ACOUSTIC DESIGN OF WATER FEATURES FOR THE BUILT ENVIRONMENT

L Galbrun School of the Built Environment, Heriot-Watt University, Edinburgh, UK
TT Ali School of the Built Environment, Heriot-Watt University, Edinburgh, UK

1 INTRODUCTION

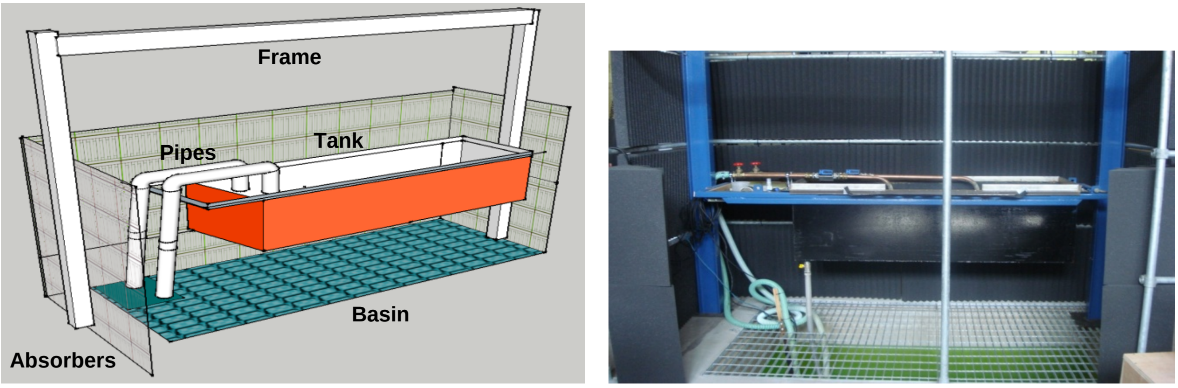
The acoustic use of water features is increasingly being considered in the built environment due to the inherent positive qualities of water sounds[1] and due to their ability to mask noise. This paper examines the acoustic properties of water generated sounds, in view of characterising the impact of design factors on the acoustics of small to medium sized water features which can be installed in both outdoor and indoor spaces such as gardens, parks, hotels' lobbies, offices and restaurants. In particular, the study looks at acoustic properties of waterfalls, cascades and fountains tested in the laboratory under controlled conditions. The paper begins by reviewing the background to the research, followed by a description of the methodology used for tests, a presentation and analysis of key results, and conclusions in which main findings and further work are discussed.

2 BACKGROUND

Water falling over water, or any solid surface, generates sound through different mechanisms. In the case of water falling over water, a low level impact sound originates from shockwaves occurring at the contact region, followed by the formation of vibrating bubbles in the water[2]. The latter sound tends to be dominant and exhibits tonal properties which are a function of the size of the bubble, as the resonance frequency of the bubble is inversely proportional to its diameter[3]. Although these fundamental mechanisms are well known, water sounds are complex and difficult to predict, a reason why research is needed to understand the interaction between design factors and acoustic properties of water features. In recent years, most of the acoustic research looking at water features has been using the soundscape approach[4]. Soundscape studies are mainly qualitative in nature, and typically examine both physical characteristics and mental perception of the aural and visual environment. Amongst those, the studies most relevant to the work presented are engineering projects which combined physical measurements, subjective evaluation and design strategies to improve the soundscape in urban spaces[1,5]. Although these soundscape projects provide an insight into the acoustic and perceptual properties of water generated sounds, their assessment is often influenced by multiple factors which make it impossible to analyse and understand water sounds in isolation. More recent studies have looked at water generated sounds and traffic noise using methods in which water sounds could be controlled and analysed in isolation[6,7]. Of particular interest is the study of Watts et al.[6], in which laboratory measurements were undertaken to capture water generated sounds under controlled conditions. In this work, spectra were measured for a stream of water falling onto water, gravel, bricks, small boulders and various combinations. Results were then compared to traffic noise spectra and recordings were used to enable subjective assessment of the tranquillity of the sounds. The results showed that the water stream and cavities used in the tests could not produce sound pressure levels at low frequencies which are high enough to mask traffic noise. However, listening tests indicated that improvements in tranquillity could be obtained even for low levels of masking, suggesting that the distracting effect of natural sounds is chiefly responsible for the perceived improvements in tranquillity. Jeon et al.[7] carried out qualitative perceptual assessment of urban soundscapes using listening tests, and found that water sounds were the best sounds to use for enhancing the urban soundscape. Furthermore, they found that the water sounds should be similar or not less than 3 dB below the urban noise level. The research considered in this paper is in line with the work of Watts et al.[6] and Jeon et al.[7].

