ACOUSTICAL DESIGN OF WATER FEATURES AND THEIR USE FOR ROAD TRAFFIC NOISE MASKING

Tahrir Taki Ali Al-Musawi

Submitted for the degree of Doctor of Philosophy

Heriot-Watt University

School of the Built Environment

October 2012

ABSTRACT

This thesis examines the physical and perceptual properties of water sounds generated by small to medium sized water features, and their use for road traffic noise masking. A wide range of design factors have been tested in the laboratory for waterfalls, cascades, fountains and jets which can typically be found in open spaces such as gardens and parks. A number of field tests were also carried out to illustrate the variability of water sounds. The results obtained indicated that estimations can be made on how design factors affect sound pressure levels, frequency content and psychoacoustic properties. Key design factor findings include the higher sounds pressure levels obtained when distributing the same amount of water over several streams rather than over one uniform stream (+2-3 dB), the increase in the overall sound pressure level at high flow rates with increasing waterfall's width (+2-3 dB), and the significant increases in sound pressure level with increasing height of falling water (+5-10 dB). Impact materials greatly affected acoustical and psychoacoustical properties, results showing however that changes in sound pressure level and spectra become less and less significant with increasing height and flow rate. Overall, water produced more mid and low frequencies (+5-10 dB compared to hard materials in the range 250 Hz – 2 kHz), whilst hard materials tended to increase the high frequency content of approximately 5 dB. Comparisons with road traffic noise showed that there is a mismatch between the frequency responses of traffic noise and water sounds, with the exception of waterfalls with large flow rates which can generate low frequency levels comparable to traffic noise. Auditory tests were carried out to assess water sound preferences in the presence of road traffic noise. These were undertaken in the context of peacefulness and relaxations within gardens or balconies where motorway noise was audible. Results showed that water sounds should be similar or not less than 3 dB below the road traffic noise level, and that stream sounds tend to be preferred to fountain sounds, which are in turn preferred to waterfall sounds. Analysis made on groups of sounds also indicated that low sharpness and large temporal variations were preferred on average, although no acoustical or psychoacoustical parameter correlated well with the individual sound preferences.

ACKNOWLEDGEMENTS

I would like to gratefully and sincerely thank my supervisor Dr Laurent Galbrun for his guidance, encouragement, patience and especially for his insight and attention to details and for being very generous with his time during my study, I have had the fortunate opportunity to have a great supervisor, for his support, knowledge and influence has helped me get this far.

A special thank you to Professor Phil Banfill for his advice and guidance.

Many thanks to the Iraqi Cultural Attaché in London for their guidance and support throughout my study, and a special thank you to the Iraqi Ministry of Higher Education and Scientific Research for funding my study.

I would also like to thank the technicians in the School of the Built Environment: Alastair MacFarlane for his assistance and David Walker for building the structure tested.

Many thanks to all my friends, colleagues and to the staff members in the School of the Built Environment for their assistance. Your help and efforts have been very much appreciated.

My deepest gratitude is expressed to my loving family, especially my mother and father for their love, patience, support and encouragement. To them I dedicate this work.

ACADEMIC REGISTRY

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Updated February 2008, November 2008, February 2009, January 2011

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GLOSSARY OF SYMBOLS

A	Absorption surface (m^2)
	Total attenuation between source and receiver (dB)
A_{div}	Attenuation due to geometrical divergence (dB)
A_{atm}	Atmospheric attenuation (dB)
A_{gr}	Ground attenuation (dB)
A_{bar}	Barrier attenuation (dB)
A_{misc}	Attenuation due to miscellaneous effects (dB)
D_C	Source's directivity (dB)
D_{CH}	Source's horizontal directivity (dB)
D_{CV}	Source's vertical directivity (dB)
D_{Ω}	Increase in directivity due to ground reflections (dB)
L	Loudness level (phon)
ΔL	Loudness level difference (phon)
L_{den}	Day-evening-night equivalent noise level (dBA)
L_{night}	Night equivalent noise level (dBA)
L_p	Sound Pressure Level (dB re 2×10^{-5} Pa)
L_w	Sound Power Level (dB re 10^{-12} W)
L_{WP}	Sound Power Level due to propulsion noise of a vehicle (dB re 10^{-12} W)
L_{WR}	Sound Power Level due to rolling noise of a vehicle (dB re 10^{-12} W)
L_{eq}	Equivalent continuous noise level (dB)
$L_{eq,T}$	Equivalent continuous noise level averaged over a period T (dB)
L_{Aeq}	A-weighted equivalent continuous noise level (dB)
L_{Ceq}	C-weighted equivalent continuous noise level (dB)
L_{10}	noise level exceeded 10% of the time (dB)
L_{50}	noise level exceeded 50% of the time (dB)
L_{90}	noise level exceeded 90% of the time (dB)
L_{masq}	Background noise level not requiring masking (dBA)
N	Loudness (sone)
N'	Specific loudness (sone)

Q	Directivity factor
R	Roughness (asper)
R^2	Coefficient of determination
S	Sharpness (acum)
	Surface area (m^2)
T	Reverberation time (s)
	Averaging time period (s, min or hour)
V	Volume (m^3)
W	Power (W)
a_R , b_R	Rolling noise coefficients (IMAGINE, 2007)
a_P , b_P	Propulsion noise coefficients (IMAGINE, 2007)
d_r	Source receiver distance (m)
d_p	Source receiver distance projected on ground plane (m)
f	Frequency (Hz)
f_{mod}	Modulation frequency (Hz)
h_S	Source height (m)
h_R	Receiver height (m)
h_m	Mean height of propagation (m)
p	Pressure (N/m^2)
	Significance level
r	Distance (m)
	Radius of a water bubble (m)
r^*	Critical distance (m)
t	Time (s)
v	Vehicle's speed (km/h)
v_{ref}	Reference vehicle's speed (70 km/h)
α	Absorption coefficient
$\bar{\alpha}$	Average absorption coefficient
φ	Horizontal directivity angle (Radians)
ψ	Vertical directivity angle (Radians)
π	3.14159 …
ρ	Correlation coefficient (Spearman test)

log	$\log_{10}$ logarithm to base 10
PVC	Polyvinylchloride
SPL	Sound Pressure Level (dB)

LIST OF CONFERENCES AND PUBLICATIONS

List of conference presentations and publications (to date) of the author.

Ali TT, Acoustic design of water features, *SBE Postgraduate Student Conference*, School of the Built Environment, Heriot-Watt University, Edinburgh, 16-18 June 2010.

Ali TT, Acoustic design of water features, *SBE Postgraduate Student Conference*, School of the Built Environment, Heriot-Watt University, Edinburgh, 20-22 June 2011.

Galbrun L and Ali TT, Acoustic design of water features for the built environment, *Proceedings of the Institute of Acoustics*, 33(4), 112-119, Acoustics 2011, Glasgow, 14-15 September 2011.

Galbrun L and Ali TT, Perceptual assessment of water sounds for road traffic noise masking, *Proceedings of the Acoustics 2012 Nantes Conference*, 2147-2152, Acoustics 2012, Nantes, France, 23-27 April 2012.

Galbrun L and Ali TT, Acoustical and perceptual assessment of water sounds for road and their use over road traffic noise, submitted to the *Journal of the Acoustical Society of America* in May 2012.

CHAPTER 1

Introduction

1.1 General introduction

This thesis examines the acoustic design of water features and their use for masking road traffic noise. The work is largely based on laboratory measurements and focuses on small to medium sized water features which can be used in gardens and parks. Although the analysis is directed towards road traffic noise and outdoor environments, it is important to note that the water sounds examined can be used in both outdoor and indoor spaces (*e.g.* hotel lobbies, offices and restaurants). In particular, the design findings obtained for the water sounds tested are applicable to both outdoor and indoor conditions.

The amount of noise sources present within urban environments and the high noise levels associated with them are often responsible for lowering quality of life. Past research has focused on lowering and controlling noise levels, but the current trend is rather on improving products` sound quality and on promoting the use of positive sounds such as water features (Kang, 2007). This approach finds its place in the concept of the soundscape, for which a sound is simultaneously a physical environment and a way of perceiving that environment. The soundscape effectively represents an “auditory landscape” including all sounds surrounding us, both positive and negative, where positive sounds include sources as diverse as water, bird songs, temple bells and wind in trees (Schafer, 1994). Within that context, water features can raise the quality of the environment through their inherent positive qualities, as well as play an important role as a masking element over unwanted sound.

The evaluation of soundscapes is complex and is typically based on both physical and perceptual analysis. The research presented in this thesis therefore fits with the soundscape approach, as it examines the acoustic design of water features by taking into account both their physical and perceptual properties.

1.2 Justification of the research

Ten years ago, the environmental noise directive 2002/49/EC (EC, 2002) was published by the European Communities. This document set out a strategy for dealing with environmental noise at European level and affected the interests and priorities of researchers working in acoustics of the built environment. The directive resulted in the creation of noise maps for large agglomerations as well as major roads, railways and airports. Descriptors which could be used across Europe were defined, and it was pointed out that local noise action plans could be developed after the mapping had been completed. This directive was focused on noise levels and annoyance, and it was soon pointed out that this strategy would not be sufficient for dealing with urban noise (Raimbault and Dubois, 2005). Since then, a large number of studies have been using the wider soundscape approach, in an attempt to gain a better understanding of how to assess aural environments and how to improve them. In particular, the use of positive sounds has been highlighted as a beneficial solution which is ignored by traditional noise control engineering approaches.

The research presented in this thesis falls within that context, as water sounds have been identified as pleasant features which can improve the soundscape (Kang, 2007). However, the acoustic design of water features has been rarely analysed thoroughly. A review of the literature shows that studies looking in detail at the acoustic and perceptual properties of water sounds are limited and recent (Watts *et al.*, 2009; Jeon *et al.*, 2010 and 2012; Nilsson *et al.*, 2010; De Coensel *et al.*, 2011). Furthermore, previous research only analysed in detail the water sounds generated by large features (Jeon *et al.*, 2012) and small streams (Watts *et al.*, 2009), whilst an in depth analysis of the many types of small to medium sized water features which can be found in gardens and parks is not available. This thesis fills this gap by examining the impact of design factors on the acoustical and psychoacoustical parameters of small to medium sized water features, as well as analysing the perceptual assessment of water sounds in relation to road traffic noise masking.

1.3 Aims and objectives

The main aim of the research is to develop the knowledge and understanding of the acoustical and perceptual properties of small to medium sized water features, particularly in relation to road traffic noise masking. The originality of the work lies in the very large variety of features which could be tested in the laboratory and analysed thoroughly in terms of acoustical and psychoacoustical properties as well as perception.

More specifically, the objectives of the research can be listed as:

- Examine how design factors (flow rate, waterfalls' edge design and width, height of falling water and impact materials) affect the acoustical and psychoacoustical properties of a wide range of small to medium sized water features (waterfalls, cascades, fountains and jets)
- Analyse the variability of water sound properties by testing features which cannot be built in the laboratory (*e.g.* long streams and large fountains)
- Identify the preferred sound pressure level of a wide range of water sounds over road traffic noise, within the context of peacefulness and relaxation
- Identify the preferred water sounds over road traffic noise, within the context of peacefulness and relaxation
- Identify correlations between the preferences obtained and the physical properties measured for the water sounds and traffic noise

Ultimately, the findings obtained will be used to inform soundscape design of water features in view of improving the urban sound environment.

1.4 Methodology

Three different methodological approaches have been used to address the research objectives:

1. Laboratory tests (around 75% of test time)
2. Field tests (around 5% of test time)
3. Auditory tests (around 20% of test time)

1.4.1 Laboratory tests

A large amount of time was devoted to laboratory tests in order to obtain a detailed description of how design factors affect water sounds. A variety of water features were constructed in the laboratory such as waterfalls, cascades, fountains and jets. To give a sense of dimensions and justify the ‘small to medium sized’ categorisation, it can be noted that the features examined ranged from a small and shallow upward jet (couple of centimetres high), up to a 1 m wide waterfall with a height of falling water of 2 m. The laboratory rig structure used, allowed testing different features and measuring physical parameters (spectrum, sound pressure levels) and psychoacoustical parameters (loudness, sharpness, roughness and pitch strength) under controlled conditions. Additionally, binaural audio recordings were made in view of the auditory tests.

Waterfalls were tested with different widths, edges, heights of falling water, flow rates and impact materials. Different fountain designs and combination of upward jets were also tested with different flow rates and impact materials. The results obtained allowed identifying how design factors impact on acoustical and psychoacoustical parameters.

1.4.2 Field tests

A limited number of field measurements were carried out on features which could not be built and tested in the laboratory, in order to obtain an indication of the variability of water sounds’ properties. Field measurements included large fountains, large waterfalls and a variety of streams with varying characteristics (*e.g.* large and deep stream, or narrow and shallow stream). The methods used and properties examined were identical to those used for the laboratory tests.

1.4.3 Auditory tests

In order to identify preferences and subjects’ perception, paired comparisons of water sounds were performed using auditory tests. These were carried out to identify the preferred sound pressure level of water sounds over road traffic noise, as well as the preferred water sounds over road traffic noise. A variety of water sounds were selected for these tests, based on their large range in frequency content (waterfalls, fountains, jets, a cascade and a natural stream). Subjects were recruited and asked to assess preferences within the context of peacefulness and relaxation. Sample sizes used for the analysis were of around thirty subjects, with a typical age of 25-30 years old, an equal split between males and females, and a wide variation in cultural groups.

The preference scores obtained were correlated with physical properties using regression and correlation analysis. Statistical analysis of differences between gender, age and cultural groups were also carried out to identify consistency and variations within the samples tested.

1.5 Outline of the thesis

Chapter 2 describes the background information required for the research and critically reviews the literature presented. An overview of water features is given in terms of categorisation, historical development and design. This is followed by a review of previous research work relevant to the study.

Chapter 3 explains the test structures and procedures used for the study. A description of the laboratory rig structure and features tested is initially given, followed by an explanation of the acoustical and psychoacoustical parameters used and their measurement procedures, as well as a brief overview of the perceptual methods applied.

Chapter 4 illustrates the findings obtained regarding the impact of design factors of small to medium sized water features on acoustical and psychoacoustical parameters. The chapter outlines the impact of flow rate, waterfalls’ edge design and width, height of falling water, and impact materials. Only key results are given in this chapter (full set of results available in Appendices A to H).

Chapter 5 presents the results obtained for field tests, in view of illustrating the variability of water sounds through comparisons between laboratory and field results. The field tests presented include large fountains, large waterfalls and a variety of streams with varying characteristics (*e.g.* large and deep stream, or narrow and shallow stream). Additionally, a number of seashore sounds are also examined.

Chapter 6 examines the use of water sounds for road traffic noise masking. The analysis includes comparisons of water sound spectra with road traffic noise spectra, as well as perceptual assessments obtained from auditory tests.

Chapter 7 contains a summary of the conclusions and suggestions for future work.

Appendices A to H include the full set of laboratory results in relation to the impact of design factors on acoustical and psychoacoustical parameters, and Appendix I includes road traffic noise predictions.

CHAPTER 2

Literature review

2.1 Introduction

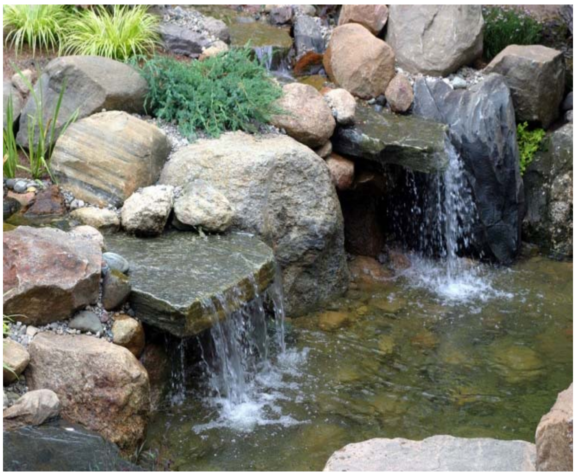
This chapter describes the background information required for the research and critically reviews the literature presented. The chapter first provides an overview of water features, including a description of the different forms they can take, as well as their use and development through history. Water features design, installation and construction principles are then described, with drawings showing typical systems used. A review of previous work relevant to the study is then presented, including general soundscape studies in which water features were analysed mainly in relation to their contribution to the aural environment in urban areas, as well as more recent research which looked in more detail at the acoustical and perceptual properties of water sounds. Following from this review, a critical discussion of previous research is given at the end of the chapter.

2.2 Water features

2.2.1 General introduction

People enjoy the sight and sound of moving water, as it can play an important role in providing relaxation as well as entertainment, while also adding aesthetic appeal to the landscape (Kaplan, 1987). In order to have a better understanding of the "primary landscape qualities of water" (Kang, 2007), it is worth describing its uniqueness.

Water permeates the natural world (Fig. 2.1) and represents the freedom, power and purity in its natural existence (Symmes, 1998). Its special relationship with humans is complex because of its great need and great fear at the same time. Its fear is related mainly to the danger of too much water which can lead to flooding, or the too little water which can lead to thirst and death of the different living creatures existing on earth. Water is one of the most important elements on earth for human survival, as people need water to stay alive as well as for refreshing. Furthermore, people enjoy



(a) Small streams and pond (Credit: Flickr)

(b) Stream (Credit: Flickr)

(c) Waterfall (Credit: Flickr)

Figure 2.1 Examples of water features found in nature.

seeing, hearing and touching water for sensual pleasure (Symmes, 1998). It has even been suggested that water has an attraction that is beyond and above any other materials and elements, as well as pointed out that its ionizing effect creates a feeling of well being, whilst its sound might even touch some early memories of life within the womb (Hirst, 2009). The landscape architect S. Jellicoe also suggests that "*the underlying attraction of the movement of water and sand is biological. If we look more deeply we can see it as the basis of an abstract idea linking ourselves with the limitless mechanics of the universe*" (Hirst, 2009).

Figure 2.2 Fountain jet used within an urban environment. (Credit: Flickr)

As water is one of the basic elements needed for living, it has been expressed over time in a symbolic way using different displays. Depending on the facilities and technologies available, civilizations have expressed water in different forms such as fountains, powered jets, waterfalls and cascades (Lohrer, 2008). Such water features can be located in squares and open spaces within urban environments (e.g. Fig. 2.2), as well as within indoor spaces such as shopping centres, hotels or other commercial buildings, where they can be used to improve comfort (e.g. mask traffic noise or neighbourhood noise) or promote social gathering for the public (Symmes, 1998).

2.2.2 Defining water features

A water feature can simply be defined as a system of running water (Lohrer, 2008). Such a feature can take many forms, including fountains, water jets, waterfalls and cascades. For example, it can be as simple as a basin, or as complex as a monumental structure where water emerges in a variety of shapes. Despite the wide ranging types of features which can be designed, water displays can be categorised into two main types:

1. Waterfalls (including cascades), and
2. Fountains

It is important to note that this categorisation is based on a design viewpoint rather than an acoustic viewpoint.

Waterfalls and cascades

A natural waterfall can be defined as a river or stream that flows or drops vertically over an edge, cliff or slope. It is a symbol of power and wild nature, which has a dynamic of its own and is normally the sole feature of water display. A waterfall can touch nothing on its way down or it can cascade over the rock face or any other element.

Waterfalls are mainly formed when a river is young (Carreck, 1982). These start as narrow and deep channels, then, as sand and stones are carried by the watercourse, the water gradually increases its speed at the edge of the waterfall, therefore increasing the capacity of the surface of the waterfall (Fuller, 2009). Waterfalls are usually formed in rocky areas. The water falling over the rock shelf draws back, forming a horizontal pit which is parallel to the waterfall wall; as the pit gradually grows deeper, the waterfall collapses and is replaced by a steep slope stretch of river bed (Carreck, 1982).

Waterfalls can also occur from a river flowing over rocky steps forming what is called a cascade. Another type of waterfalls is a block waterfall, where water is not broken by rocks or steps, and where the width of the flow is wider than the length. When a large amount of water is forced to flow through a narrow vertical flow, it forms what is called a ‘chute’ (World Waterfalls, 2010).

One dramatic example of large natural waterfalls is the Niagara Falls shown in Fig. 2.3. Smaller size waterfalls are however much more common and abound in nature, an example of which is given in Fig. 2.4. In addition to natural waterfalls, it is worth noting that artificial waterfalls, such as the one shown in Fig. 2.5, also exist and are often installed in garden and parks because of their ‘natural looking’ quality which cannot be achieved by other types of water features.

Fountains

The word fountain originally refers to a natural spring or source and is derived from the Latin term *fons* or *fontis*. From an architectural perspective, a fountain can be defined as

Figure 2.3 The Niagara Falls in North America. (Credit: Flickr)

Figure 2.4 Small waterfall in the Pentland Hills, Edinburgh.

Figure 2.5 Artificial waterfalls. (Credit: Flickr)

Figure 2.6 Fountains in Baghdad (left: Kahramana). (Credits: Webshots and Flickr)

an artificial structure that can pour water into a basin and/or push water into the air (Prevot, 2006). Fountains are most commonly located in open urban spaces such as parks, gardens and city squares, but can also be found inside courtyards or enclosed spaces within buildings. Two examples are given in Fig. 2.6 for outdoor fountains found in the city of Baghdad in Iraq.

Types of fountains

Based on the type of water flow, fountains can be categorised into three main types (Hirst, 2009):

1) Upward flow fountains

These fountain designs are mostly used as public fountains located in gardens and open spaces, and are typically described as a display features for the public, due to their visual and aesthetic qualities (Fig. 2.7). The display and water shape of such fountains can quickly be changed by adjusting the flow rate, as well as adapted with music to make it a ‘dancing fountain’. Furthermore, lighting can be added to the jets to alter their appearance and to add an extra sparkle to the scene. In this advanced technique the water itself becomes the display, instead of being part of the display, an example of which is the Bellagio fountain in Las Vegas, a large dancing water fountain synchronized to music (Fig. 2.8).

Figure 2.7 Upward jets fountain in Hyde Park, London. (Credit: Flickr)

Figure 2.8 Fountain of Bellagio hotel in Las Vegas. (Credit: Flickr)

2) Downward flow fountain

In this type of fountains the water comes down, giving a natural display of falling water. It can be combined with monuments or simple channels or basins design, where water flows downward from a high position to a lower one. It can be a combination of artificial or natural elements. An example of this is the Princess Margaret fountain in Toronto (Canada), which consists of three progressive circular basins where the water flows from the two top basins downward.

Figure 2.9 The Princess Margaret fountain in Toronto. (Credit: Flickr)

3) A combination of upward and downward flows

This type of fountain is a mixed design of water going up and water coming down by using different jets and basins, providing a combination of upward moving and downward falling water. These fountains are typically large outdoor structures which create water splashes in different directions. An example of this is given by the Trafalgar Square fountain in London (Fig. 2.10), where combinations of upward and downward jets are used, together with basins from which water falls. Another example of this is the Ross fountain located in the Princes Street Gardens in Edinburgh (Fig. 2.11), which has at its top a female figure holding a torch with a jet of rising water, combined with water flowing downward from a number of small basins as well as one large basin.

Figure 2.10 The Trafalgar Square fountain, London. (Credit: Flickr)

Figure 2.11 The Ross fountain, Edinburgh. (Credit: Wikipedia)

2.3 A historical review of water features

Water has been affecting the economical and political aspects of history through different civilizations, therefore shaping our world. All civilizations have developed near sources of water to fulfil their daily needs, as well as to use water for transportation, trade and exploration. In the past, water features like fountains were designed for drinking and washing purposes, but they were also used as landmarks where public could meet and gather, especially in hot climates where such features were also used to refresh the air (Symmes, 1998). These were connected to the main water supply system of the whole city and were operated by gravity. Although fountains were first of all functional, they were decorated with different designs through the use of natural materials that could be shaped and transformed into art and ornaments (Symmes, 1998).

The first use of water features in history appeared in the ancient civilizations of the Middle East in Mesopotamia and in Egypt (Hirst, 2009). Ancient Egyptians (3100 BC to 600 BC) used rectangular fish pond fountains in the enclosed courtyards of their homes surrounded by trees; these were used for both functional and aesthetic needs. Different civilizations developed slight stylistic differences, depending on their way of living and cultural needs (Turner, 2008). The Mesopotamians (5300 BC to 600 BC) used fountains for drinking, as well as for watering gardens and fields. The most ancient basin fountain dates from 3000 BC and was discovered at the Mesopotamian city of Tello. A stone fountain dating from 2000 BC was also found at the Mesopotamian site of Mari (Hirst, 2009). The fountains of early civilizations depended on running water from rain and other natural sources to keep them functioning. In ancient Rome (8th century BC to 5th century AD), water was described as a gift from the gods and aqueducts were used to provide regular water supply from the mountains to the cities of the Roman Empire. The water supplied was used for drinking, bathing and for fountains. The aqueducts were built from stones and bricks, with channels of flowing water. The water was either run under the ground in tunnels or above the ground in stone channels, and some of the aqueducts were built on arched bridges (Fig. 2.12) over valleys and large gaps of land (Hodge, 2002).

Figure 2.12 Roman aqueducts. (Credit: Flickr)

The channels of the aqueducts were normally 6 inch slope per 100 feet, to provide the gradient needed for water benefiting from the use of gravity. The public fountains were uncovered free standing fountains and basins located in different places along the streets of the city, which were fed by continuous flows of water supplied from hills. These were normally decorated with bronze and different stone masks of heroes and animals. Romans also had small fountains in atriums or in courtyards (Grimal, 1994). Fountains in private gardens were usually placed against a wall and were fed by rainwater from the roof of the building. The pump that was used for small fountains was a small cylinder pump, which can be defined as a force pump containing two vertical cylinders. It was invented by Ctesibius of Alexandria (3rd century BC). Romans developed ingenious designs such as fountain jets pushing water into air by using the pressure of water from aqueducts flowing from higher sources and long distances to create a hydraulic force (Grimal, 1994).

In ancient times, methods of water managing and ingenious solutions were also developed for extracting hidden water to surface (Symmes, 1998). One of the solutions was the Qanat developed by Persians in the 1st century BC, which is a canal buried below ground level to transport water to different locations and reservoirs. Another tool used in Mesopotamia was the Saqiya, also known as the Persian water wheel (Fig. 2.13). This is an animal-powered mechanism made of one horizontal wheel and one vertical wheel with interlocking wooden gears, and with clay pots attached to the vertical wheel.

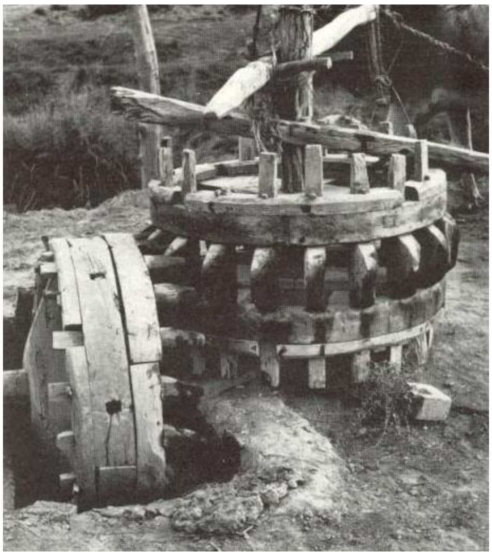


Figure 2.13 Persian water wheel (Saqiya) used to extract water. (Credit: Bayyinat)

When the animal moves in a circle, rotating the horizontal wheel, it also rotates the vertical wheel, which dips the pots into the water one after another, and as each pot reaches the top of the wheel, it pours the water into a wooden reservoir (Covington, 2006). In the 13th century, Al-Jazari, an engineer from Mesopotamia, designed hydraulic pumps and water wheels based on advanced principles (Covington, 2006). This device, together with the devices developed by the European inventors Philo and Heron, provided the techniques for hydraulic automata of Renaissance water features (Hopwood, 2004).

Water played an important symbolic role in many religions, from the rivers in the gardens of Eden to the fountains mentioned in the holy Koran. When Arabs ruled over Persia they found water designs which Persians had developed with their long established settlements, and many of those designs can be found on the garden patterns of Persian carpets and rugs. By the 8th century AD, this lead to form a mixture of Islamic and Persian garden styles, which then spread to Spain with the Arabs in the 13th century. An example of such styles can be found in the Alhambra palace in Granada, Spain, where fountains are placed within the palace courtyards. The ‘lion fountain’ of the Alhambra palace is shown in Fig. 2.14, where four stone lined channels holding the running water can be seen, with a central fountain basin supported by twelve lions (Hopwood, 2004).

Figure 2.14 Alhambra lion fountain in Granada. (Credit: Atharmian)

Residential architecture in the Islamic civilization introduced water features within courtyard houses with the objective of obtaining cooler temperatures. These features helped in reducing the temperature and reflecting the sunrays, as well as in providing cool air ventilation inside the house (Azab, 2009). In general, Islamic fountains were designed close to the ground, and served the function of cooling the courts through evaporation. From the 9th to the 16th centuries, the Islamic societies had experienced the control of moving water and hydrology. Gutters, pipes and aqueducts were used to capture rainfall and channel it to giant cisterns (Covington, 2006).

In the Renaissance period (14th to 17th century) Italy and particularly Rome had developed unique water features using the water supply from hills, combined with the development of water pumps and the use of basic piping and gravity. The Renaissance was a cultural movement that affected life in all aspects, including history, philosophy, politics, religion and art. Renaissance scholars searched for human emotion and realism in art (Perry *et al.*, 2003), its style promoting classical balance, simplicity, and harmony. This was reflected on fountains, and marked a new phase in their design, as sculptures and monumental features became more prominent (Perry, 2011). During the Italian Baroque period, which followed the Renaissance, fountains became even more complex, with compositions of basins, sculptures and water displays. The styles of Rome were outstanding and spread all over Europe (Symmes, 1998). The best example of a Roman water feature is the Trevi fountain, which is the largest baroque fountain in Rome representing the fusion of architecture and sculpture. It was designed by Nicola Salvi in the 18th century.

Figure 2.15 The Trevi fountain in Rome. (Credit: Destination 360)

Other grand designs were created around Europe during the Baroque period, such as the fountains in the gardens of Versailles (Fig. 2.16), which were built under king Louis XIV of France in view of expressing his power over nature (Prevot, 2006).

In the 18th century, landscape and oriental garden styles arose to present more natural effects with water. In such styles, fountain jets were rarely used; instead designers turned their interest to cascades and waterfalls to give a more natural flow for water (Hirst, 2009). This period presented a more naturalistic stylised form of gardening. Rivers and ponds were placed in a haphazard way surrounded with trees and scattered shrubs to look more natural (Hirst, 2009).

Figure 2.16 The fountains of Versailles. (Credit: Flickr)

Figure 2.17 Cascade in Harewood House, England. (Credit: Harewood)

Since the Industrial Revolution in the 19th century, hydraulic technology advanced significantly, therefore allowing the development of large and spectacular water works all over the world, creating visual and aural water effects to provide entertainment for the public. New fountains became a symbol of art and urban decoration (Symmes, 1998). With improved engineering knowledge, skills and electric hardware, massive scale water features were constructed. New constructions and materials made it possible to recycle water and to propel it very high (as high as 140 m). The fountains of the International Expositions made in London, Paris, New York and other cities between 1851 and 1964, introduced fountains made from glass and exotic materials and combined architecture, technology and theatre. These were the first fountains programmed to be operated with music (Symmes, 1998).

In the second half of the 21st century, water entertainment technology advanced even further. Musical water shows now use jets which are fully computer controlled. One of the great examples of such technology is the fountain of the Bellagio hotel in Las Vegas, shown earlier in Fig. 2.8. Such features can display water shows which are programmed and choreographed by engineers with computers aid. Another such example is the Miracle Mile automated musical fountain in Las Vegas. This fountain is based on a pre–programmed system which uses the venue's own live background music to animate the water and lights in real time. The latter respond to loudness, bass, and treble, as well as rhythm, dynamic range, and other subtler components of the music.

Figure 2.18 Miracle Mile automated musical fountain, Las Vegas. (Credit: Wikipedia)

Apart from such specific applications, it is also worth noting that, unlike the more traditional constructions discussed earlier, it is now common to incorporate water features within enclosed spaces such as shopping centres, hotel lobbies, offices or restaurants (Fig. 2.19). In addition to the aesthetic qualities provided, these are normally used as architectural features which can provide entertainment (e.g. in a shopping centre), or promote relaxation (e.g. in a lobby). Furthermore, several manufacturers now sell small devices which can be easily installed in private gardens (Fig. 2.20).

This historical review shows that the purpose of water features has shifted with time from its functional role towards more decorative goals, combining architectural structures with different forms of water displays, in view of providing people with aesthetic pleasure and entertainment. However, recent studies discussed in section 2.6 point out that a more functional use of water features is now being considered in urban design, in particular with the objective of improving its soundscape. The review has also pointed out a number of traditional designs, such as the shallow jets used in Islamic courtyards, which have consequently been tested in this research.

Figure 2.19 Indoor water features. (Credit: Creative Rock)

Figure 2.20 Garden water features. (Credit: Oase)

2.4 Designing with water

In the book of Lohrer (2008), the design of water features is examined from the viewpoint of landscape architecture. According to Lohrer, designing with water is very unique and is generally influenced by the following factors:

- The way of handling it in the chosen location
- Its role as an architectural element
- Its function
- Its expression as a symbolic power

When designing with water, the designer has to deal with its individual dynamism, such as the visual relationship between the water and the viewer. The designer should also define the features of design and the direction of water movement. Depending on the site and specific water typology it is possible to use either flowing water, jets, still water or falling water. The designer normally also decides the amounts of water and the speed of flow. Another factor that should be considered is the level of reference, *i.e.* the location of the water element in relationship to the eye level (Fig. 2.21). Lowering the water level will offer a good view, while a higher angle offers a more powerful experience especially from a further distance (Lohrer, 2008).

Materials can also be added to the design in order to simulate natural effects, and sculptures can be used to create a personal preference, and/or to develop a moving scene by either having the water emitted from the sculpture, or by having water rebounding on the sculpture.

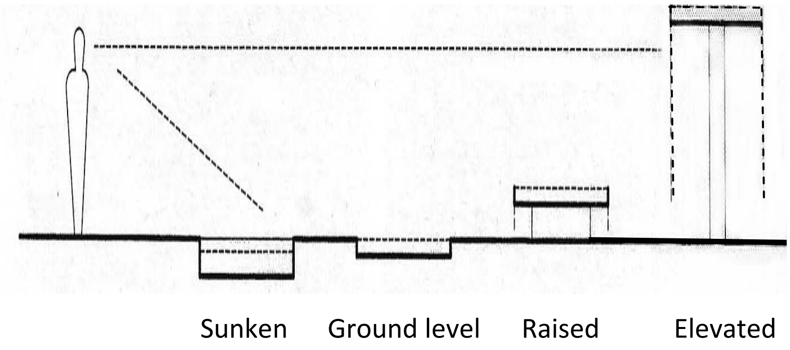


Figure 2.21 Water features with different eye levels (Lohrer, 2008).

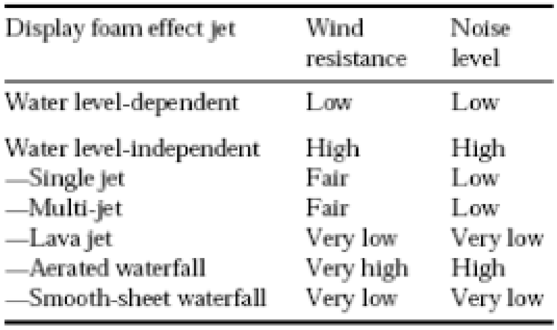
To summarise, the followings are important factors that are normally taken into account when designing water features (Lohrer, 2008):

- Visual relationship between the water and the viewer (e.g. the eye level)
- Design features (e.g. overall shape, architectural elements, treatment of basin, borders or edges)
- Consideration on whether to use flowing water, jets, still water or falling water
- Type of layout (e.g. fountain, waterfall, jets, cascade)
- Direction of water movement
- Flow rate / Amount of water
- Height of water feature
- Impact surface

Most of these design factors have been examined in the research presented, and are outlined in Chapter 3. It is also worth noting that the sound generated by water is not explicitly listed by Lohrer as a significant factor taken into account by designers. Although this does not mean that sound is not considered, it suggests that for most cases sound design is based on general experimental knowledge (*e.g.* higher flow rate: louder sound; hard material: high frequency sound).

The CIBSE Guide G (2004) examines the design of water features from an engineering viewpoint by describing installation types and typical components (see section 2.5). In this guide, reference to noise is only made in terms of noise level (Table 2.1), showing again the limited consideration given to the acoustic design of water features.

Table 2.1 Fountain displays and their characteristics
in terms of wind resistance and noise level (CIBSE, 2004).



Display foam effect jet	Wind resistance	Noise level
Water level-dependent	Low	Low
Water level-independent	High	High
—Single jet	Fair	Low
—Multi-jet	Fair	Low
—Lava jet	Very low	Very low
—Aerated waterfall	Very high	High
—Smooth-sheet waterfall	Very low	Very low

2.5 Water features installation

This section describes installation principles used for small to medium sized fountains and waterfalls comparable to the ones tested in the research presented. It also describes the types of pumps used in different water feature designs, and illustrates fountain attachments.

2.5.1 Fountain installation

Fountains can be built from a range of materials such as concrete, bricks, metal and stone. The construction principles depend on the design objectives and the type of water movement. Furthermore the location of the fountain and the pump size required can have a high impact on the design. In practice, a fountain is composed of the three main elements shown in Fig. 2.22 (CIBSE, 2004):

- A basin or reservoir filled with water
- A submersible or dry pump to re-circulate the water
- A fountain attachment

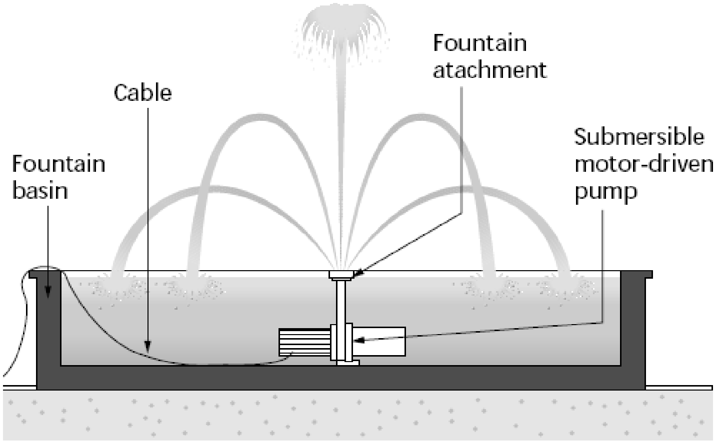


Figure 2.22 Typical fountain installation (CIBSE, 2004).

The system typically has a waterproof basin encased in the ground which provides a reservoir for the water. The submersible pump is the main recirculation system and is fixed below the water head of the basin, helping to recycle and filter the water. Dry pumps can also be used but need to remain outside the water in a chamber, with pipework connecting them to the reservoir. The fountain needs to access an electricity outlet for the electric pump. An outlet pipe is fixed to run up the water to the top, and an adjustment screw or valve is normally provided on pumps to give the ability to adjust the fountains' water flow rate. A sculpture built from any material can also be added to a fountain and water can flow over the sculpture or be emitted from it depending on individual designs.

2.5.2 Waterfall and cascade installation

When designing a waterfall, the installation uses free falling water which requires large volumes of water to be pumped to a high position. This is achieved by using a pipe system fixed to a circulation pump in a basin, from where the pump fills an upper basin, from where water falls downward in a constant and vertical way leading to a reservoir (Fig. 2.23). Constructions of the surfaces and edges can be developed to give a natural waterfall. Steps and stones can be added to form a water cascade and to create a more natural scene. A water outlet attached to a drainage pipe is normally provided to facilitate the cleaning and emptying of the water basin.

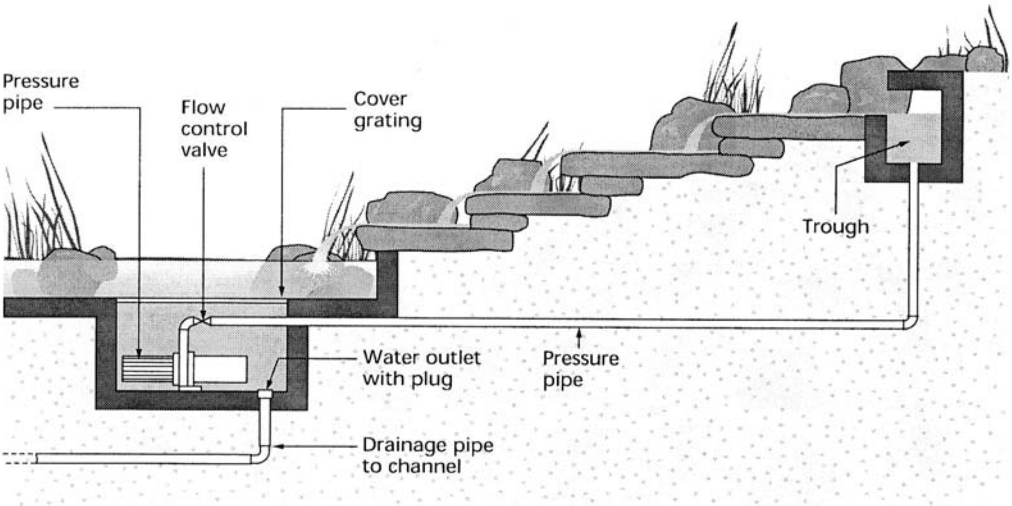


Figure 2.23 A typical cascade installation (CIBSE, 2004).

2.5.3 Pumps

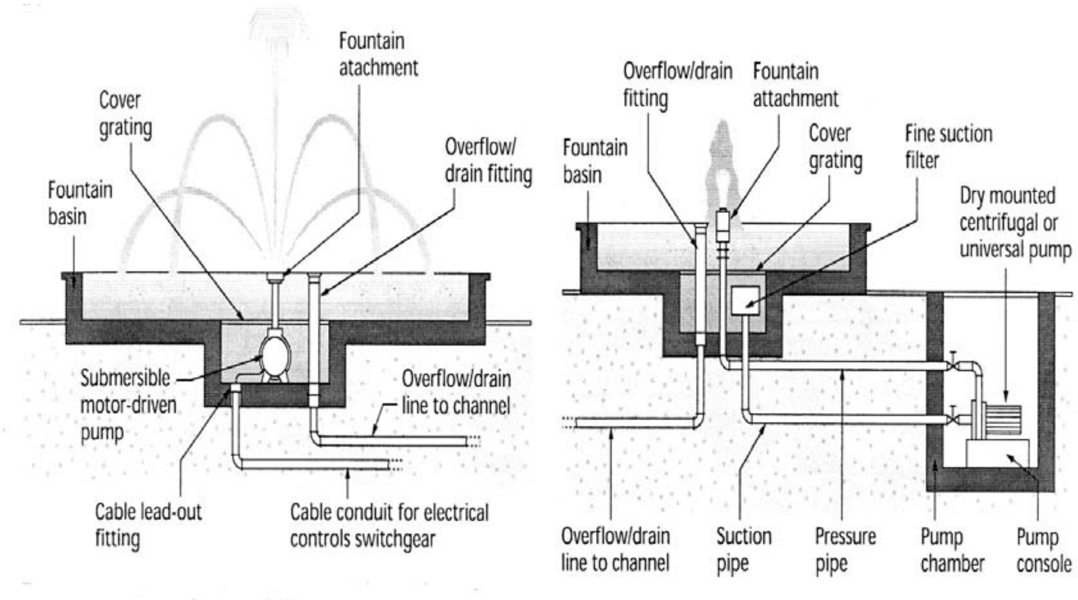
The artificial display of water is performed by using different heights of falling water, which can be achieved by using different pressures created by pumps. The following outlines the types of pumps used in water feature designs:

- Submersible pumps: these pumps are fixed inside the water, and fountain attachments or jets can be fixed directly to them as shown in Fig. 2.24(a).

- Dry pumps: these types of pumps are fixed outside the water in a chamber which is connected to a reservoir by using pipes. They are more complex to integrate which makes them more expensive, and are normally used in large public water feature installations as shown in Fig. 2.24(b).

Pumps should always be carefully enclosed by a grille for protection against accidents. They should also be protected against impurities with filters and grit traps. Pumps can be automatically controlled by computer programs or by using a float switch or magnetic switch control.

In waterfalls and cascades the width of the overflow determines the volume of water needed to be pumped to the waterfall, once the water flow is determined then the pump head can be known. The pump head for a water feature installation is the vertical distances from the basin surface to the point where the water comes out of the pipe into the water feature higher basin. The pump must have the ability to deliver the volume of



(a) Submersible pump fountain (b) Dry pump fountain

Figure 2.24 Typical fountain displays (CIBSE, 2004).

water needed in a water feature design. When using a large pump in large commercial fountains, there is normally not enough room in the actual fountain to place the large pump and filtration equipments. A large chamber is then needed to complete the fountain installation, as shown in Fig. 2.24(b).

Filtration elements are designed to remove suspended particles from a process stream of water to maintain water quality and clarity, the size of a filter being a function of the basin's capacity (CIBSE, 2004). Also water treatment (chlorine) should be used to stop bacteria and algae from developing in the water, and a simple metering pump is normally used to dispense the chemical solution.

2.5.4 Jets and nozzles

Fountains typically consist of different rising jets which vary in the water pressure and height they can deliver, and which can be arranged in different forms. The water rising from them can be in a rhythmic pattern of movement or constant, or a combination of both. These forms result from the water pressure as well as the fixed nozzles on the jets which can be used to shape the water display.

Jets and nozzles come in different designs resulting in different water shapes. The followings illustrate some of the jet shapes typically used in fountains (Lohrer, 2008):

- Single jet nozzles (Fig. 2.25): creates a clear water rise that can reach large vertical heights of several meters
- Foam jet nozzles (Fig. 2.26): adds air to water creating a foamy scene and sound
- Water filled nozzles (Fig. 2.27): creates water forms like bells or dome shapes
- Fan shape water spray nozzles (Fig. 2.28): creates a closed spring of water like a fan shape water spray at an angle
- Multi-jet nozzles (Fig. 2.29): creates an arranged group of rising water that falls separately or emerges together to form a certain display
- Sphere effect nozzles (Fig. 2.30): creates a water form like a sphere shape
- Finger nozzles (Fig. 2.31): creates a diagonal or vertical sheet of water.

When air is added to the nozzles the water becomes foamy and bubbly. To create a misty fountain, high pressure valves are used. The misty spray of water helps in lowering the air temperature creating pleasant refreshment in summer.

There is actually no limit to the designs and combinations which can be created, and the above are listed purely to give a sense of the variety of designs which can be made with jets. Several of these designs have been tested in the research presented and are described in Chapter 3.

Figure 2.25 Single jet nozzles. (Credit: Oase)

Figure 2.26 Foam jet nozzles. (Credit: Oase)

Figure 2.27 Water filled nozzles. (Credit: Oase)

Figure 2.28 Fan shaped nozzle. (Credit: Oase)

Figure 2.29 Multi-jet nozzles. (Credit: Oase)

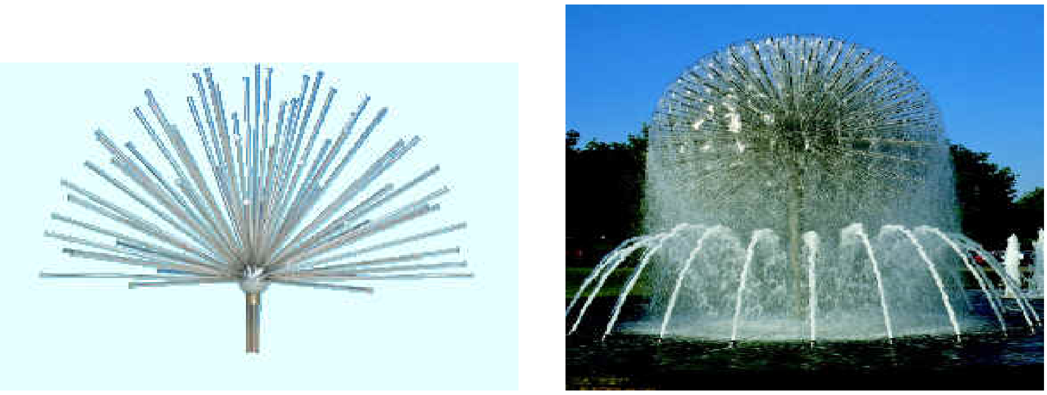


Figure 2.30 Sphere effect nozzle. (Credit: Oase)

Figure 2.31 Finger jet nozzles. (Credit: Oase)

2.6 Previous research

This section gives an overview of the previous work carried out in studies relevant to the research presented. The context to the work is first given by illustrating the background to environmental noise research and its development over recent years. The concept of the soundscape is then outlined and studies using this approach are discussed. The review of previous work begins with fairly general soundscape studies and develops through research which examined water sounds in more details. The studies reviewed are typically based on a combination of acoustical and perceptual analyses of the soundscape, and the majority of these tend to focus on the urban sound environment. The basic theory of how water sounds are generated is also presented in this section. Definitions of the acoustical and psychoacoustical parameters mentioned in the following pages can be found in Chapter 3. Furthermore, it can be noted that psychoacoustical parameters are typically used for the perceptual evaluation of sound, and the ones considered in this study are limited to loudness, sharpness, roughness, fluctuation strength, and pitch strength.

2.6.1 Background

Since the 1990s, many efforts have been made for reducing noise in urban environments. In particular, several initiatives of the European Union (EU) pointed out the need for tackling noise in urban environments (*e.g.* see the 'Fifth Action Program for the Environment' (EC, 1993) and the 'Green Paper' on future noise policies (EC, 1996)). In 2002, the European Communities published the environmental noise directive 2002/49/EC (EC, 2002) which set out a strategy for dealing with environmental noise. The directive initially requested the creation of noise maps within urban areas of EU countries, as there was no reliable and comparable data available within the EU, and as it was necessary to have comparable criteria and common methods in order to be able to implement effective solutions. It was pointed out that local planning objectives could be developed only after the mapping had been completed. The indicator L_{den} (day-evening-night equivalent noise level) was the descriptor chosen for noise mapping and annoyance correlation, whilst L_{night} was the descriptor chosen for sleep problems. Since then, noise maps have been created for different types of sources, namely road, rail, aircraft and industrial noise, and action plans have been proposed locally. Ultimately, it is hoped that these actions will lead to a long term strategy at EU level.

The approach taken by the environmental noise directive focuses on noise levels and noise annoyance. It does not look at detailed properties of the sound, as only a single dBA value is used in the maps. However, studies have shown that decreasing sound pressure levels does not always improve acoustic comfort in the urban environment (Kang, 2007), and that a simple decrease of noise levels and the elimination of noise sources are insufficient to account for urban environment improvement (Raimbault and Dubois, 2005). It is within that context that soundscape studies have gained more attention, as these go beyond the basic concepts of noise level and noise annoyance. This is discussed below in some detail.

2.6.2 The soundscape approach

The soundscape term was coined by Murray Schafer in the 1970s to define our sonic environment and its complexity (Schafer, 1994). The soundscape effectively represents an "auditory landscape" including all sounds surrounding us, both positive and negative, and is sometimes also referred to as the "total acoustic environment" (Schafer, 1994). Its approach is very broad as it relies on both physical characteristics and mental perception of the aural environment. The evaluation of a soundscape is therefore a complicated issue which involves the interaction between different sounds and a variety of factors which are not limited to acoustics (Kang, 2007). This concept has obtained greater interest in research communities over the last decade, as it has been shown that pleasant sounds present within the environment can play an important role in acoustic comfort (Raimbault *et al.*, 2003). Such pleasant/positive sounds include sources as diverse as water, bird songs, temple bells and wind in trees. The research presented is therefore in line with the soundscape approach, as it promotes the use of positive sounds produced by water features.

The identification of sounds is an important part of soundscape evaluation, and it can be noted that the perceptual and qualitative analysis of sound is often more complex than the analysis of physical qualities (Southworth, 1969). Most of the methodologies used to assess soundscapes rely on semantic scales (*e.g.* natural vs. artificial, not enveloping vs. enveloping, smooth vs. rough), ordinal scales (*e.g.* rating of comfort from 1 to 5) and correlations with acoustical or psychoacoustical parameters (*e.g.* L_{Aeq}). The soundwalking methodology (Lynch, 1960), where subjects discriminate and evaluate sounds around them while walking, is also often applied to assess urban acoustic environments (Berglund and Nilsson, 2006; Semidor, 2006). In practice, the complexity of soundscape characterisation is such, that a wide range of methodologies have been used as well as criticised by different researchers, and it can be noted that the standardisation of the procedures for assessing soundscapes are still being discussed in the ISO TC43 SC1 WG 54 (perceptual assessment of soundscape quality). This can be better appreciated through the illustration of a number of relevant studies which are given below. For the definitions of the acoustic parameters mentioned in this review, refer to Chapter 3.

Raimbault and Dubois (2005) examined how the notion of soundscape can be used for conceiving ambient sound environments in cities. Assessments made by city planners and city users showed differences in the verbal descriptions used to characterise different soundscapes, therefore highlighting the difficulties of describing the sound qualities of an environment. In view of overcoming such difficulties, the authors argued that human-centred categorisation would help soundscape representations and decision making.

Berglund and Nilsson (2006) developed a tool for measuring soundscape quality which was based on twelve attributes (soothing, pleasant, light, dull, eventful, exciting, stressful, hard, intrusive, annoying, noisy and loud). Correlations were made between these attributes and the sound pressure level $L_{Aeq,30s}$, results showing that loudness was strongly associated with sound pressure level, followed by annoyance, whereas the attribute pleasant was least well associated. However, it was also found that outdoor soundscapes tend to be preferred, even for cases where indoor sound pressure levels are much lower. This invalidated the mere use of sound pressure level of soundscapes as an indicator of soundscape quality.

Raimbault (2006) examined qualitative judgements of urban soundscapes through the use of questionnaires and semantic scales. Findings indicated that the appraisal of soundscapes depends not only on acoustical features but also on personal and social variables of the subjects. Analysis of subjects’ comments indicated a lack of consensus about semantic words such as ‘temporal’, ‘spatial’ and ‘activity’. The author argued that this might be related to two cognitive representations that can be applied to assess urban soundscapes: a “holistic hearing” referring to a global representation of the urban soundscape, and a “descriptive listening” where sound sources are discernable. As different situations can lead to different processing, the study suggests that the use of global descriptors might not be appropriate for evaluating soundscapes, whilst analysis of subject-centred categories might be helpful, as variations in users’ attitudes and types of situations can be crucial.

Polack *et al.* (2008) examined the urban soundscape using morphological parameters (*e.g.* one way vs. double way road; weak traffic vs. heavy traffic). Results indicated that listeners are able to associate a sound to a type of site, but are not able to recognise the period of the day. Subjects described the soundscape with sources and less frequently with physical descriptions, and findings also showed that sound sources related to nature induce a relaxing character to soundscapes, whilst traffic events at short intervals show a lower rating.

Acoustic comfort evaluation in urban open public spaces has been examined by Yang and Kang (2005), who used fourteen case study sites across Europe. The factors that were used for subjective evaluation in the urban open public spaces were based on ordinal scales (rating 1 to 5) and included also nominal scales (comfort – discomfort, quiet – noisy, pleasant – unpleasant, natural – artificial, like – dislike, gentle – harsh). Traffic noise was present in all the sites examined either as the main sound or as background noise. The other sound elements present were different human activities as well as natural sounds such as water sounds. The study was part of an overall physical comfort investigation including visual, thermal and lighting aspects, where climate conditions and urban morphology were also considered. $L_{Aeq,1min}$ was measured for each interview and subjects were asked to evaluate the sound level. Results showed that the home environment, cultural factors, lifestyle and personal preferences can play an important role. Subjects from noisy home environments as well as warm climates (where windows are usually opened) are used to noisy urban open public spaces. Results show a strong correlation between the subjective evaluation of sound level and $L_{Aeq,1min}$, but above 73 dBA the subjective evaluation varies significantly and becomes more unpredictable. Subjective evaluation is closely related to L_{Aeq90}, which can be used as a measure of background noise. It was for example found that with a lower background noise level people feel quieter. The study showed that correlation between sound level and acoustic comfort is much lower than the correlation between the sound level and the subjective evaluation of noise. The analysis of individual sources showed that for a given sound pressure level humans have a different perception of the individual sounds. Demolition sounds were perceived as the noisiest, as opposed to fountain sounds. An interesting finding was that higher sound levels due to fountains (levels above 70 dBA) were evaluated as acoustically comfortable. This suggests that water features could be used as masking sounds even at high levels.

The application of the soundscape approach in the evaluation of urban public spaces has also been studied by Rychtarikova *et al.* (2008). This work examined the sound complexity of urban environments by using a combination of acoustical and perceptual descriptors to evaluate the soundscape in a city. Data was collected using the soundwalking method across different public spaces in Leuven, Belgium. Psychoacoustic parameters (loudness, sharpness, roughness and fluctuation strength) and sound pressure levels (L_{Aeq}, L_{10}, L_{50}, L_{95}) were used to evaluate the urban soundscape. Words were used to define soundscape categories, namely ‘keynote sounds’, ‘the sound signals’, ‘the soundmark’, ‘the rhythm’ and ‘the harmony’. Findings suggest that the combination of these acoustical and perceptual descriptors can provide a good characterisation of the soundscape. Furthermore, results suggest that percentile values give a detailed representation of the soundscape and can be a useful tool in soundscape analysis.

The above studies give an idea of the variety of methodologies and findings which can be obtained from soundscape research. The complexity of soundscapes’ characterisation clearly points towards the necessity of multidisciplinary approaches, but the large variability in situations and context suggests that global descriptors are unlikely to be sufficient.

2.6.3 Aural and visual interaction

The literature available shows that the interaction between aural and visual stimuli has been examined by several researchers, as these two senses are the ones most closely related to the perception of soundscapes. Relevant studies related to this interaction are discussed below.

Carles *et al.* (1999) studied the correlation between sound and images, focusing on a limited number of natural environments. The ratings in the results given for natural sounds were good, especially for water features, whilst man made sounds and urban images had a low rating.

The influence of the visual setting on sound ratings in an urban environment was studied by Viollon *et al.* (2002). This work examined the influence of the visual setting on sound judgments. The study was based on an experimental procedure in artificial audiovisual environments and two scales were used for perceptual evaluations (pleasant – unpleasant, stressful – relaxing). Eight sound environments were selected and combined with different sounds (*e.g.* voices, footsteps, traffic noise and bird songs). The results of sound conditions alone of the sound stimuli were grouped into the following three clusters: (a) Bird songs alone which were rated very pleasant and relaxing; (b) Bird songs with background urban traffic noise and footsteps were rated as pleasant and relaxing; (c) Sounds involving human presence (footsteps, hubbub of voices) and road traffic noise were rated unpleasant and stressful. When both aural and visual stimuli were tested, results indicated that the effect of visual scenes varied with the type of sounds. The main finding was that the more urban the visual settings, the less pleasant and relaxing the perceived sound environment.

The selection and introduction of sounds to improve the soundscape in public spaces was examined by Jang and Kook (2005). In this study, sounds (water, temple bells and music) were played with different projected images selected from different spaces (park, garden, bus terminal and street). The test was made in a laboratory using audio and video sources. Results indicated that when involving sound with different images projected, the evaluation of harmony varied depending on the selected location. Subjective evaluation for park showed a high preference for temple bells which are in harmony and fit with the target place, but sound did not improve the environment in gardens that are natural and calm. In the bus terminal, results indicated that adding any sound only amplifies the noisiness, whilst in the street natural sounds and traditional music had a positive effect. For noisy environments such as traffic noise, results suggested that the introduced sound should have a significantly lower level than the existing sound level, in order to promote comfort and harmony with the space and act as a background feature rather than a sound mark.

Image evaluation and spatial analysis of the sound environment of urban street areas was studied by Ge and Hokao (2005). This work examined the sound in streets of Saga City in Japan, by using physical and perceptual properties. The sound pressure level $L_{Aeq,1min}$ was measured for each area and site interviews were carried out to identify preference and congruence. Results showed that different places can give people different feelings to the same sound with the same physical properties. The addition of visual elements did not affect preference ratings significantly but did affect semantic differential profiles. For busy streets, the influence of visual factors on the sound environment was low, as the soundscape was primarily defined by its high noise level. However, quiet areas were influenced significantly by their landscape, and the use of natural components appeared to be effective in such areas.

The above studies highlight the mutual interactions between aural and visual stimuli and how these can affect perception and preferences. Whilst some of the studies provide fairly predictable results (*e.g.* the soundscape of natural environments tend to be preferred to man made environments (Carles *et al.*, 1999; Viollon *et al.*, 2002)), more subtle interactions tend to affect perception. In extreme cases sound perception can be negligible as the visual stimuli dominates perception (Jang and Kook, 2005), whilst the opposite can occur in very noisy environments (Ge and Hokao, 2005).

2.6.4 Theory of water generated sounds

Although some of the studies reviewed so far did include water sounds, these did not examine or analyse the acoustical and perceptual properties of such sounds in any detail. Such a review is given in the following section, but prior to it, it is necessary to provide the theory of the basic mechanisms involved in water sound generation, as an understanding of such mechanisms is essential.

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 (Franz, 1959). 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. This is shown by Minneart's formula (Minneart, 1933), which under normal atmospheric conditions is equal to (Leighton, 1994)

$$f = \frac{3}{r} \tag{2.1}$$

where f is the resonance frequency of the bubble and r is the radius of the bubble. This formula applies to a bubble in a liquid, where it pulsates due to small-amplitude oscillations. For the audible range of 20 Hz – 20 kHz, bubbles producing sound have therefore a radius varying between 1.5 mm and 150 mm (where large bubbles correspond to low frequencies and small bubbles correspond to high frequencies). Underwater bubbles create a sound which propagates to the surface of the liquid where it is transmitted to air. As stated previously, this sound tends to be dominant over impact sound. Furthermore, each bubble creates secondary droplets which are responsible for the formation of new bubbles.

The detailed mechanisms of water sound generation are therefore complex, but it can be noted that the variables of primary importance affecting the frequency spectrum and the amplitude of the sound are the shape, size, and velocity of the water drop, as well as the density and acoustic properties of the water (Franz, 1959). Other variables which can influence the sound produced are the viscosity and the surface tension of the water, as well as the density, compressibility, pressure and viscosity of the air above the water. In general, the water dropping at intermediate velocities produce more bubble sound than the water dropping at either low or high velocities, and the small water drops trap smaller bubbles than do the large drops and that produces sound of higher frequency (Franz, 1959). In reality, as several drops and bubbles are present, statistical approaches are normally used for modelling water sounds (Leighton and Walton, 1987).

Although these fundamental mechanisms are well known, water sounds are complex and difficult to predict, a reason why experimental research can help understanding the interaction between design factors and acoustic properties of water features.

2.6.5 Water sound studies

Although some of the soundscape studies reviewed in sections 2.6.2 and 2.6.3 included water sounds, it can be noted that no detailed analysis was given about them. In most cases, soundscape studies assess water generated sounds in the presence of several over sound sources, so that their assessment is often influenced by multiple factors which make it impossible to analyse and understand water sounds in isolation. More recent studies (in particular from 2009 onwards) have looked at water generated sounds using methods in which water sounds could be controlled and analysed in isolation. These are presented in this section as ‘studies focusing on physical properties’, ‘studies focusing on perceptual properties’ and ‘detailed studies looking at both physical and perceptual properties’.

Studies focusing on physical properties

Yang (2005) analysed the characteristics of three water features in Chatsworth Garden in the Peak District, England. From the sound spectra shown in Fig. 2.33 it was found that water sounds normally have noticeable mid to high frequency components around 2-8 kHz, justifying why water sounds tend to be noticed from the background. The spectra also showed that different designs can produce different sound frequencies. In his review of Yang’s study, Kang (2007) points out that the spectrum of water features is designable and that, high-frequency components normally come from the water splash itself, whilst low-frequency components can be generated from a large flow of water raised to a very high level and then dropped to a water body or hard surface.

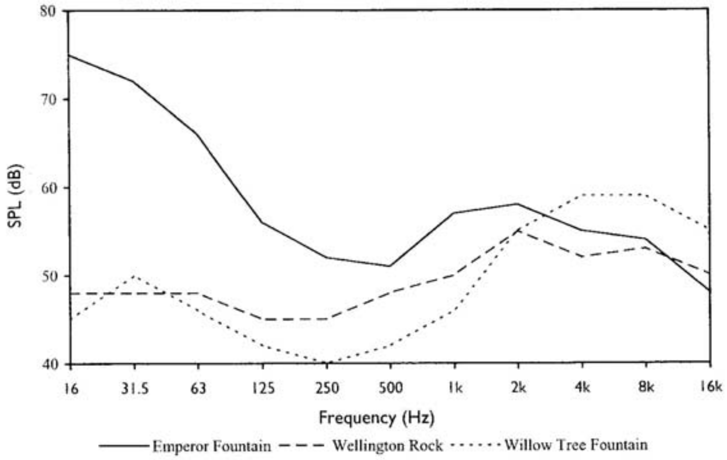
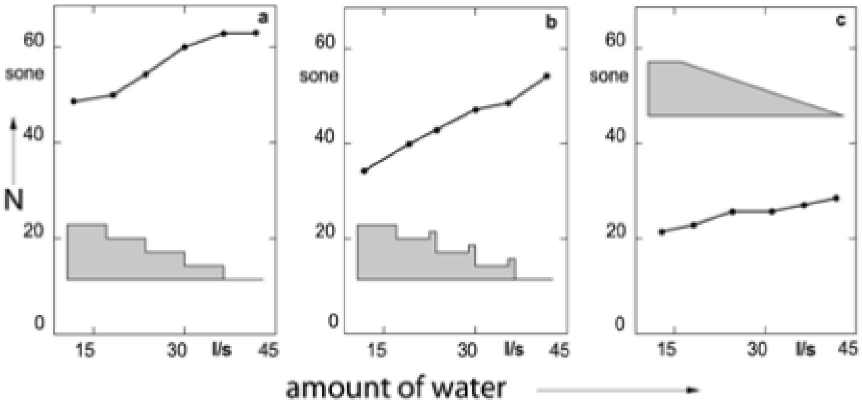


Figure 2.32 Comparison of the spectra of three water features in the Chatsworth Garden, England (Yang, 2005).



(a) Four straight steps (b) Four steps with basins (c) Gentle grade slope

Figure 2.33 Loudness vs. Flow rate for three waterfall constructions (Fastl, 2005).

Fastl (2005) analysed the loudness produced by different types of large waterfalls, including a design with four straight steps (Fig. 2.34(a)), one with four steps with basins (Fig. 2.34(b)), and a gentle grade slope (Fig. 2.34(c)). Figure 2.34 (a) clearly shows that the increase of water results in an increase in loudness (N) up to a certain point, whilst above that point the loudness tends to remain constant. Fig. 2.34(b) shows a fairly linear relation between the amount of water and loudness, whilst the impact of flow rate on loudness is rather small for the slope structure of Fig. 2.34(c). These results indicate that different patterns of loudness vs. flow rate can be obtained for different designs of large waterfalls.

Kang (2012) examined the diversity of the urban waterscape of the Golden Route of Sheffield, England. Changes in sound pressure levels, frequency and time were analysed, as well as variations in the psychoacoustic parameters loudness, roughness, sharpness and fluctuation strength, and results showed large variability in both acoustic and psychoacoustic measures for the several water features examined. Questionnaire surveys showed that water sounds are the preferred sounds in the soundscape, and that the first noticed sound is not necessarily the loudest one. Finally, the author also pointed out that quieter water features can attract attention visually, as well as by making people try to hear the sound they produce, therefore making them effective attention maskers.

Studies focusing on perceptual properties

Katayama (2003) studied the characteristics of different sounds of seashore waves which were compared and analyzed in terms of comfort level. Seashore sounds are important in view of waterfront development and design, but very little is available in the literature regarding their soundscape. In this study, acoustic measurements and audio recordings were undertaken at a natural sandy shore, a natural rocky shore and an artificial shore (vertical embankment) of a coastal zone of Japan. Auditory tests were then carried out using the recorded data, as well as using comparable seashore sounds available from commercial compact discs (imitation sounds). The latter were found to have broader spectra and larger high frequency contents, which had presumably been added at the mixing stage “in order to be easy to listen to” (Katayama, 2003). Results from the auditory tests showed that the sound of the natural sandy shore tended to be preferred to the rocky shore, which was in turn preferred to the artificial shore. Field recordings were preferred to imitation sounds, although differences were not significant.

Boubezari and Bento Coelho (2003; 2004) produced audibility maps of the Rossio Square in Lisbon, Portugal. A large fountain was present in the middle of this square, and water sounds, human activities and road traffic noise characterised its soundscape. Measurements and listening tests were carried out to obtain an intelligible description of the noise masking properties of the fountain. Sixty sound recording fragments of 30 seconds were taken at 10 m intervals, and were played in auditory tests together with a masking pink noise. The sound pressure level of the latter was varied until subject could not hear the water sound from the fountain. The audibility map obtained for the fountain is shown in Fig. 2.32, where L_{masq} corresponds to the background noise level not requiring any masking pink noise. The figure shows that sound from the fountain is not perceived in points close to the sidewalks of the fountain were the sound of traffic is dominant. This study illustrates how simple sound pressure level measurements and auditory tests can be used to produce audibility maps. In the example given, the map is used to identify masking properties of water features, but the same procedure was used by the authors to produce an audibility map of road traffic noise.

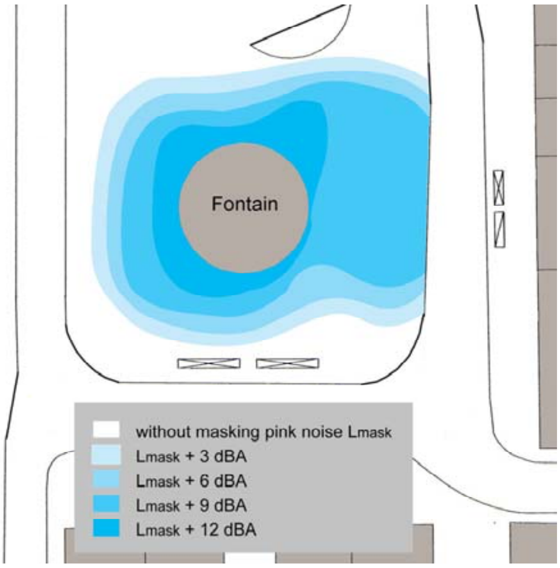


Figure 2.34 Fountain sound masking (Boubezari and Bento Coelho, 2003).

Semidor and Venot-Gbedji (2009) looked at the role of fountains as a natural element in acoustic urban comfort. Data was collected from different cities around Europe (Barcelona, Bristol, Brussels and Genoa), where soundwalks were carried out to qualify the urban soundscape which was characterised by transport, human activities, mechanical activities and natural elements (water, air flows and movements, animals). All the squares analysed were large, with high traffic density and high buildings surrounding them. Results showed that fountains acted as distinct sound marks, as their high frequencies were higher than background noise; comparisons with measurements made when the fountains were turned off proved this clearly. Fountains were effective in masking urban noise, although fountains placed in the centre of large squares were normally not audible at the periphery of the squares. The authors therefore argued that the use of several small fountains, rather than one large fountain, would be more effective in improving the urban comfort. Furthermore, they suggested that fountains could be placed at the periphery of the square where traffic noise is normally dominant, rather than only towards its centre.

Nilsson *et al.* (2010) examined the auditory masking of a fountain against road traffic noise. Recordings were undertaken in a city park in Stockholm, Sweden, which was exposed to traffic noise from a main road, as well as fountain sounds. Auditory tests showed that the fountain sound reduces the loudness of road traffic noise close to the fountain, and that the fountain sound was equally loud or louder than the road traffic noise at a distance of 20-30 m from the fountain. On the other hand, combinations made in the laboratory for a singular fountain sound and a singular road traffic noise showed that the latter is harder to mask than fountain sound, and that the partial loudness of both sources was considerably lower than expected from a model of energetic masking. This suggested that target-masker confusion might reduce the overall masking effect of environmental sounds.

De Coensel *et al.* (2011) carried out a listening test on different parameters such as loudness, eventfulness and pleasantness of stimuli that combines traffic noise with sound of a fountain or bird songs at different sound pressure levels. Results showed that adding the sound of a fountain reduced the loudness of traffic noise only if the traffic had low temporal variability, whilst adding bird songs significantly enhanced the soundscape pleasantness and eventfulness, even for road traffic noise with high temporal variability. This suggests that temporal variability might affect the perception of water sounds against road traffic noise, although it should be noted that only one type of water sound was used in this study.

<u>Detailed studies looking at both physical and perceptual properties</u>

Watts *et al.* (2009) studied the masking effect of water sounds over road traffic noise. The research was based on laboratory measurements used to capture water generated sounds under controlled conditions. A water feature (small weir) was set up inside the laboratory to produce different sounds of water, and spectra were measured for a stream of water falling onto water, gravel, bricks, small boulders and various combinations. The height of the weir was set to either 0.3 m or 0.4 m, and its width was kept constant at 0.1 m. Two flow rates were used (1.11 or 0.55 litres/sec) and a microphone was placed at 1.10 m above the floor level. Initial tests showed little differences between the two heights considered, so that the analysis was finally concentrated on fourteen sounds produced at a weir height of 0.3 m. The sounds were obtained from the different impact materials mentioned above and from a number of combinations (*e.g.* boulders with cavity vs. boulders closely packed). Recordings of 10-20 seconds were undertaken for each test and background noise was measured before starting each test. Octave band spectra of the water sounds were obtained for the range 63 Hz – 8 kHz (lower frequencies being unreliable because of background noise) and compared with typical traffic noise spectra (city street at 7.5 m and motorway at 110 m). For masking comparisons, levels of all the spectra were normalised to 67.4 dBA, results showing that road traffic noise tends to produce lower frequencies than the sound of water (Fig. 2.35). Traffic noise at frequencies of 1 kHz and below were either above or similar to the sound pressure level of water, whilst the opposite applied to frequencies above 1 kHz. Although some of the water sounds produced significantly more low frequencies than others, even the most effective features were approximately 10 dB below traffic noise at 63 Hz and 125 Hz. This indicated that it is difficult to mask low frequency traffic noise without generating much louder water sounds. Conversely, at mid and high frequencies the masking of water sounds was effective. Perceptual assessments were then carried out. A balcony garden with a water feature was setup in a semi-anechoic chamber and fourteen subjects assessed the perceived changes in tranquillity of fourteen different water sounds in the presence of road traffic noise. The preferred water sounds could be linked to natural sounds such as rainfall and flowing water in a stream, whilst one of the worst sounds was thought to originate from water entering a sewer. “Hollowness” was identified as a negative feature, whilst a light temporal variation was considered positive. Subjects preferred higher frequency sounds, such as those produced by water falling onto small boulders. This resulted in sounds with higher sharpness being also preferred (as sharpness increases with high frequency content). These

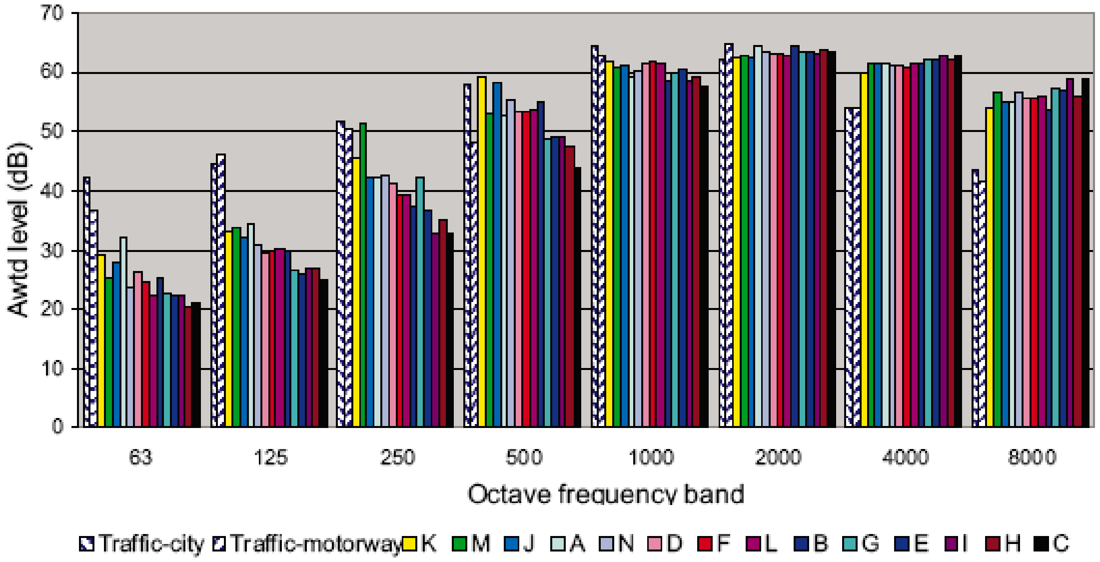


Figure 2.35 Spectra of fourteen water sounds
adjusted to an overall level of 67.4 dBA (Watts *et al.*, 2009).

findings suggest that water features generating natural sounds should be used to improve the perceived tranquillity of traffic noise rather than man made sounds, and sounds should have small levels of low frequency. Furthermore, 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.* (2010) carried out qualitative perceptual assessment of urban soundscapes using auditory tests. The study evaluated urban soundscapes containing combined noise sources (construction and traffic noises), as well as water sounds. Soundwalks were carried out in sixteen urban spaces in Seoul and Bundang to identify the annoyance of construction noise and road traffic noise combined together. Based on semantic scales used for the assessment of soundwalks, relationships of L_{Aeq} vs. Annoyance were derived, were the percentage of 'highly annoyed' and the percentage of 'annoyed' were examined. Results showed that the perception of acoustic comfort and loudness is strongly related to annoyance. Auditory tests made on road traffic noise, construction noise and combinations of these two, also showed that annoyance ratings vary with the type of construction noise (stationary vs. fluctuating vs. intermittent vs. impulsive) and the level of the road traffic noise. The study also examined the use of water sounds for masking, in view of improving soundscape perception. Auditory tests made identified water sounds, such as streams and waves of lake, to be the best natural sounds for enhancing the urban soundscape (Fig. 2.36).

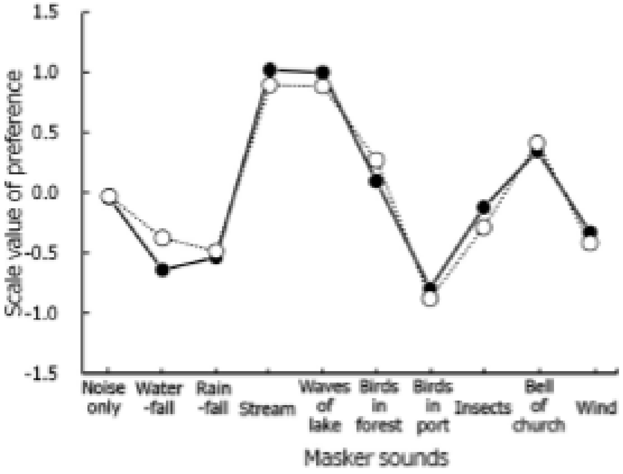


Figure 2.36 Preferred natural sounds as masker of urban noises (● road traffic noise and ○ construction noise). (Jeon *et al.*, 2010)

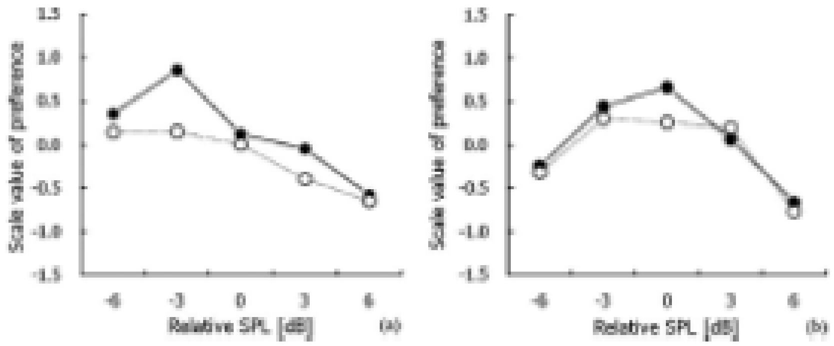


Figure 2.37 (a) Preference vs. relative SPL for road traffic noise. (b) Preference vs. relative SPL for construction noise (●Stream and ○Waves of lake). (Jeon *et al.*, 2010)

These tests were carried out in the presence of either road traffic noise or construction noise. Furthermore, it was found that the water sounds should be similar or not less than 3 dB below the urban noise level (Fig 2.37).

You *et al.* (2010) investigated the acoustic characteristics of different types of water features to evaluate their suitability for improving the soundscape with road traffic in urban spaces. Recordings were taken for different water features (streams, waterfalls, fountains and water sculptures) in different urban spaces, and auditory tests were performed to identify the preferred level difference between the sound of water and traffic noise. This was done in view of improving the urban soundscape and making it more pleasant for people. Results showed that the preferred sound pressure level of all of the five water sounds examined was around 3 dB lower than the road traffic noise level. This was found regardless of whether road traffic noise was played at 55 dBA or at 75 dBA. These results expand from those presented by Jeon *et al.* (2010), where only the 55 dBA level was considered and only two types of water sounds were tested. Furthermore, it was found that when the water sound had more low frequencies, it was more effective in masking road traffic noise.

Jeon *et al.* (2012) examined the use of water sounds in urban open spaces for road traffic noise masking. Acoustical and psychoacoustical data of thirteen water features, as well as images, were obtained from urban open places, and experiments were carried out for an audio-only condition, as well as for an audio-visual condition. Measurements showed a good variability between the water spectra, with sharpness values significantly scattered across water sounds (fountains exhibiting greater sharpness), whilst roughness and fluctuation strength did not exhibit significant variations. Preference scores and semantic scales were used to asses the sounds, results showing that preference scores for the urban soundscape are affected by the acoustical characteristics of water sounds and visual images of water features (especially for lower levels of traffic noise), and that preferences are significantly related to adjectives describing “freshness” and “calmness”. “Freshness” tended to be associated to water sounds with high sharpness (*i.e.* high frequency content), whilst “calmness” was associated to water sounds with low sharpness (*i.e.* low frequency content). Sharpness was also significantly correlated with preference scores. In particular, greater sharpness resulted in higher preferences under both audio-only and audio-visual conditions.

2.7 Discussion

The literature has shown that the qualities of water features have been recognised by a large number of studies for a variety of reasons, ranging from purely functional reasons (*e.g.* drinking and refreshing), to relaxation, aesthetic appeal and entertainment (Kaplan, 1987; Symmes, 1998; Kang, 2007; Hirst, 2009).

A historical review pointed out that the purpose of water features has shifted with time from its functional role towards more decorative goals, combining architectural structures with different forms of water displays, in view of providing people with aesthetic pleasure and entertainment. However, recent research studies reviewed in section 2.6 point towards a more functional use of water features as sound masking elements (Watts *et al.*, 2009; Jeon *et al.*, 2010; You *et al.*, 2010; Nilsson *et al.*, 2010; De Coensel *et al.*, 2011; Jeon *et al.*, 2012).

Although a basic categorisation was given for water features (waterfalls (including cascades) and fountains), the variability of features shown indicated that there are no limits in terms of design, as any type of upward or downward jets, waterfalls and sculptural elements can be combined to create very different features.

Current design guidelines suggested that most of the emphasis is placed on the functional and aesthetic qualities of the features developed, whilst sound properties do not appear to be a significant factor taken into account by designers (Lohrer, 2008). Although this did not mean that sound is not considered, it suggested that for most cases sound design is based on rules of thumb. Installation principles used for small to medium sized water features comparable to the ones tested in this research were also illustrated.

The review of acoustic research relevant to this work initially pointed out the efforts made in recent years towards reducing environmental noise. This has resulted in the development of noise maps and action plans at EU level (EC, 2002), followed by some criticism towards the limited benefits offered by these, and the need for more comprehensive approaches. Within that context, soundscape studies have gained interest amongst researchers and several studies have pointed out the benefits of using multi-disciplinary approaches for improving the acoustics of urban environments (Raimbault *et al.*, 2003; Yang and Kang, 2005; Berglund and Nilsson, 2006). However, the large variability and complexity of soundscape methodologies used by different studies also pointed out the need for some standardisation of procedures.

Soundscape research showed that the use of pleasant sounds can play an important role in acoustic comfort (Raimbault *et al.*, 2003), and as water is one of most commonly mentioned positive sounds, the research presented falls within the soundscape approach. Although several soundscape projects have provided an insight into the acoustic and perceptual properties of water generated sounds, these have often been influenced by multiple sources and factors which have made it difficult to analyse and understand water sounds in isolation (*e.g.* Boubezari and Bento Coelho, 2003; Yang and Kang, 2005; Semidor and Venot-Gbedji, 2009). However, more recent studies have used methods in which the water sounds could be controlled and examined accurately, and these studies are very relevant to the work presented in this thesis. In particular, the experimental studies of Watts *et al.* (2009) and Jeon *et al.* (2010; 2012) have contributed to the understanding of water generated sounds and their perception, but it should be noted that a detailed investigation of water sound characteristics has only been made for large features (Jeon *et al.*, 2012) and small streams (Watts *et al.*, 2009). An in-depth analysis of small to medium sized water features (*e.g.* as found in gardens and parks) is not available in the literature, but the correct design of these features is essential for improving the urban soundscape. The research presented in this thesis therefore fills this gap by examining the impact of design factors on the acoustical and psychoacoustical parameters of small to medium sized water features, as well as analysing the perceptual assessment of water sounds in relation to traffic noise masking.

Previous studies showed the importance of aural and visual interactions in the perception of the soundscape, but it is worth mentioning that this aspect was not examined in the current research, as it was considered to be beyond the scope of the work.

Finally, it can be noted that the basic mechanisms of water sound generation were also briefly illustrated, as these provide a fundamental insight into the acoustical and psychoacoustical analysis of water sounds given in Chapter 4.

