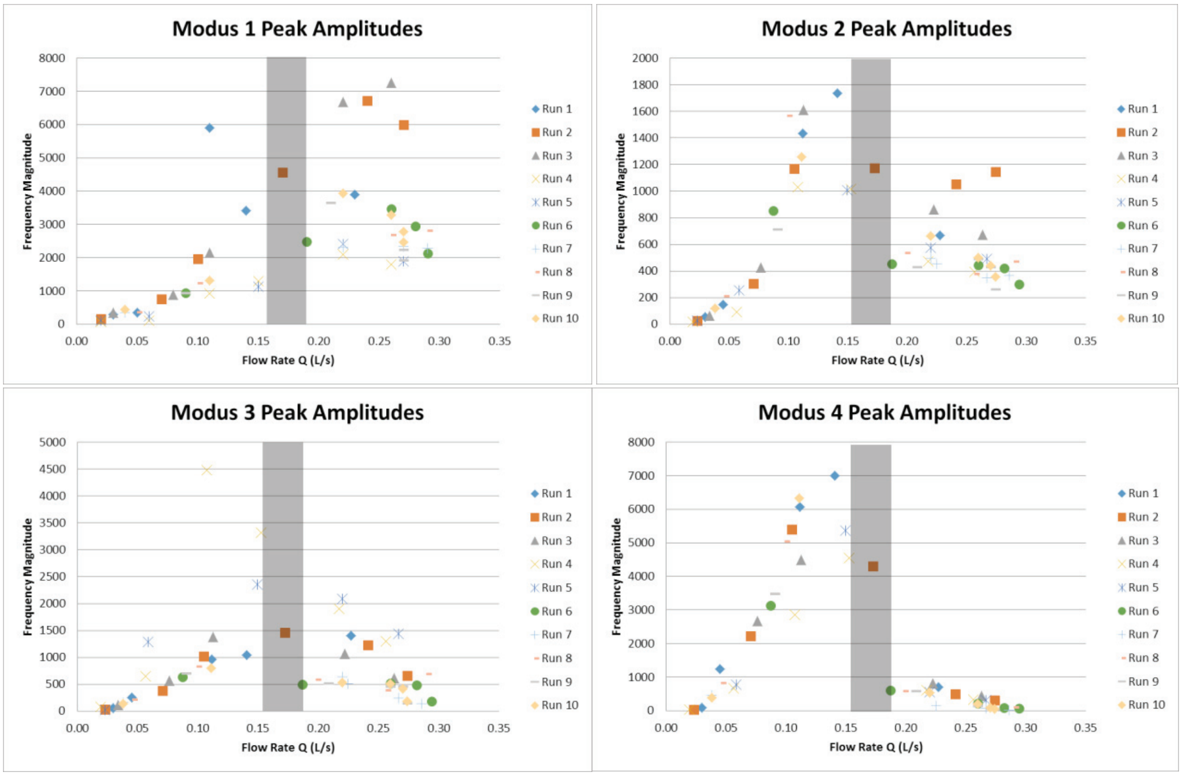


Figure 3 : Results of analyses in the frequency domain.

6. Flow rate estimation models

Various possible models were devised by which flow rate could uniquely be described by trend lines fitted to the various frequency and amplitude scatter graphs, as described above. The limited scope of this study did not allow for an optimal model to be sought. Three models were devised and provided reasonable results, one of which is presented in this paper.

A flow chart of the discontinuous flow rate estimation model (DISFLOREM) is presented in Figure 4: consider the Modus 1 frequency amplitude (magnitude), A_{M1}, based on the FFT-analysis of the sound signal. Considering Modus 1 (top left in Figure 2), a unique solution is only achieved for values of $A_{M1} < 1500$. Thus, if $A_{M1} > 1500$ it is necessary to consider another relationship, namely the Modus 4 frequency amplitude of the sound signal, A_{M4} (refer to Figure 5a). However, if $A_{M1} < 1500$ Equation 2 is used to solve for Q. Now, if $A_{M1} > 1500$ and $A_{M4} < 950$ Equation 1 is used to solve for Q as a function of A_{M4}, else Equation 2 is used to solve for Q.

In order to solve Q with Equation 2 the average RMS value is obtained from the trend line shown in Figure 5b. The solution would be the lower of the two Q-values found, because only the left-side of the scatter graph was used to fit the trend line (this was done by deleting all the data points to the right of the corresponding Q).