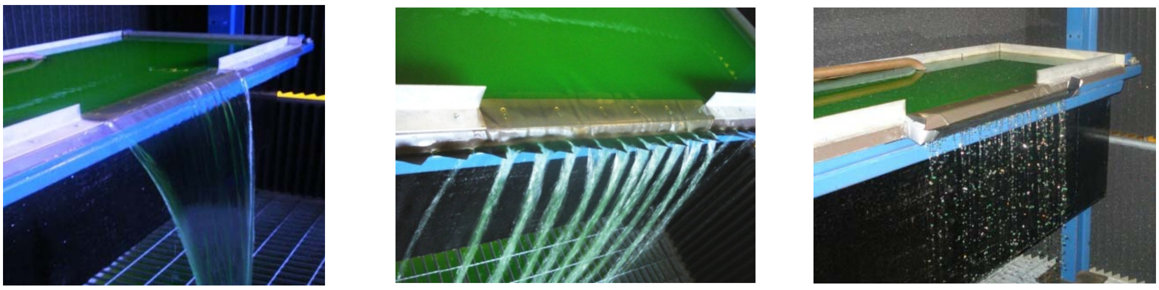
3 METHODOLOGY

A variety of waterfalls, fountains and cascades were constructed in the laboratory. This allowed testing different designs and measuring physical parameters (e.g. spectrum and sound pressure level) as well as psychoacoustical parameters (e.g. loudness, sharpness and roughness) under controlled conditions. The structure built (Figure 1) consisted of a basin encased in the floor and into which water falls, and a tank 1.5m long x 0.5m wide x 0.5m high fixed at a higher level. Two submersible pumps were fixed in the basin and used to circulate water to the upper tank (variable flow rate of up to 150 litres per minute); the tank was attached to a frame which allowed it to reach a maximum height of 2.5m above the floor level. Measurements were carried out at a distance of 0.5m from the centre section of the basin (impact area of falling water) and 1m above floor level. This receiver position was chosen for its dominant direct field, and absorption panels were also installed around the structure to minimise sound reflections from adjacent surfaces. Acoustic parameters were measured using an integrating sound level meter Brüel and Kjaer Type 2250, with a data averaging period of 20 seconds. In section 4, frequency responses are presented in octave bands for the 63Hz-16kHz range; lower frequencies are not included, because of the dominant background noise. Audio recordings were also carried out with a digital sound recorder (Zoom H4n) connected to Brüel and Kjaer Type 4190 half inch microphones attached to a dummy head. The audio recordings were needed for calculating psychoacoustics parameters through Matlab, as well as in view of listening tests. Waterfalls were tested with different widths, heights of falling water, flow rates and impact materials (concrete, metal, stones, boulders and gravel). Furthermore, different waterfall edges were tested, including a plain edge, a saw edge and an edge made of small holes (2mm diameter), as these were found to be representative of a variety of edge conditions (Figure 2). Different fountain designs, cascades, as well as combinations of upward jets were also tested, and some examples of the configurations examined are given in Figure 3.



(a) Three dimensional drawing (b) Picture of the structure

Figure 1 Laboratory structure used for testing water generated sounds.