CHAPTER 3

Test structures and procedures

3.1 Introduction

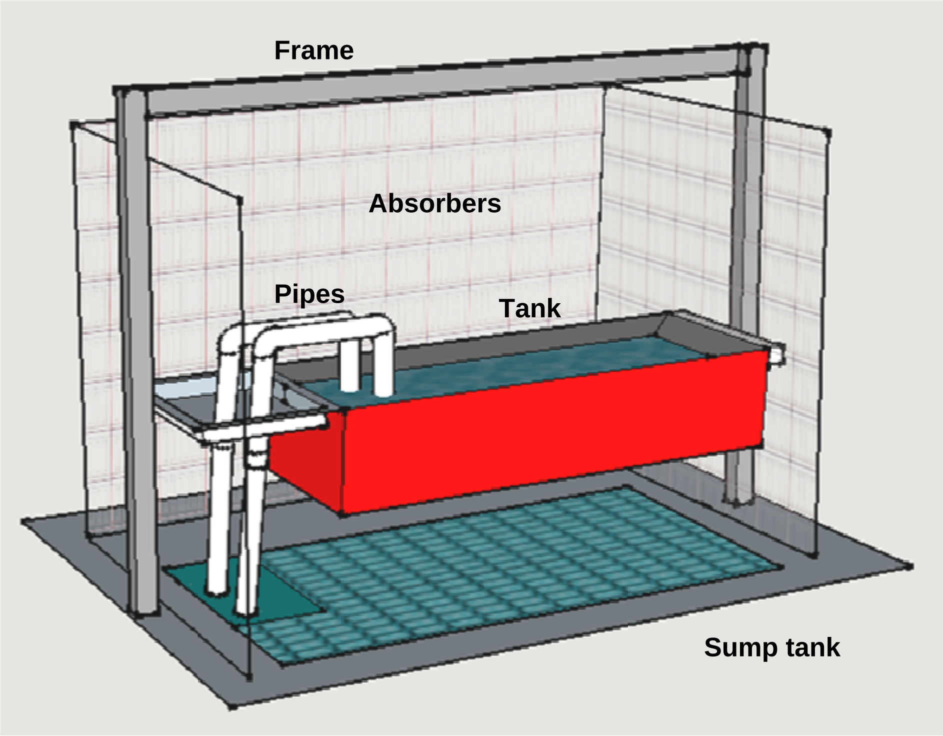
This chapter explains the test structures and procedures used for the study. A description of the laboratory rig structure and features tested is initially given, followed by an explanation of the acoustical and psychoacoustical parameters used and their measurement procedures, as well as a brief overview of the perceptual methods applied. Details about measurements carried out for field tests are given in Chapter 5, and a comprehensive description of the perceptual methods used is available in Chapter 6.

3.2 Laboratory rig structure and water features tested

A location was needed to test water sounds. After exploring a number of options, it was concluded that the drainage laboratory in the School of the Built Environment of Heriot-Watt University was the appropriate place where to test water features, because of the following benefits:

- A large sump tank built into the floor
- The availability of water and a drainage system
- Low levels of background noise
- Accessibility to the adjacent acoustic laboratory and equipment

A test rig structure was therefore built in the drainage laboratory (Fig. 3.1). The structure consisted of a sump tank encased in the floor and into which water falls (2.0 m long × 1.2 m wide × 1.2 m high), and a tank (1.5 m long × 0.5 m wide × 0.5 m high) fixed at a higher level. Two submersible pumps were fixed in the sump tank and used to circulate water to the upper tank or to fountain extensions (variable flow rate of up to 150 litres per minute (75 l/min per pump)); the tank was attached to a frame which allowed it to reach a maximum height of 2.5 m above the floor level. Absorption panels



(a) Three dimensional drawing (not to scale).

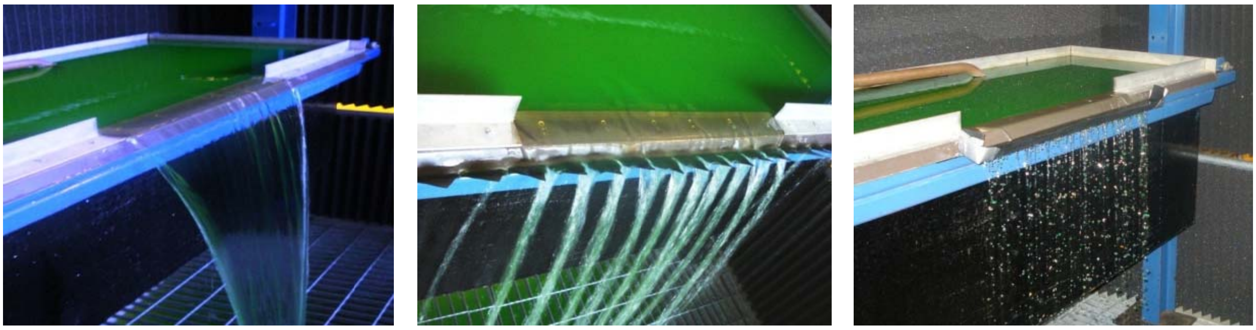
(b) Picture of test structure with tank fixed at 1.0 m (height of falling water).

Figure 3.1 Laboratory structure used for testing water generated sounds.

and bass traps were also installed around the structure to minimise sound reflections from adjacent surfaces (see 3.4.3 for details). A variety of waterfalls (Fig. 3.3), fountains, cascades and jets (Fig. 3.4) could be tested using this structure.

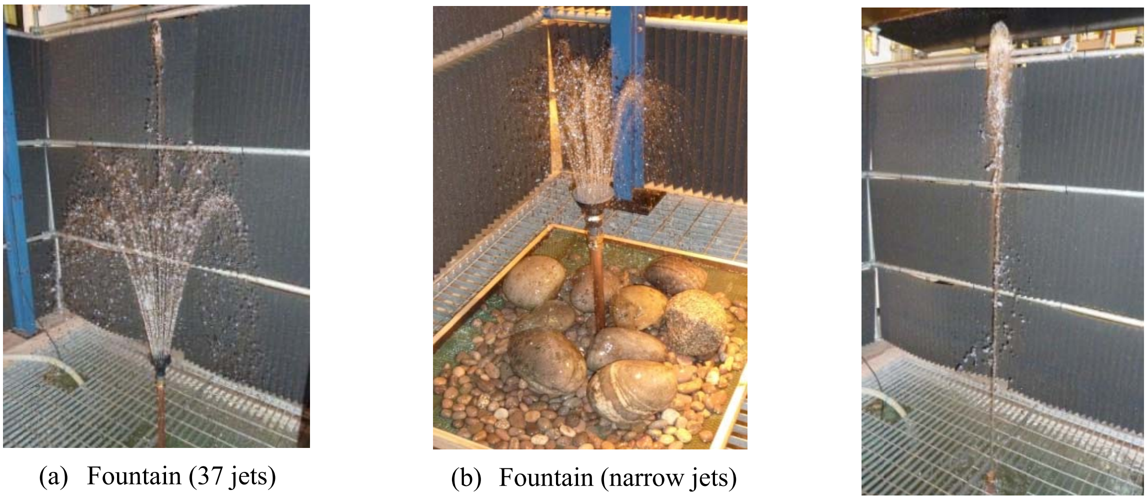
Waterfalls were tested with different widths (0.25 m, 0.50 m, 1.00 m, and 1.50 m), through the use of metal brackets attached on top of the tank's edge (Fig. 3.3). The brackets were fixed around the edges to force water to exit along one side. On that side, an aluminium strip was attached at 50 degrees to ensure a uniform curtain of falling water, which was otherwise not occurring. Different heights of falling water (0.50 m, 1.00 m and 2.00 m), flow rates (from 5 l/min to 150 l/min, measured with the electronic digital flow meter GPI Model A204-LM-S100N-A1) and impact materials were also tested (Fig. 3.2). The latter included concrete blocks (0.44 m × 0.22 m × 0.10 m), a metal plate (1.05 m × 0.40 m × 0.002 m), stones like pebbles (30-60 mm), boulders (150-250 mm) and gravel (10-20 mm). The materials were placed over a floor underlay in a specially constructed plywood box (see Fig. 3.4(g)) which had flexible pipes draining the water into the sump tank, the latter ensuring that no noise was generated from the drainage of water. Furthermore, different waterfall edges were tested. These were cut from polyvinylchloride (PVC) and fixed under the to aluminium strip (Fig. 3.3). The edges tested included a plain edge, a sawtooth edge and an edge made of holes of varying dimensions (2 mm, 20 mm or 40 mm diameter), as these were found to be representative of a variety of edge conditions (Fig. 3.3). A plain edge results in a uniform 'curtain' of water falling over the impact material, whilst a sawtooth edge design creates several streams of water and tests indicated that is effectively equivalent

Figure 3.2 Impact materials used for tests, from top left to bottom right: gravel, pebbles, boulders, concrete block and metal plate.

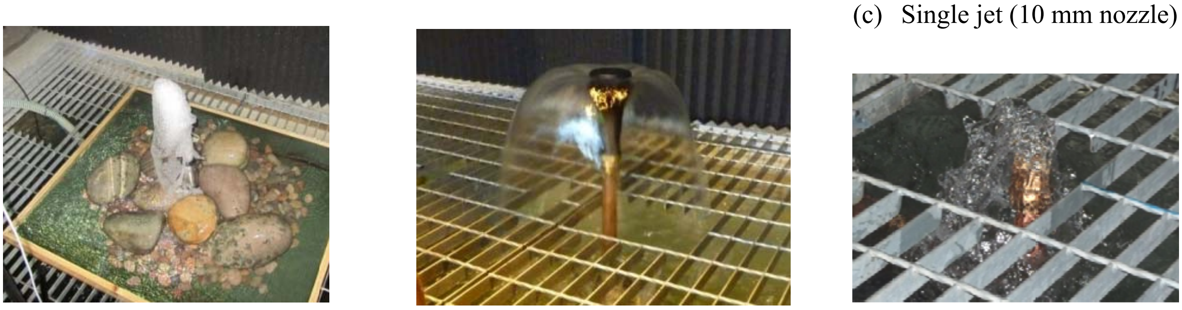


(a) Plain edge (b) Sawtooth edge (c) Small holes edge

Figure 3.3 Waterfall edges.



(a) Fountain (37 jets) (b) Fountain (narrow jets) (c) Single jet (10 mm nozzle)



(d) Foam fountain (e) Dome fountain (f) Single jet (25 mm nozzle)

(g) Cascade (4 steps) (h) Metal slope (i) Two jets (15 mm nozzle)

Figure 3.4 Examples of water features tested in the laboratory.

to an edge comprising large holes, but has the advantage of not being limited in terms of diameter's size. As the sawtooth edge results are presented in the following chapters, the results for edges made of large holes (20 mm and 40 mm) have not been included. On the other hand, the edge made of small holes (2 mm diameter) was useful for representing a 'rain' type of water distribution and its results will be presented.

Different fountain designs, cascades, as well as combinations of upward jets were also tested and examples of these features are shown in Fig. 3.4. All these were tested with different flow rates and impact materials.

The fountains tested included a 3-tier fountain made of 37 jets, a dome fountain (uniform distribution of water from 35 l/min), a foam fountain mixing air with water (a flow rate of at least 30 l/min was needed for the "air sound" to become audible) and the 3-tier fountain with narrower jets (2 mm instead of the original 3 mm). Extensions of 0.5 m and 1.0 m were also added to fountains' heads to examine the effect of height.

The jets used had different nozzle diameters (5 mm, 10 mm, 15 mm and 25 mm), and either one, two or four jets combinations were tested. The nozzles were made from copper discs with holes cut in their middle. Variations in flow rate allowed changing the height reached by water, and it can be noted that narrow nozzles could easily make water go higher than five metres.

A cascade made of four steps (Fig. 3.4(g)) and a slope (Fig. 3.4(h)) were also tested. The steps making up the cascade were concrete blocks which were covered by sheets of PVC. The latter were placed over the blocks as well as along their sides, in order to allow water to slide down the steps rather than leak on the sides because of the changes in flow provoked by the rough and porous concrete. The slope tested was made of two metal plates lying against the concrete blocks. Cascade and slope tests were carried out with stones, boulders and gravel as impact materials.

3.3 Acoustical and psychoacoustical parameters measured

This section describes the fundamental acoustical and psychoacoustical parameters used in the research.

3.3.1 Sound pressure level

Sound that we hear in air is due to compression waves propagating through the air. The compression causes minor fluctuations in pressure, p, measured in N/m^2 or Pascals (Pa) which cause the ear drum to vibrate. These pressure fluctuations are very small and vary over a wide range, from 2 x 10^{-5} N/m^2 (about the quietest sound that we can hear) up to 200 N/m^2 (pain). As the ear operates on a logarithmic scale, a more convenient parameter to use for pressure than Pascals is the decibel (dB), which is based on a logarithmic unit. The sound pressure level (SPL) uses decibels and is by definition equal to

$$L_p = 10log\frac{p^2}{p_0^2} = 20log\frac{p}{p_0}\ \text{(dB)} \tag{3.1}$$

where p is the pressure (Pa) and p_0 is the reference pressure which is equal to 2×10^{-5} Pa. The Root Mean Squared (RMS) pressure is effectively used in equation (3.1) and is equal to

$$p = \left(\frac{1}{T}\int_0^T p^2(t)dt\right)^{1/2} \tag{3.2}$$

for an averaging period T. This corresponds to a statistical measure of the varying magnitude of pressure and can be related to the average energy contained in the wave. In other words, the acoustic pressure and sound pressure level are normally based on mean values of the instantaneous pressure variations.

Typically, sound level meters can measure the SPL using either a slow time constant for the averaging period T (1 second), or a fast time constant (0.125 seconds). For most practical cases, it is however more useful to obtain an average reading over a longer time period. This can be done by using the equivalent continuous noise level, $L_{eq,T}$, which is the sound pressure level of a steady sound that has the same energy as the fluctuating sound in question over a given period T, and is given by

$$L_{eq,T} = 10log\left[\frac{1}{T}\int_0^T \frac{p^2(t)dt}{p_0^2}\right] \tag{3.3}$$

This parameter is widely used in practice, as it allows a single number for a noise that varies considerably with time and is otherwise difficult to quantify. It is extensively used in standards and regulations and is often based on A-weighted levels which are more representative of loudness perceived by individuals (see 3.3.2), in which case it is denoted as $L_{Aeq,T}$.

In environmental noise studies, it is common to calculate the continuous equivalent noise levels exceeded over a certain amount of time. The most common descriptors used in this sense are the following percentile noise levels,

- L_{10} : noise level exceeded 10% of the time
- L_{50} : noise level exceeded 50% of the time
- L_{90} : noise level exceeded 90% of the time

These levels give a good indication of the statistical maximum (L_{10}), average (L_{50}) and background noise (L_{90}) levels measured, and the difference between L_{10} and L_{90} can be used to give an indication of temporal variations. Such descriptors are normally obtained directly from most commercial sound level meters, without any need for post-processing data.

The minimum and maximum levels measured over any given time period can also be used to quantify variations and are denoted L_{Smin} and L_{Smax} if the slow time constant was used in measurements, or L_{Fmin} and L_{Fmax} if the fast time constant was used.

Fundamental relations between pressure and power

Relationships between pressure and power are given here to illustrate how the sound pressure level of water sounds can vary with distance. The sound pressure level can be related to the sound power level radiated by a source either outdoor or indoor. For outdoor propagation

$$L_p = L_w - 10logS \tag{3.4}$$

where L_p is the sound pressure level (dB re 2×10^{-5} Pa), L_w is the sound power level (dB re 10^{-12} W) and S is the surface through which sound propagates. For example, for a point source radiating sound spherically, S is equal to $4\pi r^2$, where r is the distance between the source and receiver. The SPL of a point source decreases by 6 dB each time the distance is doubled (inverse square law).

The sound pressure level generated in a room depends on the reflected sound and therefore on the absorption of the walls and floors, and can be found from the following equation

$$L_p = L_w + 10log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\bar{\alpha})}{A}\right) \tag{3.5}$$

where Q is the directivity factor of the source, $\bar{\alpha}$ is the average absorption coefficient of the room, r is the distance between the source and receiver (m) and A is the total absorption of the room (m^2). Equation (3.5) assumes a diffuse sound field and shows that the sound pressure level in a room decreases with increasing distance from the source and with increasing absorption. The relation between absorption and reverberation time is given in section 3.3.3.

3.3.2 Weighting filters

The human ear is a complex mechanism and does not respond equally to sound of different frequencies. The range of human hearing extends from 20 Hz to 20 kHz and can cover a large range of different sound pressure levels, but the ear is more sensitive at mid frequencies and less sensitive at low and high frequencies. This perceptual factor can be taken into account by adding appropriate weighting filters to the SPL measured.

The corrections commonly used are shown graphically in Fig. 3.5. Four different weighting scales are given, the most common being the A and C weighting scales, which are available on most commercial sound level meters. The A-weighting correction corresponds roughly to the inverse curve of the 40 phon equal loudness contour (see 3.3.4 for loudness definition and contour curves). It is the weighting most commonly used to obtain a physical measure of loudness, as it has been shown to correspond most closely to the ear response.

The B scale corresponds to the inverse curve of the 70 phon equal loudness contour, but is rarely used in practice. The C scale is linear at most frequencies, with small

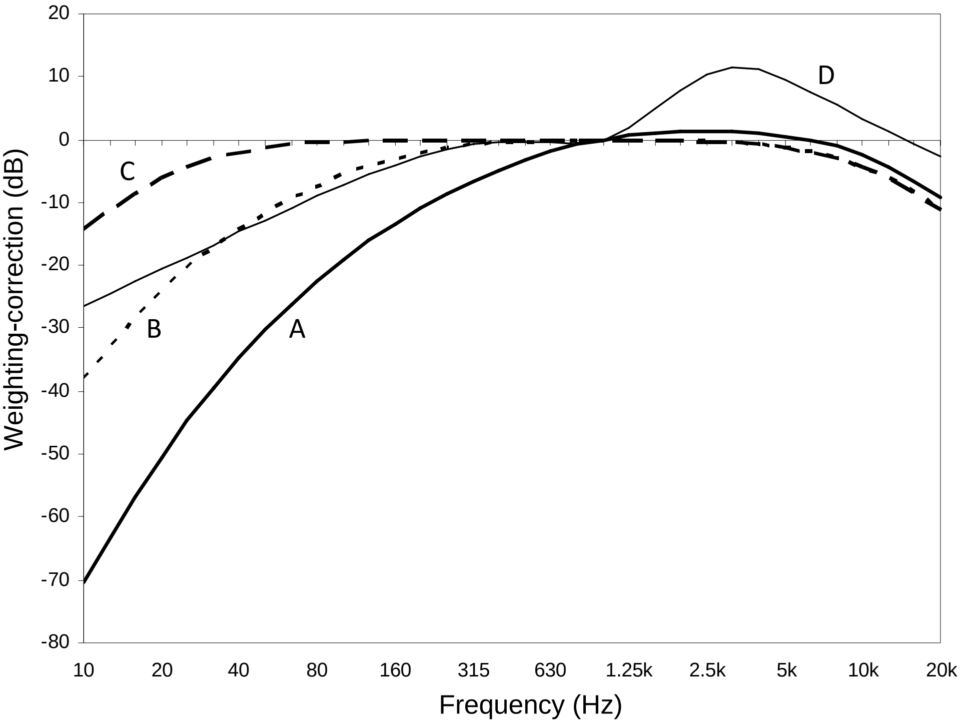


Figure 3.5 Weighting filters A, B, C and D.

corrections applied below 200 Hz and above 1250 Hz. Levels measured in dBC can be compared to dBA levels to identify whether or not the noise measured is dominated by low frequencies. As a rule of thumb, for differences greater than 20 dB the noise measured is considered to be low frequency dominant. The D weighting is specifically used for aircraft noise measurements, and is fairly representative of the bandwidth and level of aircraft flyover noise.

In this research, only the A and C weighting filters have been used.

3.3.3 Reverberation time

Calculations made in section 3.4.3 are based on the reverberation time which is therefore described here. In an enclosed space, sound continues to be reflected from surfaces for a period of time after a source has been stopped. This prolongation of sound is called reverberation and is one of the most important parameters affecting the quality of sound in a room. Reverberation time is affected by the size of the room and the amount of absorptive or reflective surfaces within the room. A room with highly absorptive surfaces will absorb the sound and stop it from being reflected back into the room. This creates a space with a short reverberation time. Reflective surfaces reflect sound and increase the reverberation time within the room. In general, larger spaces have longer reverberation times than smaller spaces. Reverberation time can be defined as the time taken for the sound pressure level to decay of 60 dB after the sound source is stopped, and it can be calculated from Sabine's formula

$$T = 0.161\frac{V}{A} \tag{3.6}$$

where V is the room's volume (m^3) and A is the room's absorption (m^2), which can be calculated from the sum of the absorption of each surface, as

$$A = \sum_i S_i \alpha_i \tag{3.7}$$

where S_i is the surface area of element i (m^2) and α_i is the absorption coefficient of the corresponding element. Sabine's formula is simple and works well in diffuse fields where the average absorption of all surfaces within the room is less than about 0.2. However, it is commonly used even for higher absorptions, as it has proven to be appropriate for most practical cases.

3.3.4 Psychoacoustic parameters

Psychoacoustics is the scientific field that describes the relations between the physical and the perceptual evaluations of sound, and is closely related to the concept of sound quality. The psychoacoustic parameters typically used for sound quality evaluation are loudness, sharpness, roughness, fluctuation strength and pitch strength. These are described below in some detail.

Loudness

Loudness is a subjective measure related to the hearing system and is a function of the amplitude and frequency of vibration. Loudness quantifies the strength of sensation (Fastl and Zwicker, 2007) and is therefore a quality of sound which should not be confused with an objective parameter such as the sound pressure level. Loudness tests were first carried out in the 1920's, the procedure consisting simply in playing pure tones (*i.e.* sine waves) at different frequencies and asking subjects to adjust the

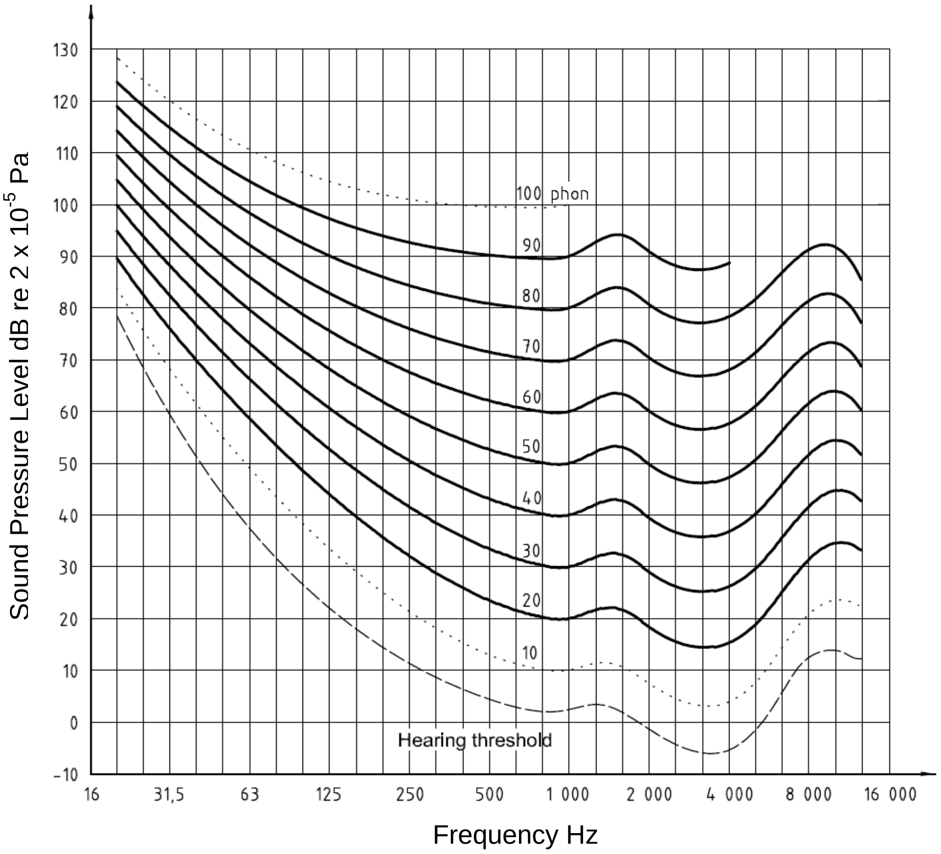


Figure 3.6 Equal loudness contours (ISO 226 © BSI 2003).

amplitude in order to obtain a loudness equal to the one perceived at 1000 Hz. Equal loudness contour curves could then be established, as shown in Fig. 3.6. The unit used for these curves is the phon, and corresponds to the sound pressure level of the equal loudness contour curve at 1 kHz. The phon scale applies to loudness levels, but not to loudness. It is arbitrary and has no physical or physiological basis, but this scale is convenient as it can be directly related to decibels. In this scale, a change in 10 phons corresponds approximately to a doubling in the strength of sensation (*i.e.* loudness). Alternatively, loudness can be expressed in sones, a scale according to which a doubling in loudness corresponds to a doubling in sones (*e.g.* 60 sones is twice as loud as 30 sones). The relationship between phons, used for the loudness level L, and sones, used for the loudness N, is given by

$$L = 40 + 10 log_2 N \tag{3.8}$$

The contour curves of Fig. 3.6 show that the human ear is more sensitive to tones in the region between 2000 Hz – 5000 Hz where the curves are at their lowest (Mayer, 1978). The figure also shows that loudness is both a function of amplitude and frequency. For low sound pressure levels (*e.g.* 20 phon curve), the amplitude needs to be increased significantly at low frequencies in order to sound as loud as mid-frequencies (*i.e.* the slope of the 20 phon curve is high at low frequencies). However, for high sound pressure levels (*e.g.* 90 phon curve) such increases are less significant (*i.e.* the slope is smaller at low frequencies).

Loudness can be calculated from (Fastl and Zwicker, 2007)

$$N = \int_{0}^{24\,Bark} N'dz \tag{3.9}$$

where *N'* is the specific loudness and the integral is taken over all critical-band rates. A detailed description of psychoacoustic models and factors is not given here, as psychoacoustic parameters were simply used as evaluation tools in this study. Details of such models can be found in Fastl and Zwicker (2007).

Sharpness

Sharpness is best described as the comparison between the amount of high frequency energy and the total energy in a sound (Fastl and Zwicker, 2007). This parameter is related to its frequency content, but is independent from its loudness, and is measured in acum.

Sharpness plays an important role in sound quality, as a large proportion of high frequency energy results in a high sharpness which gives an aggressive quality to the sound. Typically, high levels of sharpness are associated with higher annoyance levels. The sharpness calculations made in this study were obtained from the following formula

$$S = 0.11 \frac{\int_0^{24\,Bark} N'g(z)z\,dz}{\int_0^{24\,Bark} N'dz} \tag{3.10}$$

where S is the sharpness, N' is the specific loudness and g is an additional factor which is critical-band-rate dependant (Fastl and Zwicker, 2007).

Fluctuation strength and roughness

For slight differences between the frequencies of two tones, amplitude fluctuations or modulations can be perceived (Kang, 2007). An impression of regular loudness changes is normally perceived up to about 15 Hz, and this can be quantified by the fluctuation strength. This sensation has a maximum level at around 4 Hz, after which it decreases. Above 15 Hz, and up to 300 Hz, the sensation becomes the impression of roughness. Roughness reaches its maximum near modulation frequencies of 70 Hz and decreases at higher modulation frequencies (Fastl and Zwicker, 2007). These factors describe temporal variations of sound, where the fluctuation strength is described by slower sound variations up to 15 Hz, and roughness is perceived as faster variations (Fastl and Zwicker, 2007). The unit used for fluctuation strength is the vacil, where the value of 1 vacil is the 60 dB, 1 kHz pure tone that is 100% modulated in amplitude at a modulation frequency of 4 Hz. Similarly, the unit used for roughness is the asper, where the value of 1 asper is the 60 dB, 1 kHz pure tone that is 100% modulated in amplitude at a modulation frequency of 70 Hz.

Qualitatively, roughness may be described as ‘grating’ (Kang, 2007). A rough character of a sound usually causes an unpleasant hearing impression, and rough sounds include for example the humming of an electric razor or a sewing machine (Kang, 2007).

Roughness can be modelled using a complex formula, but the following approximation is often applied (Fastl and Zwicker, 2007)

$$R \sim f_{mod} \Delta L \tag{3.11}$$

where R is the roughness and is dependent on the modulation frequency f_{mod} and the loudness level difference ΔL. The more complex model used in this research is the one of Daniel and Weber (1997).

Pitch strength

Pitch strength, also known as tonality, is defined as the distinctness of pure tones in a complex noise (Kang, 2007). Audible pure tones contained in a broadband noise may be annoying, although the contribution to the total loudness may not be significant. Pitch sensation can range from faint pitch to strong pitch, which leads to the definition of pitch strength. For example, a pure tone of 1 kHz produces a strong pitch sensation, whereas a high pass noise with a cut off frequency of 1 kHz produces a faint pitch, but despite these differences in pitch strength both sounds produce approximately the same pitch (Fastl and Zwicker, 2007). The pitch strength model used in this research is the one of Camacho (2007), which is based on a Sawtooth Waveform Inspired Pitch Estimator (SWIPE).

3.4 Equipment, software and preliminary measurements

Details of the equipment used for tests are given in this section, together with some preliminary data obtained to validate the methods selected. The latter includes background noise data of the laboratory used for tests, measurements made to select the receiver position, and repeatability values obtained from waterfall tests.

3.4.1 Equipment and software

Acoustic parameters such as sound pressure levels and spectra were measured using an integrating sound level meter Brüel and Kjaer Type 2250 (Fig. 3.7(a)), with a data averaging period of 20 seconds. This is a precision Type 1 sound level meter which complies with BS EN IEC 60804 (2000), as well as a Class 1 sound level meter complying with BS EN IEC 61672-1 (2003). This sound level meter was also employed to measure loudness. The Brüel and Kjaer utility software BZ5503 was used to extract the data measured.

Audio recordings were carried out with a digital sound recorder Zoom H4n (Fig. 3.7(b)) connected to Brüel and Kjaer Type 4190 half inch microphones attached to a dummy head Sennheiser MKE 2002 (Fig. 3.7(c)). The half inch microphones were connected to microphone power supplies Brüel and Kjaer Type 2804. The binaural recordings were made over 20 seconds, with an audio sample size of 16 bit and a sample rate of 44 kHz. These recordings were used for calculating psychoacoustics parameters through Matlab using the module PsySound3 (sharpness, roughness and pitch strength). The following default time steps were used in the calculations: 49 ms for sharpness, 186 ms for roughness and 10 ms for pitch strength. The audio recordings were also used for the auditory tests, and played through closed studio headphones Beyerdynamic DT 150.

(a) Sound Level meter (b) Sound recorder

(c) Dummy head with microphones (d) Headphones

Figure 3.7 Equipment used in the laboratory tests.

The submersible pumps used were clean water pumps with a rated input of 400W, a maximum flow rate of 150 l/min, and a maximum delivery height of 8 m. In practice, the pumps delivered only a maximum of 75 l/min for a 1.0 m high waterfall.

The following manufacturing fountain extensions were used for tests: 1) Oase Vulkan 37-2,5 K (3-tier fountain with 37 jets); 2) Oase Lava 36-10 K (dome fountain); 3) Oase Schaumsprudler 35-10 E (foam fountain).

The twelve absorption panels used around the rig structure were 'Auralex 2 inch studiofoam wedges' (1.22 m × 0.61 m × 0.05 m) and the eight bass traps used were 'Auralex LERND bass traps' (0.43 m × 0.43 m × 0.61 m, where 0.61 m is the height). Absorption coefficients of these foam absorbers are available on the manufacturer's website in the document RAL-A93-58 (1993) for panels ($\alpha = 0.1$ at 125 Hz, $\alpha = 0.3$ at 250 Hz, $\alpha > 0.9$ at and above 500 Hz), and RAL-A96-74 (1996) for bass traps ($\alpha > 0.95$ at and above 100 Hz).

3.4.2 Background noise

Background noise measurements were carried out prior to testing every water feature. In order to minimise background noise levels, the tests were carried out in the late afternoon and evening, when no people were present within the laboratory, and when there was no noticeable outdoor activity in the yard adjacent to the laboratory. Fig. 3.8 shows noise levels representative of the drainage laboratory. The data corresponds to different days, therefore giving an indication of the variability present (equivalent sound pressure levels ranging between 25-35 dBA approximately). The impact of the noise produced by the submersible pumps used is also given in Fig. 3.9, where averages made over several measurements are given for the following conditions: 1) Pumps switched off; 2) One pump switched on; 3) Two pumps switched on (this applies only to flow rates greater than 75 l/min). The results suggest that the impact of pump noise is not significant, as also shown by the A-weighted averages obtained for the three conditions which are respectively 27.7 dBA, 29.3 dBA and 31.7 dBA. Although these levels are reasonably low and well below all the water sound pressure levels tested, it should be noted that frequencies below 63 Hz tended to be dominated by background noise. It can also be noted that the 63 Hz and 125 Hz octave bands were occasionally affected by background noise for some water features (and when this occurs, it is pointed out within the analysis of results). In that respect, Fig. 3.9 can be used together with the spectra of water sounds to have an indication on whether low frequencies are affected by background noise or not.

3.4.3 Receiver position

Although the drainage laboratory offers the advantages listed in section 3.2, it is an enclosed space with reflections that can affect the characterisation of sound sources. In order to minimise the effects of reflections on results, a number of tests were carried out to identify an acceptable receiving position for the measurements. This was done through reverberation time tests which allowed working out the critical distance of the drainage laboratory (distance where the direct field is equal to the reverberant field (Fig. 3.10)).

Water was not used in these experiments. Instead, an omnidirectional source made of twelve speakers was used to generate sound. The sound source was located at the centre of the structure where the water features were to be tested, and the height of the sound

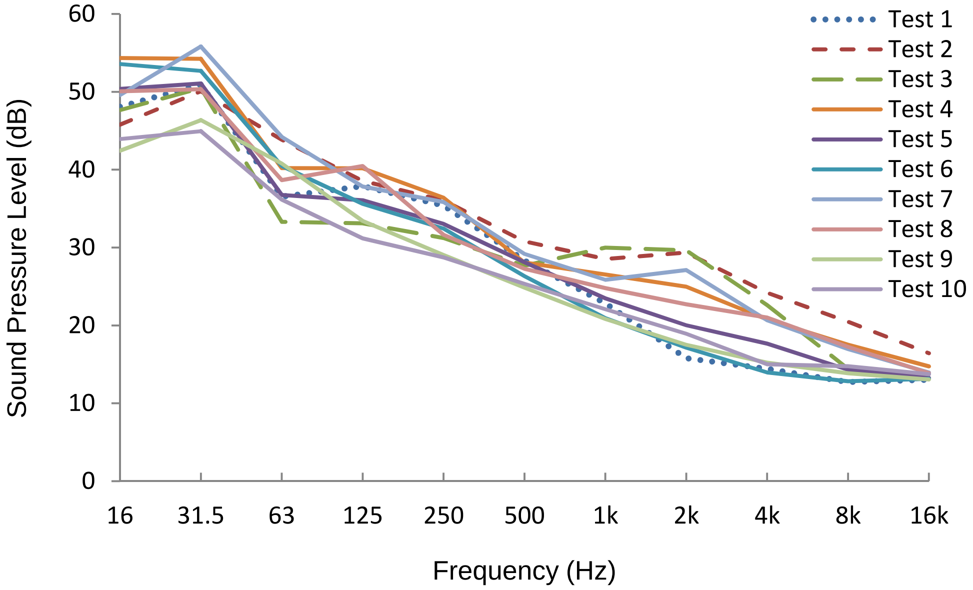


Figure 3.8 Ten background noise measurements carried out in the drainage laboratory of Heriot-Watt University.

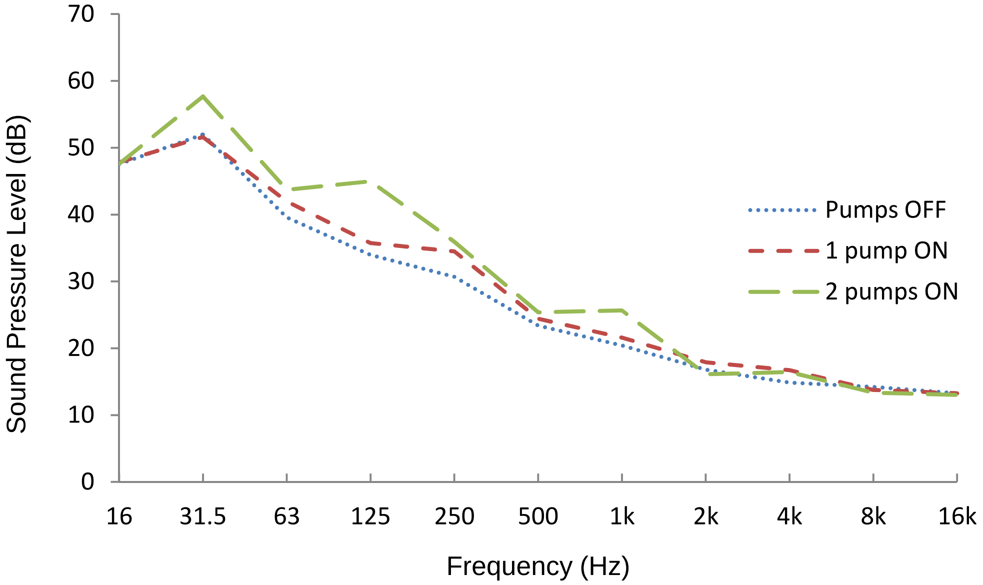


Figure 3.9 Average background noise measurements carried out in the drainage laboratory of Heriot-Watt University, with submersible pumps either switched off or on.

source was either 0.5 m (Fig. 3.11) or 1.2 m (Fig. 3.12) above the floor level. A sound analyser Norsonic Type 823 was used to measure reverberation time. The receiver's microphone was placed at 1.2 m above the floor, and at six different distances from the vertical axis of the sound source: 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m and 3 m. Initially measurements were made without using absorption panels around the structure. The results of Fig. 3.13 show a significant increase in reverberation time between position 1, which is 0.5 m from the source, and position 6 which is 3 m away from the source. This is due to the increasing contribution of surface reflections with distance (Fig. 3.10). Tests were repeated with three sides of the structure covered with absorption panels and bass traps (Fig. 3.12). Fig. 3.14 shows a significant decrease in the reverberation time with absorption, which is clearly beneficial for the type of tests carried out. Absorbers were therefore used throughout the laboratory tests.

In order to identify an appropriate distance between the source and receiver, the critical distance was calculated. The critical distance r^* of a point source radiating sound over a sphere can be found from the equation

$$r^* = \sqrt{\frac{A}{16\pi(1-\bar{\alpha})}} \tag{3.5}$$

where A is the total absorption in the room (m^2), and $\bar{\alpha}$ is the average absorption coefficient.

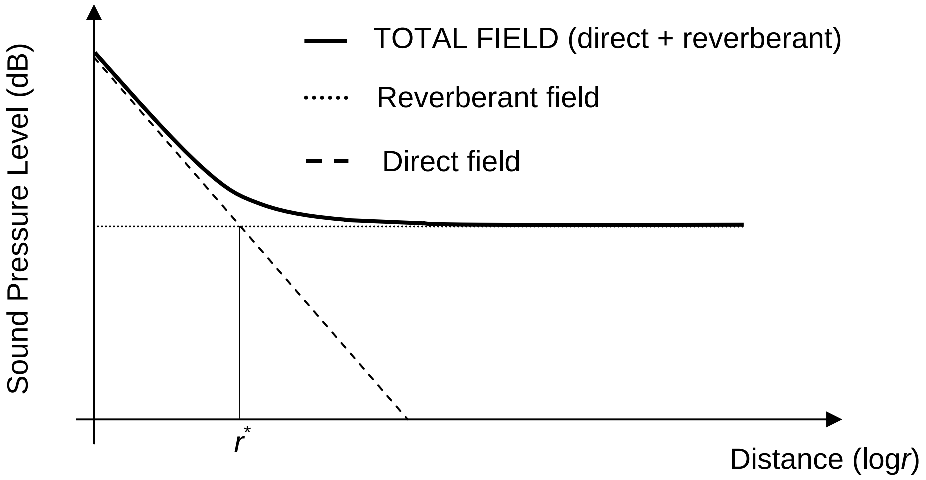


Figure 3.10 The relationship between the direct sound and the reverberant sound in a room (r^* = critical distance).

Figure 3.11 Setup used for reverberation time tests:
no panels and omnidirectional sound source placed
0.5 m above the ground (with water inside the sump tank).

Figure 3.12 Test structure covered with absorption panels and bass traps,
and sound source placed 1.2 m above the ground.

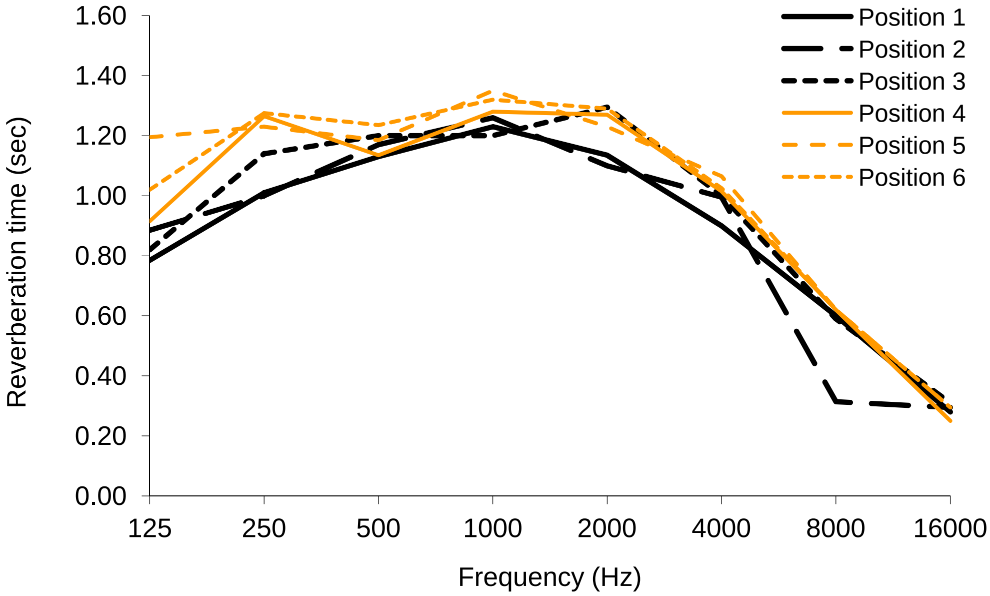


Figure 3.13 Reverberation time measurements for a source height of 0.5 m and without absorbers around the source.

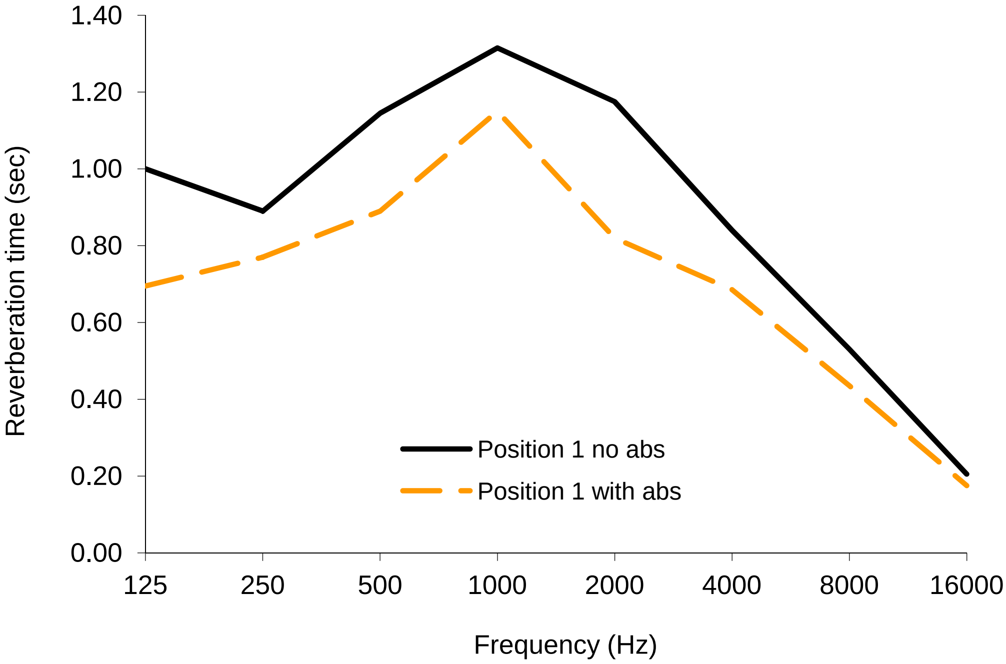


Figure 3.14 Reverberation time measured at position 1 with and without absorption panels and bass traps placed around the source.

The spherical assumption produces a shorter critical distance (*i.e.* worst case scenario). The laboratory used was a very large space of dimensions 20 m × 15 m × 7 m, and assuming the highest reverberation time of 1.4 seconds (see Fig. 3.13), the lowest critical distance was found to be equal to 2.5 m. For a point source, the direct SPL decreases by 6 dB when the distance is doubled. Consequently, if the critical distance is 2.5 m, the direct field will be 12 dB above the reverberant field at 0.62 m. This suggests that at 0.5 m from the source, the influence of the reflected sound should be negligible. In practice, fountains and jets were always placed at the centre section of the sump tank with the receiver at a horizontal distance of 0.5 m from this centre section. For waterfalls, the receiver was placed at a horizontal distance of 0.6 m from the edge of the tank, as in practice this corresponded to 0.5 m from the impact area of falling water.

For completeness, waterfall's tests were also undertaken for different receiver heights: 0.2 m or 1.0 m above the floor (and at a horizontal distance of 0.5 m from the centre section of the impact area of falling water). The 1.0 m height was chosen for being representative of a person seated (ear height at 1.2 m above water, considering that the water level in the sump tank was approximately 0.2 m below the floor level). This test was carried out to have an appreciation of how the sound pressure level can change with height. Results of Fig. 3.15 show that the sound pressure level increases significantly when closer to the floor (5-6 dB), both because of the closer position to the impact surface of water and because of the reflections coming from the floor.

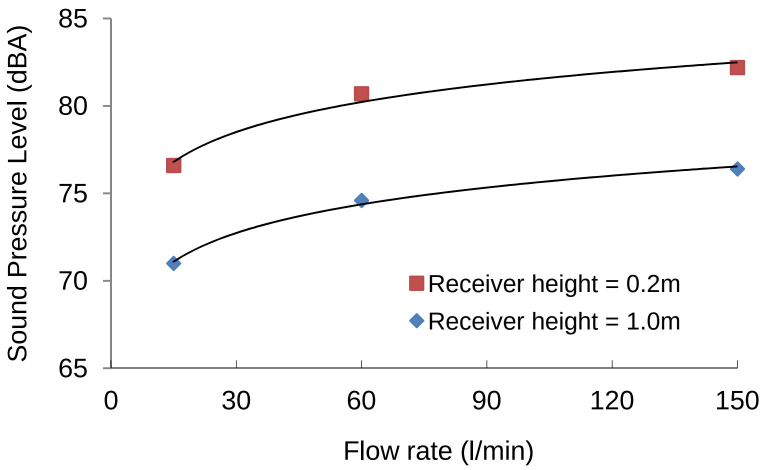


Figure 3.15 SPL vs. Flow rate: impact of receiver's height on sound pressure level for a sawtooth edge waterfall.

Following from the results discussed above, a position of 1.0 m above the floor and a horizontal distance of 0.5 m from the impact area of falling water was used throughout the tests, as it was found to be representative of a person seated in the vicinity of a water feature, whilst still being dominated by the direct field.

3.4.4 Repeatability

In practice, repeated tests are not expected to have numerically identical results, as variations in a number of factors and environmental conditions can occur (*e.g.* variability in instrumentation responses and changes in humidity, temperature and atmospheric pressure). Repeatability values can be obtained from mutually independent tests run with the same method on identical test material in the same laboratory with the same equipments by the same operator within short intervals of time (ISO 140-2, 1991).

Repeatability tests were carried out for two different waterfall edges, a plain edge and a sawtooth edge with a 1.0 m width and 1.0 m height. A flow rate of 15 l/min was used for the plain edge and three different flow rates (15 l/min, 60 l/min, and 150 l/min) were used for the sawtooth edge. For each case the test was repeated 10 times, re-adjusting the flow rate each time, as well as re-positioning the sound level meter each time (same position). Fig. 3.16 to 3.18 give the repeated results of $L_{\mathrm{Aeq,20s}}$. The standard deviations obtained for each case are presented together in Fig. 3.19, which shows a minimum of 0.13 dB and a maximum of 0.51 dB. These values indicates that repeatability of tests is good and that the measurements methods used are consistent and reliable.

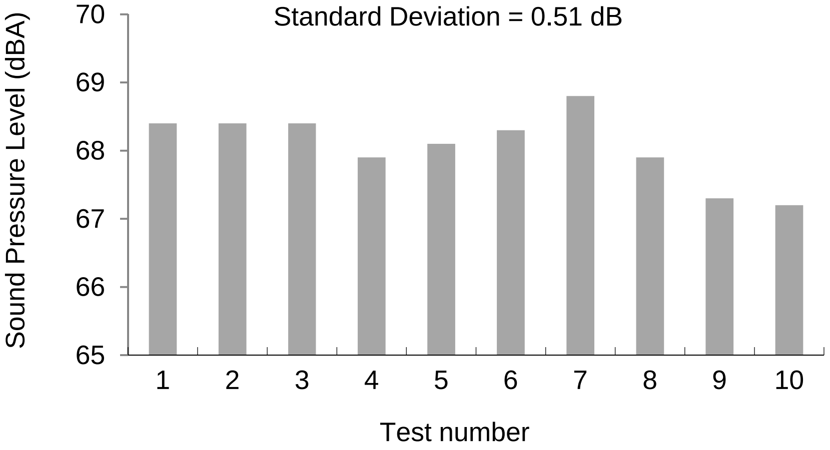


Figure 3.16 Sound pressure level obtained test for 10 tests carried out on the plain edge waterfall (1.0 m height and 1.0 m width) with a 15 l/min flow rate.

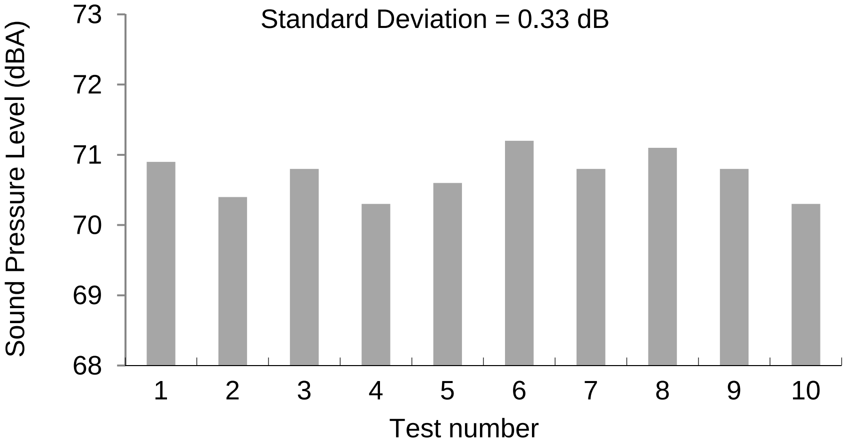


Figure 3.17 Sound pressure level obtained test for 10 tests carried out on the sawtooth edge waterfall (1.0 m height and 1.0 m width) with a 15 l/min flow rate.

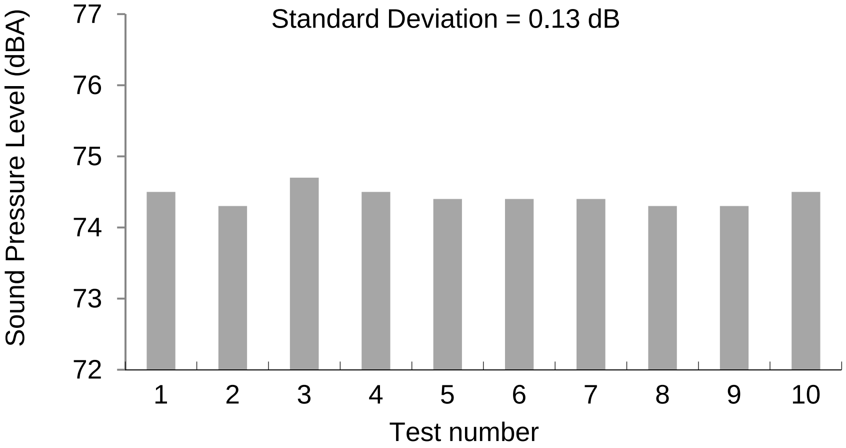


Figure 3.18 Sound pressure level obtained test for 10 tests carried out on the sawtooth edge waterfall (1.0 m height and 1.0 m width) with a 60 l/min flow rate.

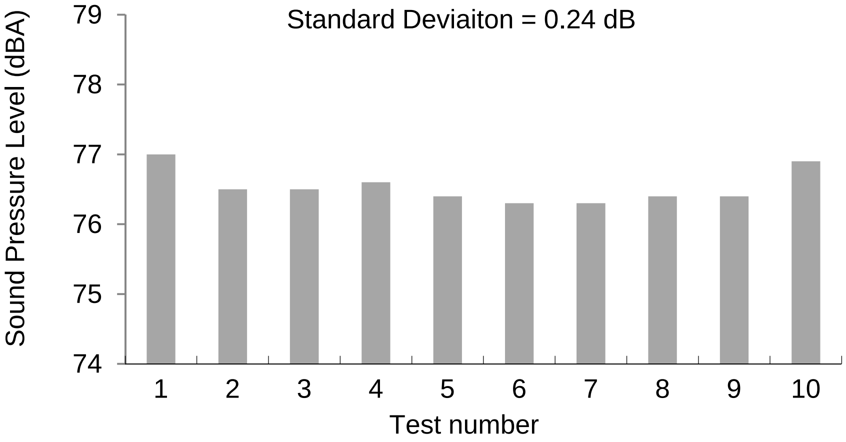


Figure 3.19 Sound pressure level obtained test for 10 tests carried out on the sawtooth edge waterfall (1.0 m height and 1.0 m width) with a 150 l/min flow rate.

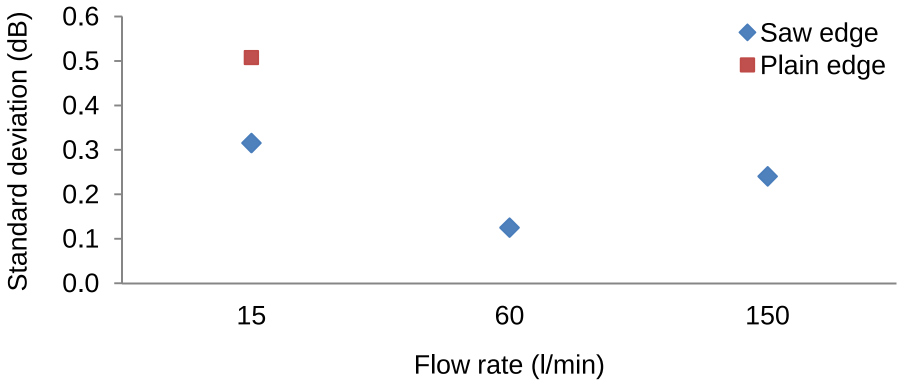


Figure 3.20 Standard deviation obtained for the different tests.

Repeatability is given for L_{Aeq} only, as this parameter correlates best with the perception of loudness. However, it should be noted that repeatability tests made on frequency spectra do show larger variations towards the 63 Hz and 125 Hz frequencies, where the standard deviation can be in the order of 3 dB and 2 dB respectively (whilst the standard deviation is always lower than 1 dB above 500 Hz). Some measurements' variability is therefore to be expected at the lower frequencies, but it can be noted that this is not expected to affect sound perception significantly.

3.5 Perceptual assessment

This section gives a short overview of the methods used for perceptual assessment (details about the methods and measurements are given in Chapter 6).

Auditory tests have been carried out to evaluate water sound preferences. The evaluation of water sounds have been made in the presence of road traffic noise recorded next to a motorway (Fig. 3.21). The equipment and software used for road traffic noise measurements were the same as what was illustrated in section 3.4.1.

The sound files including road traffic noise and water sounds were produced using the audio editing software Cubase LE 4. This software allowed combining different sound recordings, as well as calibrating the signals of each recording. Calibration of the signals was made using a custom made head and torso model with microphones placed inside the ears and connected to a sound level meter, and with closed headphones Beyerdynamic DT 150 used to play the signal (Fig. 3.22).

(a) Bridge over motorway

(b) Field next to motorway (200 m from it)

Figure 3.21 Pictures showing the site used for road traffic noise measurements and recordings.

Figure 3.22 Setup used for the calibration of recorded signals.

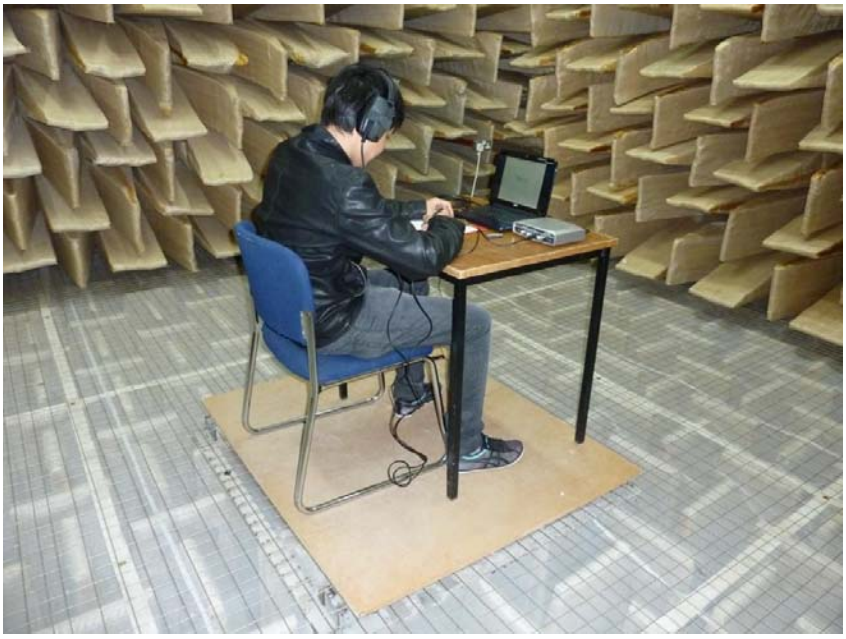


Figure 3.23 Auditory tests carried out in the anechoic chamber of Heriot-Watt University.

The auditory tests carried out for the research were limited to paired comparisons which allowed obtaining ratings of preferred sound pressure levels and preferred water sounds. The recordings were played from a laptop through a USB sound card M-Audio MobilePre, with the closed headphones Beyerdynamic DT 150 connected to it. The tests were carried out in the anechoic chamber of Heriot-Watt University (Fig. 3.23), a highly insulated space with a background noise level of around 21 dBA during tests (including noise from the laptop used).

3.6 Conclusions

This chapter described the test rig structure used to test water sounds in the laboratory, as well as the different types of water features tested. The acoustical and psychoacoustical parameters used in the study have also been explained, together with the equipment, software and measurement procedures used. Measurements carried out in the laboratory showed that background noise (including pumps' noise) was low and not expected to affect the measurements of most water features, with the exception of few cases where the 63 Hz and 125 Hz noise levels were not negligible (this is pointed out in the results of Chapter 4). The receiver's position was also carefully selected to be representative of a person seated in the vicinity of a water feature, with measurements not being affected by the room's reflections. The repeatability of tests also showed that the measurements methods used were consistent and reliable. A brief description of the perceptual methods used was also given at the end of the chapter.

Measurement details of the field tests are given in Chapter 5, whilst a comprehensive description of the perceptual methods used can be found in Chapter 6.

CHAPTER 4

The impact of design factors on acoustical and psychoacoustical parameters[1]

4.1 Introduction

The analysis presented in this chapter illustrates the findings obtained regarding the impact of design factors of small to medium sized water features on acoustical and psychoacoustical parameters. The chapter outlines the impact of flow rate, waterfalls' edge design and width, height of falling water, and impact materials. All the results presented in this chapter were obtained from tests carried out in the laboratory. A considerable amount of data was collected and only key results are presented in this chapter, but the full set of results can be found in Appendices A to H.

4.2 Flow rate

4.2.1 L_{Aeq} vs. Flow rate

The effect of flow rate on the equivalent continuous noise level L_{Aeq} has been examined for all the different types of water features illustrated in Chapter 3. Results are shown in Fig. 4.1 for waterfalls with different edges, and in Fig. 4.2 for a fountain, an upward jet and a cascade. The figures indicate that the equivalent continuous sound pressure level, L_{Aeq}, increases logarithmically with flow rate, *i.e.* large increases are observed at low flow rates, whilst small increases occur at high flow rates (best fit regression lines are given throughout the chapter). Results given in Appendix A show that this occurs for all types of small to medium sized water features (waterfalls, fountains, jets, cascade and sloping surface), the only exception being the plain edge waterfall with a low height of falling water of 0.5 m (Fig. 4.1(a)).

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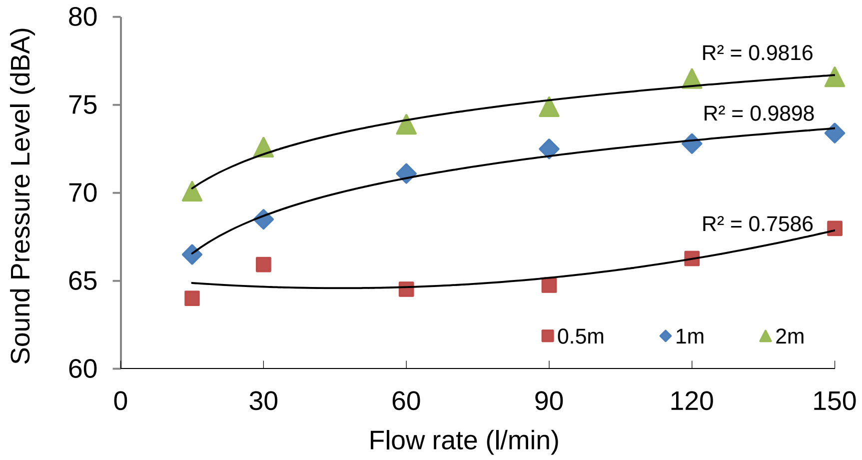
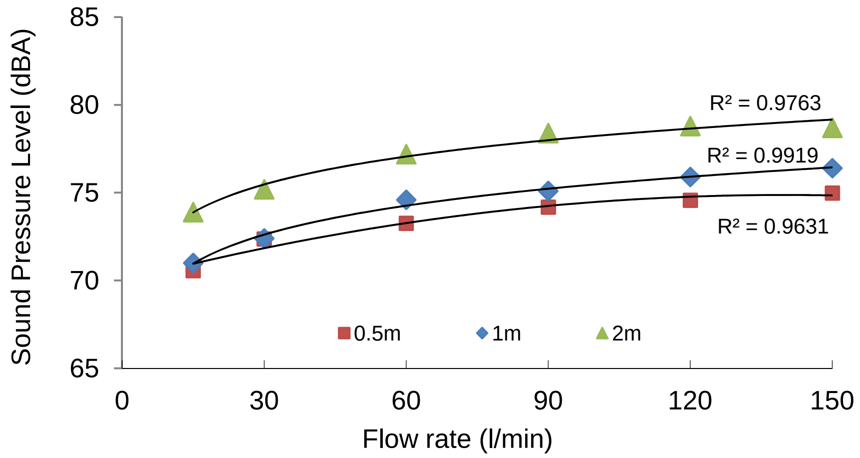
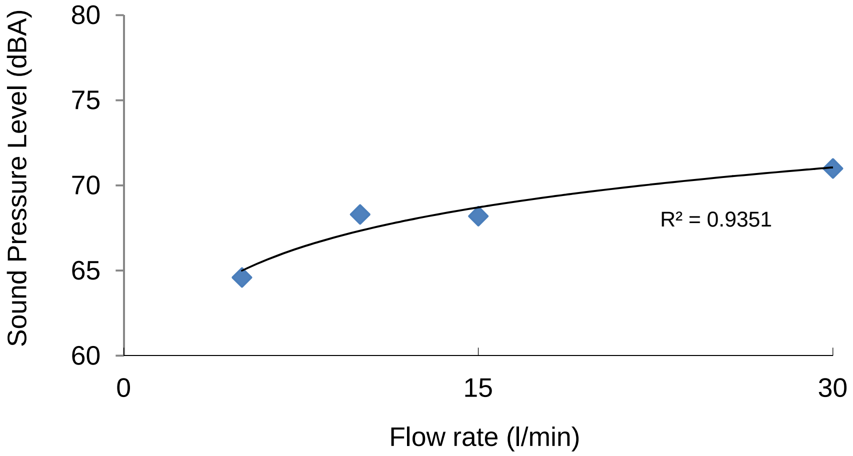
[1] Some sections of this chapter are based on the paper *Acoustical and perceptual assessment of water sounds and their use over road traffic noise*, by Laurent Galbrun and Tahrir T. Ali submitted to the Journal of the Acoustical Society of America in May 2012.



(a) Plain edge waterfall of 1 m width with various heights of falling water



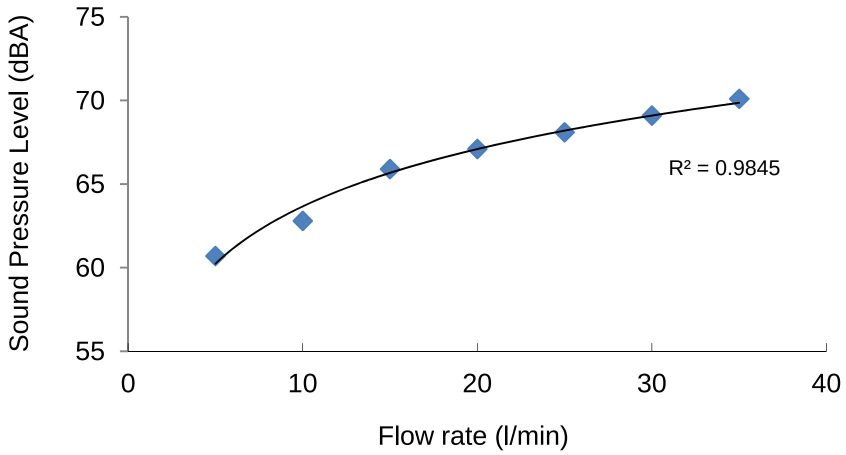
(b) Sawtooth edge waterfall of 1 m width with various heights of falling water



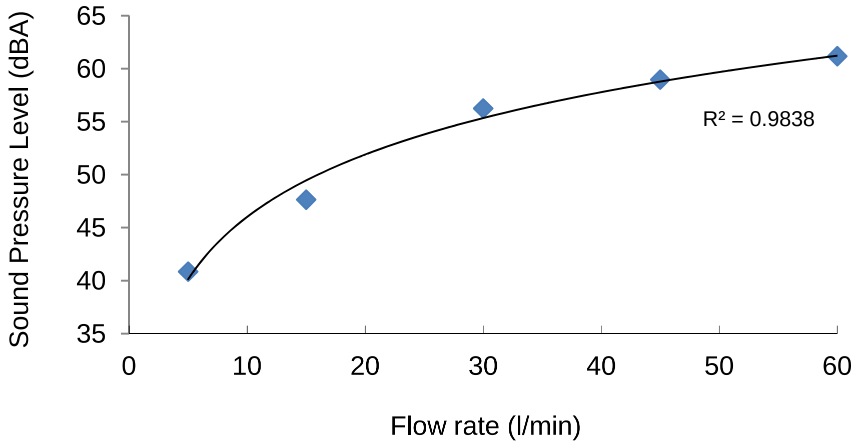
(c) Small holes edge waterfall (1 m height and 1 m width)

Figure 4.1 L_{Aeq} vs. Flow rate for waterfalls,

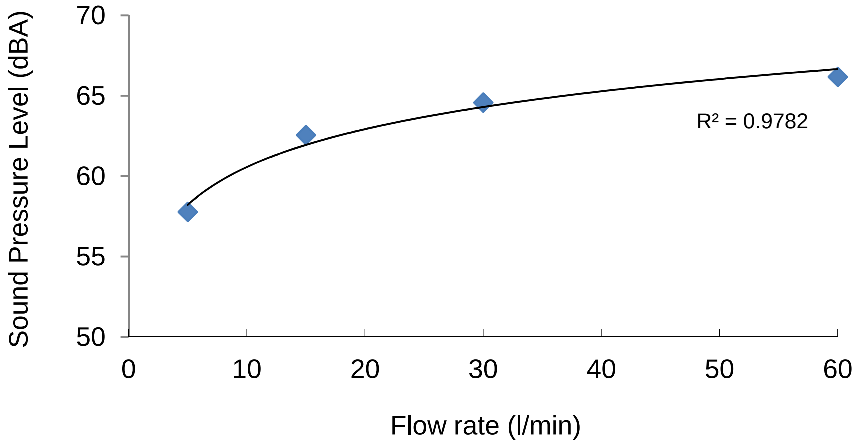
with regressions (best fit lines) and coefficient of determination R^2.



(a) Fountain with 37 jets and 0.5 m extension



(b) Jet with 25 mm nozzle



(c) Cascade over stones

Figure 4.2 L_{Aeq} vs. Flow rate for a fountain, a jet and a cascade, with regressions (best fit lines) and coefficient of determination R^2.

This trend was confirmed when the parameter used was loudness instead of L_{Aeq} (see Appendix B). This finding was compared with the results obtained by Fastl (2005) who measured the loudness of three large cascade structures operated at different flow rates. In contrast to the results discussed above, Fastl's data shows that loudness increases with flow rate without following a single predictable trend. This suggests that the acoustic properties of small to medium sized water features might not be applicable to larger water features.

Results also suggest that waterfalls have a smaller range of variation in L_{Aeq} which are in the order of 5-10 dB, typically in the range of 65-75 dBA, whilst for fountains the extent of variations is normally larger than for waterfalls (up to 15 dB) with typical L_{Aeq} levels of 50-70 dBA (see Appendix A). For jets with large nozzles (25 mm and 15 mm), the extent of variations can be as high as 25 dB (25 mm nozzle: 40-60 dBA; 15 mm nozzle: 50-75 dBA). For jets with narrow nozzles, variations in the order of only 5 dB occur (10 mm nozzle: 65-70 dBA; 5 mm nozzle: 60-65 dBA). The cascade tested shows L_{Aeq} variations of around 10 dB (55-65 dBA), whilst the slope produces the lowest levels in the range 40-55 dBA. These results indicate that waterfalls are normally louder than fountains, jets and cascades, as they can use higher flow rates and larger amounts of water which produce more bubbles.

Finally, it can be noted that the small holes edge data of Fig. 4.1(c) was restricted in terms of flow rates, as only a limited amount of water could pass through its 2 mm holes. In Appendix A (Fig. A16 to A18) it can also be seen that the dome fountain operated effectively in two modes: below 35 l/min the dome shape was irregular, whilst above this flow rate a uniform curtain of water occurred; this clearly affected the sound properties of this feature.

Main findings:

- Logarithmic increases of L_{Aeq} with flow rate for almost all small to medium sized water features
- Waterfalls are louder than any other type of water feature
- Waterfalls have a smaller range of variation in L_{Aeq} compared to fountains, jets and cascades

- A slope design with water flowing over it (and not falling over it from any height) produces the lowest sound pressure level between all types of water features
- The sound pressure level L_{Aeq} varies in the range 40-75 dBA for all the water features tested in the laboratory

4.2.2 Spectra vs. Flow rate

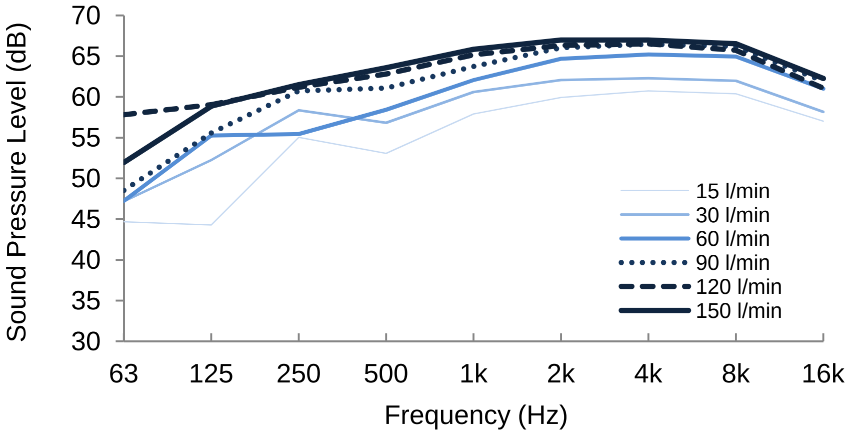
The water sounds produced by all the features tested are mid and high frequency dominant, with most of the energy contained in the 500 Hz – 16 kHz octave bands (Fig. 4.3, 4.4 and 4.5). These are effectively wide band sounds, and for most of the features tested the sound pressure level is greater than 55 dB within those frequencies (all results of spectra vs. flow rate are available in Appendix C).

The changes in flow rate appear to affect the sound pressure level equally for all frequencies above 500 Hz (dominant range), whilst the low frequency changes tend to be variable and less significant for all water features (*e.g.* Fig. 4.4 and 4.5), except waterfalls with plain and sawtooth edges (Fig. 4.3(a) and 4.3(b)). The waterfall with the small holes edge cannot produce low frequencies because of its narrow streams which cannot generate large bubbles (refer to equation (2.1)). Referring back to the background noise present in the laboratory (Fig. 3.9), it can also be noted that the sound pressure level of fountains and jets at 63 Hz is likely to have been affected by background noise, which was found to be in the region of 40 dB at 63 Hz.

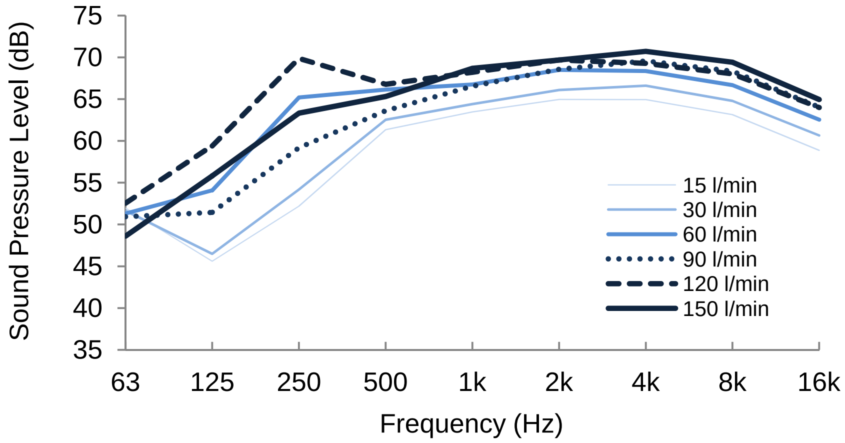
Overall, results show that low frequency sounds cannot be easily generated by increasing the flow rate in features such as fountains, jets, as well as cascades and sloping surfaces (see Appendix C). However, low frequencies can be produced in waterfalls by increasing the flow rate.

Main findings:

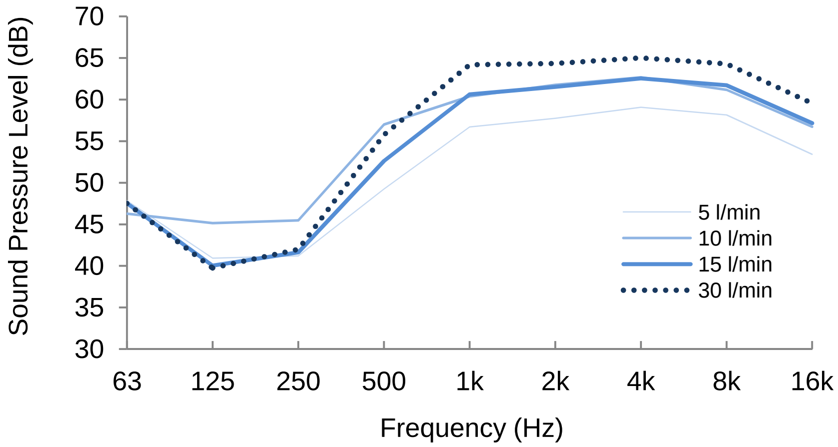
- Water produces wide band sounds dominated by the 500 Hz - 16 kHz frequencies
- Increases in flow rate affect sound pressure level increases equally above 500 Hz
- With the exception of waterfalls, increasing the flow rate is not an effective way of generating low frequency sounds
- Large nozzle jets with low flow rates and no extension can be used to produce sounds that have a fairly flat frequency response



(a) Waterfall plain edge (1 m width and 1 m height)

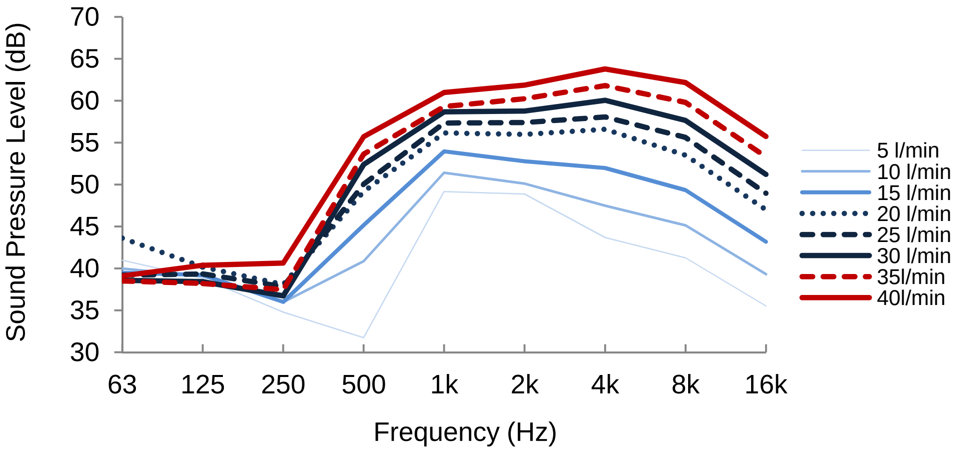


(b) Waterfall sawtooth edge (1 m width and 1 m height)

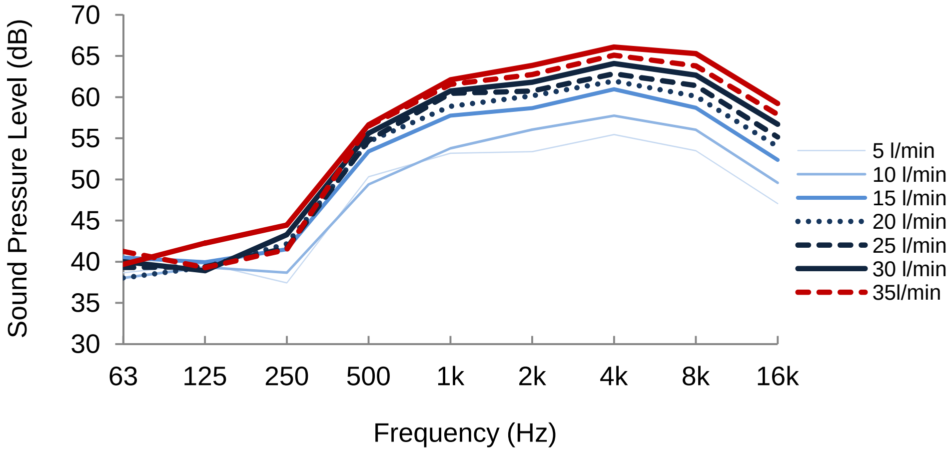


(c) Waterfall small holes edge (1 m width and 1 m height)

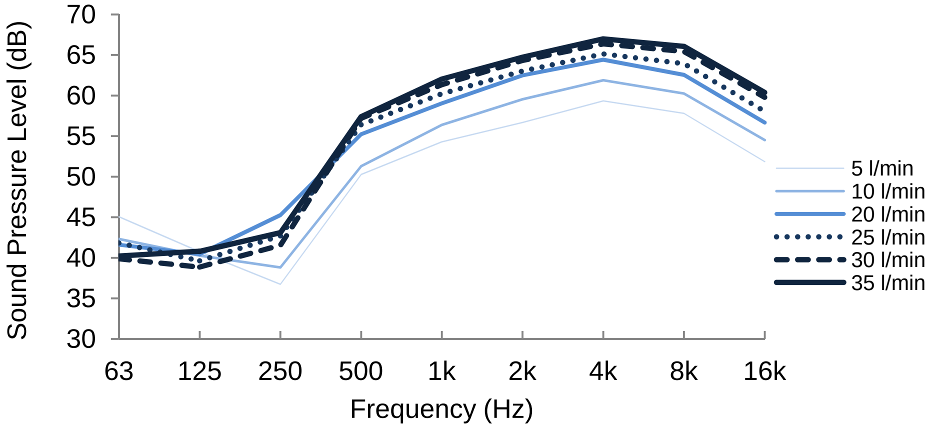
Figure 4.3 Spectra of waterfalls obtained for different flow rates.



(a) Fountain 37 jets (no extension)

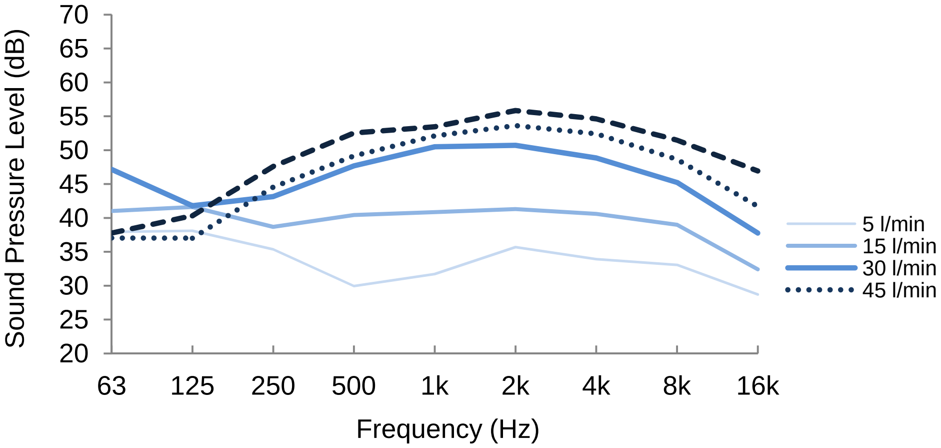


(b) Fountain 37 jets (0.5 m extension)

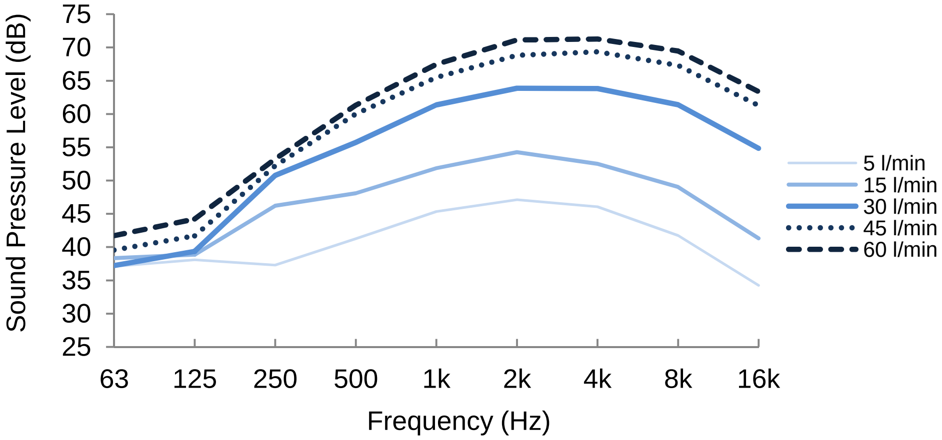


(c) Fountain 37 jets (1.0 m extension)

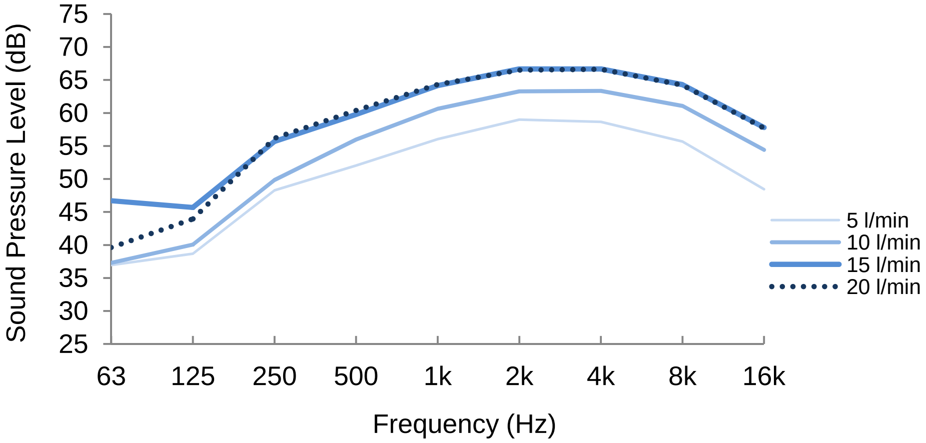
Figure 4.4 Spectra of fountain with 37 jets obtained for different flow rates.



(a) Jet 25 mm nozzle



(b) Jet 15 mm nozzle



(c) Jet 10 mm nozzle

Figure 4.5 Spectra of upward jets obtained for different flow rates.

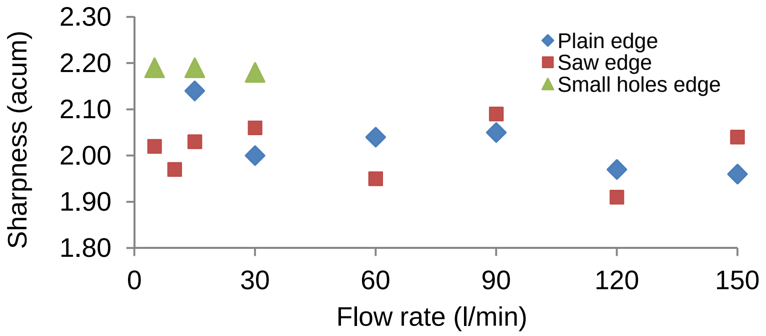
4.2.3 Psychoacoustic parameters vs. Flow rate

Regarding the effects of flow rate on psychoacoustical parameters (Fig. 4.6, 4.7 and 4.8), it can be noted that sharpness (typical values of 1.70–2.25 acum) and pitch strength (typical values of 0.05–0.10) exhibit no clear trends for waterfalls, whilst for cascades, fountains and jets there is a small increase in sharpness with flow rate and the increase is linear (whilst pitch strength tends to be fairly constant). On the other hand, roughness decreases logarithmically with flow rate for all the water features tested (decreases of 0.10 to 0.30 asper), with the exception of the jet with a 5 mm nozzle, for which it tends to increase with flow rate.