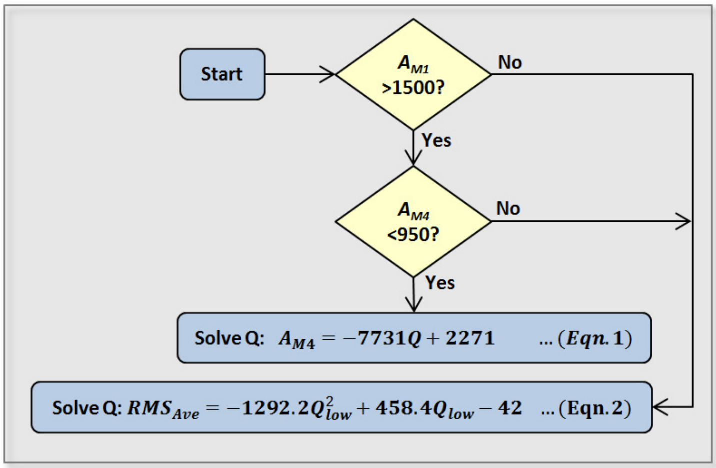
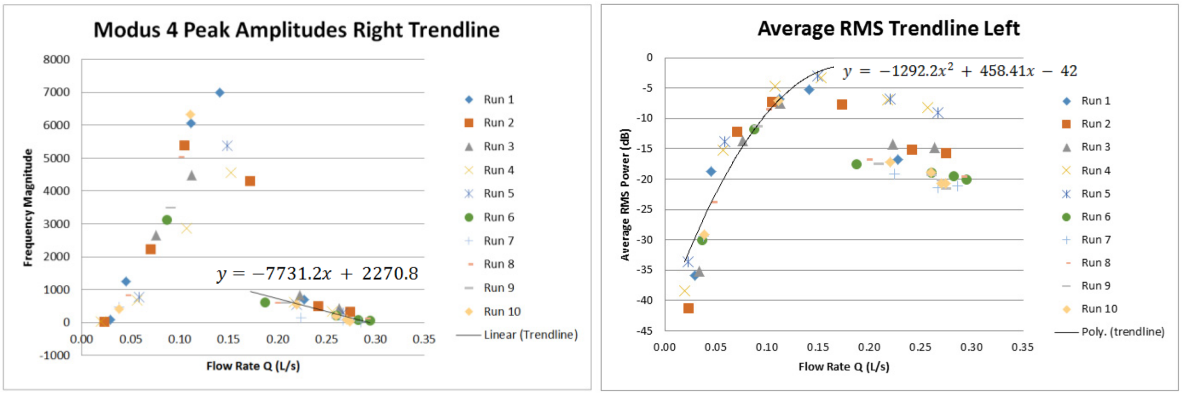


Figure 4 : Flow diagram of DISFLOREM model.



(a) (b)

Figure 5: Trend lines used to estimate flow rate with DISFLOREM.

7. Verification and application

The data points that were initially excluded from the analysis were used to verify the results produced by DISFLOREM. Table 3 shows the applicable values required to solve for flow rate using DISFLOREM. The actual measured flow rate is tabulated next to the flow rate determined by DISFLOREM. The last column in the table shows the percentage error (calculated value compared to the measured flow rate).

Table 3 : Verification - modelled flow rates and actual flow rates for 5 readings.

Run	Reading	Modus 1 Peak Amp.	Modus 4 Peak Amp.	Avg. RMS Power	$A_{M1}<1500$, or $A_{M1}>1500$ & $A_{M4}>950$	$A_{M1}>1500$ & $A_{M4}<950$	Q_M (L/s)	Q_{Act} (L/s)	Error (%)
1	6	4891	352	-35.85		●	0.24	0.25	3
3	4	3243	6591	-1.43	●		0.17	0.16	-6
5	3	839	2754	-4.91	●		0.13	0.09	-32
7	2	1276	3804	-9.87	●		0.10	0.10	≈ 0
9	1	401	262	-33.42	●		0.02	0.03	38

Practical application of the method to evaluate water use from outdoor taps by recording sound is currently under way - mainly to gain insight into the timing and duration of all water use events. Sound recorders were installed in a case study site in the city of Lilongwe, Malawi, to assess the water use by home owners for irrigation of urban crops (i.e. vegetables).

One of the challenges when selecting a recorder was the battery life, but consideration was also given to sampling rate, maximum duration of recording, on-board file size, recorder capacity, recording quality, and the option to fit an external microphone. The selected equipment allowed for recording of between 3 and 44 days' continuous sound signal, depending on the desired recording quality. The external microphone was considered essential in order to hide the recorder with its batteries (or the solar charge input plug) in a custom-built watertight container and thus expose only the relatively small and inexpensive microphone near the tap. The most notable advantages of recording sound were that no plumbing changes were required, the cost was low compared to water meters and data loggers, equipment could easily be moved around if necessary, and the fact that any outdoor tap with accessible pipework could be monitored.

8. Conclusions

The main conclusion that can be drawn from this study is that valuable information regarding flow rate and water use can be obtained by recording and analysing the sound of flow at a tap. Also, various relationships could be drawn between sound and flow rate, as with the DISFLOREM presented in this paper. DISFLOREM provided reasonable accuracy based on limited verification of model results to 5 readings, with an average 15% error and 3 of the 5 readings within 6% error. The reported errors are larger than typical water meter reading errors, which are in the order of 0-5%.

In all the results (refer to Figure 2 and Figure 3) there seems to be a possible discontinuity between flow rates between 0.16L/s and 0.18L/s, but insufficient data was available in this narrow flow range to investigate the problem further. Assuming realistic values for the tap diameter, roughness and viscosity, an approximate Reynolds number was determined as a matter of interest. It seems that the Reynolds numbers fall approximately in the transitional turbulent regime for flow rates in the region of 0.16L/s to 0.18L/s, thus possibly explaining the discontinuity at this flow rate (Figure 2 and Figure 3). The fact that the water flow is in a transitional state could explain the somewhat weaker relation achieved for flow rates above 0.18L/s (turbulent), compared to flow rates lower than 0.15L/s (laminar), for all the models tested in this study, including those that were not reported on in this paper.

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