(a) Plain edge (b) Saw edge (c) Small holes edge

Figure 2 Waterfall edges.

(a) Cascade (b) Fountain (32 jets) (c) Foam fountain jet

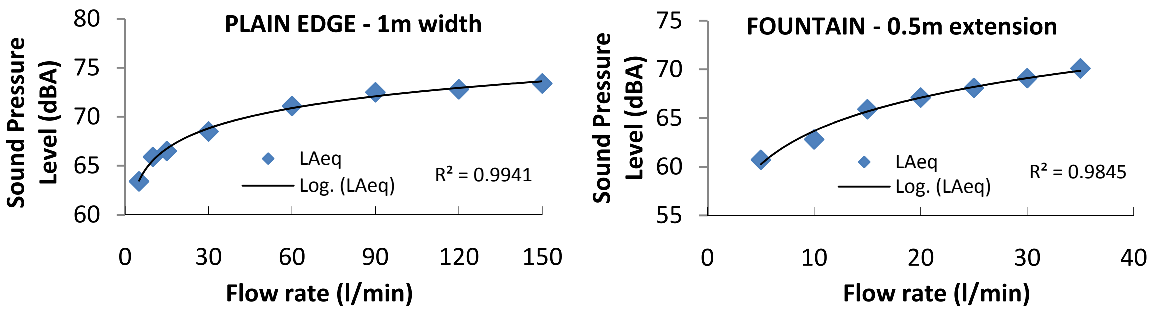
Figure 3 Examples of water features tested.

4 RESULTS

A considerable amount of data has been obtained from the research, but the analysis presented here is limited to the key findings obtained regarding the impact of design factors on acoustic parameters. The analysis of psychoacoustic parameters and listening tests carried out within the study are not presented, as these form part of ongoing work. The section outlines the acoustic impact of flow rate, waterfalls' edge design and width, height of falling water, and impact materials. Furthermore, masking properties of water generated sounds over road traffic noise are also discussed.

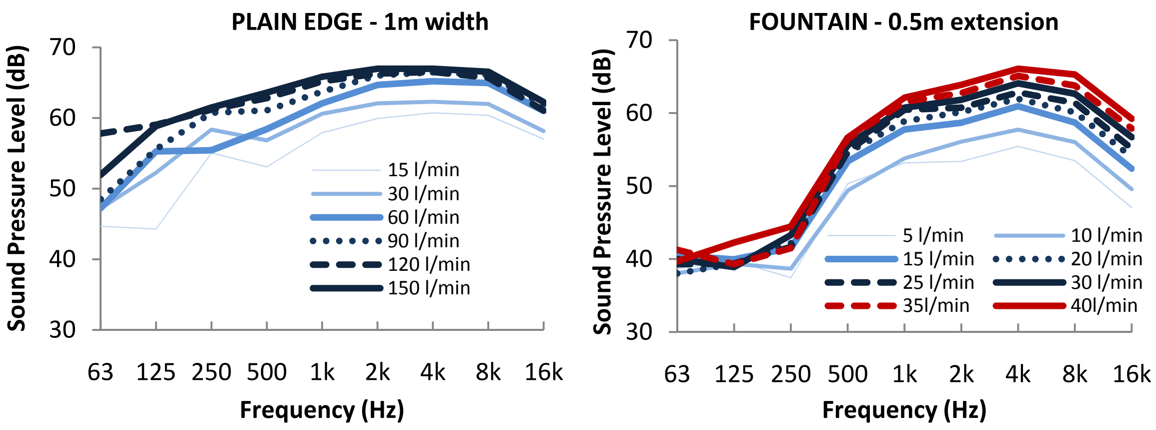
4.1 Flow rate

Results indicate that the equivalent continuous sound pressure level, L_{Aeq}, increases logarithmically with flow rate for all types of small to medium sized water features (waterfalls, fountains, jets and cascades). This can be seen in Figure 4, where large increases at low flow rates and small increases at high flow rates are observed. Results also suggest that waterfalls have a smaller range of variation in L_{Aeq} and are normally louder compared to fountains, jets and cascades. It can be noted that the logarithmic trend is confirmed even when the parameter used is loudness instead of L_{Aeq}. These results can be compared with Fastl[8] who measured the loudness of three large cascade constructions, results showing that loudness increases with increasing amounts of water. However, different trends of loudness versus flow rate were found for the large designs tested.