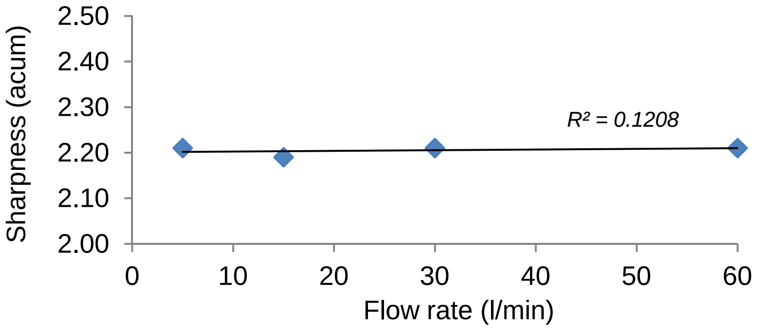
4.3 Waterfalls' edge design

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 sawtooth edge design creates several streams of water (Fig. 3.3) and hence several localised pockets of bubbles. As already pointed out in Chapter 3, it can be shown that the sawtooth 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 (2 mm diameter) is also useful for representing a 'rain' type of water distribution. These three edge designs (plain edge, sawtooth edge and small holes edge) were found to be representative of a variety of waterfalls and results obtained from these are given in Fig. 4.9 and Fig. 4.10 (all spectra results are available in Appendix D).

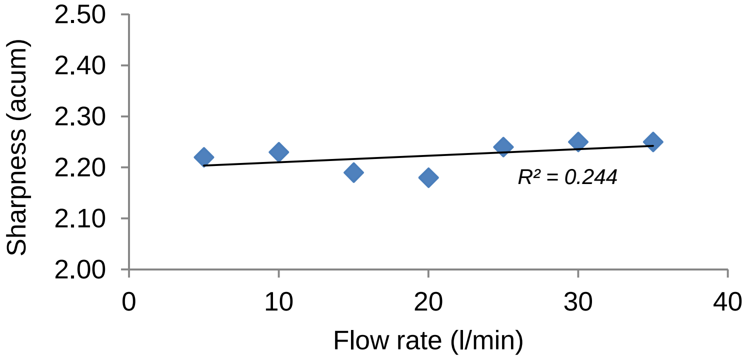
Fig. 4.9 shows that higher sound pressure levels L_{Aeq} are obtained when distributing the same amount water over several streams (sawtooth edge and small holes edge) rather than over one uniform stream (plain edge). This is due to the generation of a larger amount of small bubbles from the several streams, the smaller bubbles producing the mid-high frequency content which is dominant in water sounds (refer to equation (2.1)). As previously pointed out, 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). Sound pressure levels produced by the small holes design lie somewhere between the plain edge and sawtooth edge designs. It can also be noted that the logarithmic trend of L_{Aeq} with flow rate is unaffected by the type of edge design.



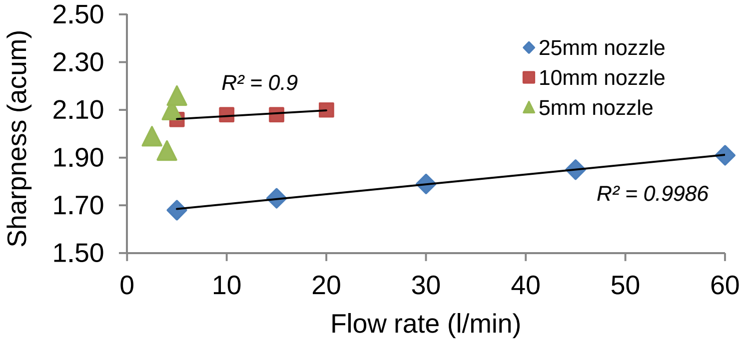
(a) Waterfalls of 1 m height and 1 m width



(b) Cascade over stones

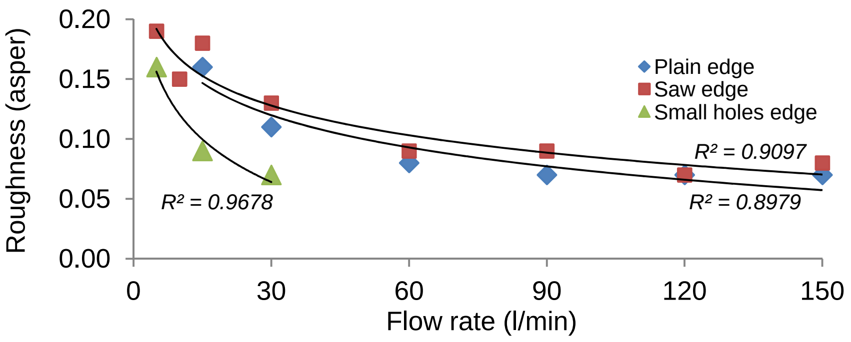


(c) Fountain (37 jets) with 0.5 m extension

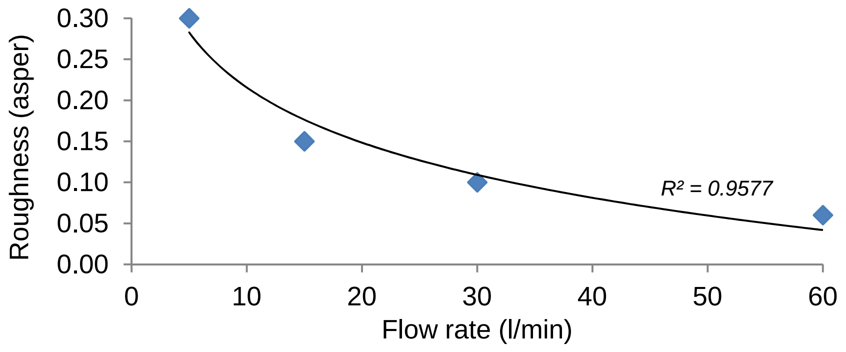


(d) Jets

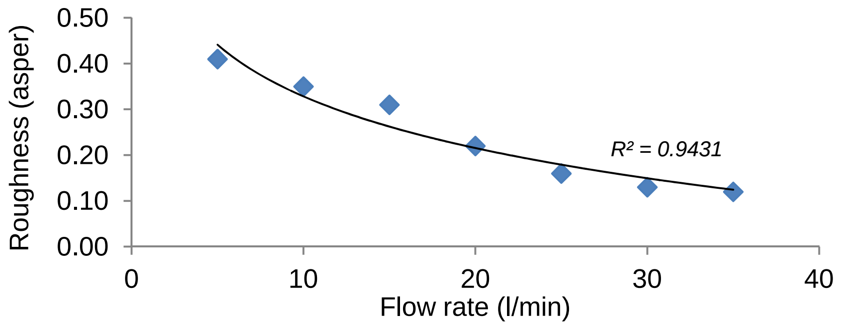
Figure 4.6 Sharpness vs. Flow rate for different water features, with regressions (best fit lines) and coefficient of determination R^2.



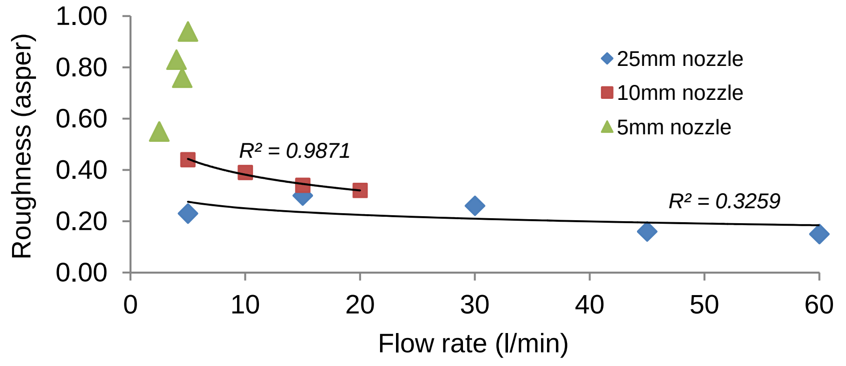
(a) Waterfalls of 1 m height and 1 m width



(b) Cascade over stones

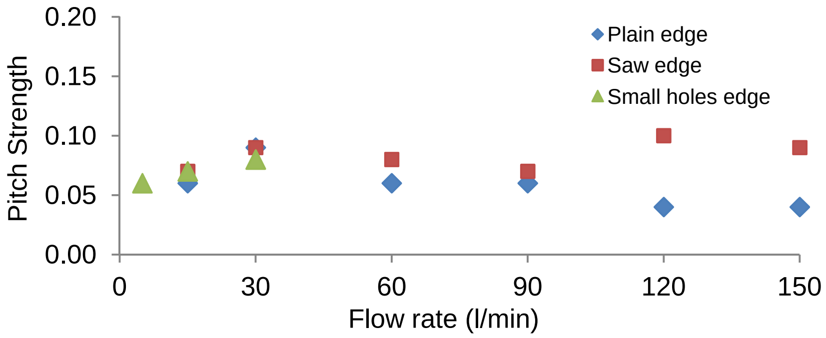


(c) Fountain (37 jets) with 0.5 m extension

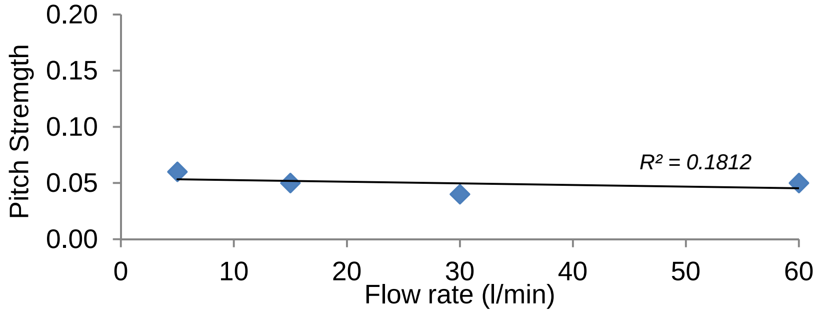


(d) Jets

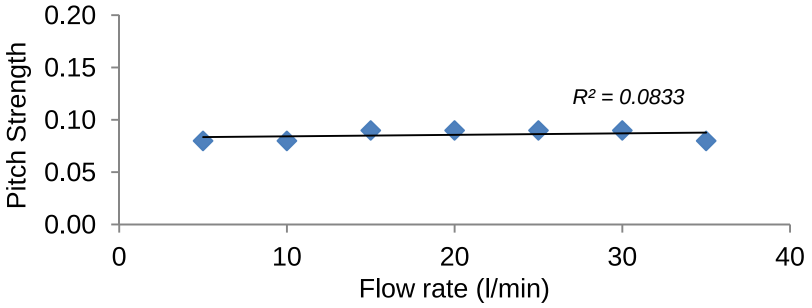
Figure 4.7 Roughness vs. Flow rate for different water features, with regressions (best fit lines) and coefficient of determination R^2.



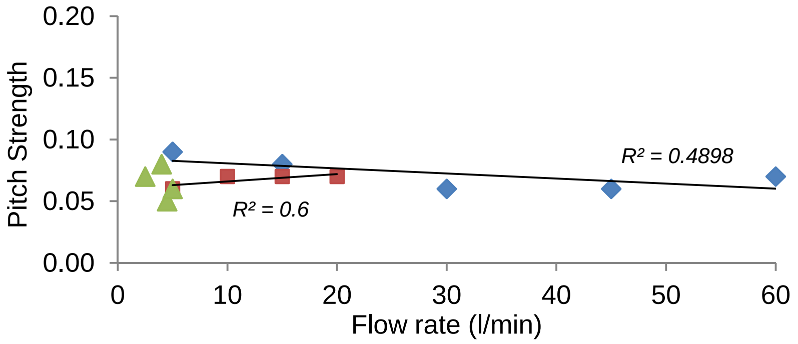
(a) Waterfalls of 1 m height and 1 m width



(b) Cascade over stones



(c) Fountain (37 jets) with 0.5 m extension



(d) Jets

Figure 4.8 Pitch Strength vs. Flow rate for different water features, with regressions (best fit lines) and coefficient of determination R^2.

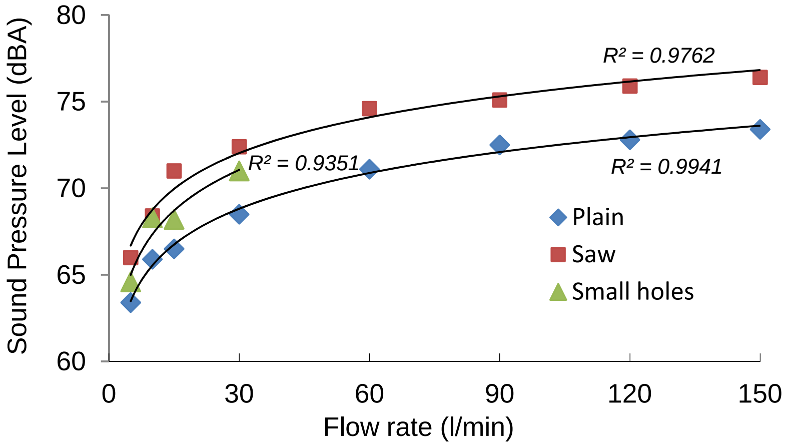
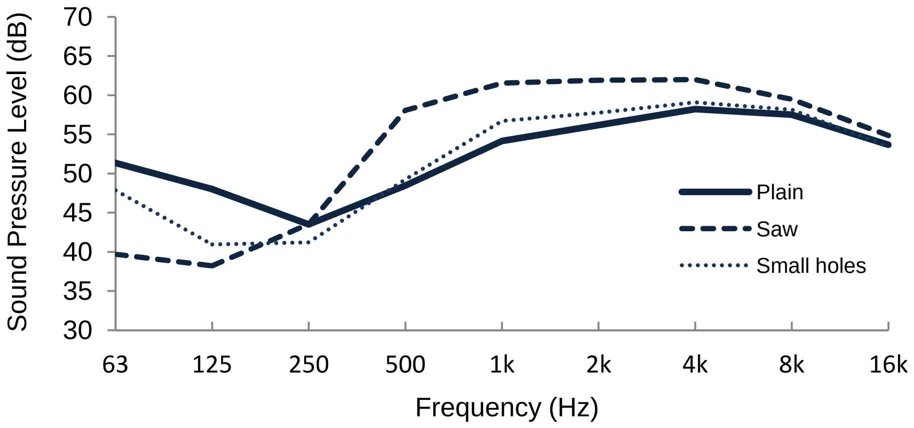


Figure 4.9 L_{Aeq} vs. flow rate for different types of waterfall edges, with regressions (best fit lines) and coefficient of determination R^2.

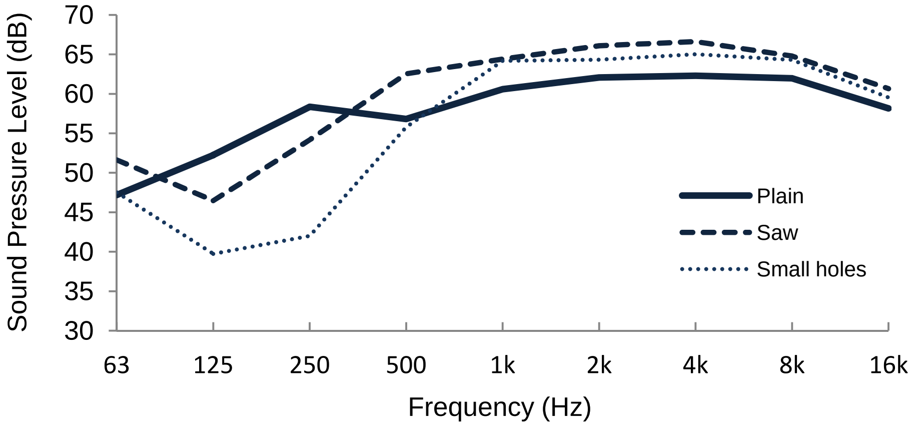
Frequency analysis is given in Fig. 4.10. When comparing sawtooth edge results with plain edge results, it can be seen that for a low flow rate (*e.g.* 5 l/min) the largest increases in sound pressure level occur between 500 Hz and 4 kHz, whilst at a mid flow rate (*e.g.* 30 l/min) the increases tend to be more uniformly distributed between 500 Hz and 16 kHz. For very high flow rates (above 90 l/min), low frequencies levels are slightly higher for the plain edge design (in the order of 5 dB at 63 Hz and 125 Hz), as the latter can generate larger bubbles from its single wide stream (refer to equation (2.1)). In contrast, the small holes edge design has the smallest low frequency content because of its narrow streams (refer to equation (2.1)). Finally, it can be noted that the proportion of high frequencies is reflected in the sharpness (Fig. 4.6), as the small holes edge produces a higher sharpness compared to the plain and sawtooth edges (≈ +0.20 acum). In contrast, the variations in roughness (Fig. 4.7) and pitch strength (Fig. 4.8) are small (Roughness ≈ -0.05 asper for the small holes edge on average, Pitch Strength ≈ +0.02 for the sawtooth edge on average).

Main findings:

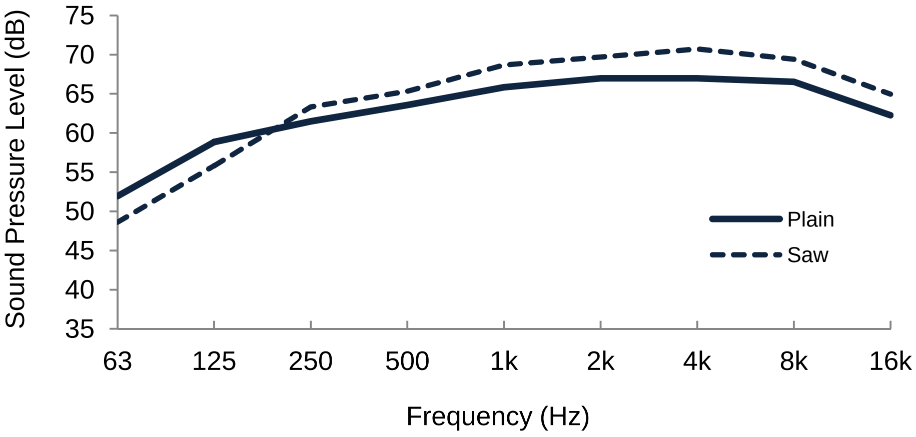
- Several streams of water, as opposed to one large stream of water, increases the overall sound pressure level of 2-3 dB (for identical flow rates)
- Edge design does not affect the logarithmic trend of L_{Aeq} with flow rate
- The plain edge design has the highest low frequency content, whilst the small holes edge design has the smallest low frequency content and highest sharpness



(a) Waterfalls' spectra at 5 l/min



(b) Waterfalls' spectra at 30 l/min



(c) Waterfalls' spectra at 150 l/min

Figure 4.10 Impact of the waterfall's edge design on spectra (1 m height and 1 m width waterfall).

- The sawtooth edge and small holes edge designs are more effective than the plain edge at generating mid and high frequencies

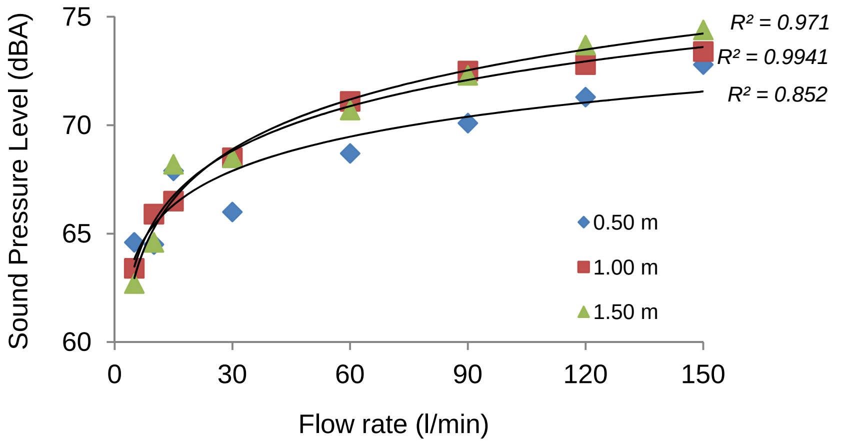
4.4 Waterfalls' width

Tests have been made for different widths of waterfalls and the results obtained for the continuous equivalent noise level are shown in Fig. 4.11. For the plain edge and sawtooth edge designs, increases in L_{Aeq} are observed when the width is enlarged from 0.50 m to 1.50 m. The increases tend to be larger at higher flow rates, where they are in the order of 2-3 dB. On the other hand, no clear trend is observed for the small holes edge waterfall of Fig. 4.11(c). This might be related to the fact that large flow rates could not be achieved for this edge type.

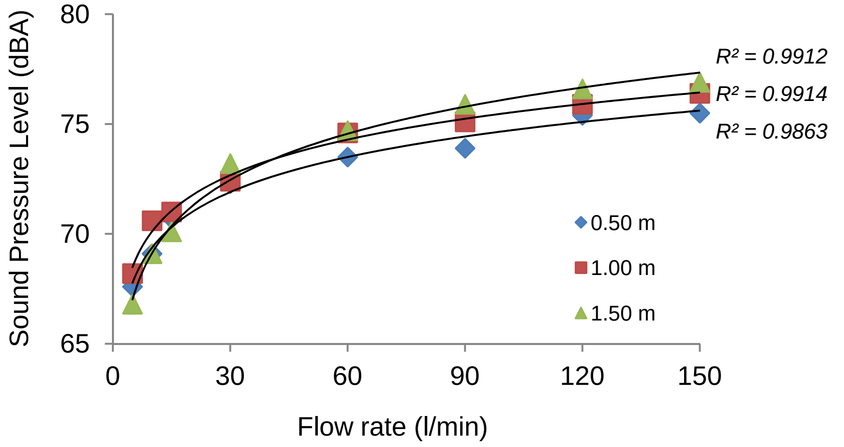
Analysis was also made on constant width flow rates, *i.e.* identical flow rates delivered in terms of litres per meter (or more precisely, in litres per minute per meter). Results obtained are given in Fig. 4.12 and 4.13 for a flow rate of 120 l min^{-1} m^{-1} (results obtained for all flow rates are available in Appendix E), where it can be seen that the sound pressure level increases with larger waterfalls' widths. On average, it was found that 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. For low flow rates (60 l min^{-1} m^{-1}), the increase in sound pressure level is uniform between 500 Hz and 16 kHz, whilst for higher flow rates (120 l min^{-1} m^{-1} and 240 l min^{-1} m^{-1}) the increase is uniform above 250 Hz (see Appendix E).

Main findings:

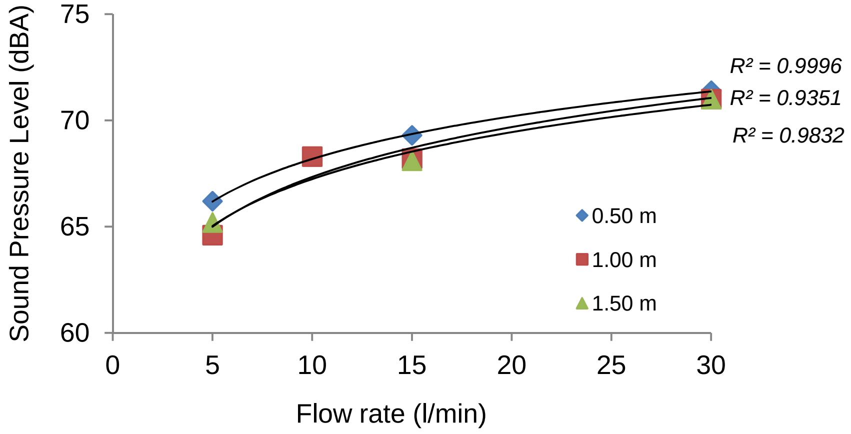
- At high flow rates, an increase in the width of a waterfall tends to increase the overall sound pressure level of 2-3 dB
- For constant width flow rate (*i.e.* identical flow rates delivered in terms of litres per meter), a doubling in width corresponds approximately to an increase in L_{Aeq} of 3 dB



(a) Waterfall plain edge

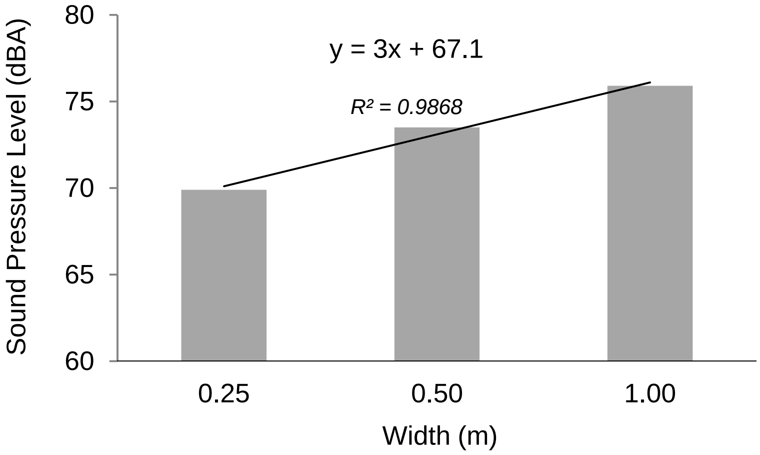


(b) Waterfall sawtooth edge

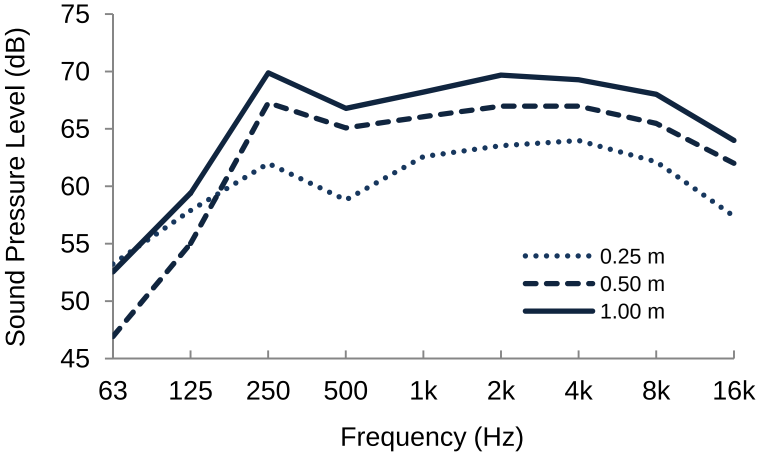


(c) Waterfall small holes edge

Figure 4.11 The impact of waterfalls' width on the sound pressure level L_{Aeq}, with regressions (best fit lines) and coefficient of determination R^2.

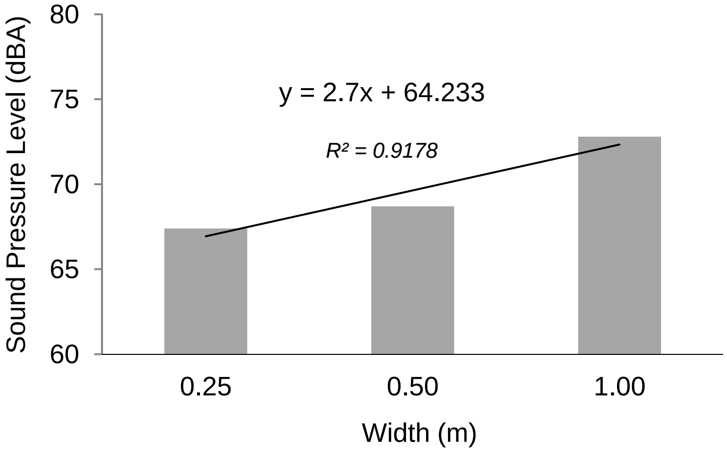


(a) L_{Aeq} vs. width (with best fit regression and coefficient of determination R^2)

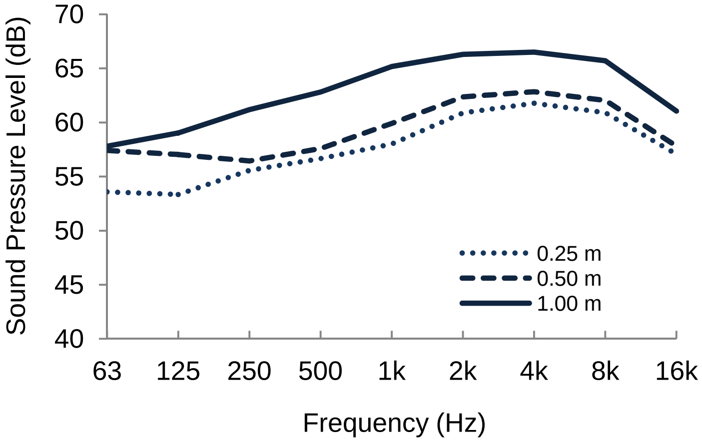


(b) Spectra vs. width

Figure 4.12 Waterfall sawtooth edge: the impact of constant width flow rate on the sound pressure level (120 l min^{-1} m^{-1}).



(a) L_{Aeq} vs. width (with best fit regression and coefficient of determination R^2)



(b) Spectra vs. width

Figure 4.13 Waterfall plain edge: the impact of constant width flow rate on the sound pressure level (120 l min^{-1} m^{-1}).

4.5 Height of falling water

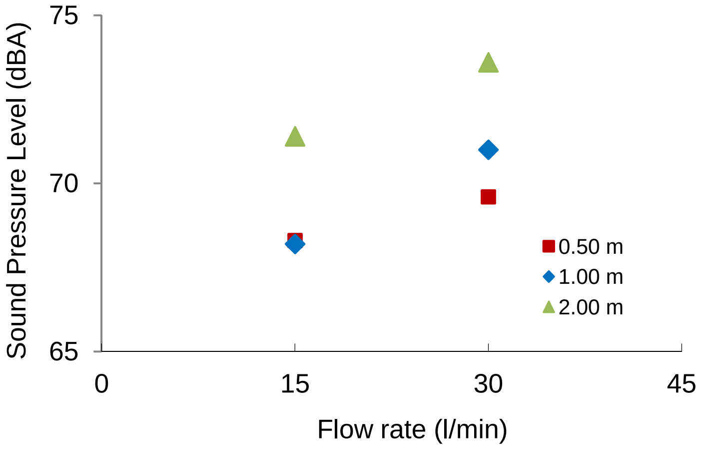
Looking back at Fig. 4.1, together with Fig. 4.14 shown on the following page, it is interesting to note that an increase in the height of falling water can increase L_{Aeq} levels noticeably (up to +10 dB), with the exception of waterfalls operated at low flow rates for the 0.50 m and 1.00 m impact heights. This suggests that waterfalls of low height, operating at low flow rates, produce similar sounds, a trend which is not observed in fountains (Fig. 4.14(c)).

Fig. 4.15 shows that the height from which water falls affects the shape of the frequency response, but changes are not uniform across all frequencies (all the waterfalls and fountain spectra are available in Appendix F). Overall, increases are more uniform above 500 Hz, but the spectral changes observed vary for each feature and do not exhibit a predictable trend.

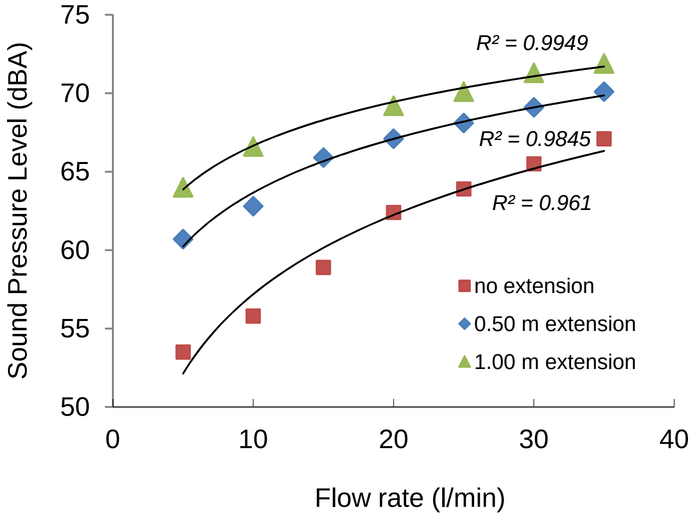
On average, sharpness (Fig. 4.16) and roughness (Fig. 4.17) tend to increase with the height of falling water, whilst the pitch strength (Fig. 4.18) decreases. However, the variations observed are not significant (Sharpness ≈ +0.10 acum, Roughness ≈ +0.10 asper, Pitch Strength ≈-0.05), and no trends can be given due to the fact that only three heights were tested.

Main findings:

- Increasing the height of falling water can increase the sound pressure level significantly (5-10 dB), with the exception of waterfalls of low heights operated at low flow rates (waterfalls of 1 m height or less, with a flow rate of 15 l/min or less)
- The height from which water falls affects the shape of the frequency response, but the spectral changes do not exhibit a predictable trend

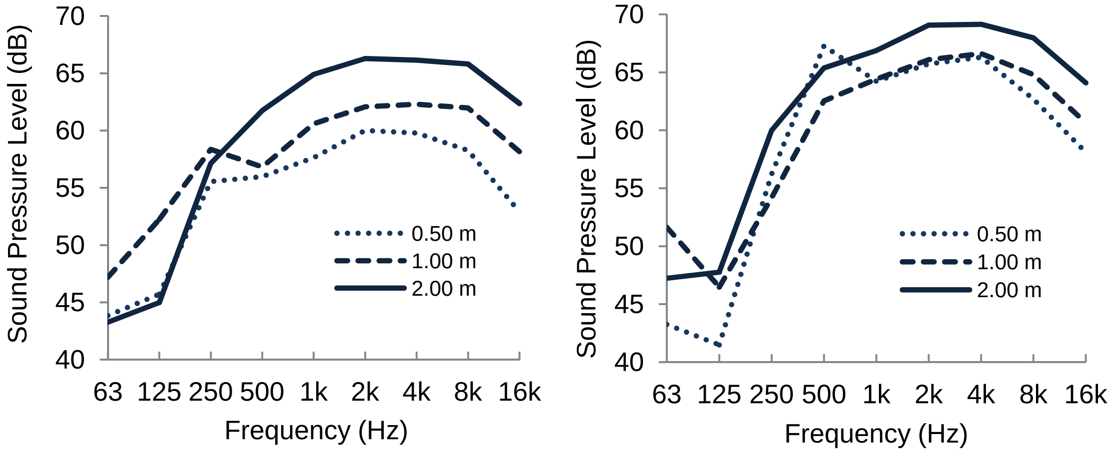


(a) Waterfall small holes (1 m width)



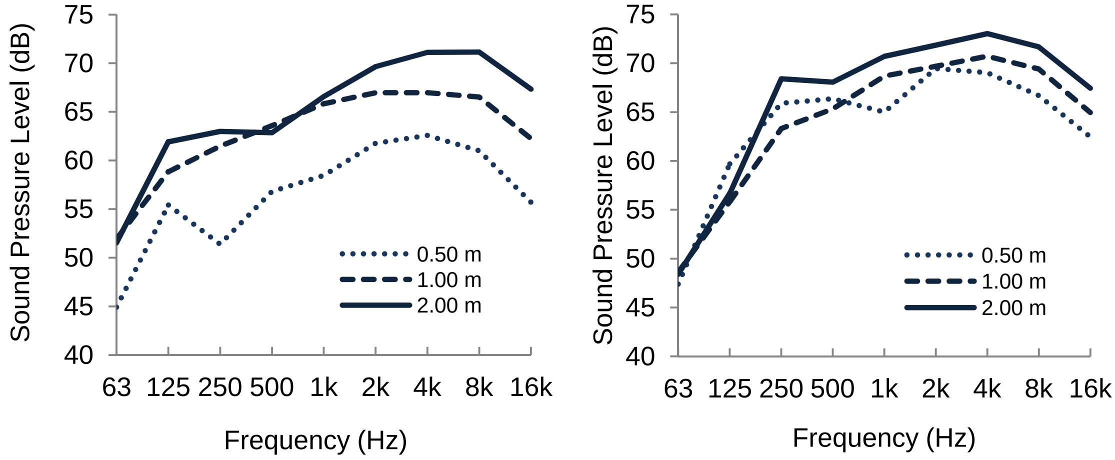
(b) Fountain (37 jets), with regressions (best fit lines) and coefficient of determination R^2

Figure 4.14 The impact of the height of falling water on L_{Aeq}.



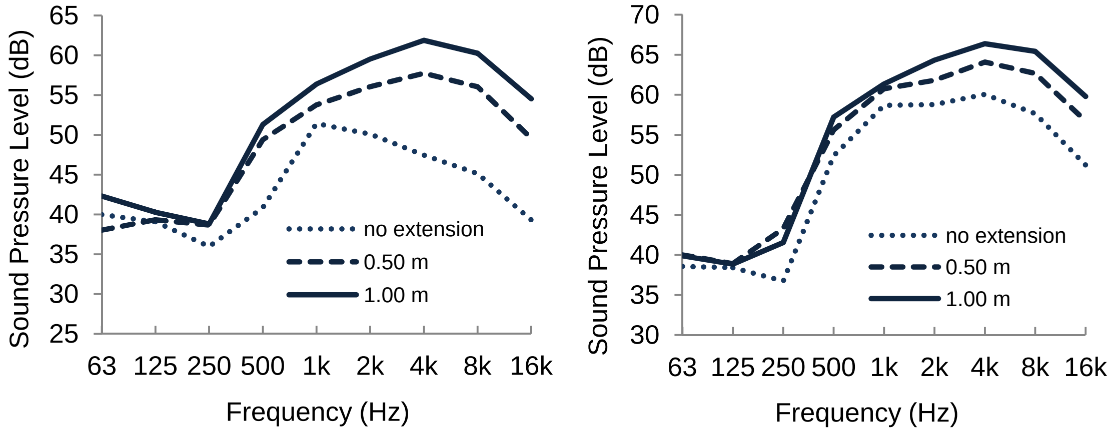
(a) Waterfall plain edge 30 l/min

(b) Waterfall sawtooth edge 30 l/min



(c) Waterfall plain edge 150 l/min

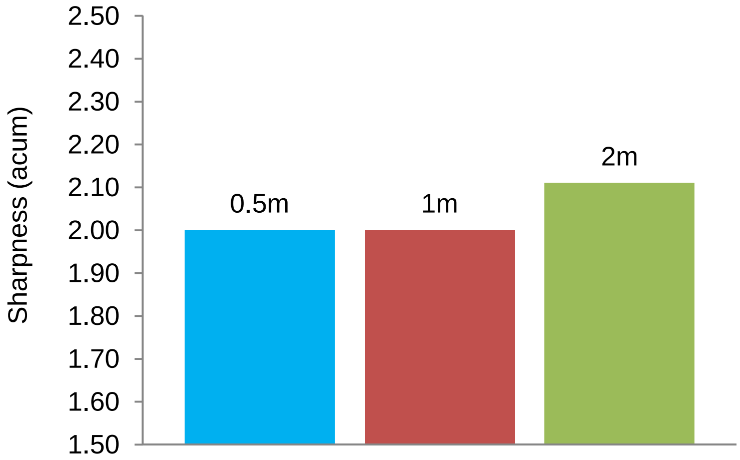
(d) Waterfall sawtooth edge 150 l/min



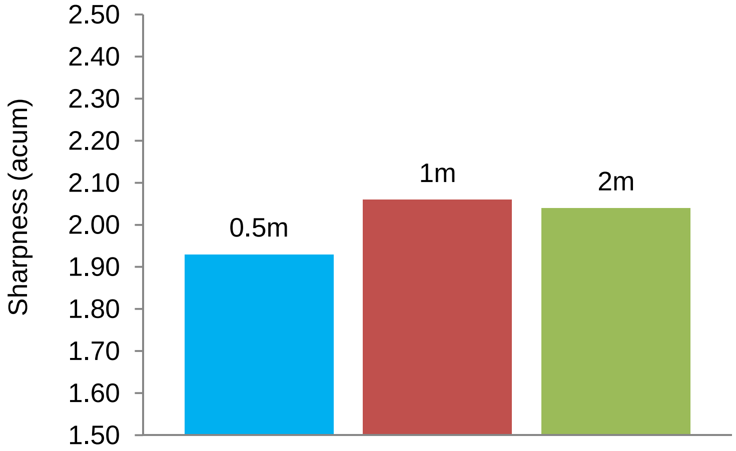
(e) Fountain (37 jets) 10 l/min

(f) Fountain (37 jets) 30 l/min

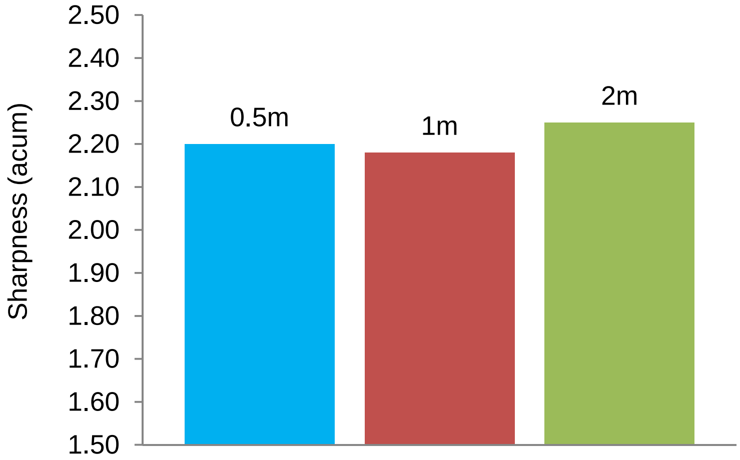
Figure 4.15 The impact of the height of falling water on spectra.



(a) Waterfall plain edge 30 l/min

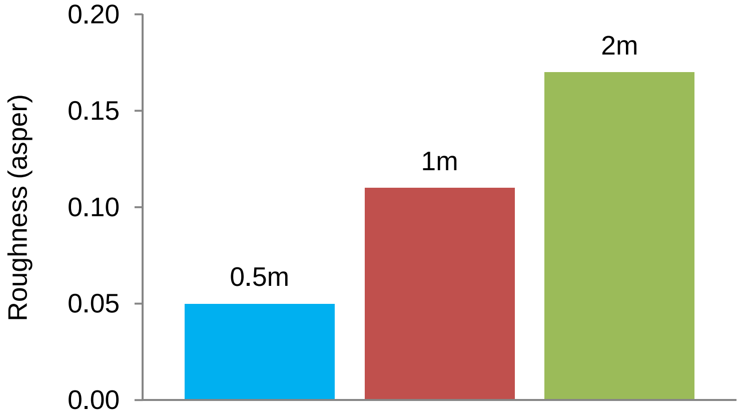


(b) Waterfall sawtooth edge 30 l/min

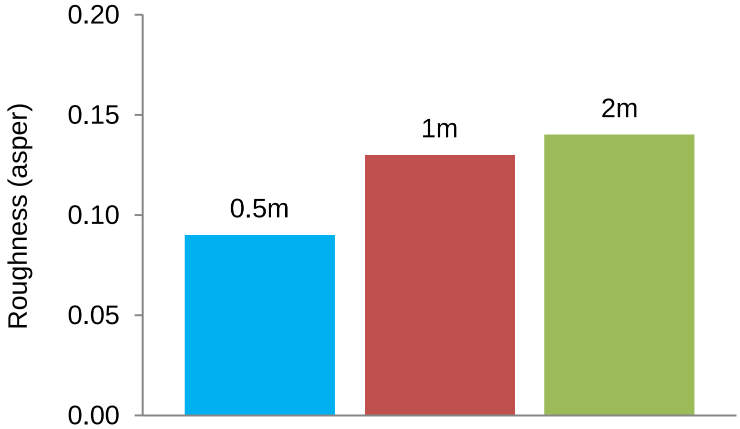


(c) Waterfall small holes edge 30 l/min

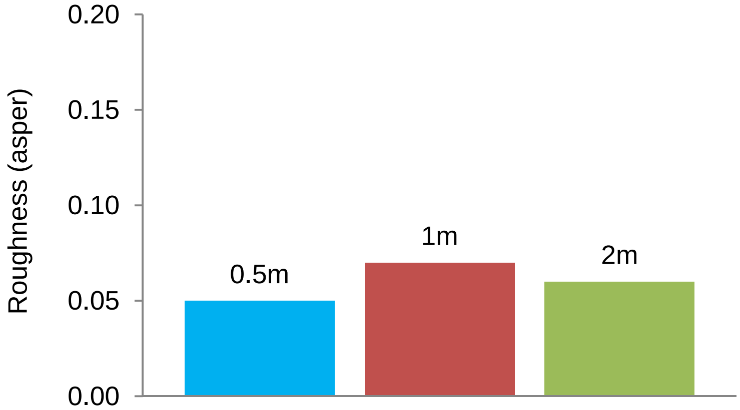
Figure 4.16 The impact of the height of waterfalls on sharpness.



(a) Waterfall plain edge 30 l/min

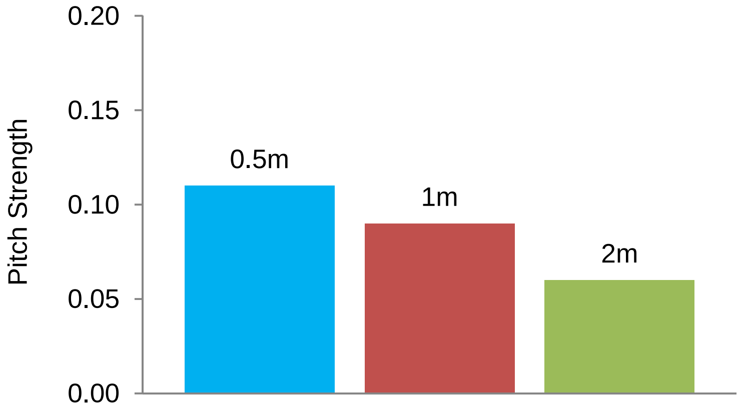


(b) Waterfall sawtooth edge 30 l/min

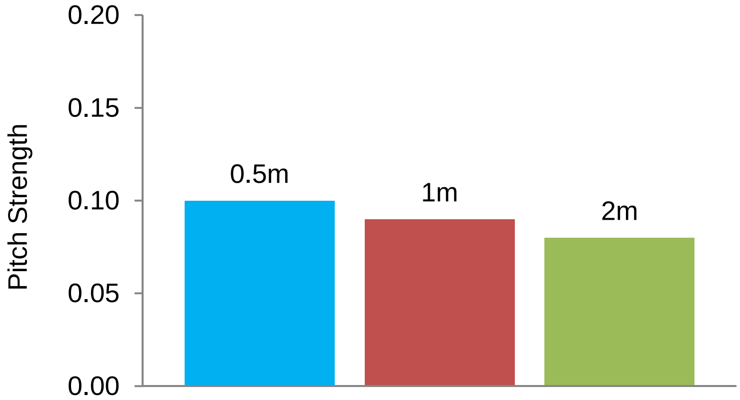


(c) Waterfall small holes edge 30 l/min

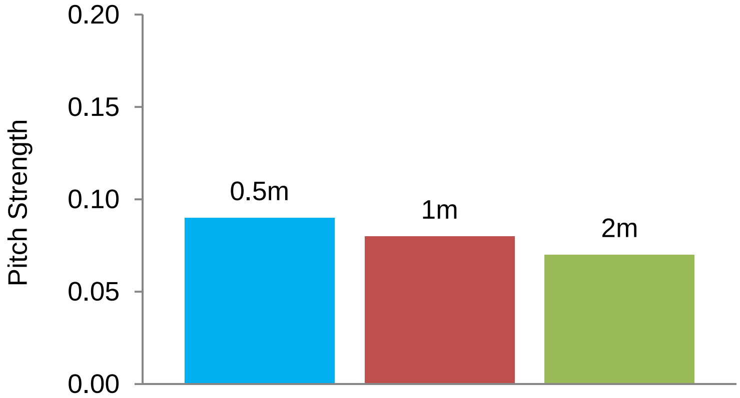
Figure 4.17 The impact of the height of waterfalls on roughness.



(a) Waterfall plain edge 30 l/min



(b) Waterfall sawtooth edge 30 l/min



(c) Waterfall small holes edge 30 l/min

Figure 4.18 The impact of the height of waterfalls on pitch strength.

4.6 Impact materials

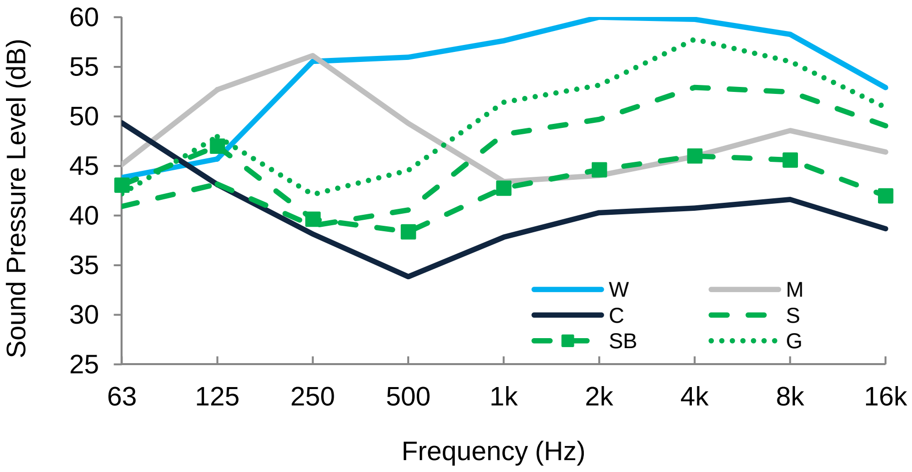
Impact materials can greatly affect the acoustical and psychoacoustical properties of water features. Changes in properties vary with the type of feature considered and a large set of results are presented in this section to illustrate this (waterfalls with different edges and heights, as well as fountains and jets). The impact materials considered include water, concrete, metal, stones, boulders and gravel (more details can be found in Chapter 3, section 3.2). The complete set of results obtained from laboratory experiments is available in Appendix G, and the main findings are summarised at the end of this section.

4.6.1 Waterfalls

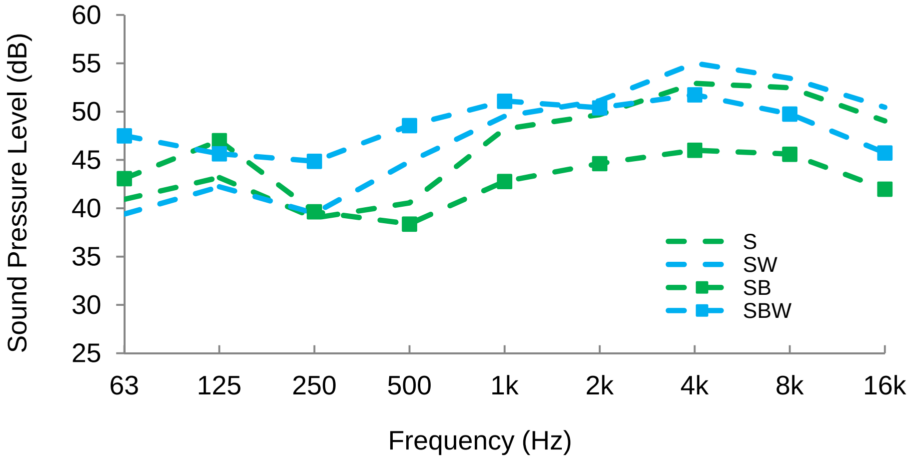
Waterfall plain edge – 0.5 m height

Results of the continuous equivalent sound pressure level are given in Fig. 4.19 for the waterfall with a plain edge and a height of falling water of 0.5 m. 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. Stones (pebbles) and gravel present irregular surfaces which allow the formation of pockets of water and hence vibrating bubbles, so that the L_{Aeq} observed for these materials is higher than the one observed for plain surfaces (in the order of 5-10 dB higher on average).

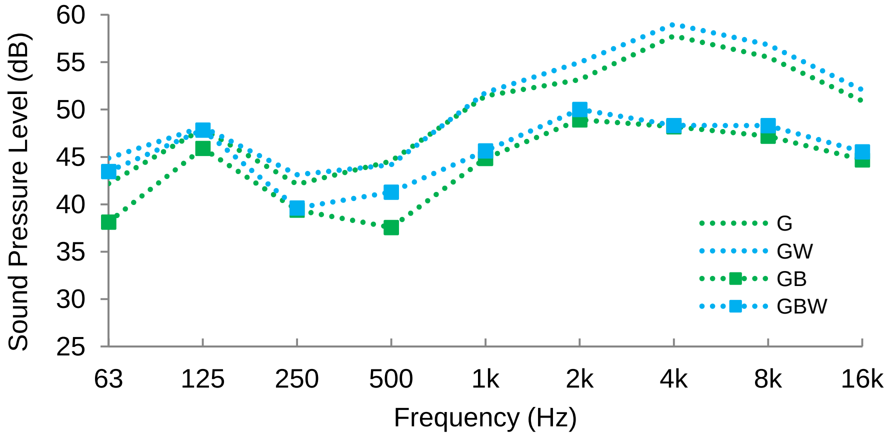
Figure 4.19 L_{Aeq} of waterfall plain edge 0.5 m height, 1 m width and 30 l/min, with different impact materials.



(a) Combinations of materials



(b) Combinations of materials including stones



(c) Combinations of materials including gravel

Figure 4.20 Spectra of waterfall plain edge 0.5 m height, 1 m width and 30 l/min, with different impact materials.

For a medium flow rate of 30 l/min (Fig. 4.19), 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, see Appendix G1). The former might be due to the easy formation of bubbles between gravel 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 have also been tested over stones or gravel. These tend to make water slide over them which limits bubbling sounds, hence resulting in lower L_{Aeq} levels, as can be seen in Fig. 4.19. Combinations of solid materials and water have also been tested, and results are consistent with the previous findings, showing that higher L_{Aeq} levels are obtained when water is present.

The spectra of Fig. 4.20(a) show that water exhibits significantly higher levels than most impact materials at mid frequencies (250 Hz-2 kHz). Stones, gravel and boulders are dominated by high frequencies, whilst the metal and concrete configurations have spectra that are medium to low frequency dominant at 30 l/min, with higher levels below 500 Hz, and are fairly flat across frequencies at high flow rates. Fig. 4.20(a) also shows that the metal plate has a noticeable peak at 250 Hz that is due to a resonance in the plate. Fig. 4.20(b) and 4.20(c) illustrate how the presence of water, within stones or gravel, increases the mid and high frequencies, whilst boulders decrease those.

Comparisons of these results with the data presented below for the sawtooth and small holes edges should be made bearing in mind what was observed while carrying out the tests: the uniform curtain of water produced by the plain edge tended to force water to slide on the sides of the impact material (*i.e.* water did not bounce up), whilst the sawtooth and small holes edges generate localised streams which bounce over it.

Waterfall sawtooth edge – 0.5 m height

The findings are similar to those discussed for the plain edge, but the changes in L_{Aeq} observed are significantly smaller: approximately 5 dB variation between water and metal/concrete, and 2-3 dB between metal/concrete and stones/gravel (Fig. 4.21). It should also be noted that the spectra of metal and concrete are less flat and exhibit much more mid and high frequencies (Fig. 4.22). These results suggest that the multiple streams generated by the sawtooth edge increase the impact sound as well as the amount of water falling over water (*i.e.* splashing), compared to the plain edge where water was pushed towards the sides of the impact material.

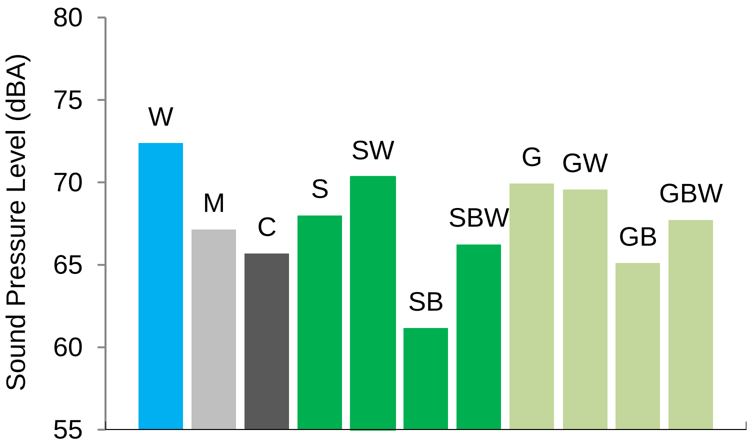


Figure 4.21 L_{Aeq} of waterfall sawtooth edge 0.5 m height, 1 m width and 30 l/min, with different impact materials.

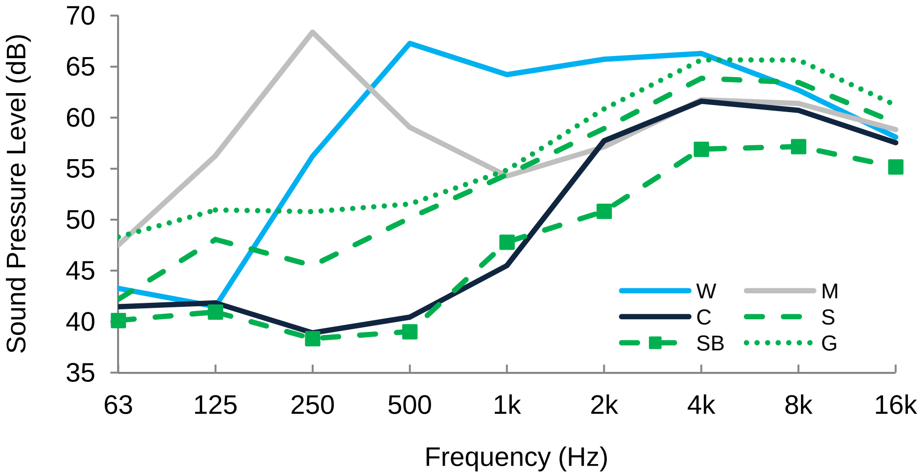


Figure 4.22 Spectra of waterfall sawtooth edge 0.5 m height, 1 m width and 30 l/min, with different impact materials.

Waterfall small holes edge – 0.5 m height

The findings obtained for the waterfall with the small holes edge are identical to those discussed for the sawtooth edge (results can be seen in Appendix G3).

Waterfall plain edge – 1 m height

The findings are comparable to those discussed for the plain edge with a 0.5 m height. However, the difference observed between the water and the metal/concrete tests are smaller (Fig. 4.23 and 4.24), especially for the 30 l/m flow rate (difference in L_{Aeq} of only 2-3 dB), suggesting that the height clearly increases the impact sound generated.

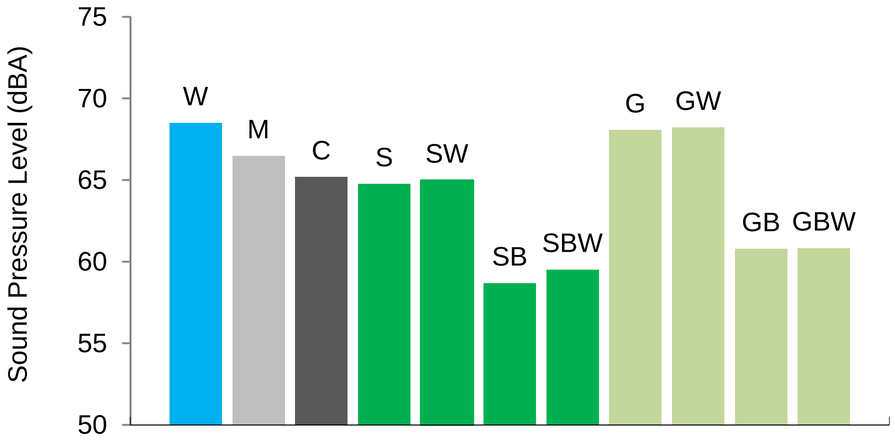


Figure 4.23 L_{Aeq} of waterfall plain edge 1 m height, 1 m width and 30 l/min, with different impact materials.

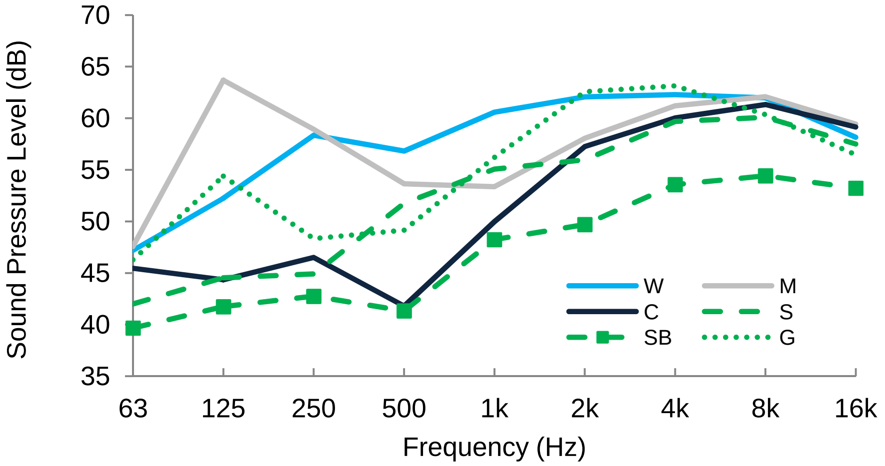


Figure 4.24 Spectra of waterfall plain edge 1 m height, 1 m width and 30 l/min, with different impact materials.

It can also be noted that the increase in impact sound is significantly higher than the increase in bubbling sound (increase for water: 3-8 dB; increase for metal/concrete: 10-15 dB).

Waterfall sawtooth edge – 1 m height

Fig. 4.25 and 4.26 show results which are comparable to the waterfall with a plain edge at a 1 m height. The difference is that at higher flow rates (*e.g.* 60 l/min), the levels for metal and concrete are now higher than for water (Fig. 4.27 and 4.28). At this height, gravel also produce consistently higher L_{Aeq} levels compared to stones,

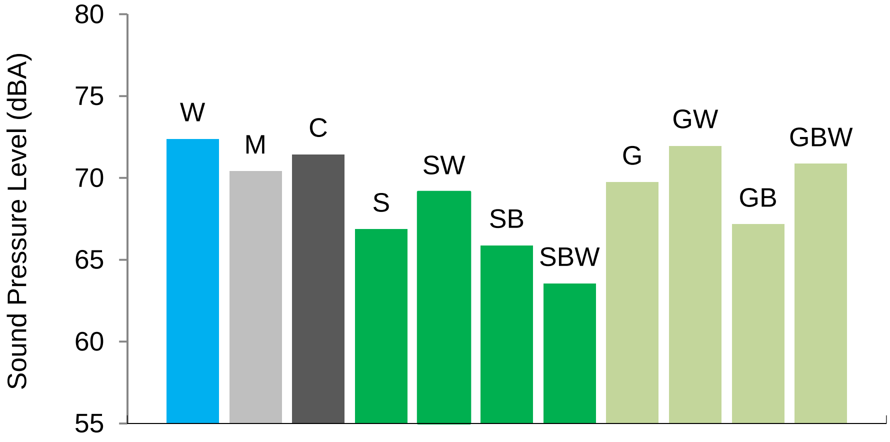


Figure 4.25 L_{Aeq} of waterfall sawtooth edge 1 m height, 1 m width and 30 l/min, with different impact materials.

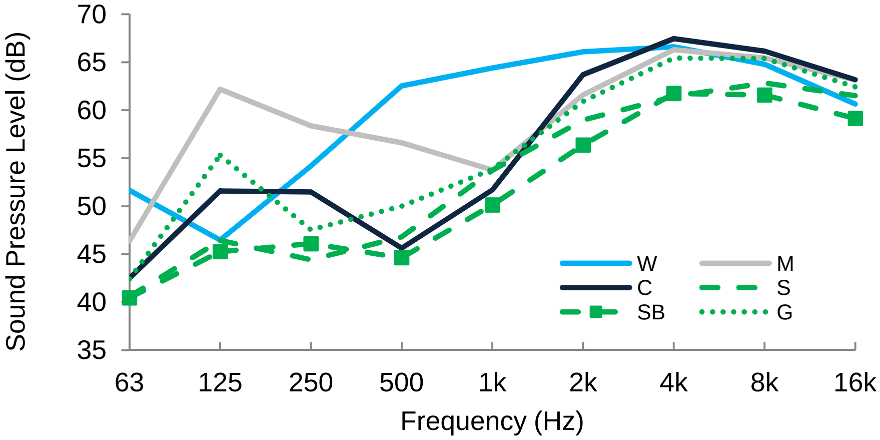


Figure 4.26 Spectra of waterfall sawtooth edge 1 m height, 1 m width and 30 l/min, with different impact materials.

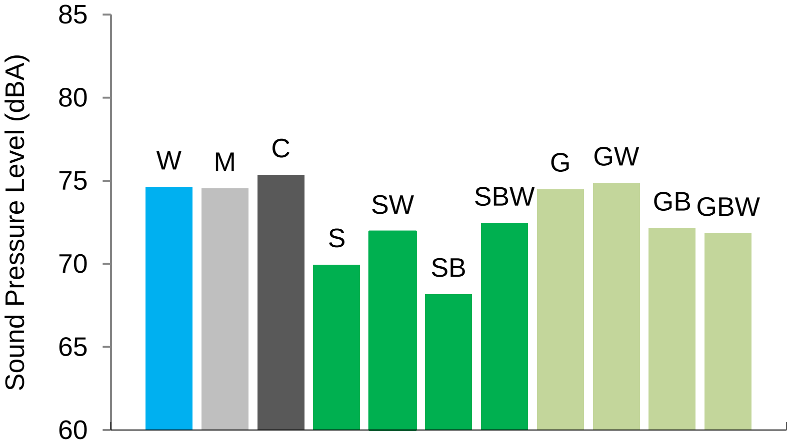


Figure 4.27 L_{Aeq} of waterfall sawtooth edge 1 m height, 1 m width and 60 l/min, with different impact materials.

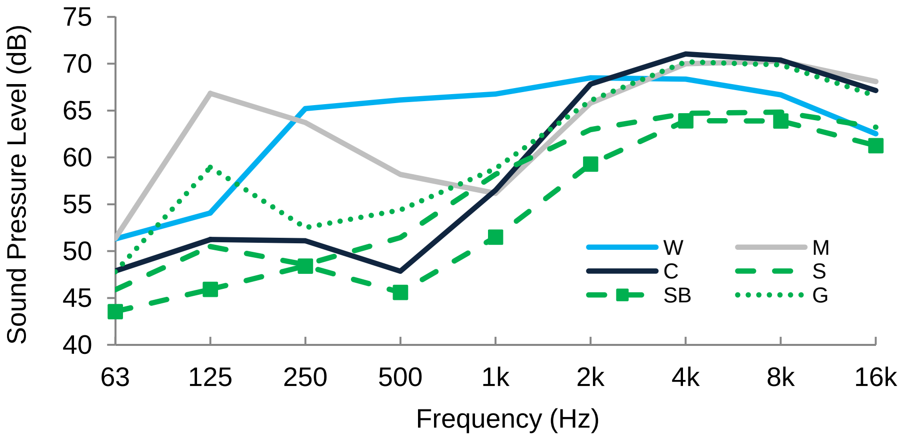


Figure 4.28 Spectra of waterfall sawtooth edge 1 m height, 1 m width and 60 l/min, with different impact materials.

in the order of 2-5 dB depending on the flow rate (see Appendix G5).

Waterfall small holes edge – 1 m height

Relatively small differences in L_{Aeq} are observed between all impact materials (maximum difference of approximately 5 dB). Water still produces the highest L_{Aeq} level (Fig. 4.29), suggesting that the streams of water are too narrow to generate high impact sound.

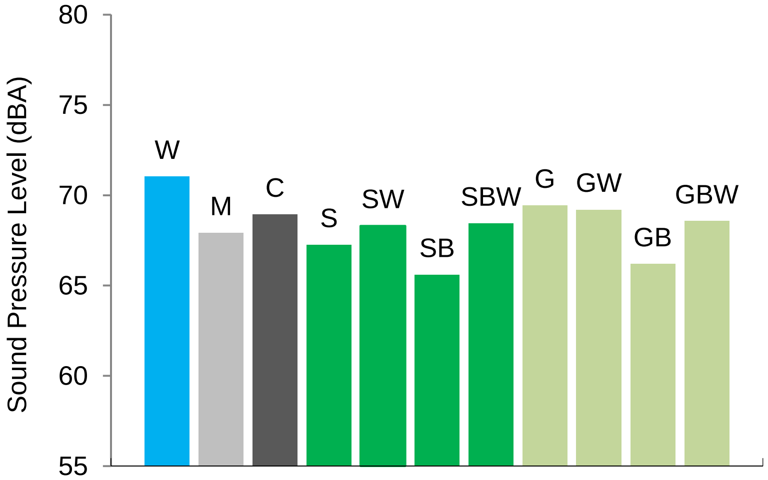


Figure 4.29 L_{Aeq} of waterfall small holes edge 1 m height, 1 m width and 30 l/min, with different impact materials.

Waterfall plain edge – 2 m height

In contrast with the 0.5 m and 1 m heights, the 2 m height waterfall generates higher L_{Aeq} levels for impact over solid materials (Fig. 4.30). Differences between sound pressure levels are however small (maximum 3 dB). All the solid impact materials tested (metal, stones and gravel) produced very similar L_{Aeq} levels, with a maximum difference of 1.5 dB. As found for the 0.5 m and 1 m heights, solid materials still exhibit less mid frequencies compared to water (Fig. 4.31). In contrast with the 0.5 m and 1 m cases, the metal plate now exhibits a spectrum clearly dominated by mid and high frequencies.

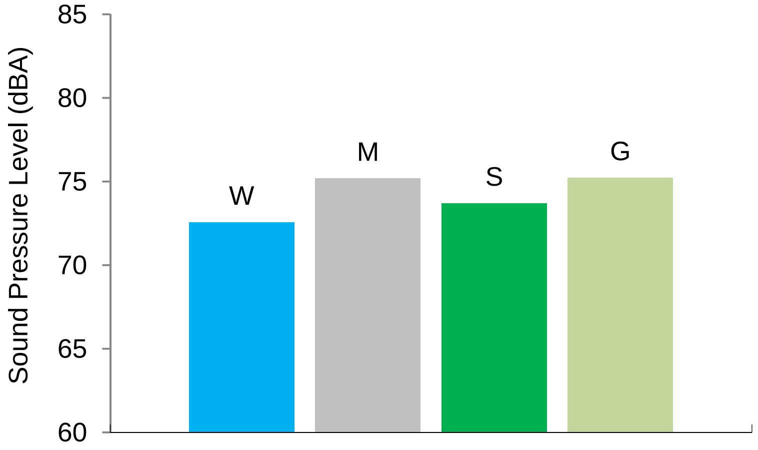


Figure 4.30 L_{Aeq} of waterfall plain edge 2 m height, 1 m width and 30 l/min, with different impact materials.

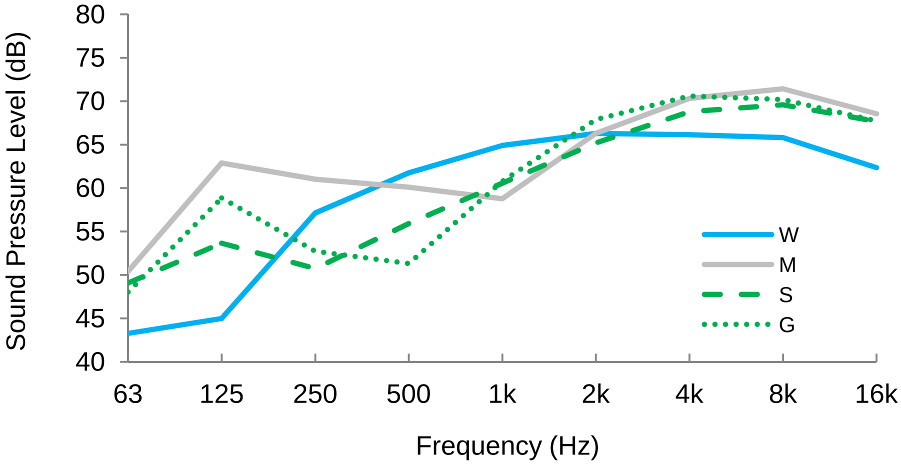


Figure 4.31 Spectra of waterfall plain edge 2 m height, 1 m width and 30 l/min, with different impact materials.

Waterfall sawtooth edge – 2 m height

The findings are comparable to those discussed for the plain edge and 2 m height, with similar values for the differences observed between the impact materials (Fig. 4.32 and 4.33). The only minor difference is represented by water producing a slightly higher L_{Aeq} than stones.

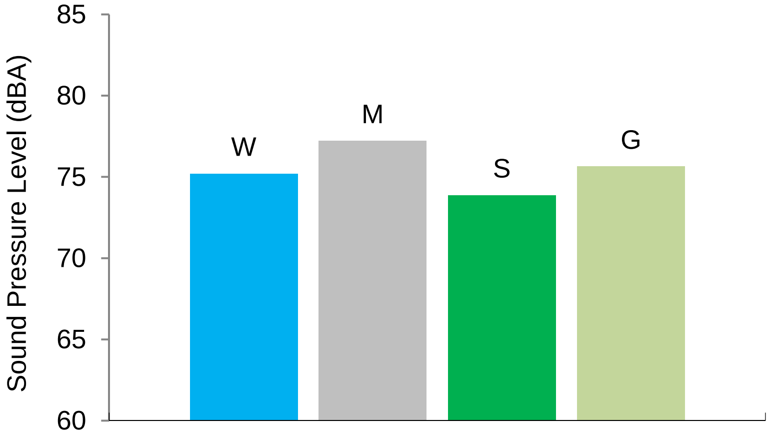


Figure 4.32 L_{Aeq} of waterfall sawtooth edge 2 m height, 1 m width and 30 l/min, with different impact materials.

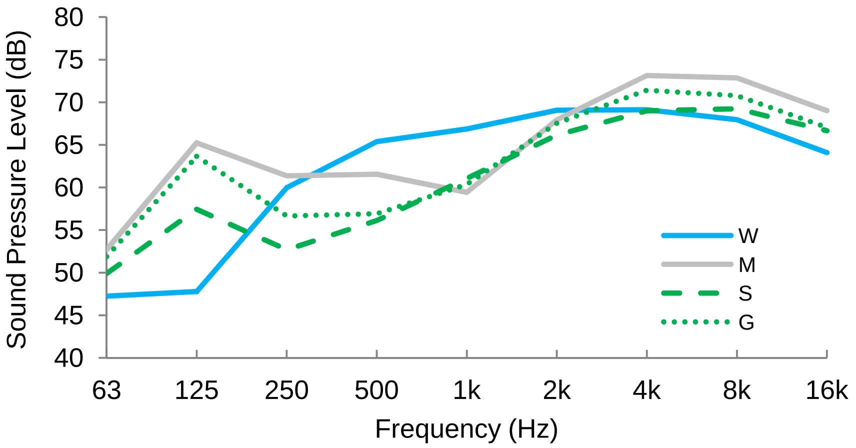


Figure 4.33 Spectra of waterfall sawtooth edge 2 m height, 1 m width and 30 l/min, with different impact materials.

Waterfall small holes edge – 2 m height

As can be seen in Fig. 4.34, findings are again comparable to those discussed for the sawtooth edge at a 2 m height. The only difference appears in the frequency responses (Fig. 4.35) which exhibit less low frequencies (especially around 250 Hz), because of the narrow streams used.

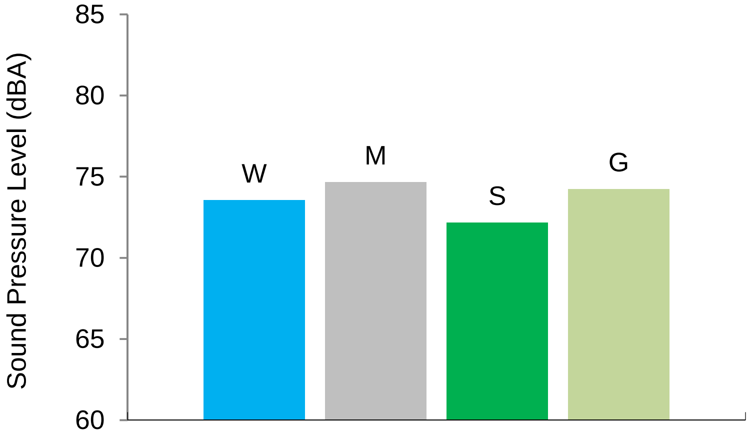


Figure 4.34 L_{Aeq} of waterfall small holes edge 2 m height, 1 m width and 30 l/min, with different impact materials.

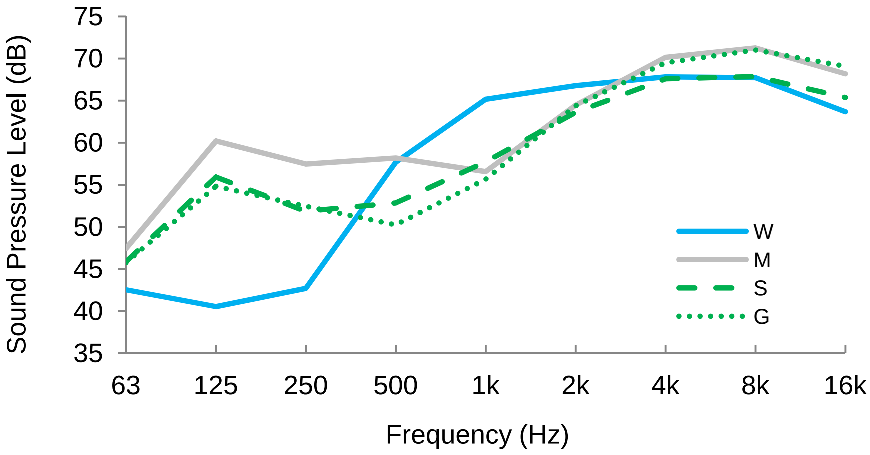


Figure 4.35 Spectra of waterfall small holes edge 2 m height, 1 m width and 30 l/min, with different impact materials.

<u>Impact materials – Waterfalls' main findings</u>

- The use of different impact materials produces large variations in L_{Aeq} levels for low heights of falling water, with differences which can be greater than 10 dB; however, when the height is increased, the differences tend to be reduced because of the increase in impact sound (*e.g.* maximum differences of 3 dB for a 2 m height)
- Plain solid surfaces produce the lowest L_{Aeq} levels due to the absence of vibrating bubbles, whilst water tend to generate higher levels; this is however no true for large heights (*e.g.* 2 m), in which cases solid materials tend to produce higher levels

- Pockets of water can be produced between stones and gravel, a reason why higher levels tend to be obtained for these impact materials; on the other hand, boulders generate low levels as they tend to make water slide over them (*i.e.* no bubbling sound is present)
- The use of water as an impact material generates more mid frequencies compared to hard materials (+5-10 dB in the range 250 Hz – 2 kHz)
- A plain edge tends to produce larger differences in level than a sawtooth edge or a small holes edge, especially for low heights of falling water; this is due to its curtain of water being forced towards the sides of the impact materials (*i.e.* limited splashing)

4.6.2 Fountain (37 jets)

Different results were obtained depending on the flow rate and height of falling water. At a flow rate of 15 l/m (Fig. 4.36), larger variations in L_{Aeq} were observed (up to 7-8 dB), compared to only 2-3 dB at 30 l/min (Fig. 4.37). Stones produced the highest L_{Aeq} level when no extension was used, whilst water produced the highest L_{Aeq} level when a 0.5 m extension was used, and gravel produced the highest L_{Aeq} level when a 1 m extension was used (see Appendix G10). This illustrates the variability of sound characteristics in terms of height and flow rate.

Similarly to what was found for waterfalls, water produced more mid frequencies around 500 Hz and 1 kHz (Fig. 4.38 and 4.39), regardless of flow rate and height (see Appendix G10).

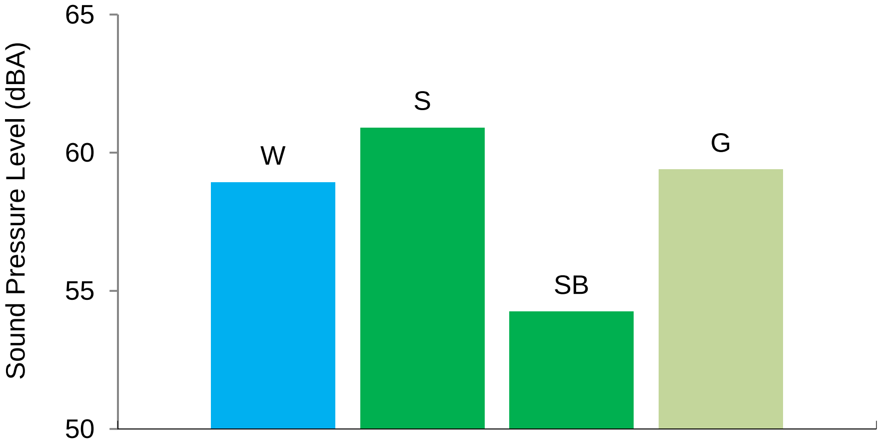


Figure 4.36 L_{Aeq} of fountain (37 jets) with no extension, 15 l/min, and different impact materials.

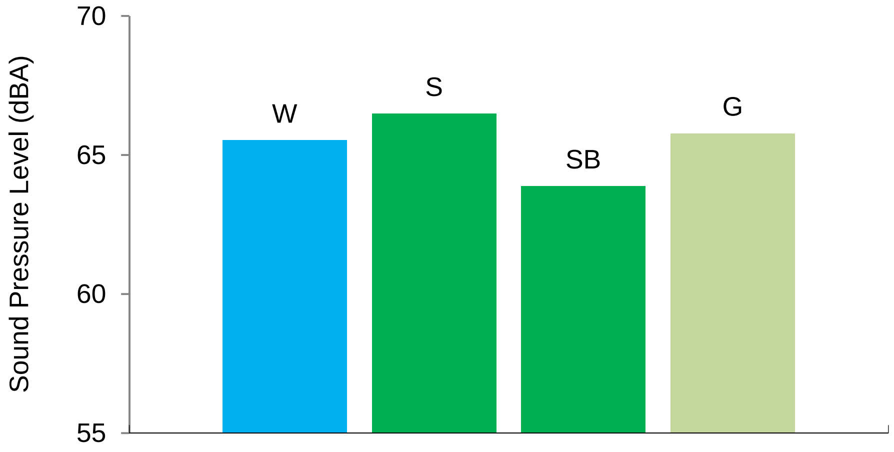


Figure 4.37 L_{Aeq} of fountain (37 jets) with no extension, 30 l/min, and different impact materials.

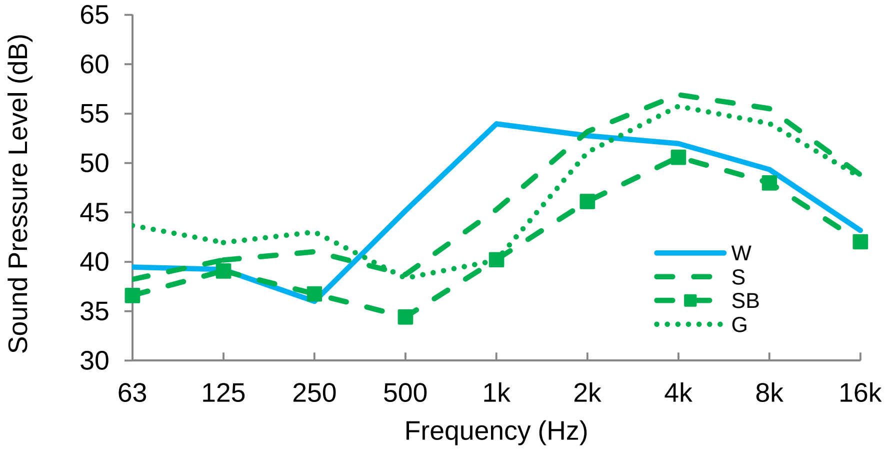


Figure 4.38 Spectra of fountain (37 jets) with no extension, 15 l/min, and different impact materials.

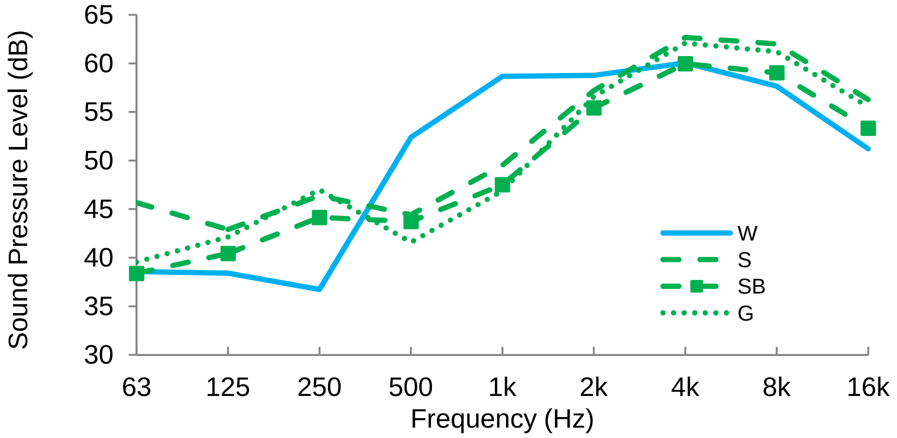


Figure 4.39 Spectra of fountain (37 jets) with no extension, 30 l/min, and different impact materials.

4.6.3 Foam fountain

Fig. 4.40 shows small differences in L_{Aeq} levels for a flow rate of 30 l/min (less than 2 dB), and Fig. 4.41 shows that for 45 l/min the differences are even smaller (less than 1 dB). These small variations are also reflected in the frequency responses (Fig. 4.42 and 4.43), where it can however be noted that water produces more mid and low frequencies. It is important to point out that the foam fountain mixes air with water, therefore generating an airborne sound which is not present in normal fountains where sound is generated by impact and bubbles. This explains the lower importance of the impact sound, and hence the impact surface.