(a) Waterfall (1m height) (b) Fountain (32 jets)

Figure 4 Sound pressure level L_{Aeq} vs. flow rate.



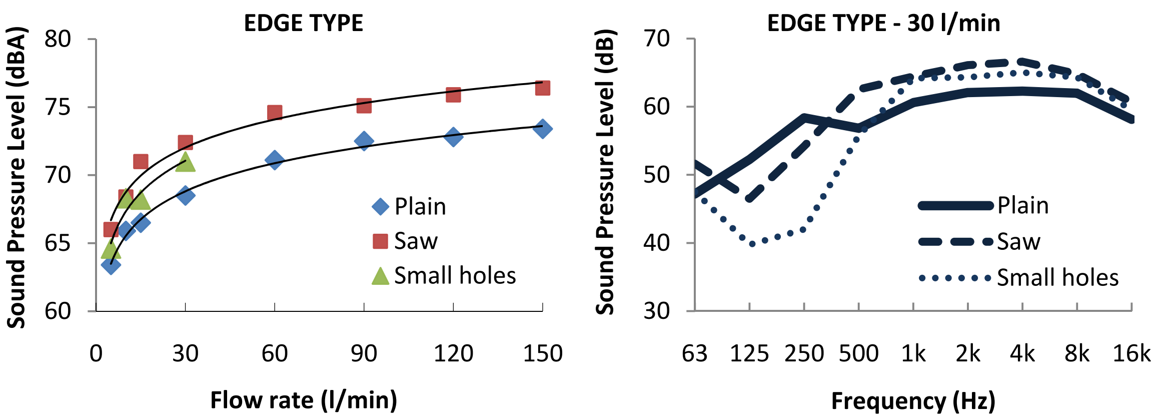
(a) Waterfall (1m height) (b) Fountain (32 jets)

Figure 5 Spectra obtained for different flow rates.

The water sounds produced by all the features tested are mid and high frequency dominant, with most of the energy contained in the 500Hz-16kHz octave bands (Figure 5). The changes in flow rate appear to affect the sound pressure level equally for all frequencies above 500Hz (dominant range), whilst the low frequency changes tend to be variable and less significant for all water features except waterfalls. Overall, results show that low frequency sounds cannot be easily made by increasing the flow rate in features such as fountains, cascades and jets.

4.2 Waterfall's edge design

The edge design of a waterfall affects the way in which water is distributed over the impact surface (water or solid material). A plain edge results in a uniform 'curtain' of water falling over the impact material, whilst a saw edge design creates several streams of water (Figure 2) and hence several localised pockets of bubbles. It can be shown that the saw edge design is effectively equivalent to an edge comprising large holes, with the advantage of being flexible and not limited in terms of diameter's size. An edge made of small holes (2mm diameter) is also useful for representing a 'rain' type of water distribution. Results shown on Figure 6(a) indicate that higher sound pressure levels L_{Aeq} are obtained when distributing the same amount water over several streams (saw edge and small holes) rather than over one uniform stream (plain edge).