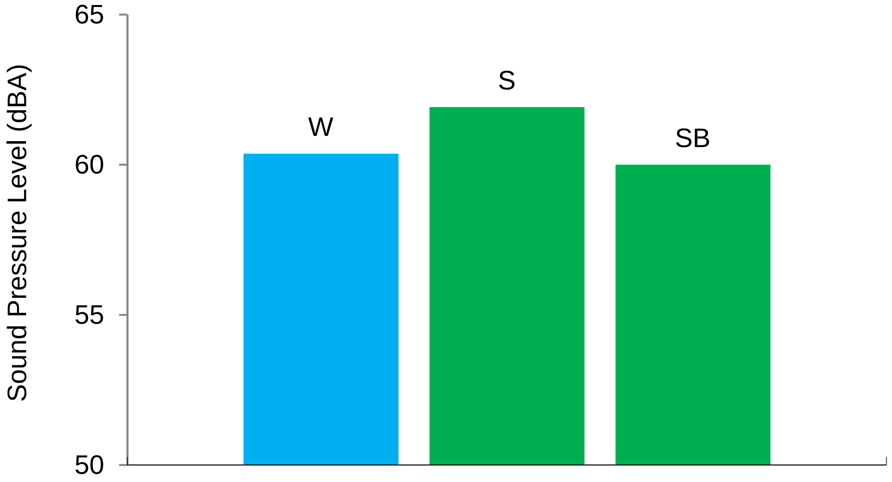


Figure 4.40 L_{Aeq} of foam fountain with no extension, 30 l/min, and different impact materials

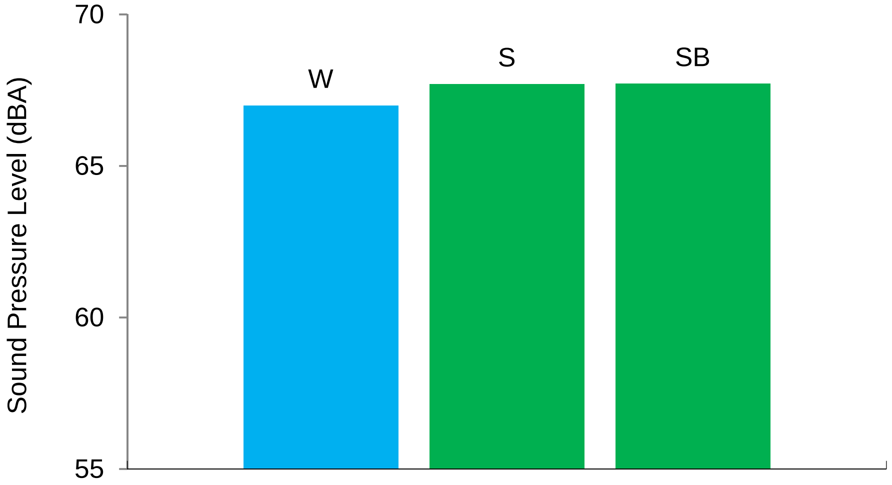


Figure 4.41 L_{Aeq} of foam fountain with no extension, 45 l/min, and different impact materials

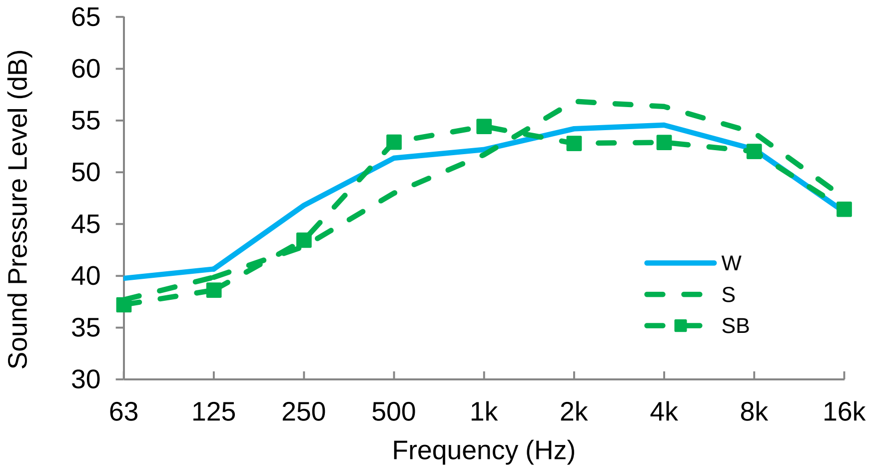


Figure 4.42 Spectra of foam fountain with no extension, 30 l/min, and different impact materials.

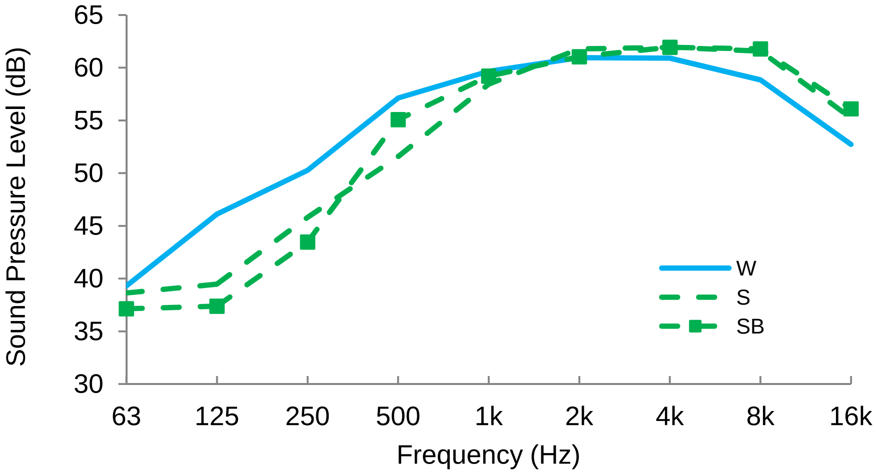


Figure 4.43 Spectra of foam fountain with no extension, 45 l/min, and different impact materials.

4.6.4 Jets

25 mm nozzle

Some variability in results was observed depending on the flow rate, with no clear pattern shown, but with small differences in L_{Aeq} of 2-3 dB at most (see Appendix G11). Stones produced more high frequencies, especially at the low flow rate of 15 l/min shown in Fig. 4.44 (around +5 dB at 2 kHz and 4 kHz), and the spectra were fairly flat when no extension was used. When an extension was used, more mid and high frequencies were produced (Fig. 4.45), due to the vibrating bubbles generated by the higher height of falling water.

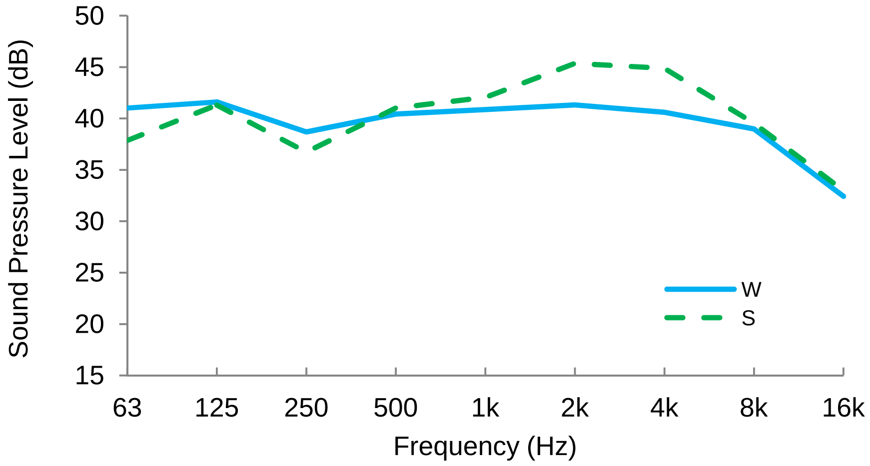


Figure 4.44 Spectra of jet with 25 mm nozzle and no extension, 15 l/min, and different impact materials.

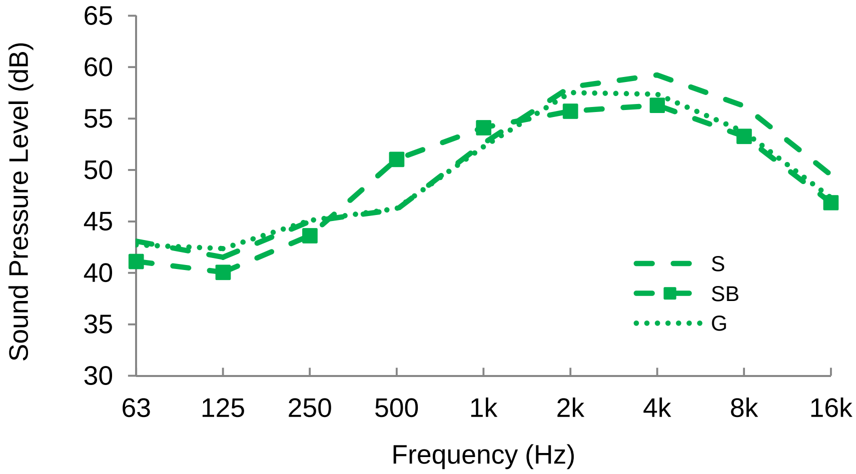


Figure 4.45 Spectra of jet with 25 mm nozzle and 0.5 m extension, 30 l/min, and different impact materials.

15 mm nozzle

Similarly to the 25 mm nozzle results, the variability in L_{Aeq} is relatively small (up to 3.5 dB at most; see Appendix G11). Unlike the 25 mm nozzle, water produces more mid frequencies between 250 Hz and 2 kHz, as can be seen in Fig. 4.46. The spectral content does not vary much with height and is not significantly different for the various impact materials tested, with the exception of water. This can be seen in the figures of Appendix G11.

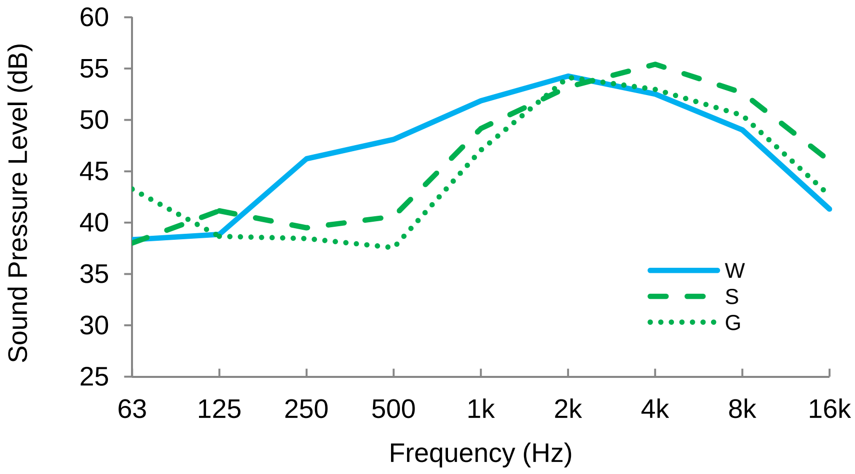
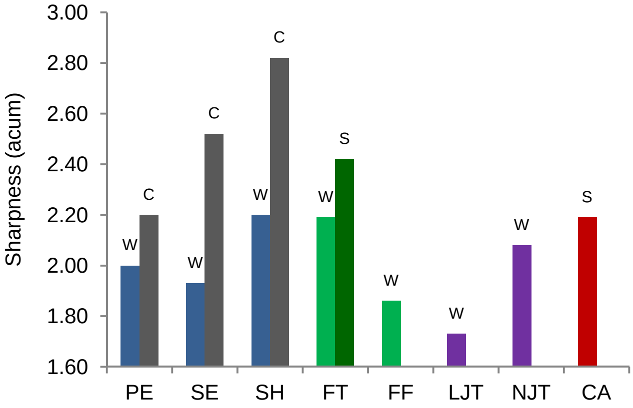


Figure 4.46 Spectra of jet with 15 mm nozzle and no extension, 15 l/min, and different impact materials.

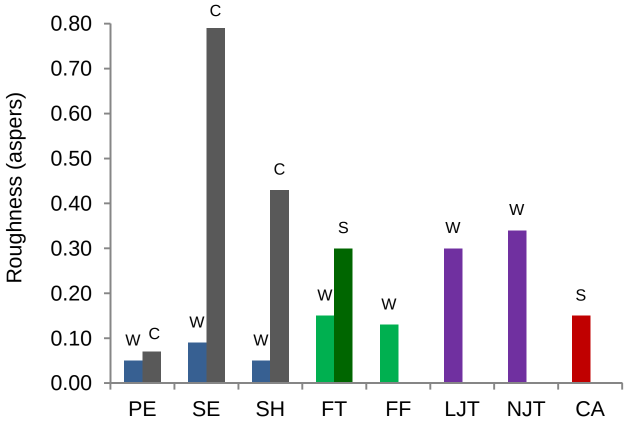
Finally, it can be noted that for narrower jets the effect of impact materials is difficult to evaluate, as a single narrow jet impacts only over a very small surface, so that the impact properties are variable and fairly random.

4.6.5 Psychoacoustic parameters

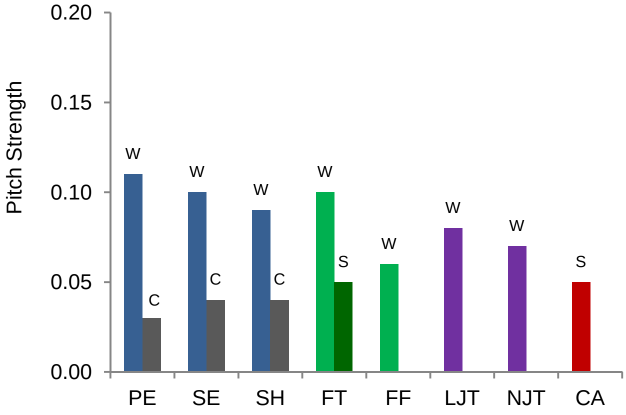
Psychoacoustic results are given in Fig. 4.47 for a variety of water features. In line with the results obtained for spectra, Fig. 4.47(a) shows that the sharpness increases with solid materials, the highest sharpness being produced by waterfalls over concrete and the lowest sharpness being produced by the large jet over water. Fig. 4.47(b) also shows that roughness tends to increase with solid materials, whilst the pitch strength is higher when water is the impact material (Fig 4.47(c)). The variations are significant for sharpness (+1.09 acum) and roughness (+0.74 asper), but relatively small for pitch strength (+0.08). It can also be noted that these sharpness and roughness variations are much larger than when water is the only impact material considered (see also sections 4.2, 4.3, and 4.5).



(a) Sharpness



(b) Roughness



(c) Pitch Strength

Figure 4.47 The effect of impact materials (W: water; C: concrete; S: stones) on the sharpness (a), roughness (b), and pitch strength (c) of a variety of water features.

PE: Plain Edge waterfall. SE: Sawtooth Edge waterfall. SH: Small Holes edge waterfall. FT: Fountain (37 jets). FF: Foam Fountain. LJT: Large Jet (25 mm nozzle). NJT: Narrow Jet (10 mm nozzle). CA: Cascade. The waterfalls were of 1m width with a height of falling water of 0.5 m. The flow rate for all water features was 30 l/min, with the exception of LJT, NJT and CA for which it was 15 l/min.

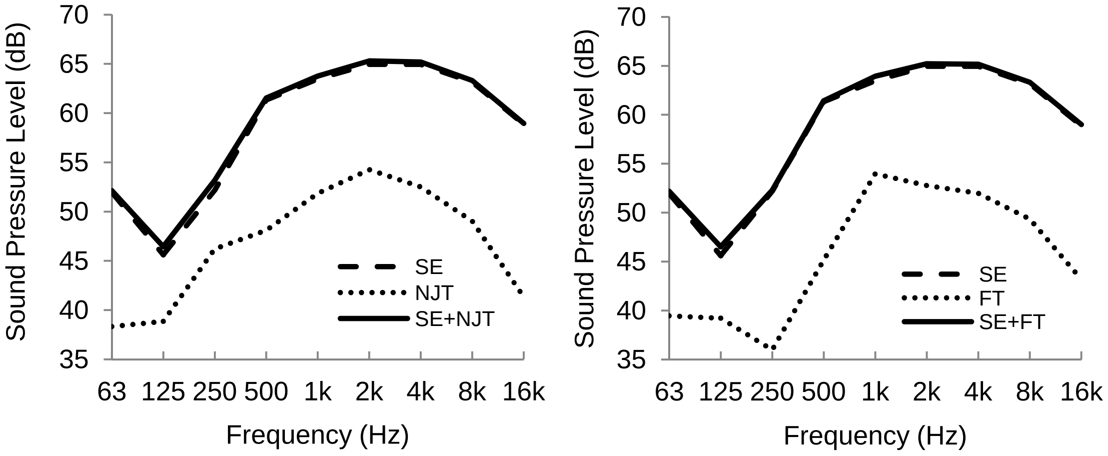
4.6.6 Impact materials' main findings

- The largest differences in L_{Aeq} levels (up to 10 dB) occur in low height waterfalls (compared to fountains and jets)
- In waterfalls, the bubbling sound tends to dominate the impact sound, which is why water as an impact material tends to produce higher L_{Aeq} levels; however, the opposite tends to occur for fountains and jets
- Increasing the height of falling water increases the impact sound and decreases the differences between the sounds produced by the various impact materials
- Increasing the flow rate increases the splashing sound, therefore decreasing the differences between the sounds produced by the various impact materials
- The use of water as in impact material is good for creating mid frequencies (+5-10 dB compared to hard materials in the range 250 Hz – 2 kHz)
- A foam fountain works as an airborne source, and is consequently less responsive to impact materials

4.7 Combinations of water features

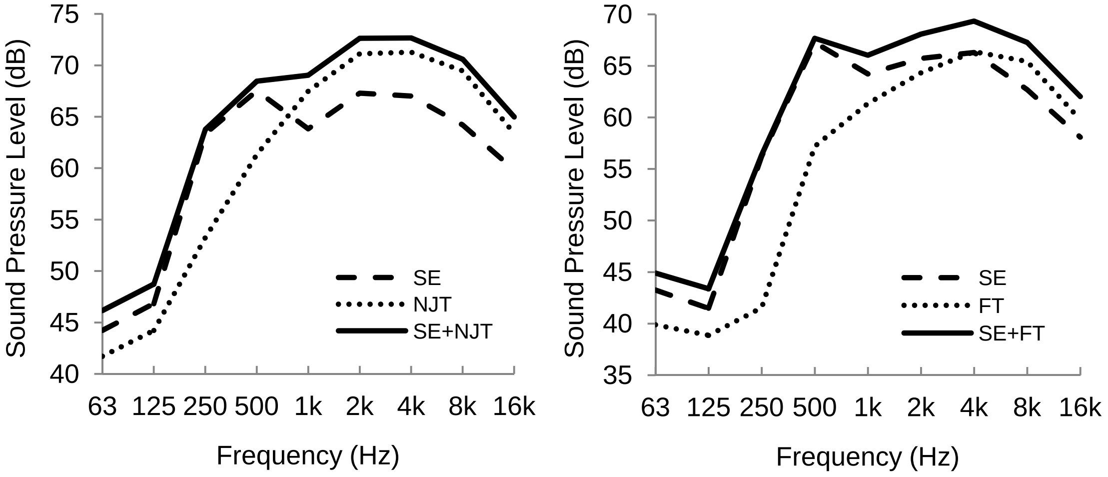
In Chapter 2 it was pointed out that water features can be made of a combination of upward and downward flows, but all the results presented so far applied to either downward flows or upward flows. This section gives an insight into how different flows can be combined and how this affects the sound spectra (more results can be found in Appendix H).

Fig. 4.48 illustrates the combination of a sawtooth edge waterfall (SE) of 1 m width with a narrow jet (NJT, 15 mm nozzle), as well as the combination of a sawtooth edge waterfall (SE) of 1 m width with a fountain made of 37 jets (FT). The results show that at low flow rates and for a waterfall height of 1 m, the waterfall's sound dominates. The narrow jet contributes to the sound spectra only at high flow rates for which the jet reaches a large height, and when the waterfall height is reduced to 0.5 m. Similarly, the fountain's contribution is noticeable only at high flow rates and when the fountain's height is increased (1 m extension) and the waterfall's height is decreased (0.5 m height). This suggests that waterfalls tend to dominate the sound spectra, unless upward flows fall from high levels. In the case of combinations of upward flows (*e.g.* jet with fountain), no sound tends to dominate clearly, and the characteristics of both features



(a) SE 1 m height + NJT (15 l/min)

(b) SE 1 m height + FT (15 l/min)



(c) SE 0.5 m height + NJT (60 l/min)

(d) SE 0.5 m height + FT 1 m height (30 l/min)

Figure 4.48 Examples of spectra obtained from combining upward (NJT: narrow jet, FT: fountain (37 jets)) and downward flows (SE: sawtooth edge waterfall).

affect the overall sound spectra (see NJT + FT in Appendix H). These results were predicted from the separate measurements made on SE, NJT and FT, as no measurements were made on combinations of water features. In practice, the sound obtained from such combinations would normally originate from different source positions, so that more complex effects can be expected.

4.8 Summary of findings

In this chapter a considerable amount of data has been presented regarding the impact of design factors on acoustical and psychoacoustical parameters. The chapter analysed the impact of flow rate, waterfalls' edge design and width, height of falling water, and impact materials, and key findings are summarised in Table 4.1 (for the ranges used in this table check Table 4.2).

Results showed that L_{Aeq} increases logarithmically with flow rate for most small and medium sized water features, with increases in sound pressure level that are fairly uniform above 500 Hz, but are variable below that frequency.

Waterfalls were found to be louder than any other type of water feature, as they can use higher flow rates and larger amounts of water which produce more bubbles. Their range of variation in terms of L_{Aeq} was however smaller than the ones of fountains, jets and cascades.

All the water sounds were found to be mid and high frequency dominant, with most of the energy contained in the 500 Hz – 16 kHz octave bands (with the exception of the plain edge waterfall of low height over concrete or metal). It was also found that increasing the flow rate is not an effective way of generating low frequencies, with the exception of waterfalls.

Higher sound pressure levels (+2-3 dB) were obtained when distributing the same amount of water over several streams (sawtooth edge and small holes edge waterfalls) rather than over one uniform stream (plain edge). This was due to the generation of a larger amount of small bubbles from the several streams, the smaller bubbles producing the mid-high frequency content which is dominant in water sounds (see equation (2.1)).

Table 4.1 Summary of findings showing how design factors affect acoustical and psychoacoustical properties of water features. Note that the absolute values given apply to the specific receiver position used for the tests (*i.e.* in practice these can vary depending on the receiver's position).

Design factor	Water feature	L_{Aeq} (dB)	Spectrum	Sharpness (acum)	Roughness (asper)	Pitch strength
Flow rate	Waterfalls (1m height, 1m width)	Medium to high: 65-75 Variability with flow rate: +5-10	Dominant range: 500 Hz – 16 kHz Low frequencies can be generated by increasing the flow rate. SPL increases with flow rate across all frequencies	Low to high: 1.90-2.20 No significant variation with flow rate	Medium to high: 0.07-0.19 Logarithmic decrease with flow rate	Low to medium: 0.04-0.10 No significant variations with flow rate
	Fountains	Medium: 50-70 Variability with flow rate: +10-15	Dominant range: 1 kHz – 8 kHz Similar increases in SPL above 500 Hz	High: 2.18-2.25 Small increase with flow rate	High: 0.12-0.41 Logarithmic decrease with flow rate	Medium: 0.08-0.09 No change with flow rate
	Jets	Very low (25mm) to high (15mm): 40-75 Variability with flow rate: +10-25	Dominant range: 500 Hz – 16 kHz Similar increases in SPL above 500 Hz	Very low (25mm) to high (5mm): 1.68-2.16. Tendency to increase with flow rate	High: 0.15-0.94 No clear trend with flow rate; Increases with narrow nozzles	Medium: 0.05-0.09 No significant variations with flow rate
	Cascade	Medium: 55-65 Variability with flow rate: +10	Dominant range: 1 kHz – 8 kHz Similar increases in SPL above 500 Hz	High: 2.19-2.21 No significant variation with flow rate	Medium to high: 0.06-0.30 Logarithmic decrease with flow rate	Low to medium: 0.04-0.06 No change with flow rate
	Slope	Very low to medium: 40-55 Variability with flow rate: +15	Dominant range: 250 Hz – 16 kHz Similar increases in SPL above 500 Hz	Very low to medium: 1.66-1.96 Tendency to increase with flow rate	Medium: 0.04-0.09 No significant variations with flow rate	Low to medium: 0.03-0.07 Small increase with flow rate
Waterfall's edge design (1m h., 1m w.)	Plain	Lowest levels: 63-73	Increase in low frequency content	Medium: 1.96-2.14	Medium to high: 0.07-0.16	Low to medium: 0.04-0.09
	Sawtooth	Highest levels: 66-76	Increase in mid-high frequency content	Medium: 1.91-209	Medium to high: 0.07-0.19	Medium: 0.07-0.10
	Small holes	Between plain and sawtooth: 65-71	Decrease in low frequency content	High: 2.18-2.19	Medium to high: 0.07-0.16	Medium: 0.06-0.08
Edge width	Waterfalls	0.5m to 1.5m: +2-3 dB at high flow rates For constant width flow rates, a doubling in the width corresponds to an increase of 3 dB	Similar increases in SPL above 250 Hz for constant width flow rates	No significant change	No significant change	No significant change
Height of falling water	Waterfalls	0.5m to 2m height: 5-10 dB increase	Changes not uniform across frequencies	Increase with height: +0.10	Increase with height : +0.10	Decrease with height: -0.05
	Fountains	No ext. to 1m ext.: 5-10 dB increase	Changes not uniform across frequencies	Increase with height: +0.30	Increase with height: +0.10	Decrease with height: -0.05
Impact material	Waterfalls	Large differences of up to 10 dB (0.5m height) Reduced differences at 2m height (3 dB) Water generates significantly higher levels (+10 dB) at low heights, but hard materials generate higher levels at large heights (+2-3 dB)	Water generates more mid frequencies compared to hard materials (5-10 dB), which generate more high frequencies (approx.+5 dB)	Very large increases with hard materials: up to +0.60	Very large increases with hard materials: up to +0.70	Water produces the highest pitch strength: +0.05
	Fountain	15 l/min : variations of 7-8 dB; 30 l/min: variations of 2-3 dB; No extension: stones produce the highest level; Extension: water produces the highest level	Water generates more mid frequencies compared to hard materials (5-10 dB), which generate more high frequencies (approx. +5 dB)	Large increases with hard materials: +0.20	Large increases with hard materials: +0.15	Water produces the highest pitch strength: +0.05
	Foam fountain	Small differences (less than 2 dB) due to airborne sound	Hard materials generate more mid-high frequencies (2-5 dB)	Large increases with hard materials: +0.20	Small decreases with hard materials: -0.03	Water produces the highest pitch strength: +0.02
	Jets	Small differences (1-3 dB)	Hard materials generate more high frequencies (approx. +5 dB)	Increases with hard materials for high level jets: +0.10	Decreases with hard materials: -0.10	Small decrease with hard materials: -0.02

Table 4.2 Ranges of acoustical and psychoacoustical parameters applied to the characterisation of water sounds given in Table 4.1.

L_{Aeq} (dB)		Sharpness (acum)		Roughness (asper)		Pitch strength	
< 40	Very low	< 1.75	Very low	< 0.05	Low	< 0.05	Low
40-50	Low	1.75-1.95	Low	0.05-0.10	Medium	0.05-0.10	Medium
50-75	Medium	1.95-2.15	Medium	> 0.10	High	> 0.10	High
>75	High	2.15-2.35	High				
>85	Very high	> 2.35	Very high				

Furthermore, it was found that the plain edge design has the highest low frequency content.

At high flow rates, an increase in the width of a waterfall tended to increase the overall sound pressure level (+2-3 dB). Results also suggested that increasing the height of falling water can increase the sound pressure level significantly (+5-10 dB), with the exception of waterfalls of low heights operated at low flow rates.

Tests showed that impact materials can greatly affect acoustical and psychoacoustical properties. This was particularly true for low height waterfalls, in which case large differences in L_{Aeq} (up to 10 dB) and spectra were observed. In waterfalls, the bubbling sound tended to dominate the impact sound, but the opposite occurred for fountains and jets. For all features, water produced more mid and low frequencies (+5-10 dB compared to hard materials in the range 250 Hz – 2 kHz), due to the sound generated from vibrating bubbles, whilst hard materials tended to increase the high frequency content of around 5 dB (with the exception of the plain edge waterfall of low height). Results also showed that changes in sound pressure level and spectra, due to the different impact materials, become less and less significant with increasing height and flow rate.

Variations of psychoacoustic parameters with flow rate, waterfalls' edge design and height of falling water were limited. In contrast, variations in sharpness and roughness were significant when different impact material were used. Both sharpness and roughness increased with solid materials (up to +0.60 acum and +0.70 asper respectively), whilst the pitch strength was higher when water was the impact material, although the changes observed for the latter were small (+0.05).

Results obtained from the combination of upward and downward water flows suggested that waterfalls tend to dominate the sound spectra, unless upward flows fall from high levels. In the case of combinations of upward flows (*e.g.* jet with fountain), no sound tended to dominate clearly, and the characteristics of both features affected the overall sound spectra.

In conclusion, the analysis presented has shown that a great variety of water sounds can be produced by varying the design of small and medium sized water features and that estimations can be made on how these factors affect sound pressure levels, frequency content and psychoacoustic parameters.

CHAPTER 5

Field tests: illustrating the variability of water sounds

5.1 Introduction

Field tests are described in this chapter. These tests were carried out to obtain data of water features which could not be built and tested in the laboratory. These included large fountains, large waterfalls and a variety of streams with varying characteristics (*e.g.* large and deep stream, or narrow and shallow stream). Additionally, a number of seashore sounds were also examined. All the data on natural waterfalls and streams was obtained in the Edinburgh area, whilst data on large fountains was recorded in Rome (Italy) and seashore sounds were recorded in Mallorca (Spain). The diverse data obtained has allowed comparing laboratory results with field results and identifying the extent of variations in acoustical properties of a varied sample of water sounds.

5.2 Water features tested

A description of the water features tested is given below, whilst the analysis of results is given in the following section. Several features have been tested in the field, but only the features selected for the comparisons of section 5.3 are illustrated here. The methods used for measurements are identical to those described in Chapter 3 (acoustic measurements made using the sound level meter Brüel and Kjaer Type 2250, and audio recordings made using the digital sound recorder Zoom H4n, with built-in microphones; the averaging and recording period used was 20 seconds). For all measurements, the receiver position was chosen to be representative of a person seated in the vicinity of the water feature. Being too close to a feature was avoided because of nearfield effects (changes in spectral shapes), as was being too far from a feature, because of interference with background noise. Consequently, most measurements were undertaken at 1 m height above the ground level, at the edge of the streams or fountains tested, or few meters away from waterfalls. Detailed information about the receiver position used for each feature is given in the following sections.

5.2.1 Streams

Fig. 5.1(a) and 5.1(b) show the Water of Leith, a small river flowing through Edinburgh. Tests were carried out at several locations of the Water of Leith but only two measurements were retained for the analysis, due to the similarities observed between results. The first location (Fig. 5.1(a)) was approximately 250 m South of Gorgie Road, with buildings acting as a sound barrier between the road and the measurement position (*i.e.* road traffic noise was barely audible). At this location, the stream showed a combination of shallow and deeper depths of water, with stones present on the river's bed. The stream was approximately 6 m wide and located next to a Y junction, where one stream was splitting into two streams. The equipment was placed at the edge of the stream and 1 m above the water level. The second location used for the Water of Leith (Fig. 5.1(b)) was in Dean Village (Edinburgh), where the stream was deeper and the flow rate observed was higher. The stream was approximately 8 m wide and few large stones were visible on the river's bed. The equipment was placed at the edge of the stream and 2 m above the water.

Fig. 5.1(c) shows a junction of shallow streams flowing over stones tested in the Pentland Hills (South of Edinburgh). Measurements were carried out at the top edge of the junction (two streams merging), with one source stream 2 m on the right, the other source stream 2 m on the left and the new stream 5 m in front (shown in Fig. 5.1(c)). Measurements were undertaken 1 m above water.

5.2.2 Waterfalls and cascade

Two waterfalls and one cascade were tested in the field and are shown in Fig. 5.2.A relatively high waterfall (approx. 10 m high) was tested in the Pentland Hills at two different positions. The higher position (Fig. 5.2(a)), was at a distance of 3 m from the rocks where the two main streams were impacting. The lower position (Fig. 5.2(b)) was at a distance of 5 m from a 1.5 m high waterfall falling onto water.

A large weir (man made waterfall with a very large flow rate) was tested along the Water of Leith in Dean Village and is shown in Fig. 5.2(c). It was approximately 12 m wide, with a height of falling water of around 3 m. Measurements were undertaken on the North side of the river, next to the top edge of the weir (*i.e.* 3 m above the downstream level of water).

(a) Wide stream (Gorgie Road)

(b) Wide stream (Dean Village)

(c) Junction of shallow streams (Pentland Hills)

Figure 5.1 Streams tested in the field.

(a) Waterfall over rocks (Pentland Hills) (b) Waterfall over water (Pentland Hills)

(c) Large weir (Dean Village)

(d) Cascade (Heriot-Watt University, Edinburgh campus)

Figure 5.2 Waterfalls and cascade.

A cascade with four steps (*i.e.* four changes in level) was also tested on the Edinburgh campus of Heriot-Watt University. The cascade was approximately 3 m wide with stones on its bed and a fairly large flow rate. Measurements were undertaken at the edge of the cascade and 1.5 m above water level.

5.2.3 Large fountains

Three large fountains were tested in Rome (Italy), a city which is renowned for its many baroque fountains.

The fountain designed by Carlo Maderno, and built at the beginning of the 17th century, was tested in Saint Peter's square. This fountain is made of two basins, with water from the upward jets impacting on its top stone element and falling onto the upper basin, and from there onto the lower basin (Fig. 5.3(a)). Measurements were undertaken at the edge of the lower basin and 1 m above the ground level.

The famous fountain of the Four Rivers, designed by Gian Lorenzo Bernini (17th century), was tested in Piazza Navona. This is a complex sculptural feature representing four major river gods of the four continents. Sculptures of the four gods constitute the fountain, and a total of ten water streams fall into its large basin (two on the South West side, three on the South East, two on the North East and three on the North West). The waterfalls' widths vary between 0.2 m and 1.0 m approximately, and the height of falling water is approximately 1 m for all the streams. Measurements were undertaken on the South West side, at the edge of the basin, 1 m above the ground level, in front of the waterfall shown on the right picture of Fig. 5.3(b). Tests were undertaken in the late evening, when the activity present around the fountain was limited (*i.e.* low background noise).

Finally, the last feature tested in Rome was the 'Fontana Mostra dell'Acqua Vergine' from Giuseppe Valadier, built at the beginning of the 19th century and shown in Fig. 5.3(c). This fountain is located underneath the Pincian Hill, next to Viale Gabriele D'annunzio. The originality of this feature is that it combines two upward jets at its centre, with water falling along the back walls of the fountain. Measurements were undertaken at the North end of the fountain, at the basin's edge and 1 m above the ground level (see right picture of Fig. 5.3(c)).

(a) Maderno’s fountain, St. Peter’s Square

(b) Bernini’s fountain, Piazza Navona (Credit: Flickr for the left picture)

(c) Valadier’s fountain, Pincian Hill (jets and water falling along back walls)

Figure 5.3 Large fountains tested in Rome, Italy.

5.2.4 Seashores

Fig. 5.4 shows Cala Barques in Mallorca (Spain), which was used to measure seashore sounds under two different conditions: a calm sea (Fig. 5.4(a)) and a stormy sea (Fig. 5.4(b)). These tests allowed examining large temporal variations and periodic patterns which were not present in any of the other water features tested.

(a) Calm sea (b) Stormy sea

Figure 5.4 Seashore tested in Mallorca, Spain.

5.3 Results

This section examines the results obtained from the field tests, including comparisons between field and laboratory data for spectra, L_{Aeq}, $L_{A10} – L_{A90}$ (temporal variations) and psychoacoustic parameters (sharpness, roughness and pitch strength).

5.3.1 Spectra

Fig. 5.5 to 5.8 give the spectra of streams, waterfalls/cascade, large fountains and seashore sounds respectively. These show that stream sounds tend to be dominated by the 500 Hz – 2 kHz range, whilst waterfalls tend to have a flatter frequency response and tend to be dominated by the 500 Hz – 4 kHz range (up to 8 kHz if the impact material is solid, like in the case of the waterfall impacting on rocks). The large fountains tested clearly exhibit more high frequencies than the other features, with a typical dominant range of 1 kHz – 8 kHz. Seashore sounds of Fig. 5.8 show that a stormy sea can exhibit significant mid to low frequencies (125 Hz – 500 Hz), whilst a

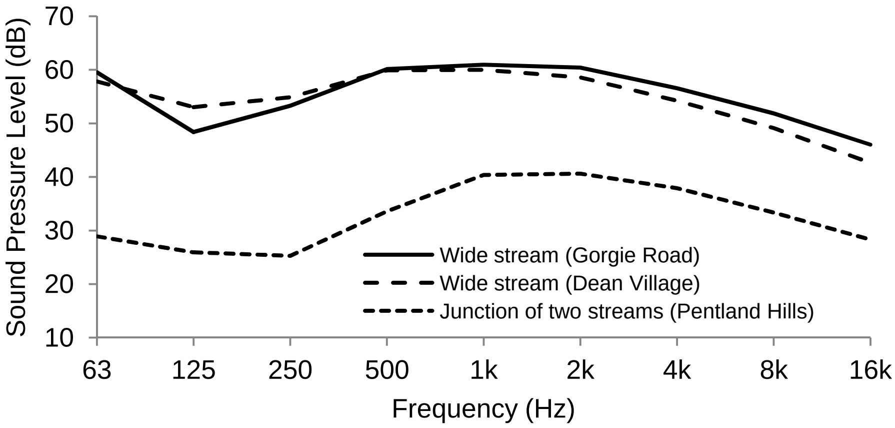


Figure 5.5 Spectra of streams.

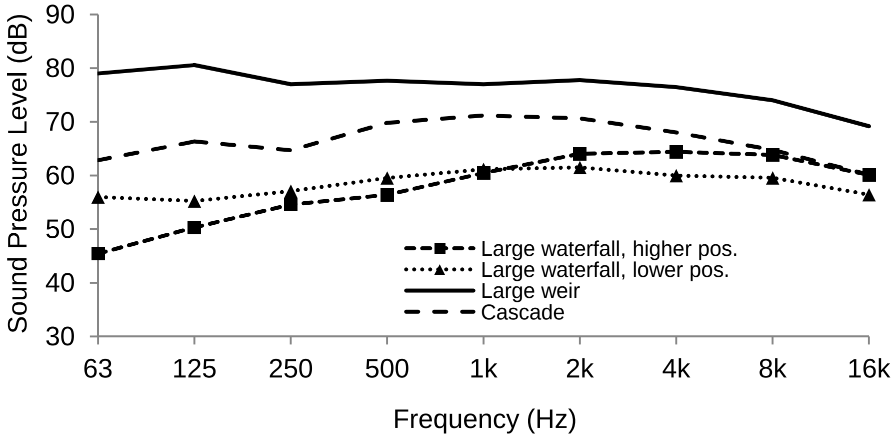


Figure 5.6 Spectra of waterfalls and cascade.

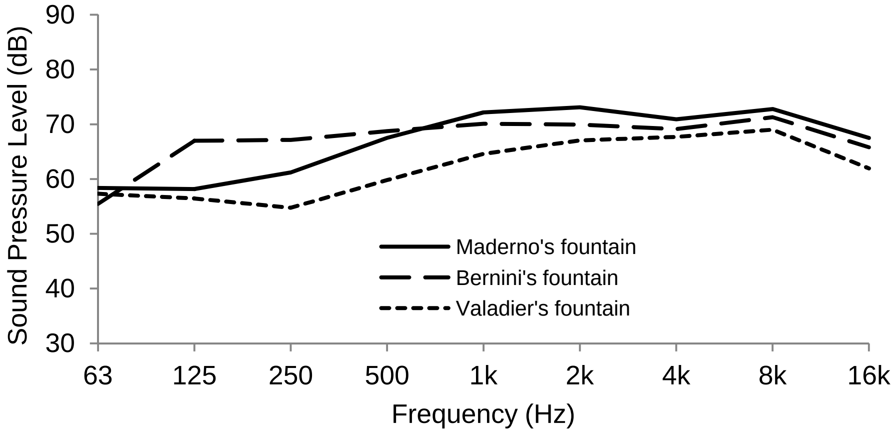


Figure 5.7 Spectra of large fountains.

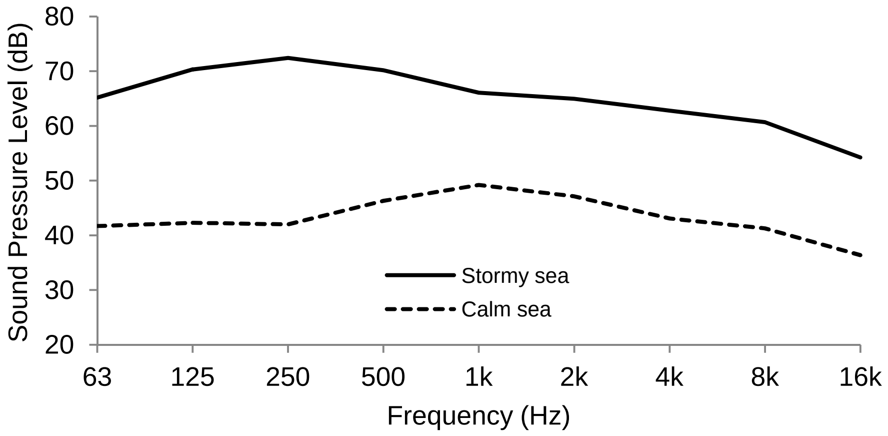


Figure 5.8 Spectra of seashore sounds.

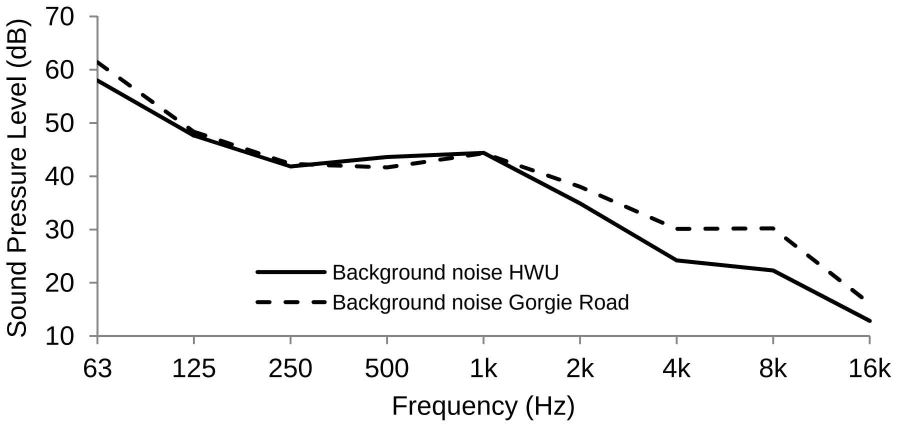


Figure 5.9 Background noise spectra of Heriot-Watt University campus and Water of Letih (Gorgie Road).

calm sea exhibits a spectrum comparable to streams (*i.e.* 500 Hz – 2 kHz dominant range).

It should be noted that some of the results presented were affected by background noise at low frequencies. This is the case for features measured in urban and sub-urban environments, in particular in places where road traffic noise was audible (*i.e.* Heriot-Watt campus and measurements undertaken in the vicinity of Gorgie Road). Fig. 5.9 shows the background noise measured at these two locations, and it can be seen that the 63 Hz and 125 Hz background noise could be as high as 60 dB and 50 dB respectively. Therefore, the ‘wide stream’ results of Fig. 5.5 are affected by background noise at

63 Hz and 125 Hz. Similarly, the results of Fig. 5.7 might have been affected by background noise at 63 Hz, although it was not measured at these locations where large variability in noise was occurring due to changes in activity (*e.g.* people talking in St Peter's Square and Piazza Navona).

Several laboratory spectra are given in Fig. 5.10 in view of comparisons with the field data presented (see Table 5.1 for the definition of acronyms). These results show that most of the water sounds tested in the laboratory are dominated by the 500 Hz – 8 kHz frequencies. In comparison, the spectra obtained for streams and seashore sounds have flatter frequency responses. This is due to the limited amount of splashing sounds (*i.e.* high frequencies) in streams and seashores, as water does not fall over water from any significant height, so that small bubbles are not produced. Instead, sound is mainly due to the large bubbles created from water flowing around obstacles, as well as from the impact of water against such obstacles. The fountains tested in Rome are the only features that clearly exhibit a high frequency content which is comparable to fountains tested in the laboratory. Field and laboratory results are also comparable for waterfalls, the only exception being the large weir of Fig. 5.6 which produced significantly more low frequencies.

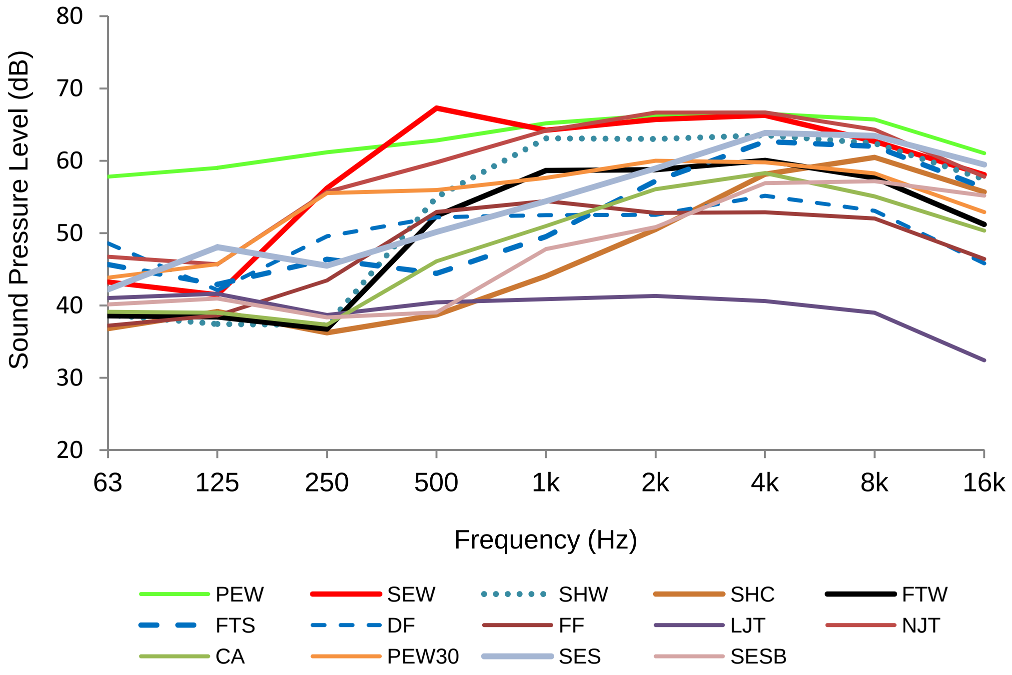


Figure 5.10 Spectra measured in the laboratory (see Table 5.1 for acronyms).

Table 5.1 Properties of laboratory sounds used for comparison with field results.

Sound code	Water feature type	Impact material	Flow rate (l/min)	Height (m) &Width (m)
PEW	Plain Edge Waterfall	Water	120	1.0 - 1.0
SEW	Sawtooth Edge Waterfall	Water	30	0.5 - 1.0
SHW	Small Holes Waterfall	Water	30	0.5 - 1.0
SHC	Small Holes Waterfall	Concrete	30	0.5 - 1.0
FTW	Fountain (37 jets)	Water	30	-
FTS	Fountain (37 jets)	Stones (pebbles)	30	-
DF	Dome fountain	Water	30	-
FF	Foam fountain	Stones & boulders	30	-
LJT	Large jet	Water	15	-
NJT	Narrow jet	Water	15	-
CA	Cascade (4 steps)	Stones (pebbles)	15	-
PEW30	Plain Edge Waterfall	Water	30	0.5 – 1.0
SES	Sawtooth Edge Waterfall	Stones (pebbles)	30	0.5 - 1.0
SESB	Sawtooth Edge Waterfall	Stones & boulders	30	0.5 - 1.0

5.3.2 Continuous equivalent noise level L_{Aeq}

Field results (Fig. 5.11) obtained for the equivalent continuous noise level L_{Aeq} show large variations of approximately 40 dB between the quietest and loudest water sounds measured (45-85 dBA), whilst laboratory results (Fig. 5.12) show a variation of approximately 25 dB (48-73 dBA). The range of levels obtained is much larger for field tests, as both large flow rates (*e.g.* weir of Water of Leith and Maderno’s fountain in Rome) and very shallow streams (*e.g.* Pentland Hills) can be found in open spaces. It can also be noted that the majority of laboratory sounds tested were in the 60-70 dBA range, whilst field results covered a wider range, from quiet streams (45-55 dBA) to fairly loud fountains and waterfalls (75-85 dBA).

5.3.3 Temporal variations $L_{A10} – L_{A90}$

The extent of temporal variations can be quantified by $L_{A10} – L_{A90}$, a level difference which gives an indication of the variability of the sound measured. Results obtained both in the field (Fig. 5.13) and in the laboratory (Fig. 5.14) suggest that most water sounds are fairly constant in level, as $L_{A10} – L_{A90}$ is typically in the order of 1-2 dB and rarely exceeds 5 dB. Exceptions are represented by natural sounds which are periodic (*e.g.* seashore sounds) or have irregular flow rates (*e.g.* natural streams, or jets and

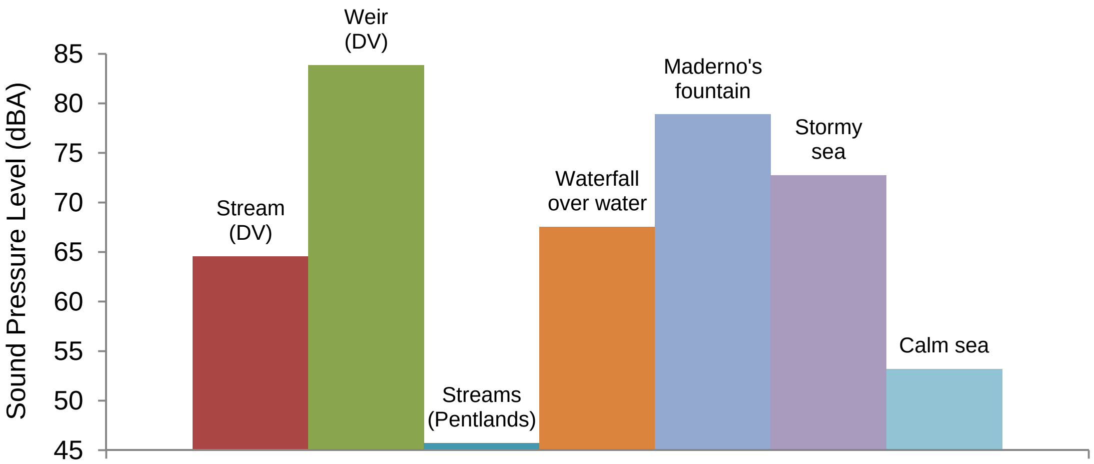


Figure 5.11 L_{Aeq} levels measured in the field (DV: Dean Village).

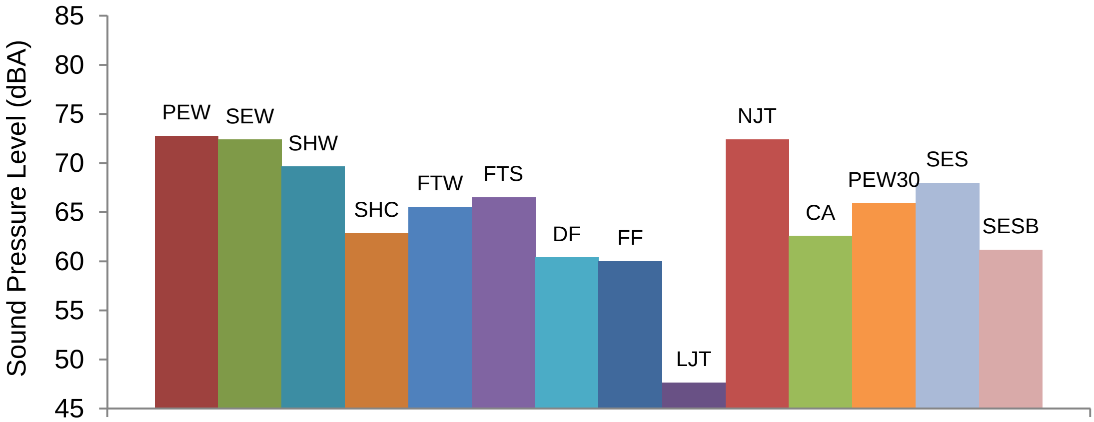


Figure 5.12 L_{Aeq} levels measured in the laboratory.

fountains operated at very low flow rates). Irregular flow rates can in fact be obtained from pumps running at very low speed, as the rotation of the pump's blades is not constant when the flow rate is too low. This type of operational setting can be found in the shallow jets of Islamic gardens and courtyards, and results show that the "large jet" tested in the laboratory (25 mm nozzle) is representative of this type of feature. This "large jet" feature provided the largest variation in level when operated at a low flow rate of 15 l/min ($L_{A10} – L_{A90}$ of approx. 5 dB). As expected, the largest variation in $L_{A10} – L_{A90}$ was obtained from the seashore (calm sea with a level difference of 17 dB).

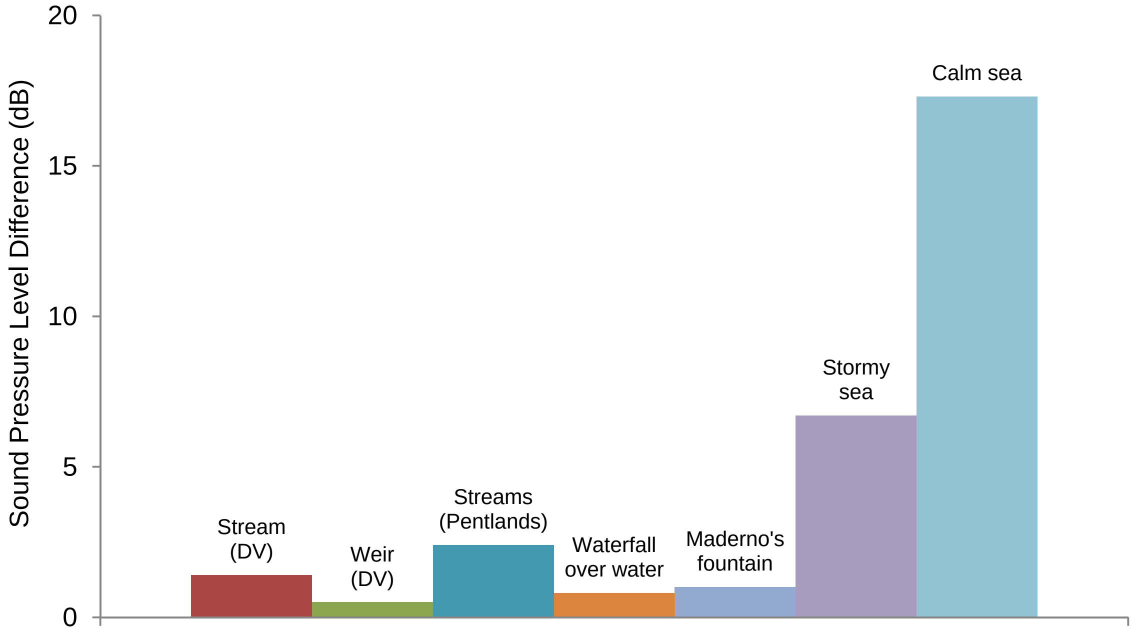


Figure 5.13 Temporal variations $L_{A10} - L_{A90}$ measured in the field (DV: Dean Village).

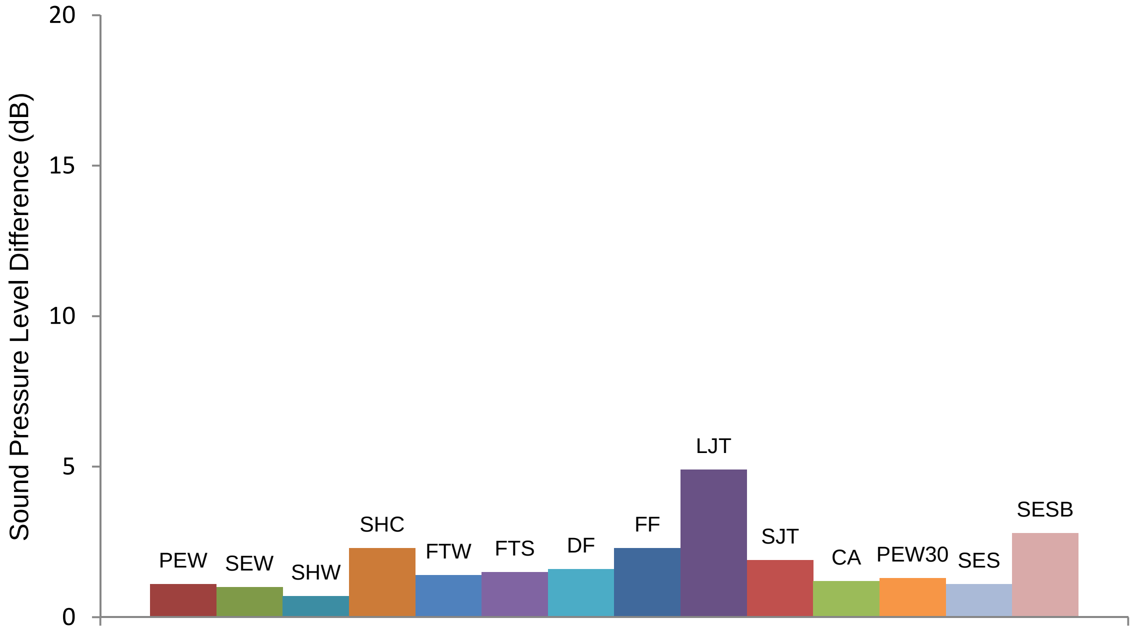


Figure 5.14 Temporal variations $L_{A10} - L_{A90}$ measured in the laboratory.

5.3.4 Sharpness

The sharpness of water sounds measured in the field (Fig. 5.15) tends to be lower than the one of sounds measured in the laboratory (Fig. 5.16). This is due to the fact that the high frequency content of field sounds is lower. Sharpness varies between 1.6-2.2 acum for field tests, and between 1.7-2.8 acum for laboratory tests. Natural streams and seashore sounds have the lowest sharpness, whilst waterfalls and fountains over solid materials exhibit the highest sharpness (see SHC and FTS in Fig. 5.16).

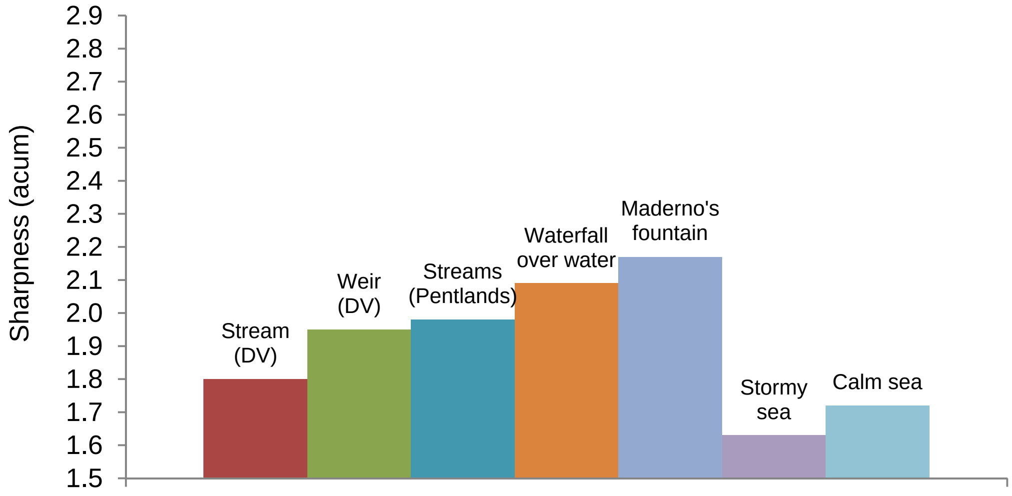


Figure 5.15 Sharpness of water features measured in the field (DV: Dean Village).

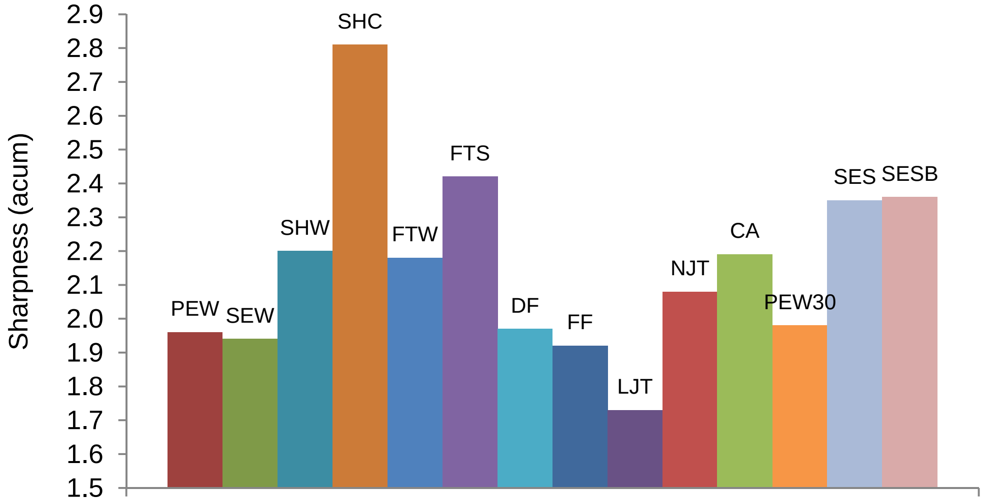


Figure 5.16 Sharpness of water features measured in the laboratory.

5.3.5 Roughness

Overall, roughness tends to be lower for field sounds (Fig. 5.17) compared to laboratory sounds (Fig. 5.18). The roughness varies between 0.05-0.27 asper for field tests (0.05 asper: wide and deep stream; 0.27 asper: shallow stream with low flow rate), and between 0.04-0.37 asper for laboratory tests (0.04 asper: waterfall with small holes edge; 0.37 asper: fountain over stones). Most sounds (both field and laboratory) are in the range 0.05-0.15 asper. It can also be noted that the presence of hard impact materials (*e.g.* concrete, stones and boulders) tends to increase the roughness of water sounds (see Fig. 5.18).

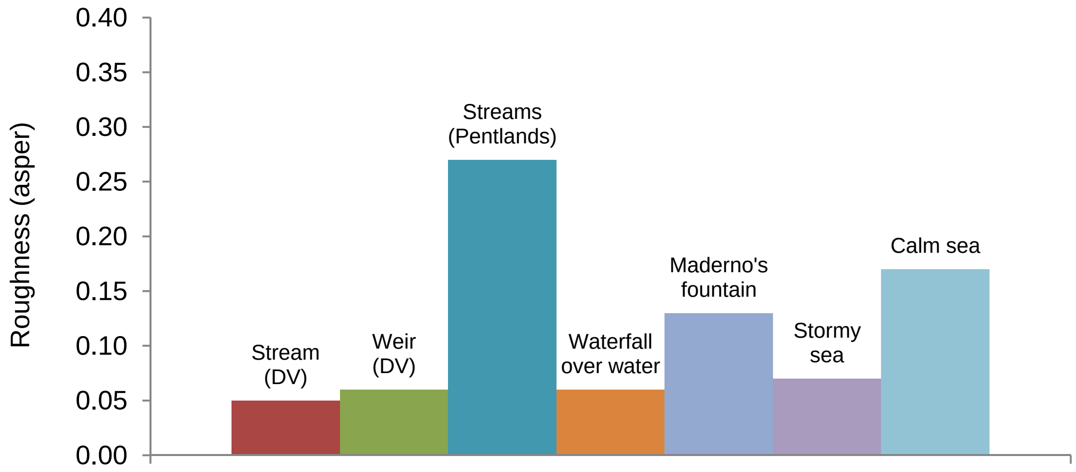


Figure 5.17 Roughness of water features measured in the field (DV: Dean Village).

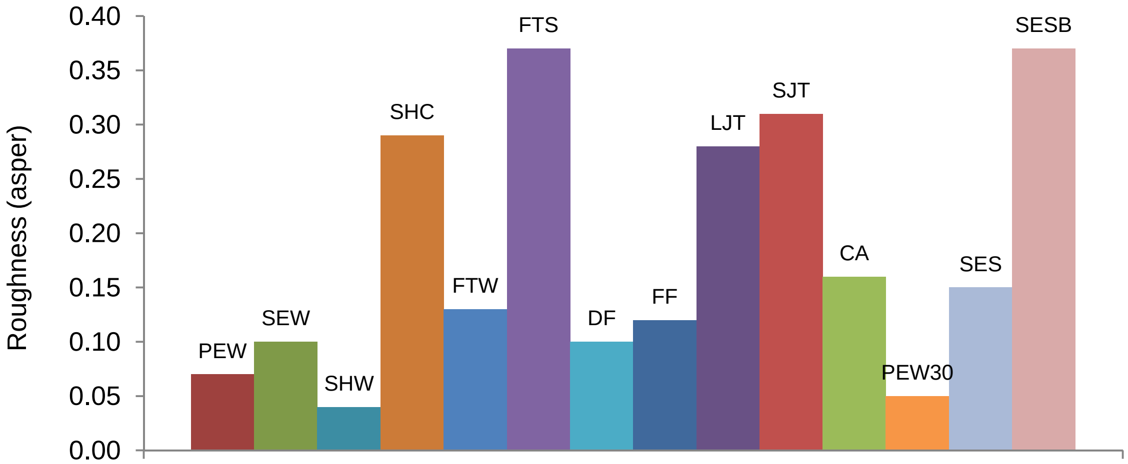


Figure 5.18 Roughness of water features measured in the laboratory.

5.3.6 Pitch Strength

Most of the water features tested have a Pitch Strength in the range 0.05-0.08. This is the case of the field results shown in Fig. 5.19, whilst laboratory results (Fig. 5.20) show larger variations, from 0.03 (waterfall with small holes edge and water impacting over concrete) to 0.14 (dome fountain). Results indicate that hard materials reduce the Pitch Strength (see FTW vs. FTS, and SHW vs. SHC).

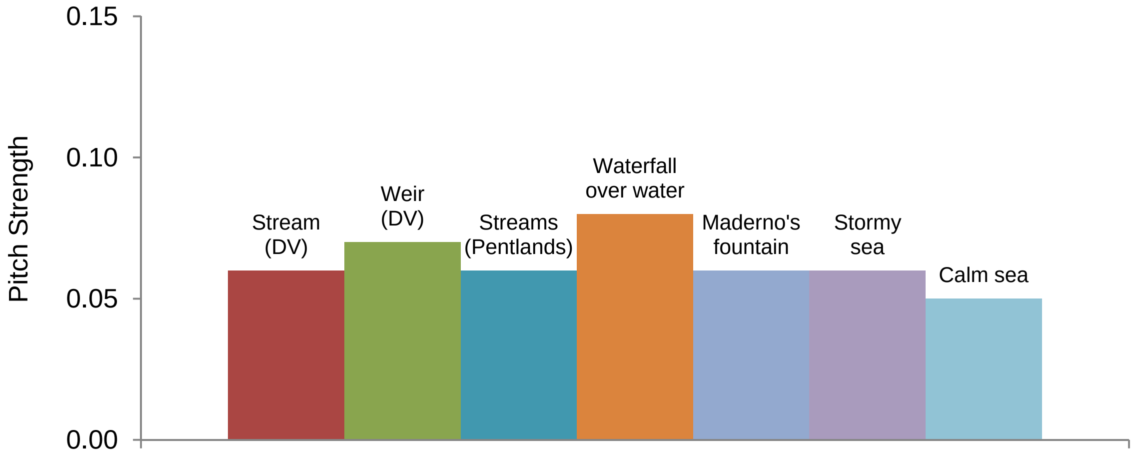


Figure 5.19 Pitch Strength of water features measured in the field (DV: Dean Village).

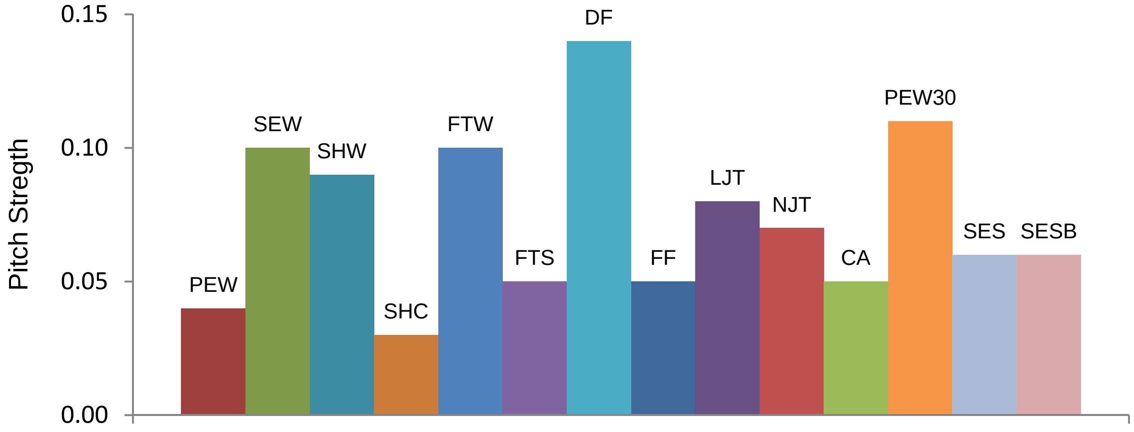


Figure 5.20 Pitch Strength of water features measured in the laboratory.

5.4 Conclusions

Comparisons made between field and laboratory results have shown that very quiet and very loud water sounds can be found in open spaces. Such field tests can then provide a wide range of levels, which cannot be easily replicated in laboratories where test structures can only have limited dimensions. For example, it is difficult to model features such as a very large waterfall/fountain, or a long natural stream.

Results showed that the spectra of natural streams and seashore sounds are flatter than those of other water sounds, with a clear absence of high frequency splashing sounds. The water sounds measured in the field also tended to be more variable and irregular in nature (higher $L_{A10} - L_{A90}$), a characteristic which can be replicated in the laboratory, but which is atypical.

Finally, psychoacoustic results showed that the sharpness and roughness tended to be higher for laboratory sounds compared to field sounds, and larger variations were also observed in the pitch strength of laboratory results.

These field results complement those obtained in the laboratory and provide water sounds with different characteristics which can be used for the masking and perceptual analysis presented in the following chapter.

CHAPTER 6

The use of water sounds for road traffic noise masking[1]

6.1 Introduction

This chapter examines the use of water sounds for road traffic noise masking. The analysis includes comparisons of water sound spectra with road traffic noise spectra, as well as perceptual assessment obtained from auditory tests. The latter were based on peacefulness and relaxation within spaces such as gardens and parks, and were used to identify the preferred sound pressure level of water sounds over traffic noise, as well as the preferred water sounds in the presence of road traffic noise.

6.2 Road traffic noise masking

To compare the ability of water sounds to mask traffic noise, a number of road traffic noise spectra were predicted as well as measured in the field for dense road traffic (*e.g.* motorways). Dense road traffic with low temporal variability was considered representative of a real case scenario where masking by small to medium sized water features could be used, for example in a garden or park with audible road traffic noise.

6.2.1 Road traffic noise predictions

Predictions were made using source models of the IMAGINE project (2007) and propagation models of ISO 9613 (Part 1: 1993, Part 2: 1996). The sources models include input data defining the sound power levels of various categories of vehicles (light, medium, medium/heavy and heavy vehicles), whilst the propagation models provide the formulae to be used for predicting sound pressure levels at the receiver (ISO 9613-2, 1996), as well as atmospheric absorption data to be used in the calculations (ISO 9613-1, 1993).

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[1] Large sections of this chapter are based on the paper *Acoustical and perceptual assessment of water sounds and their use over road traffic noise*, by Laurent Galbrun and Tahrir T. Ali submitted to the Journal of the Acoustical Society of America in May 2012.

For the predictions made in this chapter, only the following categories of vehicles were considered:

- Category 1 : light vehicles such as cars and vans
- Category 2: medium heavy vehicles, such as buses, light trucks and heavy vans, and medium heavy trucks (2 axles only)
- Category 3: heavy vehicles such as buses and heavy trucks (3 or more axles)

In the propagation model of ISO 9613-2 (1996), vehicles are simplified into two point sources: the lower source at 0.01m above the road, identified as the tyre/road source (rolling noise), and the higher source, or propulsion noise, which has a different height depending on the vehicle category. Details of the propagation model used for predictions are given below, including the definition of sources and attenuation mechanisms.

Tyre/road (rolling) noise

The sound power level emitted by a vehicle through rolling noise is given by the following equation

$$L_{WR} = a_R(f) + b_R(f) log\left(\frac{v}{v_{ref}}\right) \tag{6.1}$$

where v is the vehicle's speed, v_{ref} =70 km/h is the reference speed, and $a_R(f)$ and $b_R(f)$ are the rolling noise coefficients given for each vehicle category in one-third octave bands (IMAGINE, 2007).

Propulsion noise

The sound power level emitted by a vehicle through propulsion noise is given by

$$L_{WP} = a_P(f) + b_P(f)\left(\frac{v - v_{ref}}{v_{ref}}\right) \tag{6.2}$$

where v is the vehicle's speed, v_{ref} =70 km/h, $a_P(f)$ and $b_P(f)$ are the propulsion noise coefficients for each main vehicle category in one-third octave bands (IMAGINE, 2007).

Sound Pressure Level at receiver

The continuous equivalent downwind sound pressure level at a receiver position is calculated from

$$L_{fT}(DW) = L_W + D_C - A \tag{6.3}$$

where L_w is the sound power level of the source, D_C (dB) is the source's directivity and A is the total attenuation between the source and receiver in dB. The latter can be found from

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \tag{6.4}$$

where A_{div} is the attenuation due to geometrical divergence, A_{atm} is the attenuation due to atmospheric absorption, A_{gr} is the attenuation due to ground effect, A_{bar} is the attenuation due to a barrier and A_{misc} is the attenuation due to miscellaneous effects, all of which are expressed in dB.

Directivity

Directivity is defined as (Harmonoise, 2004)

$$D_C(f, \varphi, \psi) = D_{CH}(f, \varphi) + D_{CV}(f, \psi) \tag{6.5}$$

where $D_{CH}(f, \varphi)$ is the horizontal directivity and $D_{CV}(f, \psi)$ is the vertical directivity, expressed in dB.

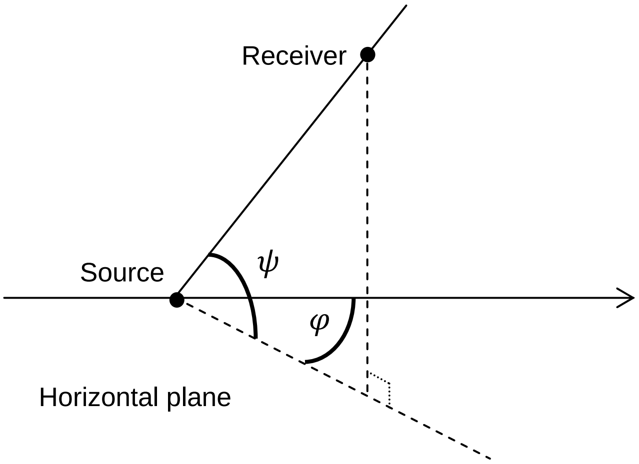


Figure 6.1 Geometry for the directivity functions, showing the angles used in the directivity formulae (Harmonoise, 2004).

For a point source at a 0.01 m height (rolling noise), the following horizontal directivity is to be used (Harmonoise, 2004)

$$D_{CH}(\varphi) = 0;\ f \leq 1250\text{ Hz}, f \geq 8000\text{ Hz}$$
$$D_{CH}(\varphi) = (-1{,}5 + 2{,}5abs\ (\sin(\pi/2 - \varphi)))\sqrt{\cos(\psi)}; \qquad (6.6)$$
$$1600\text{ Hz} \leq f\ \leq\ 6300\text{ Hz}$$

For a point source at a 0.3 m height (propulsion for light vehicles), the following horizontal directivity is to be used (Harmonoise, 2004)

$$D_{CH}(\varphi) = 0 \qquad (6.7)$$

For a point source at a 0.75 m height (propulsion for vans, buses and trucks), the following horizontal directivity is to be used (Harmonoise, 2004)

$$D_{CH}(\varphi) = \left(1{,}546\left(\frac{\pi}{2} - \varphi\right)^3 - 1.425\left(\frac{\pi}{2} - \varphi\right)^2 + 0.22\left(\frac{\pi}{2} - \varphi\right) + 0.6\right)\sqrt{cos\psi} \qquad (6.8)$$

When the vertical angles between the source and receiver are small, the vertical directivity is close to zero. This applies to the distances considered in this chapter, *i.e.* the vertical directivity has been ignored in the predictions presented. Formulae of the vertical directivity can be found in the Deliverable 9 of the Harmonoise project (2004).

Geometrical divergence

Attenuation due to spherical divergence of a point source can be calculated in dB from

$$A_{div} = 20log(d_R) + 11 \qquad (6.9)$$

where d_r is the source-receiver distance in metres.

Atmospheric absorption

Attenuation due to air absorption can be calculated in dB from

$$A_{atm} = \frac{\alpha d_r}{1000} \tag{6.10}$$

where α is the atmospheric attenuation coefficient, in decibels per kilometre (ISO 9613-1, 1993), and d_r is the source-receiver distance in metres.

Ground effect

Predictions presented in this chapter assume a porous ground between the road and receiver. For porous grounds with vegetation (ground factor *G* close to 1), the ground attenuation can be calculated in dB from

$$A_{gr} = 4.8 - \frac{2h_m}{d_r}\left[17 + \frac{300}{d_r}\right] \geq 0 \tag{6.11}$$

where h_m is the mean height of the propagation path above the ground and d_r is the distance from the source to receiver, in metres. When using equation (6.11), there is an increase in sound power level of the source due to ground reflections near the source and the term D_Ω should be added to the directivity correction D_C as

$$D_\Omega = 10log\left[1 + \frac{d_p^2 + (h_s - h_r)^2}{d_p^2 + (h_s + h_r)^2}\right] \tag{6.12}$$

where h_s is the source height, h_r is the receiver height and d_p is the distance from source to receiver as projected on the ground plane, all expressed in metres.

The attenuations A_{bar} and A_{misc} were ignored for the predictions presented in this chapter.

Predictions results

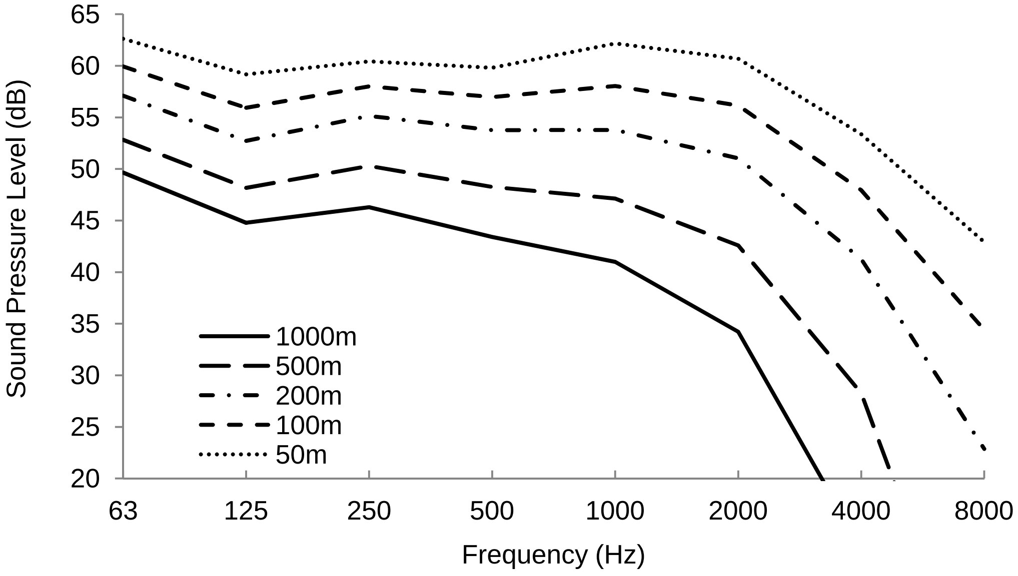
The receiver's height used for predictions was h_r = 1.5 m and the average height of propagation was calculated from ISO 9613-2 (1996, formula on page 8). The source height h_s varied depending on the source (0.01 m for rolling, 0.3 m for propulsion of light vehicles, and 0.75 m for propulsion of vans, buses and trucks).

Predictions have been made for a dense traffic of 3000 vehicles per hour and spectra are shown in Fig. 6.2 for various distances between the receiver and road, and various vehicles' speeds. Fig. 6.3 shows the spectra normalised to 60 dB. Results of Fig. 6.2 indicate that the dense road traffic noise predicted is dominated by mid and low frequencies. The decrease in sound pressure level with distance tends to be fairly uniform at these mid and low frequencies, but larger decreases are observed at high frequencies because of atmospheric absorption. The change in frequency content of road traffic noise for different distances can be clearly seen in the normalised spectra of Fig. 6.3. Predictions have been repeated for different traffic densities as well as different proportions of vehicles' categories (Appendix I), and results show that the general shape of road traffic noise spectra and variations with distance remain comparable to the results presented above.

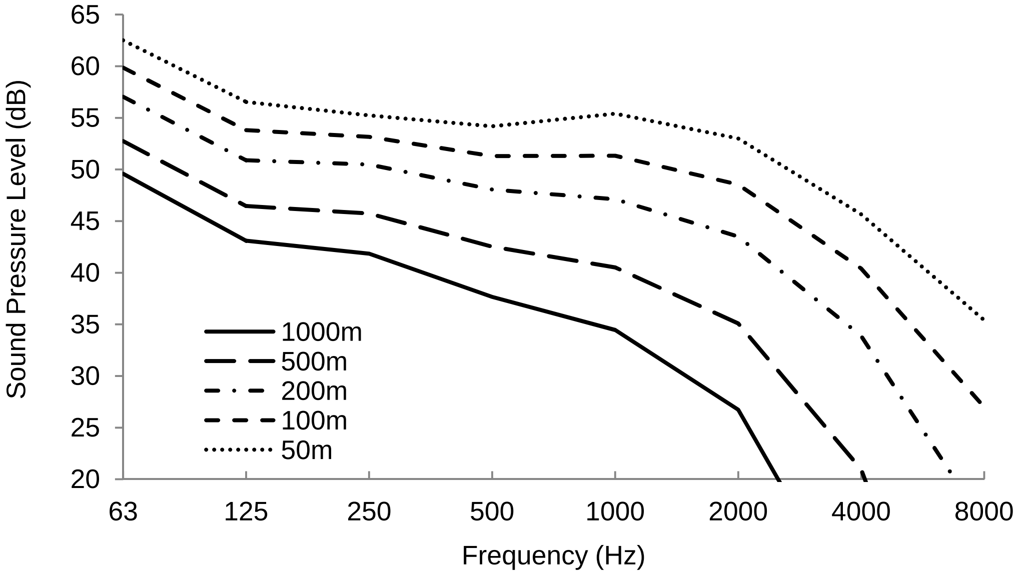
6.2.2 Road traffic noise measurements

Measurements were carried out in a field located next to the M8 motorway (Edinburgh - Glasgow). Fig. 6.4 gives a satellite view of the site, where it can be seen that a road with a bridge passing over the motorway was also present next to the field where tests were undertaken. However, this road had no vehicles passing during the measurements. It can also be seen in Fig. 6.4(b) that the motorway was not a straight line. Measurements were undertaken at various distances from the centre of the motorway: 50 m, 100 m, 150 m and 200 m. In all cases, the receiver's height was 1.2 m above ground.

Fig. 6.5 shows the results measured, together with the 200 m prediction calculated from the source models of the IMAGINE project (2007) and propagation models of ISO 9613 (1993, 1996). It is important to note that this field measurement does not match the conditions used in predictions, so that the differences shown in Fig. 6.5 between the

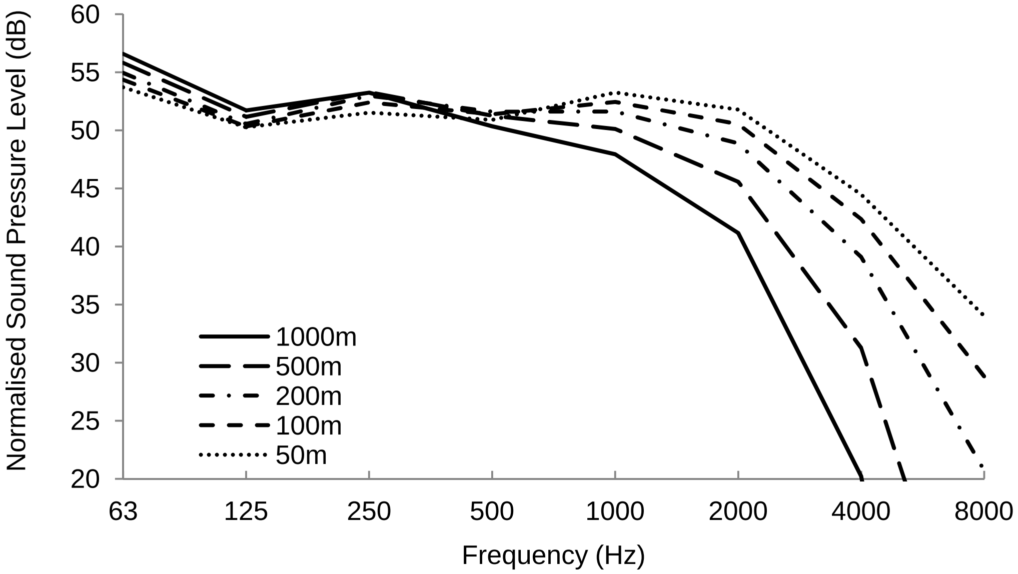


(a) Spectra corresponding to the following vehicles' speeds:
Category 1 *v* = 120 km/h; Category 2 *v* = 95 km/h; Category 3 *v* = 95 km/h.

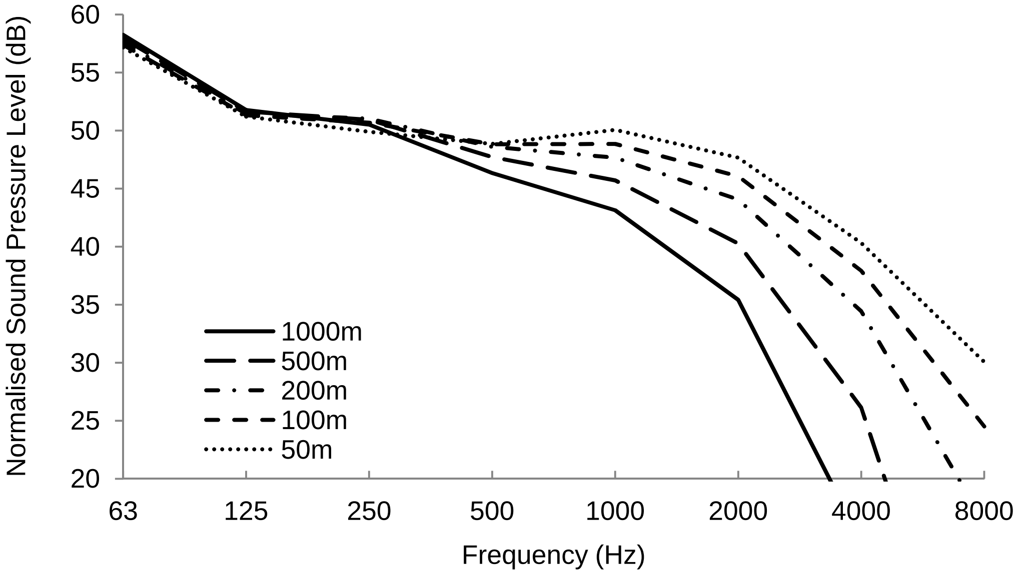


(b) Spectra corresponding to the following vehicles' speeds:
Category 1 *v* = 70 km/h; Category 2 *v* = 50 km/h; Category 3 *v* = 50 km/h.