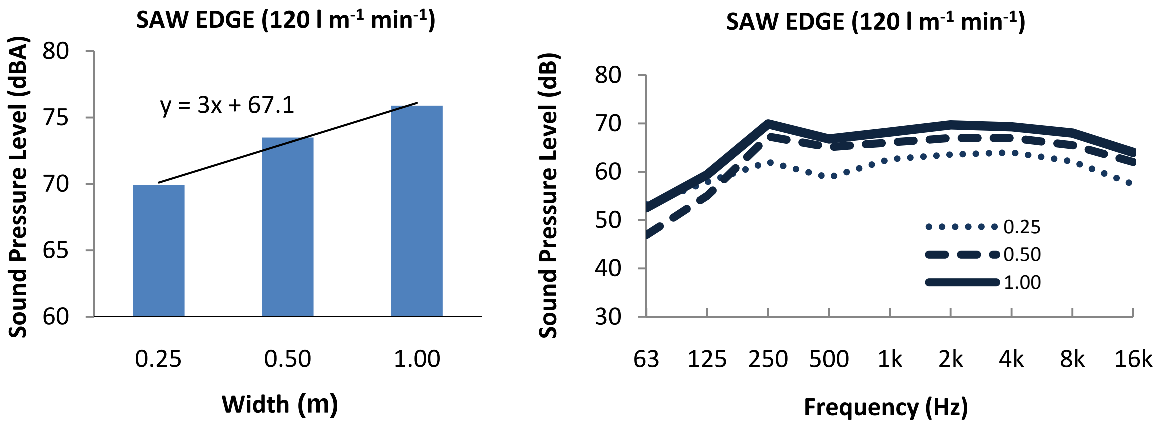
(a) L_{Aeq} vs. flow rate (b) Spectra

Figure 6 Impact of the waterfall's edge design on sound pressure level (1m height waterfall).

The small holes edge design is restricted in terms of flow rates, as only a limited amount of water can pass through its holes (in the order of 30 l/min for the design tested). It can also be noted that the logarithmic trend of L_{Aeq} with flow rate is unaffected by the type of edge design. Spectra (Figure 6(b)) indicate that the small holes edge does not produce low frequencies, as the bubbles generated are too small, whilst the plain edge design tends to be the most effective design for producing low frequencies.

4.3 Waterfall's width

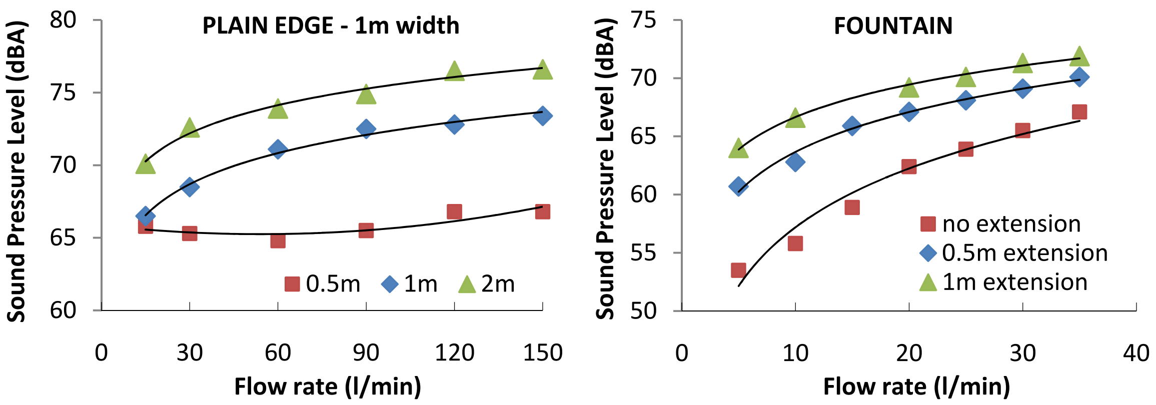
Constant width flow rates, i.e. identical flow rates delivered in terms of litres per minute per meter, produce higher L_{Aeq} levels for larger waterfalls' widths. On average, a doubling in the width corresponds to an increase in L_{Aeq} of 3 dB. This is in line with theory, as doubling the width corresponds to a doubling in the power of the sound source, a rule which can therefore be used for estimating sound pressure levels of large water features. For low flow rates (60 l m^{-1} min^{-1}), the increase in sound pressure level is uniform between 500Hz and 16kHz, whilst for higher flow rates (120 l m^{-1} min^{-1} and 240 l m^{-1} min^{-1}) the increase is uniform above 250Hz (Figure 7(b)).



(a) L_{Aeq} vs. width (b) Spectra vs. width

Figure 7 The impact of the waterfall's width on the sound pressure level.

4.4 Height of falling water



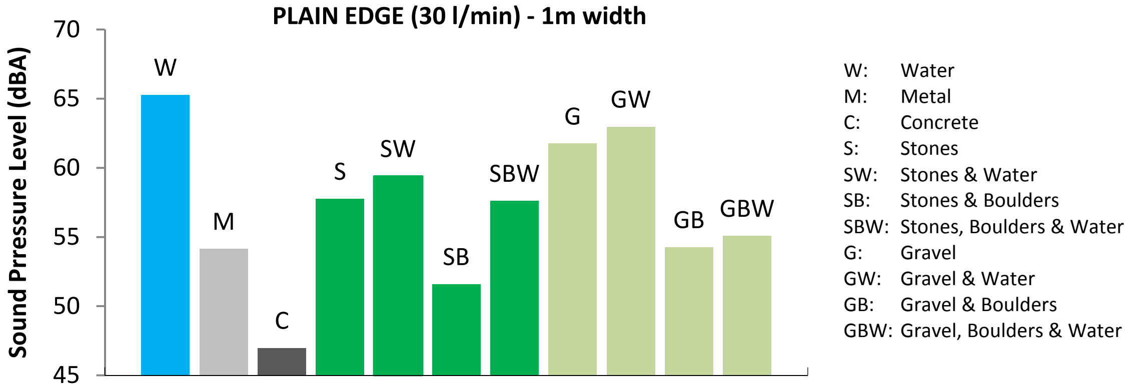
(a) Waterfall (b) Fountain (32 jets)

Figure 7 The impact of the height of falling water on L_{Aeq}.

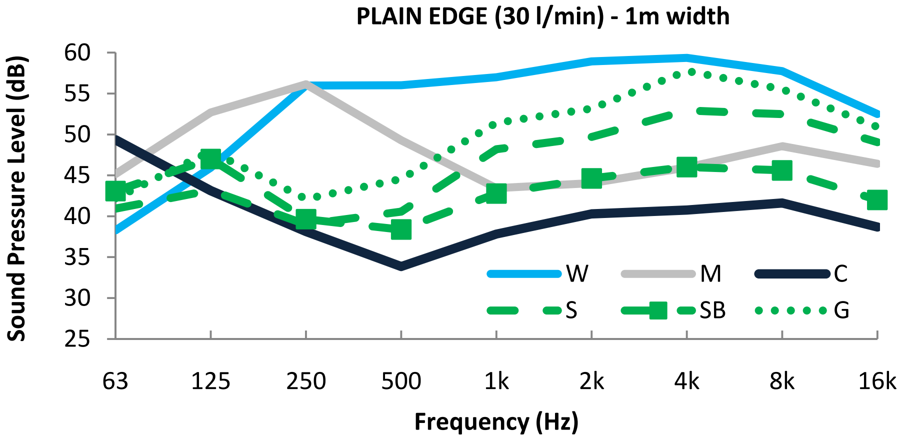
Results indicate that, unlike the 1m and 2m height results, a low waterfall height of 0.5m does not comply with the logarithmic trend of L_{Aeq} with flow rate. In particular, it is interesting to note that the L_{Aeq} levels of the 15 l/min flow rate are very close for the 0.5m and 1m impact heights (less than 1.5 dB difference for the three edge design tested), but not for higher flow rates. This suggests that waterfalls of low height, operating at low flow rates, produce similar sounds. The height from which water falls affects the shape of the frequency response, but changes are not uniform across all frequencies. Overall, increases are more uniform above 500Hz, and it can be noted that waterfalls and fountains exhibit fairly different trends.