Figure 6.2 Spectra of road traffic noise with 84% category 1, 6% category 2 and 10% category 3 vehicles.



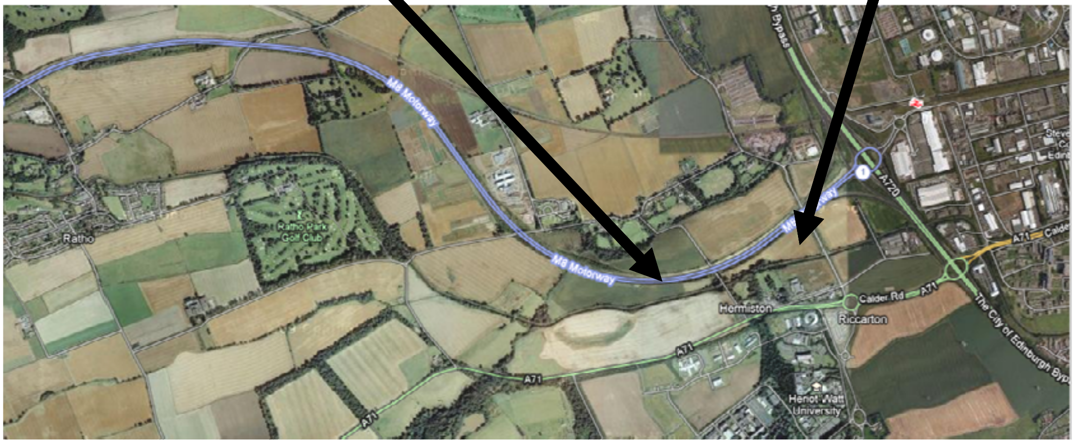
(a) Normalised spectra corresponding to the following vehicles' speeds: Category 1 v = 120 km/h; Category 2 v = 95 km/h; Category 3 v = 95 km/h.



(b) Normalised spectra corresponding to the following vehicles' speeds: Category 1 v = 70 km/h; Category 2 v = 50 km/h; Category 3 v = 50 km/h.

Figure 6.3 Normalised spectra of road traffic noise (to 60 dB) with 84% category 1, 6% category 2 and 10% category 3 vehicles.

(a) Close view



(b) Zoomed out view

Figure 6.4 Satellite view of the site used to measure road traffic noise.

predicted and measured spectra at 200 m can be explained by a number of factors such as the non linear profile of the motorway, the fact that the motorway was at a lower height than the field (approximately 5 m lower), as well as differences between the effective and assumed vehicles' speeds and traffic density. However, it is important to note that these differences are not relevant for the analysis presented here, as the latter only aims to compare typical spectra shapes of traffic noise and water sounds (section 6.2.3). The measurements also show that the shape of the road traffic noise spectra remains similar for the various distances considered.

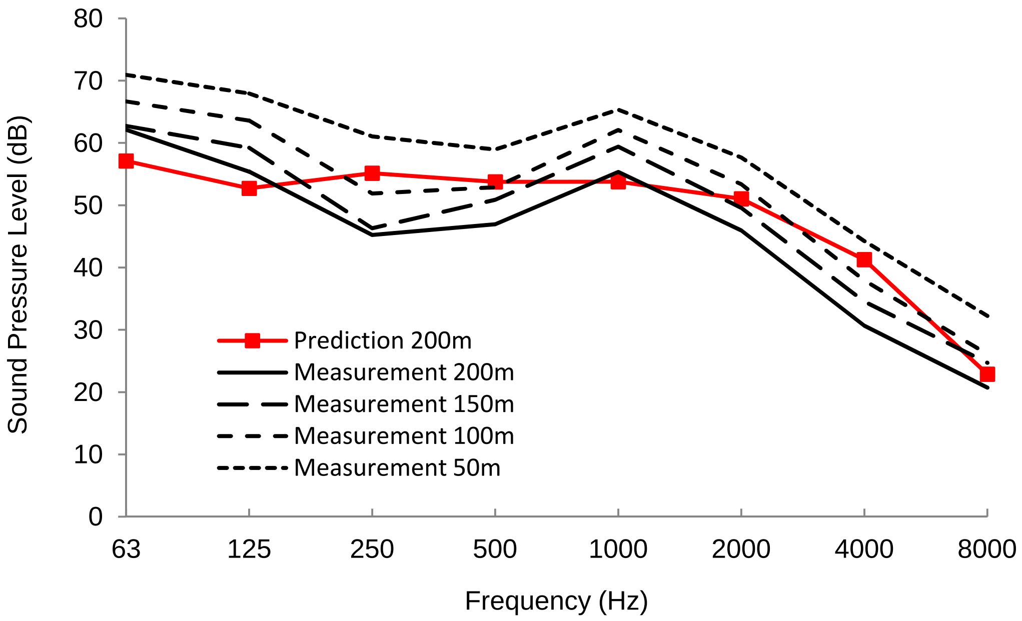


Figure 6.5 Comparison of sound pressure level predicted at 200 m and field measurements made at varying distances.

6.2.3 Water sounds vs. Traffic noise

A busy motorway located at 200 m from a receiver was considered as representative of a real case scenario (typical noise level of 55-60 dBA). The predicted spectrum of road traffic noise at a distance of 200 m between a motorway and receiver was calculated in section 6.2.1 and is shown in Fig. 6.6. The prediction has an A-weighted level of 58 dBA. The spectrum of road traffic noise measured in a field at 200 m from the centre of a busy motorway (M8 Edinburgh – Glasgow, UK) was given in section 6.2.2 and is also shown in Fig. 6.6. This is the traffic noise which was used in the auditory tests of section 6.3, and has an A-weighted level of 56 dBA. As discussed in the previous section, the differences between the predicted and measured spectra can be explained by a number of factors which are however unimportant for the analysis presented here. Together with road traffic noise, Fig. 6.6 shows a variety of water sound spectra which have been selected based on their large variability in frequency responses (see Table 6.1 for the definition of acronyms).

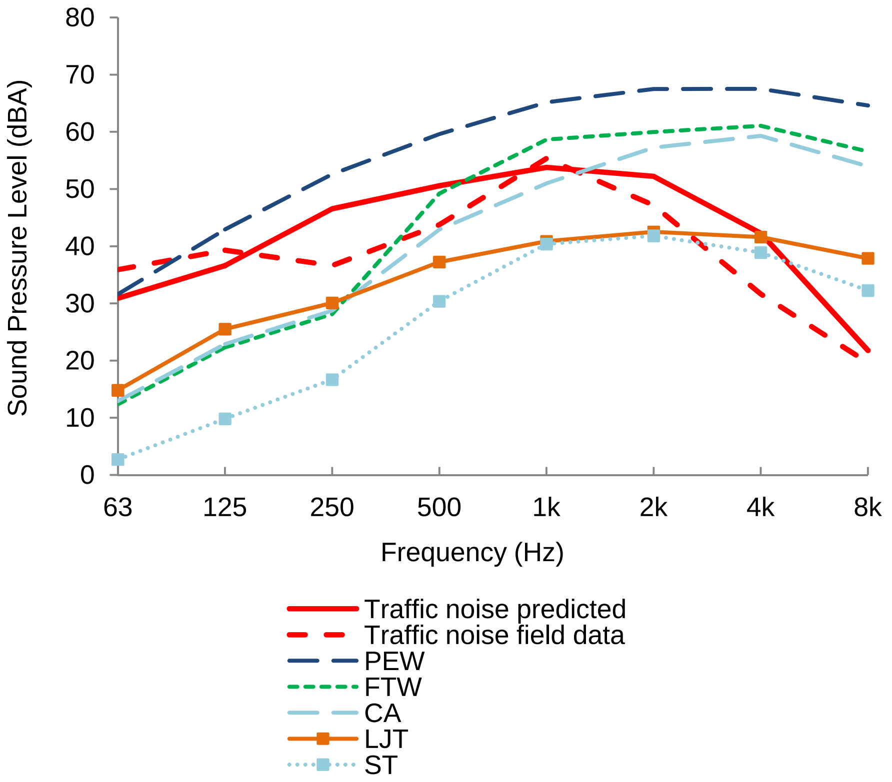


Figure 6.6 A-weighted spectra of predicted and measured road traffic noise and measured water sounds (see Table 6.1 for definition of acronyms).

In terms of human perception, expressed in the figure by the A-weighted sound pressure level, traffic noise is dominated by frequencies in the 250 Hz-2 kHz range, whilst most water sounds are characterised by the 500 Hz-8 kHz range. There is therefore a mismatch between the spectra of traffic noise and water sounds. This confirms the findings from Watts *et al.* (2009) regarding the difficulty of generating low frequencies by using water sounds. However, results presented here show that a waterfall with a large flow rate (PEW) can generate high sound pressure levels at mid and low frequencies (below 500 Hz). The fountain (FTW) and the cascade over stones (CA) are dominated by high frequencies, whilst the stream measured in the field (ST) has less high frequency content and is comparable to the waterfall (PEW) for its shape; the large jet (LJT) has the flattest frequency response. Although only the waterfall's result corresponds to a high flow rate, it can be noted that all the other water features would not produce much more low frequencies if their flow rate was increased (see Chapter 4). This clearly limits the masking properties of most small to medium sized water features against road traffic noise.

The comparisons of Fig. 6.6 are limited to a distance of 200 m, but results of section 6.2.1 showed that the spectra of road traffic noise at 50 m and 100 m have higher levels but a similar shape, so that the findings discussed above remain valid. For larger distances, the main difference is represented by the significant reduction in the high frequency content of road traffic, which is anyway easily masked by water sounds (*i.e.* the findings discussed above remain valid).

This analysis of frequency responses is complemented by results obtained from auditory tests which are presented in the following section, as only perceptual tests can provide an insight into the subjective rating of water sounds for road traffic noise masking.

6.3 Perceptual assessment

This section describes the procedures used in the auditory tests carried out for the study, together with the results obtained from these. Firstly, a test was carried out to identify the preferred sound pressure level of water sounds over road traffic noise, and secondly, another test was carried out to identify the preferred water sounds in the presence of road traffic noise. Twelve different water sounds have been used in these tests (Table 6.1), where sounds have been categorized either as waterfalls, fountains (made of one or more upward jets) or streams (note that LJT has been defined as a stream because of its very shallow and irregular distribution of water: low pressure is present at its large nozzle's opening, therefore resulting in a unsteady operation of the pump and a high value of $L_{A10} - L_{A90}$). These sounds have been played over road traffic noise recorded in a field located 200 m from the centre of a busy motorway (see section 6.2.2 for details). Figure 6.7 illustrates the normalised spectra of the twelve water sounds and the traffic noise, to give an indication of the auditory tests' perception. All spectra shown in the figure were normalised to 55 dBA.

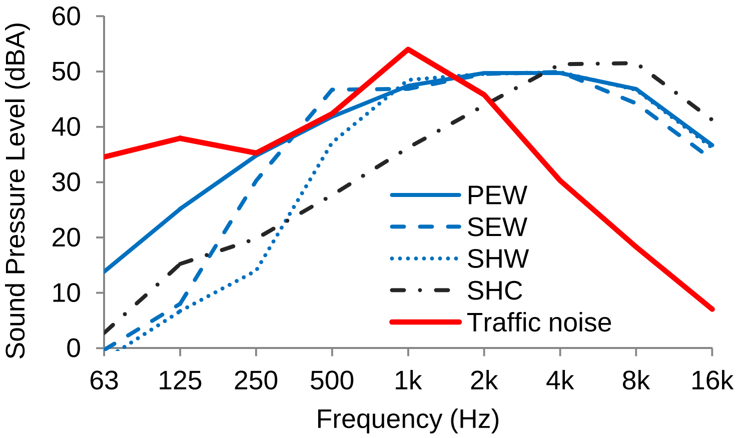
6.3.1 Preferred sound pressure levels

Methods

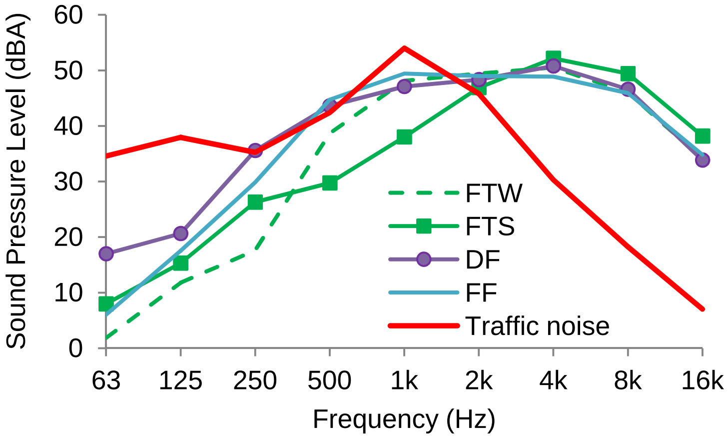
The procedure used was the same as the one developed by Jeon *et al.* (2010), with a constant traffic noise level played at 55 dBA, and with water sounds played at either 49,

Table 6.1 Properties of water sounds and road traffic noise used in the auditory tests, including acoustic and psychoacoustic parameters of the sounds normalized to 55 dBA. Category numbers: 1 = Waterfall, 2 = Fountain, 3 = Stream. The numbers in italic were calculated from sounds including both road traffic noise and water sounds. Fountain extensions and jets were placed at water level; the large jet had a nozzle's diameter of 25 mm, and the narrow jet had a nozzle's diameter of 10 mm.

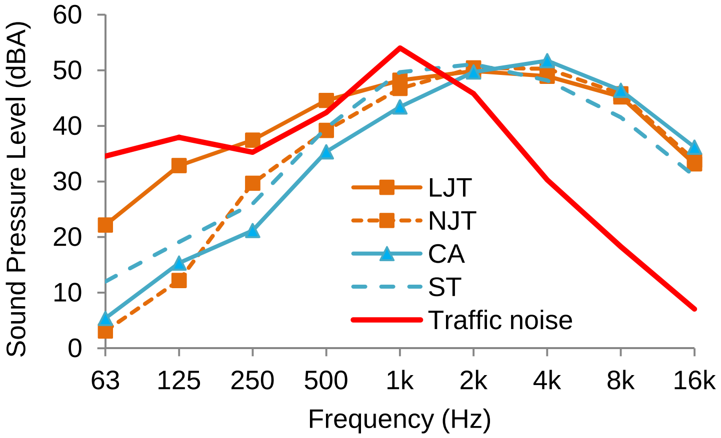
Sound code	Water feature type & Category number	Impact material	Flow rate (l/min)	Height (m) &Width (m)	L_{A10}-L_{A90} (dB)	L_{Ceq}-L_{Aeq} (dB)	Sharpness (acum)	Roughness (asper)	Pitch Strength
PEW	Plain Edge Waterfall – 1	Water	120	1.0 - 1.0	1.1 *1.4*	-0.3 *2.8*	1.98 *1.70*	0.03 *0.04*	0.04 *0.07*
SEW	Sawtooth Edge Waterfall – 1	Water	30	0.5 - 1.0	1.0 *1.6*	-0.1 *2.7*	1.92 *1.59*	0.05 *0.05*	0.10 *0.07*
SHW	Small Holes Waterf. – 1	Water	30	0.5 - 1.0	0.7 *1.4*	-1.0 *2.5*	2.23 *1.71*	0.02 *0.04*	0.09 *0.08*
SHC	Small Holes Waterf. – 1	Concrete	30	0.5 - 1.0	2.3 *1.7*	-1.5 *2.0*	2.95 *2.03*	0.23 *0.19*	0.03 *0.07*
FTW	Fountain (37 jets) – 2	Water	30	-	1.4 *1.5*	-0.9 *2.7*	2.21 *1.67*	0.07 *0.08*	0.10 *0.08*
FTS	Fountain (37 jets) – 2	Stones (pebbles)	30	-	1.5 *1.6*	-1.5 *2.5*	2.51 *1.82*	0.21 *0.13*	0.05 *0.08*
DF	Dome fountain – 2	Water	30	-	1.6 *1.5*	0.3 *2.8*	1.96 *1.61*	0.07 *0.05*	0.14 *0.08*
FF	Foam fountain – 2	Stones & boulders	30	-	2.3 *1.6*	-0.2 *2.8*	1.91 *1.61*	0.09 *0.09*	0.05 *0.07*
LJT	Large jet – 3	Water	15	-	4.9 *2.1*	4.9 *2.9*	1.73 *1.42*	0.28 *0.19*	0.08 *0.07*
NJT	Narrow jet – 2	Water	15	-	1.9 *1.6*	-0.9 *2.5*	2.09 *1.67*	0.19 *0.16*	0.07 *0.08*
CA	Cascade (4 steps) – 3	Stones (pebbles)	15	-	1.2 *1.4*	-1.3 *2.7*	2.21 *1.71*	0.10 *0.09*	0.05 *0.08*
ST	Stream – 3	Stones and water	N/A	-	2.4 *1.7*	-1.4 *2.5*	1.99 *1.61*	0.29 *0.21*	0.06 *0.08*
RTN	Road Traffic Noise	-	-	-	2.7	7.8	1.04	0.03	0.09



(a) Waterfalls.



(b) Fountains.



(c) Jets, cascade and stream.

Figure 6.7 Normalised spectra of road traffic noise and water sounds used in the auditory tests.

52, 55, 58 or 61 dBA (*i.e.* -6 dB, -3 dB, 0 dB, +3 dB or +6 dB relative to the road traffic noise level). The test was carried out for six different water sounds: SHW, PEW, CA, FTW, FF and LJT (refer to Table 6.1 for details).

The listening test included ten paired comparisons per water sound, for a total of sixty paired comparisons. Furthermore, ten comparisons were repeated in order to identify the consistency of subjects. In view of statistical validity, the sequence of paired comparisons was randomised, so that sounds were presented in a different order for each subject.

Thirty four subjects who reported normal hearing ability participated in the test (seventeen males and seventeen females), all of which were either students or researchers working at Heriot-Watt University (age details given in the results' section). The test was carried out in the anechoic chamber of Heriot-Watt University, a highly insulated space with a background noise level of around 21 dBA during tests (including noise from the computer used).

Instructions were initially given to the subjects, who had to imagine that they were relaxing in a balcony or garden where they could hear road traffic noise from a nearby motorway as well as a water feature (same as Watts *et al.* (2009)). Binaural signals were played back from a computer through closed headphones (Beyerdynamic DT 150), where each paired comparison consisted of seven seconds of sound 1, one second of silence, seven seconds of sound 2, and three seconds of silence before the next pair was played. For each comparison, subjects had to select the sound which they found more peaceful and relaxing. Considering the similarities between some of the comparisons, subjects had the option to select "no preference", but were not encouraged to do so. No visual images were used.

Five paired comparisons were initially played for familiarisation with the methods. Once the subject was clear about the procedure, the actual test could begin. This consisted of ten paired comparisons played in an automated sequence, after which the subject was free to take a break before continuing with the following ten pairs, in order to maintain a high concentration level. The test typically lasted 30 minutes per subject, including instructions and breaks.

Results and analysis

Twenty nine subjects (fifteen males and fourteen females of age distribution 19 to 34 years, average age 26.3 years, standard deviation 4.3 years) passed the consistency test (consistent judgements within a 95% confidence interval, corresponding to a repeatability of at least 6 out of 10) and were retained for the analysis of results.

The cultural groups' composition was: 'White' (10), 'Middle Eastern' (6), 'Asian' (11) and 'African/Caribbean' (2), where the numbers in brackets correspond to the number of subjects present within each group.

Results are shown in Fig. 6.8 with normalised preferences given on the vertical axis (preferences defined over the range -2 (never preferred) to +2 (always preferred)). The "no preference" option was chosen only 5% of the time, in which cases no preferences were counted for the levels concerned. For the four sounds SHW, CA, FTW and FF, the preferred water sound pressure level was the same as the road traffic noise level (0 dB difference, *i.e.* 55 dBA level), whilst for the remaining two sounds PEW and LJT, the preferred level was 3 dB below road traffic noise (*i.e.* 52 dBA level). It is interesting to note that PEW and LJT are the sounds with the highest low frequency content, *i.e.* with the better masking spectra, and a preferred sound pressure level lower than all the other water sounds. No statistically significant difference in responses was found between the different gender, age and cultural groups (Mann-Whitney test, $p > 0.05$) (Field, 2005).

Overall, these results confirm the findings of Jeon et *al.* (2010) according to which the water sounds should be similar or not less than 3 dB below the urban noise level. Furthermore, it is worth noting that You *et al.* (2010) also obtained the same results regardless of whether road traffic noise was played at 55 dBA or 75 dBA.

6.3.2 Preferred water sounds

Methods

In this test, paired comparisons were made between twelve water sounds (Table 6.1) played over road traffic noise. All the water sound pressure levels and traffic noise levels were played at 55 dBA, as results discussed in the previous section have shown that a difference of 0 dB between water sounds and traffic noise tends to be preferred.

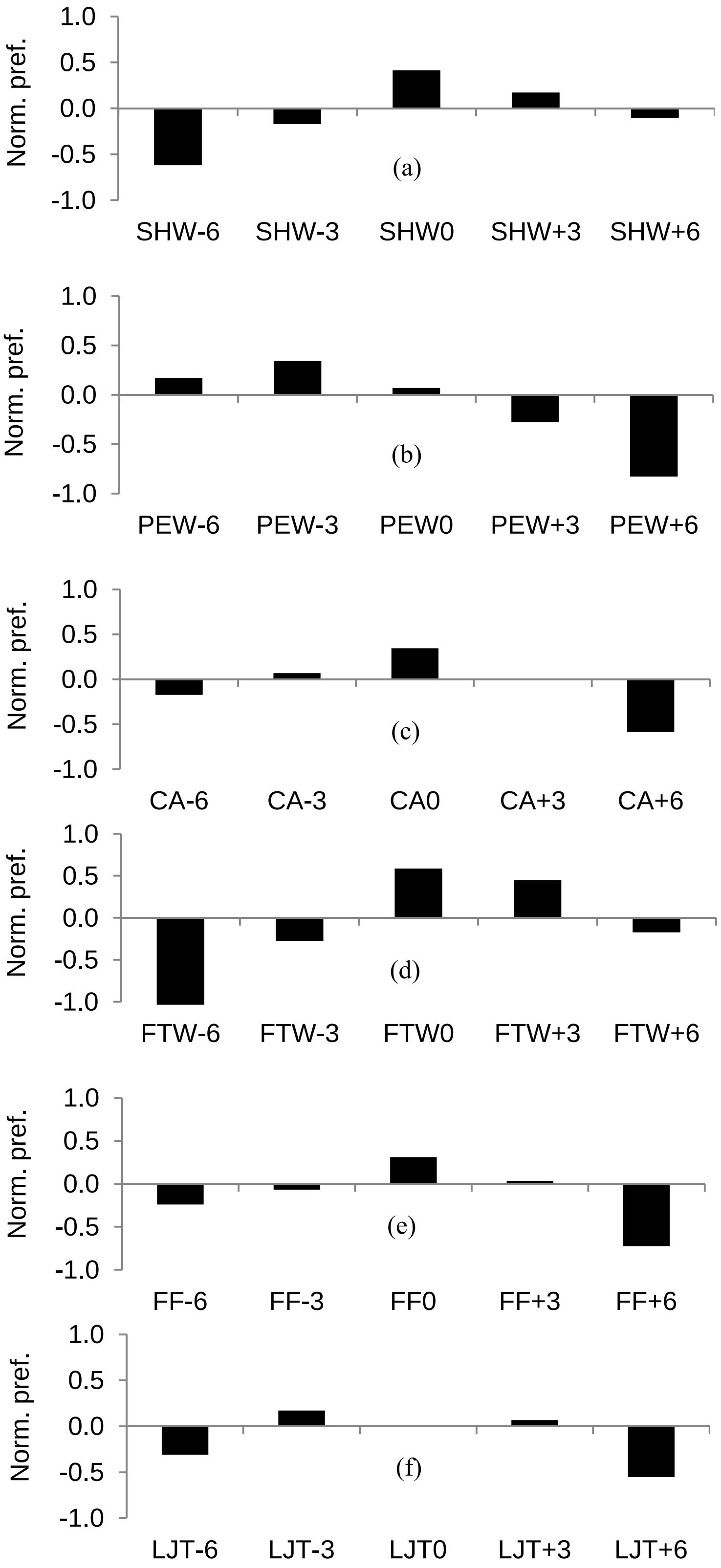


Figure 6.8 Preferred water sound pressure levels.

(a) Small holes edge waterfall (SHW). (b) Plain edge waterfall (PEW).

(c) Cascade (CA). (d) Fountain (FTW). (e) Foam fountain (FF). (f) Large jet (LJT).

A total of seventy six paired comparisons were carried out per subject, including the ten repetitions made for the analysis of consistency. Furthermore, five additional paired comparisons were made to examine the preferred edge type of a waterfall and the preferred impact material in a sawtooth edge waterfall. This requested using three additional water sounds not shown in Table 6.1: (1) A plain edge waterfall over water, with a flow rate of 30 l/min; (2) A sawtooth edge waterfall over stones, with a flow rate of 30 l/min; (3) A sawtooth edge waterfall over stones and boulders, with a flow rate of 30 l/min. The sequence of paired comparisons was randomised for all tests.

Similarly to the test made for preferred sound pressure levels, thirty four subjects who reported normal hearing ability participated in the test (seventeen males and seventeen females), all of which were either students or researchers (different sample than the previous one). The method used for instructing subjects and presenting the paired comparisons was identical to what has been described in the previous section, but the "no preference" option was not given as differences between the sounds were not subtle. The test typically lasted 35 minutes per subject, including instructions and breaks.

Results and analysis

Thirty one subjects (fifteen males and sixteen females of age distribution 20 to 45 years, average age 27.8 years, standard deviation of 4.9 years) passed the consistency test (consistent judgements within a 95% confidence interval, corresponding to a repeatability of at least 6 out of 10) and were retained for the analysis of results. The cultural groups' composition was: 'White' (14), 'Middle Eastern' (7), 'Asian' (6) and 'African/Caribbean' (4), where the numbers in brackets correspond to the number of subjects present within each group.

The results given in Fig. 6.9 (preferences defined over the range -2 (never preferred) to +2 (always preferred)) and Table 6.2 indicate that the preferred water sounds are the natural stream ST, the fountain made of 37 jets FTW, the large jet with a low flow rate and shallow distribution of water LJT, and the cascade with four steps CA. In contrast, the least liked sounds are the waterfalls with small holes SHW and SHC, the waterfall with a plain edge and a very large flow rate PEW, and the single jet with a narrow nozzle NJT. A statistically significant correlation was found between the category numbers of Table 6.1 and the preferences obtained, suggesting that stream sounds are

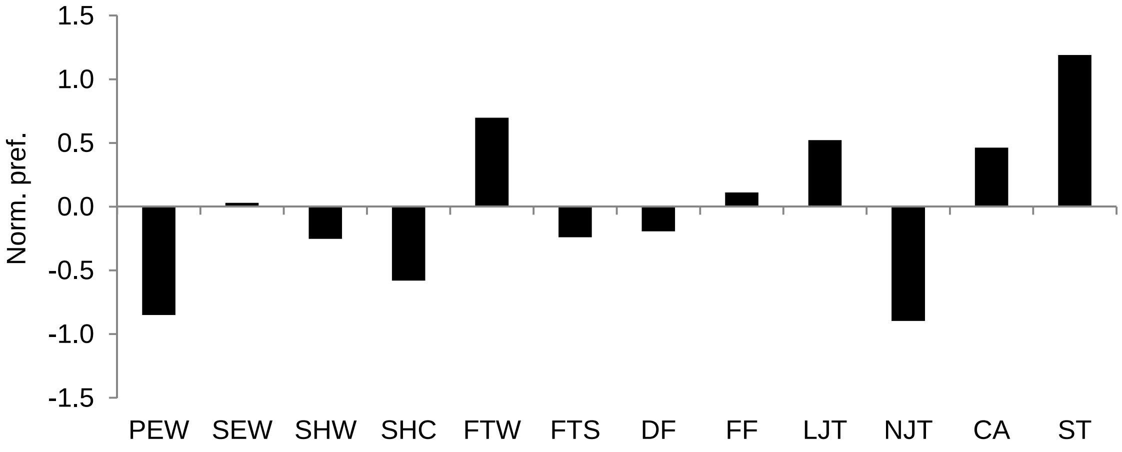


Figure 6.9 Preferred water sounds.

Table 6.2 Ranking of preferred water sounds obtained from all subjects retained for the analysis, together with clusters' ranking obtained from latent class analysis.

Sound ranking	All subjects		Cluster 1		Cluster 2	
	Sound code	Norm. pref.	Sound code	Norm. pref.	Sound code	Norm. pref.
1	ST	1.19	ST	1.12	ST	1.27
2	FTW	0.70	LJT	0.84	FTW	0.99
3	LJT	0.52	FTW	0.46	CA	0.73
4	CA	0.46	CA	0.25	LJT	0.13
5	FF	0.11	FF	0.20	SEW	0.13
6	SEW	0.03	DF	-0.03	FF	0.00
7	DF	-0.19	SEW	-0.05	SHW	-0.08
8	FTS	-0.24	FTS	-0.12	DF	-0.39
9	SHW	-0.25	SHW	-0.40	FTS	-0.39
10	SHC	-0.58	SHC	-0.50	PEW	-0.60
11	PEW	-0.85	NJT	-0.72	SHC	-0.68
12	NJT	-0.90	PEW	-1.06	NJT	-1.12

preferred to fountain sounds, which are in turn preferred to waterfall sounds (Spearman test, $\rho = 0.678$, $p < 0.05$). Results of Fig. 6.9 also indicate that water is the preferred impact material (FTW preferred to FTS, and SHW to SHC). As in the case of the preferred sound pressure level test, a statistical analysis of the results indicated no significant difference between the different gender, age or cultural groups (Mann-Whitney test with $p > 0.05$ in each case) (Field, 2005). The ratings of each sound followed a normal distribution between subjects with the Kolmogorov-Smirnov test showing no significant deviation from normality with $p > 0.05$, apart from the ratings obtained for LJT with $p = 0.043$. This normality of preference judgements with a clear peak and decline on either side suggests a stable profile for preference judgements which can generalise to the wider population. However, a concordance analysis indicated a degree of agreement between subjects which was not high (Kendall's coefficient of concordance $W = 0.32$, statistically significant at $p = 0.001$) (Field, 2005; Siegel and Castellan, 1988). This low concordance value was further explored by latent class analysis (Hagenaars and McCutcheon, 2002), a form of regression analysis which can handle non parametric data and identify clusters or sub-groups (latent classes) in a data set. Latent class analysis showed that the subjects' sample was divided into two clusters in terms of preference judgements for four of the twelve sounds. These were sounds PEW, SHW, and LJT at $p < 0.01$ and sound DF at $p < 0.05$. When these four sounds were excluded, the concordance coefficient W increased to 0.43. The results obtained for the different clusters are given in Table 6.2 (Cluster 1: seventeen subjects; Cluster 2: fourteen subjects), where it can be seen that the ranking variations are actually not significant, as the ranking positions of water sounds do not vary markedly (up or down two positions at most). This justifies the analysis based on different ranking groups shown in Table 6.3, where groups of either two, three or four sounds are given. For example, group 1-4 includes the four sounds rated on top by the thirty one subjects, *i.e.* ST, FTW, LJT and CA. Similarly to Table 6.1, the data of Table 6.3 was calculated for water sounds either including or not including road traffic noise. As the preference tests were carried out in the presence of traffic noise, the analysis should be primarily based on the italic numbers of Table 6.3; results obtained from the water sounds alone are also given in the table, as subjects have the potential to focus on the most positive and distracting sound (Watts *et al.*, 2009; Durlach, 2006).

Correlations have been examined between ranking positions and the averages of acoustical and psychoacoustical parameters of each group, and the values obtained for Spearman's correlation coefficient are given in Table 6.3. Spearman's tests indicated that the complexity of each individual water sounds does not lead to good correlations between ranking positions and any acoustical or psychoacoustical parameter. This is true when individual sounds are used for correlation tests, as well as when groups made of two sounds are used (bottom of Table 6.3). However, some trends can be observed when the analysis is made for groups including more than just two sounds. For example, analysis made for the three groups 1-4, 5-8 and 9-12, indicates that the preferred water sounds have larger temporal variations in level ($L_{A10} - L_{A90}$), larger low frequency content ($L_{Ceq} - L_{Aeq}$) and lower sharpness; on the other hand, there are no correlations with roughness and pitch strength.

The results obtained for the preferred waterfall's edge are shown in Fig. 6.10(a), where it can be seen that the sawtooth edge type is preferred to the small holes edge, which is in turn preferred to the plain edge, which has a significantly lower rating. No correlations were found between these preferences and any acoustical or psychoacoustical parameter, but these results confirm that the sound produced by a plain edge waterfall tends not to be liked. Fig. 6.10(b) illustrates preferences between different impact materials, showing that the use of boulders over stones is preferred to water, which is in turn preferred to stones alone. Previous results suggested that water is preferred to solid materials, but Fig. 6.10(b) indicates that this is not necessarily true. This ranking was correlated with higher values of $L_{A10} - L_{A90}$ ($\rho = -0.87$), which suggests that a high temporal variation can act as a prevailing positive factor.

Discussion

Jeon *et al.* (2012) found that water sounds defined by the word freshness had a higher sharpness, whilst water sounds defined by the word calmness had a lower sharpness. This is in line with the results obtained here, as the perceptual assessments were based on peacefulness and relaxation (i.e. calmness). However, the preference of low sharpness contrasts with the findings of Watts *et al.* (2009), which showed that water sounds with higher sharpness were more highly rated in terms of tranquillity. In that respect, it should be noted that the present study tested a variety of upward and

Table 6.3 Ranking groups with corresponding averages of acoustic and psychoacoustic parameters, and correlation coefficients (Spearman test). The numbers in italic were calculated from sounds including both road traffic noise and water sounds.

Sound ranking groups	L_{A10} - L_{A90} (dB)	L_{Ceq}-L_{Aeq} (dB)	Sharpness (acum)	Roughness (asper)	Pitch Strength
1-4	2.5 *1.7*	1.0 *2.7*	2.04 *1.60*	0.19 *0.14*	0.07 *0.08*
5-8	1.6 *1.6*	-0.4 *2.7*	2.08 *1.66*	0.11 *0.08*	0.09 *0.08*
9-12	1.5 *1.5*	-0.9 *2.5*	2.31 *1.78*	0.12 *0.11*	0.06 *0.08*
Corr. coeff.	-1.00** *-1.00***	-1.00** *-0.87*	1.00** *1.00***	-0.50 *-0.50*	-0.50 -
1-3	2.9 *1.8*	1.8 *2.7*	1.98 *1.57*	0.21 *0.16*	0.08 *0.08*
4-6	1.5 *1.5*	-0.5 *2.7*	2.01 *1.64*	0.08 *0.08*	0.07 *0.07*
7-9	1.3 *1.5*	-0.7 *2.6*	2.23 *1.71*	0.10 *0.07*	0.09 *0.08*
10-12	1.8 *1.6*	-0.9 *2.4*	2.34 *1.80*	0.15 *0.13*	0.05 *0.07*
Corr. coeff.	-0.40 *-0.32*	-1.00** *-0.95*	1.00** *1.00***	-0.20 *-0.40*	-0.40 *-0.45*
1-2	1.9 *1.6*	0.2 *2.6*	2.10 *1.64*	0.18 *0.15*	0.08 *0.08*
3-4	3.1 *1.8*	1.8 *2.8*	1.97 *1.57*	0.19 *0.14*	0.07 *0.08*
5-6	1.7 *1.6*	-0.2 *2.8*	1.92 *1.60*	0.07 *0.07*	0.08 *0.07*
7-8	1.6 *1.6*	-0.6 *2.7*	2.24 *1.72*	0.14 *0.09*	0.10 *0.08*
9-10	1.5 *1.6*	-1.3 *2.3*	2.59 *1.87*	0.13 *0.12*	0.06 *0.08*
11-12	1.5 *1.5*	-0.6 *2.7*	2.04 *1.69*	0.11 *0.10*	0.06 *0.08*
Corr. coeff.	-0.93** *-0.68*	-0.84* *-0.23*	0.31 *0.66*	-0.60 *-0.45*	-0.53 *0.13*

* Correlation is significant at the 0.05 level. ** Correlation is significant at the 0.01 level.

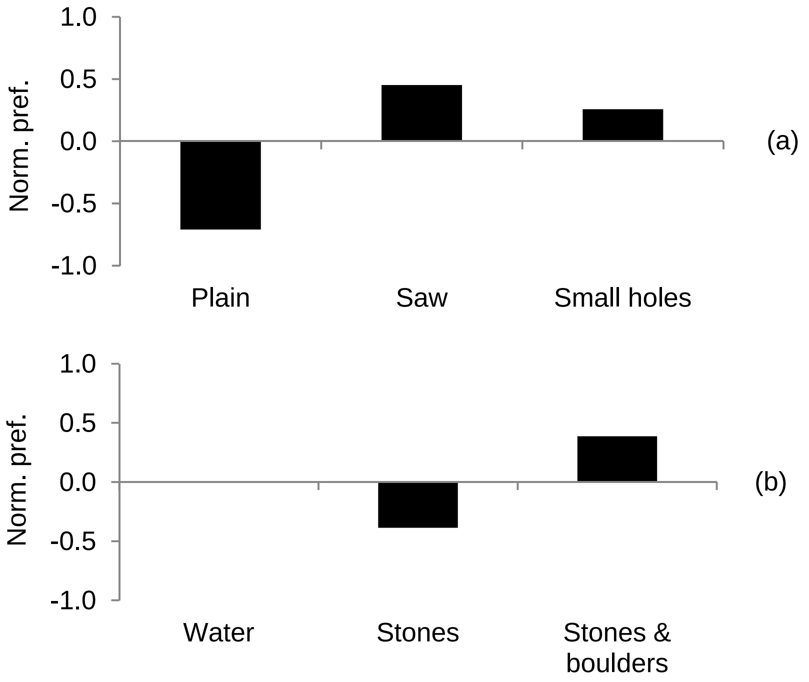


Figure 6.10 Preferred waterfall's edge (a) and preferred impact material for a sawtooth edge waterfall (b). The waterfalls were of 1m width with a height of falling water of 0.5m, and a flow rate of 30 l/min.

downwards flows, whilst Watts *et al.* (2009) examined only one downwards stream with varying impact materials. The latter case is comparable to the waterfalls tested, for which it was found that boulders were preferred to water as the impact material (i.e. higher sharpness). This might be due to the fact that a downward stream with lower sharpness tends to be associated with manmade sounds such as water falling into a drain or container, and these tend not to be liked (Watts *et al.*, 2009). Sharpness might then not be the key factor for driving preference of all types of water features, whilst temporal variations might be, according to the results obtained. This will have to be examined in more detail by further research, together with the meaning and evocative effect of the water sounds. The latter could justify the poor ratings obtained for PEW and NJT, if tests were to confirm that PEW is evocative of water falling into a drain or container, and that NJT resembles a water tap (i.e. manmade sounds).

It is also worth pointing out that the shallow stream sound (ST) was the only field recording used in these tests, but was by far the preferred water sound. This stream showed large temporal variations and a strong spatial quality clearly reflected in the left and right channels of the binaural recording (the sound was measured at the junction of two streams), all characteristics which were less pronounced in the laboratory generated sounds. This suggests that the use of multiple features as sound sources can increase envelopment and improve sound perception, an aspect that will need to be examined in more detail by future soundscape research.

6.4 Conclusions

Road traffic noise was predicted and measured for dense traffic with low temporal variability, which was considered to be representative of a real case scenario where the masking by a small to medium sized water feature could be used (*e.g.* in a garden or park). Results showed that road traffic noise is dominated by mid to low frequencies for all types of conditions considered (*i.e.* varying vehicles speeds and varying percentages of vehicles' categories).

The data presented indicated that there is a mismatch between the frequency responses of traffic noise and water sounds, as traffic noise is dominated by frequencies between 250 Hz and 2 kHz, whilst most water sounds are characterised by the 500 Hz-8 kHz octave bands (A-weighted sound pressure levels for human perception). Most of the small to medium sized water features tested cannot generate enough low frequencies to mask road traffic noise, but unlike the streams tested by Watts *et al.* (2009), results have shown that waterfalls with large flow rates can generate low frequency levels which are similar to those of road traffic noise.

Perceptual assessments were made in the context of peacefulness and relaxation within gardens and balconies where road traffic noise from a motorway was audible. Auditory experiments indicated that the water sounds should be similar or not less than 3 dB below the road traffic noise level. This was found for six different water sounds showing a large range in frequency content (two waterfalls, two fountains, a jet and a cascade), thus further validating the results obtained by Jeon *et al.* (2010) and You *et al.* (2010). Similarly, the test looking at preferred water sounds was undertaken using twelve different water sounds which were representatives of a wide range of designs, as well as a wide range of acoustical and psychoacoustical properties. The analysis of preferred water sounds showed that no single acoustical or psychoacoustical parameter can be used to assess individual sound preferences, as multiple factors affect water sounds' perception. However, it was found that gentle sounds with low flow rates, which are typical of natural streams, tended to be preferred. Stream sounds were preferred to fountain sounds, which were in turn preferred to waterfall sounds. Analysis made on groups of sounds also showed that low sharpness and large temporal variations were preferred on average. Furthermore, water was preferred to hard impact materials, with the exception of the sawtooth edge waterfall, in which case boulders were preferred (apparently because of the larger temporal variations produced).

It is important to remember that these findings are specific to gardens and parks in the context of peacefulness and relaxation. For example, soundscape preferences and contexts can be different in urban squares, as suggested by the significant correlations with 'freshness' (*i.e.* high sharpness) found by Jeon *et al*. (2012).

CHAPTER 7

Conclusions

7.1 Introduction

This chapter outlines the main findings and conclusions of the research. A summary of the conclusions is given for all chapters and suggestions for further research are presented.

7.2 Conclusions

The aim of this thesis was to to develop the knowledge and understanding of the acoustical and perceptual properties of small to medium sized water features, particularly in relation to road traffic noise masking. A large variety of water features have been tested in a controlled environment, and the design factors affecting the acoustical and psychoacoustical properties of water sounds have been examined thoroughly. The variability of water sounds has also been analysed through a number of field tests, whilst their use in view of road traffic noise masking has been examined through acoustical analysis and preferences obtained from auditory tests.

Chapter 2 provided the background information required for the research and critically reviewed the literature. The positive qualities of water were highlighted and a historical review of water features was given, showing how their purpose has shifted with time from its functional role towards more decorative, aesthetic and entertainment goals. Current design guidelines suggested that sound properties are not amongst the primary factors taken into account by designers, although soundscape studies are now pointing towards a more functional use of water features. The review of acoustic research showed that current work focuses on multi-disciplinary approaches such as the soundscape concept, for which physical and perceptual properties of the aural environment need to be examined together for effective assessment. Previous studies also highlighted the importance of introducing pleasant sounds (*e.g.* water sounds) within the environment, but it was found that only few recent studies have examined the acoustical and perceptual properties of water sounds in some detail. In particular, an in-depth analysis of small to medium sized water features was not available in the literature, therefore justifying the research proposed.

Chapter 3 explained the test structures and procedures used for the study. A description of the laboratory rig structure and designs tested was given. The acoustical and psychoacoustical parameters used were defined and their measurement procedures were explained. The perceptual methods applied were also reviewed, although a comprehensive description of these is available in Chapter 6. The impact of laboratory background noise, receiving position used for measurements and repeatability, were also examined in order to justify the measurements methods used and their validity.

Chapter 4 presented the results obtained from laboratory tests regarding the impact of design factors on acoustical and psychoacoustical parameters. A considerable amount of time was devoted to the construction of these features and their testing, in order to obtain a significant amount of data which allowed carrying out a detailed analysis. This also provided a pool of results and audio recordings which will be very useful for future soundscape studies using water sounds. The design factors considered included the impact of flow rate, waterfalls' edge design and width, height of falling water, and impact materials. Results pointed out that a variety of water sounds can be produced by varying the design of small to medium sized water features, and that estimations can be made on how these factors affect sound pressure levels, frequency content and psychoacoustic parameters. Overall, results showed that low frequency sounds cannot be easily generated by increasing the flow rate in features such as fountains, jets, as well as cascades and sloping surfaces. However, low frequencies can be produced in waterfalls by increasing the flow rate, especially for waterfalls with a plain edge. Results indicated that L_{Aeq} increases logarithmically with flow rate for most small and medium sized water features, waterfalls being louder than any other type of water feature, as they can use higher flow rates and larger amounts of water which produce more bubbles. All the water sounds were found to be mid and high frequency dominant, with most of the energy contained in the 500 Hz – 16 kHz octave bands. Higher sound pressure levels (+2-3 dB) were obtained when distributing the same amount of water over several streams (sawtooth edge and small holes edge waterfalls) rather than over one uniform stream (plain edge). At high flow rates, an increase in the width of a waterfall tended to increase the overall sound pressure level (+2-3 dB), and increasing the height of falling water could increase the sound pressure level significantly (+5-10 dB). Impact materials greatly affected acoustical and psychoacoustical properties, results showing however that changes in sound pressure level and spectra become less and less significant with increasing height and flow rate. Overall, water produced more mid and low frequencies (+5-10 dB compared to hard materials in the range 250 Hz – 2 kHz), whilst hard materials tended to increase the high frequency content of approximately 5 dB. Variations of psychoacoustic parameters with flow rate, waterfalls' edge design and height of falling water were limited. In contrast, variations in sharpness and roughness were significant when different impact materials were used (up to +0.60 acum and +0.70 asper respectively). Both sharpness and roughness increased with solid materials, whilst the pitch strength was higher when water was the impact material, although the changes observed for the latter were small (+0.05). Results obtained from the combination of upward and downward water flows suggested that waterfalls tend to dominate the sound spectra, unless upward flows fall from high levels. In the case of combinations of upward flows (*e.g.* jet with fountain), no sound tended to dominate clearly, and the characteristics of both features affected the overall sound spectra.

Chapter 5 described field tests carried out to obtain data from water features which could not be built and tested in the laboratory. This allowed comparing laboratory results with field results, and identifying the extent of variations in acoustical properties of a diverse sample of water sounds. Data was collected for natural waterfalls and streams, as well as large fountains and seashores. Results showed that very quiet and very loud water sounds can be found in open spaces. The spectra of natural streams and seashore sounds were flatter than other water sounds, with a clear absence of high frequency splashing sounds. Water sounds measured in the field tended to be more irregular, with higher temporal variations. Psychoacoustic results showed that sharpness and roughness tended to be higher for laboratory sounds, and larger variations were also observed in the pitch strength of laboratory results.

Chapter 6 examined the use of water sounds for road traffic noise masking. The analysis included comparisons of water sound spectra with road traffic noise spectra, as well as perceptual assessment obtained from auditory tests. Road traffic noise was predicted and measured for dense traffic with low temporal variability, which was considered to be representative of a real case scenario where the masking by a small to medium sized water feature could be used (*e.g.* in a garden or park). Results showed that road traffic noise is dominated by mid to low frequencies for all types of conditions considered, water sounds' data showing that most of the small to medium sized water features cannot generate enough low frequencies to mask road traffic noise. An exception was however represented by waterfalls with large flow rates, which can generate low frequency levels which are similar to those of road traffic noise. Auditory tests were based on peacefulness and relaxation within spaces such as gardens and parks, and were used to identify the preferred sound pressure level of water sounds over traffic noise, as well as the preferred water sounds in the presence of road traffic noise. Experiments indicated that the water sounds should be similar or not less than 3 dB below the road traffic noise level. These results were obtained for six different water features representative of a wide range of sounds (two waterfalls with different edges and flow rates, two fountains, a large jet and a cascade). Similarly, the test looking at preferred water sounds was undertaken using twelve different water sounds which were representatives of a wide range of designs, as well as a wide range of acoustical and psychoacoustical properties. The analysis of preferred water sounds showed that no single acoustical or psychoacoustical parameter can be used to assess individual sound preferences, as multiple factors affect water sounds' perception. However, it was found that gentle sounds with low flow rates, tended to be preferred. Stream sounds were preferred to fountain sounds, which were in turn preferred to waterfall sounds. Analysis made on groups of sounds also showed that low sharpness and large temporal variations were preferred on average. Furthermore, water tended to be preferred to hard impact materials.

7.3 Impact of the research

The area of research considered in this thesis can guide acoustic design based on the idea of improving sound environments by adding pleasant sounds, rather than reducing noise, which may be more difficult and costly. The findings obtained are particularly relevant to urban designers as well as architects, who can use these novel results to inform the soundscape design of water features (the previous literature lacking such a detailed description of their acoustical and perceptual properties).

7.4 Suggestions for further research

This section lists a number of suggestions which could be applied to develop the research further. These go from simple variations in the tests carried out, in view of adding detailed information to the results obtained, to the development of significantly different tests, in view of including additional factors and/or consider different contexts.

The acoustical and psychoacoustical analysis looking at the impact of design factors was very comprehensive and detailed, but was focused on small to medium sized water features. Results obtained by Fastl (2005) for large cascade structures suggested that the findings obtained for small to medium sized water features might not be applicable to large features. This could be examined by further research.

The large amount of water sounds' data available could be used to develop sound maps of individual water sounds which could be used for planning purposes. For example, these maps could be used to identify the most appropriate water features to be used in gardens or parks for specific traffic noise environments, knowing that the water sounds should be similar or not less than 3 dB below the road traffic noise level.

Perceptual assessments were carried out for the specific context of peacefulness and relaxation within gardens and balconies where road traffic noise from a motorway was audible. First of all, a motorway has low temporal variability, but De Coensel *et al.* (2011) showed that perception changes if noise with high temporal variability is used as background. Auditory tests could therefore be repeated with traffic noise showing high temporal variability, *e.g.* using city street noise rather than motorway noise.

The motorway noise used in the auditory tests was limited to a distance of 200 m. Results showed that spectra at 50 m and 100 m have higher levels but a similar shape, so that the normalised levels should not vary significantly and findings should remain valid. However, at great distances a large reduction occurs in the high frequency content of road traffic noise. As these high frequencies of road traffic noise are masked by water sounds, perception should not change significantly for large distances. However, this should be validated by future research.

The spatial context of the auditory tests could be moved to an urban square, in which case entertainment might prevail over peacefulness and relaxation as the preference criterion. This would be particularly interesting in view of comparisons with the results obtained by Jeon *et al.* (2012), who identified freshness as significantly related to preferences (more than calmness).

The preference tests carried out were based on paired comparisons only. In order to further develop the characterisation of the water sounds recorded, semantic differential scales and rating scales could be used in perceptual tests. In line with this characterisation, it was pointed out that the meaning and evocative effect of certain sounds might have played a role in some of the preference results obtained. For example, the poor rating of the waterfall with a plain edge and a very large flow rate (PEW) might have been due to the fact that its sound was evocative of sewage systems. Similarly, the single jet with a narrow nozzle (NJT) resembled a water tap sound, which may again have been evocative of sewage systems. These ‘meaning’ and ‘evocative’ effects will also have to be examined by future research.

The use of multiple water sound sources could also be examined, in view of identifying the impact of increased envelopment on sound perception. This suggestion stems from the fact that the stream field recording used in the auditory tests was by far the preferred water sound, and the only one exhibiting high envelopment. The increase in water sounds’ envelopment might therefore increase their sound quality, but this should be quantified and confirmed by further research.

The comparison of preferences between seashore sounds and other water sounds would also be interesting, as the former have a high temporal variation and an evocative effect which are unique. Seashore sounds were not included in the current auditory tests, as these were not considered to be representative of typical urban environments, and these are not designable water features.

Previous research has shown that visual perception can interfere significantly with audio perception. This interaction was not analysed in this thesis, but this is an obvious factor that should be investigated by future research. Of particular interest is the visual impact of water feature displays rather than their background, as the impact of natural against artificial settings is well known and recognised. Preference tests could therefore be carried out with sounds alone vs. images alone vs. sounds and images, for different water features shown in the same environment. This could give an insight into the preferred types of water displays, as well as explain the interaction between their aural and visual characteristics.

Finally, in this thesis, perceptual assessments of water sounds were applied to outdoor environments and road traffic noise only. The large database of water sounds available could be used to analyse their use within indoor spaces (*e.g.* hotel lobbies, offices and restaurants). In particular, the use water sounds could be analysed for speech privacy and/or relaxation and/or purely for entertainment (*e.g.* in shopping centres).

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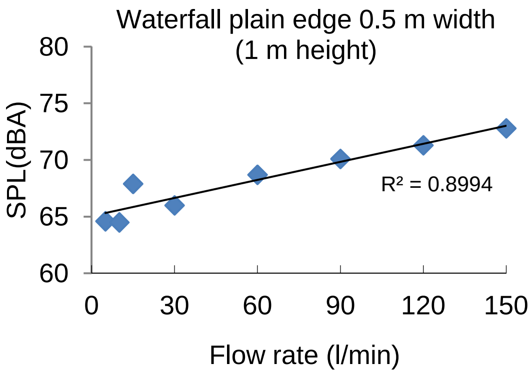
Appendix A: L_{Aeq} vs. Flow rate

Results of L_{Aeq} vs. Flow rate are given in this appendix for all the different types of water features tested.



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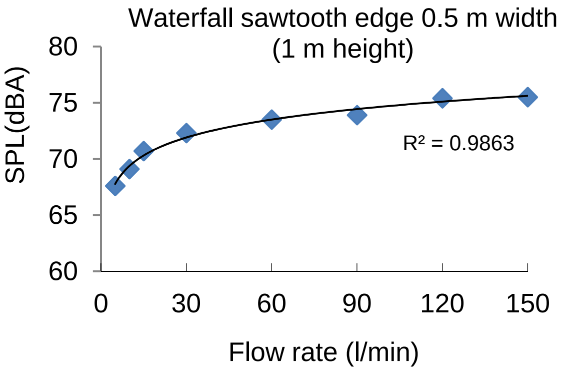

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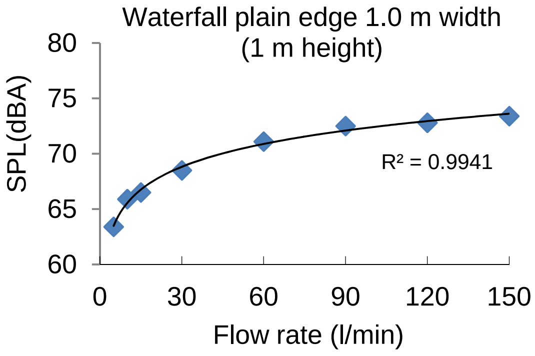

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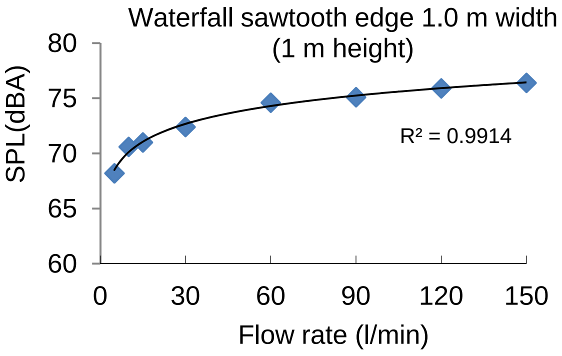

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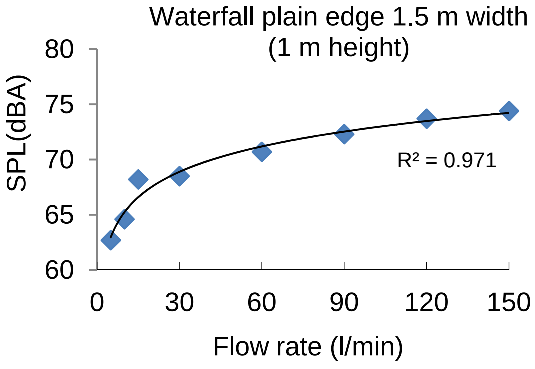

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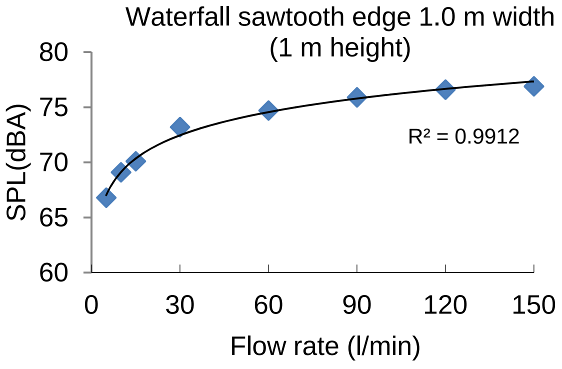

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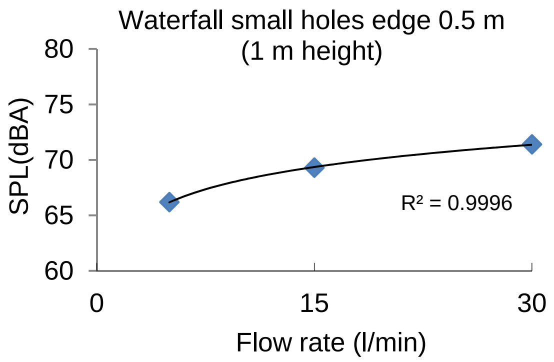

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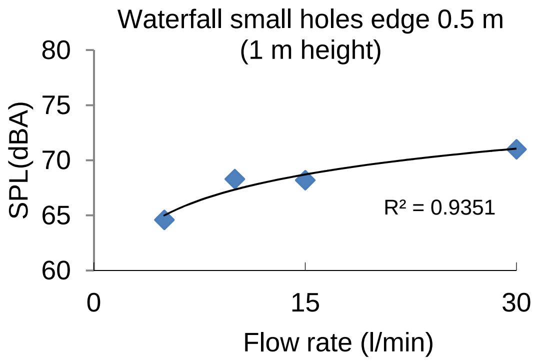

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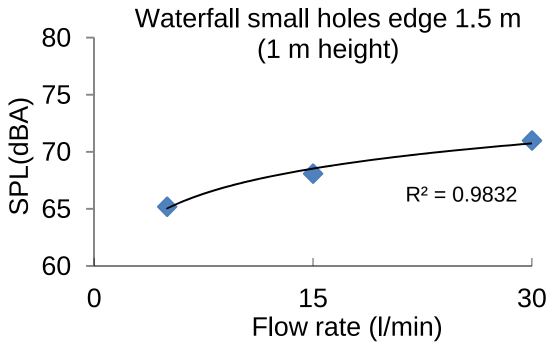

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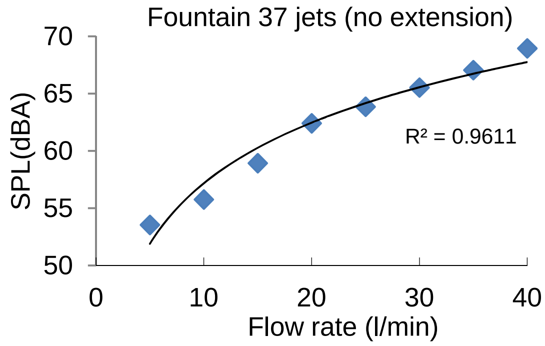

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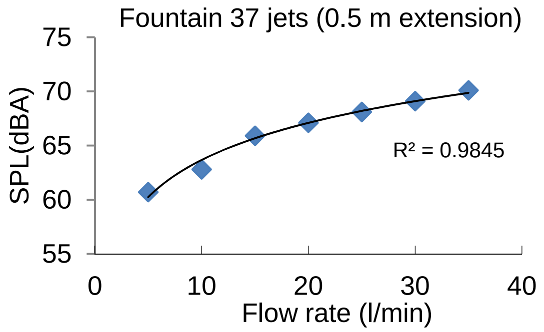

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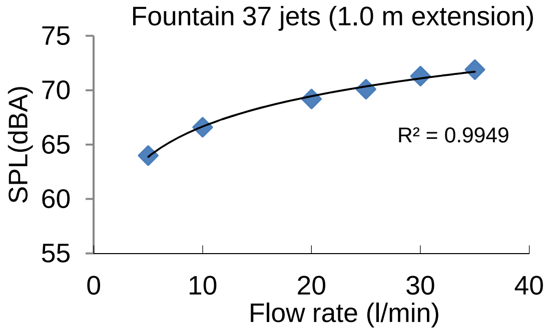

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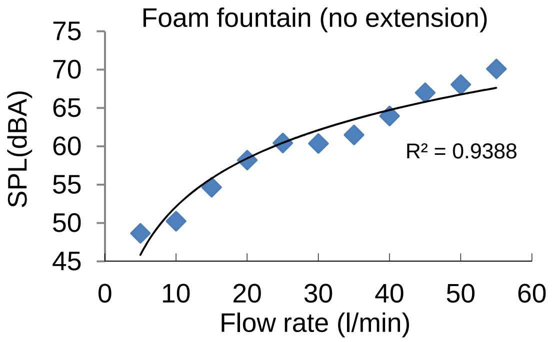

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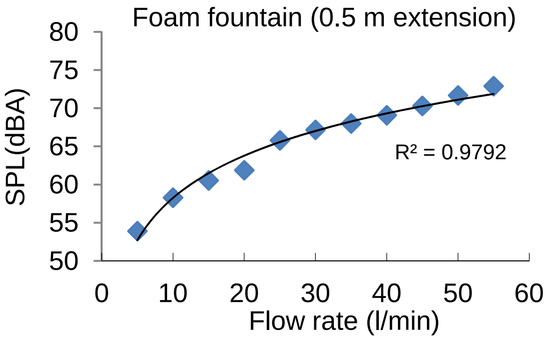

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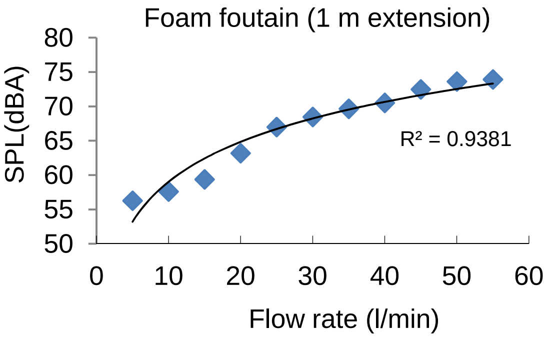

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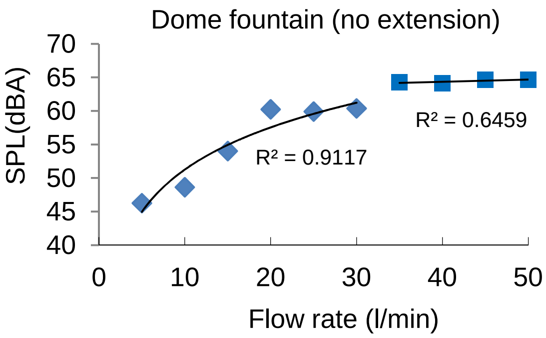

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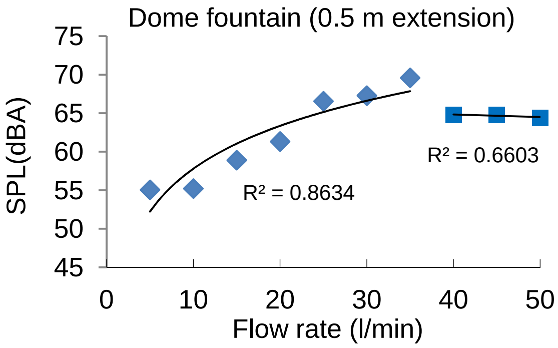

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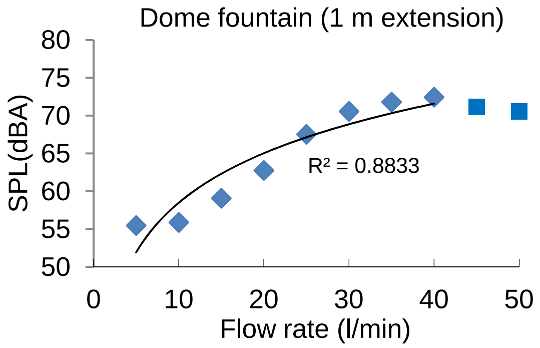

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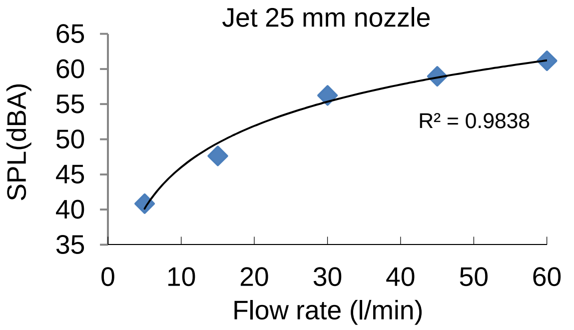

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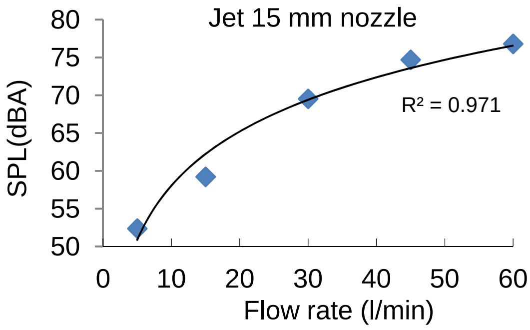

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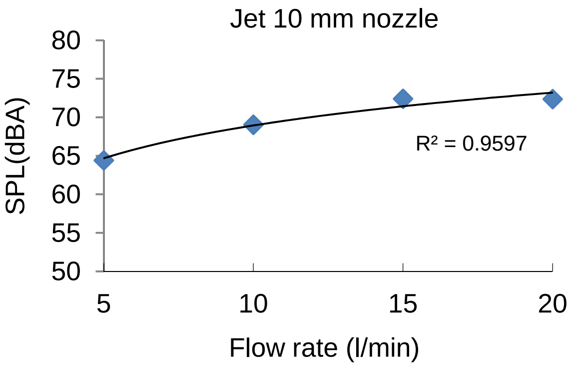

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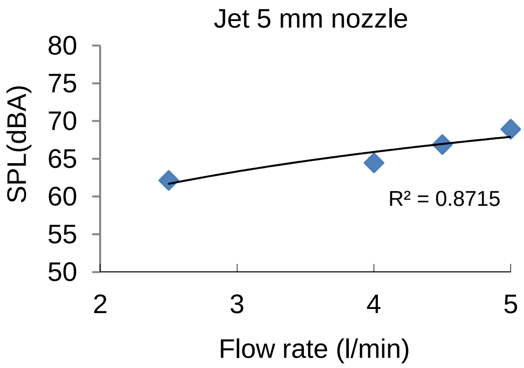

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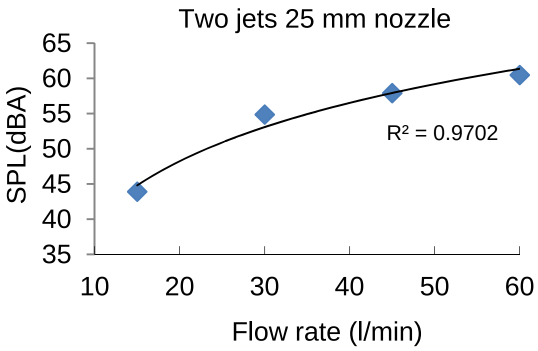

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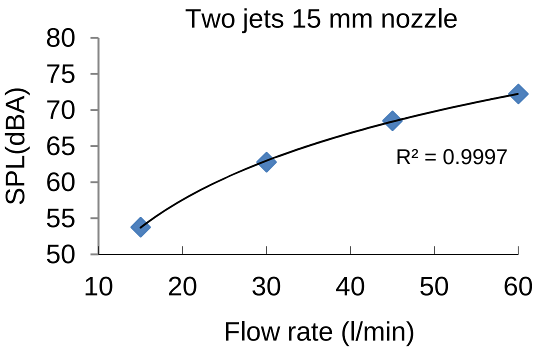

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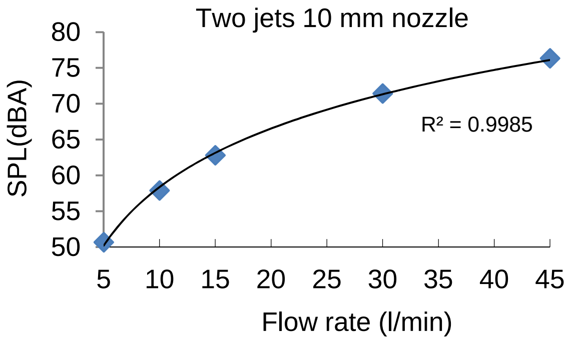

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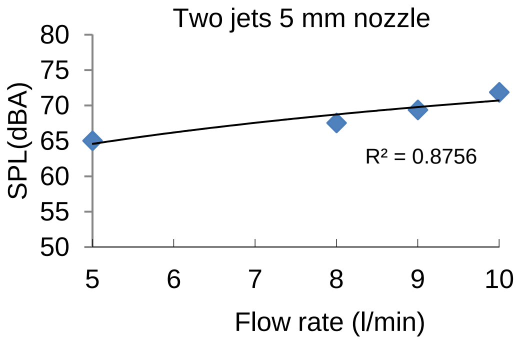

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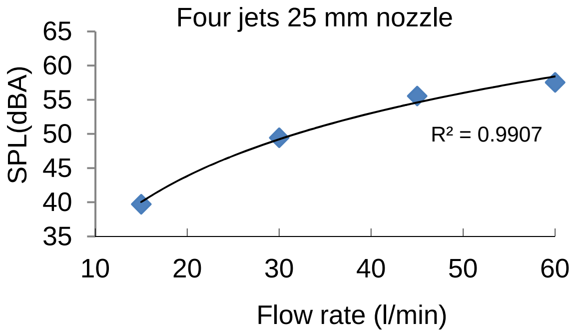

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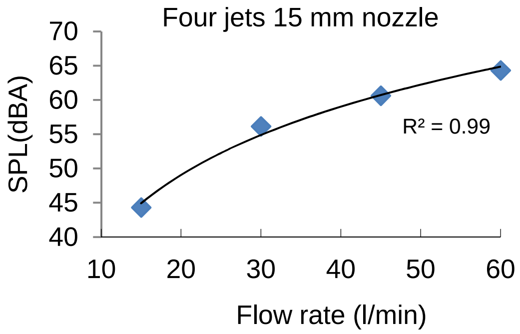

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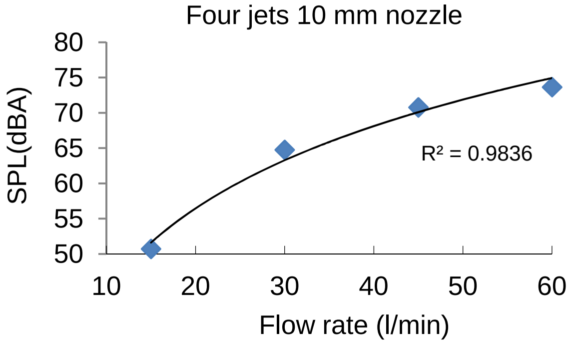

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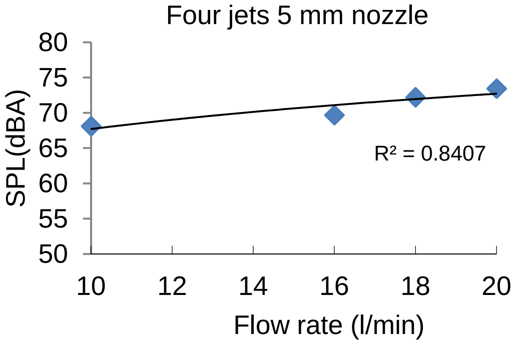

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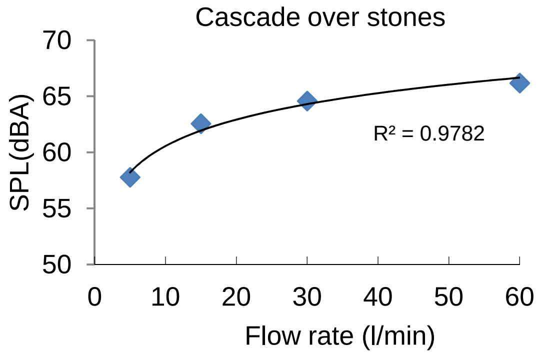

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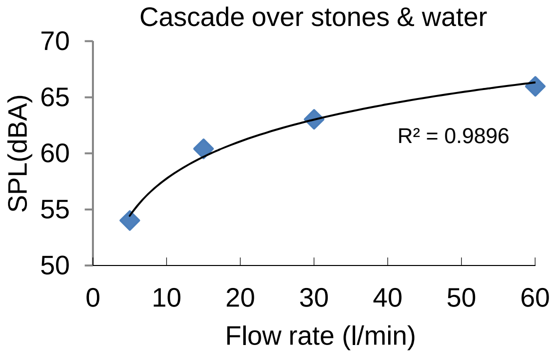

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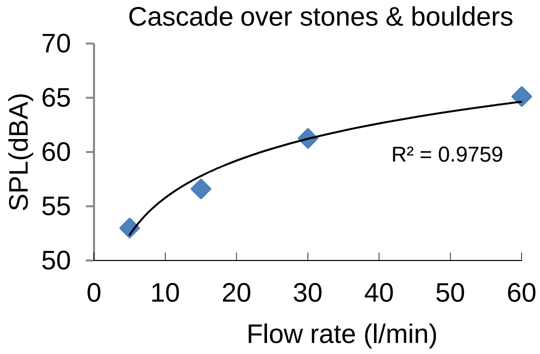


Figure A33

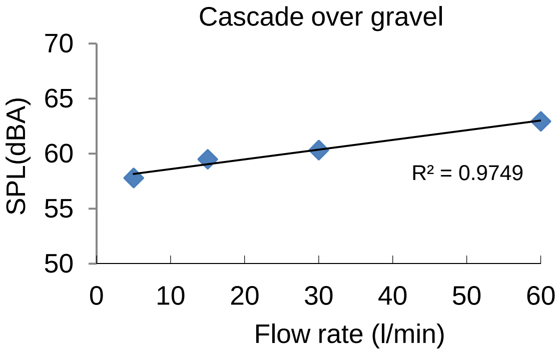


Figure A34

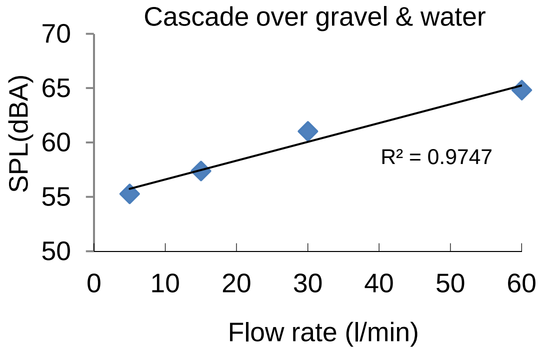


Figure A35

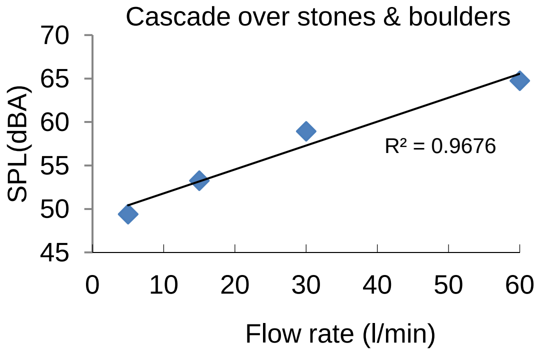
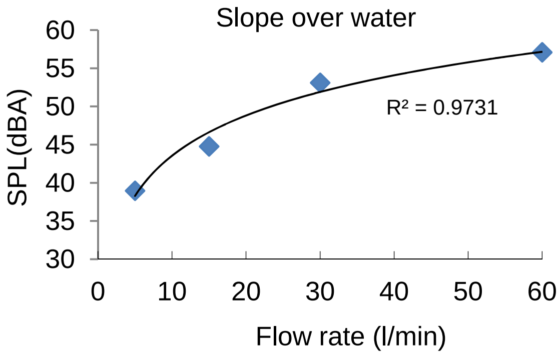


Figure A36



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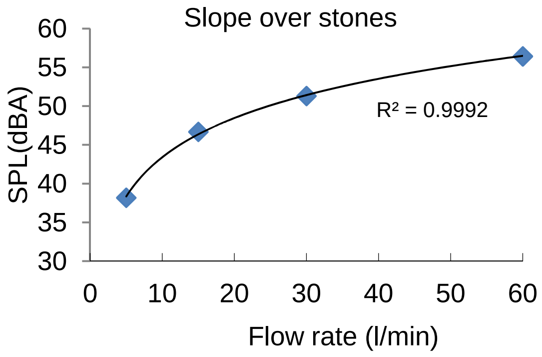

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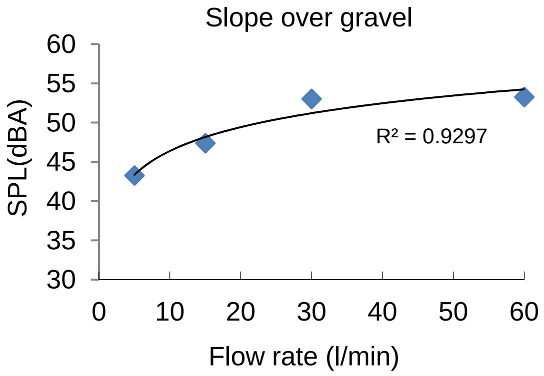

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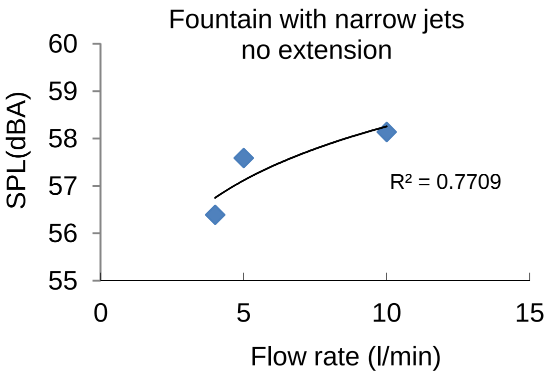
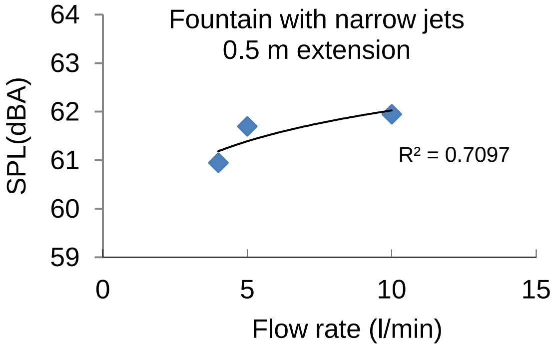


Figure A40



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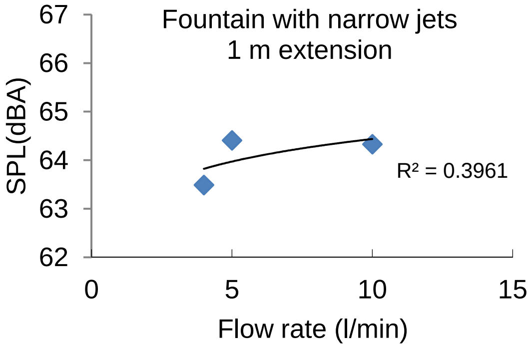


Figure A42

Appendix B: Loudness vs. Flow rate

Results of Loudness vs. Flow rate are given in this appendix for a sample of the water features tested.

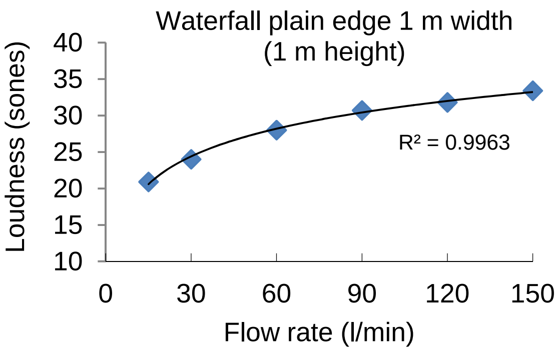


Figure B1

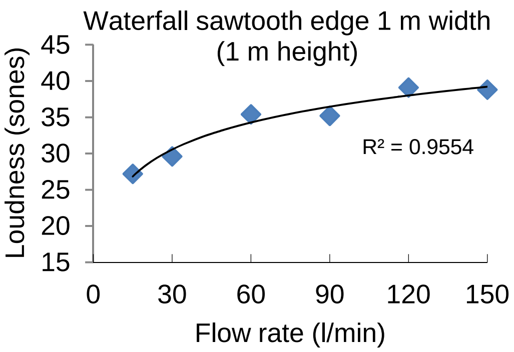


Figure B2

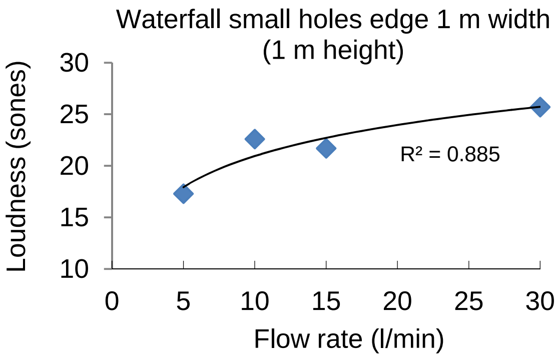
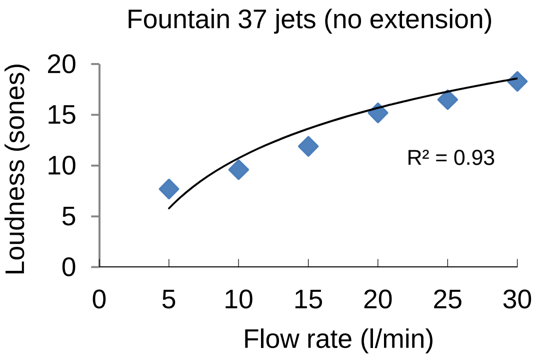


Figure B3



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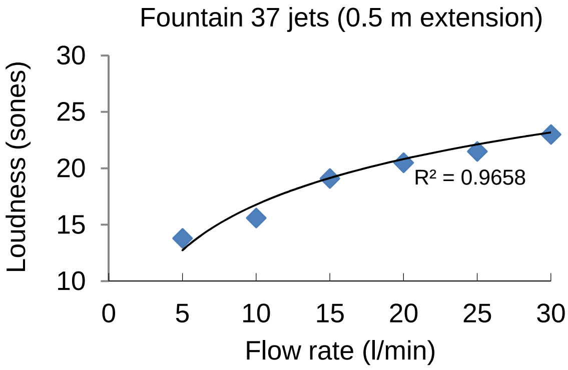

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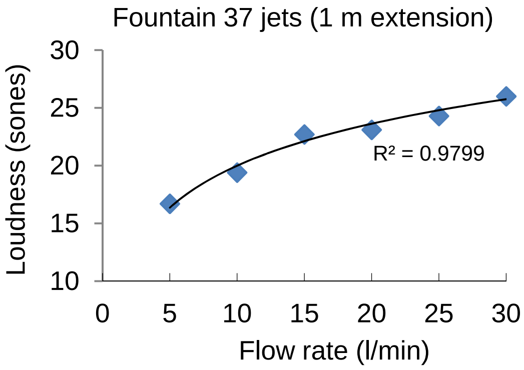


Figure B6

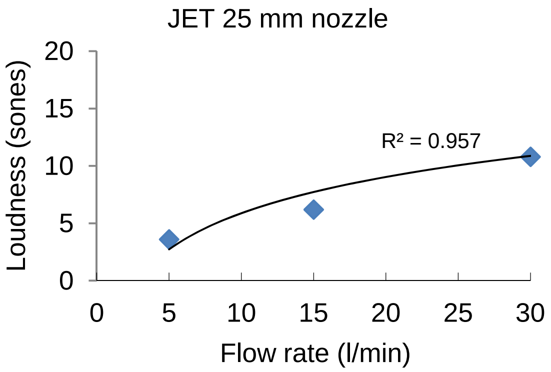


Figure B7

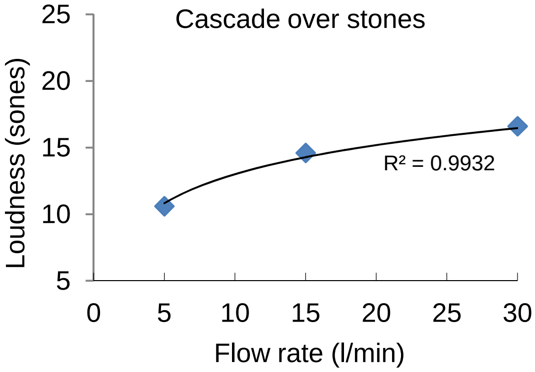


Figure B8

Appendix C: Spectra vs. Flow rate

Results of Spectra vs. Flow rate are given in this appendix for all the different types of water features tested.