4.5 Impact materials

Results obtained indicate that impact materials can greatly affect the acoustic properties of water features. This is particularly true for low height waterfalls, such as the 0.5m height waterfall for which results are given in Figure 8. In this figure, it can be seen that water is the impact material producing the highest L_{Aeq}, whilst plain solid surfaces such as metal, and especially concrete, produce significantly lower levels (more than 10 dB lower). This is due to the formation of vibrating bubbles in the water, whilst rigid surfaces, such as the metal plate and concrete blocks tested, do not allow the formation of bubbles and only exhibit limited impact sound. Small stones (30-60mm) and gravel (10-20mm) are other common impact materials. These present irregular surfaces which allow the formation of pockets of water and hence vibrating bubbles. The L_{Aeq} observed for stones and gravel is therefore higher than the one observed for plain surfaces (in the order of 5-10 dB higher on average).



(a) L_{Aeq}



(b) Spectra

Figure 8 The effects of impact materials on sound pressure level for a waterfall of 0.5m height.

For a medium flow rate of 30 l/min, gravel produce a higher L_{Aeq} compared to stones, but it can be noted that the opposite happens at high flow rates (60 l/min and 90 l/min). The former is probably due to the easy formation of small bubbles between gravels at low flow rates, whilst the latter might be due to the larger amount of separate water pockets between stones at high flow rates. Boulders (150-250mm) can also be used over small stones or gravel. These reduce the area available for pockets of water, and hence result in a lower L_{Aeq}. Combinations of solid materials and water have also been tested, and results are consistent with the previous findings (i.e. higher L_{Aeq} when water is present). Stones, gravel and boulders, exhibit less low frequencies compared to water, with peaks in sound pressure level between 2kHz and 8kHz and with noticeable dips often present around 250Hz and 500Hz. In contrast, the metal and concrete configurations have spectra that are medium to low frequency dominant at 30 l/min (higher levels below 500Hz). Figure 8(b) also clearly shows that the use of water as an impact material is good for creating medium to low frequency sounds.

4.6 Road traffic noise masking

The analysis given in this section is limited to road traffic noise predicted at 100m from a motorway with a porous ground between the road and receiver, and with a traffic flow of 3000 vehicles per hour (84% category 1 with a speed of 120 km/h; 6% category 2 with a speed of 95 km/h; 10% category 3 with a speed of 95 km/h). The prediction was made using source models of the IMAGINE project[9] and propagation models of ISO 9613[10]. This is compared in Figure 9 with a variety of water sound spectra, where results show a large variability in frequency responses. In terms of subjective perception (A-weighted sound pressure level), traffic noise is dominated by frequencies in the 250Hz-2kHz range, whilst most water sounds are characterised by the 500Hz-8kHz range. There is therefore a mismatch between the spectra of traffic noise and water sounds. This confirms the findings from Watts et al.[6] regarding the difficulty of generating low frequencies by using water sounds. However, results presented here show that waterfalls with large flow rates do generate high sound pressure levels at medium and low frequencies (below 1kHz), and these are similar to traffic noise levels. This is however not true for the small holes edge design, as its streams are too narrow to generate large bubbles. The foam fountain jet, which mixes air with water, generates higher sound pressure levels than a normal fountain below 500Hz. The cascade over stones is dominated by high frequencies, whilst the large jet has a fairly flat frequency response, and although it appears to provide the best masking shape, its levels are too low; it was also found that adding more jets or increasing the flow rate does not increase its low frequencies.