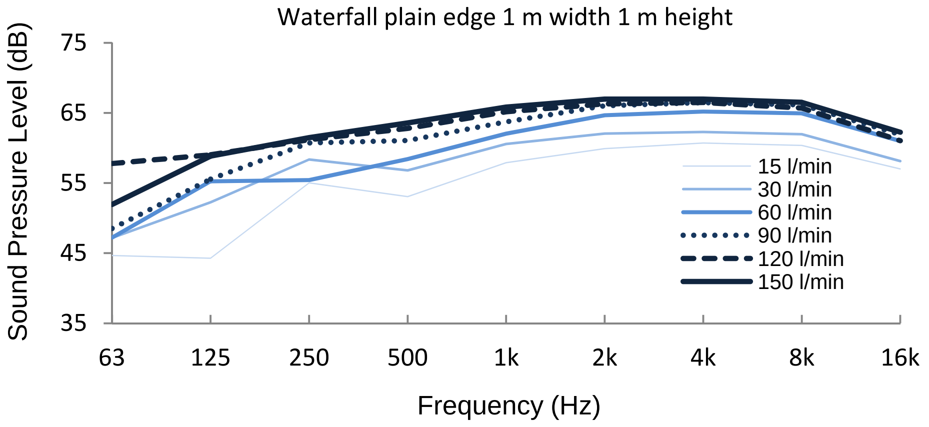


Figure C1

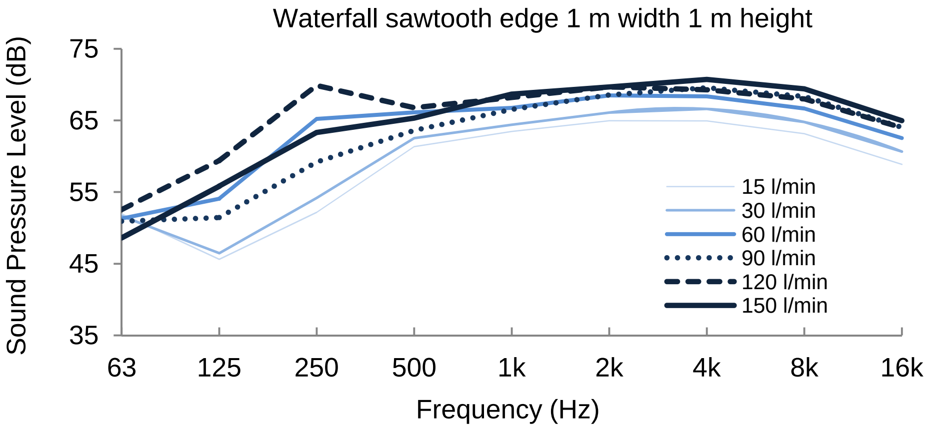


Figure C2

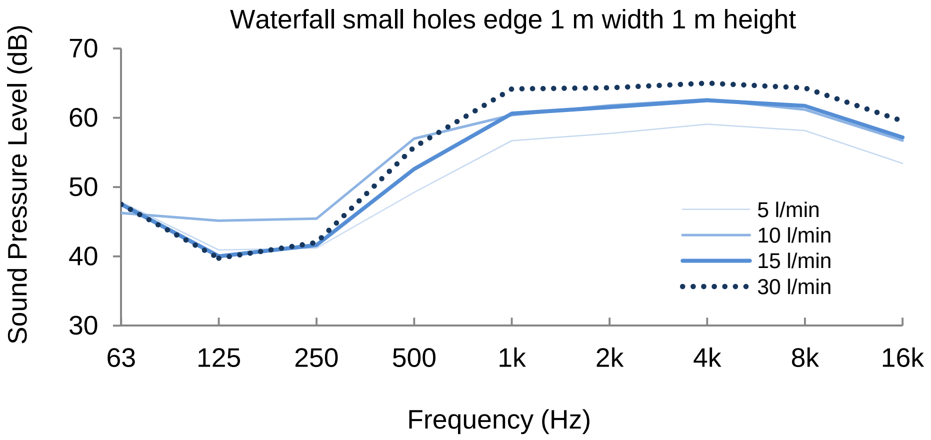


Figure C3

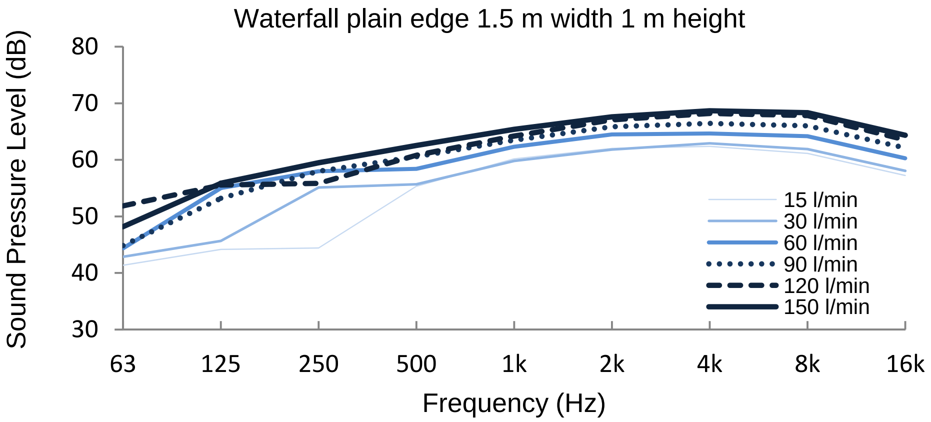


Figure C4

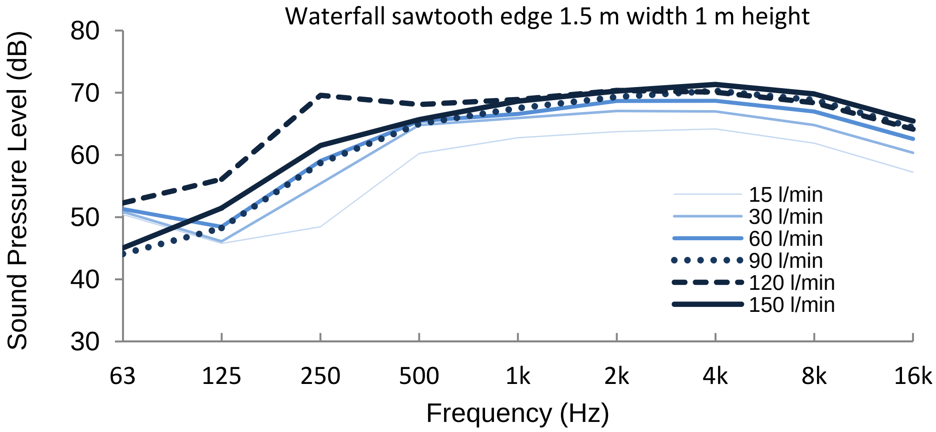


Figure C5

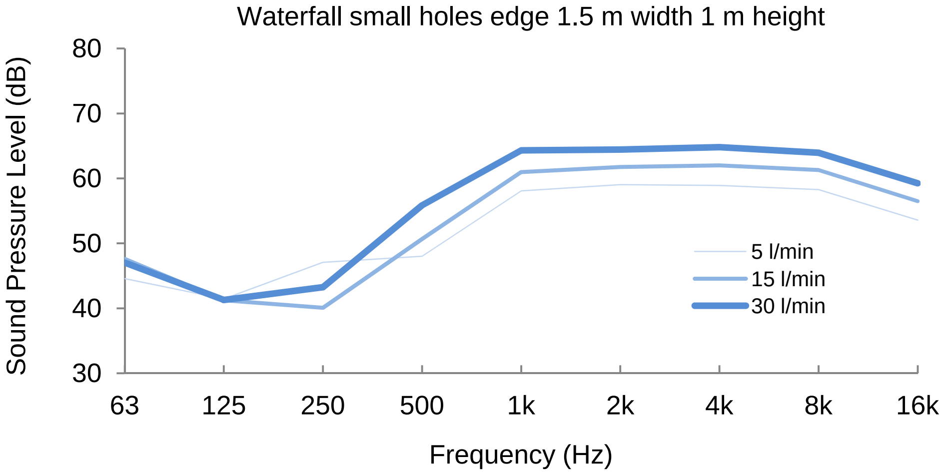


Figure C6

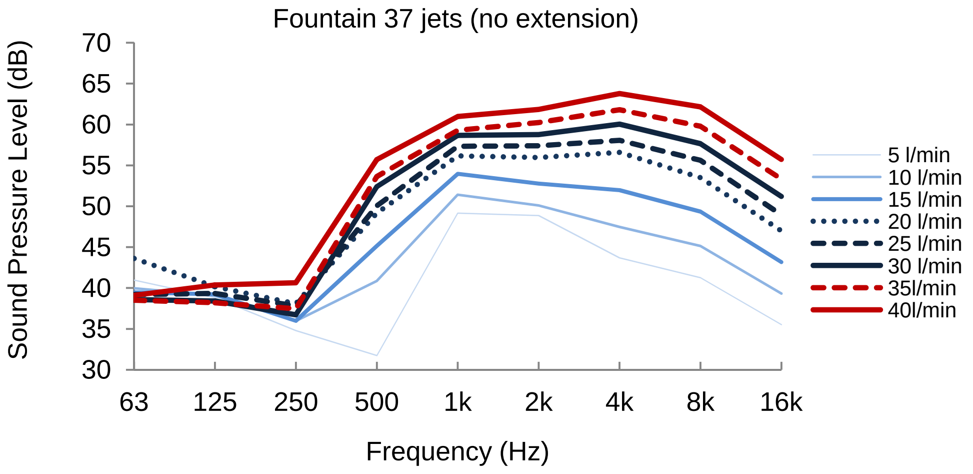


Figure C7

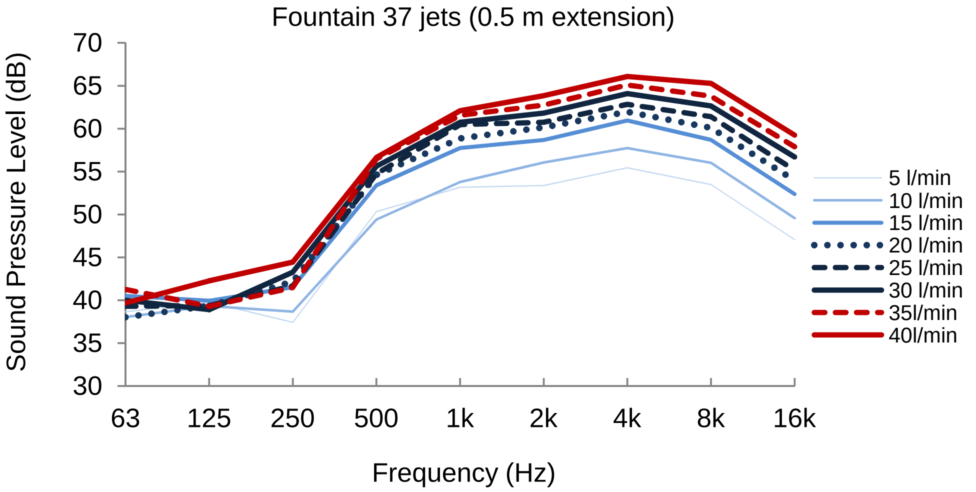
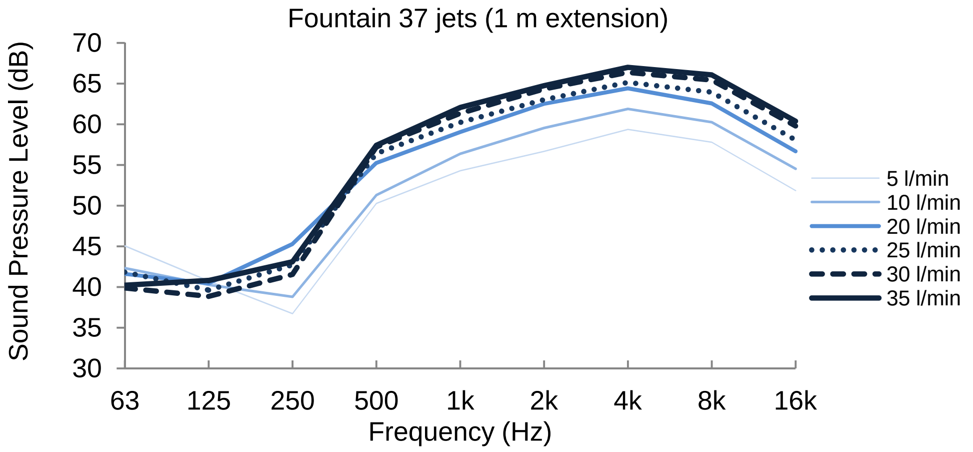


Figure C8



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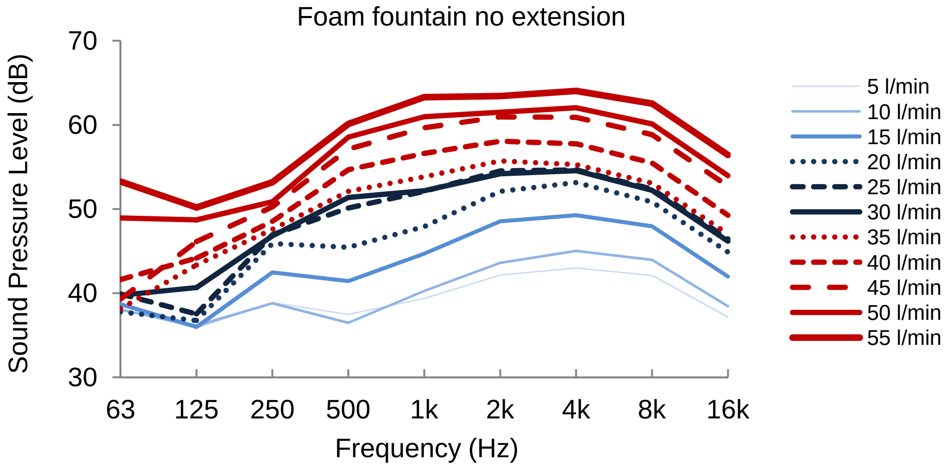

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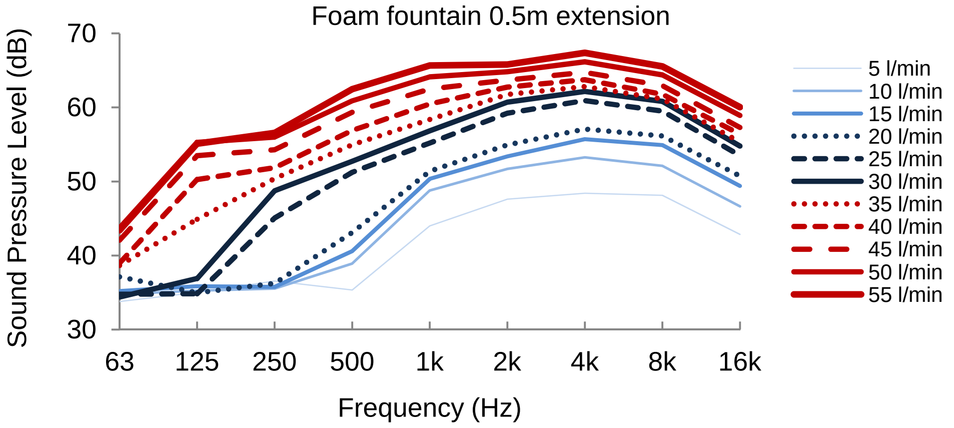
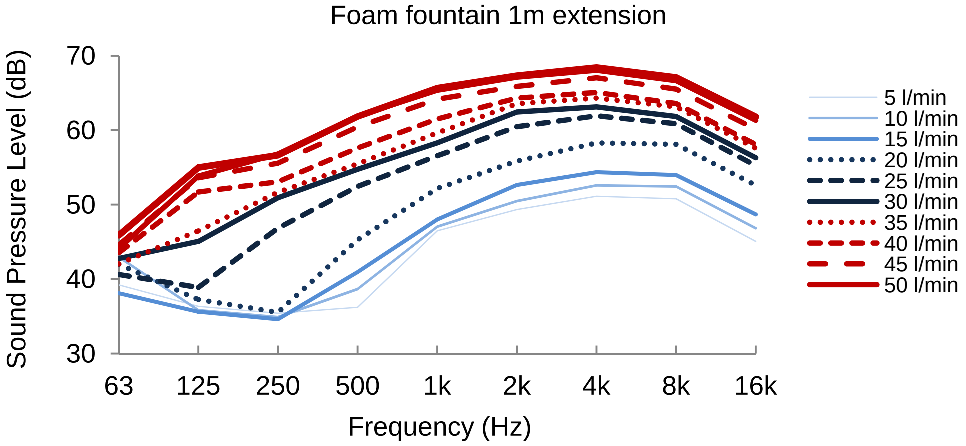


Figure C11



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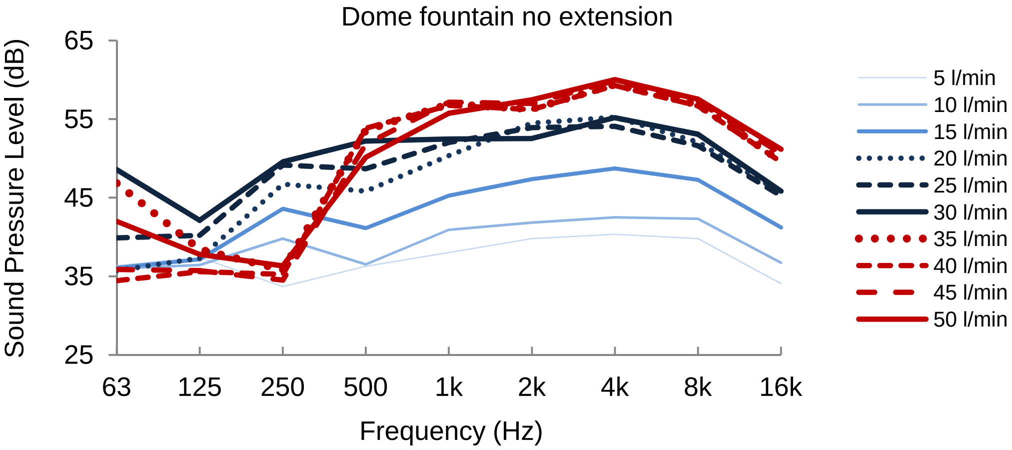

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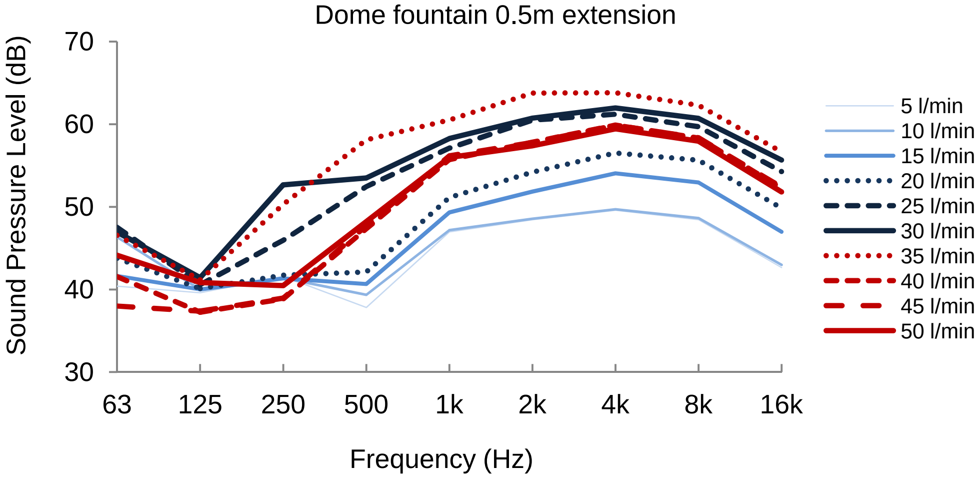

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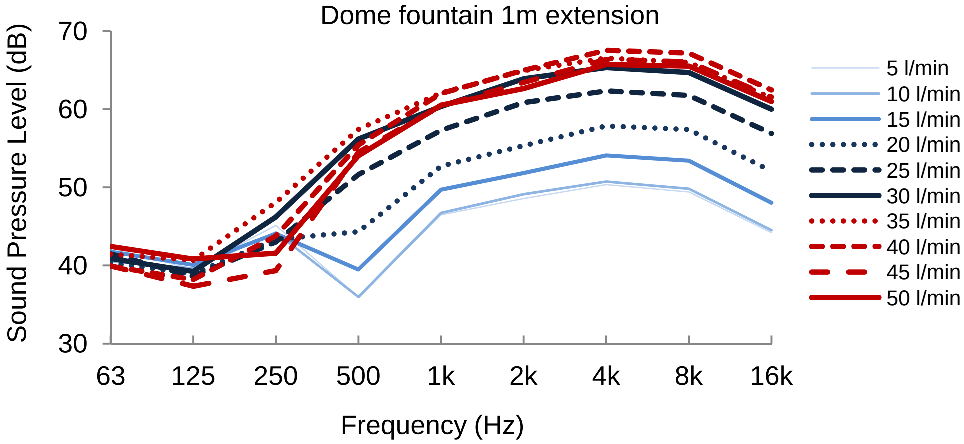

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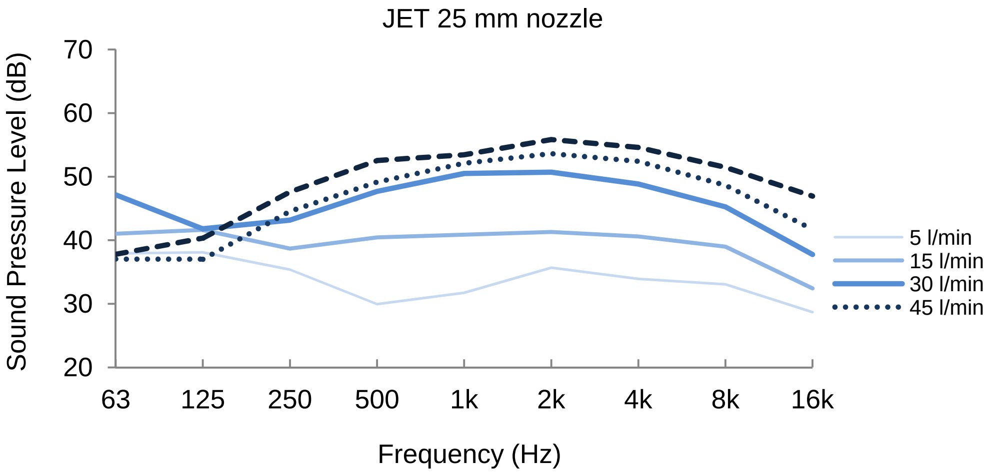

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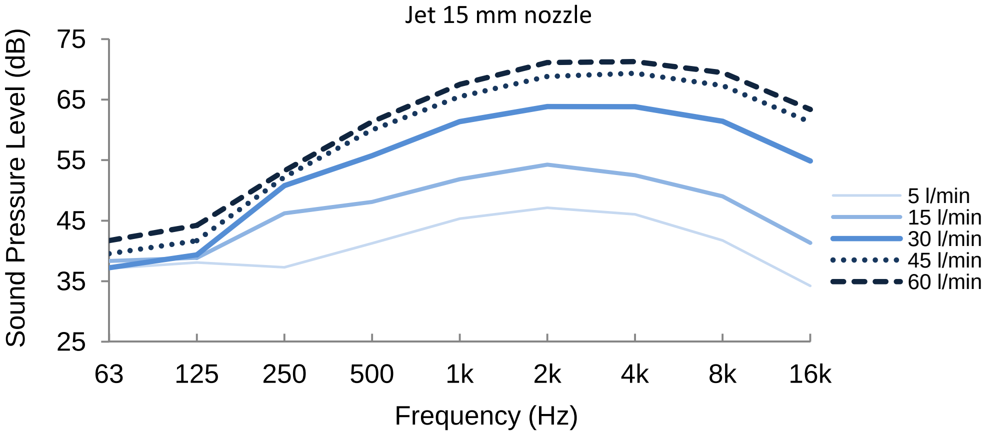

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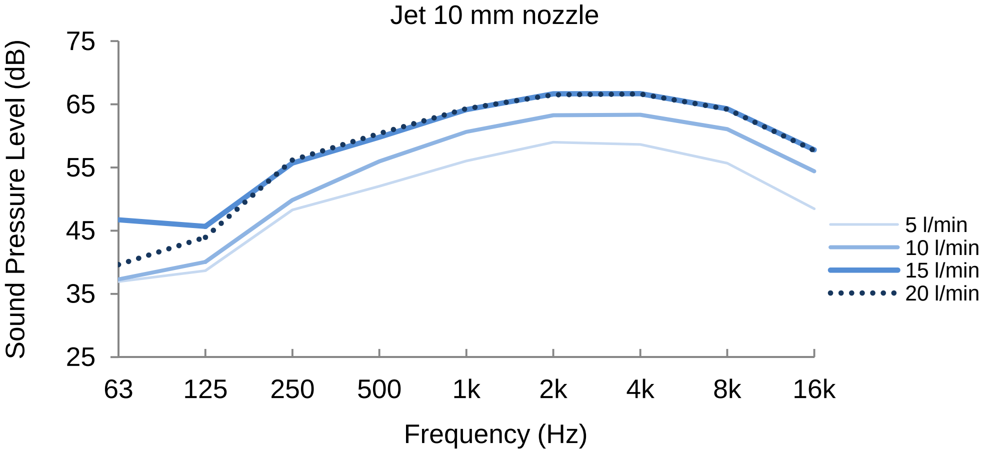

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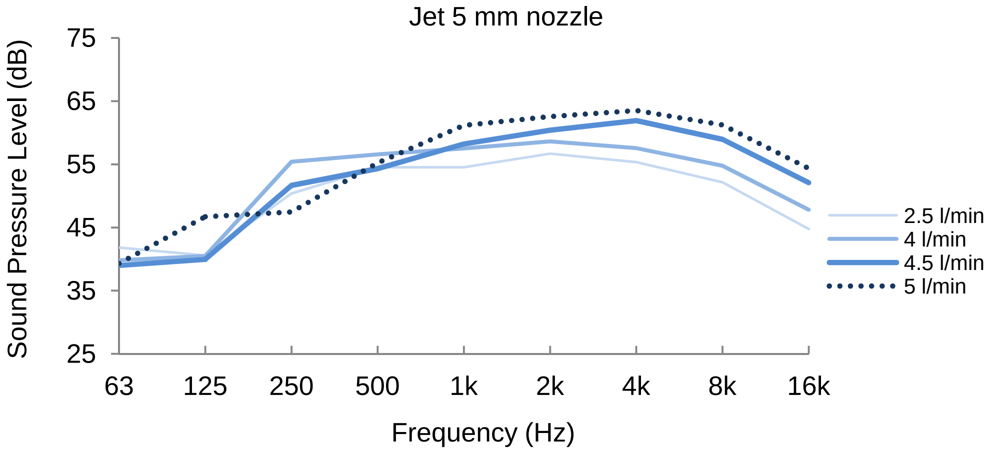

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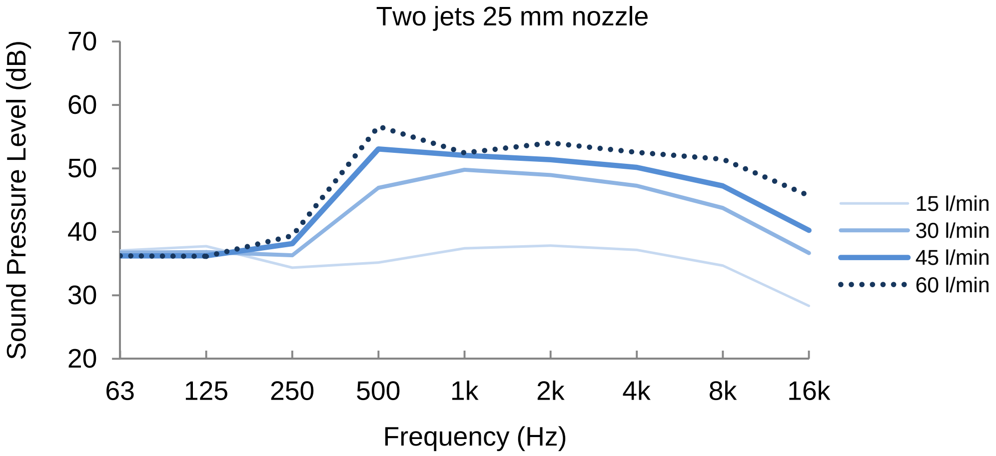

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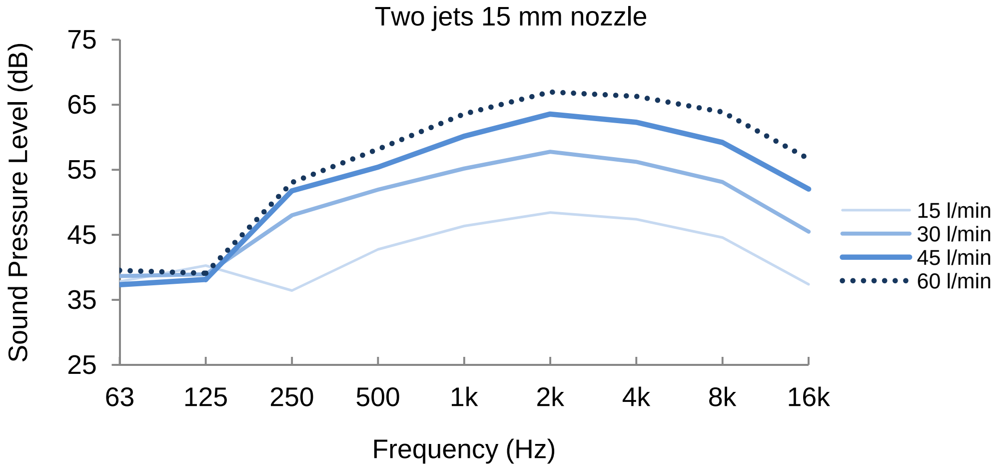

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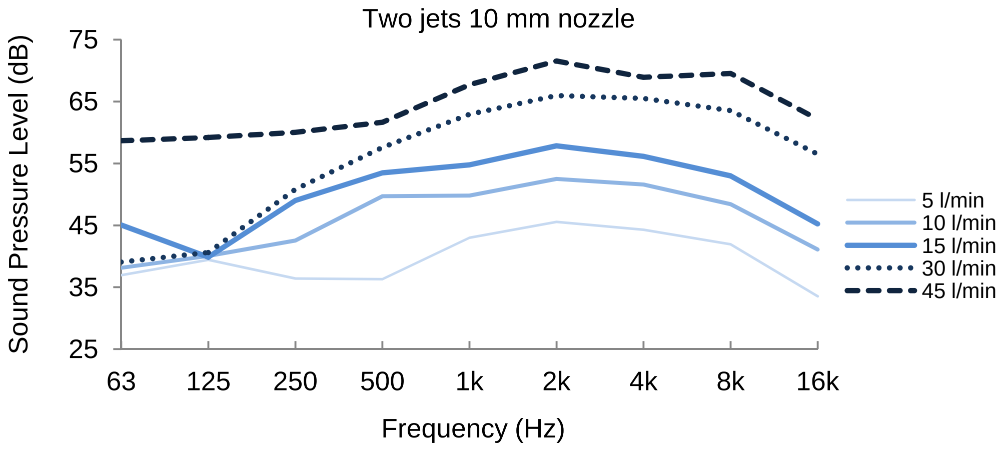

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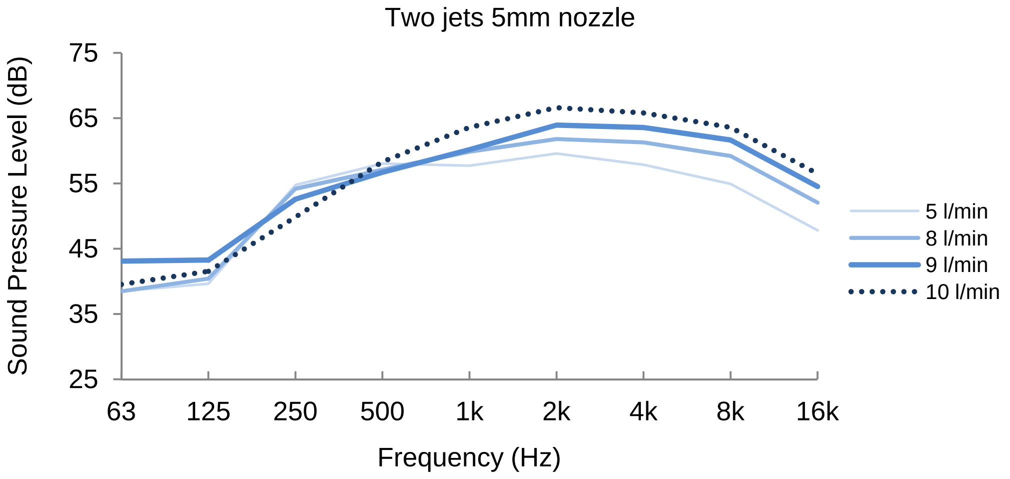

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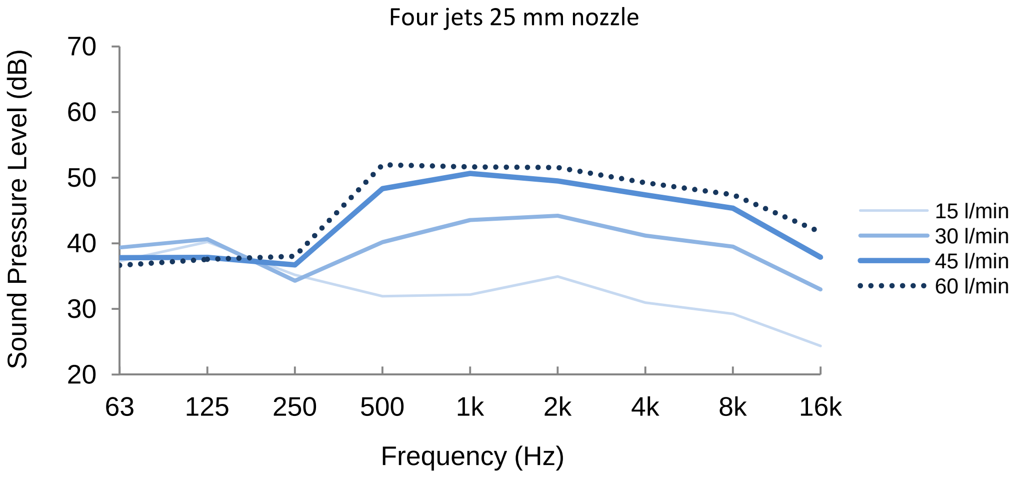

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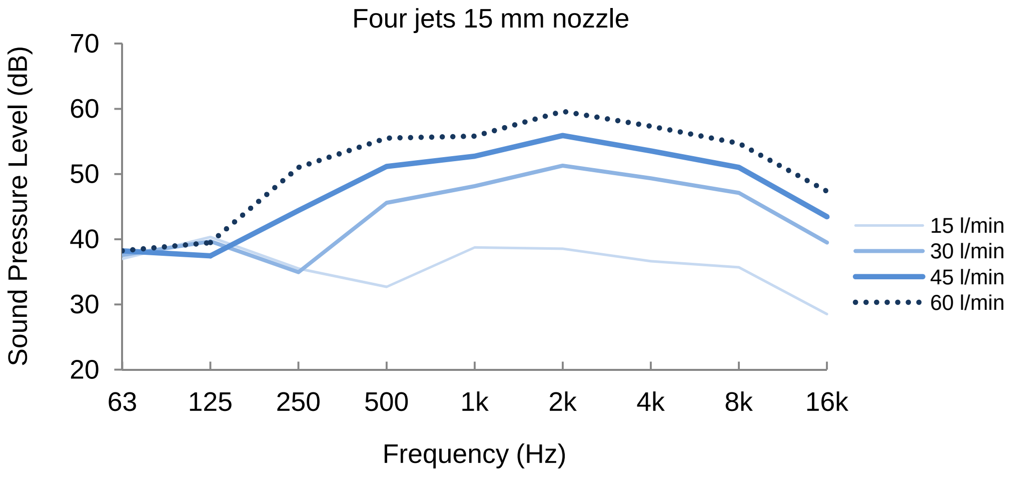

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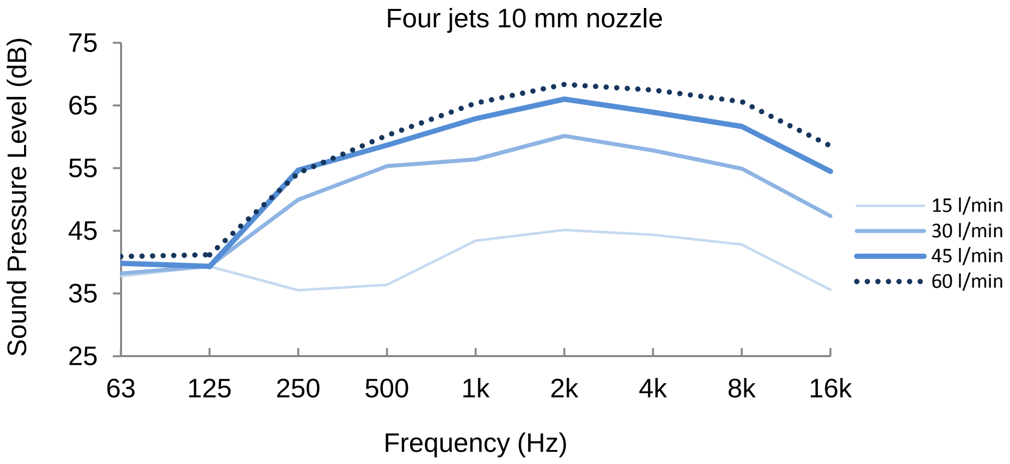

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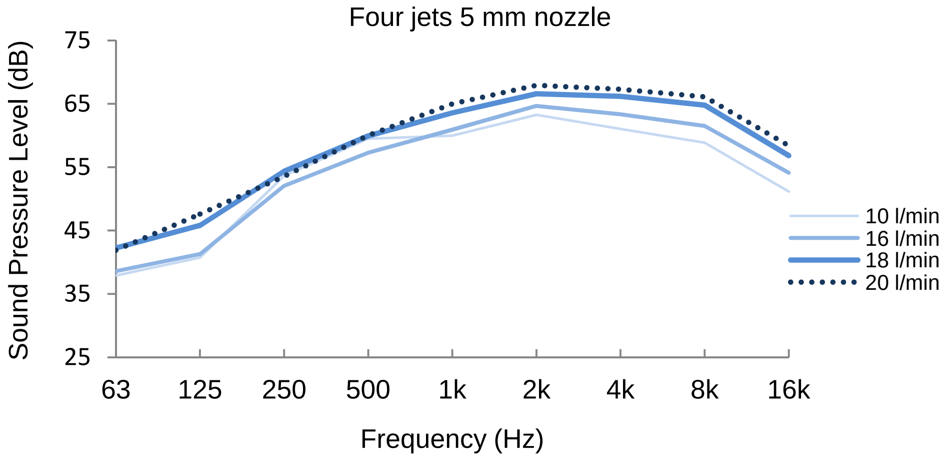

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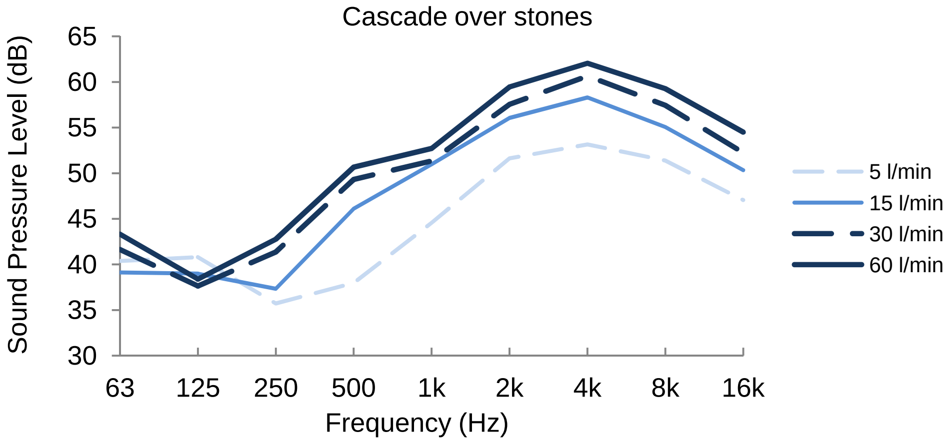

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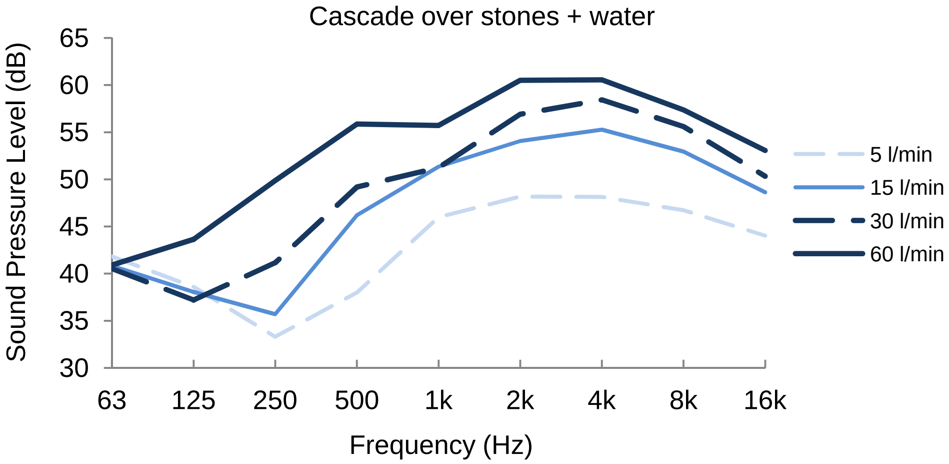

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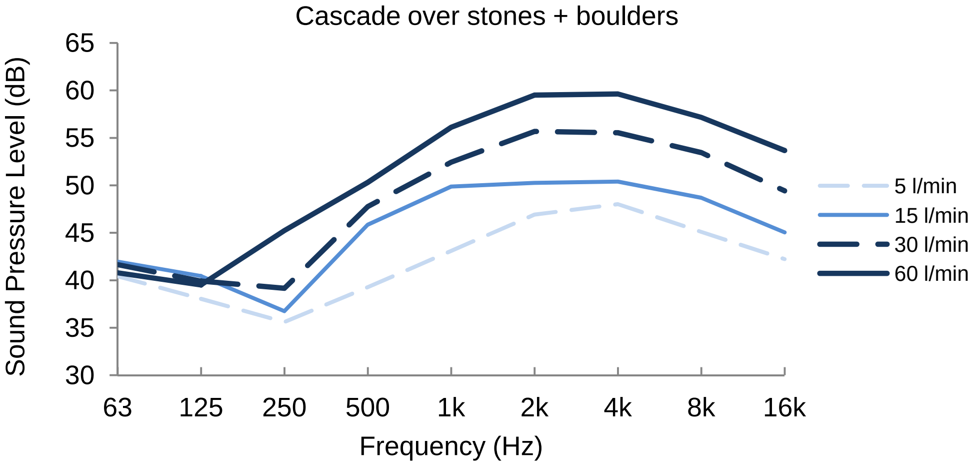

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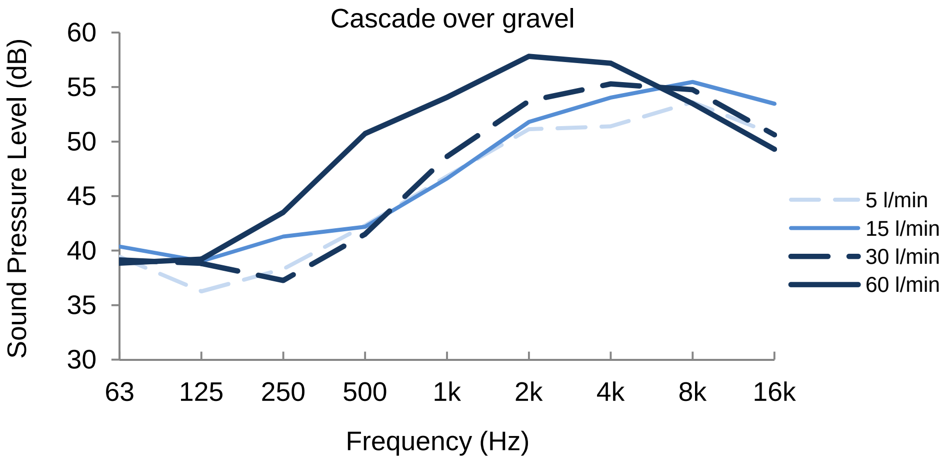
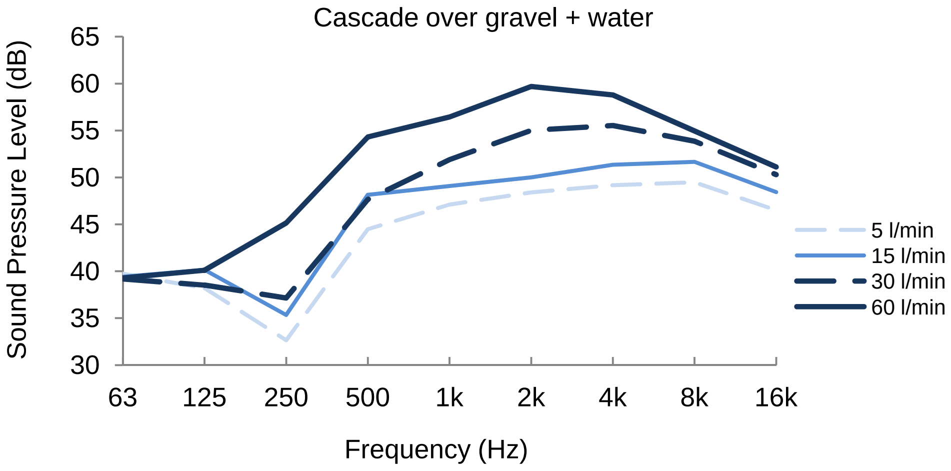


Figure C31



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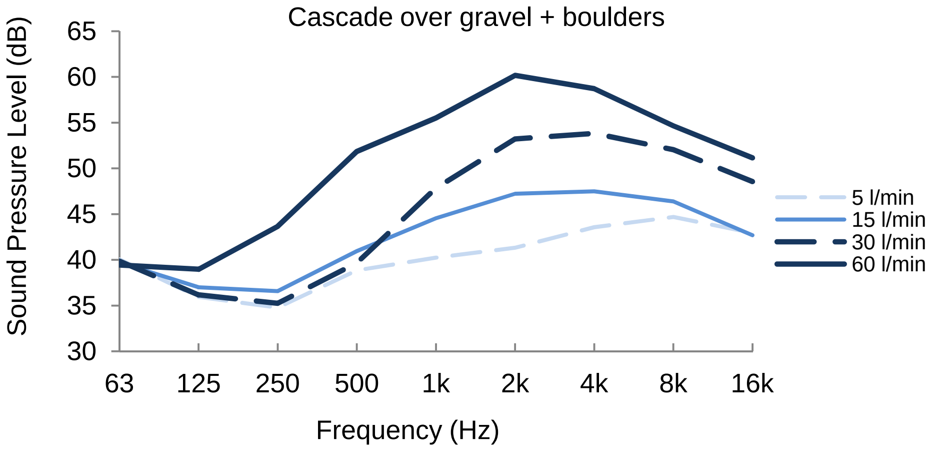

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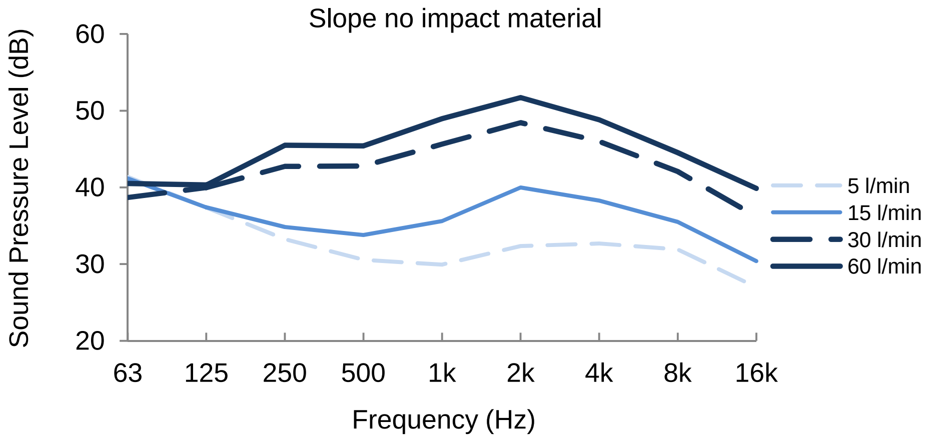


Figure C34

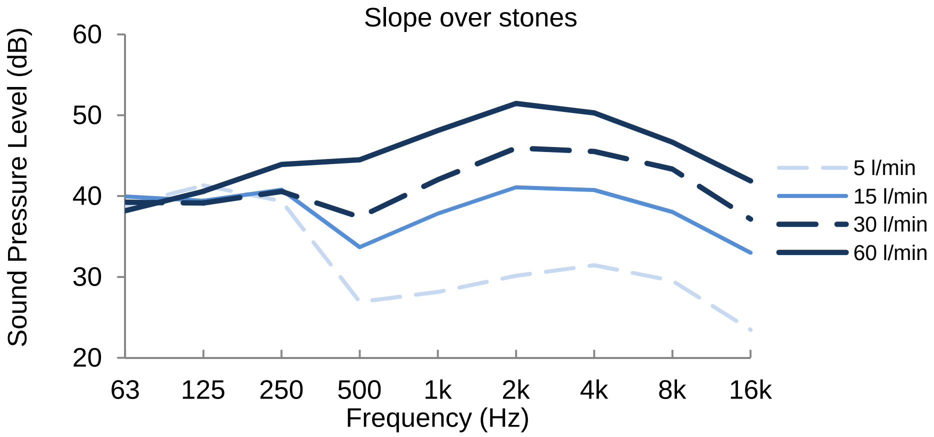


Figure C35

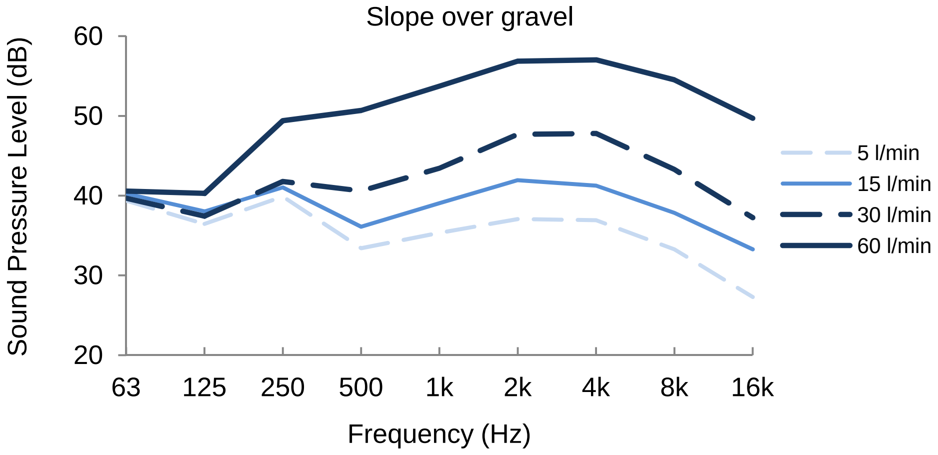


Figure C36

Appendix D: Edge design

Spectra obtained at different flow rates for the plain edge, sawtooth edge and small holes edge waterfalls are given in this appendix.

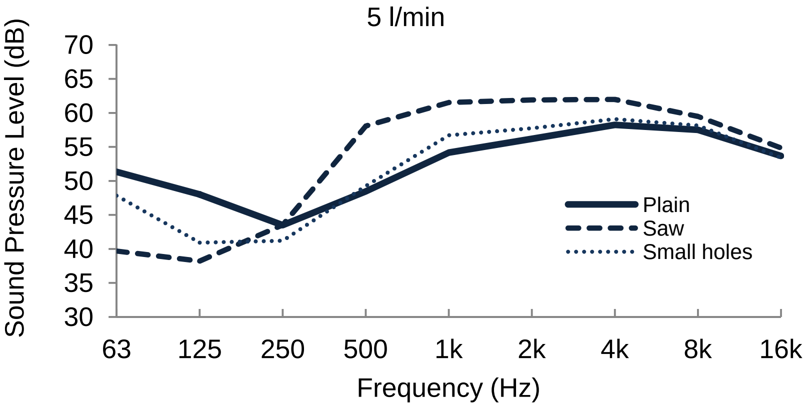


Figure D1

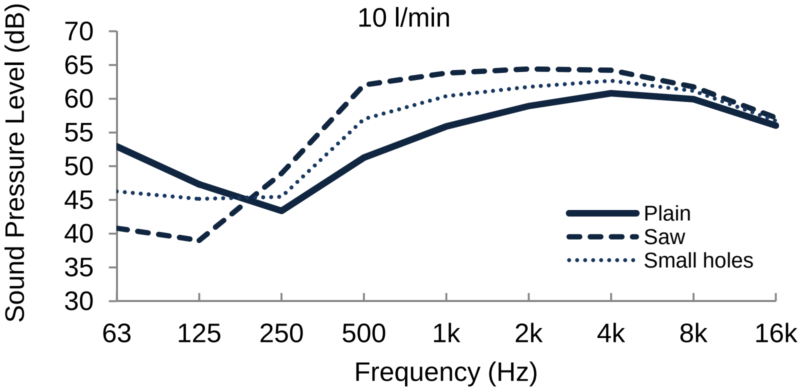


Figure D2

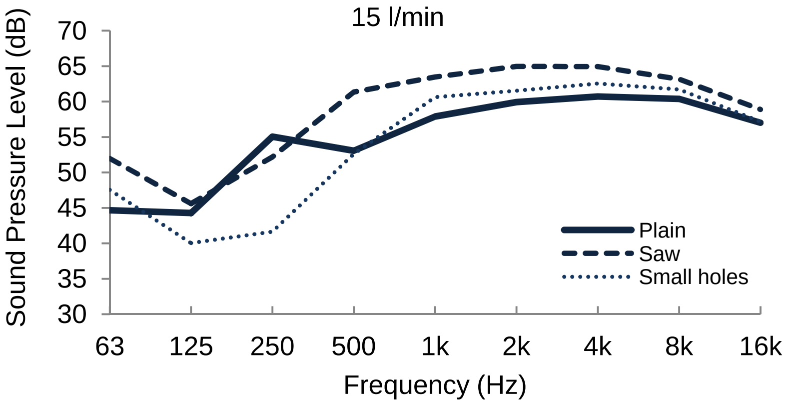


Figure D3

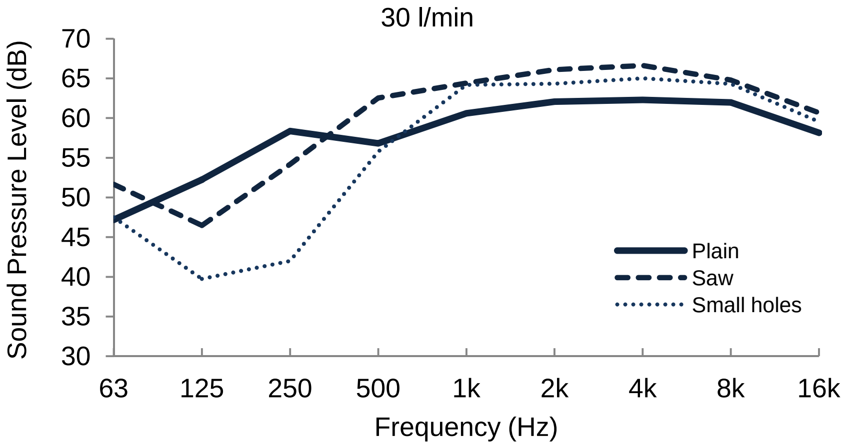


Figure D4

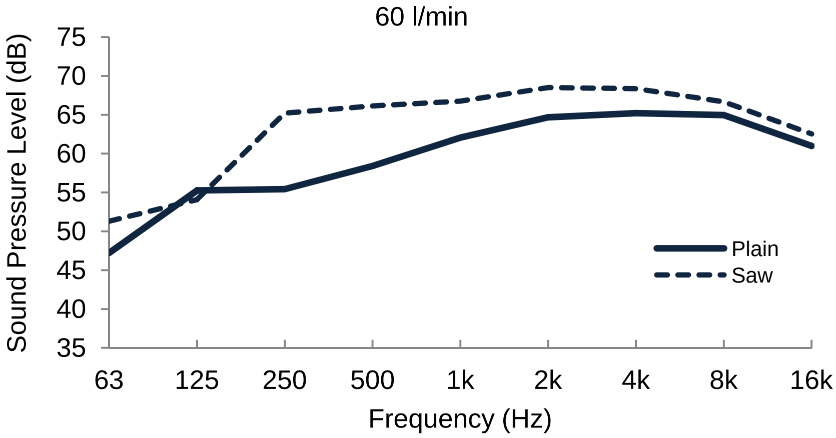


Figure D5

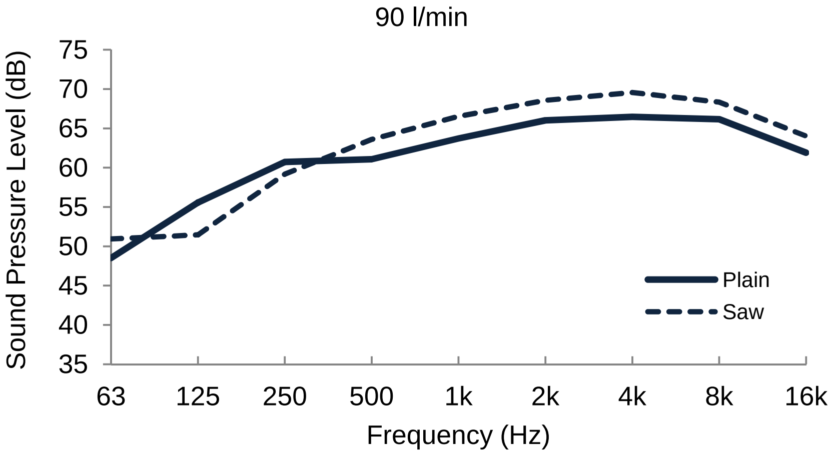


Figure D6

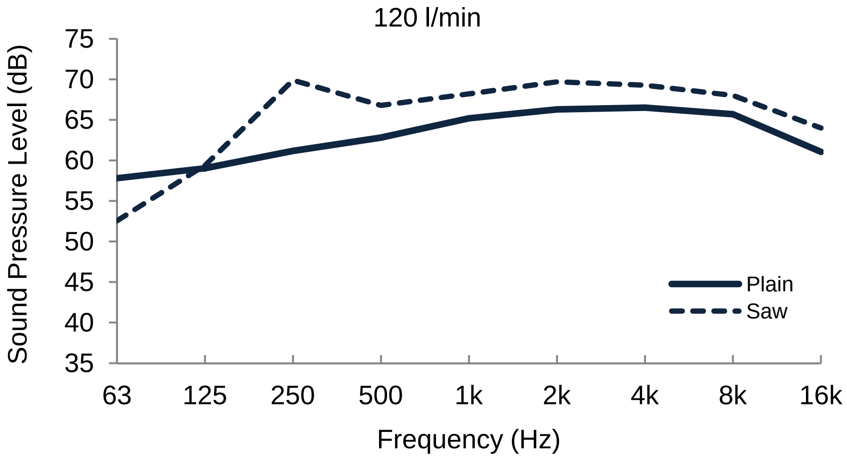


Figure D7

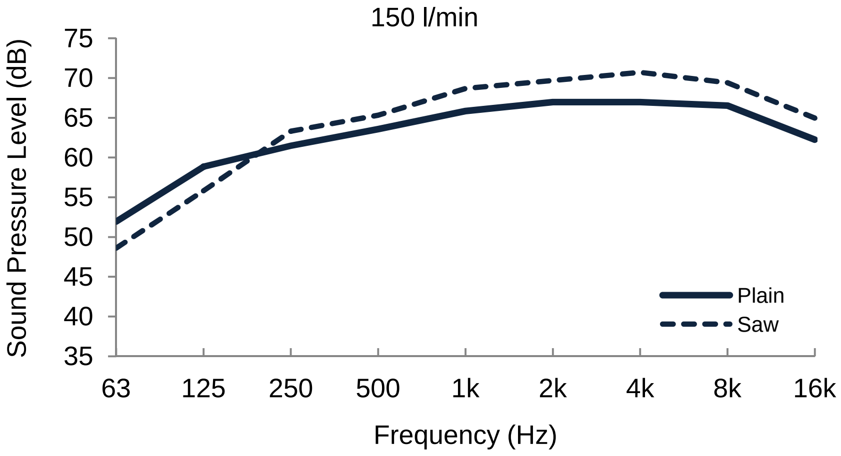


Figure D8

Appendix E: Waterfalls’ width

Results obtained for different waterfalls’ widths are given in this appendix.

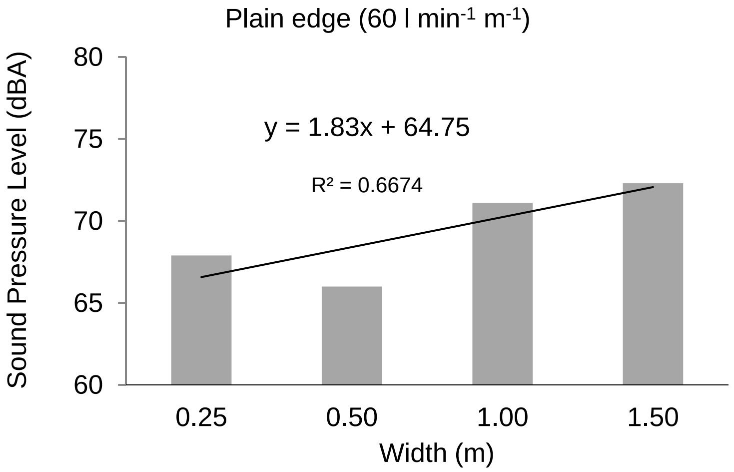


Figure E1

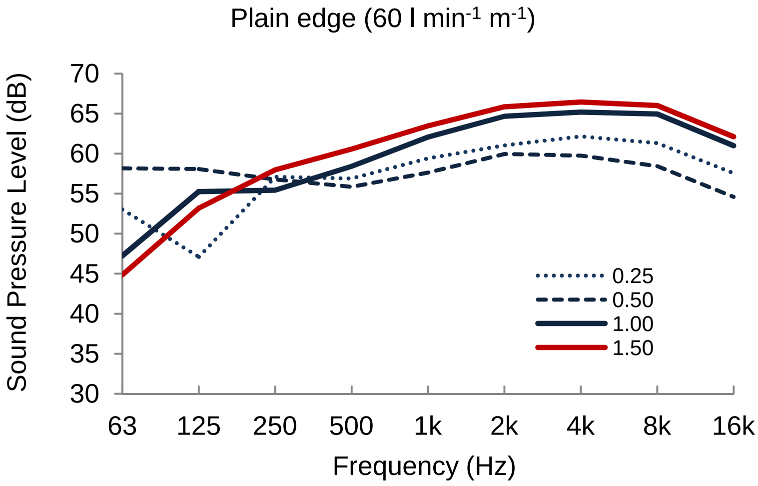


Figure E2

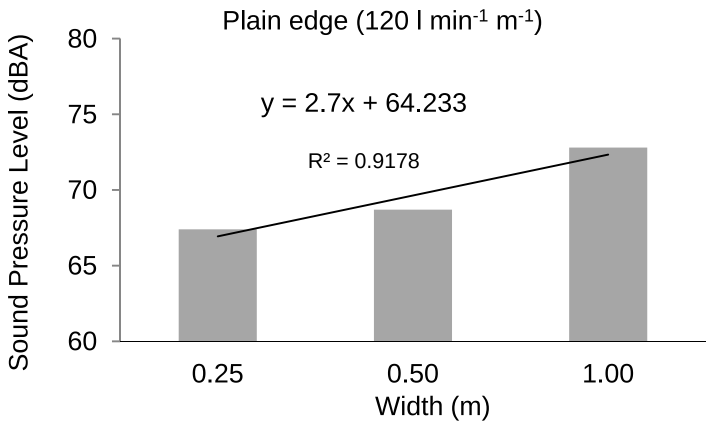


Figure E3

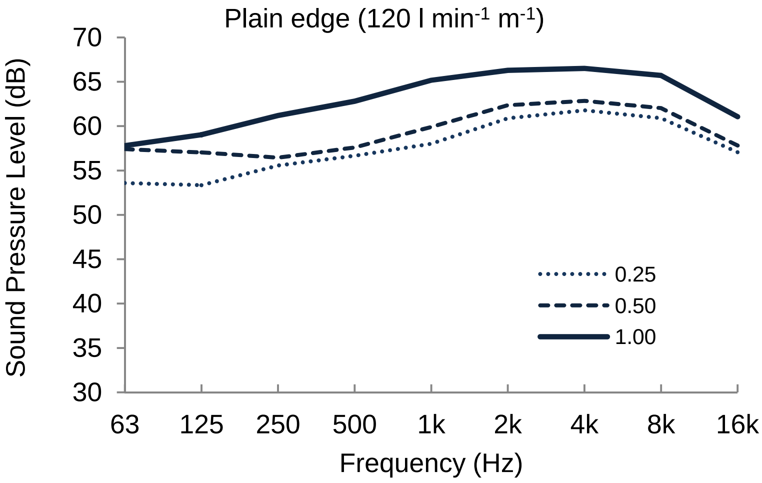


Figure E4

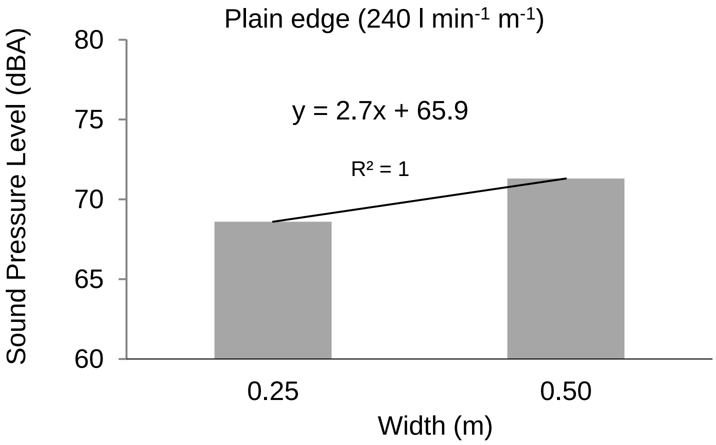


Figure E5

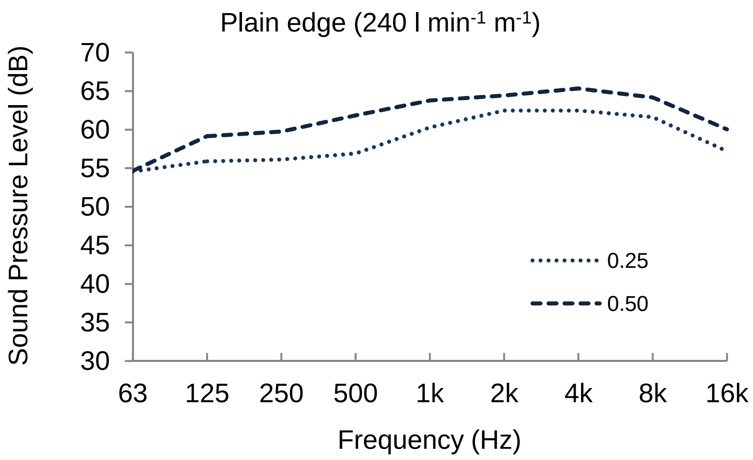


Figure E6

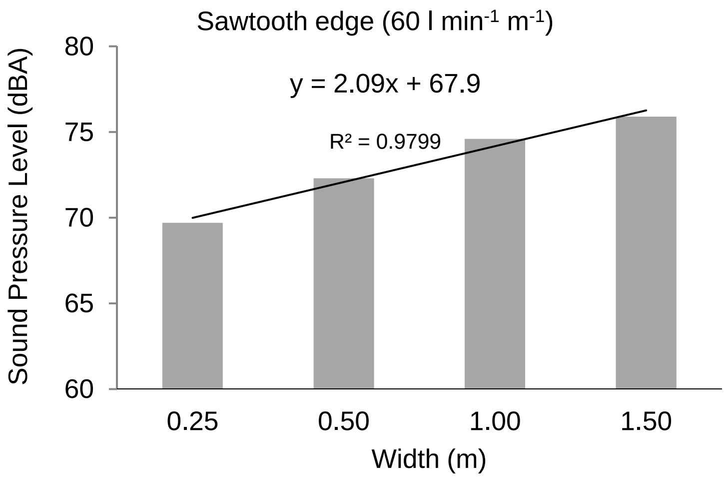


Figure E7

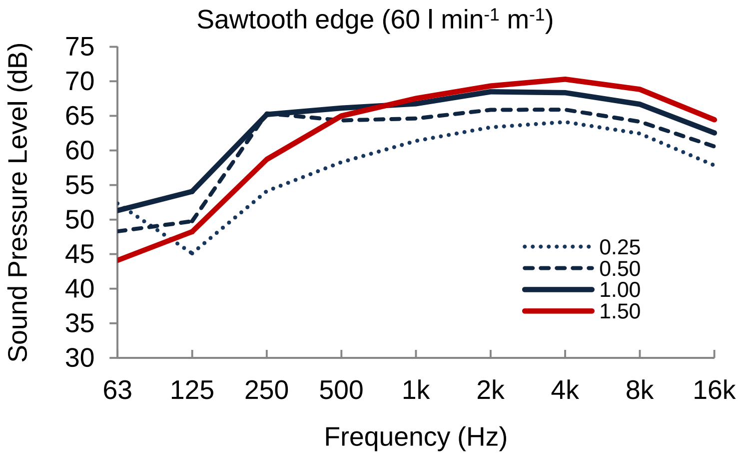


Figure E8

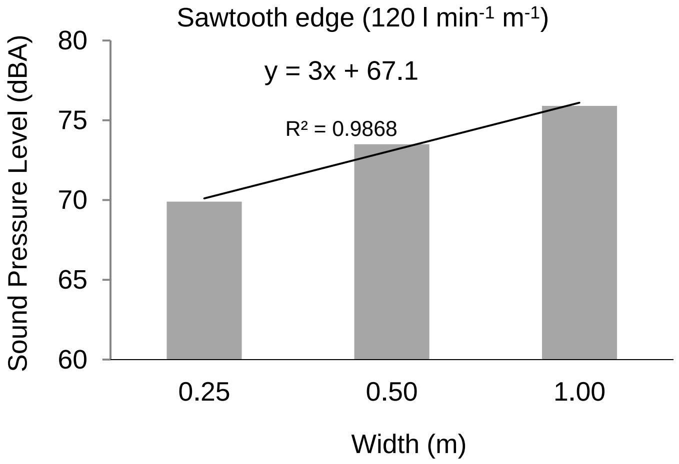


Figure E9

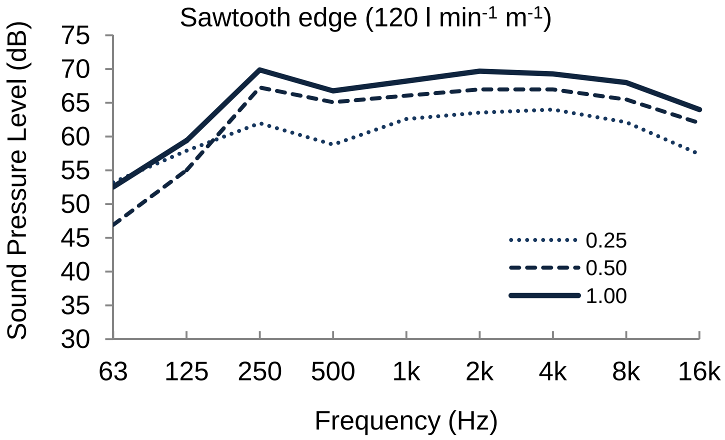


Figure E10

Figure E11

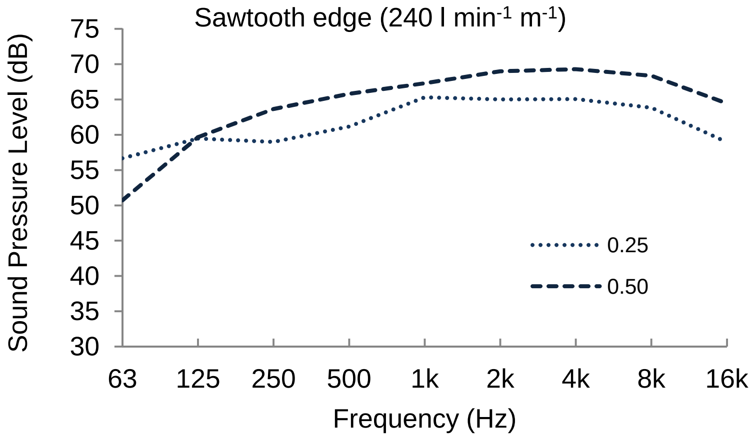

Sawtooth edge (240 l min-1 m-1)
Sound Pressure Level (dB)
75
70
65
60
55
50
45
40
35
30
63
125
250
500
1k
2k
4k
8k
16k
Frequency (Hz)
0.25
0.50

Figure E12

Appendix F: Height of falling water

Spectra obtained for different heights of falling water are given in this appendix for waterfalls and for the fountain with 37 jets.

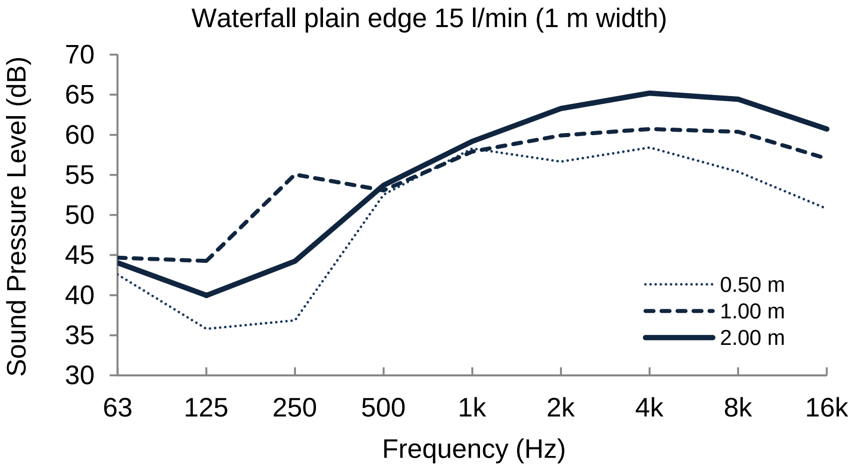


Figure F1

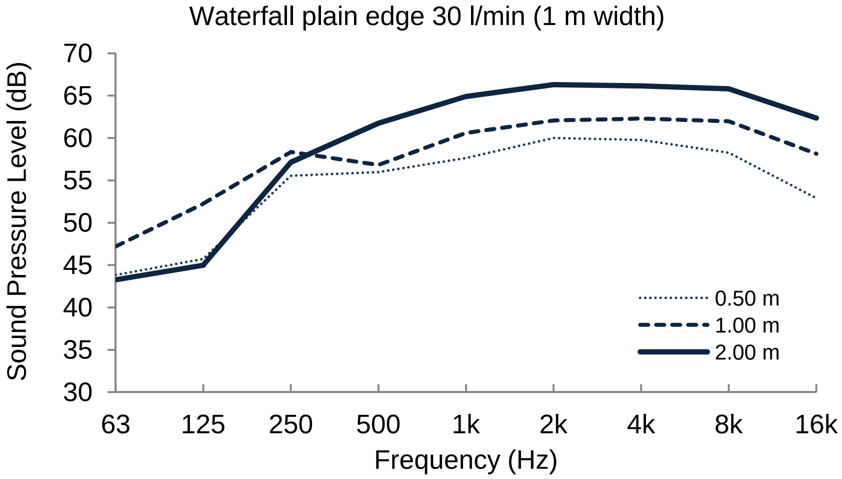


Figure F2

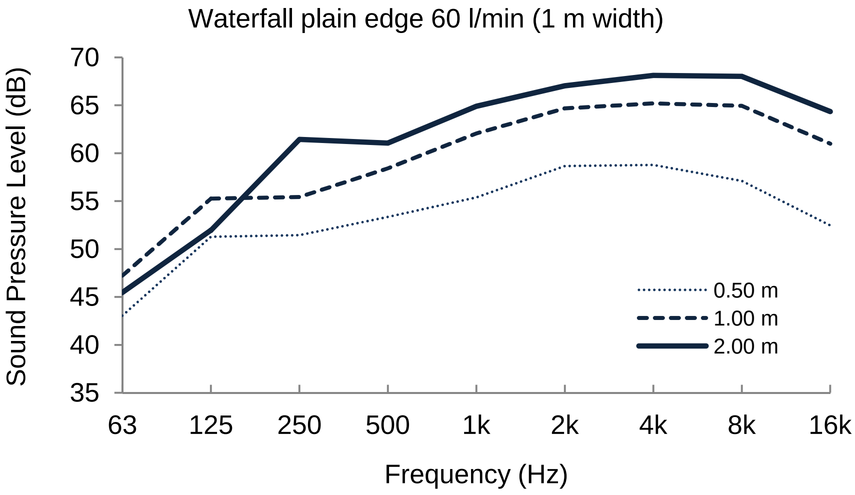


Figure F3

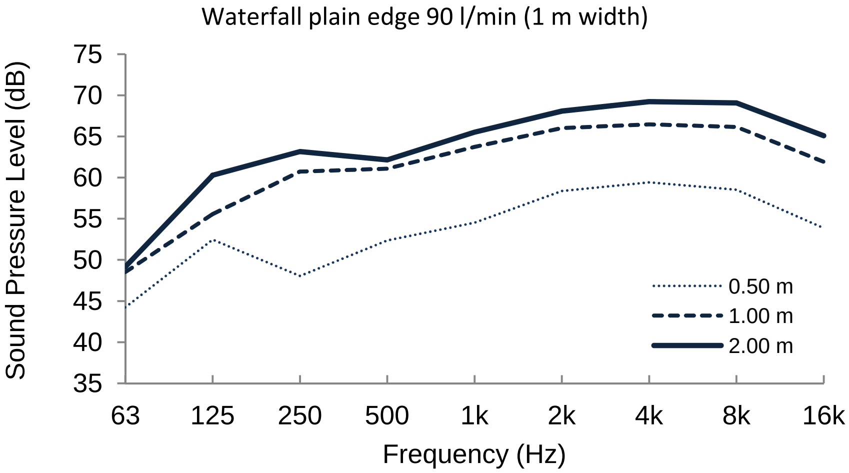


Figure F4

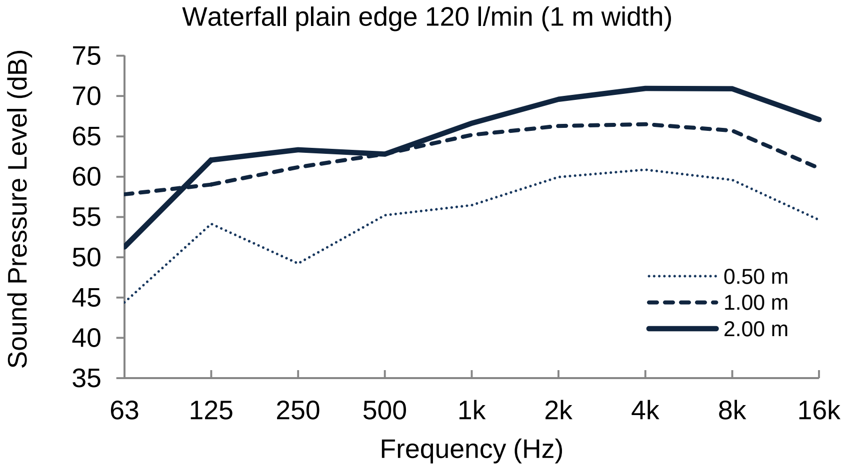


Figure F5

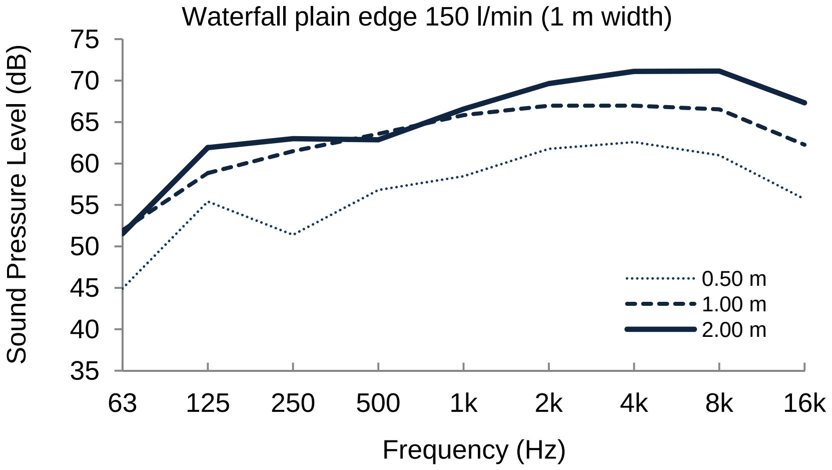


Figure F6

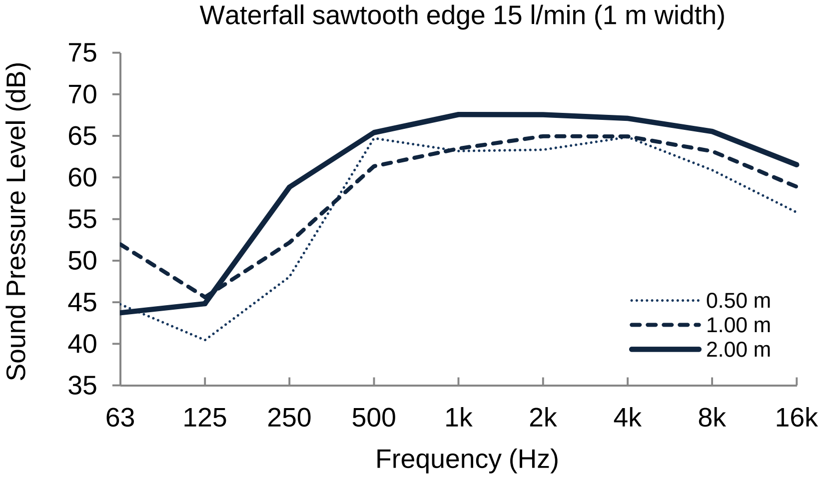


Figure F7

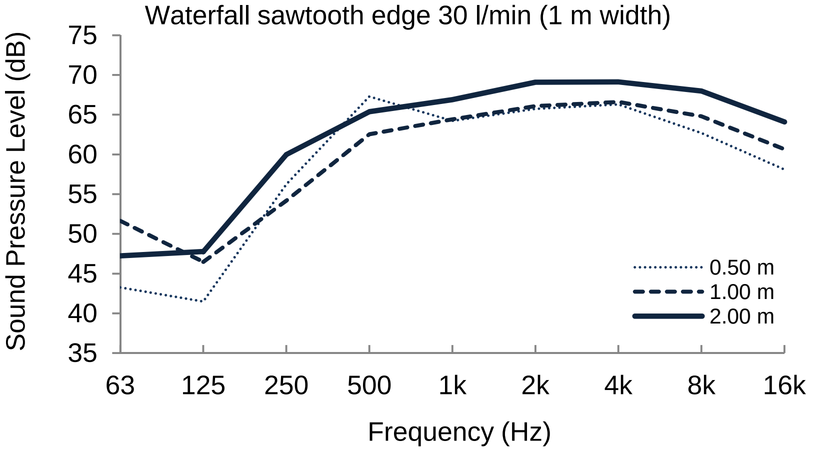


Figure F8

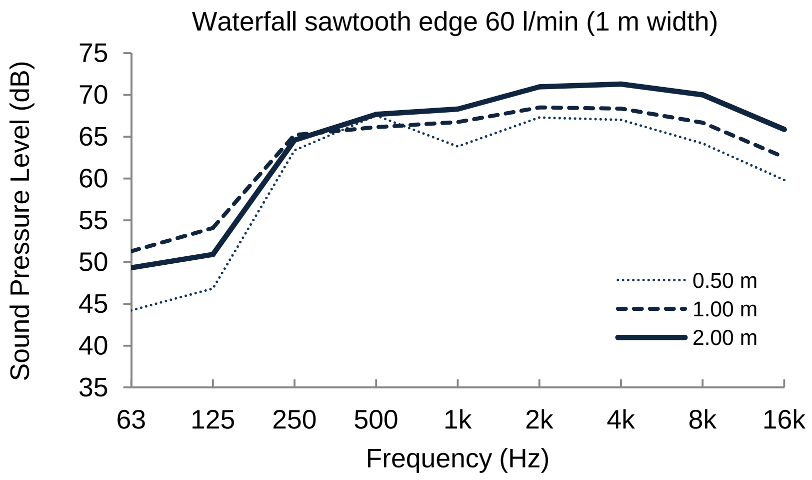


Figure F9

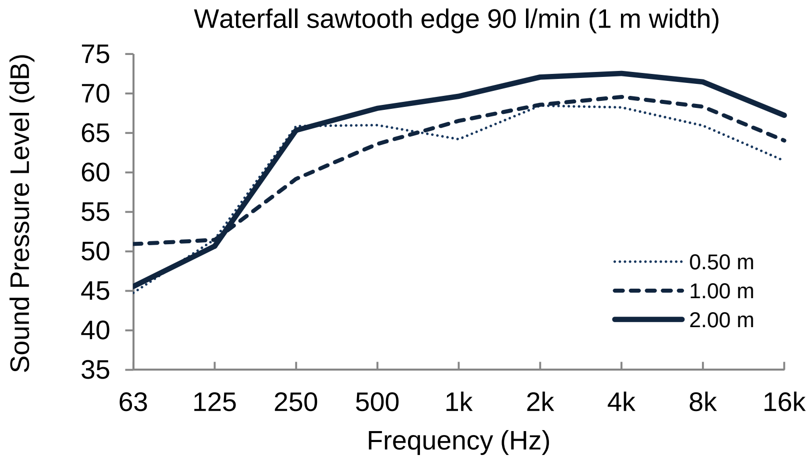


Figure F10

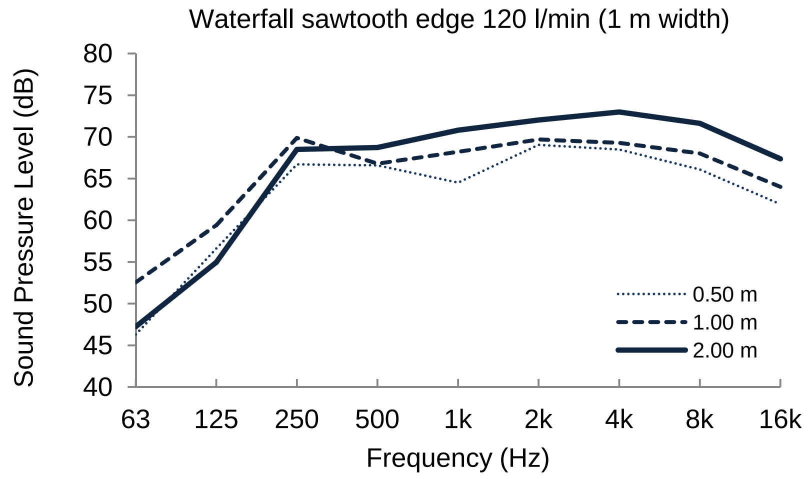


Figure F11

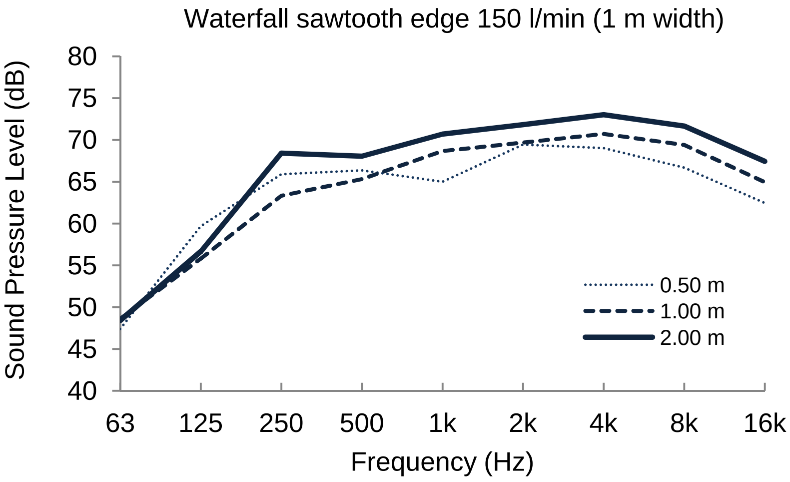


Figure F12

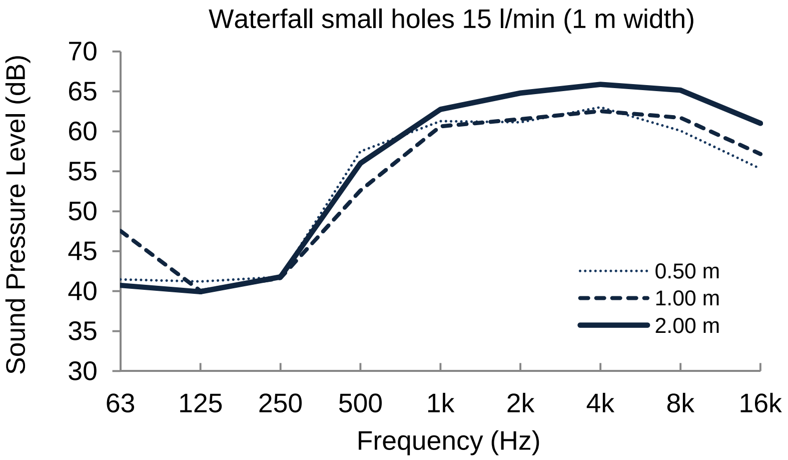


Figure F13

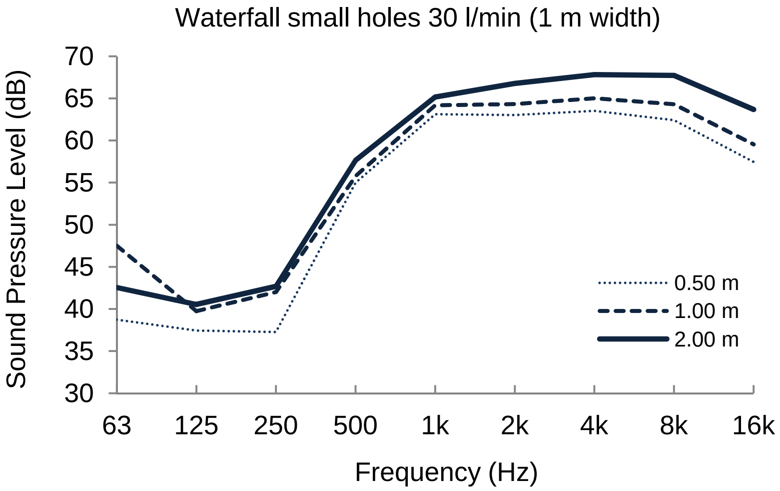


Figure F14

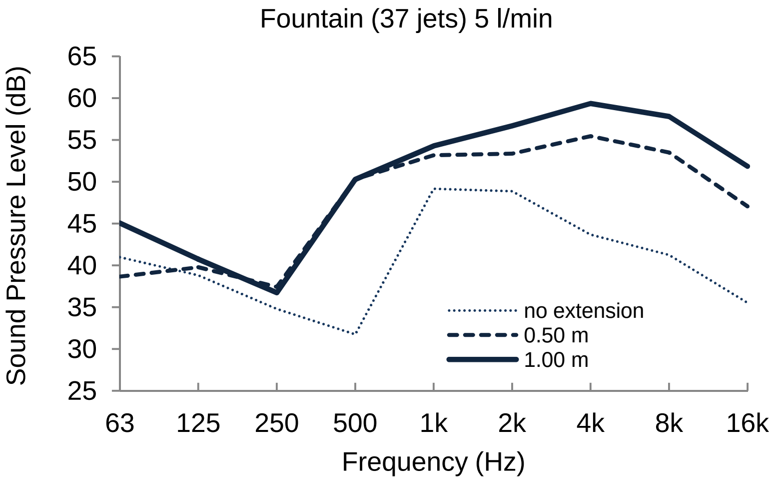


Figure F15

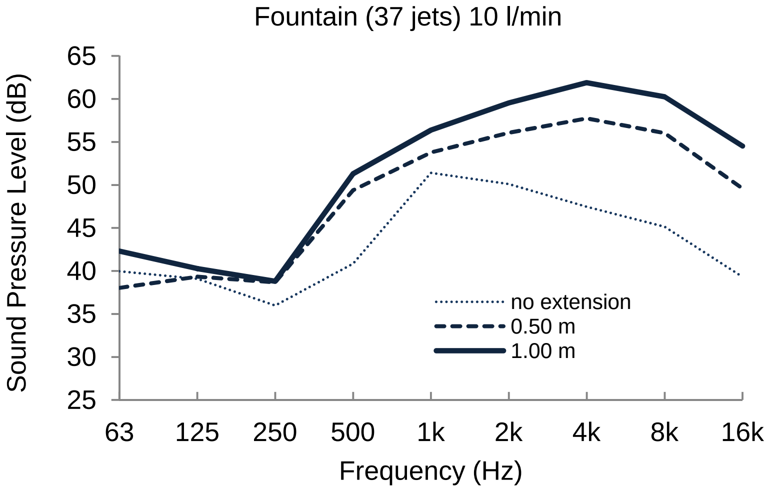


Figure F16

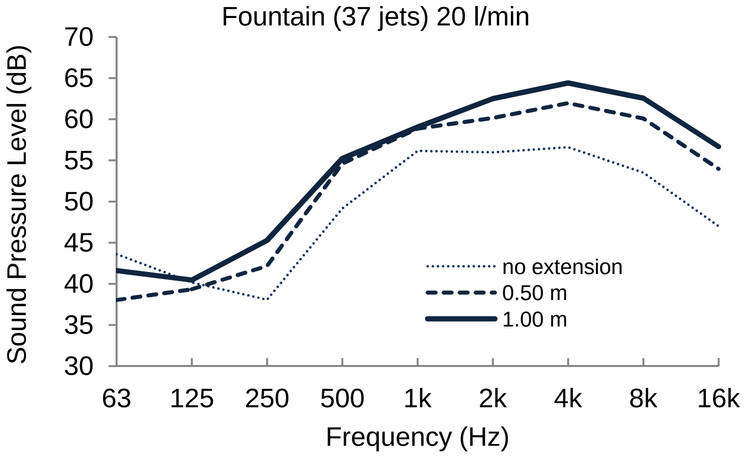


Figure F17

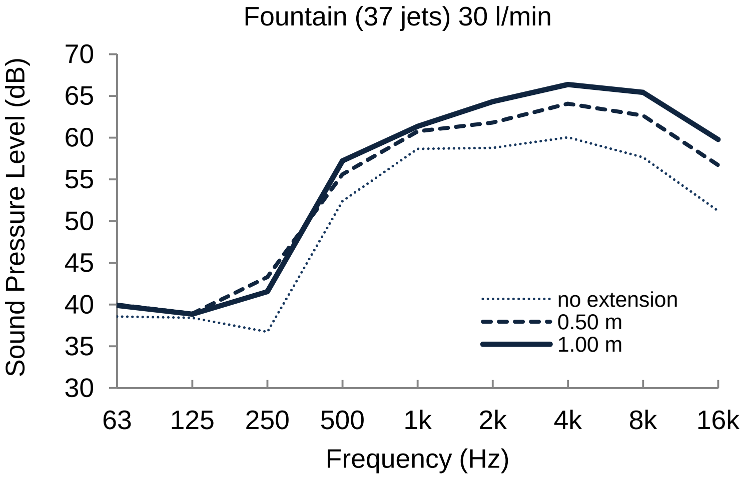

Fountain (37 jets) 30 l/min
Sound Pressure Level (dB)
70
65
60
55
50
45
40
35
30
63
125
250
500
1k
2k
4k
8k
16k
Frequency (Hz)
no extension
0.50 m
1.00 m

Figure F18

Appendix G: Impact materials

The L_{Aeq} and spectra of water features tested with different impact materials are given in this appendix.