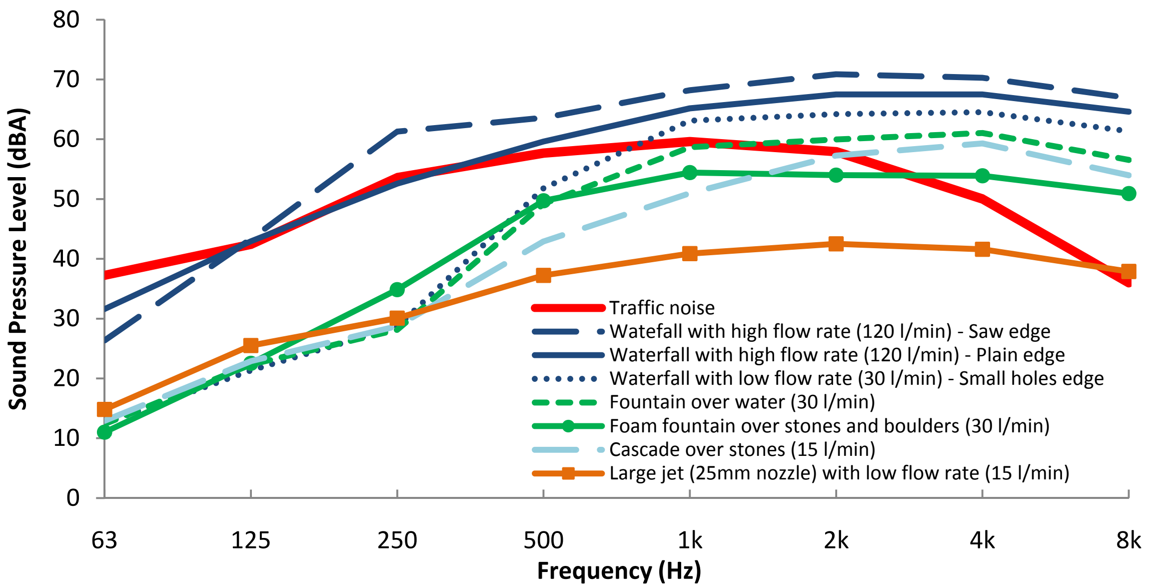


Figure 9 A-weighted spectra of road traffic noise and water generated sounds.

5 CONCLUSIONS

Results presented show that a variety of design factors can affect the acoustic of water generated sounds. Key findings include the logarithmic increase of L_{Aeq} with flow rate, with increases in sound pressure level that are fairly uniform above 500Hz, but are variable below that frequency for most water features. Due to the generation of vibrating bubbles, results also indicated that higher sound pressure levels can be obtained when distributing the same amount of water over several streams (saw edge and small holes) rather than over one uniform stream (plain edge), and that for identical flow rates per meter, a doubling in a waterfall's width corresponds to an increase in L_{Aeq} of approximately 3 dB. Other factors to take into account are the height of the falling water and the impact material. Overall, results suggest that the height increases the sound pressure level only for levels greater than 1m, and that water tends to be the impact material producing more mid and low frequencies, due to the sound generated from vibrating bubbles. The impact material's findings vary with the height of falling water and the flow rate, results showing that changes in sound pressure level and spectra become less and less significant with increasing height and flow rate. All these findings can be used for estimating the spectra and sound pressure levels of small to medium sized water features. Comparisons with road traffic noise predictions also showed that there is a mismatch between the frequency responses of traffic noise and water sounds, as traffic noise is dominated by frequencies between 250Hz and 2kHz, whilst most water sounds are characterised by the 500Hz-8kHz octave bands. However, results showed that waterfalls with large flow rates do generate high sound pressure levels at low frequencies, and that these are similar to traffic noise levels. In conclusion, it is important to point out that these findings apply to small to medium sized water features comparable to the ones tested. Furthermore, it should be noted that the results given were limited to the acoustic analysis of different designs, but ongoing work is currently looking at a number of listening tests and sound preference tests, and psychoacoustic parameters are also being analysed. This will provide the perceptual information needed to complement acoustic findings, together with a fundamental insight into any physical and perceptual correlation.

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