G1. Waterfall plain edge - 0.5 m height

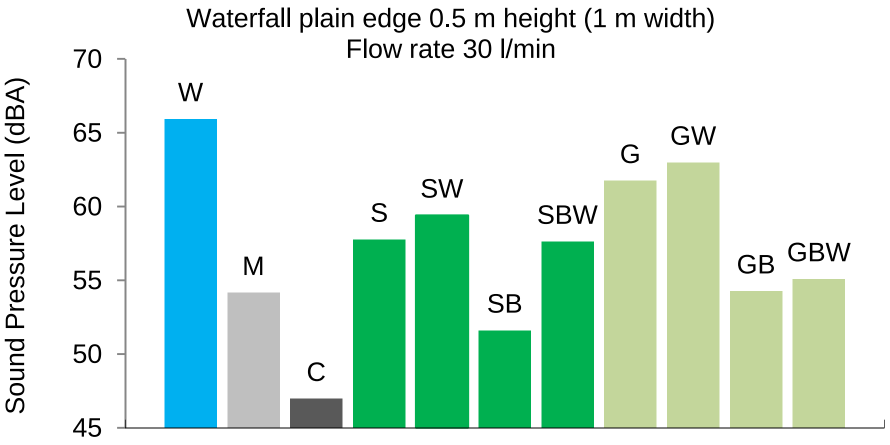


Figure G1-1

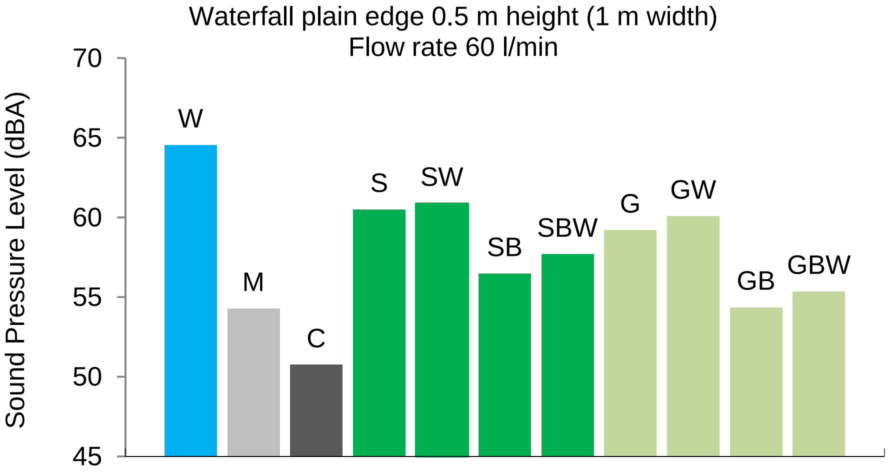


Figure G1-2

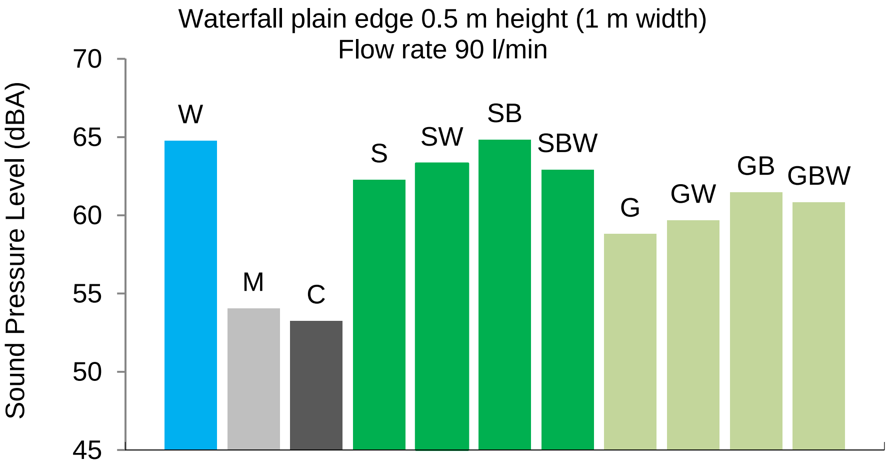


Figure G1-3

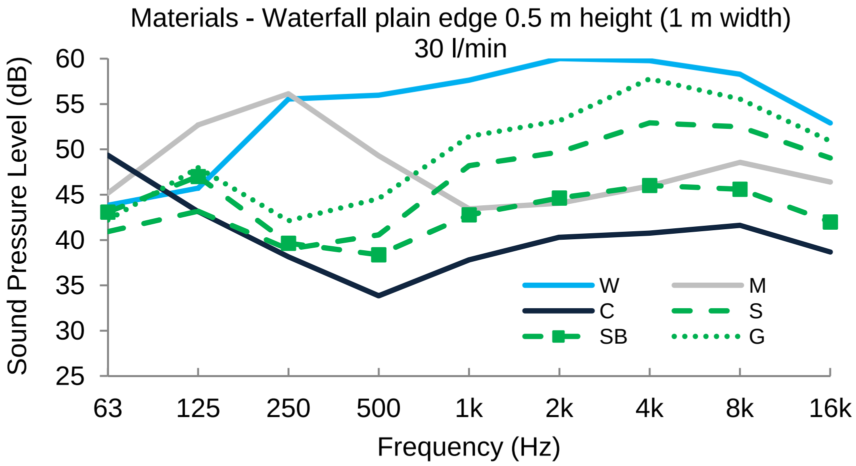


Figure G1-4

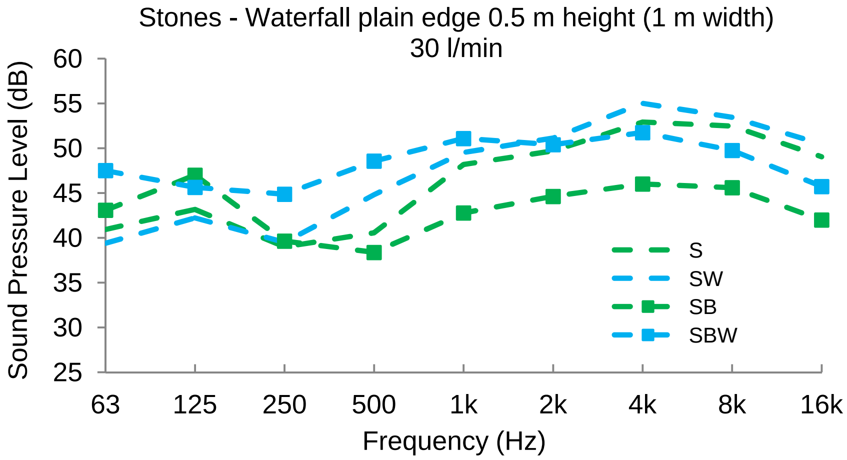


Figure G1-5

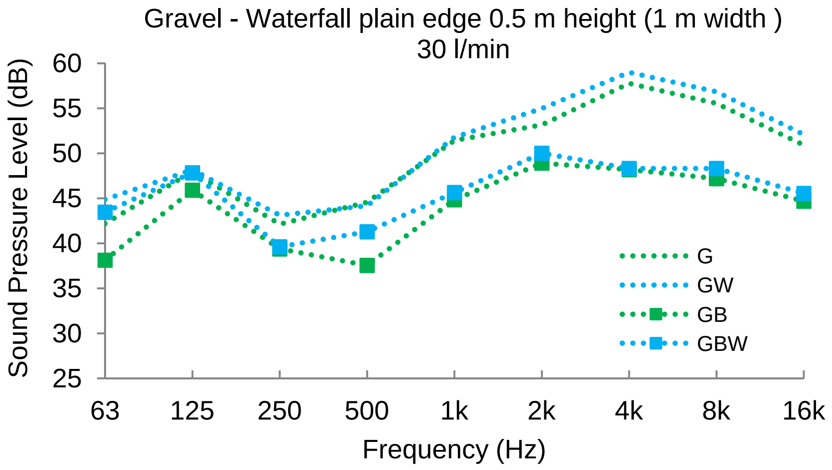


Figure G1-6

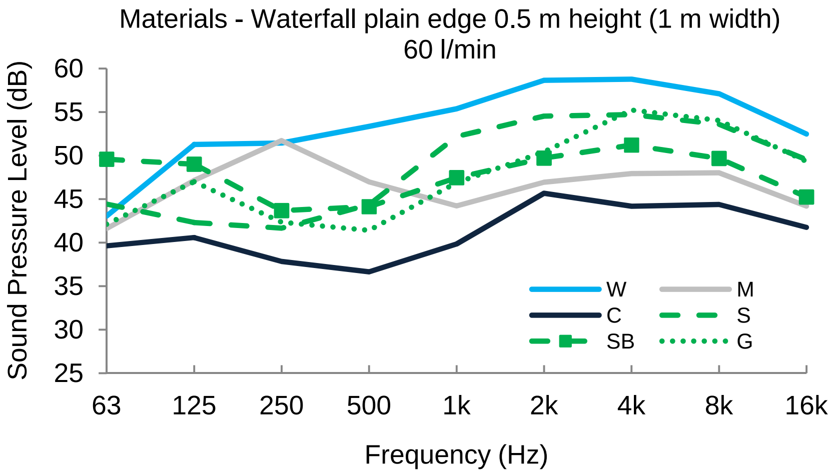


Figure G1-7

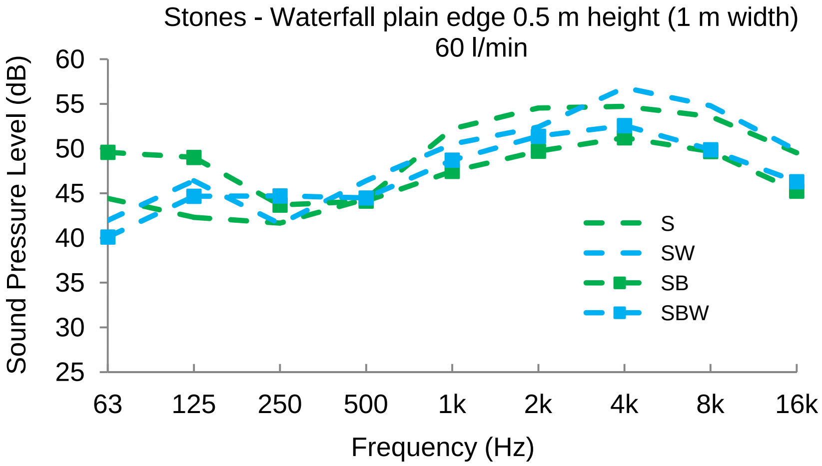


Figure G1-8

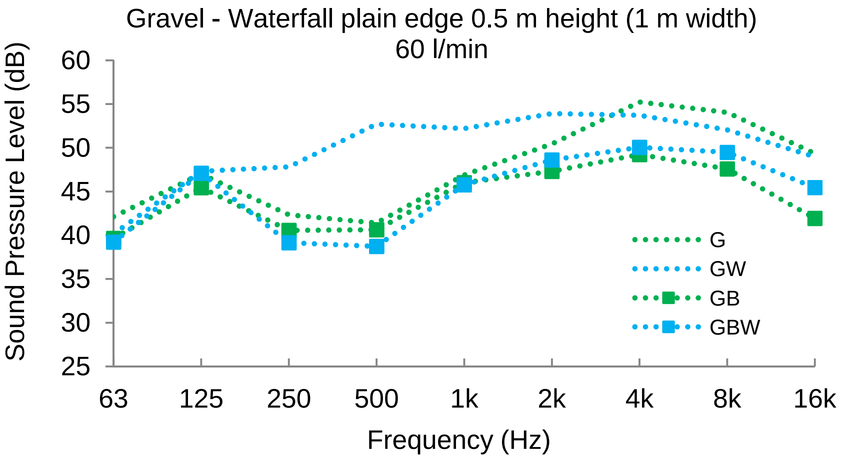


Figure G1-9

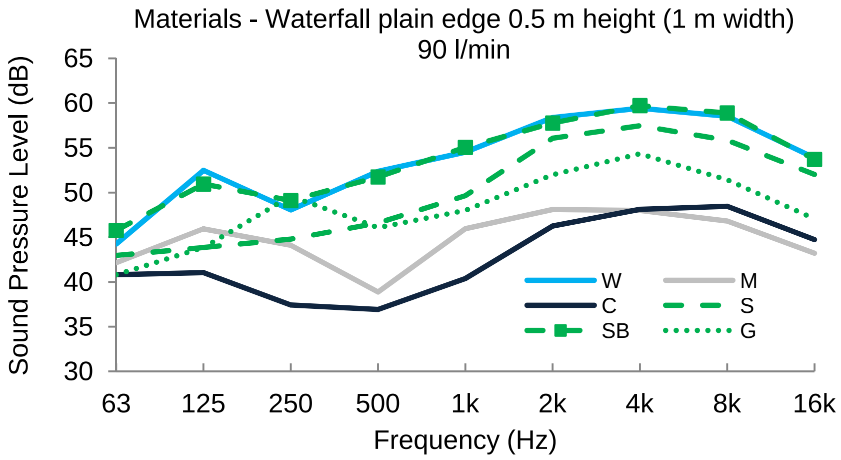


Figure G1-10

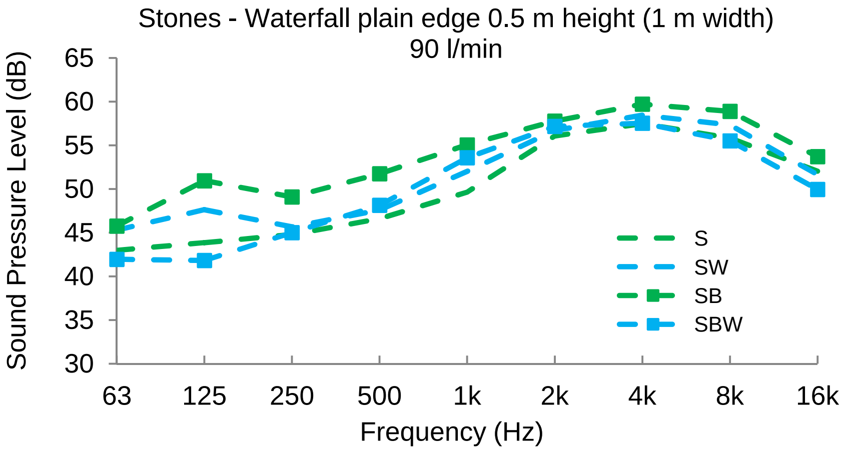


Figure G1-11

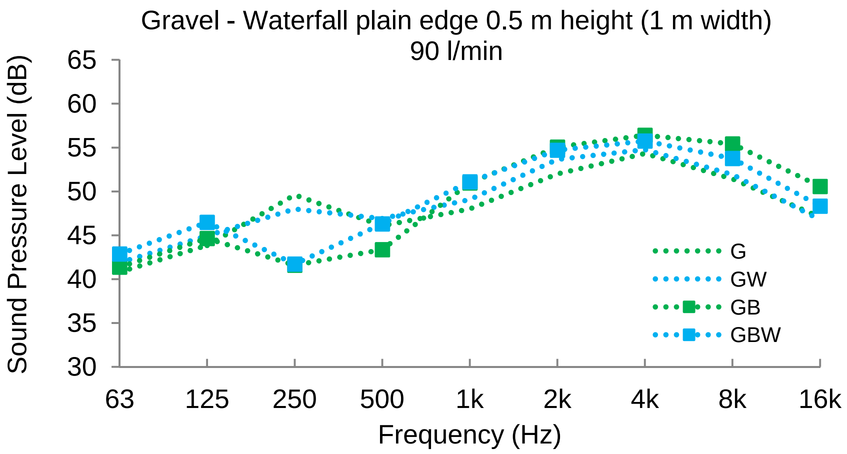


Figure G1-12

G2. Waterfall sawtooth edge - 0.5 m height

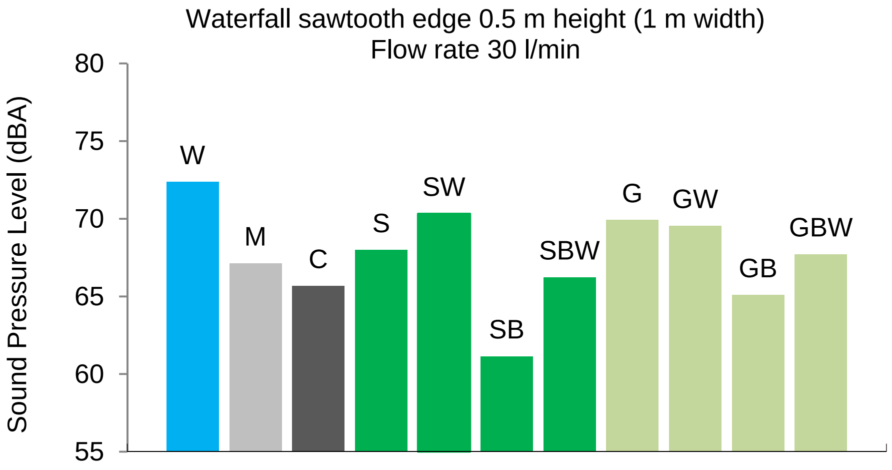


Figure G2-1

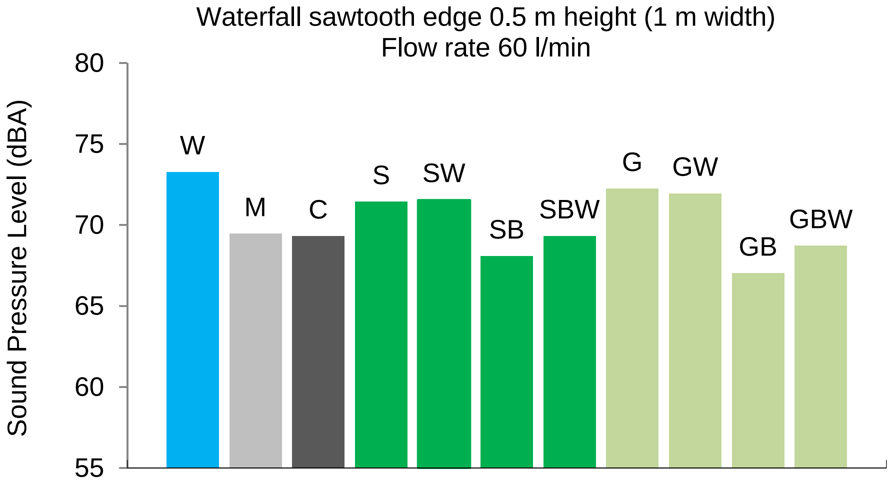


Figure G2-2

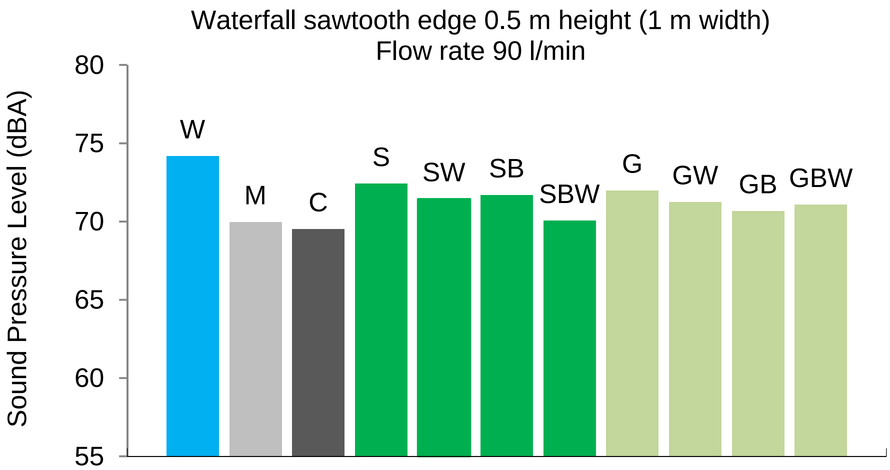


Figure G2-3

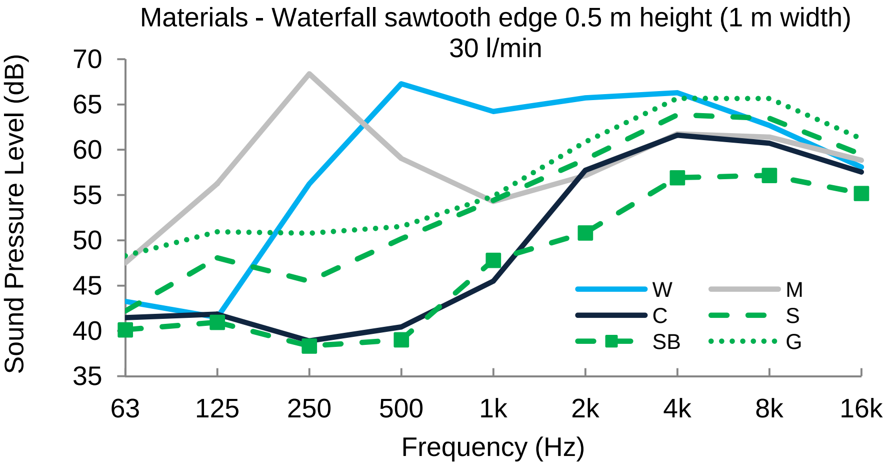


Figure G2-4

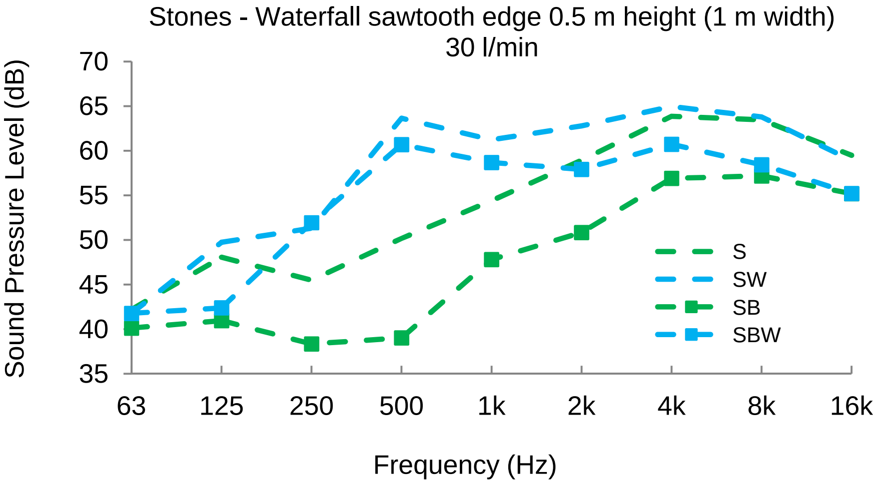


Figure G2-5

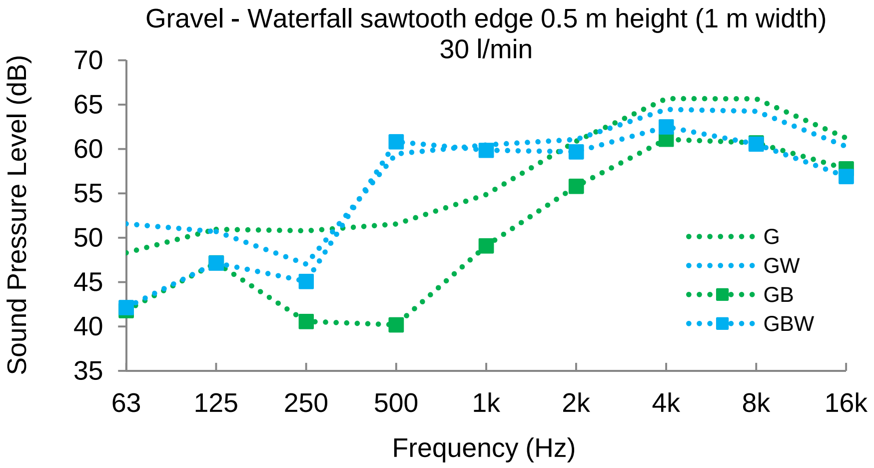


Figure G2-6

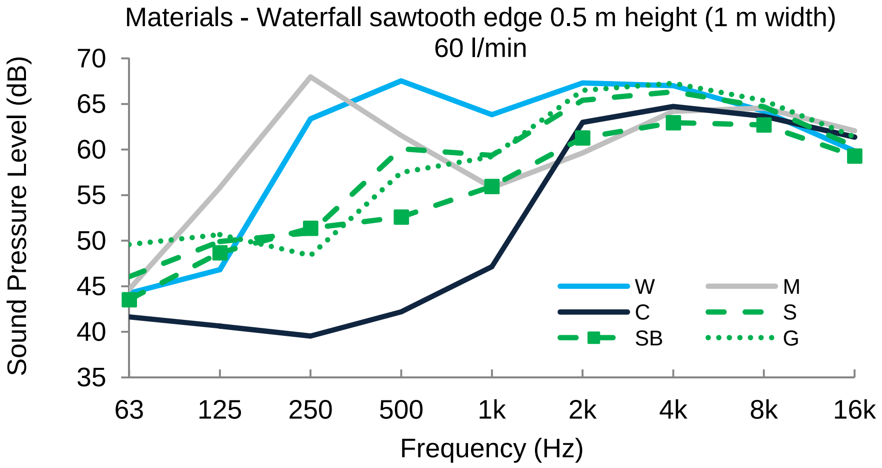


Figure G2-7

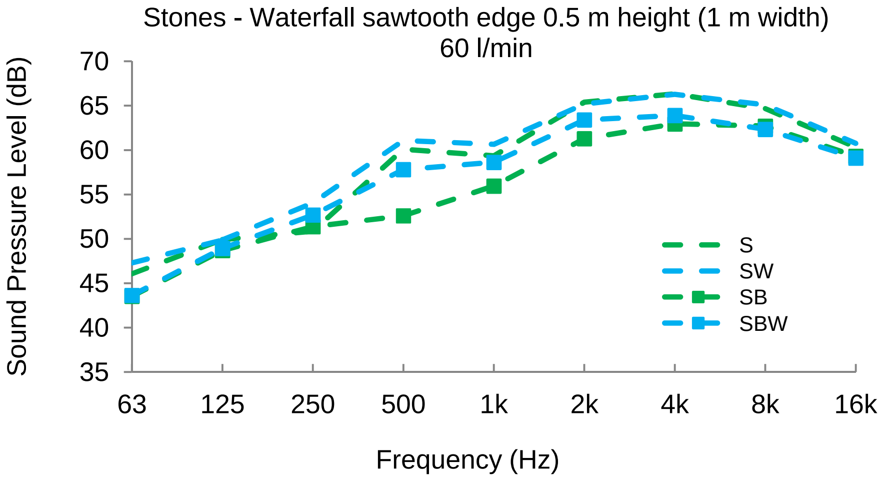


Figure G2-8

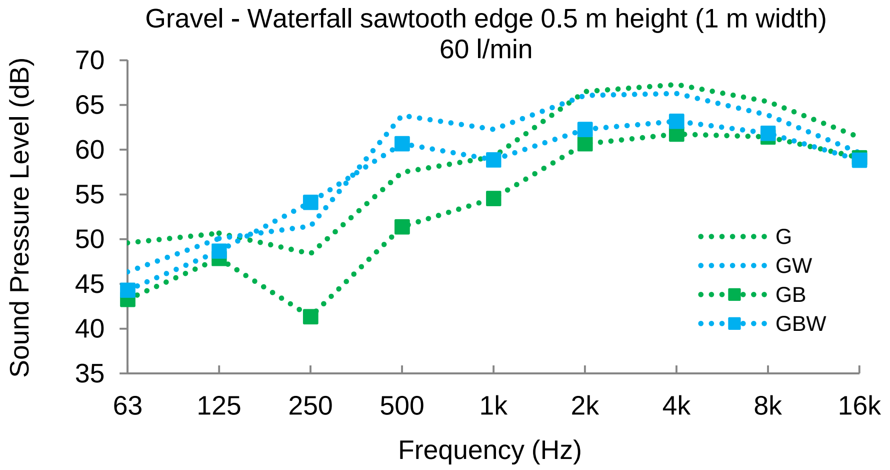


Figure G2-9

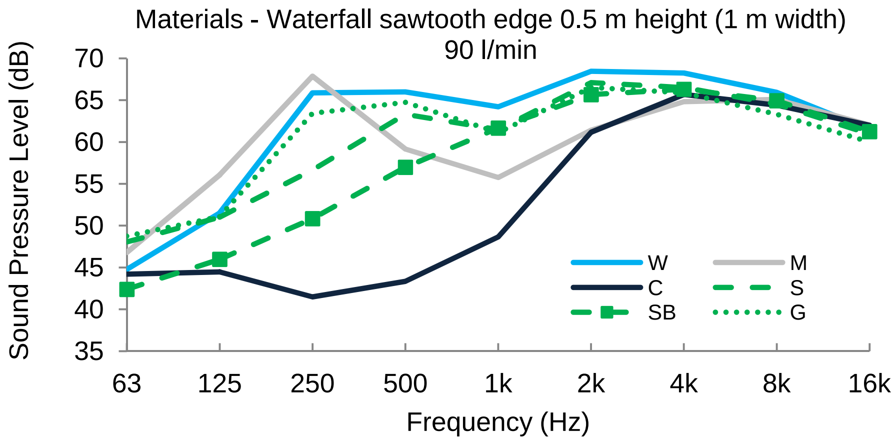


Figure G2-10

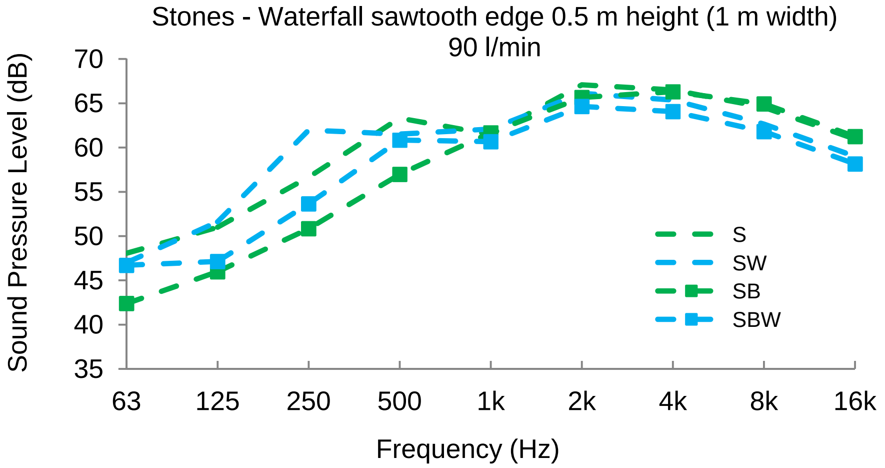


Figure G2-11

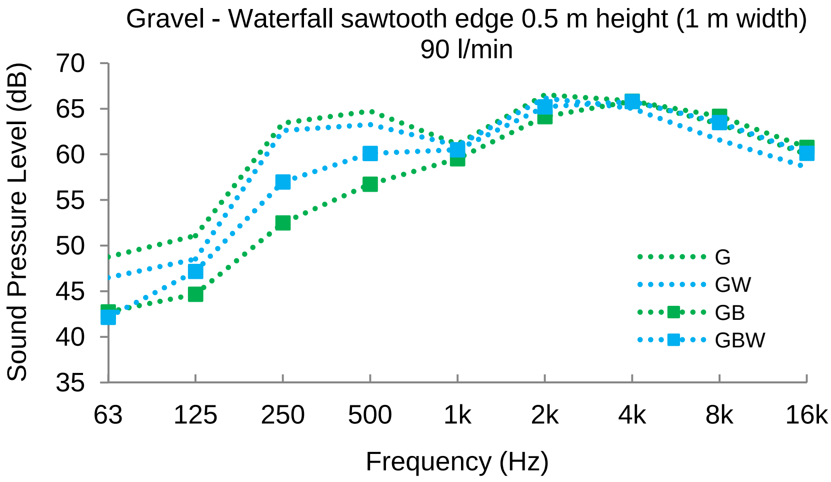


Figure G2-12

G3. Waterfall small holes edge - 0.5 m height

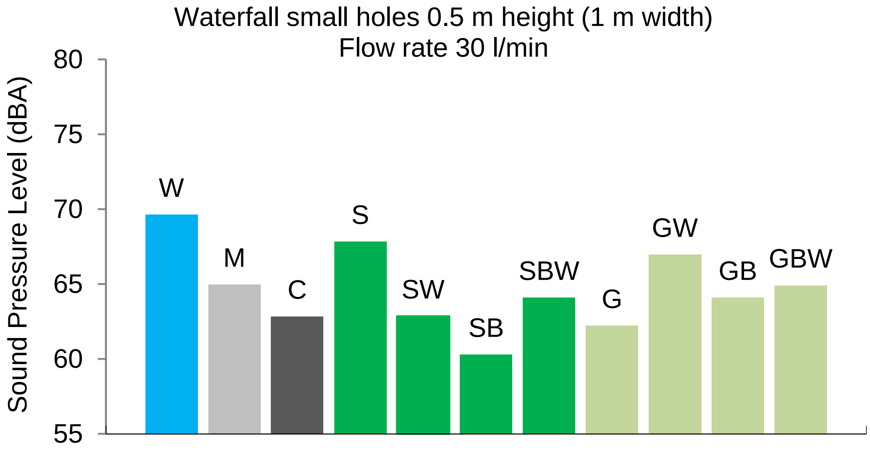


Figure G3-1

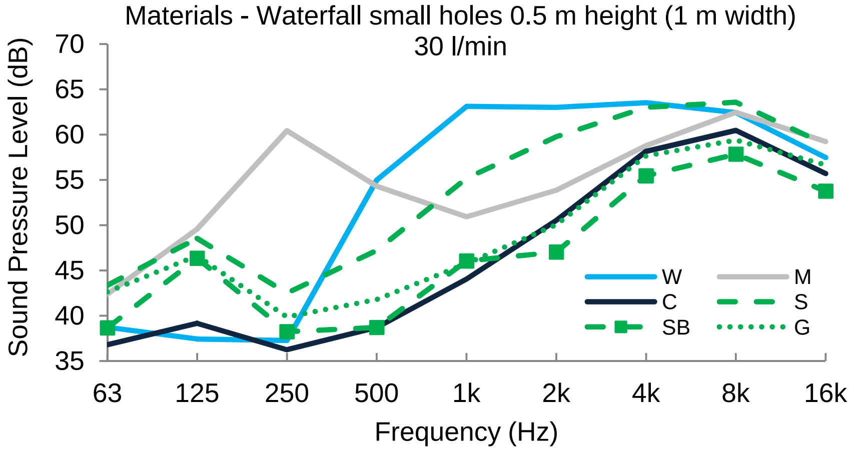


Figure G3-2

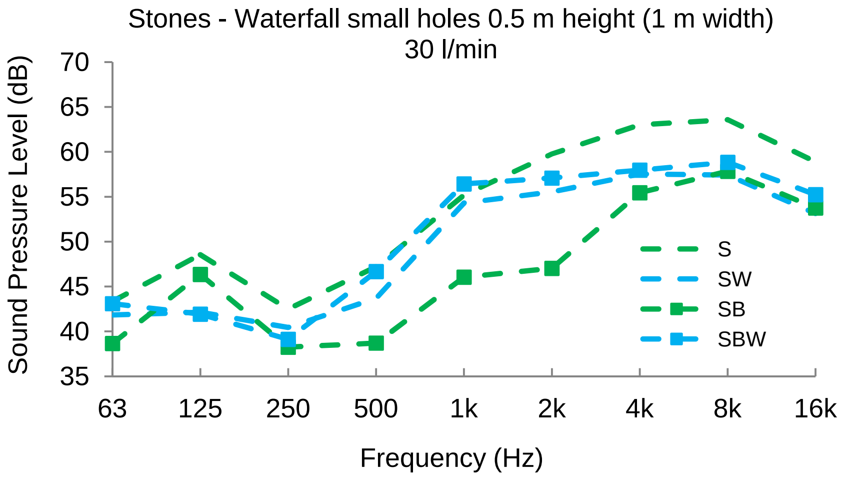


Figure G3-3

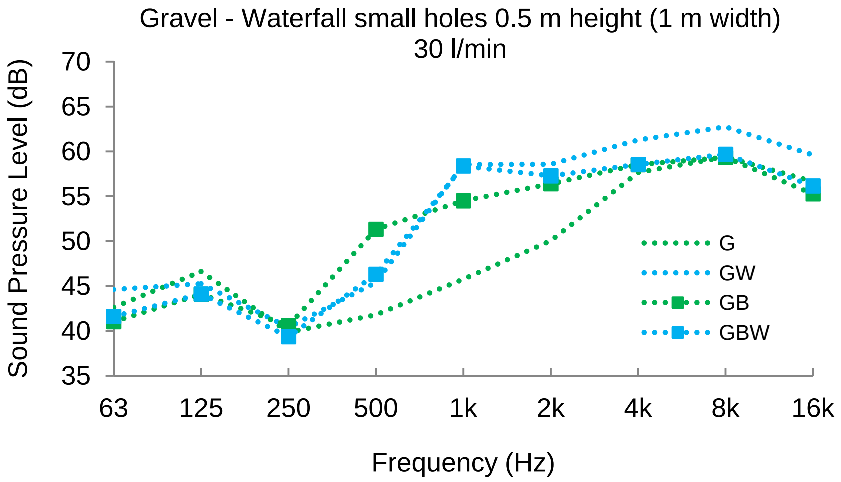


Figure G3-4

G4. Waterfall plain edge - 1 m height

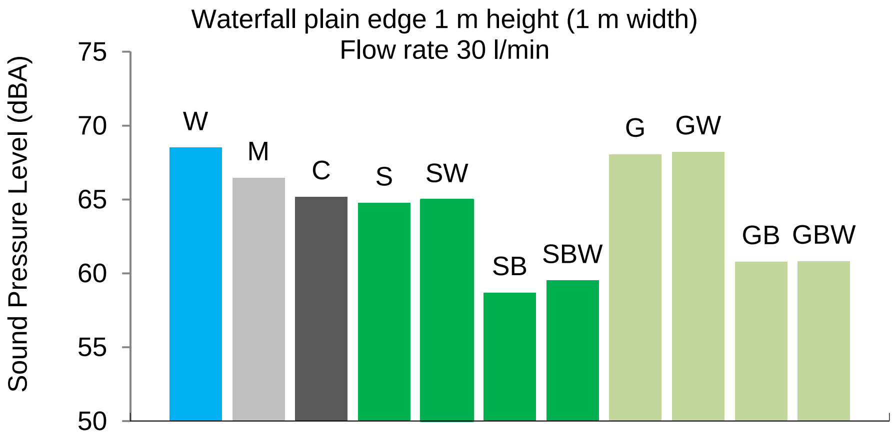


Figure G4-1

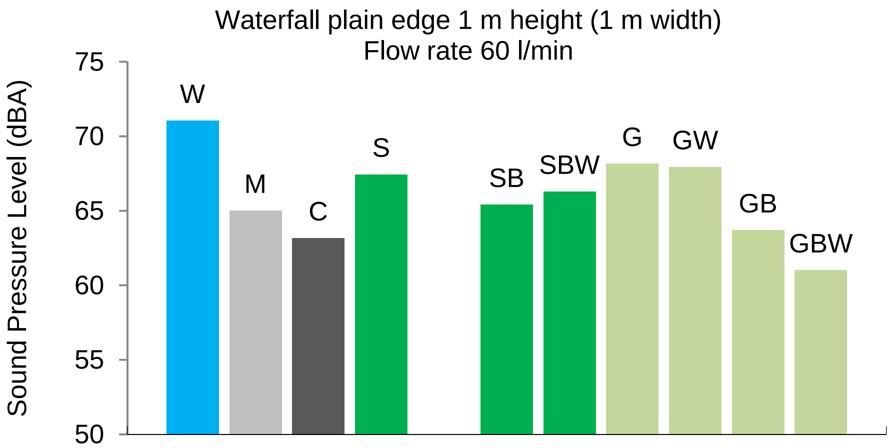


Figure G4-2

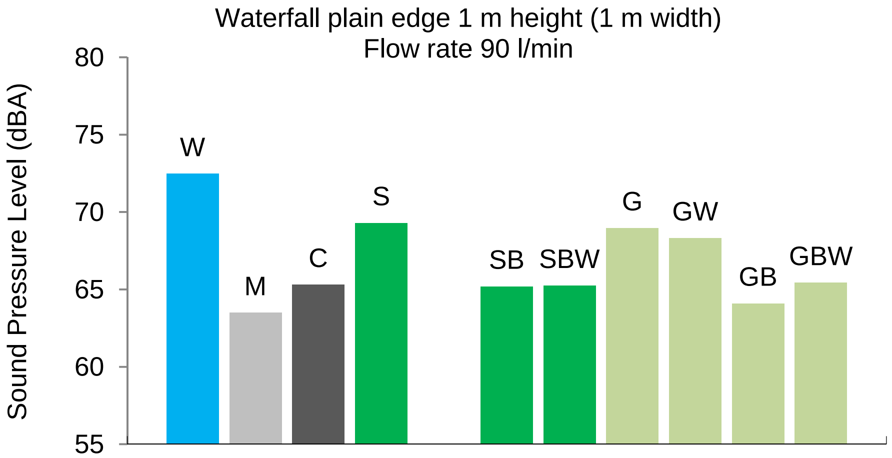


Figure G4-3

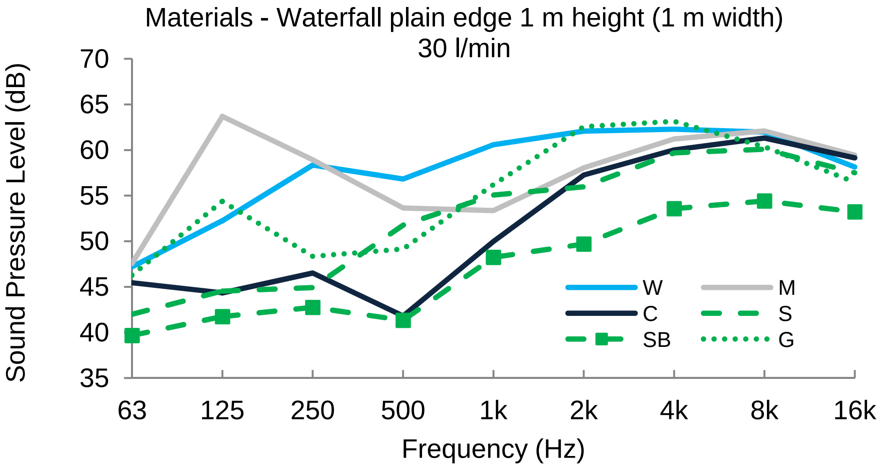


Figure G4-4

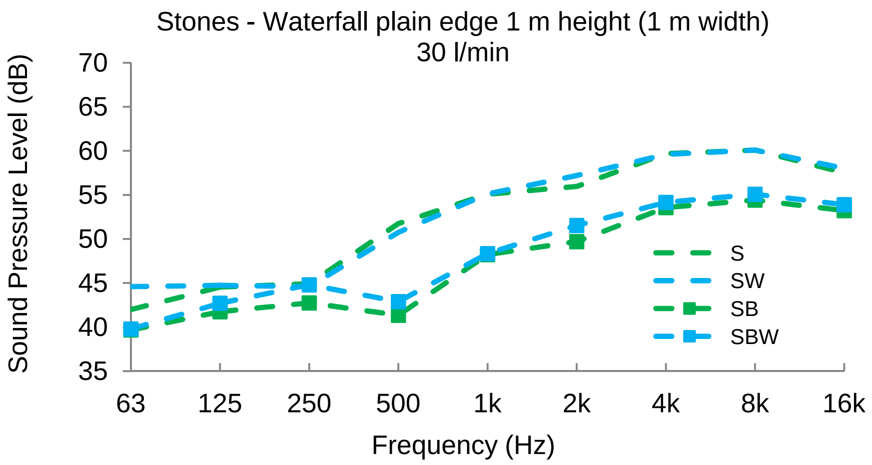


Figure G4-5

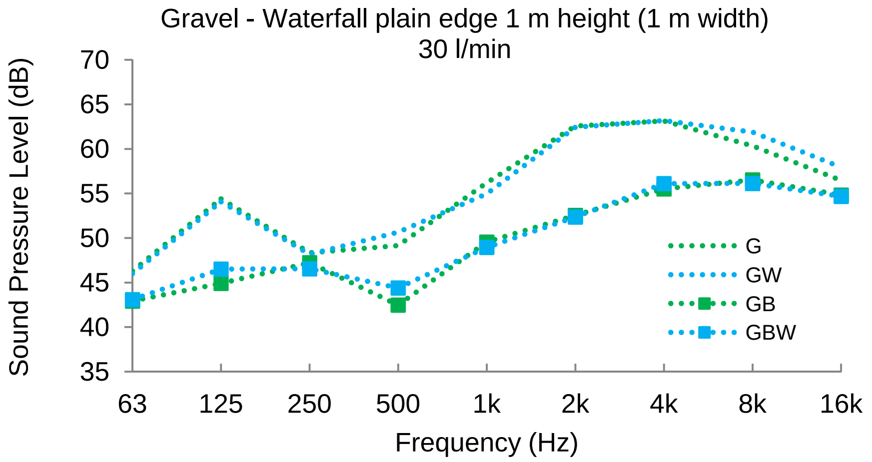


Figure G4-6

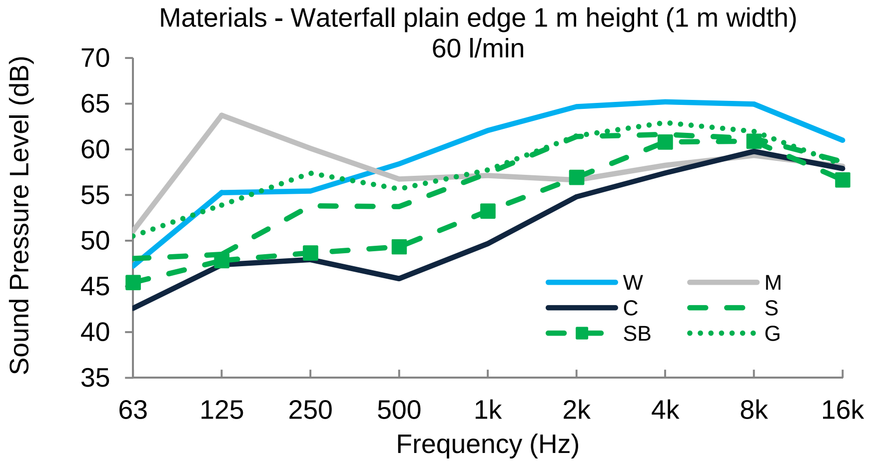


Figure G4-7

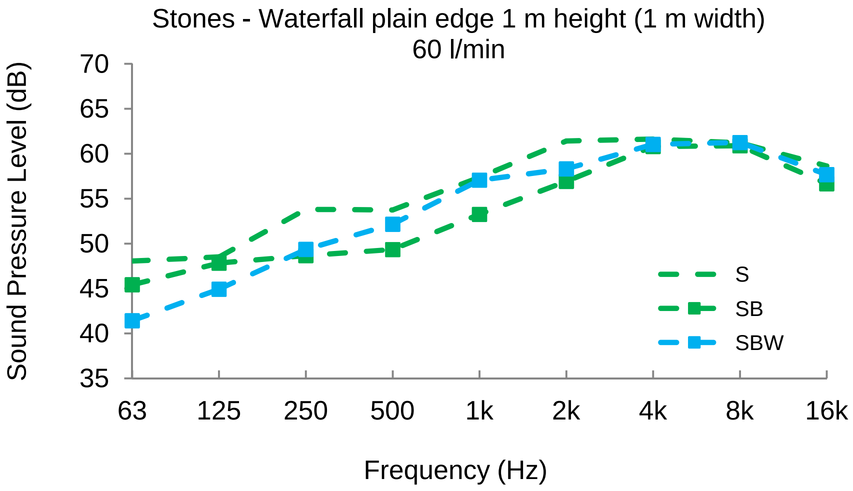


Figure G4-8

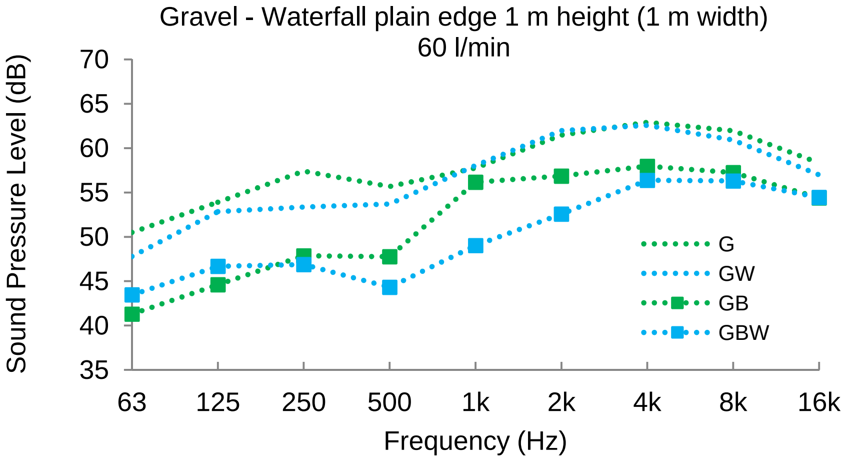


Figure G4-9

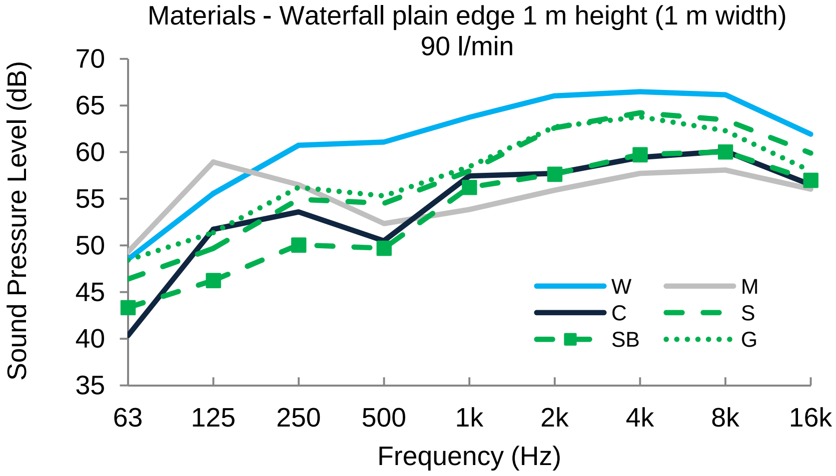


Figure G4-10

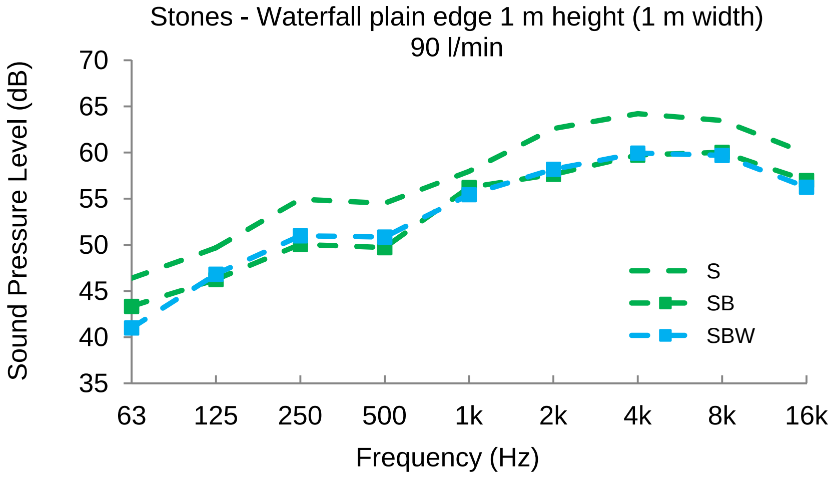


Figure G4-11

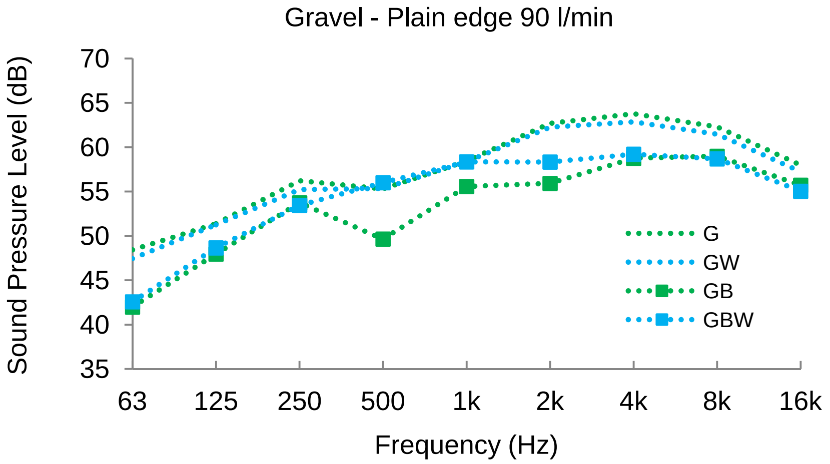


Figure G4-12

G5. Waterfall sawtooth edge - 1 m height

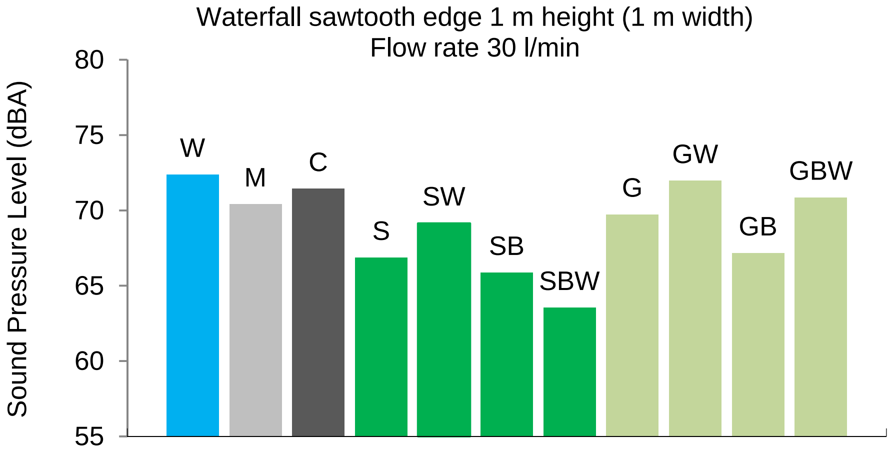


Figure G5-1

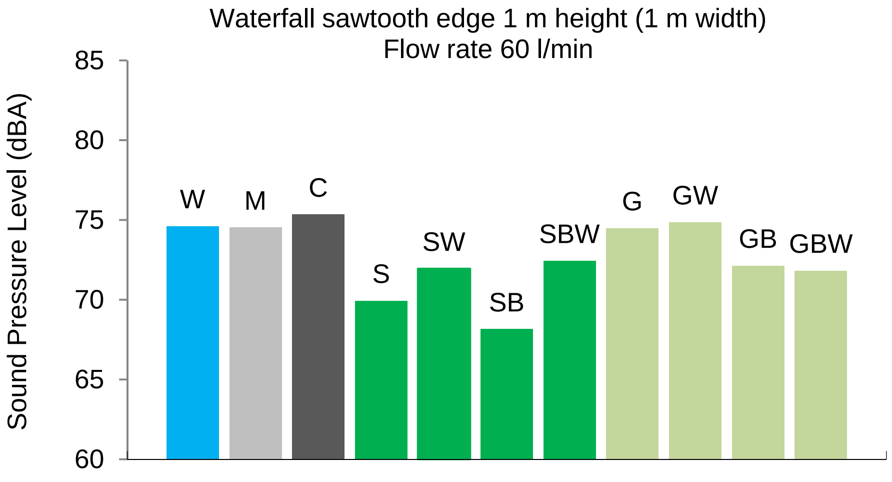


Figure G5-2

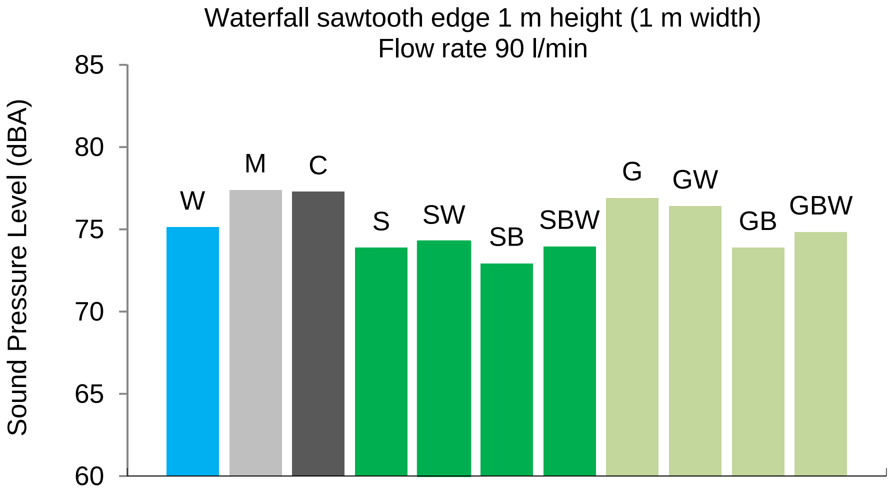


Figure G5-3

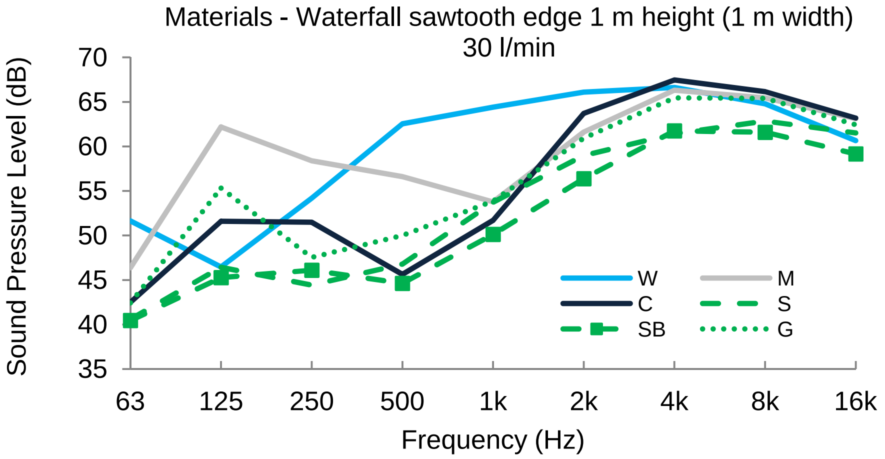


Figure G5-4

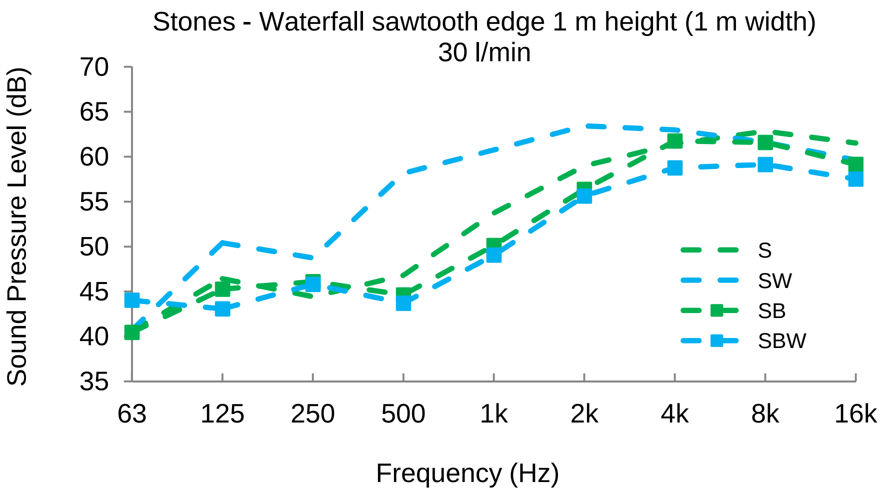
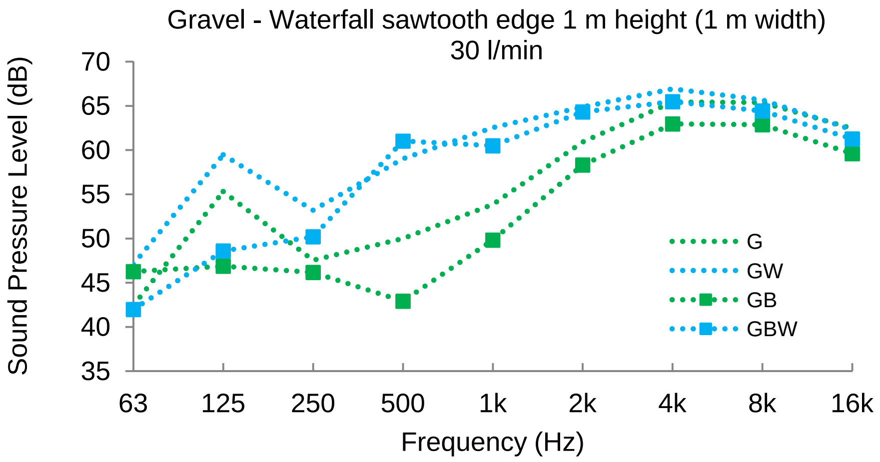


Figure G5-5



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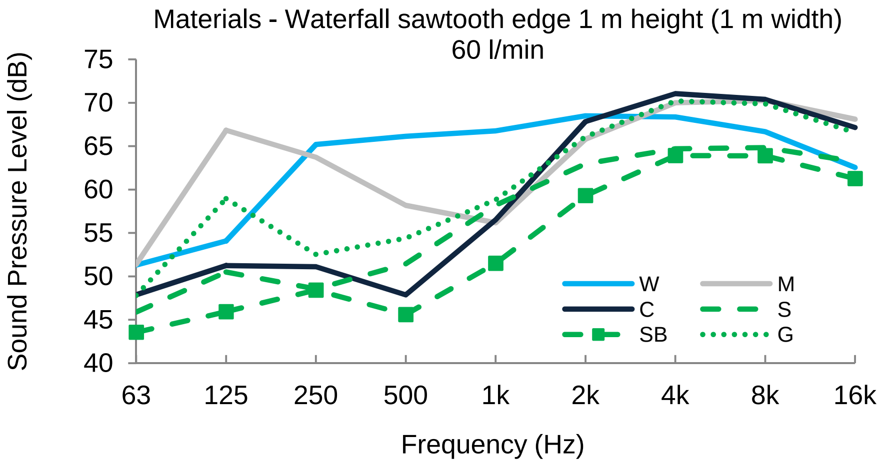

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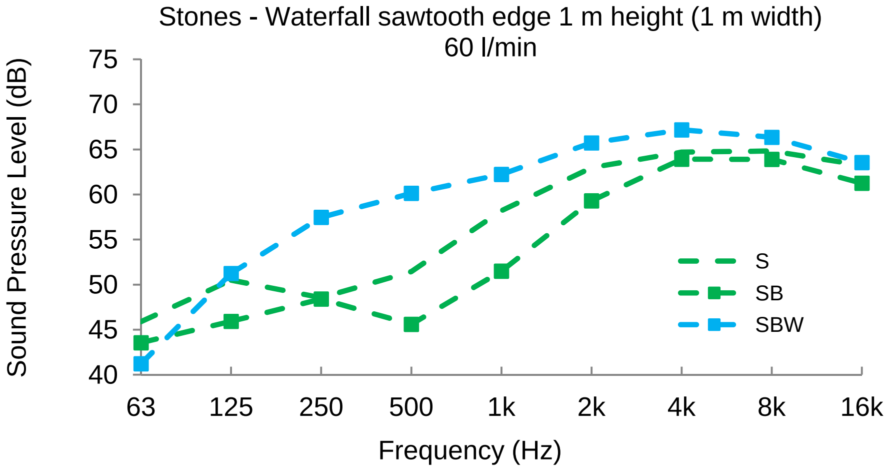

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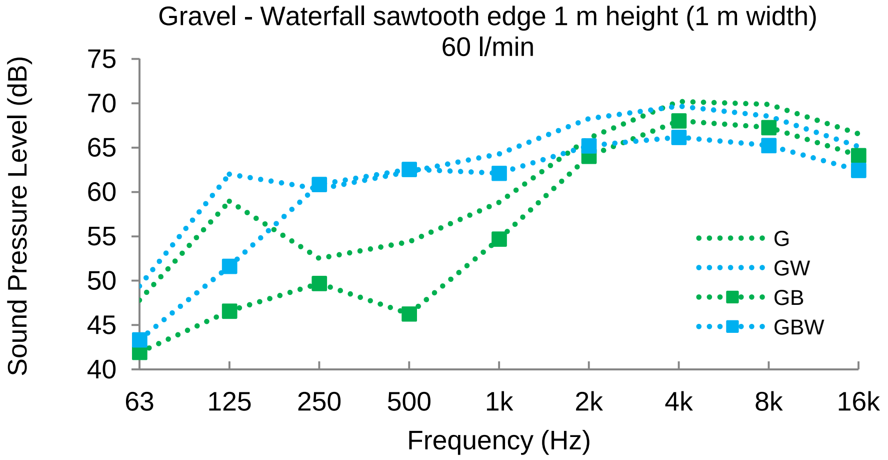

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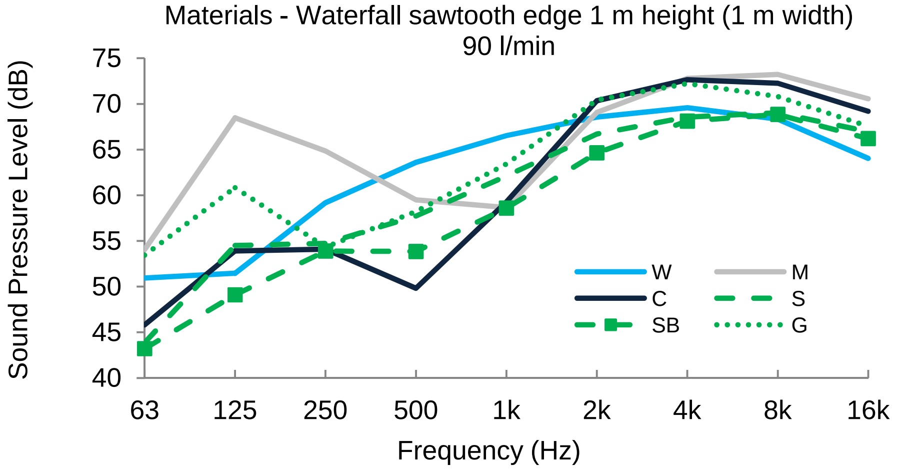

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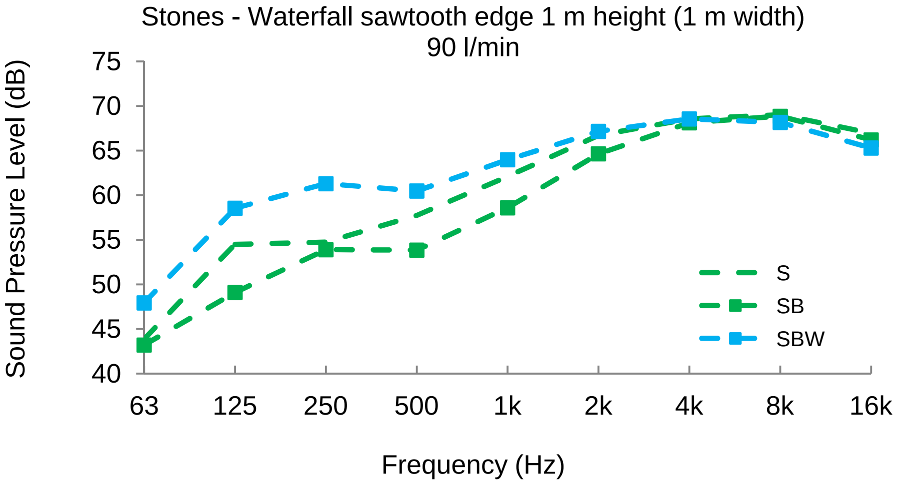

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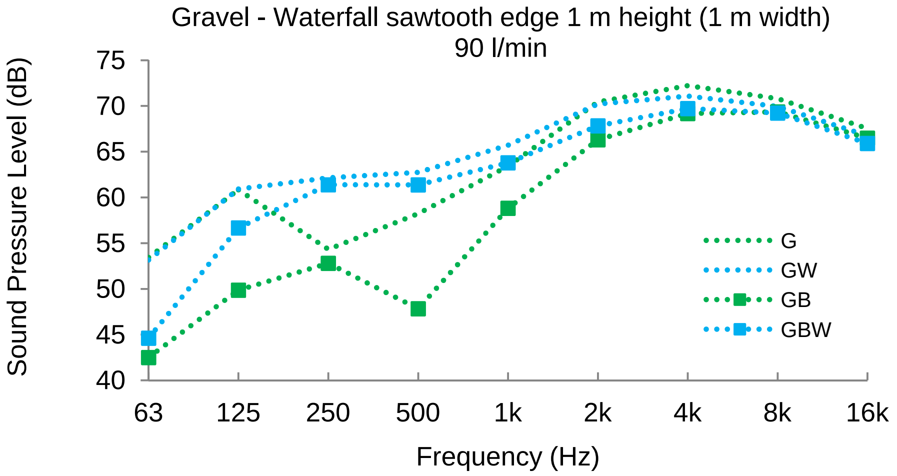


Figure G5-12

G6. Waterfall small holes edge - 1 m height

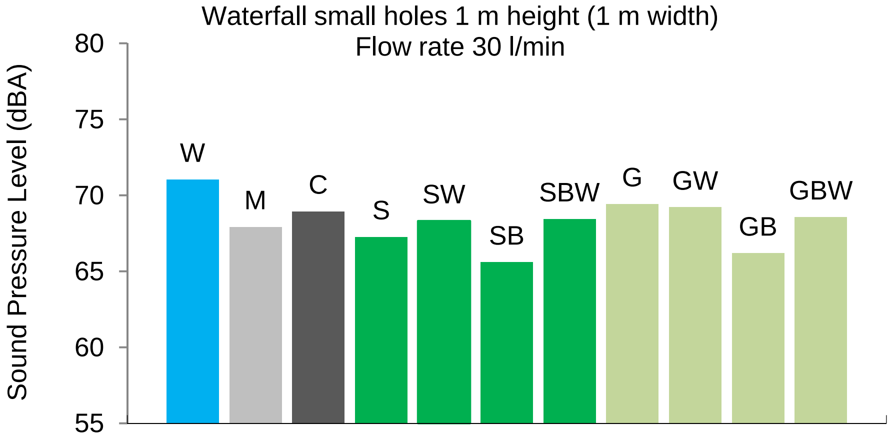
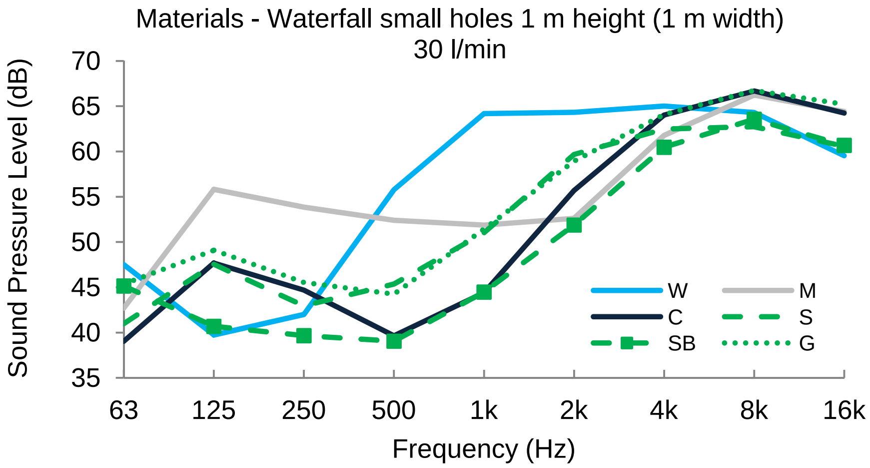


Figure G6-1



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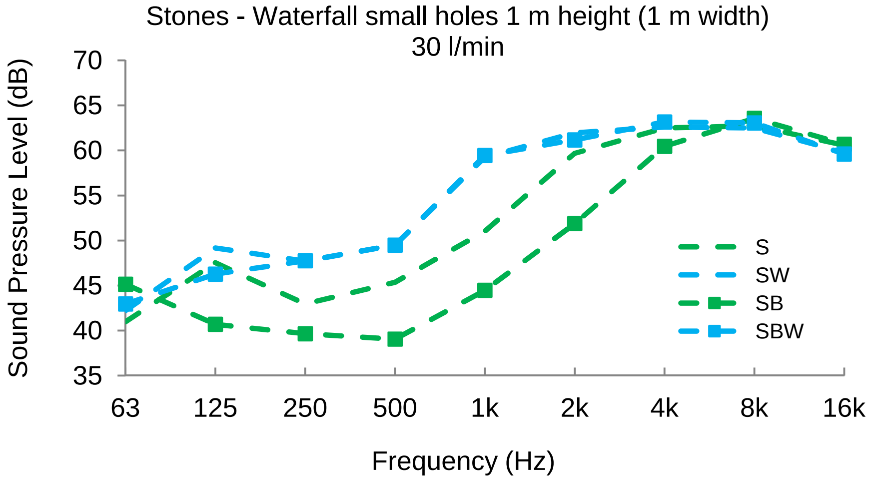

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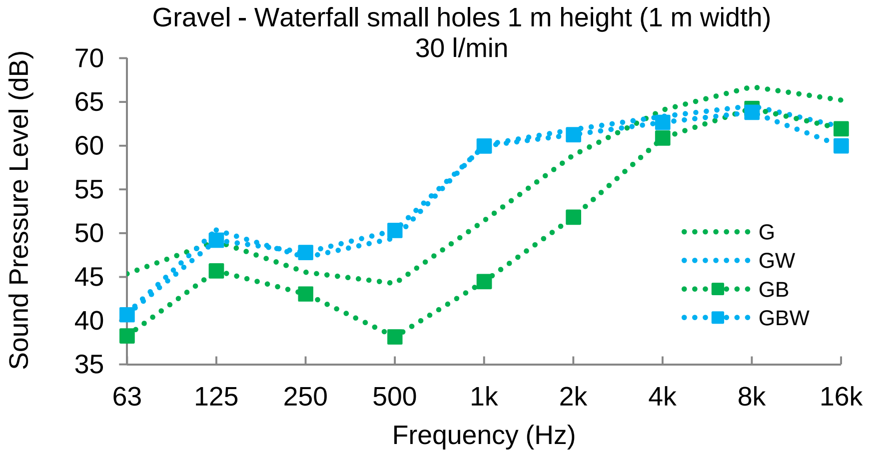


Figure G6-4

G7. Waterfall plain edge - 2 m height

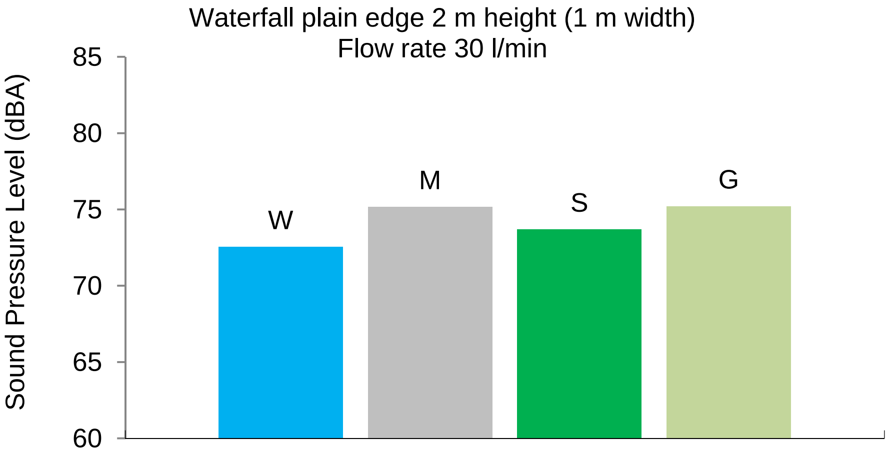


Figure G7-1

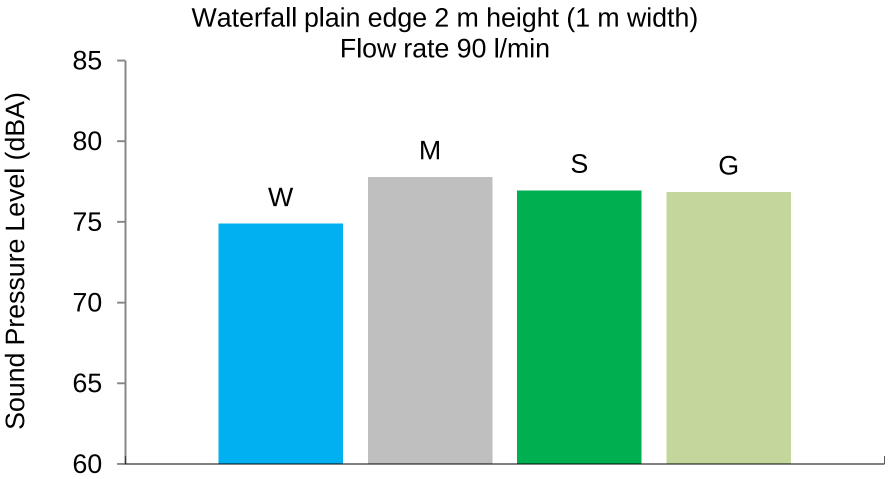
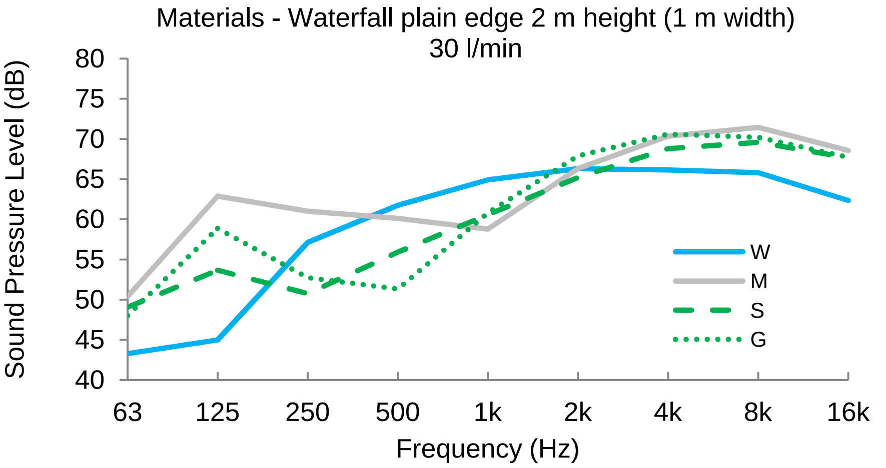


Figure G7-2



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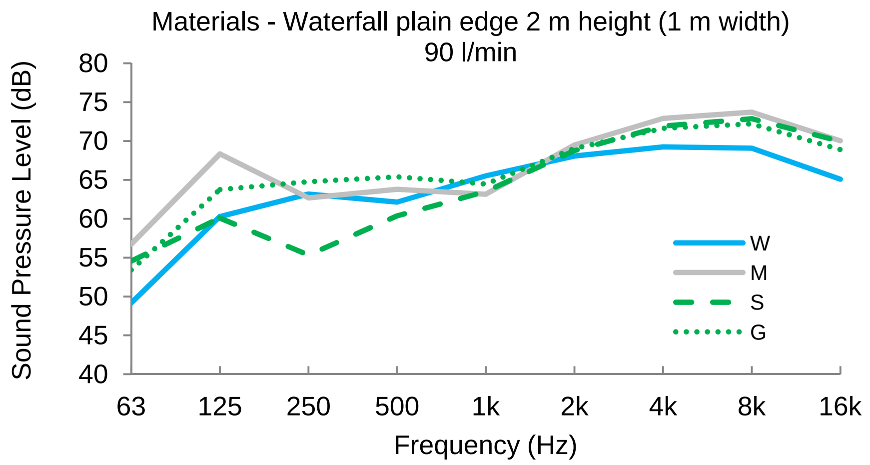


Figure G7-4

G8. Waterfall sawtooth edge - 2 m height

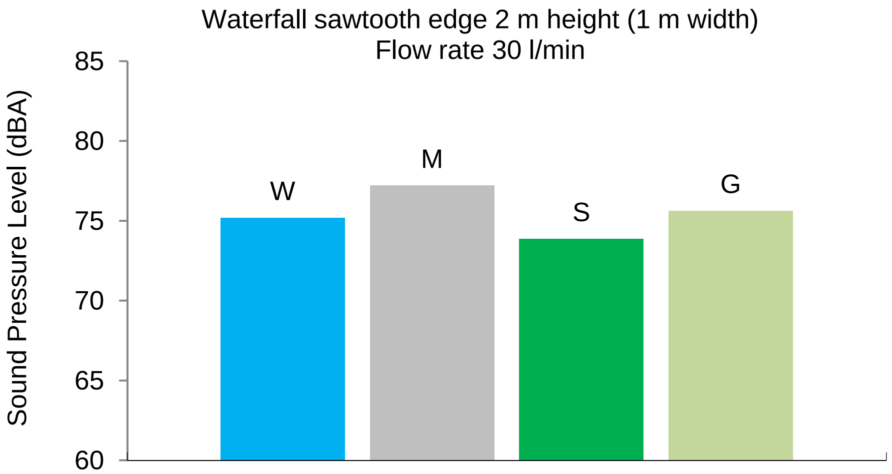
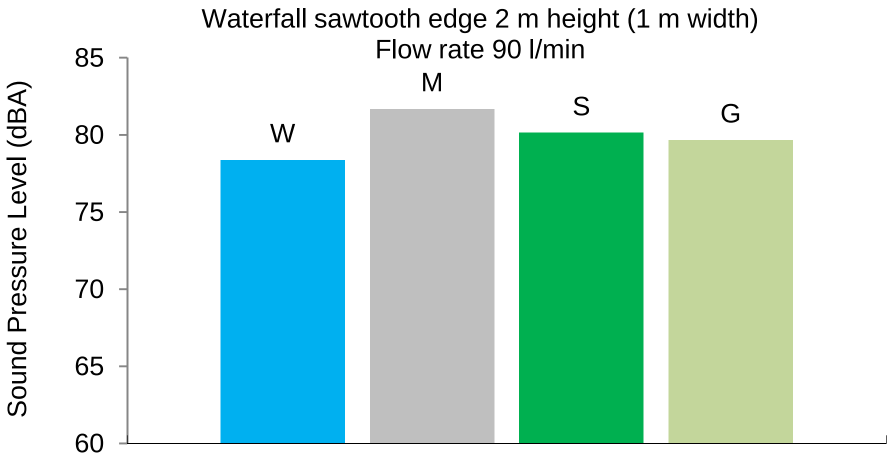


Figure G8-1



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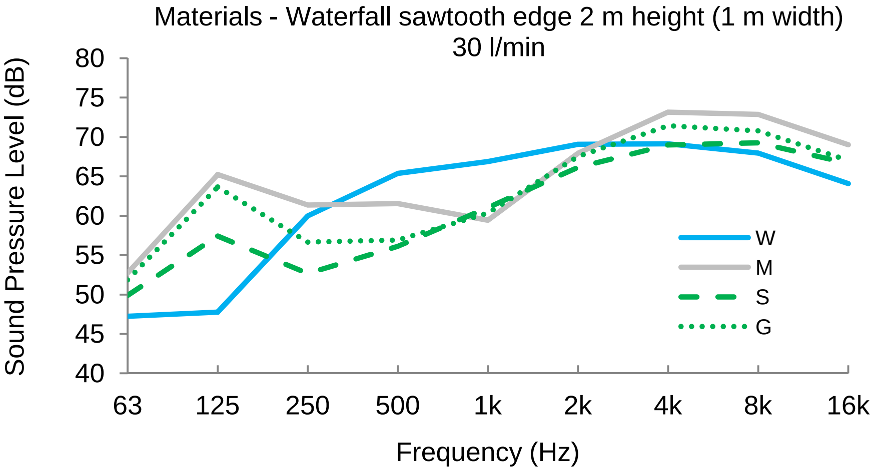

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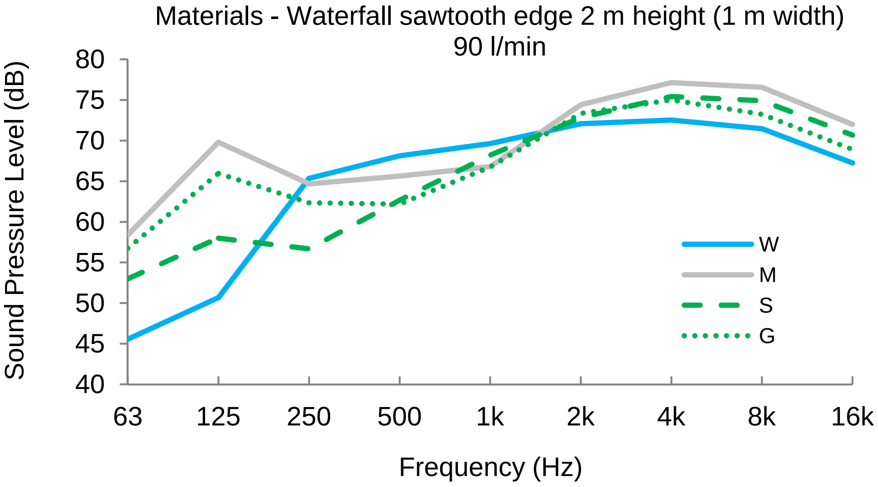


Figure G8-4

G9. Waterfall small holes edge - 2 m height

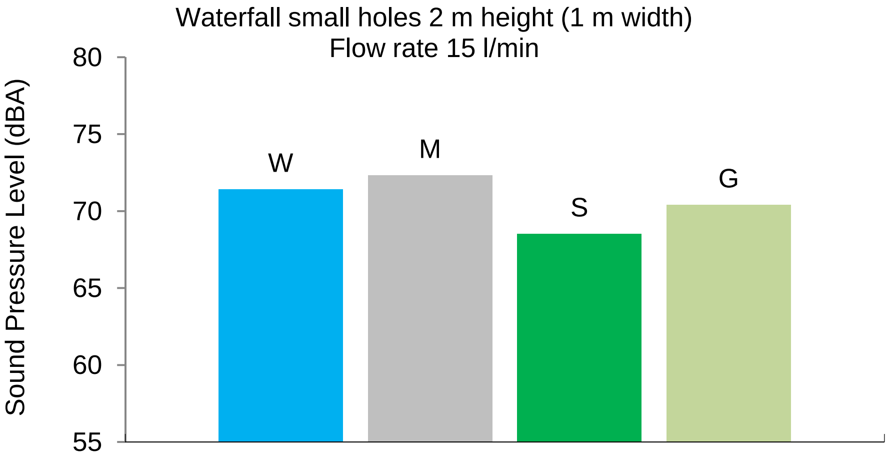
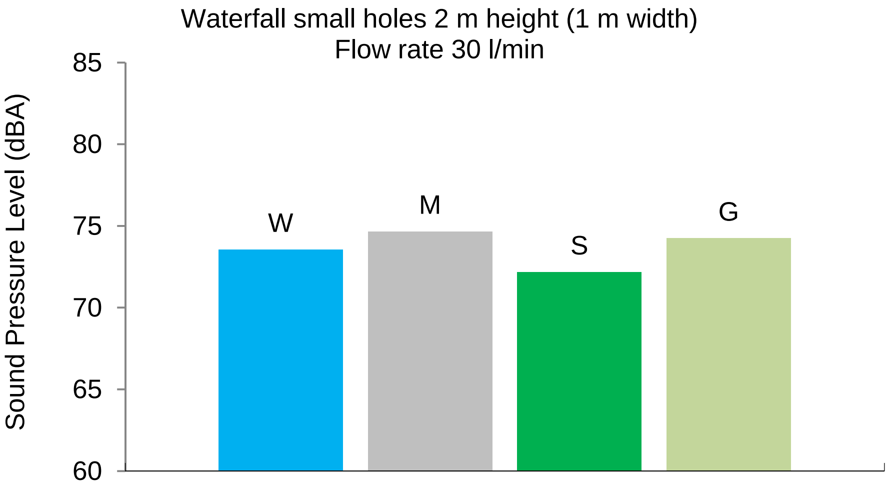


Figure G9-1



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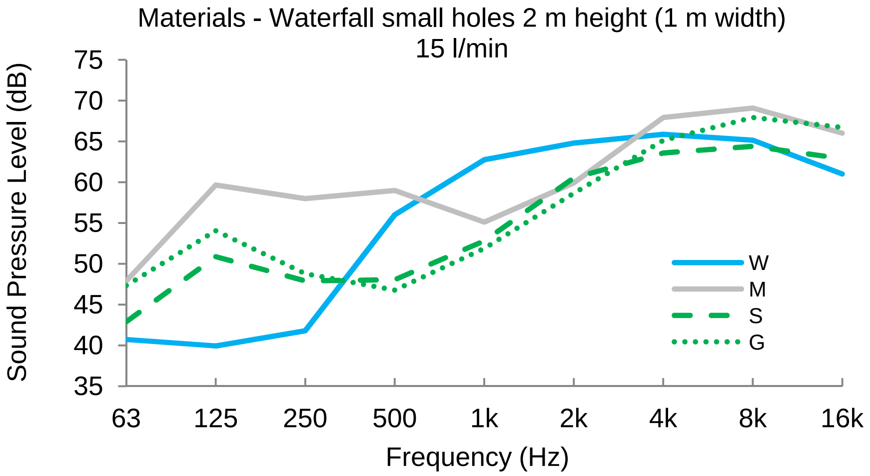


Figure G9-3

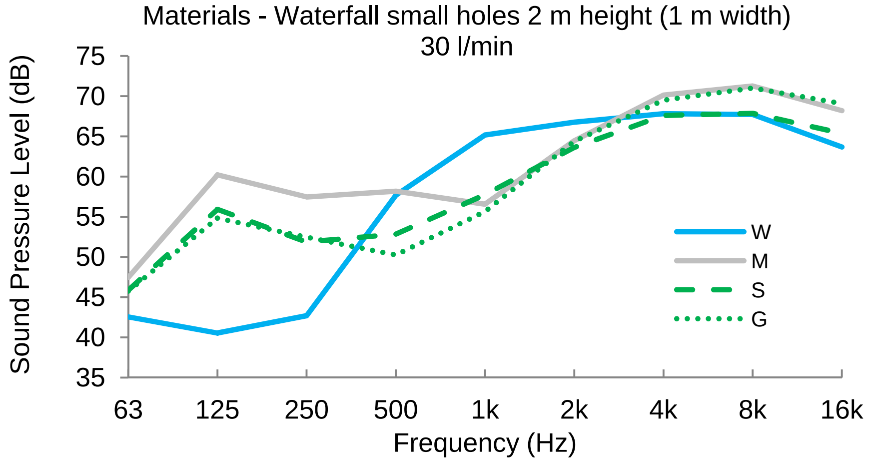
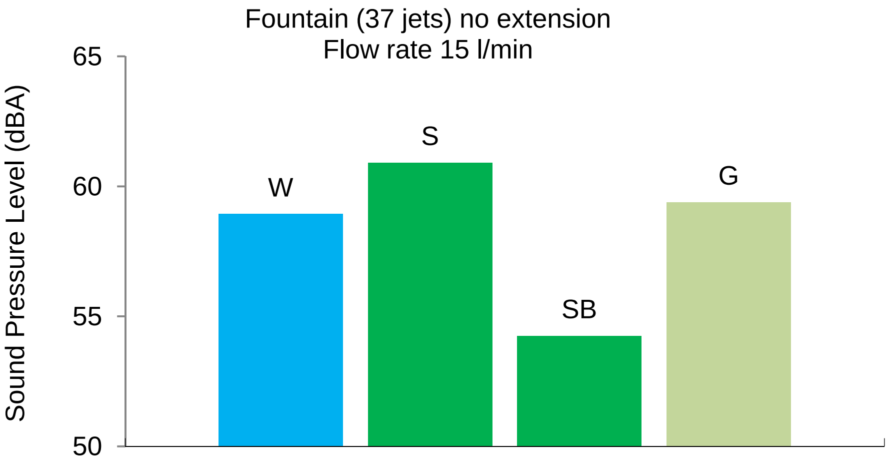


Figure G9-4

G10. Fountains



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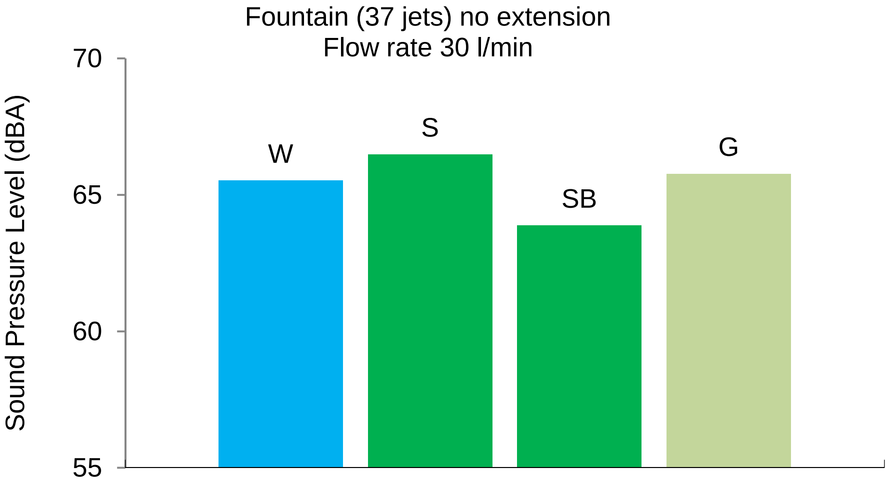

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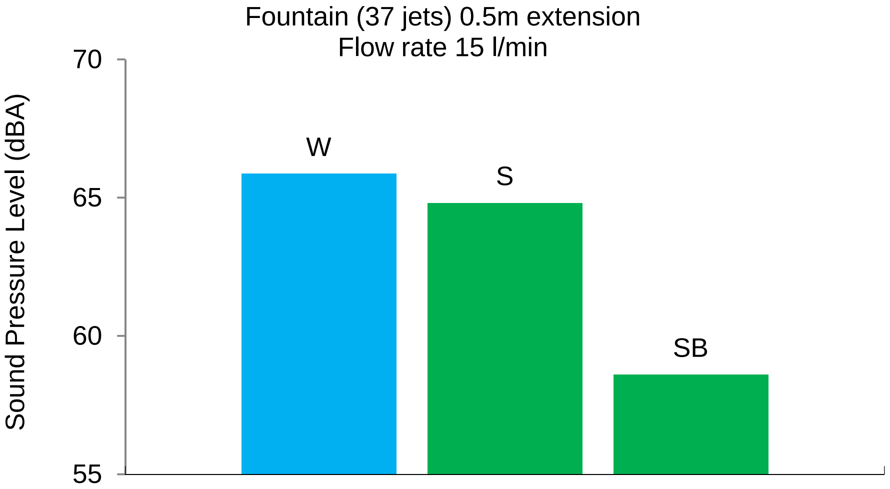

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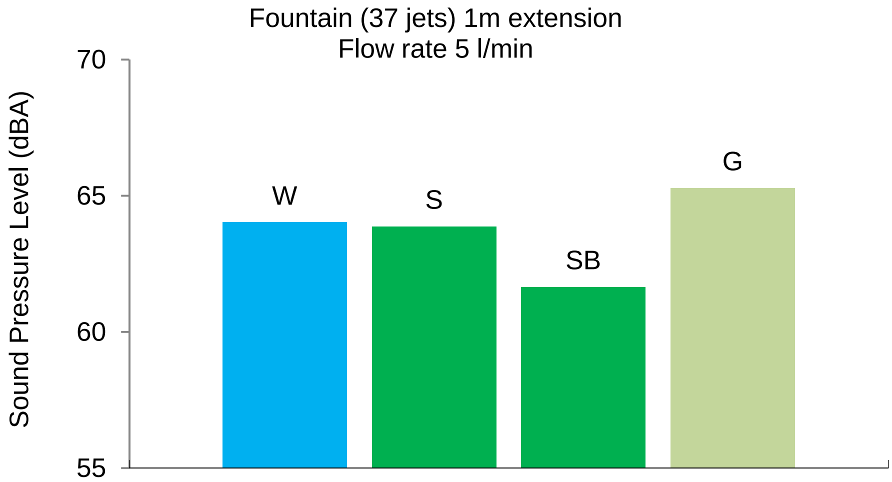

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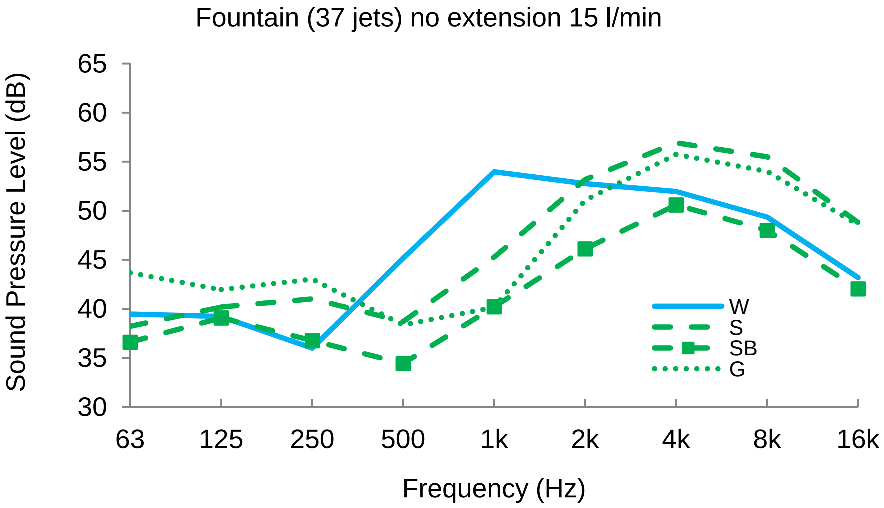

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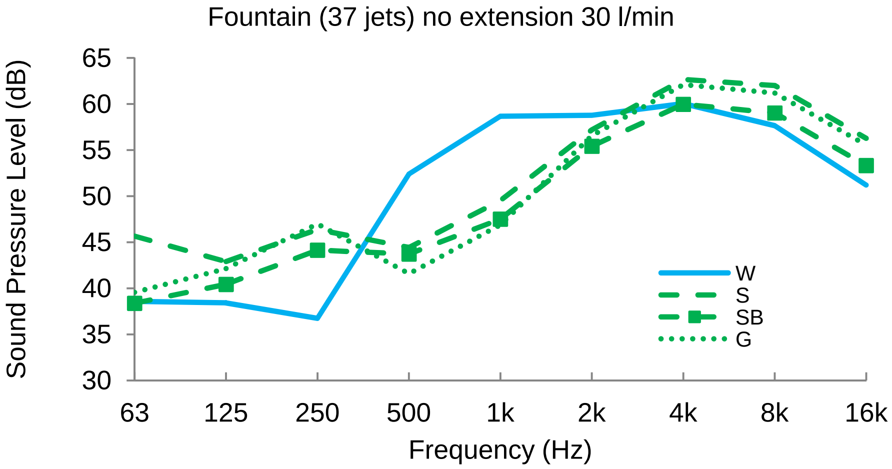

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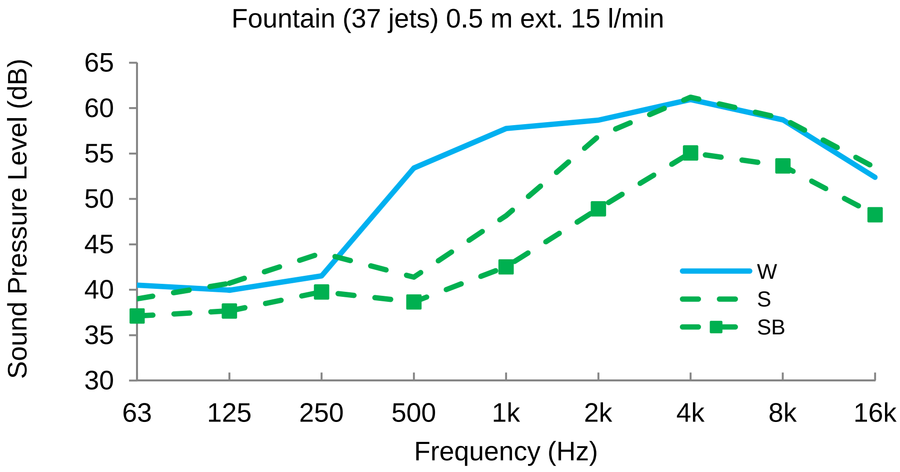

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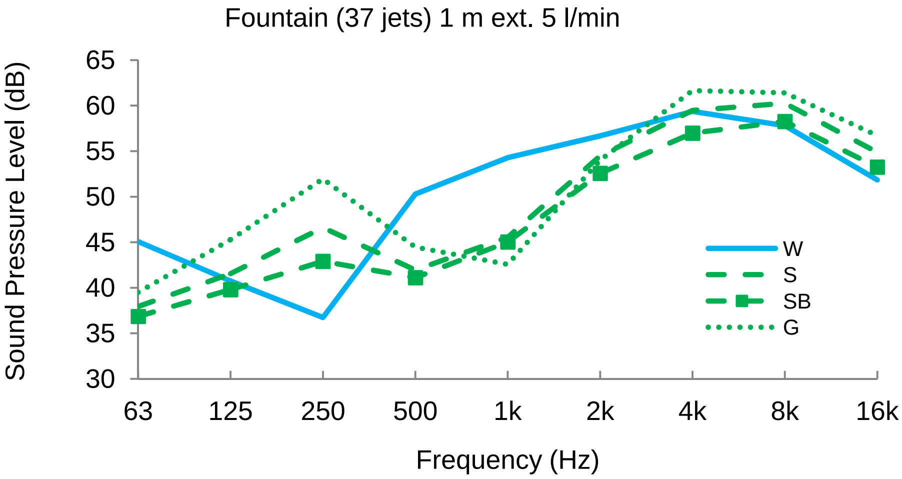

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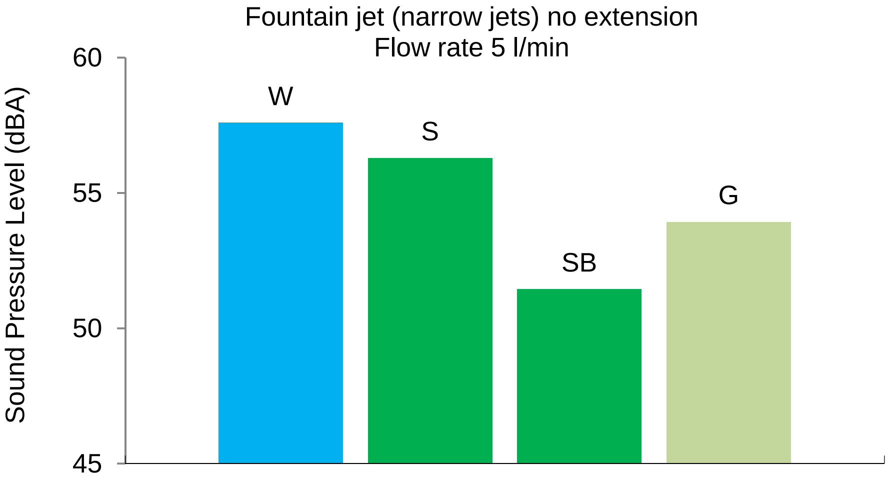

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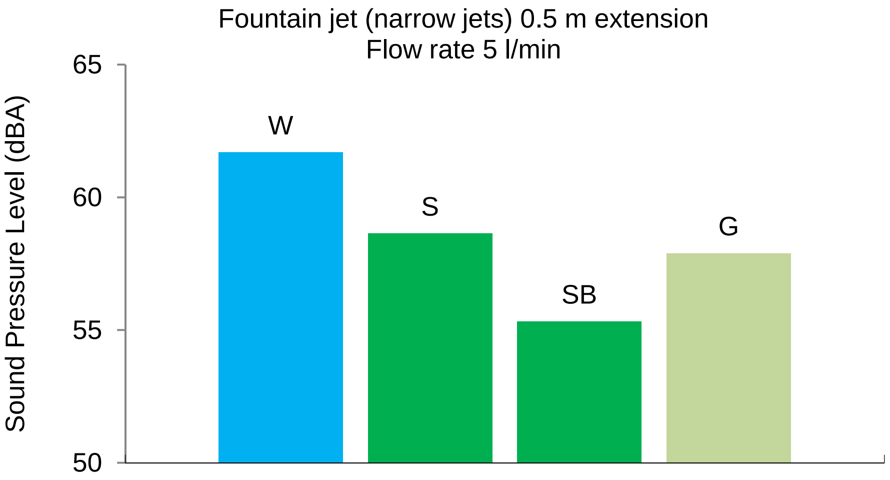

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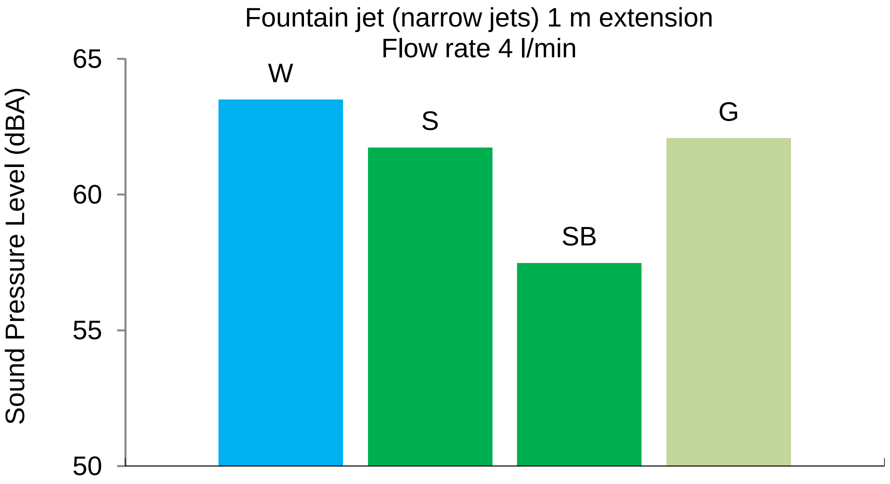

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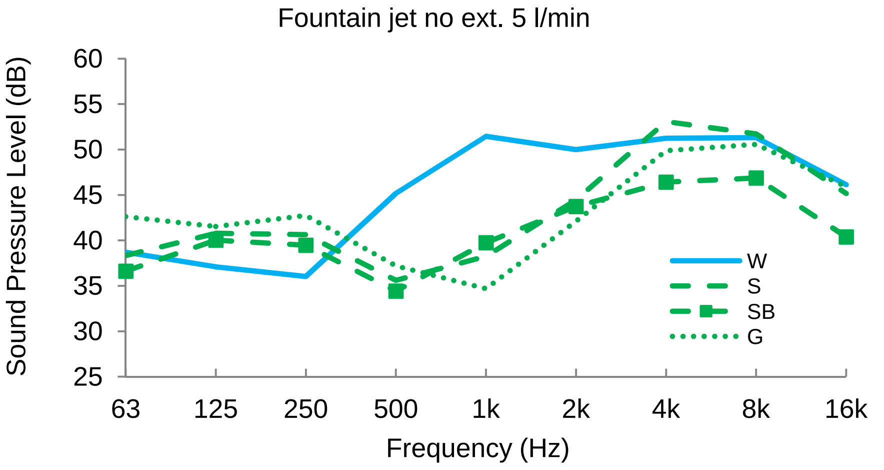

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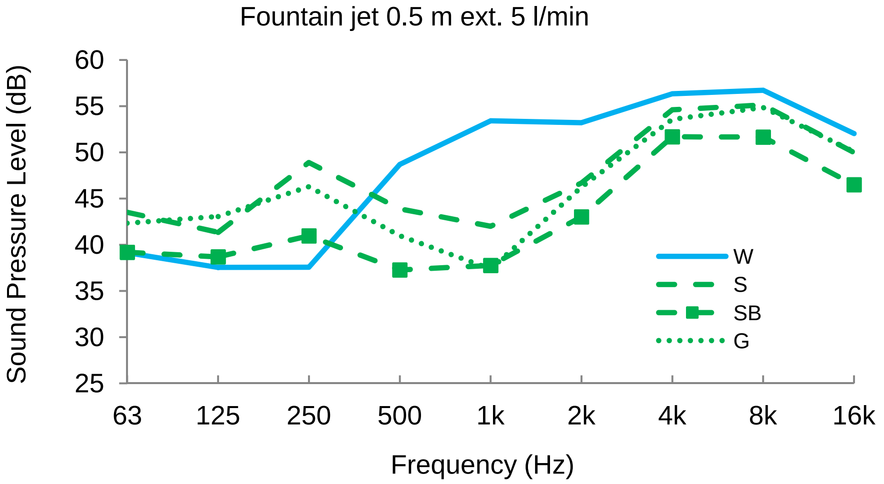

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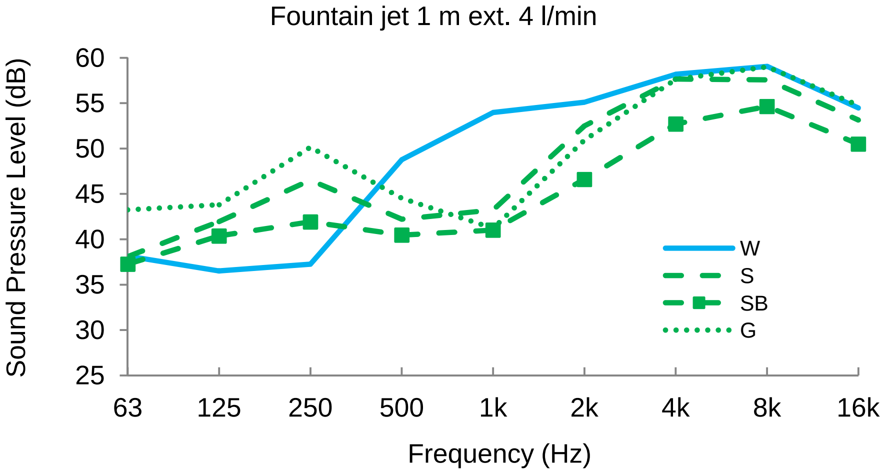

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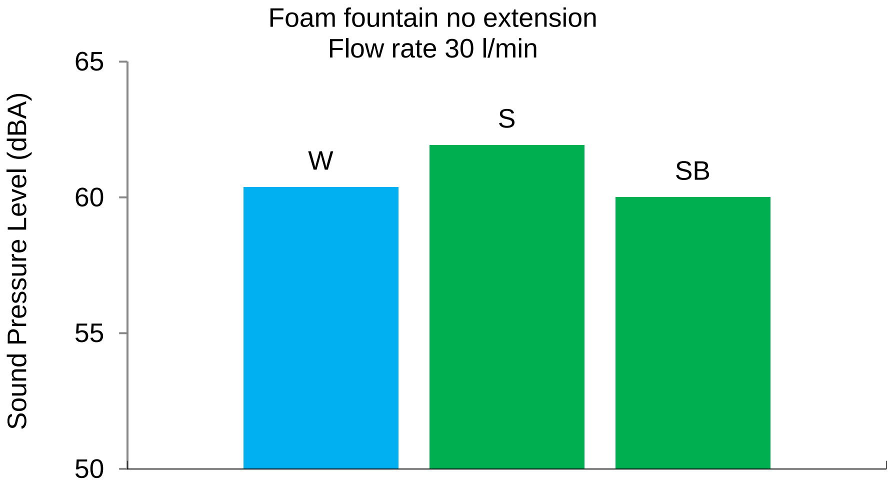

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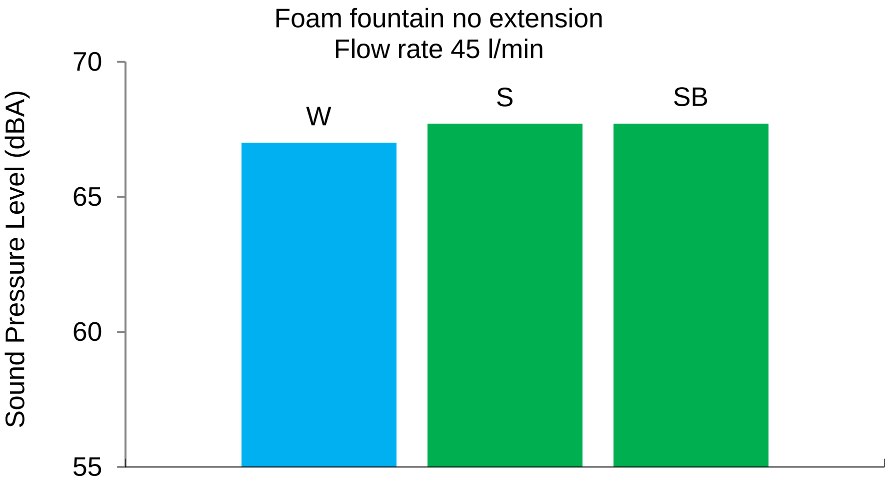

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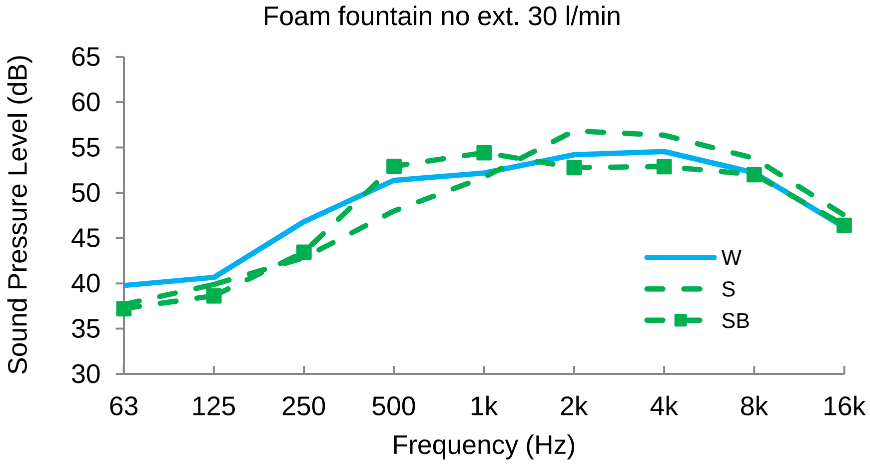

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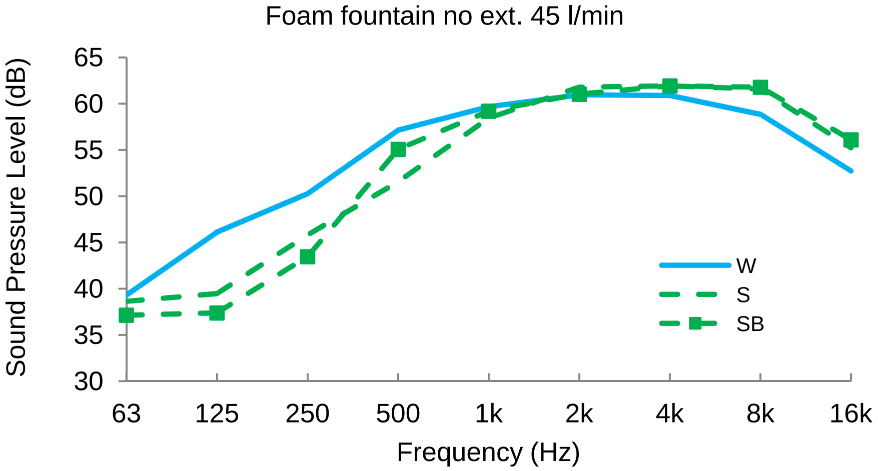

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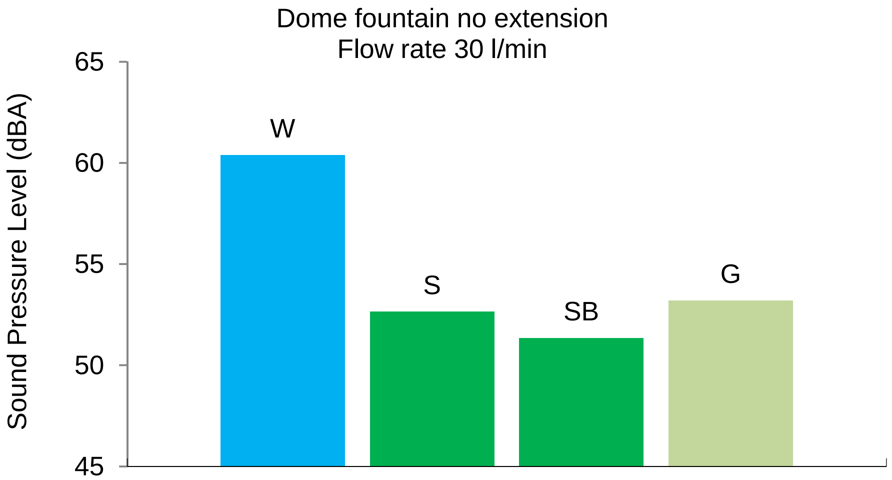

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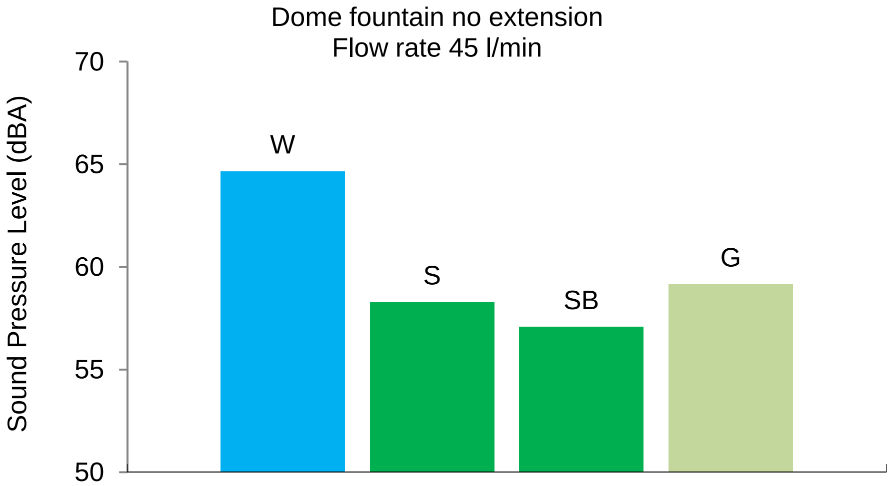

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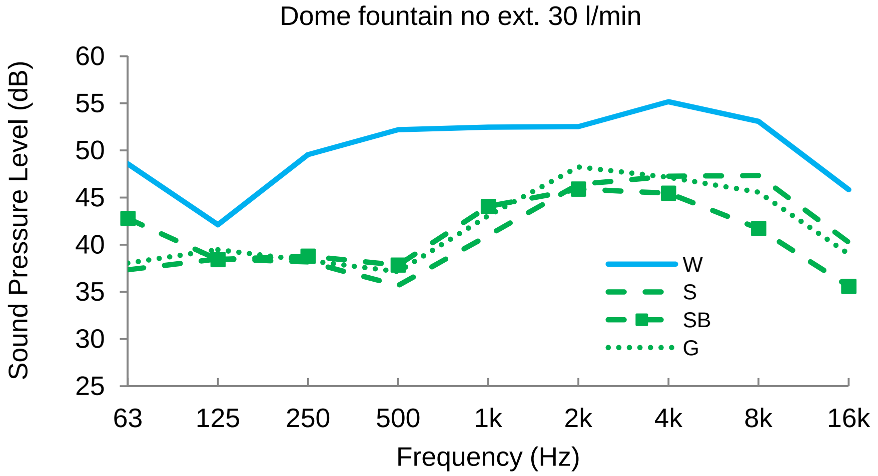

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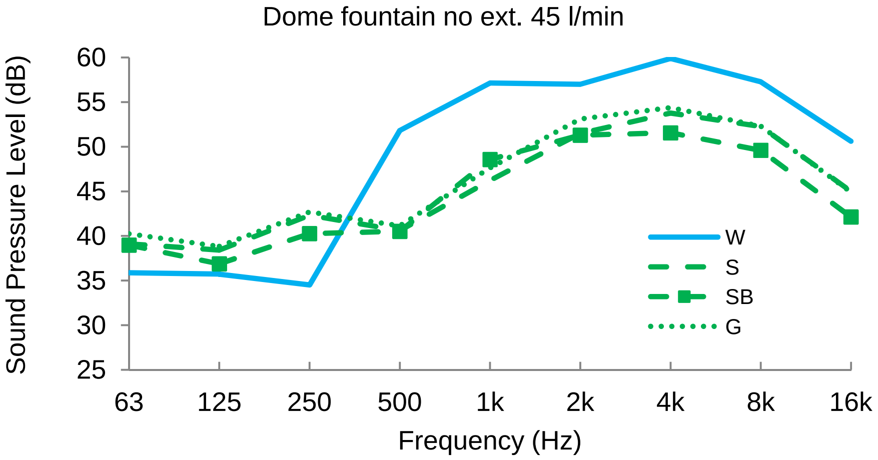


Figure G10-22

G11. Jets

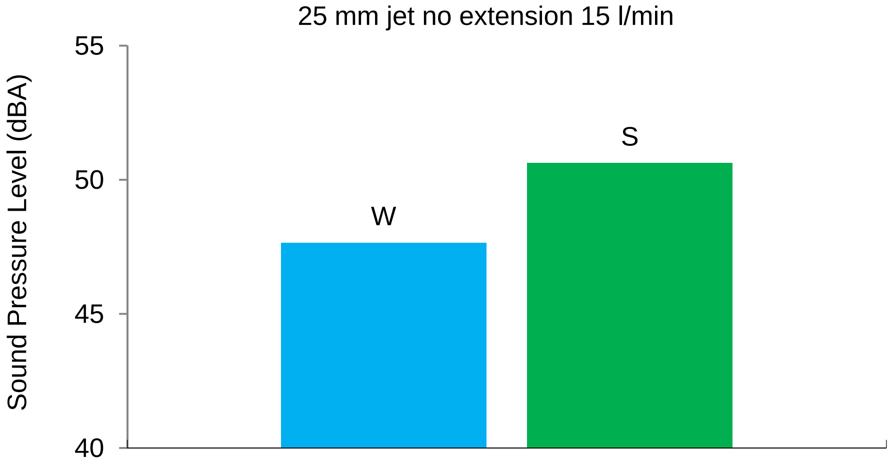
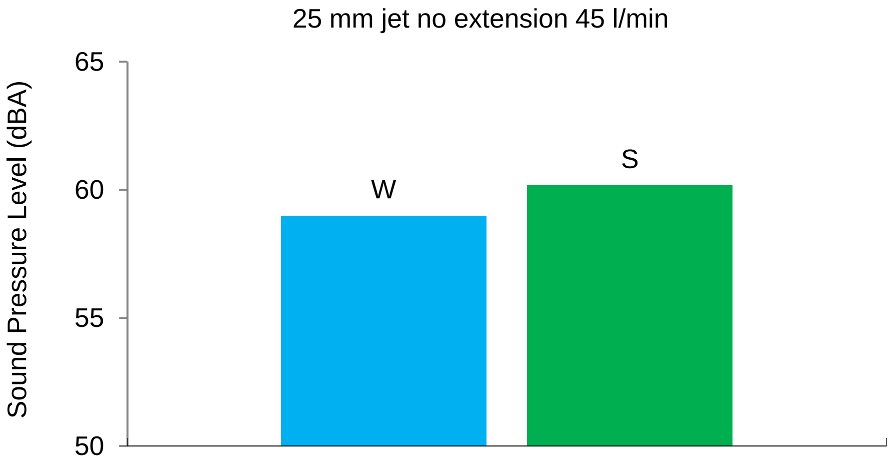


Figure G11-1

Figure G11-2



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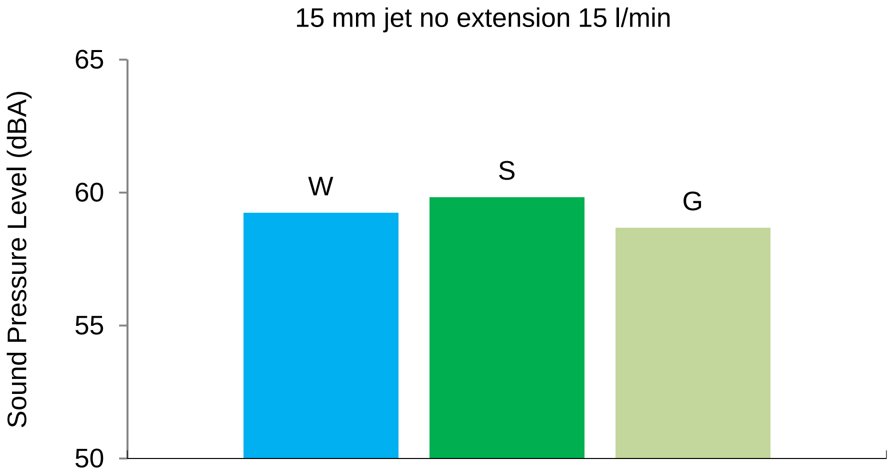

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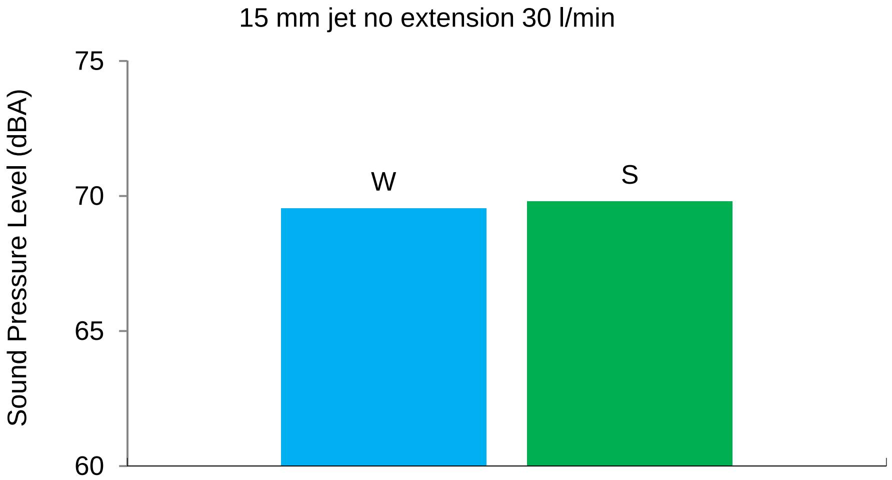

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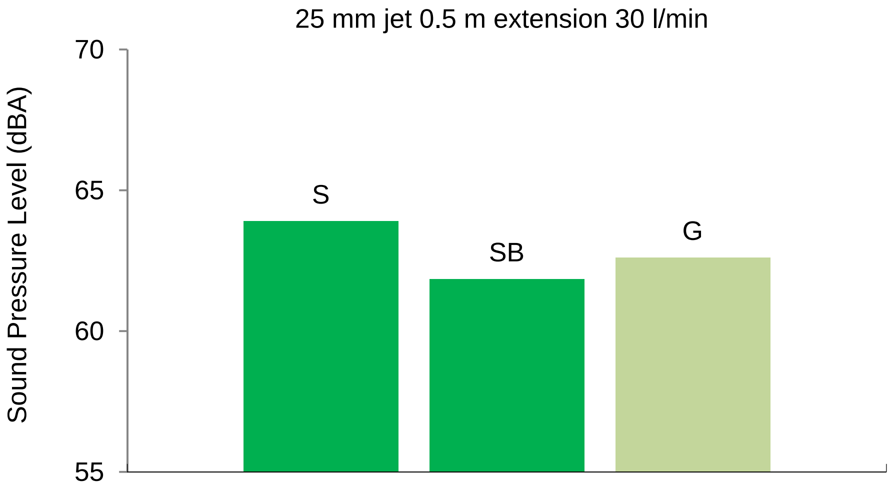

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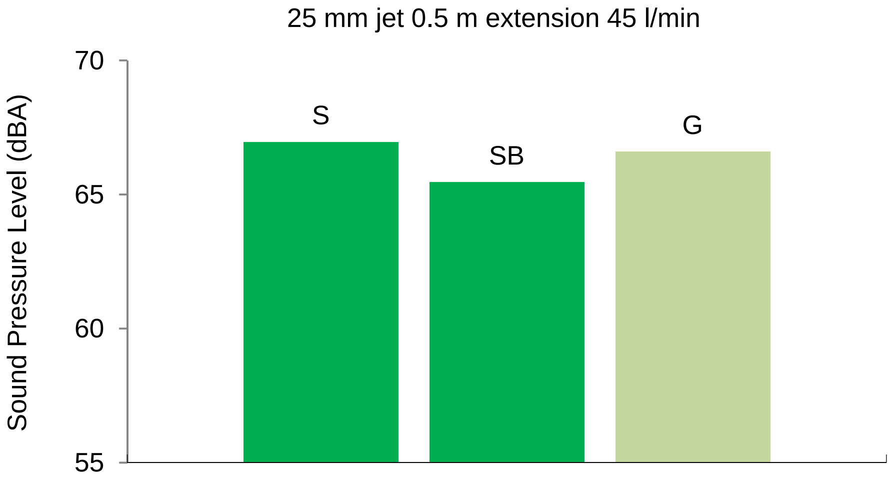

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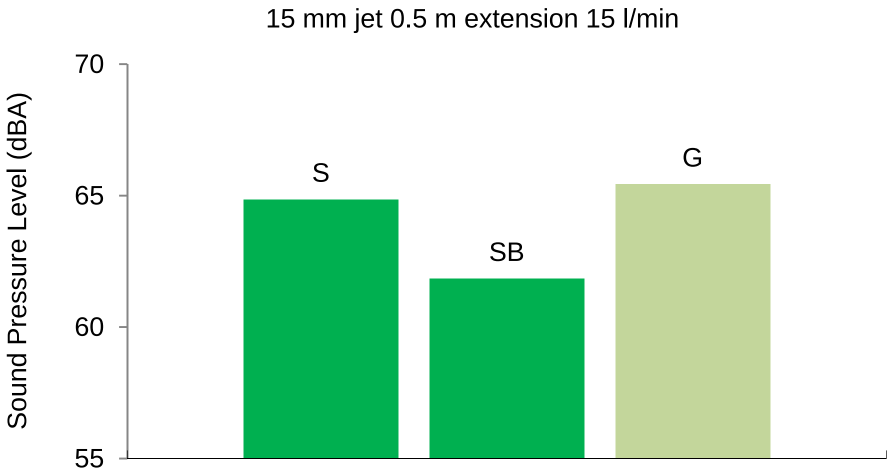
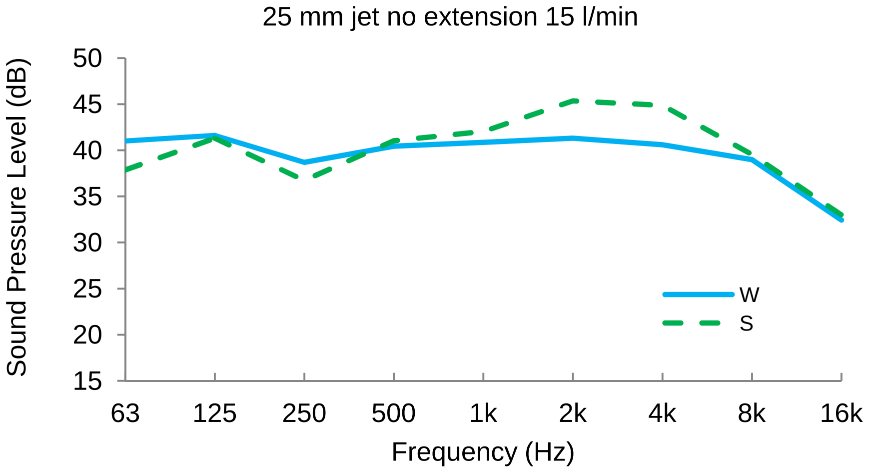


Figure G11-8

Figure G11-9



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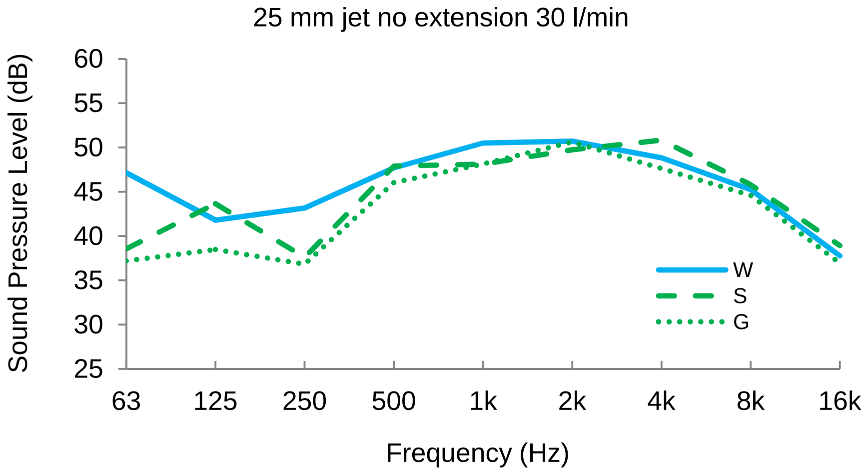

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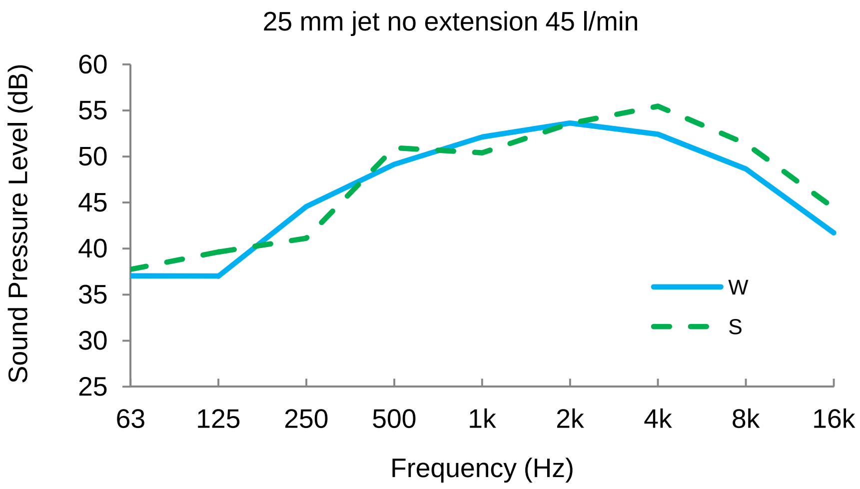

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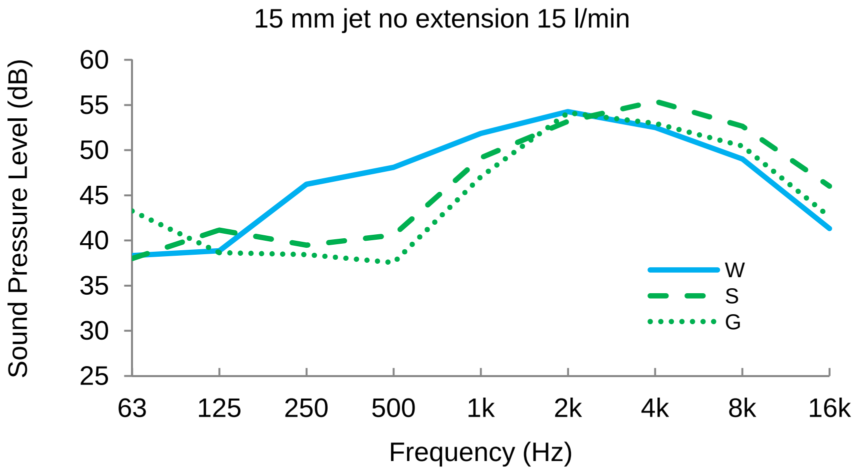

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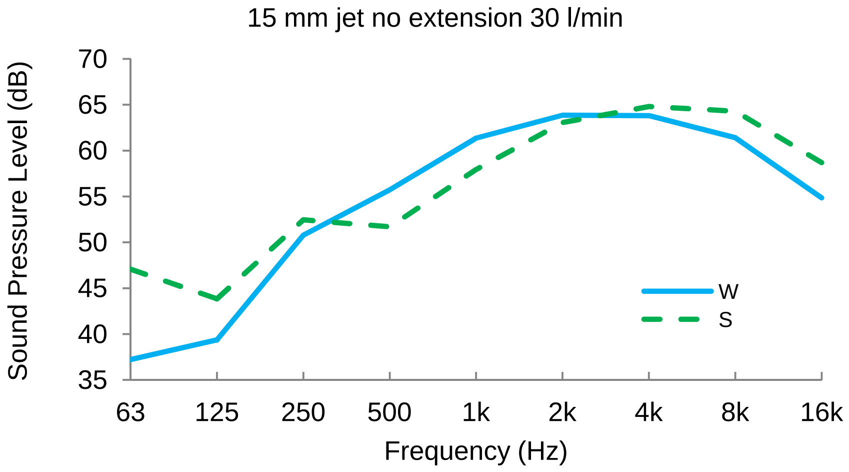

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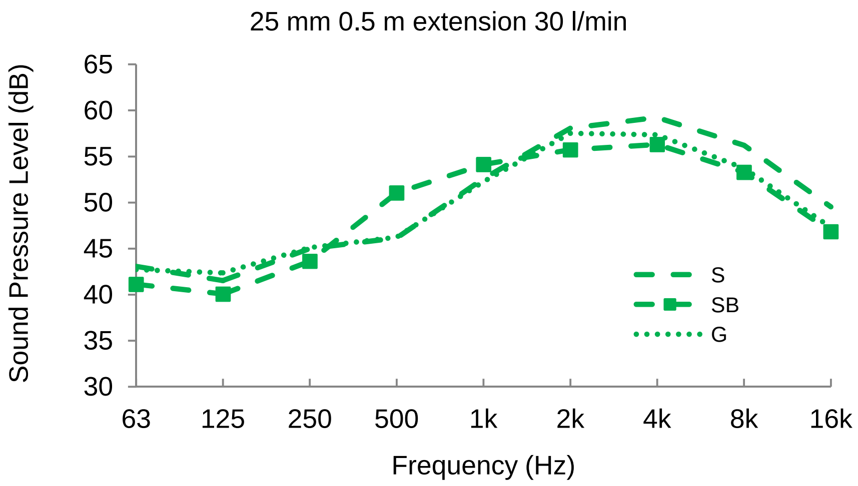

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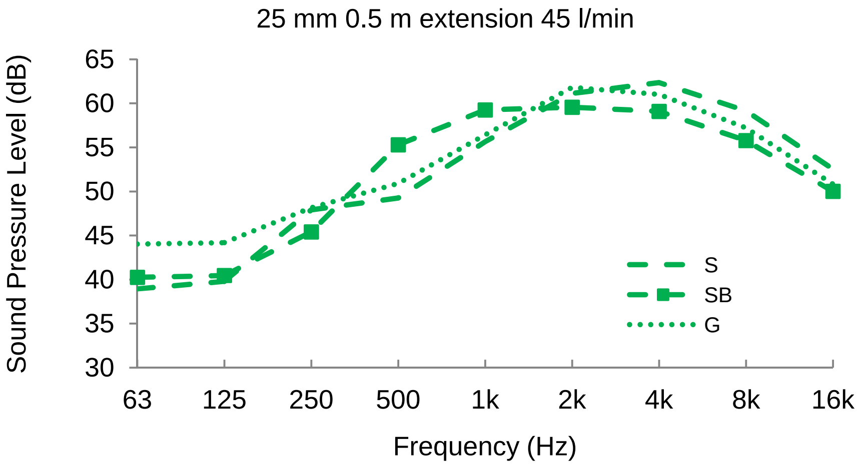

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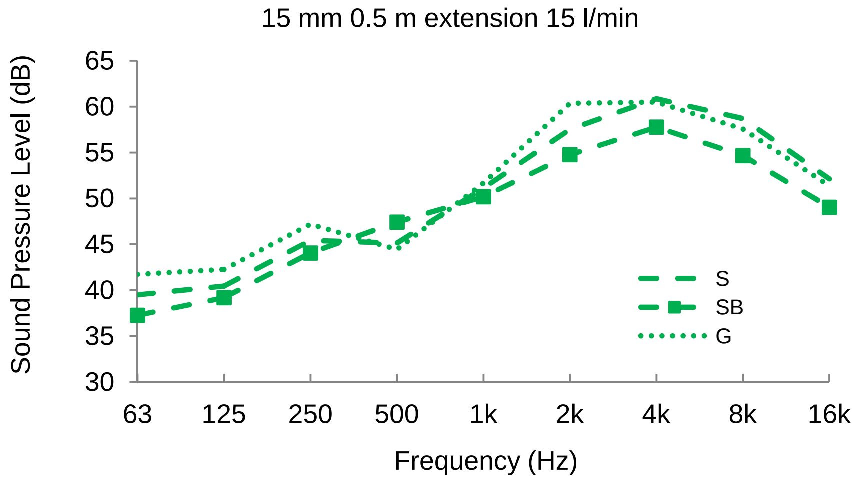

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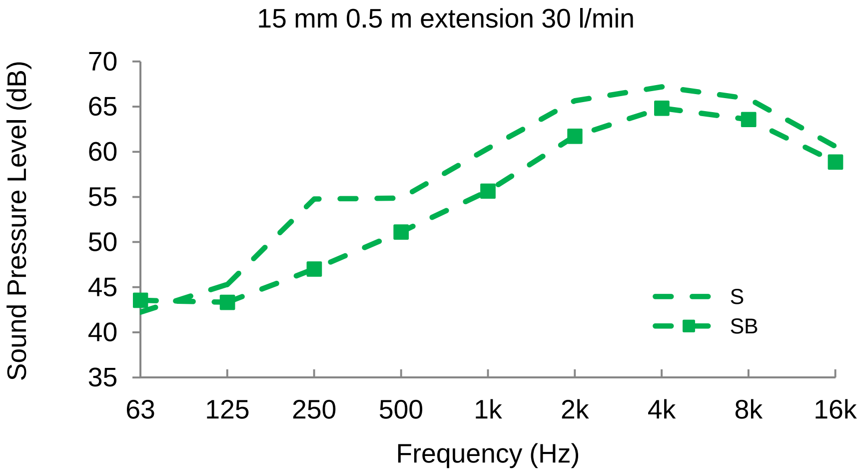
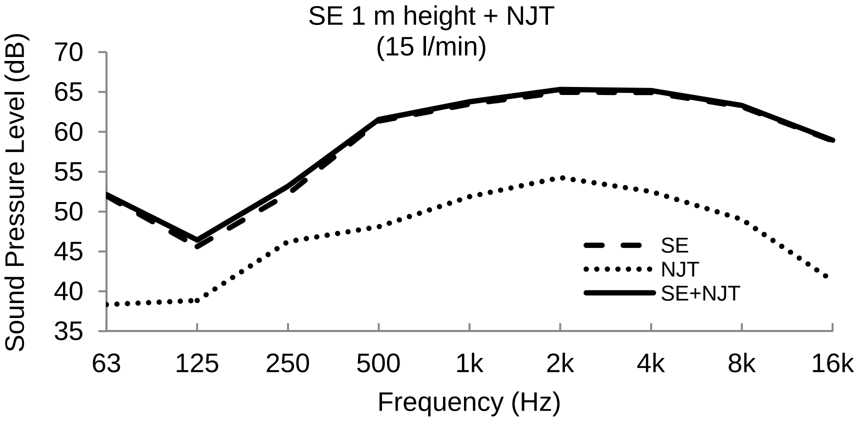


Figure G11-18

Appendix H: Combinations of water features

Spectra obtained for a number of combinations of water features. SE: sawtooth edge waterfall (1 m width). FT: fountain (37 jets). NJT: narrow jet.



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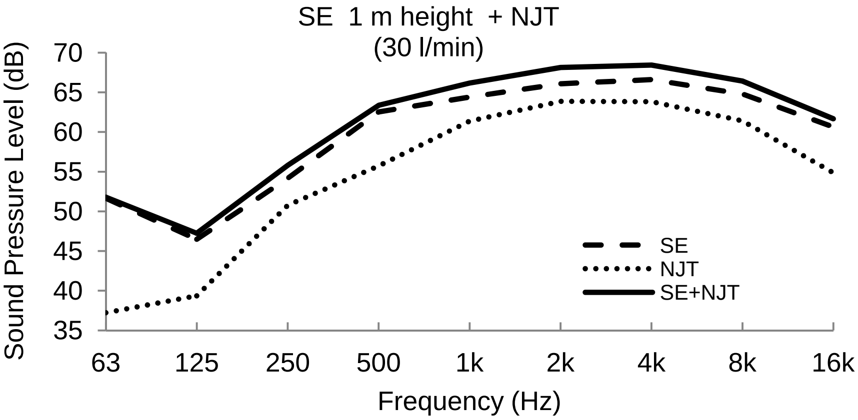

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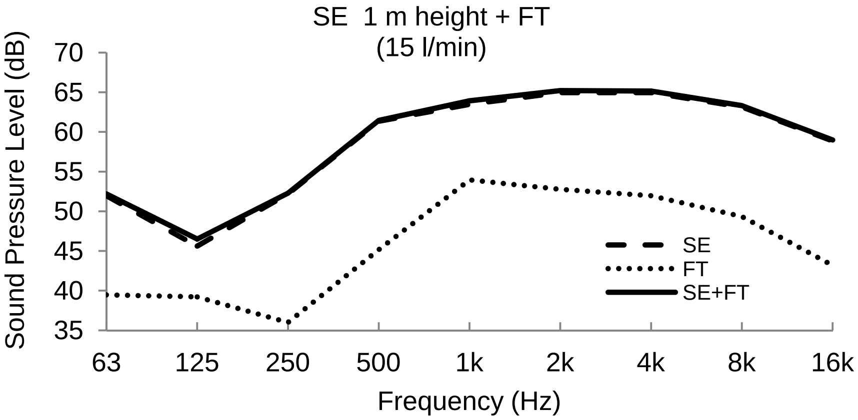

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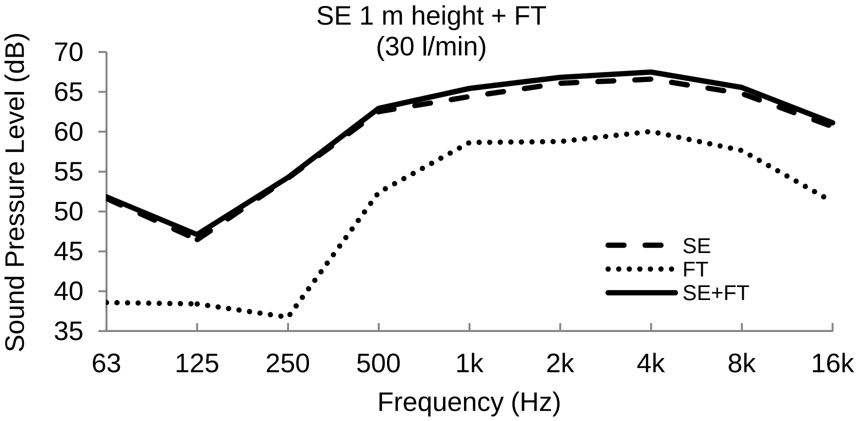

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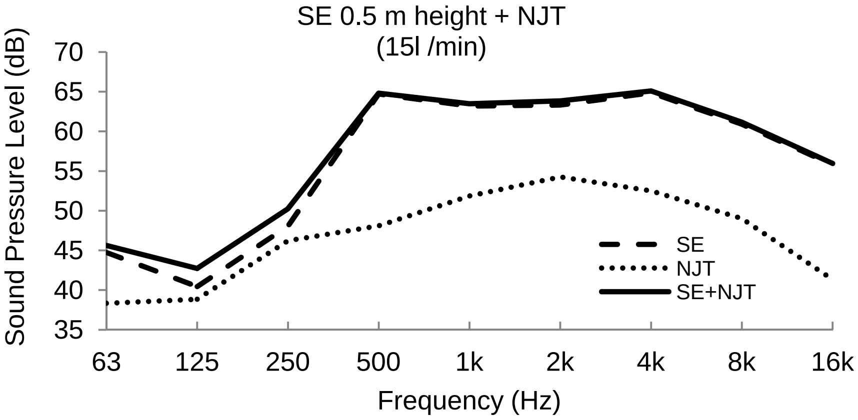

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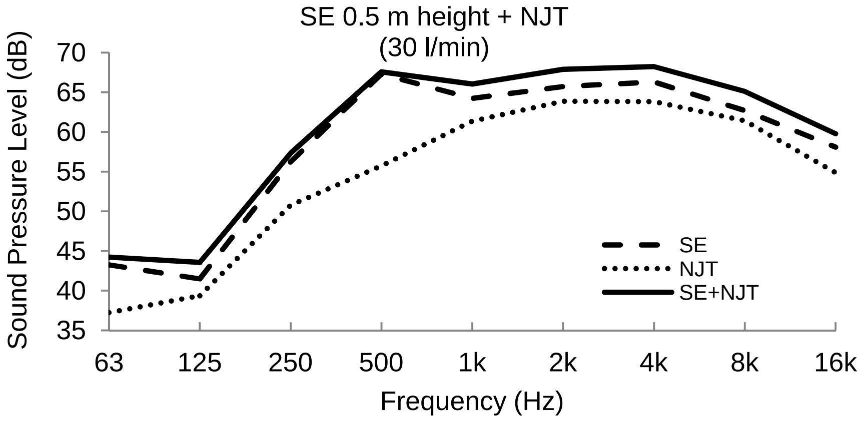

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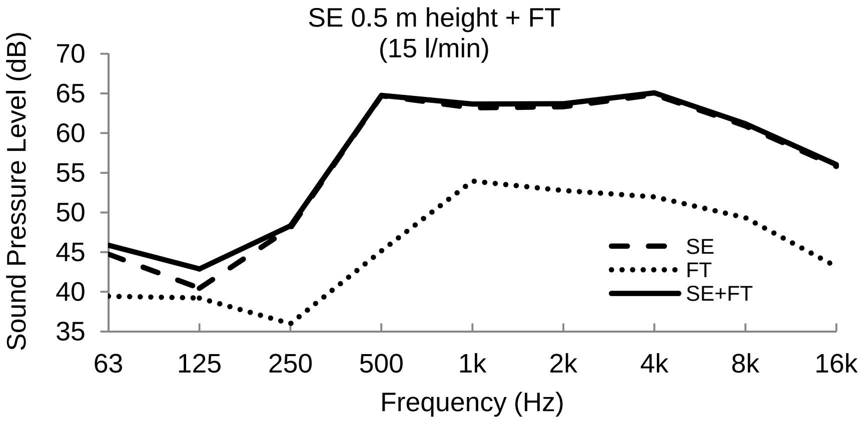

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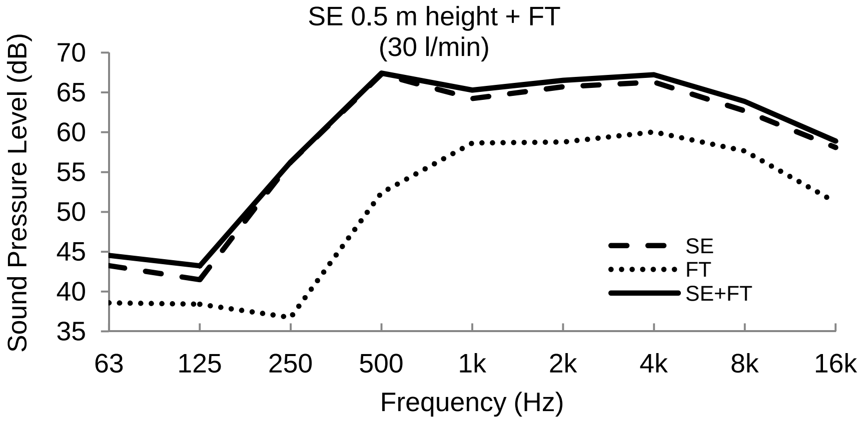

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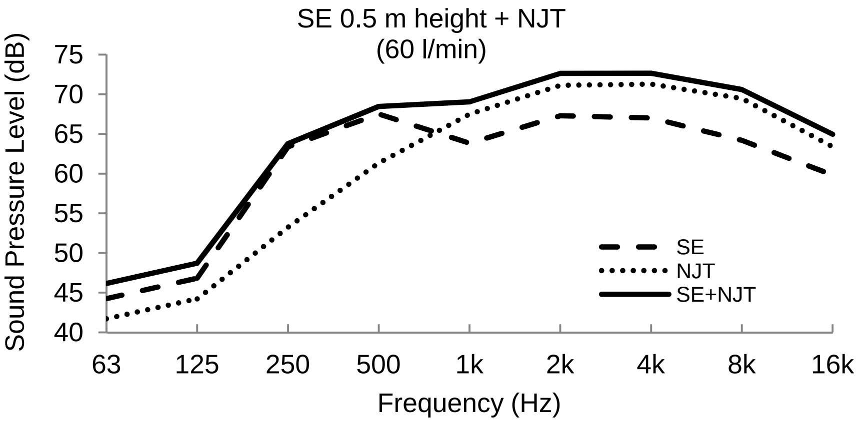


Figure H9

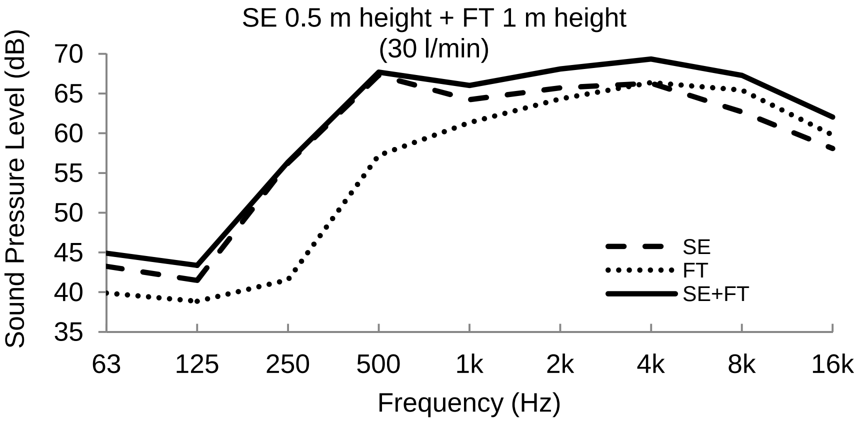


Figure H10

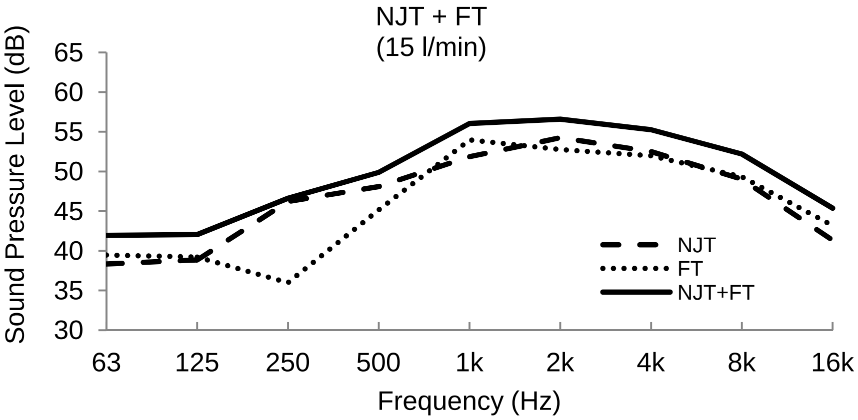


Figure H11

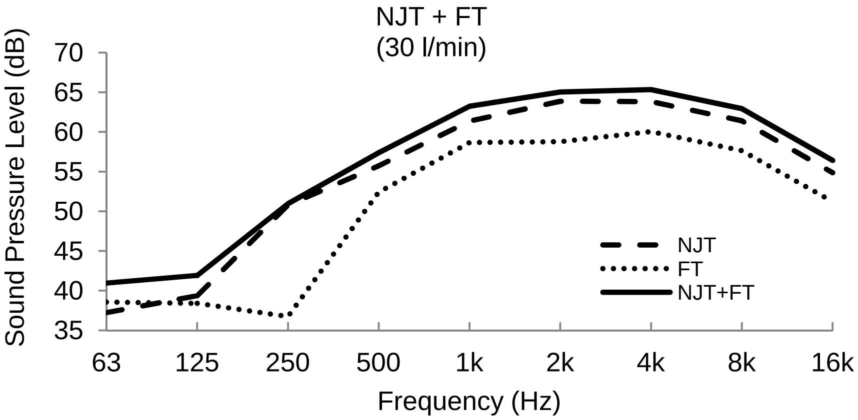


Figure H12

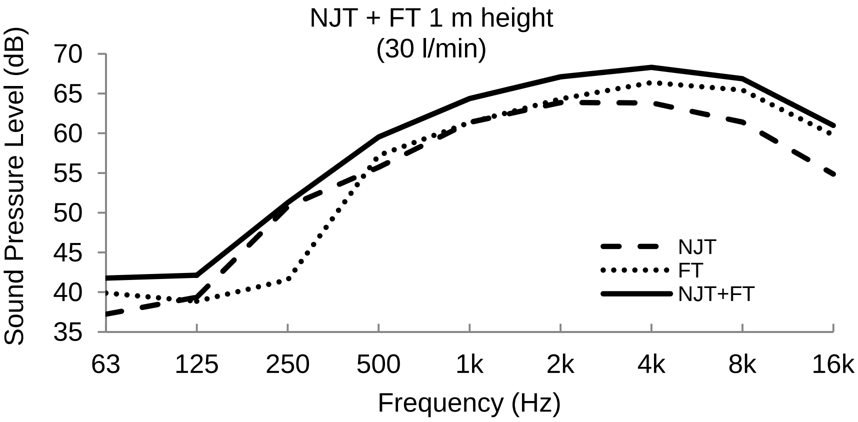
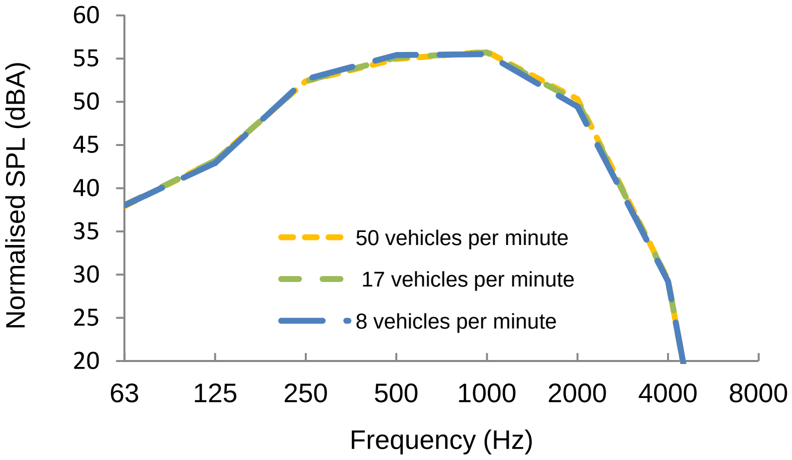


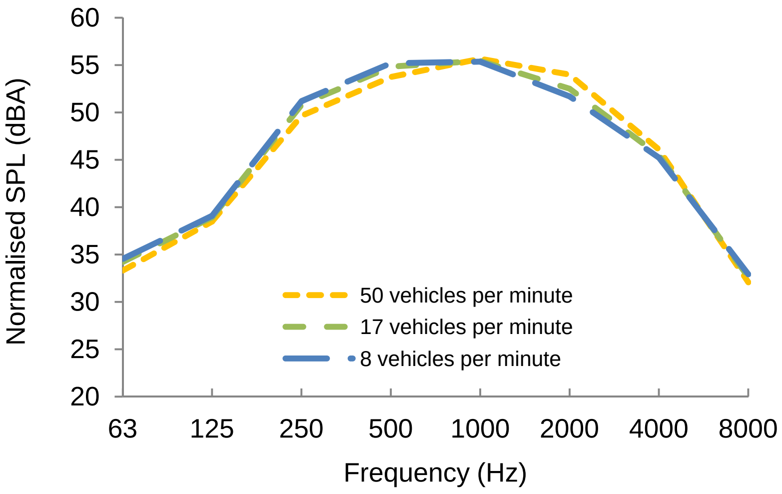
Figure H13

Appendix I: Road traffic noise predictions

Road traffic noise prediction, normalised to 60 dBA, obtained for different traffic densities and different proportions of vehicles categories.

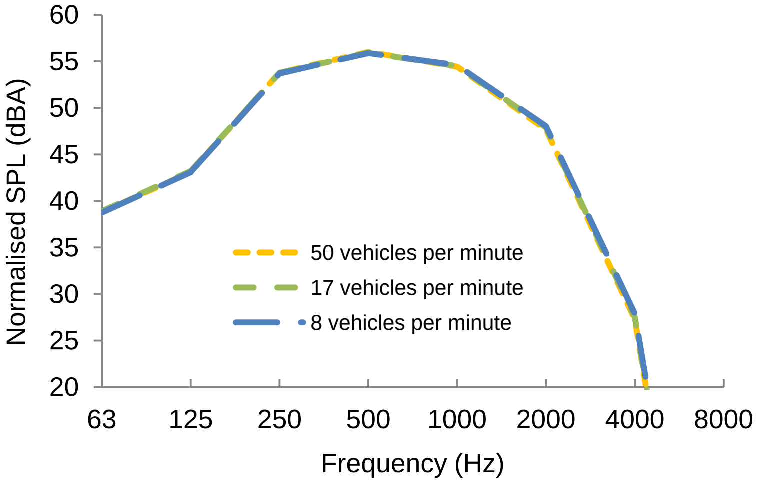


(a) Distance road receiver: 1 km

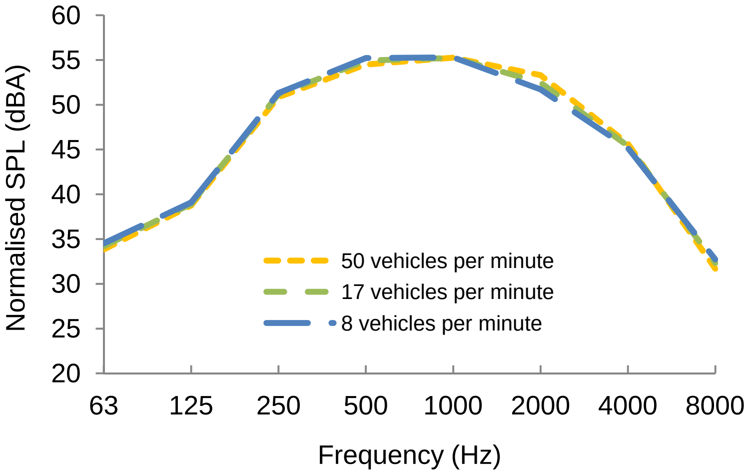


(b) Distance road receiver: 100 m

Figure I1 Normalised spectra corresponding to different traffic densities (84% Cat. 1 v_1 = 120 km/h; 6% Cat. 2 v_2 = 95 km/h; 10% Cat. 3 v = 95 km/h).



(a) Distance road receiver: 1 km



(b) Distance road receiver: 100 m

Figure I2 Normalised spectra corresponding to different traffic densities
(30% Cat. 1 v_1 = 120 km/h; 20% Cat. 2 v_2 = 95 km/h; 50% Cat. 3 v_3 = 95 km/h).